「Science of Hybrid Quantum Systems」

Project Period

2014FY～ 2019FY

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1. Preface

The Grant-in-Aid for Scientific Research on Innovative Areas "Science of Hybrid Quantum Systems" (HQS project) pursues the basic science of hybrid quantum systems. It is intended to establish a quantum coupling between different physical quantities, such as charge, Cooper pair, spin, nuclear spin, photons, and phonons, leading to various high-sensitivity sensors, highly-sensitive measurements of physical properties, and the development of new physics. By exploring so-called *Quantum Enabled Technology* that makes the best use of the functions of a hybrid quantum system, we discuss impact on a wide range of fields from science and engineering to medicine. The exploration of quantum entangled physics for various materials and physical quantities is a run-up to the quantum network.

The HQS project started in July 2015 to promote the above mentioned research fields. The main streams of quantum science and quantum technology at that time were quantum information processing, such as quantum cryptography, qubits on the basis of superconductivity, electron spin, atom and ion traps, and to integrate them toward quantum computers. The project began with the finding that there was a different approach from integrating the same type of qubits, and much of the interest in quantum science went in such a direction. Even with a small number of qubits, we have achieved unprecedented sensitivity of sensors. By developing quantum transducers with different physical quantities, we can exchange quantum information on different scales such as energy and distance. An attempt at developing a new quantum technology has started.

The planned research areas of this project were divided into four groups, A01-A04. The A01group studied the control of quantum coupling of charge (including Cooper pair), spin, and nuclear spin, and extended this to the coupling with photons and phonons. The A02 group pursued the establishment of advanced control technology for photons and the quantum coupling between photons and other physical quantities, and A03 pursued the establishment of advanced control technology for phonons and the quantum coupling between phonons and other physical quantities. The A04 group promoted the theoretical framework for advancing hybrid quantum science. This group not only theoretically supported the interpretation of various experimental results obtained from A01 to A03, especially new hybrid phenomena, but also played an important role in bundling the entire field and showing the heart of hybrid quantum systems.

A unique feature of the Grant-in-Aid for Scientific Research on Innovative Areas is the existence of open research proposals. In open research proposals, researchers who were working on coherent control of various physical systems, those who were researching classical systems but wanted to expand their research in the quantum direction by using their technologies, or those who wanted to break new ground in collaboration with researchers already participating in the HQS project conducted many wonderful studies. I was first worried that it would be difficult to collect open research proposals due to the characteristics of the research areas of the HQS project, but partly due to the relatively large budget, there were many interesting applications. We were able to adopt such high-quality research. In fact, there were many open research proposals that obtained excellent results comparable to planned research. The joint research with planned research group was also actively conducted. The headquarter management actively supporting the equipment sharing and the travel expenses required for joint research also worked in a positive direction. I believe that the all areas were united, and we were able to open up a new horizon of quantum hybridization, although it is still not enough.

Since the physical quantities are different, when researchers who have been conducting research on electric charge, electron spin, nuclear spin, photons, and phonons gathered, there was a concern that it was just a random mixture. When the HQS project started, this was the case in certain instances. However, the collaborations within the different areas have steadily progressed, and this “random” impression has faded year by year. As a representative of the HQS project, I am very pleased with this change.

As a number of joint studies progressed, some interesting directions came about. In spite of the collaboration regarding state-of-the-art technologies for the control of charge, spin, photons, and phonons toward quantum coupling, quantum control is not easy, so we could not reach “hybrid quantum” in some cases. Even in such a situation, some classical hybridizations not reaching quantum showed wonderful functions that had not existed. Just as hybrid vehicles have hybridized gasoline and electric vehicles, "hybrid quantum" has emerged as having a different meaning from quantum transducers, hybridizing classical and quantum systems in the areas of charge, spin, photons, and phonons. There may be various opinions, but I have abandoned the idea that the HQS project must be 100% quantum, and managed to actively support interesting initiatives that have emerged through hybridization regardless of “classical” or “quantum”. Many of the research areas of the HQS project involve pure basic researches, and it is difficult to directly apply such research to applications, but I believe that some of these results have attracted the interests of companies.

More importantly, through the interaction of planned research group on charge/spin, photons, phonons, theory, and open research proposals, different views on how to proceed with research and how to measure the characteristics were exchanged. I hope that we can promote hybridization as researchers and even as people by interacting with many others beyond the existing boundaries. When considering the current world situation, it is important as a researcher and as a person to maintain a hybrid sense in various aspects.

This booklet is intended to introduce the activities of the HQS project over the past five years and the research results. First, it introduces the organizations and participants of our project, and the purpose and outline of the research areas. In particular, it was glad to see that young researchers played the important roles in this project. After briefly introducing the degree of achievement of research objectives in the project, this booklet introduces 72 examples of the main results from the project’s activities. The final report is in Japanese, although both Japanese and English versions are posted for the main results. Here, we plan to provide an English version on the Web focusing on the important parts. Finally, I will list achievements, such as publications, invited talks, and awards. Please forgive us not completely covering all, because many members have participated and the project lasted for 5 years. I hope that this web booklet will help you understand the project, Grant-in-Aid for Scientific Research on Innovative Areas "Science of Hybrid Quantum Systems" (HQS project) and serve as a reference for your future research.

Project Leader, Grant-in-Aid for Scientific Research
on Innovative Area "Science of Hybrid Quantum Systems"
Professor, Tohoku University

Yoshiro Hirayama

2 Organization and members

＊The research institute / department shown here is for the period of the project.

Steering Group

Title	Principal Investigator	Department, Institution	Research period
Project Leader, International Research Support Project, Project Leader	Yoshiro Hirayama	Graduate School of Science, Tohoku University	2015 - 2019FY
Charge & Spin Group Leader, International Research Support Project, Group Leader	Koji Ishibashi	Device Laboratory, RIKEN	2015 - 2019FY
Photon Group Leader, International Research Support Project, Group Leader	Kazuhiko Hirakawa	Institute of Industrial Science, The University of Tokyo	2015 - 2019FY
Phonon Group Leader, International Research Support Project, Group Leader	Hiroshi Yamaguchi	Nanostructure Technology Research Group, NTT Basic Research Laboratories	2015 - 2019FY
Theory Group Leader, International Research Support Project, Group Leader	Kae Nemoto	Principles of Informatics Research Division, National Institute of Informatics	2015 - 2019FY

Charge & Spin Group

Name	Department, Institution	Research period
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Shinji Kuroda, Open Research Proposals	Faculty of Pure and Applied Sciences, University of Tsukuba	2016 -2017FY
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Yuimaru Kubo, Open Research Proposals	Okinawa Institute of Science and Technology Graduate University (OIST)	2018 -2019FY
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Kouichi Akahane, Co-Investigator (kenkyu-buntansha)	National Institute of Information and Communications Technology(NICT)	2015 -2017, 2019FY
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Takehiko Tawara, Open Research Proposals	NTT Basic Research Laboratories	2016 -2017FY
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Tomosuke Aono, Open Research Proposals	College of Engineering, Ibaraki University	2016 -2017FY

Mio Murao, Open Research Proposals	Graduate School of Science, The University of Tokyo	2016 -2019FY
Chikako Uchiyama, Open Research Proposals	Graduate Faculty of Interdisciplinary Research Faculty of Engineering, University of Yamanashi	2018 -2019FY
Masahiko Hayashi, Co-Investigators (renkei-kenkyusha)	Faculty of Education and Human Studies, Akita University	2015 -2019FY

Advisory Boad

Domestic Adviser

Masakazu Aono	Director, International Center for Materials Nanoarchitectonics, National Institute for Materials Science
Motoko Kotani	Principal Investigator of AIMR and Professor of Tohoku University
Hiroyuki Sakaki	President, Toyota Technological Institute(TTI)
Naoki Yokoyama	Honorary Fellow, Fujitsu Laboratories Ltd.

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Ian Walmsley	Professor, University of Oxford, UK
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Tetsufumi Tanamoto	Toshiba Corporation
Eiji Fujii	Panasonic Corporation
Tatsuro Watahiki	Mitsubishi Electric Corporation

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Toru Tomimatsu	Tohoku University
Shojun Nakayama	National Institute of Informatics
Ryota Negishi	Osaka University
Daiki Hatanaka	NTT Basic Research Laboratories
Yusuke Hama	National Institute of Informatics
Masanori Fujiwara	Kyoto University
Yuishiro Matsuzaki	NTT Basic Research Laboratories, National Institute of Advanced Industrial Science and Technology(AIST)

Secretariat

Toru Tomimatsu	Tohoku University
Yoshiko Takahashi	Tohoku University

３　Purpose and outline of the project

１．Background

Research on quantum coherent manipulation of charge, spin, and nuclear spin in quantum nanostructures were actively studied worldwide with the aim of quantum computation, thus having a significant impact as a new quantum manipulation of physical quantities. The development of quantum operation appeared from other viewpoint, which was different from the direction toward large-scale quantum computation. The D-Wave machine, which executed quantum simulations in a much simpler manner than ordinary quantum computation, had gained considerable attention. Within such research stream, as a more familiar direction, *Quantum Enabled Technology* (science and technology made possible by the control of quantum coherence) has made rapid progress worldwide, for example, for quantum high-sensitivity measurement based on quantum coupling. Such measurement is the basis of science and technology and is expected to be applied in a wide range of fields from science and engineering to medicine. The internal and external research activities promoted toward this direction revealed that the method of transferring quantum entanglement between different physical systems has played an essential role. That is, to achieve this *Quantum Enabled Technology*, a small-scale quantum-transducer function of various physical quantities is indispensable. In particular, photons and phonons are important for transporting quantum information to different locations and placing them on the measurement system. Photons have been widely recognized as a medium for connecting quantum systems, but the importance of phonons has recently attracted; thus, research on phononic crystals as well as photonic crystals has been conducted.

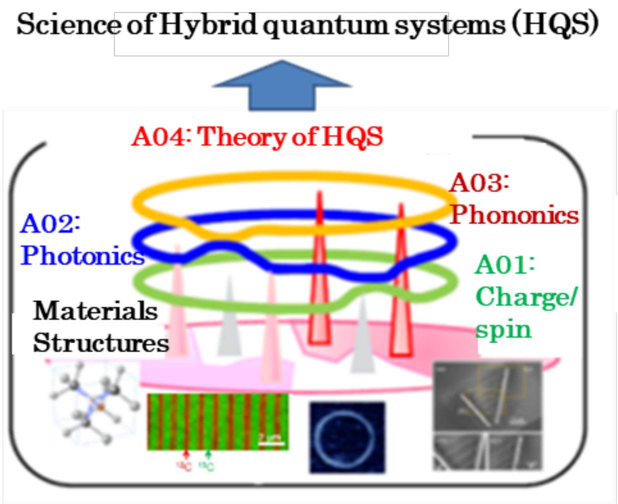

Fig. 1
Schematic diagram of our project

Taking these situations into consideration, a group of researchers active in the charge (including Cooper pair), spin, nuclear-spin, photon, and phonon research fields gathered to investigate a small but innovative hybrid quantum system between different physical quantities. They proposed establishing a project on the basis of *Quantum Enabled Technology*. Figure 1 illustrates a simple concept at the time of establishing the HQS project. This project was composed of researchers who were studying in the fields of charge (including Cooper pair), spin, nuclear spin, photons, and phonons. In particular, photons and phonons are indispensable for transferring signals over long distances and combining different quanta separating a long distance in the medium. Therefore, we strengthened photon- and phonon-related studies by setting independent planned research groups (A02 and A03). In addition, researchers of nanomaterials and nanostructures were involved because establishment of quantum coupling of various physical quantities asked new materials and innovative structures. Since the fusion of theory and experiment is indispensable in hybrid quantum science, in addition to A01 planned research (charge / spin), A02, and A03, the world's leading theoretical researchers in hybrid quantum science were assigned to A04 planned research (theory). There were only four planned research groups and no sub-groups were inside the planned research groups. This was a strategy to avoid subdividing for the sake of mutual collaboration. Various hybridizations are the most important initiatives in this project, we aimed to promote the fusion within planned research and between planned research groups by not subdividing. Furthermore, we actively adopted open research proposals that span each planned research groups, and endeavored to further promote the integration of the entire project.

2. Importance of HQS project from the perspective of improving and strengthening Japan's academic standards

There are four important roles of the HQS project from the perspective of improving and strengthening Japanese academic standards. The first role, through the HQS project, it was possible to develop in the direction of further using the superior research possessed by the participating members and contribute to the improving Japan's academic standards in each area. The A01 planned research group leaded the world in controlling charge (including Cooper pair) and electron spin, coupling between electron-spin and nuclear-spin systems, and metrology based on nuclear spins. By adding new directions to these research directions, their respective academic standards have been strengthened. The same can be said for A02 and A03. The A02 group developed world-leading research on optical control using photonic crystals, the coupling between THz and quantum structures, and the coupling between NV centers in diamonds and electromagnetic waves. The A03 group developed a phononic crystal by giving a periodic structure to an elastic body and made a world-leading contribution to the electrical control of phonon propagation. By adding new directions to these research activities, their respective academic standards have also been strengthened. The A04 planned research group had many world-class active members advocating *Quantum Enabled Technology*. In this group, the level of research raised by pursuing issues while discussing with experimental groups. Furthermore, the level of each research was further improved by collaborating with excellent open research proposals.

The second important role, and most importantly, the world-leading research groups in each quantum system have come together to collaborate with front-line theoretical research, achieving exciting hybridization in this project. Through their innovative and creative achievements described later, we can contribute to the strengthening of Japanese academic standards in the field of quantum hybridization, which is becoming increasingly important worldwide. By pushing integrated research straddling planned research in the entire project including open research proposals, innovative studies that would not have been possible without this project have launched. Some of the results are very important and will play a major role in improving and strengthening the academic standards of Japan.

The third important role is of the world-leading groups in nanotechnology participating in the project because new nanomaterials and nanostructures are indispensable for conducting highly-sensitive quantum measurements in various fields. Japan has a strong background in nanotech materials and nanostructure fabrication technology. However, many groups have focused on classical devices. By presenting a new research direction of hybrid quantum systems to these groups, it is expected that high-level technologies and expertise find a new direction and contribute to the further development of nanotechnology in Japan. The involvement of the nanotechnology groups was useful for the entire project in that new materials and structures could be seamlessly introduced into a quantum hybrid system.

The fourth important role is involving a wide variety of fields in hybrid quantum systems. We can broaden the base of researchers in quantum science, especially for young researchers. Our project is useful in solving the problem of not enough quantum researchers at Japanese universities. Since the research activities in this project do not aim for large-scale quantum integration, each group was able to work on quantum science at their own base, which helped to expand the groups researching quantum science in Japan. In particular, the Young Committee in the project contributed significantly to this. Considering the importance of quantum technology field in the future, raising the level of quantum science at universities is important from the viewpoint of improving and strengthening the academic standards of Japan.

3. Development and completion of the project studies, expectation for the future

While research on quantum transducer functions in various physical systems has progressed through the achievements of the entire project, the meaning of "hybrid quantum" has expanded. There are various stages in a hybrid quantum system, from 100% classical to 100% quantum. It is noteworthy that we can show the attractive functions even if they are not 100% quantum. They are also important for expanding hybrid quantum system to the industrial world.

Each planned research group has conducted research on topological insulators and topological Josephson junctions, high-sensitivity measurements using the correlation between electron-spin and nuclear-spin systems, quantum correlation of double-spin systems, and various quantum technologies based on theory. A representative example of theoretical success is demonstrating the possibility of and proposing a quantum measurement method for obtaining quantum gain even under realistic noise. We succeeded in showing the theoretical framework of hybrid quantum science of various physical systems in the energy domain spanning several digits. The fusion in this project was used to apply these theoretical findings to an experimental system.

Regarding the sophistication of photon and phonon control in this project, we developed circularly-polarized light emission from quantum dots controlled by chiral photonic crystals, development of the topological photonics field where the concept of topology is applied to photonic crystals, demonstration of optical waveguides without back scattering, ultra-sensitive and local measurement based on the NV center in diamonds, and the pioneering development of phononic crystals with various unique functions. Mechanical oscillators are a typical example of a "macroscopic" physical system, and can form "entangled states" with electrons, spins, and photons, which are representative of "microscopic" physical systems. It is an important platform that can challenge the fundamental proposition of how the macroscopic routine world and the microscopic system dominated by quantum mechanics are continuously connected. This direction of research naturally has high academic impact for the future.

Furthermore, as an innovative and creative part of this project, the hybridization of charge, spin, photons, and phonons has progressed beyond planned research groups and open research proposals. One impactful outcome for the future is the hybridization between charge, phonons, and THz photons by a single molecule trapped in a metal nanogap. This opens the door to a new discipline called "THz nanoscience" and shows the possibility of quantum coupling of charge, spin, phonons (molecular vibrations), and THz photons. In the hybridization of mechanical vibration and THz electromagnetic waves in a mechanical resonator structure, THz detection performance exceeding that of current devices was demonstrated before going to quantum coupling.

The researchers successfully demonstrated quantum coupling between spin and superconducting quantum systems. Nanofiber resonator quantum electrodynamics (QED) systems connected by optical fibers were also constructed. They are the basis of an original quantum network in which many resonator QED systems are coherently coupled via photons and phonons. Research has also progressed on superconducting qubits, electron/nuclear spins interactions expected as quantum memories, and novel mechanical systems as interfaces for different physical systems and photons that propagate quantum states over long distances. It is widely recognized that these may be the key to future quantum networks.

4. Main research results

Charge / spin planned research (A01) and related open proposals

This group pursued single and collective manipulation of electrons, Cooper pairs, electron spins, and nuclear spins as quantum information carriers, elucidating their background physics. This group also pursued quantum transducer function between them and photons and/or phonons. Since it is necessary to hybridize materials to hybridize quantum systems, the group expanded their research to new material systems such as carbon nanomaterials and topological insulators in addition to traditional semiconductor nanostructures. To meet the above goals, they established quantum control of electron spins and nuclear spins in novel systems consisting of silicon and compound semiconductor micro/nanostructures, and conducted highly-sensitive measurements on the basis of nuclear-spins. They also succeeded in enabling quantum control of excitons in carbon nanotubes. Furthermore, they clarified the mechanism of interaction between spin systems and microwave photons or phonons toward the hybridization of different physical systems. These results are expected to develop into hybridization of heterogeneous quanta in quantum information processing and quantum measurement. As a unique material system, this group was able to obtain a foothold in the physics of quantum states with magnetic topological insulators based on laminated and thin films, and hybrid structures of topological insulators and superconductors.

Photon planned research (A02) and related open research proposals

This group promoted research toward the quantum-transducer function based on the basis of photons and sophisticated photon control necessary for its development. To this end, they developed ultra-sensitive/local quantum measurement technology using NV centers in diamonds and had significant achievements such as achieving the world's longest T_2 time at room temperature for solid-state electron spin, world's first electrical detection of nuclear-spin-coherence, and world's highest magnetic field sensitivity by a single NV center. With the advancement in nanophotonics, the group succeeded in controlling circular polarization emission from quantum dots embedded in three-dimensional chiral photonic crystals. In addition, innovative developments such as orbital momentum control of light and topological photonics, which were not envisioned at the time of planning, were achieved. Attempts to coherently couple a nanofiber cavity-QED system of a resonator by an optical fiber network have also made significant progress. Moreover, using a metal nanogap electrode operating as a THz antenna, a single molecule was trapped and the effect of molecular vibration on electron transport was clarified. This result opened up the field of THz spectroscopy and laid the foundation for quantum hybridization of charges, phonons, and THz photons based on a molecule. It is also noteworthy that a novel high-performance THz detector was demonstrated using mechanical resonance characteristics.

Phonon planned research (A03) and related open research proposals

This group promoted research with the goal of improving the quantum-transducer function based on the basis of phonons and sophistication of phonon control toward its practical application. To this end, phononic crystal fabrication technology and quantum hybrid structure fabrication for quantum dot mechanical resonators have made significant progress, and completely new nanostructure fabrication technologies, such as isotope control of graphene growth, have been established. Regarding functional operation using quantum properties, the group developed ultra-sensitive vibration sensors using quantum dots and a technology toward quantum entanglement state generation between nuclear spins and phonons. They also demonstrated an opto-electromechanical hybrid system through the fusion of bottle-type optical resonators and semiconductor electromechanical resonators. The acquired basic technologies will be a milestone for future quantum transducers. They also proposed and demonstrated phonon conduction control focusing on the quantum nature of phonons. These achievements have created sufficient academic value and new technologies, and their objectives have been achieved at a high level.

Theoretical planned research (A04) and related open research proposals

The group proceeded with research aimed at creating a systematic theoretical study for hybrid quantum science, design guidelines and proposals for the development of *Quantum Enabled Technology*, and theoretical understanding of hybrid quantum systems in various physical systems. To achieve this goal, the phenomena of various physical systems, such as charge, spin, photons, and phonons in various fields such as quantum optics, superconductivity, semiconductor condensed matter physics, and nanostructured physics are fused, reaching universal physics and concepts through hybridization. Specific examples include several orders of magnitude expansion in the energy region of super-radiance phenomena in hybrid quantum systems. In addition, the properties of carbon nanotubes as topological insulators were clarified as well as the effect of phonons on the behavior of hybrid quantum systems. They also developed a quantum measurement method for demonstrating quantum superiority even under realistic noise through the use of new resources made possible by hybrid quantum systems and hybridization with quantum protocols such as quantum teleportation. By understanding the quantum transducer universally, the features and problems commonly found in the design of various combinations were clarified as design knowledge.

During the period of this project, we published many high-impact papers, including 1 in Nature, 1 in Nature Physics, 2 in Nature Photonics, 3 in Nature Nanotechnology, 16 in Nature Communications, 3 in Communications Physics, 4 in Science Advances, and 17 in Physical Review Letters. Reflecting a high level of research achievement, paper publication was active throughout the entire project.

The following is an overview of 72 examples from the main results. As mentioned above, hybridization has been actively promoted in this project, and there are many results that span planned research groups and open research proposals. Therefore, individual achievements will be posted in the form of summarizing the achievements of related fields regardless of the planned research groups from A01 to A04.

Best magnetic-field sensitivities with single NV centres at room temperature

E. D. Herbschleb[1], H. Kato[2], Y. Maruyama[1], T. Danjo[1], T. Makino[2], S. Yamasaki[2], I. Ohki[1], K. Hayashi[1], H. Morishita[1], M. Fujiwara[1], N. Mizuochi[1]
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Solid-state spins are a leading contender in quantum technology. Enhancing the inhomogeneous spin-dephasing time (T_2^*) and the Hahn-echo spin-coherence time (T_2) is a central issue. The electron spin plays a significant role for quantum sensing and for coherent connectivity with other qubits such as photons, nuclear spins, and superconducting qubit. Therefore, the coherence times define the physical behavior of the quantum device, and their improvement allows new perspectives for quantum applications.

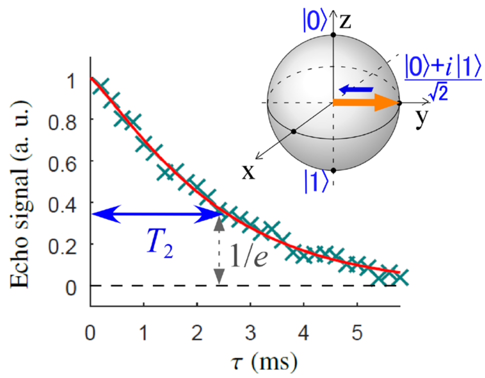

Figure 1. Results of Hahn-echo signal. The exponential-decay fit with line, T_2 = 2.43 ms.

From the viewpoint of material science, enhancements of T_2^* and T_2 have been realized by development of growth techniques. Although enrichment of the spin-zero ^{12}C and ^{28}Si isotopes greatly reduces spin-bath decoherence in diamond and silicon, the solid-state environment provides undesired interactions between the electron spin and the remaining spins of its surrounding. Here we demonstrate, contrary to widespread belief, that an impurity-doped (phosphorus) n-type single-crystal diamond realizes remarkably long spin-coherence times. Single electron spins show the longest inhomogeneous spin-dephasing time ($T_2^* \approx 1.5$ ms) and Hahn-echo spin-coherence time ($T_2 \approx 2.4$ ms) ever observed in room-temperature solid-state systems, leading to the best sensitivities. The AC magnetic field sensitivity, estimated to be 9.1 nT/(Hz)$^{1/2}$, is improved by almost a factor of two compared to previous results. The reasons for this improvement are the longer T_2, the larger Rabi contrast and the slightly higher photon count due to n-type diamond.

That the doping of phosphorus extends the spin-coherence times and gives better magnetic field sensitivities is against intuition, because phosphorus is paramagnetic at room temperature in diamond. During the CVD growth, it is known that many vacancies are generated, which causes generation of thermally stable impurity-vacancy and multi-vacancy complexes. However, their generation can be suppressed by Coulomb repulsion of charged vacancies in n-type diamond. We discuss the origin of noises by measuring noise spectroscopy and T_1 measurement.

Our research opens a new avenue for further extension of coherence times of NV centres using new synthesis techniques of quantum-grade diamond. Moreover, the elongation of coherence times in n-type semiconductor diamond paves the way to the development and application of diamond-based quantum-information, sensing and spintronics devices.

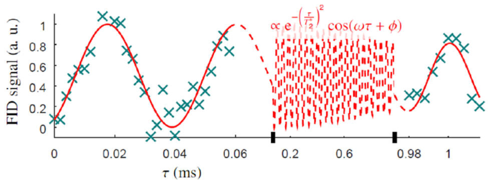

Figure 2. Result of FID measurement (data with crosses, sinusoidal exponential-decay fit with line, T_2^* = 1.54 ms).

Reference: E. D. Herbschleb, H. Kato, Y. Maruyama, T. Danjo, T. Makino, S. Yamasaki, I. Ohki, K. Hayashi, H. Morishita, M. Fujiwara, N. Mizuochi, “Ultra-long coherence times amongst room-temperature solid-state spins”, Nature Communications, 10, 3766 (2019)., DOI : https://doi.org/10.1038/s41467-019-11776-8

Room Temperature Electrically Detected Nuclear Spin Coherence of NV Centres in Diamond

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Nuclear spins have a long coherence time (T_2) due to the good isolation from environmental noise. Therefore, they are candidates for quantum memories in quantum-information devices and quantum sensors. Using nuclear spin, diamond for quantum memories, highly sensitive magnetic sensors, quantum repeaters, quantum registers, have been demonstrated at room temperature. Previously, we proposed theoretically that hybrid quantum magnetic-field sensor with an electron spin and a nuclear spin can enhance a sensitivity.[1] In these demonstrations, the detection of nuclear spin coherence is essential. So far, NV electron spins have been detected by optical techniques and electrical techniques. The electrical technique is an important technology for developing and integrating quantum devices. Furthermore, a theoretical model predicts that its detection sensitivity is approximately three times higher than that of the optical technique. While the photoelectrical detection of the electron spin coherence of an ensemble of NV centres and photoelectrical coherent spin-state readout of single NV centres at room temperature has been demonstrated, the direct electrical detection of nuclear spin coherence remains challenging.

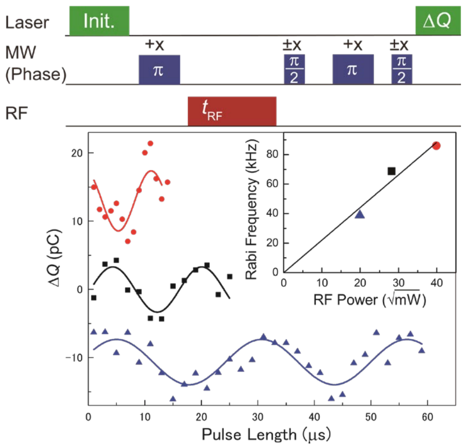

Figure 1. Pulse sequence (top) and the result (bottom) of an electrically detected nuclear Rabi oscillation. ±x indicate the phase of MW pulse. (Inset) Rabi frequencies as a function of the square root of RF power.

Here, we demonstrate electrical detection of the ^{14}N nuclear spin coherence of NV centres in diamond at room temperature. We used a pulsed electrically detected electron-nuclear double resonance technique to measure the Rabi oscillations (Fig. 1) and coherence time (T_2) of ^{14}N nuclear spins in NV centres. We observed $T_2 \approx 0.9$ ms at room temperature (Fig. 2). To the best of our knowledge, this is the first demonstrations of room-temperature electrical detection of nuclear spin coherence in diamond or any other materials. Our results will pave the way for the development of novel electron- and nuclear-spin-based diamond quantum devices.

Reference:

[1] Y. Matsuzaki, T. Shimo-Oka, H. Tanaka, Y. Tokura, K. Semba, N. Mizuochi, "Hybrid quantum magnetic field sensor with an electron spin and a nuclear spin in diamond", Physical Review A, 94, 52330 (2016).

[2] H. Morishita, S. Kobayashi, M. Fujiwara, H. Kato, T. Makino, S. Yamasaki, N. Mizuochi, "Room Temperature Electrically Detected Nuclear Spin Coherence of NV centers in Diamond", Scientific Reports, 10, 792 (2020). DOI : https://doi.org/10.1038/s41598-020-57569-8

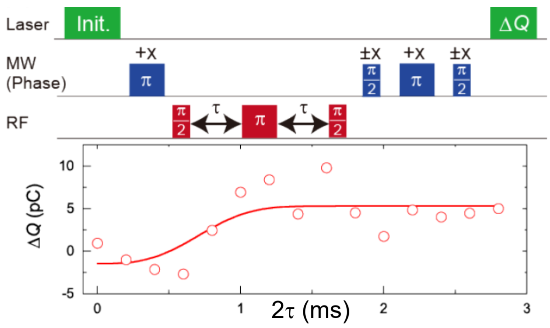

Figure 2. Pulse sequence (top) and the result (bottom) of an electrically detected spin coherence measurement of the ^{14}N nuclear spins in NV centres. ±x indicate the phase of MW pulse.

Highly Sensitive AC Magnetic Field Sensing using Nitrogen-vacancy Centers in Diamond

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[2]National Institute of Advanced Industrial Science and Technology (AIST),
[3]Institute for Chemical Research, Kyoto University, [4]NTT Basic Research Laboratories, NTT Corporation

Negatively-charged nitrogen-vacancy (NV) centers in diamond are promising for highly-sensitive nanoscale quantum sensor. It is because that spin-triplet electric ground states of NV centers can be coherently manipulated using microwave field and optically initialized/read out with long coherence time at room temperature. In this study, we propose and demonstrate two quantum protocols for highly-sensitive AC magnetic field sensing using NV center ensemble in diamond.

One of the proposed protocols is effective to improve the sensitivity for vector magnetic field sensing by multi-frequency control of electric spins of NV centers. The key idea is that four types of NV centers with different axes are simultaneously controlled by multi-frequency microwave pulses [1]. We demonstrate vector magnetic field sensing with an ensemble of NV centers in diamond via such multi-frequency control with pulsed-type measurements. We find that the sensitivity of the vector field sensing with multi-frequency control is better than that with single-frequency control for every vector component of a magnetic field [2].

Another protocol enables us to detect high-frequency (MHz range) AC magnetic field with continuous application of microwave and laser [3]. This method utilizes double resonance excitation of electron spins of NV centers. Unlike conventional methods, the proposed method does not require a pulse sequence; this greatly simplifies the procedure and apparatus needed for implementation.

Our results pave a way to implement AC magnetic sensors with high performances based on the electric spin manipulation of NV centers in diamond.

Reference:
[1] S. Kitazawa, Y. Matsuzaki, S. Saijo, K. Kakuyanagi, S. Saito, and J. Ishi-Hayase, "Vector-magnetic-field sensing via multifrequency control of nitrogen-vacancy centers in diamond", Physical Review **A 96**, 042115/1-7 (2017).
[2] K. Yahata, Y. Matsuzaki, S. Saito, H. Watanabe and J. Ishi-Hayase, "Demonstration of simultaneous vector magnetic field sensing with nitrogen-vacancy centers in diamond via multifrequency control of microwave pulses", Applied Physics Letters, **114**, 022404/1-5 (2019).
[3] S. Saijo, Y. Matsuzaki, S. Saito, T. Yamaguchi, I. Hanano, H. Watanabe, N. Mizuochi and J. Ishi-Hayase, "AC magnetic field sensing using continuous-wave optically detected magnetic resonance of nitrogen-vacancy centers in diamond", Applied Physics Letters, **113**, 082405/1-5 (2018).

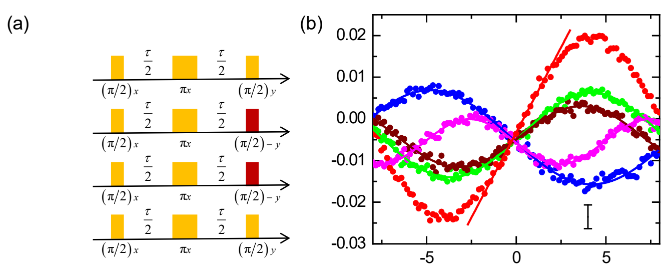

Fig. 1 (a) Microwave pulse sequence for multifrequency control of NV centers. (b) Spin echo signals vs. applied AC magnetic field amplitude using standard single-frequency control and our multi-frequency control method. Multifrequency control leads to the enhancement of the signal.

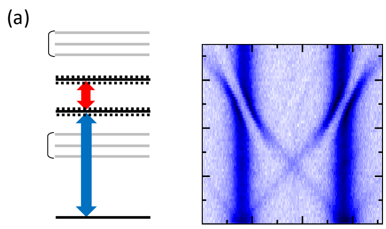

Fig. 2 (a) Energy levels of the NV centers with applied magnetic fields perpendicular to one of the four possible crystallographic axes. (b) CW-ODMR for different frequencies of the applied MW and RF fields.

Microwave Imaging in Micrometer Resolution

− Precision measurement of microwave field-distribution using Rabi oscillations −

Shuhei Nomoto[1], Giacomo Mariani[1], Satoshi Kashiwaya[2], and Shintaro Nomura[1]
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Nondestructive imaging is widely used in material characterization, medical examination, border security, and so on. The most commonly used nondestructive imaging system utilizes X-rays for applications such as medical imaging. The spatial resolution of X-ray imaging is high due to the short wavelength of less than 10 nm. However, regulatory dose limits restrict application areas of X-ray imaging. Microwave imaging may be used in areas where X-ray exposure should be avoided, and may extend the application areas of nondestructive imaging further. Antenna array has often been used for microwave imaging, but complex analysis is required by taking mutual inductance into account. Moreover, there are challenges in absolute quantification of the microwave amplitude and the spatial resolution limited by the wavelength.

Here, we have succeeded in developing a microwave imaging system in micrometer resolution by using a quantum sensor based on nitrogen-vacancy (NV) centers in diamond, which has recently been attracting considerable interests as a platform for quantum information and quantum sensing. We have successfully obtained microwave field images quantitatively at the spatial resolution of a micrometer. In our newly developed microwave image microscope, the frequency of the microwave to be detected is selected by tuning the resonance frequency of NV centers by the external magnetic field. We have measured the Rabi frequency of the electron spin in NV centers, and obtained image mappings of the microwave amplitude by using the proportionality relation between the Rabi frequency and the microwave amplitude at ambient temperature.

We demonstrate to image microwave distribution around microwave resonators (Fig. 1) with a straight wire and a tapered wire. The width of the tapered wire was modulated to spatially control the amplitude of the microwave field. The obtained microwave images in the vicinity of the straight and the tapered wires are shown in Figs. 2(a) and (c), respectively. The obtained images agree well with the simulated results by finite-difference time-domain (FDTD) analysis (Figs. 2(b) and (d)). We have obtained 22-fold enhancement the microwave amplitude, or 460-fold enhancement of microwave power by the microwave resonator.

The results of this research provide a new method for precision measurement of microwave field distribution in micrometer resolution. Our method is expected to find applications in areas such as characterizations of microwave devices or metamaterial elements, and visualization analysis of biological activities, and promotes research in quantum sensing using quantum spins.

Reference: Giacomo Mariani, Shuhei Nomoto, Satoshi Kashiwaya, and Shintaro Nomura, “System for the remote control and imaging of mw fields for spin manipulation in NV centers in diamond”, Sci. Rep. **10**, 4813 (2020). DOI: 10.1038/s41598-020-61669-w

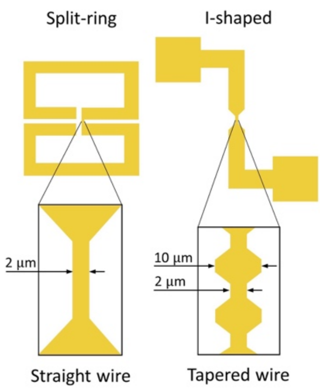

Fig. 1 Schematics of microwave resonators with a straight wire (left) and a tapered wire (right) wire.

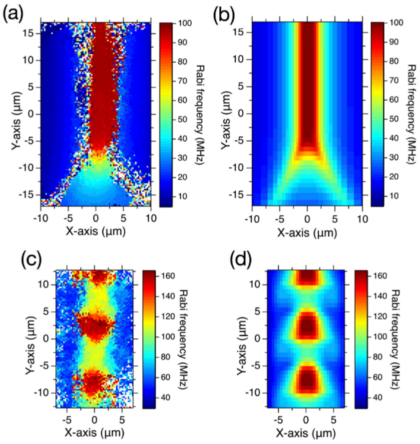

Fig. 2 Results of the microwave imaging and FDTD simulation for the resonators with (a, b) a straight wire and (c, d) a tapered wire.

Probing thermal magnon current via nitrogen-vacancy centers in diamond

－Coupling of quantum spin state with thermal magnon current－

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[1] School of Materials Science, Japan Advanced Institute of Science and Technology、
[2]Institute for Chemical Research, Kyoto University、 [3]National Institute for Materials Science

Thermally excited magnon current is being intensively investigated owing to their potential application in spin caloritronics and magnon spintronics. Conventionally, the thermal magnon current is detected by spin Seebeck effect where injected spin current is converted to electro motive force via inverse spin Hall effect. For this, large size of spin detector such as platinum thin film electrode more than micrometer is needed for signal detection. Meanwhile, the quantum sensors based on the electron spins associated with nitrogen-vacancy (NV) centers in diamond has been regarded as high-resolution (nanometer scale) and high-sensitivity sensors. Recently, it has been demonstrated that the NV center can sense AC magnetic field produced by spin waves (coherent magnon). Because the spin waves are known to be modulated by thermal magnon current exerting thermal spin transfer torque, thermal magnon current can be detected by NV center.

We report the detection of thermal magnon current mediated by coherent spin waves propagating in a magnetic insulator yttrium iron garnet (YIG) under a temperature gradient using the NV centers in diamond (Fig. 1). The NV spins hosted in a beam-shaped bulk diamond and a nanodiamond were prepared, and fingerprint of the thermal magnon current is observed via the spin waves (magnetostatic surface spin wave, MSSW) in the form of modified Rabi oscillation frequencies as a function of temperature difference formed in the lateral direction of the YIG sample (Fig. 2) as well as spin relaxation rates.

This demonstration of local probing of thermal magnon current provides a basis for creating a new device platform hybridizing spin caloritronics and spin qubits.

Reference: D. Prananto, Y. Kainuma, K. Hayashi, N. Mizuochi, K. Uchida, and T. An, “Probing thermal magnon current via nitrogen-vacancy centers in diamond”, arXiv:2007.13433

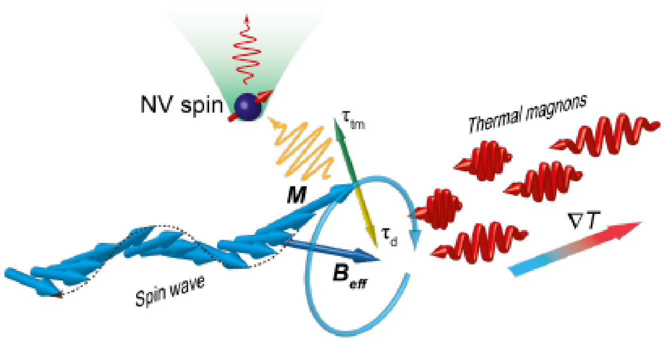

Fig. 1 Schematic of detection of thermal magnons current mediated by coherent spin waves via NV centers in diamond.

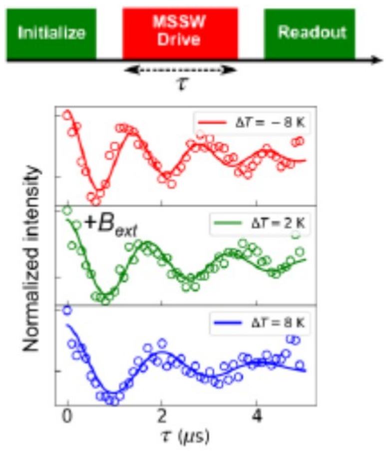

Fig. 2 Modification of Rabi oscillation frequencies of NV centers by thermal magnon current.

Operando Analysis of Electron Devices Using Nanodiamond Thin Films Containing Nitrogen-Vacancy Centers

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[1]Department of Electronics, Nagoya University, [2]School of Fundamental Science and Technology, Keio University

Operando analysis of electron devices provides key information regarding their performance enhancement, reliability, thermal management, etc. For versatile operando analysis of device, the nitrogen-vacancy (NV) centers in diamonds are potentially useful media owing to their excellent sensitivity to multiple physical parameters. However, in single-crystal diamond substrates often used for sensing applications, placing NV centers in contiguity with the active channel is difficult. This study proposes an operando analysis method using a nanodiamond thin film that can be directly formed onto various electron devices by a simple solution-based process.

We started this study from improving the detectivity of the optically-detected magnetic resonance (ODMR) of nanodiamonds. Results of the detailed noise analysis show that ODMR measurements with high SNR could be achieved in the shot-noise region, excluding the large $1/f$ noise and spike-like noises attributable to the NV centers of the nanodiamond. The SNR using lock-in detection in the shot-noise region was improved by a factor of 36 compared with the SNR using the photon counting method.

The magnetic field formed by the current and increase in temperature owing to Joule heating could be evaluated for the metal microwire fabricated on a silicon wafer under bias from the differential ODMR measurement. The spatial mapping data showed similar profile the calculated magnetic field distribution.

Because a nanodiamond thin film can be easily formed at room temperature by a solution-based process directly onto the device surface without disturbing the device property, the proposed method presents the possibility of operando analysis of various types of electron devices.

Reference: H. Uchiyama, S. Saijo, S. Kishimoto, J. Ishi-Hayase, and Y. Ohno, "Operando Analysis of Electron Devices Using Nanodiamond Thin Films Containing Nitrogen-vacancy Centers", ACS Omega 4, 7459-7466 (2019). doi:10.1021/acsomega.9b00344

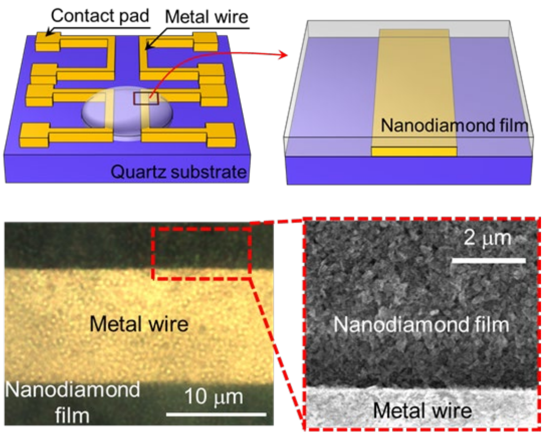

Fig. 1 Test device for operando analysis using nanodiamond thin film.

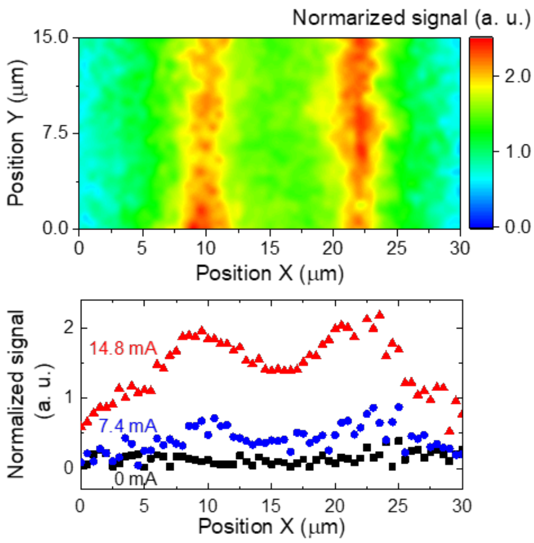

Fig. 2 Spatial distributions of the magnetic field strength in the vicinity of the metal wire.

Successful quantum teleportation transfer

— Preserving the quantum state of photons in diamond: a new development in quantum communication —

Hideo Kosaka
Yokohama National University

Professor Hideo Kosaka of the Graduate School of Engineering at Yokohama National University and a group at the University of Stuttgart in Germany have become the first in the world to successfully demonstrate a new principle whereby photons used in quantum communication can be transferred using the principle of quantum teleportation in diamond used as a quantum memory.

This success is a ground-breaking discovery showing that it is possible to transfer the quantum state of a photon to a nucleon that does not act directly, and to store this state for a prolonged period, simply by absorbing the photon with an electron in a quantum entangled state with the nucleon.

The results of this study suggest that quantum teleportation, which is the basic principle of a quantum repeater, can be achieved based on an extremely simple principle, and that the quantum state of a photon can be reliably reproduced at high speed and stored for a long time at a remote location that is not directly reachable. It is therefore expected to pave the way to dramatic improvements in the range and reliability of quantum communication networks whose absolute secrecy is guaranteed by the laws of physics.

To achieve quantum teleportation, a quantum entanglement state must first be prepared in an atom. This is achieved by using the quantum entanglement inherent in matter. The spins of an atom's constituent electrons and nucleons are connected by a force called hyperfine interaction that leads to quantum entanglement. We started by using microwaves and radio waves to purify this quantum entanglement. Next, by using this entanglement as a seed, we succeeded in transferring the quantum state of a photon to a carbon nucleon by applying a technique for quantum entanglement detection by absorption that was demonstrated previous paper (Hideo Kosaka, et. al., Phys. Rev. Lett., 114, 053603 (2015)).

The figure illustrates the operating principle of using quantum teleportation to transfer a quantum state from a photon to a carbon nucleon, which was successfully demonstrated in this study. Quantum entangled electron and nucleon are prepared in advance. In this experiment, we achieved this by irradiating with microwaves and radio waves. After that, in incoming photon is absorbed by the electron. When it is detected that the photon and electron are in a specific entangled state, the quantum state of the photon is transferred to the nucleon.

Reference: Sen Yang, Ya Wang, Thai Hien Tran, S. Ali Momenzadeh, M. Markham, D. J. Twitchen, Rainer Stohr, Philipp Neumann, Hideo Kosaka, and Joerg Wrachtrup, "High fidelity transfer and storage of photon states in a single nuclear spin", Nature Photonics (2016). DOI:10.1038/nphoton.2016.103

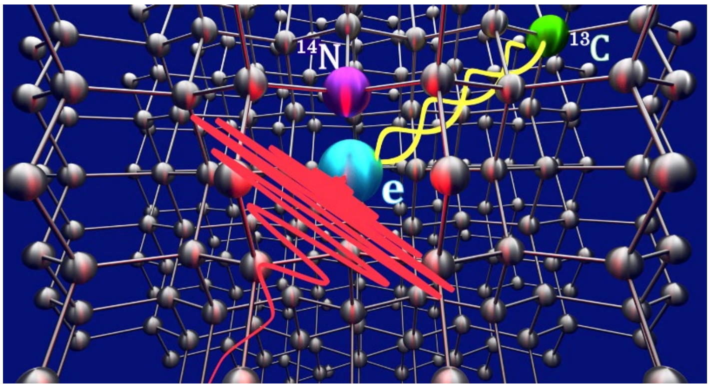

Fig. 1 Quantum teleportation using quantum entanglement in diamond. A quantum-entangled electron (e) and carbon nucleon (^{13}C) are prepared in advance. When an incoming photon excites the electron into a specific orbit, the quantum state of the photon is instantly transferred to the carbon nucleon.

Development of the world's first error-tolerant qubit

— Quantum memory and quantum sensor devices that use geometric echoes to self-stabilize —

Hideo Kosaka, Yokohama National University

For the first time ever, we have succeeded in demonstrating a new method for constructing error-tolerant qubits, which are used in quantum communication, quantum computing, and quantum measurement, and a new principle for the self-stabilization of these devices. We achieved this result by proposing an error-tolerant qubit structure that uses the electron spin of a single defect in a diamond, which is a promising form of qubit. This is a revolutionary discovery that demonstrates the possibility of self-stabilization through a technique based on a new principle called geometric spin echo, which differs completely from the conventional dynamic echo technique. We have shown that environmental noise and control errors that cause qubit destruction can be autonomously eliminated in a non-magnetic environment where the magnetic field has been completely eliminated. This is expected to result in quantum memory devices that require no error correction, and quantum sensors with the ultimate level of sensitivity.

Quantum information science has opened up a new era of information science where the traditional concept of information units ("classical" bits) is extended to quantum-dynamic information units (called quantum bits, or "qubits"). By allowing quantum effects to work on the inputs and outputs of information processing, it is possible to implement quantum computers with unprecedented computing power and fundamentally unbreakable quantum cryptography. It is also expected to be applicable to quantum measurement techniques that provide ultra-sensitive sensors. To realize these technologies, it is essential to be able to manipulate qubits accurately and store them stably. However, the qubits proposed so far have been prone to operational errors, and it has turned out to be difficult to store them reliably.

In our study, we focused on electron spin pairs at nitrogen-vacancy centers (NV centers) in diamond, and became the first in the world to demonstrate a method for constructing error-tolerant qubits and a new principle for autonomously stabilizing these qubits. An NV center consists of a nitrogen impurity paired with an adjacent carbon vacancy in a diamond, which forms a stable quantum medium resembling an isolated atom in a vacuum. It is expected that electron spin pairs localized in vacancies of this type can be used as qubits. Conventional qubits operate by using two quantum states, but our new qubits have an error-tolerant configuration resulting from the use of an auxiliary third quantum state. We have shown that a stabilization technique called geometric spin echo can be used to autonomously stabilize this qubit in an environment that is completely free of magnetic fields. This behavior is completely different from the dynamic spin echo exhibited by conventional qubits. This results in a quantum coherence time of 83 μs, which is about 140 times longer than the 0.6 μs of conventional quantum states. This shows that environmental noise and control errors that lead to qubit destruction can be autonomously eliminated in a non-magnetic environment where the magnetic field has been completely eliminated.

Reference: Yuhei Sekiguchi, Yusuke Komura, Shota Mishima, Touta Tanaka, Naeko Niikura and Hideo Kosaka*, Nature Communications, 7, 11668 (2016). DOI:10.1038/ncomms11668

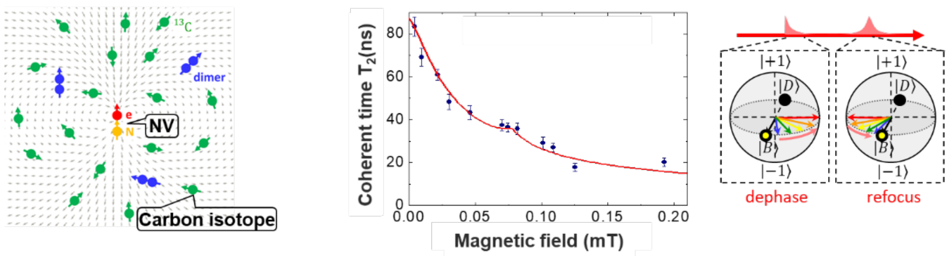

Fig. 1 Schematic diagram of NV center and spin bus arrangement (left) and magnetic field dependence of coherence time T_2 (right). The electron spin localized in the NV center creates a magnetic dipole field around it (shown by the gray arrow on the left). By applying geometric spin echo in a zero magnetic field, the dynamics of the noise-generating spin bus (^{13}C) can be effectively suppressed, resulting in a much longer coherence time T_2.

Demonstration of a new principle of optical spin control that paves the way for quantum integrated memory

— Facilitates high-speed quantum computing and quantum communication —

Hideo Kosaka
Yokohama National University

With the advent of next-generation quantum information technology based on the quantum mechanical laws of quantum computing and quantum communication, we can expect the development of computers that outperform conventional technology, and communication systems with perfect security. Various material systems with quantum properties have been proposed as the basis for realizing these technologies. In particular, methods that treat electron spins in a diamond as units of information (qubits) are known to have excellent performance in terms of information retention and integration potential. To exercise quantum-level control over the spin states of an integrated array of electrons in diamond, a technique is needed in order to control each spin individually, arbitrary and accurately. Although electron spins can be selectively controlled by using the local electric field of laser light (Fig. 1), the control methods that have been proposed and demonstrated so far only have limited control capabilities, and lack high-fidelity performance.

We have succeeded in demonstrating a technique that can use laser light to accurately control the spin of a single electron at a nitrogen vacancy (NV) center in diamond. Until now, an important consideration has been the magnitude of the energy difference imparted to the physical system by applying a magnetic field. In our research, however, we devised a method whereby the energy difference of the physical system is intentionally eliminated by strictly eliminating the magnetic field so as to make skillful use of the degree of freedom of the space that appears as a result, and we also demonstrated this method experimentally. By adopting a contrary approach to conventional methods, this technique makes it possible to perform quick non-adiabatic operations instead of time-consuming adiabatic operations. As a result, we became the first in the world to achieve highly precise and completely free control with a fidelity of over 90% at nanosecond (10^{-9} s) timescales. This is about a hundred times faster than conventional technology, but achieves three times more fidelity while using a small light power of the order of microwatts (10^{-6} W). This showed the possibility of using light to simultaneously control 10^8 NV spin states. We have also conducted theoretical simulations showing that the spin control mechanism shifts from dynamic phase rotation with low noise immunity to geometric phase rotation with high noise immunity. According to this result, it should be possible to perform all the operations required for quantum computing at a practical scale, which is expected to accelerate the pace of future quantum computing experiments.

With this result, we were able to use laser beam technology to complete each of the three basic elemental technologies required for quantum computing: writing, gate control, and reading. With a view to implementing quantum information networks, we will continue to use these technologies and will apply them to demonstrations of advanced quantum information technologies such as quantum teleportation transfer and quantum entanglement measurements. These quantum technologies have also opened the way to applications such as ultra-sensitive electromagnetic field sensing and bioimaging for handling delicate physical quantities.

Reference: Yuhei Sekiguchi, Naeko Niikura, Ryota Kuroiwa, Hiroki Kano and Hideo Kosaka*, “Optical holonomic single quantum gates with a geometric spin under a zero field”, Nature Photonics. DOI:10.1038/nphoton.2017.40

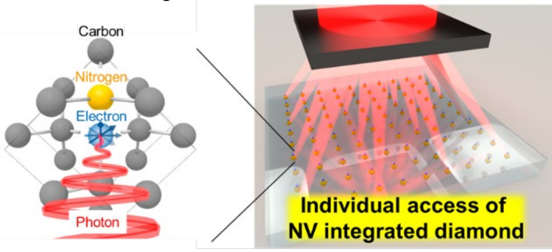

Fig. 1 Schematic diagram of a nitrogen vacancy center (NV center) in diamond and the use of a laser beam for controlling electron spin. An NV center consists of a nitrogen atom occupying a carbon site in a diamond lattice, with an adjacent vacancy. The electron spin is localized in the vacancy. Since the laser beam can be focused, it is possible to selectively control the spin of a single target electron.

Ultra-low noise microwave amplification by spin maser

− Back to the basic for quantum technologies −

Jason Ball[1], Petr Moroshkin[1], and Yuimaru Kubo[1,2]
[1] Quantum Dynamics Unit, Okinawa Institute of Science and Technology Graduate University

Current quantum information technologies at microwave frequencies require ultra-low temperature operations, typically at 10 – 100 millikelvin, because of microwave photons' tiny energy. One of the key technologies is an ultra-low noise amplification of microwave signals at the millikelvin environments. This ultra-low noise amplification has only been realized by superconducting Josephson parametric amplifiers (JPA) based on superconducting circuits. However, JPAs have suffered from smaller saturation power. The state-of-the-art JPA has a maximum input power of about -100 dBm (0.1 picowatts). Moreover, JPAs do not properly work under strong magnetic fields due to the superconductivity.

One of the other principles for amplifying microwave signals is maser, an acronym of "microwave amplification by stimulated emission of radiation" with spins in solid crystals. Although maser has been intensively studied in the late 1950s and early 1960s, it has been forgotten behind because of the rise and rapid progress of semiconductor technologies.

We demonstrate that this "maser amplifier" is indeed very interesting and promising for microwave quantum information and technology applications at millikelvin temperatures, where nobody has tried to operate a spin maser. Using P1 centers in diamond, we realized a cavity-maser amplifier with a gain of about 36 dB and a saturation power of at least -70 dBm, three orders of magnitude larger than that of the best-reported JPAs. Such an amplifier may be promising for quantum computers or magnetic resonance imaging applications.

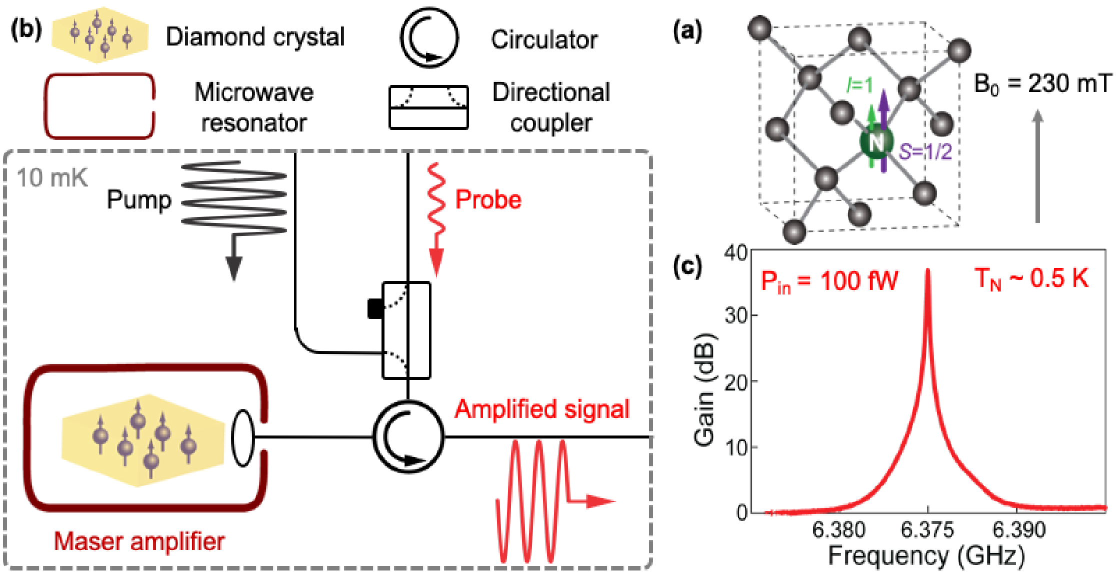

Figure: Maser amplifier demonstrated in this work. (a) P1 (nitrogen) center in diamond. (b) Experimental setup. A strong pump microwave tone generates a population inversion on one of the P1 center electron spin resonance transitions. The maser amplifier then amplifies a weak probe tone. (c) 36 dB gain has been obtained with a noise temperature T_N of about 0.5 K. Note that the power of the input probe tone of 100 fW is the saturation power of the best reported JPAs.

Ultralong relaxation times in bistable hybrid quantum systems

Andreas Angerer [1], Stefan Putz[1], Dmitry O. Krimer[1], Thomas Astner[1], Matthias Zens[1], Ralph Glattauer[1], Kirill Streltsov[1], W. J. Munro[2, 3], Kae Nemoto[3], Stefan Rotter[1], Jorg Schmiedmayer[1], and Johannes Majer[1]

[1] Technische Universität Wien、[2]NTT Basic Research Laboratories、[3]National Institute of Informatics

Nonlinearities are one of the most important sources of complexity that a systems dynamic may exhibit. In classical dynamics, it is a source of rich behavior with bistability, chaos & solitons illustrative examples. It is often deeply related to critical phenomena. Nonlinear phenomena are not only scientifically interesting, but are important in the design of many technologies; bistability is a typical example used in optical switches. On the other hand, in quantum mechanics it has been known that nonlinear behavior differs from its classical counter parts. Superradiance is a nonlinear quantum behavior that appears counterintuitive compared to classical nonlinearities. In this work, using a hybrid system of an ensemble of diamond NV centers coupled to a microwave cavity (see Fig 1), we have explored the dynamics of amplitude bistability that naturally arises.

Usually the cavity quantum electrodynamics (cQED) involved atoms or trapped ions coupled with optical light. In such cases it is difficult for atoms to have long enough coherence times so that we can explire the amplitude bistability dynamics. In our work, we instead used negatively charged nitrogen-vacancy (NV^-) centers in diamond at millikelvin temperature as artificial atoms. The low temperatures extended the life time of the artificial atoms enabling us to investigate the observe bistability in cQED and the dynamics associated with it. In the experiment, our hybrid system exhibits the amplitude bistability in new regimes of cQED with unusual decay rates for the spin system. A critical slowing down of the decay of the cavity population on the order of 11 hours was observed. This time scale is several orders of magnitude longer than that observed previously for this effect and many orders of magnitude longer than other time scales associated with our system. Further our experiment provides a useful foundation for the exploration of additional nonlinear phenomena in hybrid quantum systems and future quantum technologies that may arise from it. It paves the way for high-sensitivity magnetic field sensing & quantum metrology as well microwave isolators and diodes.

Reference : Andreas Angerer, Stefan Putz, Dmitry O. Krimer, Thomas Astner, Matthias Zens, Ralph Glattauer, Kirill Streltsov, William J. Munro, Kae Nemoto, Stefan Rotter, Jörg Schmiedmayer and Johannes Majer“, Ultralong relaxation times in bistable hybrid quantum systems”, Science Advances Vol. 3, no. 12, e1701626 (2017).

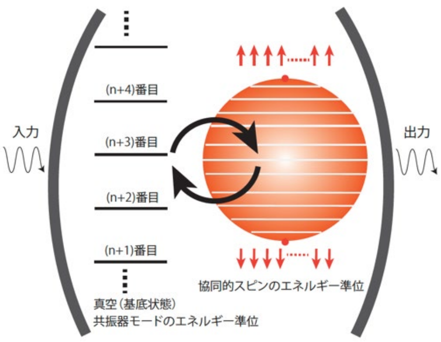

Fig.1 A schematic illustration showing our hybrid quantum system composed of an ensemble of diamond NV centers and the microwave resonator.

Superradiance from diamond

Andreas Angerer [1]、Kirill Streltsov[1], Thomas Astner[1], Stefan Putz[1], Hitoshi Sumiya[2], Shinobu Onoda[2], Junichi Isoya[2], W. J. Munro[3,4], Kae Nemoto[4], Jorg Schmiedmayer[1], and Johannes Majer[1]
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"Superradiance" looks like a flash of light from a material. What is the source of this strong short-lived emission of light? When an atom changes from one energy state to another, the difference of the energy of these two states can be emitted as light. What color of light will be emitted is dependent on the energy difference, and it can be visible or could be microwave. Superradiance can be observed then when many atoms emit light in a very short period of time. Because of the short time period associated with this behaviour, superradiance looks like a flash of light.

This phenomenon, superradiance, was predicted decades ago, however it has been regarded as difficult to realize. This is simply because the requirements for such phenomena to occur were difficult to achieve; many atoms need to be very close together to couple with the same light field (a task already difficult in a real system). In addition to this, coupling between the atoms themselves needs to be negligible, which in itself seems to be impossible due to the closest of atoms to realize superradiance.

In this work, we used a diamond nitrogen-vacancy (NV) center as an artificial atom which has a microwave energy transition. As microwaves has a much longer wave length than visible light, it is possible to pack a high density of NV centers within the few cm microwave wave-length while minimizing the interaction between NV centers. The superradiance demonstration however requires a special diamond sample, an ultra-pure one possessing a high concentration of NV centers.

The key for demonstration of superradiance is the experimental observation of the emission nonlinearity to the number of NV centers involved. It is almost impossible to count them all in the real sample, so we exploited the nature of the diamond crystal. There are four directions in how a NV center can form, and hence we could change the number of NV centers contributing to the superradiance through directional magnetic fields from an unknown number N to 4N. By measuring not only the characteristics of the microwave light emission but also the spin polarization in the sample we demonstrated superradiance in this hybrid system. This result forms the basis for the future development of microwave masers and various quantum technologies.

Reference: Andreas Angerer, Kirill Streltsov, Thomas Astner, Stefan Putz, Hitoshi Sumiya, Shinobu Onoda, Junichi Isoya, W. J. Munro, Kae Nemoto, Jorg Schmiedmayer, and Johannes Majer, Nature Physics 14,1168-1172 (2018).

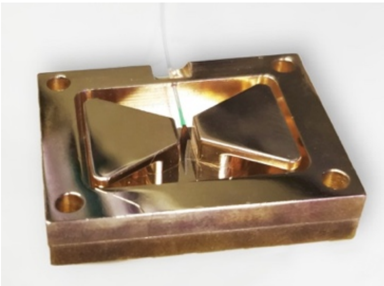

Fig.1 Photograph of the 3D microwave cavity used in the experiment. The microwave mode of the cavity couples with the ensemble of NV centers in the diamond sample placed inside the cavity.

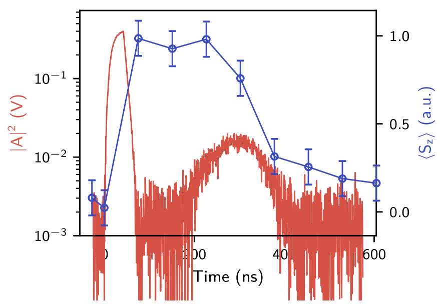

Fig.2 Plot showing the spin dynamics (blue) and microwave light emission (red). The rapid decay in the spin polarization as well as a burst of microwave photons indicates the superradiance. The decay time without superradiance is the order of 4×10^4 s.

Relaxation to negative temperatures and reservoir-assisted quantum entanglement in hybrid quantum systems

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"Relaxation" is one of the fundamental behaviors in physics and occurs when a system is coupled to an environment. In this situation the system will relax to the thermal state associated with the temperature of the environment. However, in quantum mechanics, even with a simplest model, there are dynamics unique to those quantum mechanical systems which may affect such relaxation. Superradiance is one notable example and occurs when the system composed of many atoms/spins etc is coherently coupled to the reservoir. When the system, which consists of two-level atoms, such as spins, interacts with a bosonic reservoir, we normally expect the relaxation process to occur with an exponential decay rate. However, when the spins in the system are collectively coupled with the reservoir, super-exponential decay is expected to emerge. Due to the time scales involved it is often quite difficult to observe such phenomena, however recently we have experimentally demonstrated in the microwave regime (also see "superradiance from diamond" in this report) .

In this work, we have investigated collective decay processes in hybrid quantum systems and observed counterintuitive relaxation, that is relaxation to negative temperatures. Our simple model consists of two domains of a spin ensemble coupled to a single bosonic reservoir. Assuming all those spins couple equally to the reservoir, the spin ensemble would be expected to exhibit superradiance decay. However, the two-domain structure in the ensemble allows us choose initial states with different symmetries from those associated with the systems dynamics. When this happens, the domain relaxation does not necessarily reach the thermal state, and in principle it could heat up to give thermal populations beyond the high temperature limit, i.e. one may reach the negative temperature (See Fig 1). When the size is vastly imbalanced between the two domains, the small domain can become almost fully excited, even when it was initially in its ground state.

To deepen our understanding of this relaxation dynamics, we also explored the degree of entanglement between two domains (Fig 2). As there is no direct or indirect coupling between the spin domains, we would usually not expect to see any mechanism for entanglement generation emerge. However, in this relaxation process, the system symmetry restricts the relaxation passage meaning our system can generate entanglement between the two domains.

These results suggest that when the system has multiple symmetries, the dynamics could be restricted with them, and even when the system is coupled with the reservoir, it can exhibit non-trivial dynamics. Having the initial state and the lifetime of the conservation quantities controllable, we could design unique relaxation paths that can be applied to realize new quantum technologies including quantum batteries.

Reference: Yusuke Hama, W. J. Munro, and Kae Nemoto, Phys. Rev. Lett. 120, 060403 (2018)
Yusuke Hama, Emi Yukawa, W. J. Munro and Kae Nemoto, Phys. Rev. A 98, 052133 (2018)

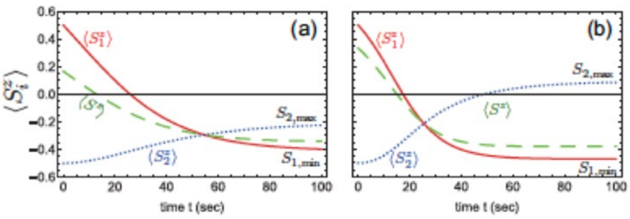

Fig.1 Illustration showing the decay processes for domain 1 (red), domain 2 (blue) and the total system (green). (a) depicts the N=2 case where N is the number of the spins in domain 1 while (b) shows the N=5 case. For both situations, the number of spins in domain 2 is one.

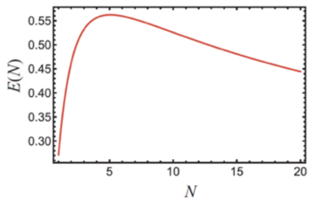

Fig. 2 Plot showing the generation of entanglement by the relaxation between domain 1 with N spins and domain 2 with 1 spin.

Quantum Metrology beyond the Classical Limit under the Effect of Dephasing

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Magnetic field sensing is an important technique, and this is widely used in many practical areas such as materials science and biology. One of the measures to quantify the performance of the magnetic field sensor is an uncertainty of the estimation described as δB. The inverse of the uncertainty is defined as a sensitivity. The suppression of the uncertainty is important for the practical purposes. When we use conventional classical sensors, for a given total measurement time T, the uncertainty of the estimation is known to be scaled as $\delta B \propto T^{-0.5}$, and we call this a classical scaling.

Many efforts have been devoted to realizing a sensitive quantum sensor that utilizes quantum properties such as superposition. Especially, a magnetic field sensor with qubits is considered as one of the most promising applications of quantum sensing. By using a superposition of a qubit, it is in principle possible to have a better sensitivity than a classical sensor if we assume an ideal case. For a quantum sensing without any noise, the uncertainty δB decreases by T^{-1} for a given total measurement time T, and we call this a quantum scaling. However, it is known that quantum states are fragile against noise, and the noise typically decreases the sensitivity of quantum sensing. Especially, under the effect of dephasing, which is one of the most common noise for the quantum magnetic field sensors, the uncertainty δB decreases just by $\propto T^{-1/2}$ even with a quantum senor in a conventional scheme, and this is the same scaling as the classical scaling.

Here, we propose a new quantum magnetic field sensor that is robust against dephasing. Even under the effect of dephasing, we can achieve a quantum scaling of $\delta B \propto T^{-1}$, and so our proposed quantum sensor beats the classical sensor in scaling. The key idea is to use quantum teleportation between qubits. Although quantum teleportation has been used in the area of quantum computation and quantum communication, we focus on the use of the quantum teleportation to suppress the dephasing. While the qubits are interacting with the target magnetic fields, we implement frequent quantum teleportation between the qubits. We show that the effect of the dephasing can be drastically suppressed while the information of the magnetic fields is encoded in the qubits in our scheme. Our results pave the way for practical quantum magnetic field sensing that would be useful for the area of materials science and biology.

Reference： Y. Matsuzaki, S. Benjamin, S. Nakayama, S. Saito, and W. J. Munro, Phys. Rev. Lett. **120**, 140501 (2018).

	Classical sensor	Quantum sensor	Our proposed new quantum sensor
Ideal case (noiseless)	$\delta B \propto T^{-1/2}$	$\delta B \propto T^{-1}$	$\delta B \propto T^{-1}$
Realistic case (with dephasing)	$\delta B \propto T^{-1/2}$	$\delta B \propto T^{-1/2}$	$\delta B \propto \mathbf{T^{-1}}$

Fig. 1 Performance of our proposed new quantum sensor to measure magnetic fields where δB denotes the uncertainty of the estimation and T denotes the total measurement time. The sensitivity of the sensor corresponds to the inverse of the estimation uncertainty. As the total measurement time increases, the uncertainty of the estimation decreases, and so the scaling between them is important to realize more sensitive magnetic fields sensors. Our proposed quantum sensor can beat the classical sensor in scaling even under the effect of dephasing that is one of the most common noise for the quantum magnetic field sensors.

Designing measurement with hybrid quantum systems

Shane Dooley[1], Michael Hanks[2,1], Shojun Nakayama[1], William J. Munro[3,1], and Kae Nemoto[1,2]
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Measurement is the fundamental basis for science and technology, and physics provides us not only the ability but also the limitation to measure physical quantities. When we hit the limitation in our measurement, our science and technology cannot go beyond the precision the measurement gives. Nanotechnology for example has rapidly developed in the last decade allowing us to measure and manipulate devices on the scale of nano-meters, but we are already seeing further improvements limited by our measurement resolution. This limitation arises from the fundamental principle of quantum mechanics and is called the quantum standard limit (shot noise limit). Such quantum noise is fundamental and cannot be eliminated by cooling or stabilizing the system. Quantum measurements (and quantum sensing) are able to challenge this fundamental limitation by applying the principle of quantum mechanics to design better measurements.

It is known that when we design measurements based on quantum mechanics, it is possible to break the quantum standard limit and reach the ultimate Heisenberg limit (the best quantum mechanics will allow). In these quantum measurements we prepare the probe to be in a quantum state with maximum sensitivity to the quantity we want to measure. This in principle allows us to reach the Heisenberg limit, however realistic measurement also involve noise around the measurement apparatus. Hence, the current problem is to circumvent these effects keeping the sensitivity the quantum measurements offers. This is a challenging problem as it is often nontrivial to distinguish the signal from the noise. In our work, we address this problem by designing the probe state to be resilient to the noise. To achieve that effect, we focus on the interaction between spins in a quantum probe. We have found that when the spin-spin interaction is strong enough, we can establish a quantum probe robust against heat noise. Fig.1 shows how the measurement scheme and how the energy spectrum can be engineered using spin-spin coupling. This energy spectrum engineering gives us the stability of the quantum probe. For instance, when J>ω, the information of ω is stored in the relative phase in the two ground states. As shown in Fig.2, the strong spin-spin interaction allows us to achieve higher sensitivity measurements.

Reference: Shane Dooley, Michael Hanks, Shojun Nakayama, William J. Munro, and Kae Nemoto, "Robust quantum sensing with strongly interacting probe systems", npj Quantum Information 4, 24 (2018)

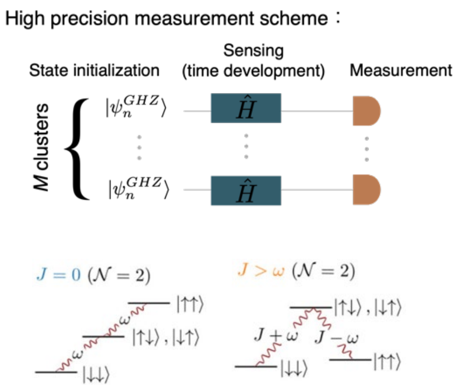

Fig.1 (Top) Schematic illustration of the measurement scheme. (Bottom) This illustrates how the energy spectrum of the probe can be manipulated by the spin-spin coupling.

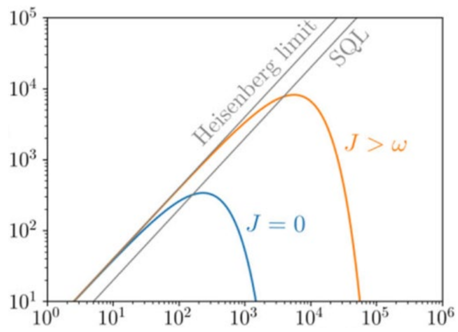

Fig. 2 Plot showing the sensitivity possible with these measurement schemes.

Robust control of two-qubit Hamiltonian dynamics

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We showed that it is possible to achieve robust control of Hamiltonian dynamics to implement an arbitrary target quantum gate for two-qubit Hamiltonian systems, including an unknown parameter by adding a single-qubit control Hamiltonian. To perform the same task with conventional feedback control, we first need to perform quantum measurements and estimate the value of the unknown parameter, then derive and design the control Hamiltonian based on the estimated value. In robust control, a control Hamiltonian is used to implement the target quantum gate for all values in the range of the parameters; therefore, estimation of the value is not necessary. Such robust controllability of quantum dynamics had only been shown for single-qubit systems before.

We first analytically proved the robust controllability of a class of two-qubit Hamiltonian dynamics based on group theory. However, we found that the running time required for the robust control using the control Hamiltonian derived by the analytical method can be very long and might not be practical. We considered a numerical method to derive the control Hamiltonian by discretization of the unknown parameters. We regarded all the discretized values within the unknown parameter range to correspond to different modes, and numerically optimize the pulse sequence for the control Hamiltonian to achieve the same target quantum gate (unitary gate) for all modes for a particular target time by using the GREPE algorithm. We analyzed the quantum gate's accuracy implemented by the optimized pulse sequence for the continuous unknown parameters. We showed that robust control of two-qubit Hamiltonian dynamics is possible with high accuracy for continuous unknown parameters even for some cases where robust controllability is not analytically proven if the parameter's discretization is fine enough.

These results suggest that it is possible to implement arbitrary quantum gates without finely calibrating the unknown parameters of the Hamiltonian by using optimized pulse sequences for some Hamiltonian systems. Calibration of parameters for running a quantum computer requires a lot of work and is very costly. The idea of robust control of Hamiltonian dynamics that allows fully controlling quantum systems without knowing all the system parameters may help realize quantum computers.

Reference : R. Sakai, A. Soeda, M. Murao and D. Burgarth, Phys. Rev. A 100, 042305 (2019). DOI:https://doi.org/10.1103/PhysRevA.100.042305

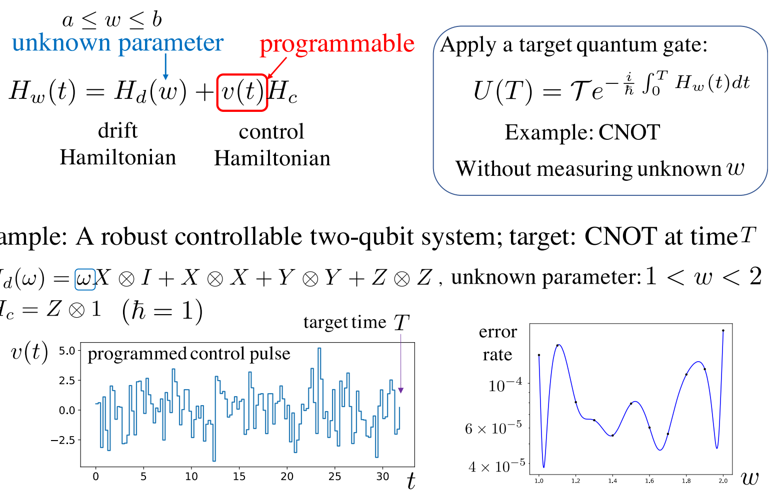

Figure: An example of a robust-controllable two-qubit Hamiltonian system and the control pulse. The error of the implemented gate is within 10^{-3} irrespective to the unknown parameter w.

Reversing Unknown Quantum Transformations: Universal Quantum Circuits for Inverting General Unitary Operations

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Reversible operations in quantum mechanics are described by unitary operators. Consider the following problem: a quantum physicist receives a physical apparatus that is guaranteed to perform some unitary operation given by a black box. Apart from its dimension, no additional information about this unitary operation is provided. We may consider that the black box is a quantum system evolving by an unknown Hamiltonian. We sometimes want to remove the effect of the unitary dynamics of the original Hamiltonian to run a desired quantum program by applying quantum gates. To remove the effect of a unitary operation, the simplest way is to apply the inverse unitary operation on the system. If we know the description of the unitary operation, we can simply apply the inverse unitary operation. However, if the unitary operation is given by a black box in this setting, is it possible to implement the action of the inverse operation without initially knowing the matrix description of the unitary? A simple strategy to solve this problem is to perform process tomography, obtain a matrix representation, find the inverse matrix that represents the inverse unitary operation and then decompose the inverse matrix in terms of elementary quantum gates. This tomographic approach suffers from a major problem: it requires infinitely many uses of the black box in question and can never be done exactly with finite uses. Is there a universal way for performing the inverse with finite uses of the black box without any errors?

In this work, we focus on exact protocols, that is, with unit fidelity, that may fail with some probability, but when successful signal their success. Based on the newly developed idea of higher order quantum operations, we present a quantum circuit whose failure probability decays exponentially in the number of the use of the black box. The circuit represents an adaptive protocol and assumes the use of the black box should be bigger than d-1 where d is the dimension of the black box unitary operation, both conditions proven necessary for exponential performance. We then present a numerical method to generate a finite set of linear algebraic constraints and formulate the problem of finding the optimal quantum circuit in terms of semidefinite programming (SDP). With this SDP approach we show that some quantum circuits with indefinite causal order have an advantage over all conventionally ordered circuits.

Reference: M. T. Quintino, Q. Dong, A. Shimbo, A. Soe da and M. Murao, Phys. Rev. Lett. 123, 210502 (2019). DOI: 10.1103/PhysRevLett.123.210502

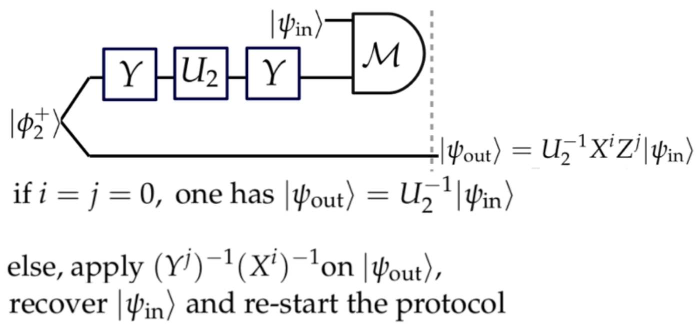

Figure: A quantum circuit to transform a black box implementing an unknown unitary operation for qubits ($d = 2$) U_2 into its inverse U_2^{-1}. First, we prepare the two-qubit maximally entangled state $|\phi_2^+\rangle$ and apply on the upper qubit the gate sequence YU_2Y, where Y is the Pauli σ_y operator, which is equivalent to applying U_2^*, the complex conjugate of U_2. We then perform a Bell measurement $\mathcal{M}$ on the upper qubit of $U_2^* \otimes I|\phi_2^+\rangle$ and on the input-state $|\psi_{\text{in}}\rangle$. After the measurement, $|\psi_{\text{in}}\rangle$ is transformed into the $U_2^{-1}X_2^iZ_2^{-j}|\psi_{\text{in}}\rangle$ with probability 1/4. When $i \neq 0$ or $j \neq 0$, we make an extra use of U_2 to recover $|\psi_{\text{in}}\rangle$ and repeat the protocol.

Exploring Protocols for Control of Quantum Transport

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According to quick developments of experimental techniques, various kinds of implementation of quantum information processing such as quantum computing and quantum cryptography have been proposed and attracting considerable attentions. To extend the field further, it would be necessary to explore protocols to control exchange of quantum information between different kind of quantum devices, for example, between quantum processing units and quantum memory devices. For this purpose, we need to control transport of quantum entities which carry quantum information. However, such quantum entities easily suffer inevitable effects from their surroundings to decrease the efficiency and accuracy of quantum transport.

In this study, we found a new way to control quantum transport by utilizing the environmental effects with referring to a model to explain an adaptation strategy of photosynthetic bacteria. The bacteria can harvest even a few photons and transport the excitations to the center of photosynthetic reaction, which enables them to live in dark circumstances as a bottom of deep lake. We referred a model to explain the light harvesting mechanism in a pigment-protein complex where transport of excitation energy through pigments can be accelerated by thermal fluctuation of surrounding protein molecules. While conventional studies on this topic have been mainly focusing on the elucidation of feature of environmental noise of the bacteria and mimicking them, we found that the controllability of quantum transport can be considerably raised by applying artificial noise on quantum systems. We found that the spatial-temporal correlation of environmental noise is essential to assist and suppress of transport of excitation energy[1,2].

In addition to the above energy transport, we also explore a protocol to control polarization of spin current. For a quantum dot under a rotating magnetic field and interaction with a lead, we found that control the amount of spin current is possible by changing the frequency of magnetic field[3]. We also evaluated the lower bound of energy to eliminate the quantum information[4].

We believe that the above studies would be basis on such as quantum switching devices and spin transistor to promote the field of quantum information processing.

Reference: [1] C. Uchiyama, W. J. Munro, and K. Nemoto, "Environmental engineering for quantum energy transport", npj Quantum Information, 4, 33 (2018). DOI:10.1038/s41534-018-0079-x [2] C. Uchiyama, W. J. Munro, and K. Nemoto, in preparation. [3]K. Hashimoto, G. Tatara and C. Uchiyama, "Spin backflow: A non-Markovian effect on spin pumping", Phys. Rev. B. 99, 205304 (2019). DOI:10.1103/PhysRevB.99.205304 [4]K. Hashimoto, B. Vacchini, and C. Uchiyama, "Lower bounds for the mean dissipated heat in an open quantum system", Phys. Rev. A 101, 052114 (2020). DOI:10.1103/PhysRevA.101.052114

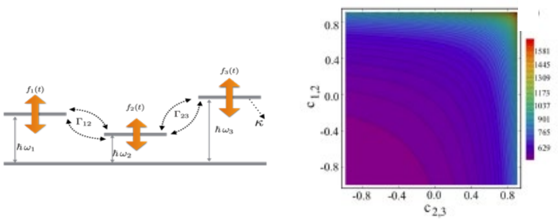

Fig. 1 Our schematic model for quantum transport(left), Dependence of average trapping time on spatial correlation of noise(right)[1].

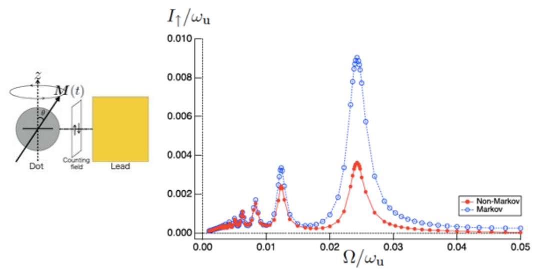

Fig.2 Our schematic model for generation of spin current (left), Dependence of amount of spin current on frequency of rotating magnetic field(right)[2].

Control of Quantum Many-body State by Observation

－Realization of Stabilizing Insulator state by Strong Dissipation－

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A quantum mechanical system changes its state by the influence of the dissipation. For the deeper understanding of the physical phenomena in real materials and the development of quantum mechanical devices, it is, therefore, important to clarify how the dissipation influences the quantum many-body system. The change of the quantum state by dissipation is closely related with the “observation” which is an important concept in quantum theory. It is expected that novel phenomena related with quantum-mechanical measurements can emerge in the dissipative quantum many-body system.

In this work, we investigated a quantum many-body system realized by ultracold ytterbium atoms in an optical lattice by introducing the dissipation with a laser beam at a specific wavelength. In particular, we focus on the “Mott insulator – superfluid quantum phase transition” observed for Bose atoms in an optical lattice. When the optical lattice potential is deep enough, the atoms form “Mott insulator state” with fixed number of particles in each lattice site to minimize the on-site interaction energy due to the repulse interatomic interaction on the one hand. On the other hand, the atoms form “superfluid state” where atoms make frequent hopping between lattice sites when the optical lattice potential becomes shallow. In this experiment, starting from the Mott insulator initial state, we slowly decreased the optical lattice depth while we apply a photo-association laser beam to induce dissipation. As a result, we find that the growth of the superfluidity is delayed due to the strong dissipation (see Fig. 1). This can be explained by a quantum Zeno effect which is a purely quantum-mechanical phenomenon.

This result broadens the range of the experimental research explored by cold atom quantum simulator into an open, dissipative quantum many-body system. Since real materials suffer from dissipation by some extent, the present work is an important step to deeper understanding of the quantum many-body phenomena in real systems as well as the development of quantum mechanical devices.

Reference: T. Tomita, S. Nakajima, I. Danshita, Y. Takasu, and Y. Takahashi, “Observation of the Mott insulator to superfluid crossover of a driven-dissipative Bose-Hubbard system”, Science Advances, 3, e1701513. (2017). DOI: 10.1126/sciadv.1701513.

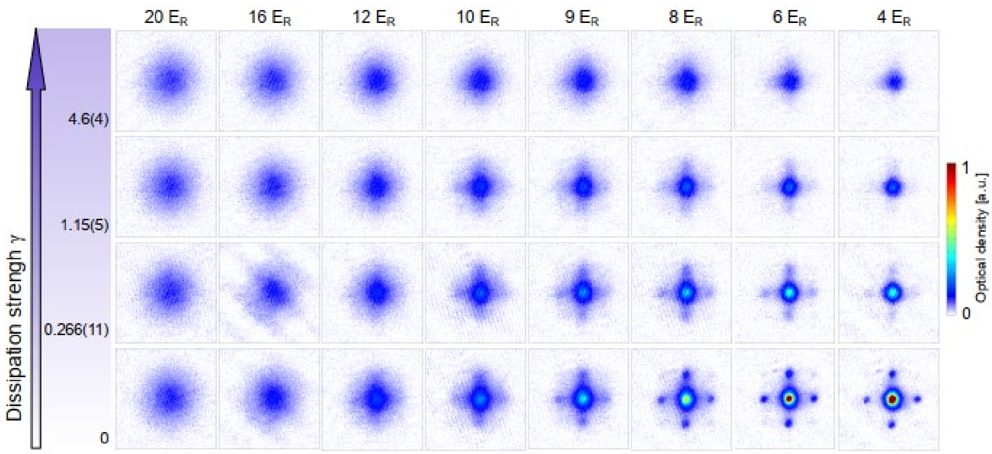

Fig. 1 False-color images of momentum distributions of atoms with various strengths of dissipation γ. The matter-wave interference peaks representing the atomic superfluidity is suppressed by strong dissipation.

Development of New Method for Observing Single Atoms in an Optical Lattice

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Recently, a quantum gas microscope technique, which is a method for observing single atoms in an optical lattice with single-site spatial resolution, has been developed. Owing to the high controllability, we can expect realization of ultimate quantum simulator using this technique. In fact, the observation of an antiferromagnetically ordered phase is reported for two-component fermions of alkali-metal atoms loaded into a two-dimensional optical lattice.

In this work, we developed a new kind of method in quantum gas microscopy for ultracold two-electron atoms of ytterbium, which is expected to have unique applications different from alkali atoms. In the conventional quantum gas microscope technique, the fluorescent photons emitted from single atoms in an optical lattice due to the irradiated resonant probe light are detected with high sensitivity camera. Different from this conventional method, our new method is based on the dispersive interaction between atoms and probe light off-resonantly applied with linear polarization. This dispersive interaction results in a rotation of polarization of the probe light (Faraday rotation) which is detected in this new Faraday quantum gas microscope (See Fig. 1). We successfully achieved 10 degrees rotation angle at the largest for the single atom. The inherent advantage of this method is the expected smaller heating effect during the measurement of atoms. We also clarify the classical theoretical limit for the heating effect of Faraday quantum gas microscopy using coherent state of probe light. In addition, we theoretically reveal the possible scheme of quantum non-destructive detection scheme of single atoms in an optical lattice by using squeezed vacuum.

This result demonstrates the important possibility of minimally destructive detection of single atoms in an optical lattice, opens the door for the study of dynamics of quantum many-body system.

Reference: R. Yamamoto, J. Kobayashi, K. Kato, T. Kuno, Y. Sakura, and Y. Takahashi, "Site-resolved imaging of single atoms with a Faraday quantum gas microscope", Phys. Rev. A 96, 033610 (2017). DOI: https://doi.org/10.1103/PhysRevA.96.033610.

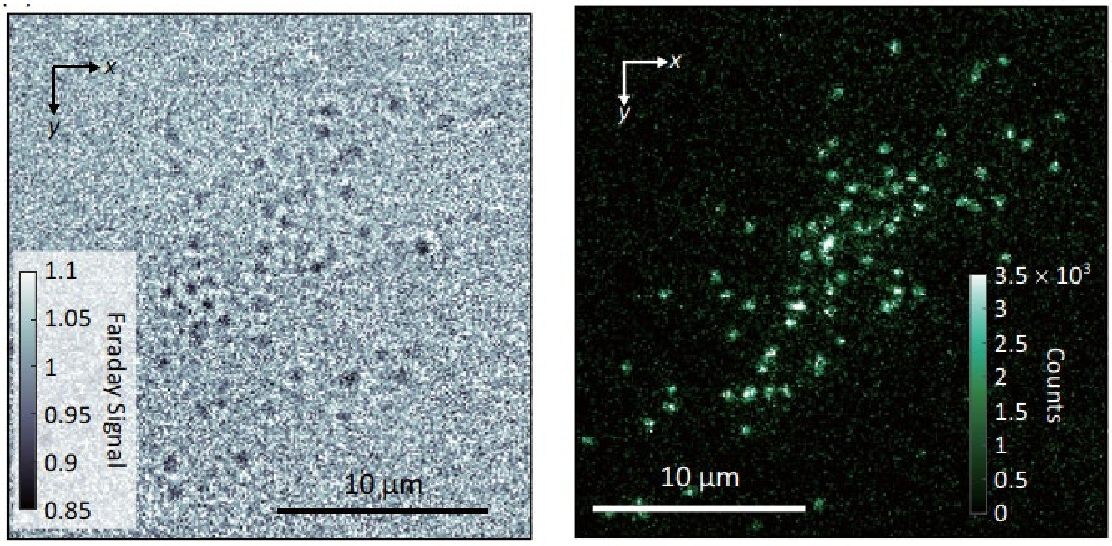

Fig. 1 Images of single atoms in an optical lattice with dispersive methods. (left)Faraday image based on the polarization rotation (Faraday rotation) angle. (right) Dark-field Faraday image based on the polarization-rotated scattering light with no incident probe light.

Photonic quantum interfaces with atoms

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The quantum internet including quantum interconnect is possible by connecting the hybrid quantum system which consists of light and matter systems. Especially, quantum interfaces with the long-distance fiber communication technology is important not only from the viewpoint of the long-distance quantum communication but also from the viewpoint of the quantum state operation by the high-performance communication technology. In this study, some progress has been made in the quantum interface between light and communication technology between neutral atoms or trapped ions.

First, we realized a high-efficiency and low-noise quantum frequency converter that translates photons of 866 nm, the resonance wavelength of calcium ions, into the 1550 nm band, the optical fiber communication wavelength. As a result, a quantum interface that fills the wavelength gap, which has been a problem in the past, has become possible, and it has become possible to read and write photons of the communication wavelength for calcium ions. By incorporating this quantum frequency converter into a calcium ion trap coupled to an optical resonator at the University of Sussex in UK, we succeeded in an experiment to convert a single photon from calcium ion to a communication wavelength band (1550 nm band). At 866 nm, only 1/1000 of the photons remain after traveling 10 km, whereas half of the photons remain at about 15 km in the 1550 nm band. By reducing the loss through this wavelength conversion, we realized 10 km single-photon fiber communication, which was the world record for trapped ions at that time. Even when the conversion efficiency is added, the efficiency sufficiently exceeds the direct transmission of a single photon of 866 nm, which clearly indicates the superiority of the wavelength converter.

Next, we realized a polarization-independent quantum frequency converter that converts the wavelength to the communication wavelength band without changing the polarization state of the photon, and realized the cold atom (Rb) quantum memory and the quantum interface of the communication wavelength photon. By incorporating the newly developed polarization-independent quantum frequency converter, the generated short-wavelength photons (780 nm) were converted into optical fiber communication wavelength bands (1522 nm). Furthermore, by entangling the cold atom (Rb) quantum memory and short-wavelength photons (780 nm) and converting them, it was confirmed that the quantum states of the cold atom (Rb) quantum memory and the optical fiber communication wavelength photons were entangled. As a result, we, for the first time, succeeded in generating entanglement of the cold atom (Rb) quantum memory and communication wavelength photon using a polarization-independent quantum frequency converter.

Reference: T. Walker et al., "Long-Distance Single Photon Transmission from a Trapped Ion via Quantum Frequency Conversion" Phys. Rev. Lett. 120, 203601, 2018. R. Ikuta et al., "Polarization insensitive frequency conversion for an atom-photon entanglement distribution via a telecom network" Nature Communications, 9, 1997, 2018.

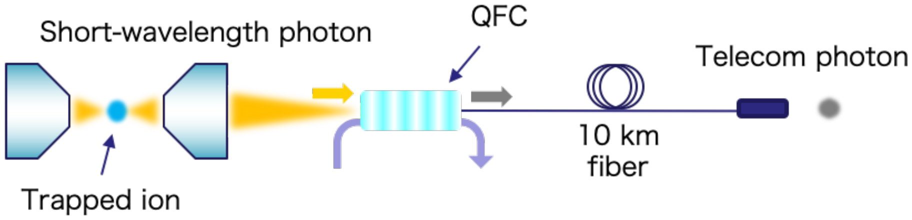

Fig. 1 10-km fiber transmission by a single photon quantum frequency converter from trapped ions

Realization of low-loss, all-fiber system for strong and efficient coupling between distant atoms

- A step closer to realizing distributed quantum computers -

S. Kato[1,2], N. Német[3], K. Senga[1], S. Mizukami[1], X. Huang[1], S. Parkins[3], and T. Aoki[1]
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A cavity-QED system is a system in which photons – elementary quanta of light – and atoms are confined within an optical resonator and interact with each other in a quantum-mechanical manner. This system has been a prototypical experimental platform for helping scientists to better understand and manipulate the quantum properties of photons and atoms, as highlighted by the award of the Nobel Prize in 2012 to physicist Serge Haroche for his 'groundbreaking experimental methods that enable measuring and manipulation of individual quantum systems.' Consequently, the expectation for cavity-QED systems to realize quantum information science technology has increased.

In order to realize such technology, integrating multiple cavity-QED systems with coherent, reversible coupling between each system was necessary, but obtaining such coupling with high enough efficiency has made this very challenging. We approached this problem by demonstrating a system consisting of two nanofiber cavity-QED systems connected to each other in an all-fiber fashion.

In each cavity, an ensemble of several tens of atoms interacts with the cavity field through the evanescent field of a nanofiber, both ends of which are connected to standard optical fibers through tapered regions and sandwiched by a pair of fiber-Bragg-grating mirrors. Multiple resonators can be connected with minimal losses using additional, standard optical fiber, making the coherent, coupled dynamics of the two nanofiber cavity QED systems possible.

Our achievement is an important step towards the physical implementation of cavity QED-based distributed quantum computation and a quantum network, where a large number of cavity QED systems are coherently connected by low-loss fiber channels. In such systems, quantum entanglement over the whole network can be created deterministically, instead of probabilistically.

Reference: S. Kato, N. Német, K. Senga, S. Mizukami, X. Huang, S. Parkins, and T. Aoki, "Observation of dressed states of distant atoms with delocalized photons in coupled-cavities quantum electrodynamics", Nature Communications, 10, 1160 (2019).

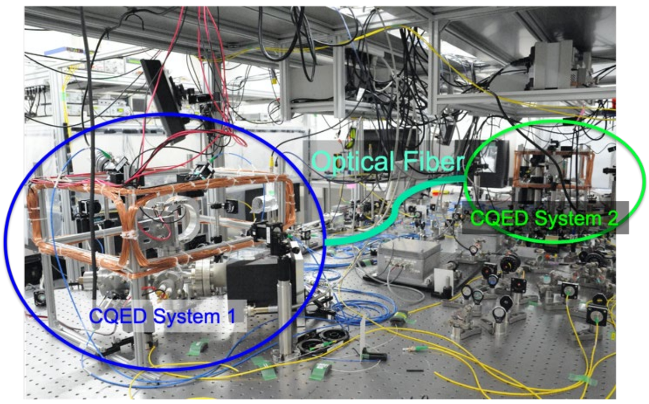

Fig. Experimental device for an all-fiber, coupled cavities-QED system

Cavity dark mode in a coupled cavity quantum electrodynamics system

- Observation of remote exchange of energy between atom and light -

D. White[1], S. Kato[1,2], N. Német[3], S. Parkins[3], and T. Aoki[1]
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We report the first observation of "cavity dark mode", a dark mode that exists in a coupled-cavities quantum electrodynamics system. The cavity dark mode is a superposition state of remote atoms and photons, and it has no photonic excitations at the atom locations, such that the atoms are not locally exposed to light fields. With the absence of local photons, we demonstrate nonlocal excitation and saturation of atoms. Such phenomena have never been observed in any kind of systems.

A dark mode is a class of normal modes in which one or more oscillators does not exhibit excitation due to destructive interference. An example of such a mode is a dark atomic state, which is prevented from absorbing a photon due to coupling induced by control fields. In addition to the widely used application of electromagnetically-induced transparency, the dark mode of a coupled system has for example been used to suppress mechanical dissipation in an optomechanical resonator. We recently demonstrated a coupled-cavity QED system, in which two nanofiber cavity QED systems are connected by an intermediate link fiber cavity. Here we observe a novel type of dark normal mode in this system (Fig. 1), in which the photonic excitations at the atom locations are dark, such that the atoms are not locally exposed to light fields. This `cavity dark mode' is robust and does not depend on cavity symmetry. With the absence of local photons, we demonstrate nonlocal excitation and saturation of atoms.

We emphasize that this is a truly macroscopic network: the cavities are each of order 1 meter long. Our observation of all normal modes of a macroscopically large quantum network (Fig. 2), observed simultaneously at two points of the network, lays the foundation for extension to larger networks of multiple atom-cavity systems for quantum information processing purposes.

Reference: D. White, S. Kato, N. Német, S. Parkins, and T. Aoki, “Cavity dark mode of distant coupled atom-cavity systems”, Phys. Rev. Lett., 122, 253603 (2019).

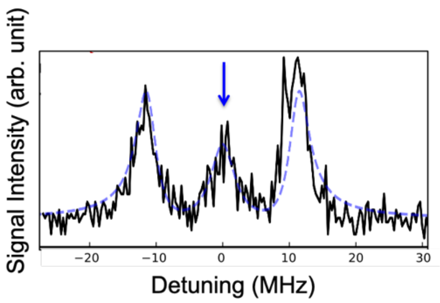

Fig. 1 Observed cavity-dark mode in a coupled cavity QED system

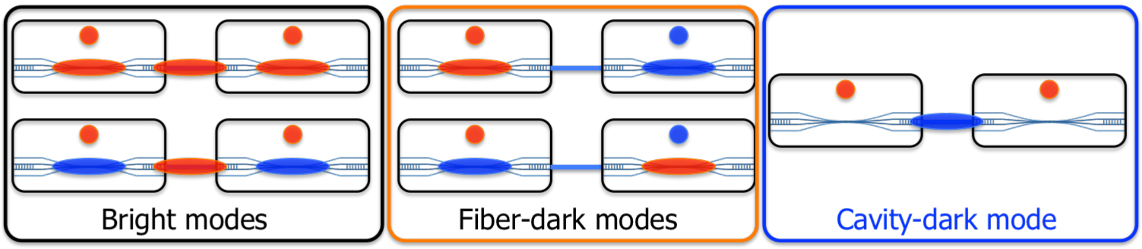

Fig. 2 Five eigenmodes of a coupled cavity QED system

Experimental all-photonic quantum repeaters

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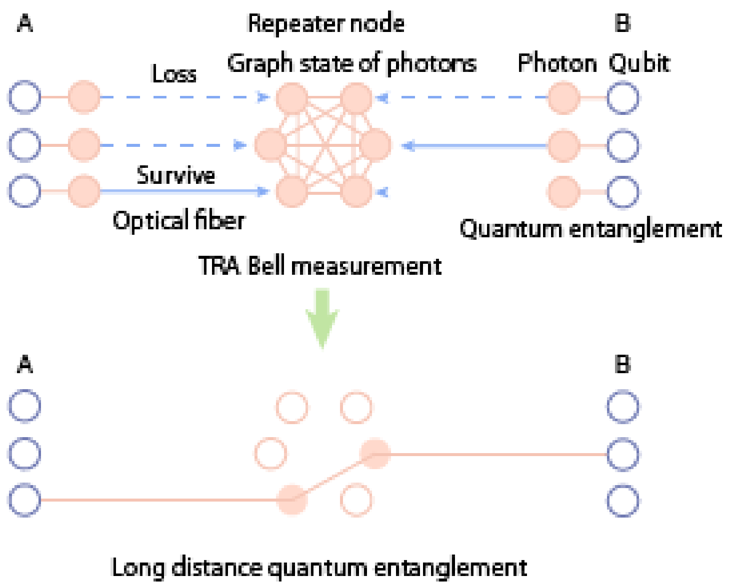
Quantum repeaters in future quantum internet, which enable hybrid quantum systems to be efficiently connected by photons, can be implemented by the mainstream processes (1) A large number of quantum memories that store quantum information are arranged at relay points, and when photons are "arrived" the quantum information is stored. (2) Process (1) is carried out in parallel by a plurality of communication paths, and when photons are "arrived", two quantum memories are selected, and then Bell measurement is carried out (We call this Adaptive Bell measurement.). As a result, quantum teleportation in which quantum information is transferred to an adjacent relay point is realized, and the photon loss is suppressed. Recently, unlike this quantum memory scheme, the NTT group has theoretically proposed a all-photonic quantum repeater that realizes quantum repeaters using only optical devices [1]. This all-photonic quantum repeater had the same effect as Adaptive Bell measurement by reversing the order of operations (1) and (2) using entanglement properties " Time Reversal".

Together with the NTT group, we organized this all-photonic quantum repeater so that it can be gradually extended from a small optical device to a large one, and proposed a Time-Reversed Adaptive Bell (TRABell) measurement as a core of it, and built a new optical system to realize this TRABell measurement. As shown in the figure, a photonic entangled state called a graph state is generated in a plurality of sites at a relay point. Photons passing through each channel are sent to each site, and measured by a Type II Fusion Gate together with photons in a graph state. At this time, if the photon is arrived, this measurement teleports the quantum state of the photon to the remaining photons in the graph state, but if no photon, the remaining photons are kept in the graph state "can be used for another channel". This allows TRABell measurements in which photons perform Bell measurements on any two communication paths the photon has arrived, and the quantum information is teleported from A to B. In order to realize this TRABell measurement, we created the simplest experimental system that generates a graph state of three photons and inputs photons into two communication channels, and conducted the experiment. From the experimental results, it was confirmed that the quantum information was teleported to the remaining photons in the graph state when the photons were arrived for both communication paths, and it was verified that the travel measurement was operated for the first time. At the same time, it was the first demonstration of the basic operating principles of quantum repeaters.



Reference : Y. Hasegawa, et al., "Experimental time-reversed adaptive Bell measurement towards all-photonic quantum repeaters" Nature Communications, 10, 378, 2019.

[1] K. Azuma, et al., "All-photonic quantum repeaters" Nature Communications 6, 6787 (2015).

Fig. 1 Quantum entanglement is generated between A and B by measuring the graph state of photons generated at the relay point and traveling with arriving photons.

Tuning Radiative Lifetime of Circularly Polarized Light by a Three-Dimensional Semiconductor-Based Chiral Photonic Crystal

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Circularly polarized light is currently used for three-dimensional (3D) displays or biochemical sensing of chiral molecules, as well as spintronics or quantum information technology through spin angular momentum transfer (spin-photon interface) with electrons/holes in solid states. Currently, such circularly polarized light is generated by using a combination of a polarizer and a waveplate or an external magnetic field. However, these methods are not suit for the future miniaturization of the integrated optical circuits, and a semiconductor-based optical device directly emitting circularly polarized light is expected. When circularly polarized light propagates, the electric/magnetic field traces a helix having a period of its wavelength scale. From the view point of the symmetry, a similar helical/chiral structure with a 3D period can tune such circularly polarized light efficiently. In this study, we prepared a semiconductor-based chiral photonic crystal (PC) having a 3D sub-micron periodicity. Since this chiral PC modifies the vacuum field connecting to circularly polarized light, we experimentally observed that the radiative lifetime for circularly polarized light emitted from semiconductor quantum dots (QDs) inside the chiral PC was tuned by the chiral structure, and therefore the direct emission of circularly polarized light was successfully obtained.

The studied structure was composed of GaAs thin layers having a stripe pattern with a 500 nm periodicity. These thin layers were stacked one-by-one with an in-plane rotation of 60° by a micro-manipulation technique, as schematically shown in Fig. 1. This left-handed chiral PC forms a circular polarization bandgap where the density of states for left-handed circularly polarized (LCP) light is suppressed and the radiative lifetime of LCP light extends. For InAs QDs in this chiral PC, we performed a time-resolved photoluminescence measurement. At 1200 nm emission wavelength in the polarization bandgap, the radiative lifetime of LCP light was found to be 10 % longer than that of right-handed circularly polarized (RCP) light, as shown in Fig. 2. By this control of the radiative lifetime of CP light, as large as 75% of the emitted light from the QDs were polarized in RCP. This result is applicable to photonics as a CP micro-laser, as well as to spintronics as a highly sensitive spin sensor by hybridization of spins and circularly polarized photons.

Reference : S. Takahashi, Y. Ota, T. Tajiri, J. Tatebayashi, S. Iwamoto, and Y. Arakawa, "Circularly polarized vacuum field in three-dimensional chiral photonic crystals probed by quantum dot emission," Physical Review B **96**, 195404 (2017). DOI : 10.1103/PhysRevB.96.195404

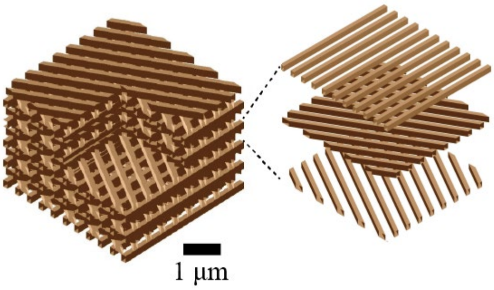

Fig. 1 Schematic diagram of the studied 3D semiconductor-based chiral PhC.

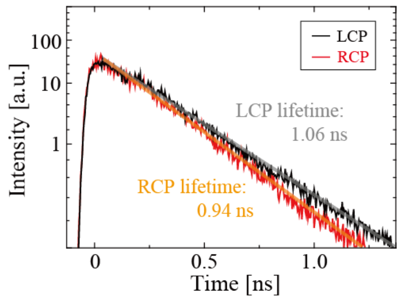

Fig. 2 Time decay of the QD emission intensity for each circular polarization component at 1200 nm wavelength.

Demonstration of a topological nanocavity laser

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Topology is a field of mathematics, which is famously employed for classifying the structures of objects from a large perspective – a well-known example is distinguishing a doughnut and a ball. Another notable application of topology is providing a brand new point of view in condensed matter physics, which was awarded by Nobel prize in physics in 2016. Currently, topology has been penetrated in various fields of physics including photonics. Topological photonics mostly concerns the optical bands of periodical patterns of permittivity. The engineering and understanding of the band topologies in momentum space have so far led to a bunch of novel pathways for controlling the flow of light. At the beginning of the research, most of the concern on topological photonics was theoretical, and proof-of-principle experiments were mainly performed using centimeter scale structures operating at the microwave frequencies. More recently, there is a sharply-growing interest in topological photonic devices that consist of nanophotonic structures and thus can operate in the optical regime. Indeed, some important photonic structures, such as optical waveguides and microring resonators, have been demonstrated on topological photonics platforms.

In this work, we design a topological photonic crystal nanocavity and demonstrate a topological nanocavity laser. Figure 1 shows a schematic of the investigated nanocavity. The device is composed of two one-dimensional photonic crystals interfaced at the center. The two photonic crystals are topologically distinct, which results in the deterministic emergence of a topological edge mode trapped at the interface. This is a consequence of the bulk-edge correspondence, a well-known principle in topological physics. Figure 1 also shows a computed field distribution of the edge mode, which exhibits tight localization at the interface – a prerequisite for utilizing as a nanocavity. The topological origin of the mode guarantees the singlemodedness, which is advantageous for many photonic applications. In experiments, we patterned the designed structure into a GaAs slab embedding InAs quantum dots as active media. Figure 2 shows emission spectra from a fabricated device under optical pumping. By increasing pump power, we succeeded in the observation of single mode lasing from the device.

The results discussed here cast new light on topological photonics. In another project, we also found a nanocavity design in a two-dimensional topological photonic crystal. These findings are important additions to topological photonics and may eventually revolutionize the technology of integrated photonics

Reference: Y. Ota, R. Katsumi, K. Watanabe, S. Iwamoto, and Y. Arakawa, "Topological photonic crystal nanocavity laser", Commun. Phys. 1, 86 (2018). DOI: 10.1038/s42005-018-0083-7

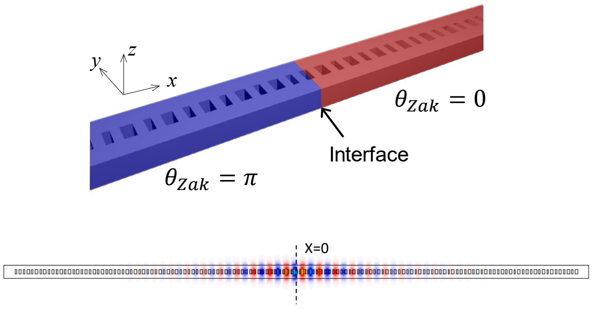

Fig. 1 Schematic of the investigated topological nanocavity (Top). Computed field distribution of the edge mode (Bottom). Zak phase, θ_{Zak}, is a topological invariant of the photonic crystal.

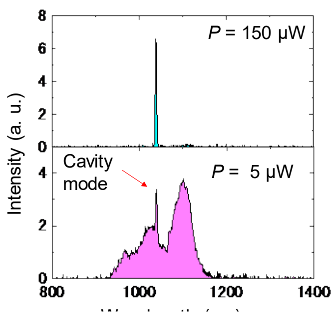

Fig. 2 Measured emission spectra of a fabiricated nanocavity taken under optical pumping.

Optical Aharonov-Bohm Effect in Single Quantum Ring

− Observation of Wigner molecule among excitons −

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When a magnetic flux is applied inside a mesoscopic ring, the interference pattern for electrons changes by the Aharonov-Bohm (AB) effect. The AB effect is usually observed by a “double-slit interference experiment” in the measurement of electric current. In an isolated ring, on the other hand, the photoluminescence spectrum shows the AB oscillation when an exciton is created by the light irradiation. This is called optical AB effect. We experimentally and theoretically study the optical AB effect in a single quantum ring in collaboration with Prof. K. Kyhm, Pusan National University, South Korea.

In our experiment, we examine a quantum ring fabricated on GaAs/AlGaAs. The quantum ring is created when a GaAs layer is grown on AlGaAs substrate in a specific condition. Figure (a) schematically depicts an exciton in the ring by the optical excitation of a pair of electron and hole. They are strongly bound to each other by the Coulomb interaction. Reflecting the different effective mass, the orbital radius is different for electron and hole. In consequence the exciton shows the AB oscillation in spite of its electrical neutrality. Figures (c)-(e) show the photoluminescence from the exciton, as a function of magnetic field B, with changing the strength of excitation light. The observed AB oscillation is in good agreement with our theoretical results (solid line). The stronger excitation light creates more extra-charges surrounding the quantum ring, which influences the exciton wavefunction in the ring through an effective electric field.

Figure (b) shows the schematic view of biexciton in the ring while Figs. (f)-(h) present the photoluminescence from it as a function of B. In our system, a biexciton is made of two excitons in which an electron and a hole is strongly bound. The two excitons are apart from each other by the Coulomb interaction, forming a “Winger molecule.” As a result, the period of the AB oscillation for the biexciton is nearly half of that for a single exciton. Remarkably the photoluminescence from the biexciton becomes discontinuous at some values of B. This is due to the change of angular momentum of the biexciton with an increase in B. The exciton in the final state has the same angular momentum as the biexciton in the initial state after the photon emission. Consequently the final state changes when the angular momentum of the biexciton changes with B, which results in the discontinuous change in the photon energy. The agreement with the theoretical results (solid line) strongly suggests the Wigner molecule formation among the excitons.

Reference: H. Kim, S. Park, R. Okuyama, K. Kyhm, M. Eto, R. A. Taylor, G. Nogues, L. S. Dang, M. Potemski, K. Je, J. Kim, J. Kyhm, and J. Song, “Light Controlled Optical Aharhonov-Bohm Oscillations in a Single Quantum Ring,” NANO Lett. **18**, 6188 (2018). DOI: 10.1021/acs.nanolett.8b02131

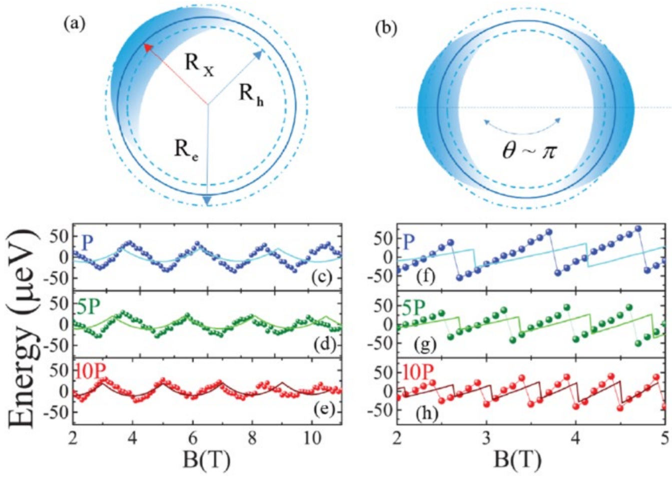

Figure (a), (b): Schematic views for exciton and biexciton in single quantum ring.
Figure (c)-(e): Photoluminescence from an exciton as a function of magnetic field *B*. The strength of excitation light *P* changes to five times and ten times larger. The theoretical result is shown by solid line.
Figure (f)-(h): Photoluminescence from a biexciton as a function of magnetic field *B*.

Novel phenomena in optical microresonators

－Demonstration of anomalous group delays and high-Q mechanical resonators－

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Whispering-gallery-mode (WGM) optical microresonators have attracted large interests as quantum photonic interfaces thanks to the strong enhancement of light-matter interactions with strongly-confined cavity photons. In this study, we aim to develop novel functionalities in this microresonators via two kinds of experiments: observing anomalous large group delays by precisely controlling waveguide-resonator coupling and demonstrating photon-phonon coupling in bottle microresonators.

The waveguide-resonator coupling is controllable in WGM microresonator system by finely adjusting the gap between a microresonator and a tapered fiber. This controllability has been applied to manipulate group delays in optical pulses with respect to its coupling strength. So far, the amount of group delays has been considered as equivalent to the time constant of the microresonator (i.e., the inverse of resonance linewidth). We observed anomalous large group delays around a singular point in the two-dimensional parameter space spanned by the coupling strength and laser detuning (Fig. 1) [1]. Such an anomalous large shift has been observed in only two- and three-dimensional optical systems by analogy of quantum weak measurement. We unveiled that the anomalous shift with this framework also appears in one-dimensional system with finite dissipation, and succeeded a principle-of-proof experiment with a microtoroid.

WGM microresonators are possible to strongly confine not only optical modes but also mechanical (acoustic) modes. Because the optical and mechanical (acoustic) modes are confined in the same structure, cavity optomechanical coupling via radiation pressure (optical strain effect) becomes available. We first observed cavity-enahnced coupling to both mechanical modes (~30 MHz) and acoustic modes (~11 GHz) in the microbottles [2, 3]. A resolved-sideband regime, where the optical cavity dissipation rate is smaller than the mechanical frequency, was obtained by using an ultrahigh-Q resonance with Q facot of 10^7 (Fig. 2). In this regime, laser cooling of mechanical motion to the phononic ground state and photon-phonon entanglement generation would be available. Moreover, to develop novel functionalities in cavity optomechanics with micrbottles, we attempted to optimize the microbottle geometry, and demonstrated near-field cavity optomechanics with optical evanescent fields from the bottle microresonators [4].

Reference:

[1] M. Asano et al., Nat. Commun. **7**, 1 (2016)　[2] M. Asano *et al.*, Laser & Photon. Rev. **10**, 603 (2016).
[3] M. Asano *et al.* Opt. Express **24**, 12082 (2016).　[4] M. Asano et al., Appl. Phys. Rev. **112**, 201103 (2018).

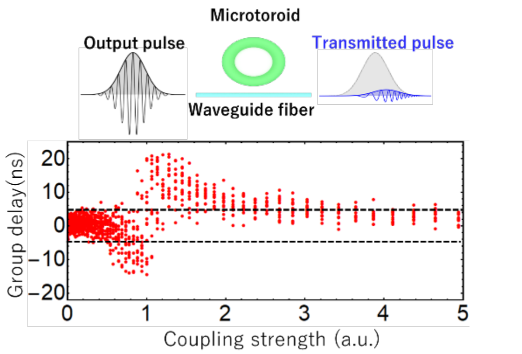

Fig. 1 Conceptual illustration of group delay control with a waveguide-resonator system (up) and group delays with respect to coupling strengths in our experiment (bottom). The time constant of the microtoroid is shown by black-dotted lines.

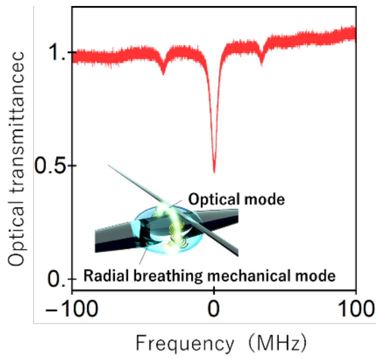

Fig. 2 Optical transmission spectra with sidebands generated via optomechanical coupling in the resolved sideband regime. The inset describes an conceptual illustration of optomechanical coupling in a microbottle.

Optical coherent transients in $^{167}Er^{3+}$

－Coherent manipulation of 4f orbital electrons at telecom-band wavelength－

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Optical coherent manipulation of the quantum superposition states in solid-state materials is one of the elemental technologies essential for the realization of quantum information networks. Since the coherence time T_2 of the optically accessible quantum 2 level system in the material determines the performance of this quantum manipulation, extending T_2 is one of the important issues. The main cause of decoherence is the fluctuation of the spin magnetic moment that exists around the quantum two-level system. We are focusing on the 4f orbital electrons of the erbium (Er), which has a two-level system accessible by telecom-band wavelength (1.53μm). By dilutely doping isotope-purified Er^{3+} to the solid crystal, we tried to suppress the fluctuation of the spin magnetic moment, extend T_2, and coherently manipulate the Er 4f orbital electron by telecom-band light.

First, Y_2SiO_5 crystals doped with 0.001% of only $^{167}Er^{3+}$, which has the only nuclear spin among the isotopes, were grown by CZ method. For this sample, the homogeneous width Γ_h of the $^{167}Er^{3+}$ hyperfine level was investigated by spectral hole burning (SHB), and T_2 was estimated from the relation of $\Gamma_h = 1 / (\pi T_2)$. As a result, the magnetic fluctuations produced by the Er isotopes themselves other than $^{167}Er^{3+}$ were suppressed, and we succeeded in extending T_2 by about 4 times (Fig. 1). We also demonstrated the coherent transient phenomenon among the Λ-like 3 levels formed by this hyperfine structure, that is, the Rabi oscillation and the photon echo (Fig. 2). Rabi oscillation is measured by the pump pulse width dependence of photoluminescence (PL) integrated intensity, and the π and π / 2 pulse area conditions are obtained from the oscillation period. When the 2-pulse photon echo was measured using this pulse condition, light conservation and regeneration with $T_2 = 12$ μs was observed. Until now, optical coherent manipulation with Er^{3+} has not been realized, and this time, by realizing a longer T_2 by purifying Er isotopes, we succeeded in coherent manipulation of 4f orbital electrons with telecom-band light for the first time.

These results show that $^{167}Er^{3+}$-doped crystals are promising as a solid material platform for quantum nodes, which are indispensable for long-distance quantum information communication. Currently, we are proceeding with isotope purification of host crystals for $^{167}Er^{3+}$ doping, and fusion of them with photonic nanostructures.

References:
T. Tawara, G. Mariani, K. Shimizu, H. Omi, S. Adachi, and H. Gotoh, "Effect of isotopic purification on spectral-hole narrowing in $^{167}Er^{3+}$ hyperfine transitions", Applied Physics Express, **10**, 042801 (2017). DOI: 10.7567/APEX.10.042801
M. Hiraishi, M. IJspeert, T. Tawara, S. Adachi, R. Kaji, H. Omi, and H. Gotoh, "Optical coherent transients in $^{167}Er^{3+}$ at telecom-band wavelength", Optics Letters, **44**, 4933 (2019). DOI: 10.1364/OL.44.004933

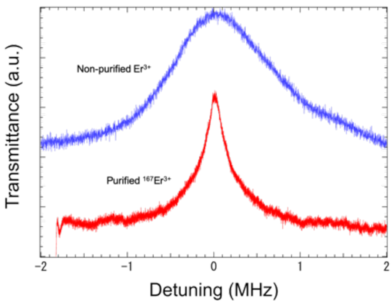

Fig. 1 SHB spectra of non-purified Er^{3+} (blue) and purified $^{167}Er^{3+}$ (red).

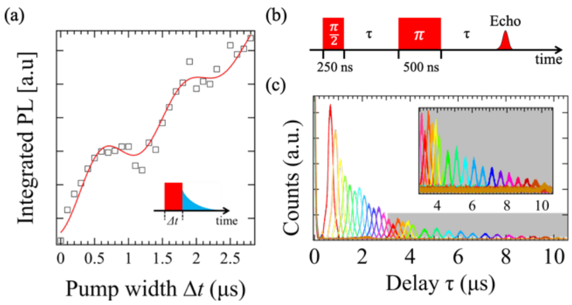

Fig. 2 (a) Rabi oscillation of PL intensity, (b, c) pulse sequence and echo signal of 2 pulse photon echo.

Coherent Coupling between Ensemble Superconducting Qubits and a Superconducting Resonator

Kosuke Kakuyanagi[1], Yuichiro Matsuzaki[1], Corentin Deprez[1], Hiraku Toida[1],
Kouichi Semba[2], Hiroshi Yamaguchi[1], William J. Munro[1] and Shiro Saito[1]
[1]NTT Basic Research Laboratories, [2]NICT

Materials formed by an ensemble of atoms exhibit various physical properties; however, it is difficult to freely control the interactions between the atoms. On the other hand, interactions between superconducting qubits in artificial atom clusters can be freely designed, which could lead to the development of multibody quantum simulators or quantum metamaterials with properties not found real materials.

In particular, hybridization of a superconducting resonator and ensembles of two-level systems has potential to realize quantum technologies. Conventional approaches have used natural systems comprising atoms and molecules to build ensembles, but the properties of such "atoms" are difficult to tailor to the properties of the device [l].

Our approach is to create an ensemble from superconducting qubits and couple them to a resonator. The properties of superconducting qubits are not intrinsic; they can be largely changed even after fabrication. Moreover, due to their large size, we can in principle achieve individual controllability. This approach has been used in previous work, but only a small number of superconducting qubits (eight in total and not an ensemble) were collectively coupled to a resonator [2].

Here, we fabricated a hybrid device composed of 4,300 superconducting flux qubits embedded in a superconducting resonator [3]. We observed a large dispersive frequency shift of 250 MHz in the spectrum as shown in Fig. 1. Our theoretical analysis showed that this frequency shift is evidence of coherent coupling between the resonator and thousands of flux qubits. Although the strength of the coupling between a single flux qubit and the resonator was much smaller than the inhomogeneous width of the ensemble, the coupling can be enhanced by collective effects, which will provides us with a measurable signal for experiments.

Our results represent the largest number of coupled superconducting qubits realized so far. Future issues to address include how to further increase the coupling strength between collective qubits and a resonator and uniformize the characteristics of the collective qubits.

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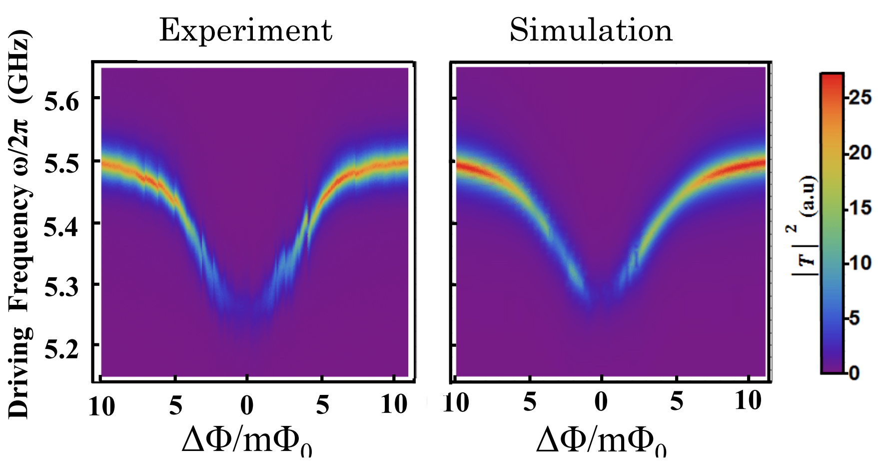

Fig. 1. Energy spectrum of a superconducting microwave resonator coupled to an ensemble of flux qubits. (Left) Experimental results. (Right) Theoretical analysis.

Experimental test of macroscopic realism using a superconducting flux qubit

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Realism is the idea that an object's state is determined before its observation. Although this idea is widely believed to hold in our lives, it has been shown that "realism" is broken in the microscopic world. The microscopic world is governed by the principles of quantum mechanics, which allows a state to have a superposition. For a superposed state, measurable values cannot be determined until they are observed. Since the macroscopic world is composed of microscopic objects, quantum mechanics could be valid even in this world, or there could be limitations to applying quantum mechanics to it. Currently, there is still no consensus about which is likely to be true.

Here, we aim to address this issue. A superconducting flux qubit is a circuit composed of several Josephson junctions and a superconducting loop. Due to the non-linearity of the Josephson junctions, this device provides a two-level system with clockwise and anti-clockwise current states. These two states contain 10^{12} electrons flowing around the circuit each second. We tested whether or not realism is broken with this macroscopic device.

In our normal world, it is accepted that we can measure macroscopic objects without disturbing them (noninvasiveness). If realism is true, any noninvasively measured result on this device should satisfy the Leggett-Garg inequality. However, if quantum mechanics is true, we could observe a violation of the inequality using noninvasive measurements.

We show that the Leggett-Garg inequality is mathematically equivalent to an experimental test to check if the noninvasive measurements affect the state of the device. Interestingly, even if the measurement is designed to be noninvasive, observation by it induces a projection according to quantum mechanics. This can change the state of the device.

In our test, we performed two experiments. First, we checked the noninvasiveness of the measurements by evaluating the classical disturbance our measurement device has on the flux qubit. Second, we compared the measured state of the flux qubit with its unmeasured state. From these experiments, we found that there is a large difference in these measured results, which cannot be explained by the classical disturbance [Fig. 1(a)]. This is a manifestation of quantum superposition. Our results conclusively demonstrate that "realism" is broken even for a macroscopic device such as a superconducting qubit [Fig. 1(b)] [1].

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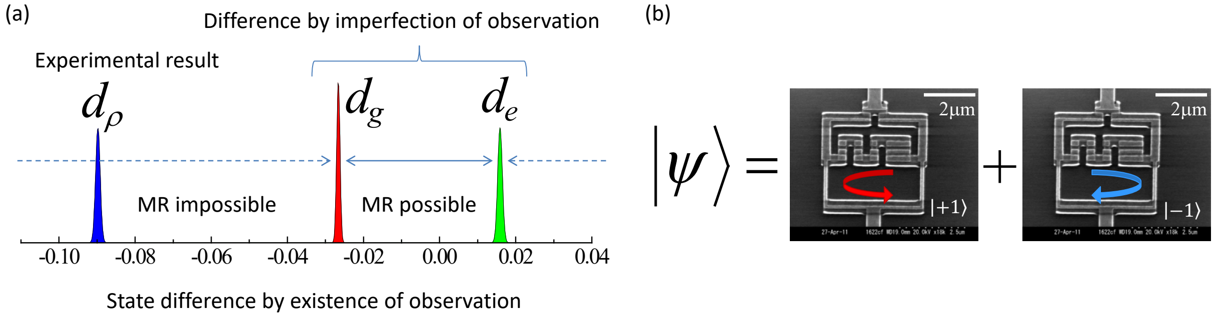

Fig. 1. (a) Differences by observation; (b) quantum superposition of current states

Electron Spin Resonance Spectroscopy Using a Superconducting Qubit

－Sensitive detection of electron spins in microscale area－

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Superconducting qubits are an important research focus for the realization of quantum computers due to their controllability and scalability. The technology for superconducting qubits has matured to the extent that small systems are readily available within the community. Such technology however can be applied to other quantum tasks. Here we apply it to the field of quantum metrology. We demonstrate an electron spin resonance (ESR) spectrometer using a superconducting flux qubit with excellent sensitivity.

First ESR is an essential tool used to obtain information about unpaired electrons in materials which is extremely useful in many distinct fields. A conventional ESR spectrometer uses a microwave cavity to detect the ESR signal. However, due to the weak coupling between the cavity and sample, the required number of electron spins in the sample is large, of the order of $\sim 10^{13}$. In this method, the applied microwave frequency is limited near the cavity resonance meaning the magnetic field is only the parameter one can sweep. On the other hand, our method directly measures the magnetization of the sample without a cavity. This feature enables us to sweep two parameters: the spin excitation frequency and the magnetic field. Furthermore, the spatial resolution is determined by the loop size of the flux qubit, which leads to much higher spatial resolution. In our current experimental setup, we realize the sensitivity of 400 spins/√Hz with a detection volume of 0.05 pl.

Fig. 1 shows a schematic diagram of our ESR spectrometer. Here the quantum state of the flux qubit is measured by using a superconducting quantum interference device (SQUID). That measured state reflects the magnetization of the sample. We sweep both the microwave frequency and magnetic field to obtain the detailed ESR spectrum. The ESR spectrum of nitrogen-vacancy (NV) centers in diamond is shown in Fig. 2 which allows us to reproduce the g-factor and zero-field splitting reported in the literature. A number of solid-state materials show complicated ESR spectrums in the low-field and low-frequency regime. Our demonstrated ESR spectrum proves that our spectrometer is useful to evaluate such materials. We have further proposed a flux qubit array could be used to obtain a spatial image of the ESR spectrum. Our method can be applied to the measurement of biomaterials or used for pathological diagnosis.

Reference: Hiraku Toida, Yuichiro Matsuzaki, Kosuke Kakuyanagi, Xiaobo Zhu, William J. Munro, Hiroshi Yamaguchi, and Shiro Saito, "Electron paramagnetic resonance spectroscopy using a single artificial atom", Communications Physics, 2, 33. (2019). DOI: 10.1038/s42005-019-0133-9

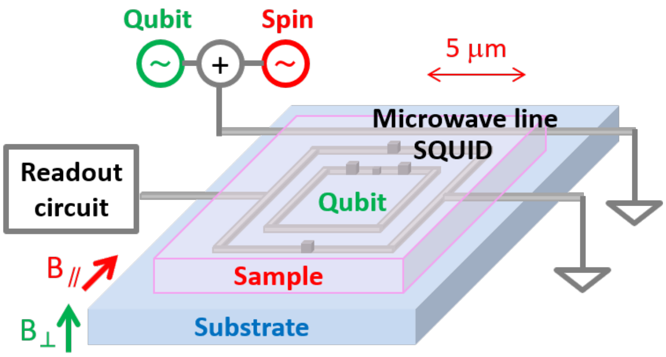

Fig. 1 Schematic diagram of the ESR spectrometer.

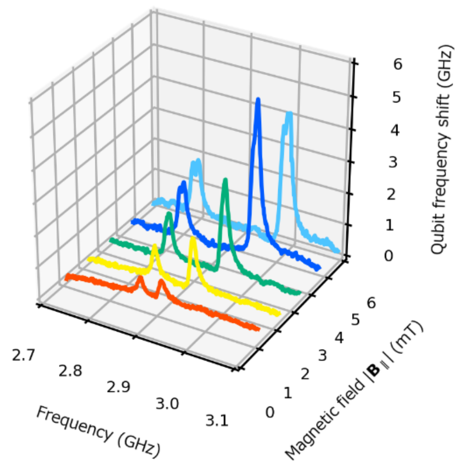

Fig. 2 ESR spectrum of NV centers in diamond.

Josephson junction with a topological insulator

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Topological insulator (TI)/superconductor hybrid structures are interesting in terms of predicted emergence of Majorana particles. The Majorana particle or Majorana zero mode is also attractive for a possible application to a topological qubit that is thought to be robust to decoherence. Until now, the direct confirmation of it has not been made though there are some experimental signatures that support its existence. It is theoretically predicted that Josephson junctions made of the topological insulator should show a 4π periodic current-phase relationship instead of the ordinary 2π periodic relationship due to the existence of the Majorana zero mode. To test this, we have carried out measurements of the current-voltage relationship under the microwave irradiation and microwave emission from the voltage-biased junctions. Based on the predicted 4π periodic current-phase relationship, the missing of the odd steps are expected in the Shapiro steps in the former measurement, and the microwave emission with half the ordinary Josephson frequency is expected in the latter measurement.

The HgTe quantum well was used as a 2-dimensional or 3-dimensional topological insulator, and Al was deposited to form the Josephson junction (Fig.1). The gate metal was deposited on top of the HgTe normal region to change the Fermi energy which should be set in the bulk bandgap. In the 2DTI, the helical edge states are formed and the supercurrent could flow through them. This was suggested experimentally by the observed SQUID-like pattern of the supercurrent in magnetic fields, rather than the Fraunhofer pattern that was expected when the supercurrent flowed uniformly in the junction. Figure 2 shows the Shapiro step measurements, where the missing odd steps are observed for the lower frequencies as expected. Figure 3 shows the microwave emission intensity mapping as functions of voltage and frequency. In addition to the ordinary Josephson frequency (f_J), half the frequency is also observed in some regions. Details have not been understood yet, but the experimental results strongly suggest the predicted 4π periodic current-phase relationship due to the Majorana zero modes.

The work has been done in collaboration with Prof. L. Molenkamp's group in Univ. Wurzburg.

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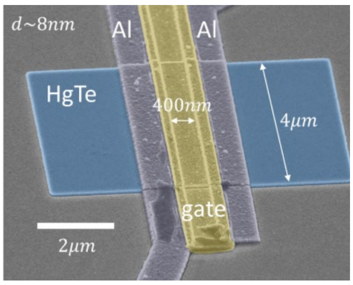

Fig 1. SEM image of the sample structure

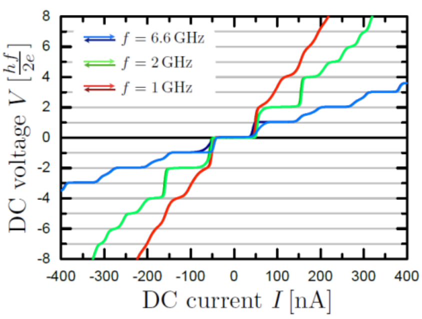

Fig 2. Shapiro step measurements

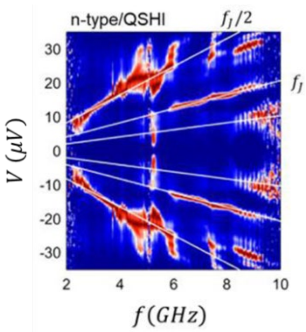

Fig 3. Emission intensity plot

Large magnetoresistance in magnetic topological insulator

− Switching of non-dissipative topological current −

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Topological current can flow without energy loss in a topological material whose electronic state in the material is characterized by its topology. These topological currents may be available at room temperature and are being actively studied around the world. The anomalous quantum Hall effect is a typical example of causing a topological current. In this state, edge current, which is a kind of topological current, can flow along the edge and domain wall of the magnetic thin film sample. If the edge current can be freely controlled by a small external stimulus, it will greatly expand the range of applications of topological current. We used the molecular beam epitaxy method, and added the magnetic elements V (vanadium) and Cr (chromium) to the topological insulator $(Bi_{1-y}Sb_y)_2Te_3$. By selectively adding magnetic elements V and Cr to the upper and lower parts of the thin film, a three-layer structure of magnetic / non-magnetic / magnetic is formed (Fig. 1A). When the electrical resistance of this heterostructured thin film was measured under a strong external magnetic field (~ -2 T), and the magnetization directions of the V-added layer and the Cr-added layer were aligned to produce the quantum anomalous Hall state (Fig. 1B). When the direction of the external magnetic field is reversed and gradually strengthened, the magnetization of the Cr-added layer with a small coercive force is reversed by a magnetic field of a certain magnitude (~ 0.2T), and the magnetization directions of the Cr layer and V layer become opposite (anti-parallel). When the two-terminal resistance between the current terminals was measured in this magnetization configuration, the resistance value exceeds 2 GΩ, which is 100,000 times larger than the 25.8 kΩ of the quantum anomalous Hall effect (Fig. 1C). Converting this to the magnetoresistance ratio, it exceeds 10,000,000 %.

This result indicates that by controlling the magnetization direction with an external magnetic field, the topology of the quantum anomalous Hall effect was changed, and the edge current could be turned on and off. In other words, our observation means the establishment of the switching principle of non-dissipative current. Furthermore, this high resistance state is called an "axion insulator" where the manifestation of quantized magnetoelectric effect is theoretically predicted. By developing a Cr and V three-layer structure, a more stable axion insulator has been realized compared to the earlier studies.

Reference: M. Mogi, M. Kawamura, A. Tsukazaki, R. Yoshimi, K. S. Takahashi, M. Kawasaki and Y. Tokura, "Tailoring tricolor structure of magnetic topological insulator for robust axion insulator", Science Advances **3**, eaao1669 (2017), DOI: 10.1126/sciadv.aao1669.

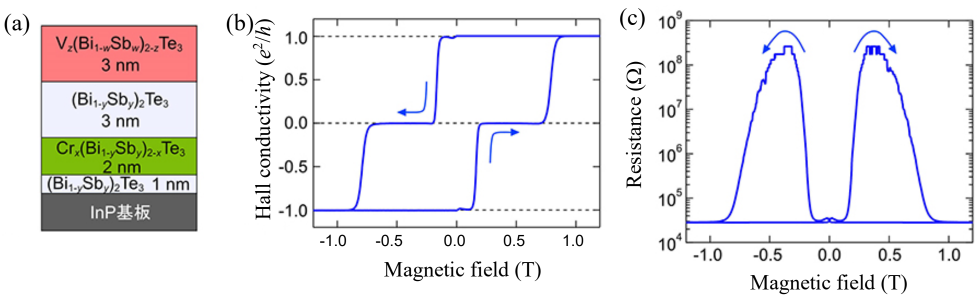

Figure 1 : (a) Layered structure of the developed tricolor heterostructure film. (b) Magnetic field dependence of Hall conductivity. Quantized Hall conductivity is observed. (c) Magnetic field dependence of the two-terminal resistance. The huge enhancement of the resistance is observed.

A new insulating state in topological insulator

－Realization of the materials platform for topological magnetoelectric effect－

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A topological insulator is a new kind of material which have an insulating bulk and metallic surface because of the topological nature of the electronic state. When a magnetic impurity is added to a topological insulator, the interaction between the magnetic moments and electrons on the surface states causes the quantum anomalous Hall effect in which an electric current flows only at the edge of the sample [Fig. 1(a)]. Besides that, it is theoretically predicted that the magnetic topological insulator exhibits an exotic electromagnetic response termed as the topological magnetoelectric effect where magnetization is induced by applying an electric field and conversely, electric polarization is induced by applying magnetic field [Fig. 1(b)]. Surprisingly, the coefficients of the topological magnetoelectric effect are determined only by the fundamental physical constants regardless of the materials parameters. To measure the topological magnetoelectric effect, it is necessary to insulate the surface state of the magnetic topological insulator. Theoretically, it is predicted that if the magnetization is aligned outward from all surfaces, the metallic surface states of the topological insulator are gapped and a perfect insulator appears. However, it has been difficult to freely control the magnetization direction with conventional magnetic topological insulators.

Therefore, aimed to control the magnetization direction, we created a heterostructure film of magnetic topological insulators. We made a magnetic/non-magnetic/magnetic three-layer structure thin film that was layered on top of each other. By adding a coercive force difference between the two magnetic layers, it is possible to control the magnetization direction of each layer independently. When the magnetizations of the two magnetic layers become antiparallel, it was observed that the thin film sample becomes insulating. This indicates that by controlling the direction of magnetization, the transport property on the surface of the topological insulator could be changed, and the quantum anomalous Hall effect could be transformed into an insulator state where the topological magnetoelectric effect is expected. This result establishes a material basis for observing the topological magnetoelectric effects in a magnetic topological insulator.

Reference: M. Mogi, M. Kawamura, R. Yoshimi, A. Tsukazaki, Y. Kozuka, N. shirakawa, K.S. Takahashi, M. Kawasaki, and Y. Tokura, "A magnetic heterostructure of topological insulators as a candidate for an axion insulator", Nature Materials **6**, 516 (2017). DOI: 10.1038/nmat4855

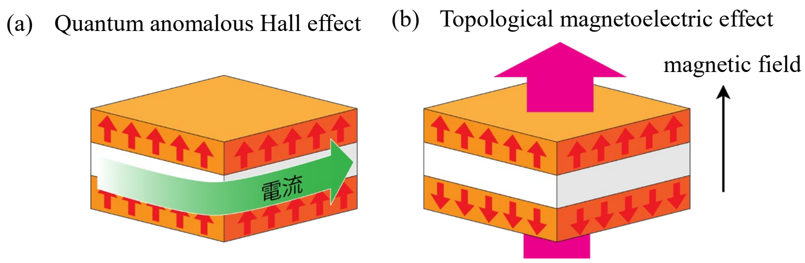

Figure 1: Schematic of the quantum anomalous Hall effect and the electromagnetic effect in a topological insulator heterostructure film. (a) When the magnetic moments (red arrow) are aligned in one direction, the current flows only at the edge of the sample (green arrow), and the quantum anomaly Hall effect appears. (b) When the magnetic moments are antiparallel, no current flows to the edge of the sample, and a perfect insulator is realized. In this insulator state, the topological magnetoelectric effect is expected: when an external magnetic field is applied, electric polarization occurs in the same direction (large pink arrow).

Current-induced breakdown of quantum anomalous Hall effect

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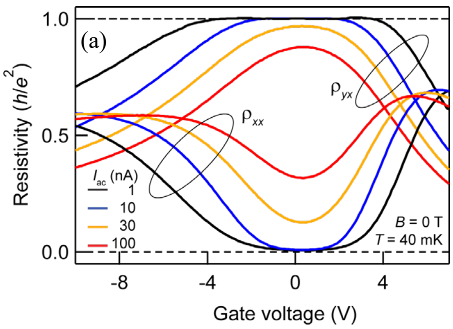
[1]RIKEN CEMS, [2]IMR, Tohoku university, [3]The Univ. of Tokyo, [4]Tokyo college, the Univ. of Tokyo

Topological insulators are materials which have an insulating bulk state and a metallic Dirac surface state. When a magnetic element is introduced into a topological insulator to make it in a ferromagnetic state, a quantum anomalous Hall effect appears where the Hall resistance value is quantized to the von Klitzing constant h/e^2. In order to observe the anomalous quantum Hall effect, it is necessary to cool the sample to a low temperature below 100 mK. When the current flowing through the magnetic topological insulator sample is increased, it is expected that the quantum anomalous Hall effect will be broken down when a certain threshold current is exceeded, and the Hall resistance value will begin to deviate from the quantized value. The threshold current that causes the quantum anomalous Hall effect breakdown is one of the important indicators showing the stability of the quantum anomalous Hall effect. Therefore, in this study, we conducted a systematic experiment to investigate the threshold current.

A magnetic topological insulator $Cr_x(Bi_{1-y}Sb_y)_{2-x}Te_3$ thin film sample was prepared using the molecular beam epitaxy, and the quantum anomalous Hall effect was observed by cooling the sample to a temperature of 30 mK using a dilution refrigerator. We observed the breakdown of the quantum anomalous Hall effect, where the Hall resistance becomes smaller than the quantized resistance value when a certain threshold current is exceeded. The breakdown of the quantum anomalous Hall effect was measured using multiple samples of different sizes. We found that the current value at which the quantum anomalous Hall effect breaks down increases in proportion to the width of the sample. This suggests that the Hall electric field generated in the sample due to the application of current causes the breakdown. Furthermore, from the temperature dependence of the resistance in the quantum anomalous Hall state, it was found that the hopping mechanism via the localized state due to impurities predominates in the electrical conduction at low temperatures. This indicates that the impurity concentration affects the threshold current for the quantum anomalous Hall effect breakdown. From the results of this study, it was found that it is necessary to reduce the impurities contained in the sample in order to observe the more stable quantum anomalous Hall effect.

Reference: M. Kawamura, R. Yoshimi A. Tsukazaki, K. S. Takahashi, M. Kawasaki, and Y. Tokura "Current-driven instability of quantum anomalous Hall effect in ferromagnetic topological insulator thin films", Physical Review Letters **119**, 016803 (2017). DOI: 10.1103/PhysRevLett.119.016803



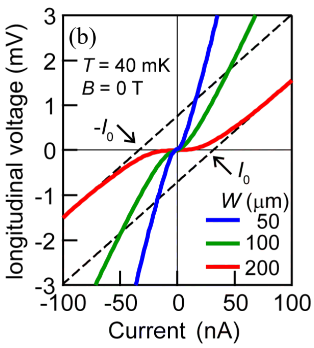


Figure 1: (a) Gate voltage dependence of the longitudinal resistance and the Hall resistance under various measurement currents. The Hall resistance deviates from the quantum resistance above 30 nA. (b) Current-voltage characteristic curve for three samples with different width. The critical current increases with increasing the sample width.

Resistively-Detected NMR in InSb Quantum Hall Systems

－Reciprocity of nuclear polarization in a quantum Hall ferromagnet－

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Extremely large g-factor of InSb two-dimensional system allows us a crossing of down spin of ground Landau-level (LL) and up spin of the first LL at ν = 2 in a tilted magnetic field, resulting in a formation of the quantum Hall ferromagnet (QHF) at ν = 2 with spin domain structures. The dynamic nuclear polarization and resistively-detected (RD) NMR have been successfully demonstrated in this InSb QHF [1]. This is the simplest QHF and provides us a chance to study the fundamental feature of dynamic nuclear polarization in QHF.

We fabricated both Corbino and Hall-bar structures based on InSb 2D system. It is well-known that the Hall-bar has chiral edge channel running one-direction; however, there is no edge channel for Corbino disk. For both structures, we can see RDNMR response at ν = 2 QHF realized in a tilted magnetic field. The RDNMR signal is symmetric for current flow direction and disappears at 2 K for the Corbino disk. On the other hand, RDNMR signal is asymmetric for current flow direction and remains up to 6 K for the Hall-bar structure. This result clearly indicates an important role of the chiral edge channel for dynamic nuclear polarization [2]. When we set the Hall-bar structure at 3 K, where bulk (edge) dominated nuclear polarization disappears (remains), we confirm clear reciprocity of the RDNMR response reflecting the characteristics of the chiral edge channel in the QHF [2].

The above-mentioned RDNMR is combined with gate-controlled InSb two-dimensional structure, resulting in successful pump-probe nuclear relaxation experiment. In contrast to a long T_1 of quantum Hall states around ν = 1 that possesses a Korringa-type temperature dependence, the temperature-independent short T_1 of the ν = 2 QHF suggests the presence of low energy collective spin excitations in the domain wall of the QHF [3].

Reference: [1] H. W. Liu, K. F. Yang, T. D. Mishima, M. B. Santos, and Y. Hirayama, Phys. Rev. B 82(RC), 241304, doi.org/10.1103/PhysRevB.82.241304 (2010) [Editor’s suggestion] [2] K. Yang, K. Nagase, Y. Hirayama, T. D. Mishima, M. B. Santos, and H. Liu, Nature Comm. 8: 15084, doi: 10.1038/ncomms15084 (2017). [3] K. F. Yang, M. M. Uddin, K. Nagase, T. D. Mishima, M. B. Santos, Y. Hirayama, Z. N. Yang and H. W. Liu, New Journal of Physics 21, 083004 doi.org/10.1088/1367-2630/ab34ce (2019).

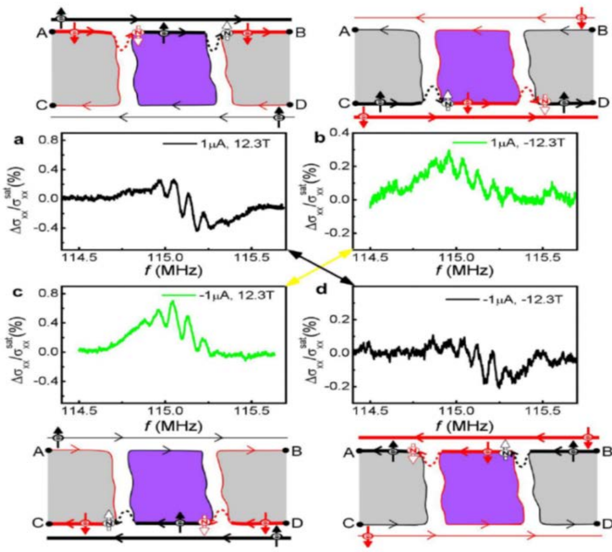

Fig. 1 Reciprocity characteristics of the RDNMR response in a Hall bar with ν = 2 QHF.

Electron evaporative cooling using asymmetric double barrier semiconductor heterostructure

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Rapid progress in high-speed, densely packed electronic/photonic devices has brought unprecedented benefits to our society. However, this technology trend has in reverse led to a tremendous increase in heat dissipation, which degrades device performance and lifetimes. The scientific and technological challenge henceforth lies in efficient cooling of such high-performance devices.

We have focused ourselves on the thermionic cooling technology, which can achieve higher cooling efficiency by properly designing the semiconductor heterostructures. Electrons thermionically emitted from the cathode transfer their kinetic energies to the anode and give rise to refrigeration in the cathode.

The aim of the present work is to demonstrate that a significant electron cooling as much as ~50 K is possible in a semiconductor heterostructure operating at room temperature. The studied AlGaAs/GaAs asymmetric double barrier heterostructure, which combines resonant tunneling and thermionic emission, was originally proposed by Chao *et al*. (Appl. Phys. Lett. 87, 022103 (2005)) as a lattice cooler. The electron temperature, T_e, in the QW as well as T_e in the electrodes are determined from photoluminescence measurements. At 300 K, T_e in the QW is remarkably reduced by as much as 50 K as the bias voltage is increased up to the maximum resonant tunneling condition. This behavior is qualitatively explained in terms of the evaporative cooling process. Evaporative cooling is known in the field of the cold atom physics. In this work, we have implemented the concept of the evaporative cooling in a solid-state system, *i.e.*, the semiconductor heterostructures, and observed a significant electron cooling as much as ~50 K at 300 K. The observed cooling behavior is quantitatively confirmed by quantum transport calculations that self-consistently couples the non-equilibrium Green's function (NEGF) formalism for electrons with the heat equation.

These results make our heterostructure device promising for a comprehensive heat management in nanodevices.

Reference: Aymen Yangui, Marc Bescond, Tifei Yan, Naomi Nagai, and Kazuhiko Hirakawa: "Evaporative electron cooling in asymmetric double barrier semiconductor heterostructures", Nature Communications, 10, 4504 (2019), DOI: https://doi.org/10.1038/s41467-019-12488-9

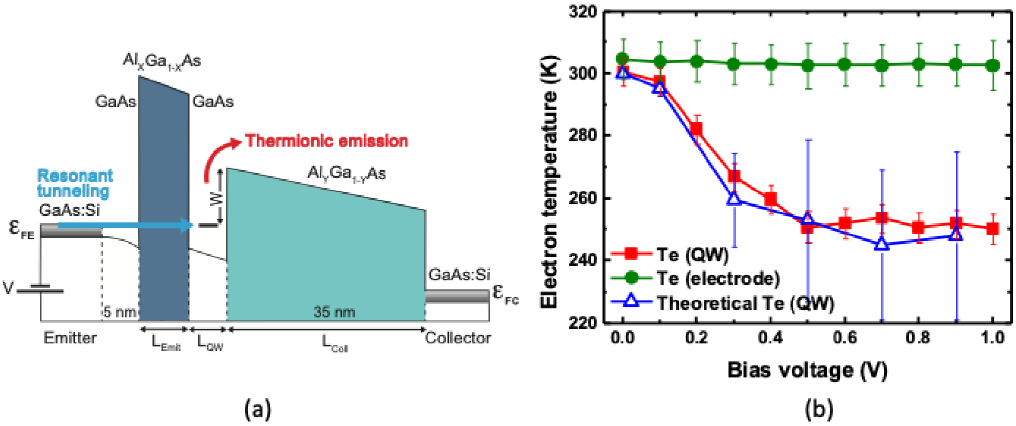

Fig. 1 (a) GaAs/AlGaAs heterojunction asymmetric double-barrier thermionic emission structure, (b) electron temperature evaluated by photoluminescence; green: electron in GaAs electrode, red: electron in quantum well, blue: Electrons in quantum wells (theory)

1-bit quantum simulation with silicon transistor

－Single spin qubit reproduce a well-known phenomenon in magnetic resonance－

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Motional narrowing (averaging) is a phenomenon that has been known for a long time in the field of magnetic resonance. Particles placed in a non-uniform magnetic environment move around quickly to equalize the effective environment, resulting in a narrowing of resonance line width. Normally, many spins are involved in magnetic resonance, and it was not possible to freely control a non-uniform environment.

By using spin qubits we have succeeded in simulating this phenomenon experimentally with a single spin and in a more controlled magnetic environment. The qubit is based on a silicon tunnel field-effect transistor, and a deep impurity introduced into this transistor function as a spin qubit. The time ensemble average of the spin state is read as the source/drain current I_{SD} of the transistor. The device was cooled to a temperature of 1.6 K and applied a static magnetic field and an AC magnetic field with microwave frequency f to cause magnetic resonance. When the gate voltage VG of the device is changed while satisfying this condition, the g-factor of spin changes due to Stark effect, and the resonance frequency changes through the change of Zeeman energy. The high-speed modulation of the resonance frequency by V_G has made the experiment described later possible.

Figure 1 (b-d) shows the results when square wave modulation (Fig. 1 (a)) is applied to the gate voltage. If the square modulation frequency is much smaller than the reciprocal of the coherence time (4 MHz), two peaks will appear (Fig. 1(d)), reflecting the resonant frequency at each stage of the modulation (*i.e.* high and low stage of the square wave). This is because the time constant of I_{SD} measurement is as slow as 1 second. As the modulation frequency of this square wave is increased, these two trivial peaks go through a complex interference pattern (Fig. 1 (c)) and eventually a single peak at a high modulation frequency (>> 4 MHz) is appeared (Fig. 1 (b)). This indicates that the spin that modulated faster than the coherence time feel the average value of the modulated external field, which can be understood as the motional averaging. Furthermore, in the result obtained in the same way when the shape of the square wave is asymmetric (Fig. 1 (e)), the spin is found to feel the external field of the weighted average value (Fig. 1 (f-h)). This result can also be regarded as an analog calculation of the weighted average value using a single qubit. These results show that useful findings can be obtained even with 1-qubit simulation, and indicate one possible direction for qubit applications with relatively low technical difficulty.

Reference: K. Ono, S. N. Shevchenko, T. Mori, S. Moriyama, F. Nori, Quantum interferometry with a g-factor-tunable spin qubit, Phys. Rev. Lett. 122, 207703 (2019). DOI : https://doi.org/10.1103/PhysRevLett.122.207703

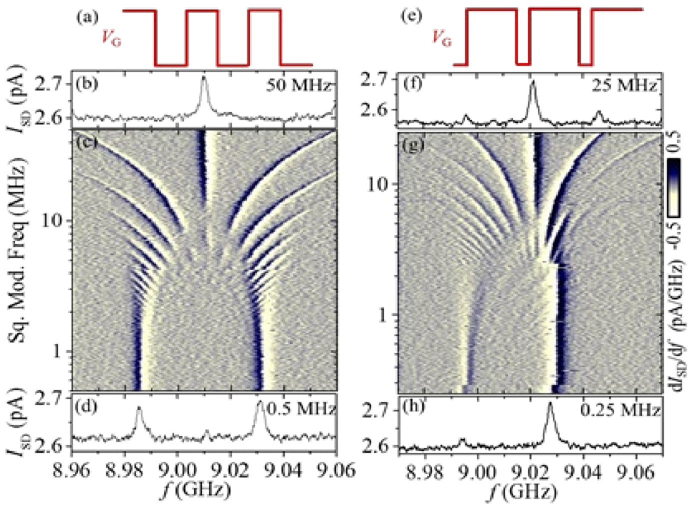

Fig.1(a) Symmetrical modulations of V_G. The high/low ratio of the square wave is fixed at 1:1. (b) Magnetic resonance spectrum at a modulation frequency of 50 MHz. (c) Modulation frequency dependence of magnetic resonance signal. The derivative of I_{SD} with respect to f was plotted to emphasize the peak position. (d) Spectrum at a modulation frequency of 0.5 MHz. (e) Asymmetrical modulations of V_G. The high/low ratio is fixed at 4:1. (f-h) A plot similar to (b-d) for asymmetric modulation.

Detection of the Kondo screening cloud

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[1] Department of Physics, City University of Hong Kong, [2]Department of Physics, KAIST,
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When a magnetic impurity is placed in a metal, the conducting electrons become entangled with the magnetic impurity and effectively screen it. This is called the Kondo effect after the Japanese theoretical physicist Jun Kondo who first revealed the role of this effect in the mid-1960s, and its strength is known as the Kondo temperature.

The cloud size is another important parameter for materials that contain more than one magnetic impurity because the spins in the cloud couple with one another and mediate the coupling between magnetic impurities when the clouds overlap. Although the Kondo effect for a single magnetic impurity is covered in textbooks on many-body physics, the Kondo cloud had not been directly detected until now despite many attempts over the past five decades. It was known to exist, but its spatial extension had never been observed, creating a controversy over whether such an extension actually existed.

In the present study, we observed a Kondo screening cloud formed by an impurity defined as a localized electron spin in a quantum dot coupled to quasi-one-dimensional conducting electrons, and then used an interferometer to measure changes in the Kondo temperature, allowing us to investigate the presence of a cloud at the interferometer end (Fig. 1). Essentially, we slightly perturbed the conducting electrons at a location away from the quantum dot using an electrostatic gate. The wave of conducting electrons scattered by this perturbation returned back to the quantum dot and interfered with itself. The Kondo cloud is a quantum mechanical object which acts to preserve the wave nature of electrons inside the cloud. Even though there is no direct electrostatic influence of the perturbation on the quantum dot, this interference modifies the Kondo signature measured by electron conductance through the quantum dot if the perturbation is present inside the cloud. We found that the length as well as the shape of the cloud is universally scaled by the inverse of the Kondo temperature, and that the cloud's size and shape were in good agreement with theoretical calculations (Fig. 2).

The size of the Kondo cloud in semiconductors was found to be much larger than the typical size of semiconductor devices. The cloud can therefore mediate interactions between distant spins confined in quantum dots, which is a necessary protocol for semiconductor spin-based quantum information processing. This spin-spin interaction mediated by the Kondo cloud is unique since both its strength and sign (two spins favor either parallel or anti-parallel configuration) are electrically tunable, while conventional schemes cannot reverse the sign. This opens up a novel way to engineer spin screening and entanglement.

Reference : I. V. Borzenets, J. Shim, J. C. H. Chen, A. Ludwig, A. D. Wieck, S. Tarucha, H.-S. Sim, M. Yamamoto, "Observation of the Kondo screening cloud", Nature 579, 210-213 (2020). DOI : 10.1038/s41586-020-2058-6

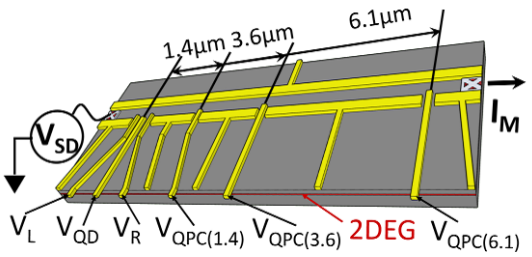

Fig. 1 Schematic illustration of the device used to observe the Kondo cloud.

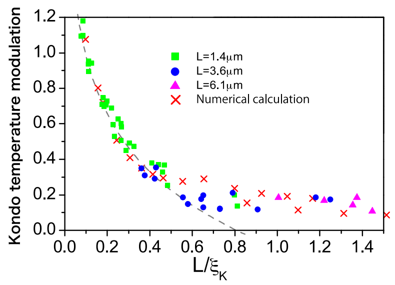

Fig. 2 Shape of the Kondo cloud plotted as a function the distance from the localized spin normalized by the cloud size.

Hybrid structure of quantum-dot and quantum-well superlattice grown by molecular beam epitaxy

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National Institute of Information and Communications Technology

Research on quantum dots (QDs) has attracted considerable attention because of their applications in high-performance optical devices such as semiconductor lasers [1]. Self-assembled InAs QDs grown on InP substrates have advantages for use in optical devices for fiber optic communication systems operating in the 1.55-μm wavelength region. InGaAlAs barrier material can be used to embed InAs, enabling the bandgap to be tailored by changing the composition of the barrier. However, compositional control of InGaAlAs is not easy because the exchange of Ga and Al atoms is insensitive to changes to the lattice constant. To overcome this problem, we developed a new growth method for embedding InAs QDs on an InP substrate. This method utilizes lattice-matched InGaAs and InAlAs superlattices (SLs) to embed the InAs QDs using the so-called digital embedding method [2]. The emission wavelength of InAs QDs could be effectively controlled by changing the SL period or ratio of the thickness of the InGaAs to that of the InAlAs.

In this study, all samples were grown by conventional solid-source molecular beam epitaxy. We fabricated six-layer QD and InGaAs/InAlAs stacked structures on an InP(311)B substrate. After the InGaAs/InAlAs SL was grown, 5 ML of InAs QDs were grown. Then, InAs QDs were embedded by InGaAs/InAlAs SL. A reference sample that had $In_{0.52}Ga_{0.24}Al_{0.24}As$ embedding layers was also grown. A transmission electron microscope (TEM) was used to observe the cross-section of the sample. In addition, photoluminescence (PL) measurements were conducted at room temperature. Figure 1 shows a cross-sectional TEM image of the sample with 2-ML SL. The image confirms that the InAs QDs were successfully embedded in the InGaAs/InAlAs SL. Because the structure of the SL was nearly perfect, the miniband of the SL could act as a barrier for the QDs. Figure 2 shows the PL spectra measured at room temperature for the reference sample (black), the sample with 2-ML SL (red), and the sample with 16-ML SL (blue). The peak wavelengths of the digital embedding samples were shorter than that of the reference sample and were shifted to shorter wavelengths with increasing thicknesses of the InGaAs and InAlAs. Therefore, this technique provides a simple method of precisely controlling the emission wavelengths of QDs. In addition, carrier dynamics can be controlled by changing the thickness of SL which leads to change of PL decay time (Fig. 3). Therefore, the interaction between the QD and SL states can be used for efficient injection and/or correction of carriers around the QD if these energy states can be controlled accurately.

Reference : [1] Kouichi Akahane et. al., J. Cryst. Growth, 432, 15 (2015).

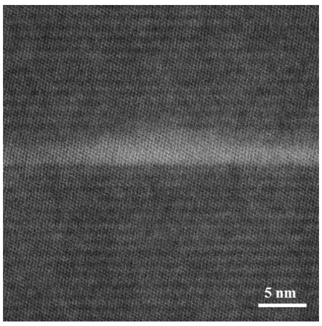

Fig. 1 Cross-sectional TEM image of sample with 2-ML SL.

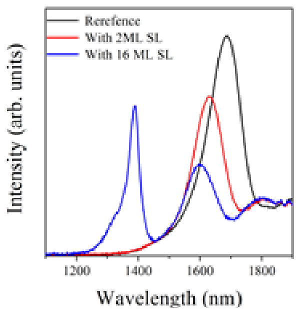

Fig. 2 PL spectra of reference sample (black), sample with 2-ML SL (red), and sample with 16-ML SL (blue).

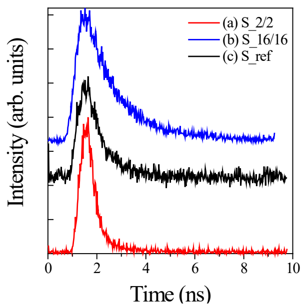

Fig. 3 PL decay of reference sample (black), sample with 2-ML SL (red), and sample with 16-ML SL (blue).

Dicke Effect in Photocurrent through Quantum Dot Array

−Sensitive detector of THz light−

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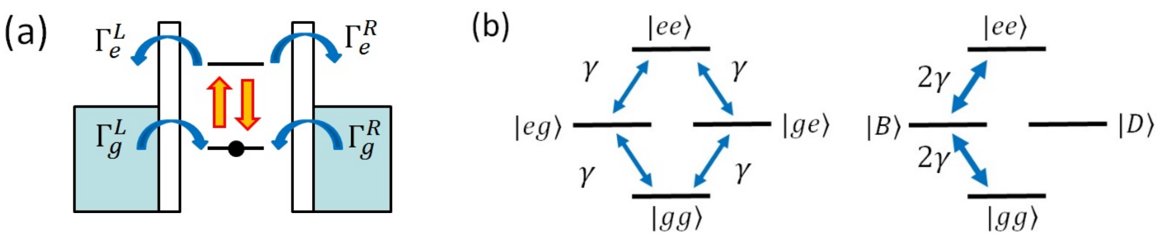
Photocurrent through a quantum dot was reported by irradiating the terahertz (THz) light [1]. In a self-assembled InAs quantum dot, discrete energy levels are separated by an energy of THz light. In the Coulomb blockade regime of a single electron transistor, the light irradiation excites an electron from an energy level below the Fermi level (E_F), $|g\rangle$, to that above E_F, $|e\rangle$, which results in an electric current without applying a bias voltage between the source and drain leads [Fig. (a)]. The direction of the photocurrent is determined by an asymmetry of the tunnel couplings of the associated energy levels, Γ_g^L, Γ_g^R, Γ_e^L, and Γ_e^R, and no current flows in the case of $\Gamma_g^L/\Gamma_g^R \neq \Gamma_e^L/\Gamma_e^R$. This system could be applied to a sensitive THz detector.

We theoretically study the photocurrent through an array of *N* quantum dots in parallel, to investigate a possibility for more sensitive THz detector by the quantum effect. The quantum dots are connected to common source and drain leads without tunnel coupling to one another. The fundamental idea is the superradiance or Dicke effect when the distance among the quantum dots is smaller than the wavelength of the light. The absorption or emission of photon makes the entangled states of *N* quantum dots: e.g., for *N*=2, the ground state $|gg\rangle$ changes to an entangle state, $|\mathrm{B}\rangle = (|eg\rangle + |ge\rangle)/\sqrt{2}$, whose transition rate to $|gg\rangle$ or $|ee\rangle$ is twice as large as that of $|eg\rangle$ or $|ge\rangle$, as shown in Fig. (b). No transition takes place to another entangled state, $|\mathrm{D}\rangle = (|eg\rangle - |ge\rangle)/\sqrt{2}$ (dark state).

First, we formulate the photocurrent through a single quantum dot in Fig. (a) using the density matrix method. It is given by

$$I/e = \left[\frac{\Gamma_e^R - \Gamma_e^L}{\Gamma_e^R + \Gamma_e^L} - \frac{\Gamma_g^R - \Gamma_g^L}{\Gamma_g^R + \Gamma_g^L}\right]\frac{g^2\Gamma_1}{(\hbar\omega - \Delta)^2 + (\hbar\Gamma_2/2)^2}$$

where g is the coupling constant between electron and light and Δ is the energy level spacing between $|g\rangle$ and $|e\rangle$. Γ_1 and Γ_2 are constants determined by $\Gamma_e^R + \Gamma_e^L$, $\Gamma_g^R + \Gamma_g^L$, and g. The photocurrent is maximal when the photon energy $\hbar\omega$ matches Δ and proportional to the asymmetric factor in the bracket. Next, we examine the photocurrent through an array of *N* equivalent quantum dots in parallel. (i) If *N* quantum dots are connected to *N* pairs of source and drain leads separately, the entangled states are destroyed by the observation of the current. Then the photocurrent is simply *N* times of that through a single quantum dot. (ii) When the quantum dots are connected to a common pair of leads with single conduction channel by identical tunnel couplings, the current is enhanced by a factor of (*N*+2)/3 if the tunneling rate is much smaller than the photon-induced transition rate. (iii) The photocurrent is generally smaller than that in case (ii) in the presence of multiple channels in the leads.



[1] Y. Zhang, K. Shibata, N. Nagai, C. Ndebeka-Bandou, G. Bastard, and K. Hirakawa, Nano. Lett. **15**, 1166 (2015); Phys. Rev. B **91**, 241301(R) (2015); *ibid.* **93**, 235313 (2016).

Ge/Si nanowire double quantum dots coupled with a microwave resonator

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Ge/Si core-shell nanowires, where holes are accumulated in a Ge core covered by a thin Si shell, have a small diameter of ~10nm and are attractive for studying physics and for spintronics applications, associated with a large spin-orbit interaction (SOI). The electron spin would be an excellent candidate for a quantum bit because of an long coherence in group four material such as Si and Ge where nuclear spins are minority. Quantum information can be exchanged between the spin and a photon when a strong coupling between them are realized. This is useful because the quantum information stored in the distant spin qubits could be exchanged through a photon in a resonator. However, an interaction between the spin and the photon (magnetic interaction) is generally weak, compared with that between a charge and a photon (electric interaction). SOI can be helpful to mediate the interaction between the spin and the photon. In real devices, decoherence exists, for example, due to the photon loss in a resonator and the qubit relaxation. To realize the coherent interaction between them, the coupling has to be larger than the decoherence rate (strong coupling). In this work, we have studied a charge coupling between the double quantum dot as a charge qubit and a photon in a resonator.

Figure 1shows the images of the sample structures. The nanowire is located on the finger gates with a hBN insulating layer in between. By applying positive gate voltages on the suitable finger gates, double quantum dots are formed with a tunable center barrier that separates the nanowire. The sample was set in a dilution refrigerator. The charge stability diagram of the double dots (Fig.2 (left)) was obtained by measuring the phase shift of the transmitted microwave as functions of the gates voltages that change a potential of each dot. The detuning between the two dot levels can be changed by sweeping the gate voltages along the arrow in Fig.2 (left). At the position where the arrow crosses the boundary of the two charge states, the molecular states should be formed as a result of the maximal coupling between the two dots. Figure 2 (right) shows the resonant frequency change of the resonator as the detuning is changed along the arrow. The behavior can be simulated by considering an interaction between the double dots and a photon with a possible decoherence. From that, we concluded the strong coupling was not realized due to the qubit decoherence larger than the coupling strength.

Reference:
Rui Wang, Russell S. Deacon, Jian Sun, Jun Yao, Charles M. Lieber, Koji Ishibashi, Nano Lett. **19**, 1052–1060 (2019)

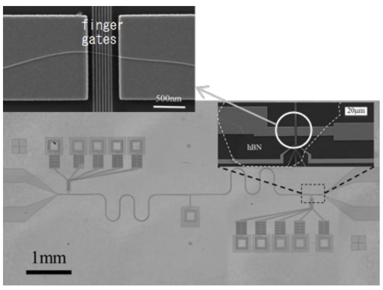

Fig.1: SEM image of the sample structures. The nanowire is located at the position where the electric field strength is maximum

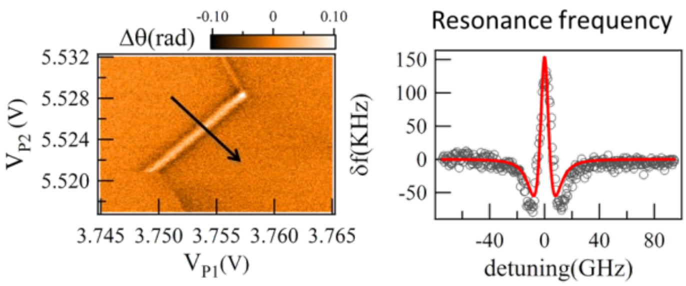

Fig.2: **(left)** Charge stability diagram of the double dot obtained by measuring the phase change of the transmitted microwave). (right) A change of the resonant frequency as the gate voltage (detuning) is changed along the allow in the left Fig.

Helical channel formation in Ge/Si core-shell nanowires

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Ge/Si core-shell nanowires, where holes are accumulated in a Ge core covered by a thin Si shell, have a small diameter of ~10nm and are attractive for studying physics and for spintronics applications, associated with a large spin-orbit interaction (SOI). SOI is also important to form a helical state where spin is locked with momentum. The helical channel is essential to realize a one-dimensional topological superconductor when superconductivity is induced in the semiconductor nanowires with a large SOI under an external magnetic field. Majorana zero-modes are expected to emerge in it, and that can constitute a topological quantum bit (qubit) which is considered to have a long coherence, an essential requirement for the quantum computer. Experimentally, it is important to demonstrate the formation of the helical state. In this work, we did it by measuring conductance of the Ge/Si nanowire in magnetic fields as the gate voltage and a magnetic field direction are changed.

Figure 2 shows an expected energy dispersion of the one-dimensional nanowire when the helical state is formed. Due to the SOI, the two bands for spin up and down states shift and the "helical gap" opens at k=0 due to the external magnetic field. Generally, the conductance of the ballistic nanowire is quantized with the number of occupied subbands. The formation of the helical gap reflects on the behavior of the conductance quantization as a reentrant quantized step with a dip when the gate voltage (Fermi energy) is swept. Figure 1 show the false color image of a typical fabricated sample. A metal gate is formed on a thermally oxidized Si substrate and a nanowire is located on top of it with a hBN insulating layer between the gate metal and the nanowire. Multiple metal contacts are deposited to flow a current. Fermi level can be changed by changing the gate voltage.

Figure 2 (right) shows the conductance near the first step as a function of the gate voltage with and without magnetic fields. The expected conductance "dip" or the reentrant behavior, indicated by an arrow, is observed on the step. The dip is also observed in no magnetic field, the reason of which is not known. The width of the helical gap should depend on the direction of the external magnetic field with respect to that of the effective magnetic field (B_{SO}) associated with the SOI, and become zero when the two fields are aligned. This expectation was confirmed by measuring the width of the dip when the external magnetic field direction was changed.

Reference:

1. Rui Wang, Russell Deacon, Jun Yao, Charles Lieber, and Koji Ishibashi, Semicon. Sci. Technol., **32**, 094002 (2017)
2. Jian Sun, Russell Deacon, Rui Wang, Jun Yao, Charles M. Lieber, Koji Ishibashi, Nano Lett. **18**, 6144-6149 (2018)

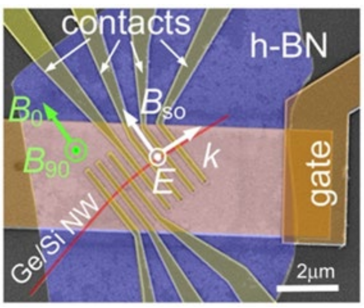

Fig.1: False color SEM image of the typical sample.

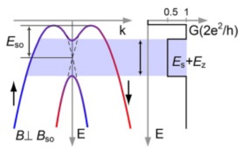

Fig.2 (left): Dispersion relation in a 1D wire under an external magnetic field. The helical gap is formed.

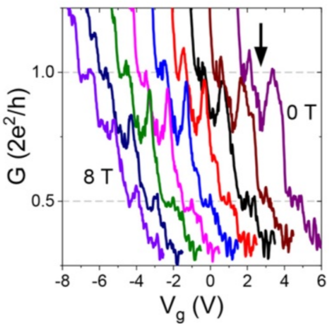

Fig.2 (right): Conductance as a function of the gate voltage with and without magnetic fields at 7.5K

Microscopic NMR in Quantum Point Contact

M. H. Fauzi* and Y. Hirayama
Graduate School of Science, CSIS, CSRN, Tohoku University

Resistively-detected NMR (RDNMR) measurement has been applied to a GaAs-based quantum point contact (QPC) and interesting characteristics are obtained in the quantum Hall regime, where spin-flip inter-edge-channel scattering occurs near the QPC. The RDNMR signal appears when filling of the both side of the QPC (ν_b) is even and that of the inside of the QPC (ν_{QPC}) is ν_b-2< ν_{QPC}< ν_b -1. First, ν_b is set to 2 (the ground Landau level). The successful RDNMR detection is confirmed down to B = 1.25 T as shown in Fig. 1. All the RDNMR signals exhibit a threefold spectra attributed to electric quadrupole interaction. Interestingly, the central NMR linewidths, which are not affected by the strain distribution discussed later, increases in proportion with field up to B = 3 T and saturate. This saturation suggests the contribution of Coulomb interaction [1].

Furthermore, RDNMR can be achieved up to the fifth Landau level, where ν_b =10 and 8 < ν_{QPC} < 9. In such situation, the magnetic field can be lower than 1 T. We are able to retain the RDNMR signals in a condition where the spin degeneracy of the first one-dimensional (1D) subband is still preserved. Furthermore, the effects of orbital motion on the first 1D subband can be made smaller than those due to electrostatic confinement. This developed RDNMR technique is a promising means to study electronic states in a quantum point contact near zero magnetic field [2].

Gate patterning on semiconductors is routinely used to electrostatically confine electrons into reduced dimensions. At cryogenic temperatures, differential thermal contraction between the patterned gate and the semiconductor often lead to an appreciable strain modulation. The impact of such modulated strain to the conductive channel buried in a semiconductor has long been recognized, but measuring its magnitude and variation are rather challenging. Here, thanks to the quadrupolar splitting in the RDNMR signal, the strain felt by the electrons flowing in the quasi one-dimensional channel is precisely detected as shown in Fig. 2. The detected strain magnitude on the order of 10^{-4} varies spatially in the nanometer scale. This result provides us an important hint for studying the effects of strain on semiconductor quantum devices. [3].

Reference: [1] A. Noorhidayati, M. H. Fauzi, M. F. Sahdan, S. Maeda, K. Sato, K. Nagase, and Y. Hirayama, Phys. Rev. B101, 035425, doi.org/10.1103/PhysRevB.101.035425 (2020). [2] M. H. Fauzi, A. Noorhidayati, M. F. Sahdan, K. Sato, K. Nagase, and Y. Hirayama, Phys. Rev. B97 (RC), 201412 doi.org/10.1103/PhysRevB.97.201412 (2018). [3] M. H. Fauzi, M. F. Sahdan, M. Takahashi, A. Basak, K. Sato, K. Nagase, B. Muralidharan, and Y. Hirayama, Phys. Rev. B100 (RC), 241301, DOI: 10.1103/PhysRevB.100.241301 (2019).

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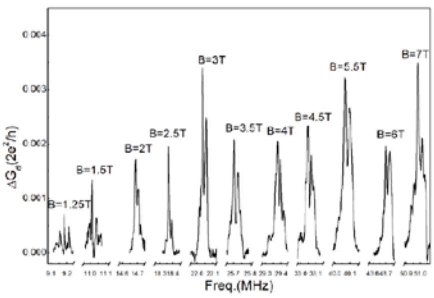

Fig. 1 Magnetic field dependence of RDNMR signals measured at ν_b =2 and ν_{QPC}< 1

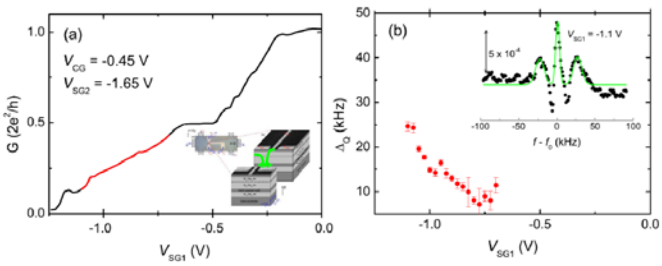

Fig. 2 (a) Diagonal magnetotransport trace as a function of V_{SG1} with V_{SG2} = −1.65 V and V_{CG} = −0.45 V. The inset shows schematic diagram of the QPC device and variation of the channel position by V_{SG1}. (b) Quadrupole splitting Δ_Q from the RDNMR spectra measured along the red line in (a). The inset shows a typical spectrum.

Dynamical nuclear spins and disorder potential effect in quantum point contacts

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[1] Faculty of Engineering, Ibaraki University

Spin polarization can be easily achieved using a magnetic field for electron spins, but not for nuclear spins. The dynamical nuclear spin polarization (DNP) uses a spin flip-flop between the electron and nuclear spin to achieve nuclear spin polarization. Recently, a method called resistivity-detecting NMR, which detects NMR signals as a change in electrical resistance, has been developed, making it possible to observe DNP formation in semiconductor nanostructures.

The DNP using quantum point contacts (QPCs) and the DNP detection by resistance-detecting NMR are considered. When a finite bias voltage is applied to the QPC at a conductance $G = e^2/h$, a dipole-type DNP is generated. The DNP orientation is reversed between the source and drain electrodes, as shown in Fig. 1. This dipolar-type DNP has qualitatively different response characteristics from the homogeneous nuclear spin polarization when detected by resistance-detection NMR. This works is done in collaboration with Dr. Kawamura, and Dr. Stano from RIKEN, and Prof. Komine from Ibaraki Univ.

The gate voltage dependence of QPC conductance reflects the QPC's potential structure; when the QPC potential is parabolic, the slope of the gate voltage dependence of the conductance gives the potential curvature. In recent experiments, the relationship between the potential curvature and the split gate length has been investigated by measuring the gate voltage characteristics of about 100 QPCs. As the split-gate length increases, one would expect the QPC curvature to decrease; however, contrary to this expectation, the curvature remains almost unchanged with the gate length. Furthermore, the results suggest that the background disorder potential causes this property.

We investigate the QPC conductance under disordered potentials using 1D and 2D tight-binding models. As shown in Fig. 2 (left), we consider the disorder potential is added to the parabolic potential energy. The disorder potential has a Gaussian correlation function in space. Given the disorder potential strength and the spatial correlation length, the effective QPC length is obtained by taking the sample average of the gate voltage dependence. As shown in Fig. 2 (right), the effective QPC length is insensitive to the QPC length. Moreover, the results even exhibit the opposite trend, where the effective QPC length weakly decreases as the QPC length increases. This work is done in collaboration with Prof. Hirayama's group.

Reference: [1] P. Stano, T. Aono, M. Kawamura, "Dipolelike dynamical nuclear spin polarization around a quantum point contact" Phys. Rev. B 97, 075440 (2018). DOI: 10.1103/PhysRevB.97.075440 [2] T. Aono, M. Takahashi, M. Fauzi, Y. Hirayama, "Quantum point contact potential curvature under correlated disorder potentials" Phys. Rev. B 102, 045305 (2020). DOI: 10.1103/physrevb.102.045305

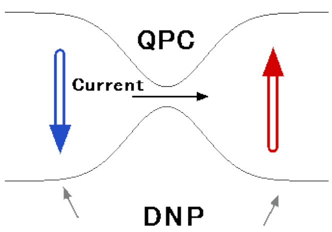

Fig. 1: Current through QPC and dipole-type DNP

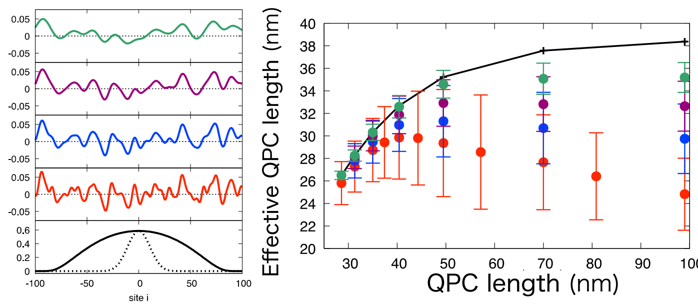

Fig. 2: **(left)**QPC potential (black curves) and Gaussian disorder potential **(right)**QPC length and effective QPC length

Theory of carbon nanotubes in hybrid systems

－Topological states and their quantum property－

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Carbon nanotubes have been extensively studied as ideal one-dimensional conductors in nanoscale. Hybrid structures, in which individual ultraclean single-wall carbon nanotubes are embedded in semiconductor devices, have been fabricated in the last two decades. Quantum transport measurements have revealed that there exist fine structures. The basic electronic property of the nanotubes can be understood from that of the graphene by employing the boundary condition in the circumference direction. However, the observed fine structures cannot be captured by this simple picture. They exhibit the unique quantum effects of the nanotubes. We have focused on these phenomena and investigated them theoretically.

The bound state spectrum arises due to the finiteness of the nanotube length. There exist two valleys in the energy bands. The valley has been widely treated as a good quantum number on the bound states. However, there have been unclear points regarding the role on the bound state. To explore this problem, we have been carried out the construction of microscopic theory.

As shown in the figure, we have constructed one-dimensional models by utilizing the rotational symmetry of the system. This model enables us the study on the bound state including the evanescent modes near the boundary. The theory has been expanded to the edge states lying in the bulk band gap. An exact relation between the edge states and a topological invariant has been found. This has revealed the topological nature of the nanotubes [1,2,3].

Furthermore, international research projects have been carried out. Formation of end spins on the topological edge states and their antiferro-, ferro-magnetic interaction under the electron correlation have been demonstrated [4]. For the hybrid system of a nanotube proximity coupled to a superconductor, emergence of the topological states localized at the edges including the Majorana quasiparticles has been investigated [5,6,7].

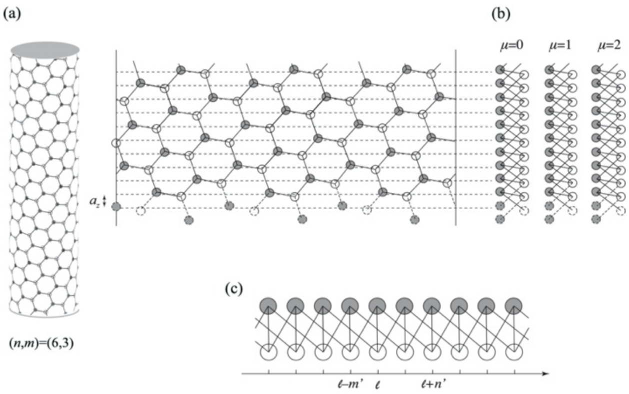

Figure Construction of 1D models for the nanotubes.

References：
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Flexible Carbon Nanotube Electrochemical Sensors

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Electrochemical sensors based on carbon nanotubes (CNTs) have great potential for use in wearable or implantable biomedical sensor applications because of their excellent mechanical flexibility and biocompatibility. However, the electrochemical activity of such materials is not yet fully understood. In addition, the main challenge associated with applications of CNT-based sensors is their uniform and reproducible fabrication on flexible plastic film. In this study, we focused on understanding the origin of the electrochemical activity of single-walled CNTs (SWNT). We also elaborated to establish a highly reliable technique to fabricate uniform flexible CNT microelectrodes on a plastic film.

We fabricated electrochemical sensors with high-quality and clean SWNT film formed by the floating-catalyst CVD technique; however so-fabricated SWNT electrodes exhibited a low electron transfer rate. Electrochemical functionalization with an H_2SO_4 solution successfully enhanced the electrochemical activity of the SWNT electrode. This method is gentle and controllable, but also effective at increasing the electron transfer rate without either degrading the potential window. We found out that there was a correlation between the electron transfer rate and the amount of defects evaluated from Raman scattering spectroscopy. XPS analysis showed that the functionalization process introduced C–O and C=O species, suggesting that these species constituted active sites for inner sphere probes.

We also realized a highly reliable technique to fabricate flexible CNT microelectrodes. In addition to using the clean CNT thin film, an oxide protection layer, which is used to cover the CNT thin film during the fabrication process, minimizes contamination of the surface. The fabricated flexible CNT microelectrodes show almost ideal electrochemical characteristics for microelectrodes with the average value of the quartile potentials, $\Delta E = |E_{3/4} - E_{1/4}|$, was 60.4 ± 2.9 mV for the 28 electrodes after the electrochemical functionalization. The CNT microelectrodes also showed the enhanced resistance to surface fouling during dopamine oxidation in comparison to carbon fiber and gold microelectrodes. The high-sensitivity detection of dopamine is also demonstrated with differential-pulse voltammetry, with a resulting limit of detection of ~50 nM. The reliability, uniformity, and sensitivity of the present CNT microelectrodes provide a platform for flexible electrochemical sensors.

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2. N. X. Viet, S. Kishimoto, and Y. Ohno, "Highly Uniform, Flexible Microelectrodes Based on Clean Single-walled Carbon Nanotube Thin Film with High Electrochemical Activity", *ACS App. Mater. Interfaces* **11**, 6389-6395 (2019). doi:10.1021/acsami.8b19252

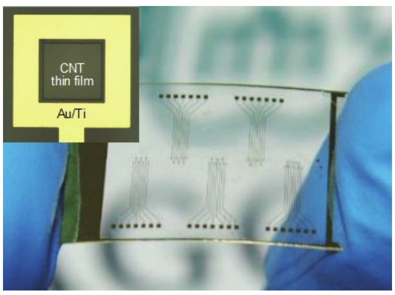

Fig. 1 Highly-uniform flexible CNT electrochemical sensors fabricated on PEN film.

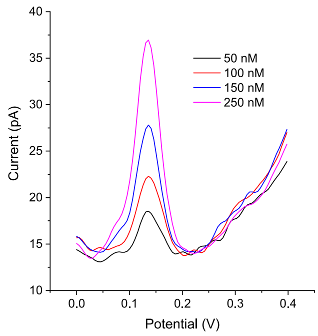

Fig. 2 High-sensitivity detection of dopamine with activated CNT microelectrode.

Modulation of Phonon in Carbon Nanotubes by Defect Formation

Takumi Inaba and Yoshikazu Homma
Department of Physics, Tokyo University of Science

A single-walled carbon nanotube (SWCNT) is a hybrid system of electrons, photon, and phonons. Phonons in SWCNTs are sensitively accessed with Raman scattering spectroscopy resonant to the quasi 1D electronic states. Together with the robust exitonic states, the resonant Raman transitions in SWCNTs are attractive as a quantum hybrid control. However, technological applications of phonons in SWCNTs remain unexplored. We need to investigate deeply the intrinsic properties of phonons in SWCNTs and their interactions with photons and electrons.

We have investigated modifications of SWCNT phonons by means of molecular adsorption, encapsulation, and defect formation to SWCNTs. Here, we report the intensity modification of the intermediate frequency mode (IFM), which is attributed to K-momentum phonons. The IFM is interesting because photons with nearly-zero momentum can couple with acoustic nonzero-momentum phonons.

The Raman spectra of IFM in the frequency range from 300 to 500 cm^{-1} were investigated using individually suspended SWCNTs, together with photoluminescence (PL) spectra which is sensitive to the defect density. Owing to the introduction of defects due to the use of an intense excitation laser, Raman peaks originating from K-momentum phonons (IFM and D-mode peaks) were enhanced, while Γ-momentum phonons (radial breathing mode: RBM, out-of-plane transverse optical mode (oTO), and G-mode peaks) were decreased. The intensities of each Raman peak from a (11, 3) SWCNT are plotted against the PL intensity in Fig. 1(c). The intensities of Γ-momentum phonons, RBM, oTO and G-mode, decrease linearly correlating with the PL intensity. By contrast, the IFM and D-mode intensities increase inversely-correlates with the PL intensity. For K-momentum phonons, presence of defects is essential because K-momentum phonons need to be elastically scattered by disorder or defect of the graphene lattice. Therefore, the K-momentum phonon intensity can be modulated by introducing defects. In other words, the photon-phonon coupling can be enhanced by defects.

The application of those phononic properties of SWCNTs to quantum information technologies is still challenging, but the understanding them deeply will hopefully bring a breakthrough in this field.

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*https://www.researchgate.net/publication/337706741_IFM_Animation

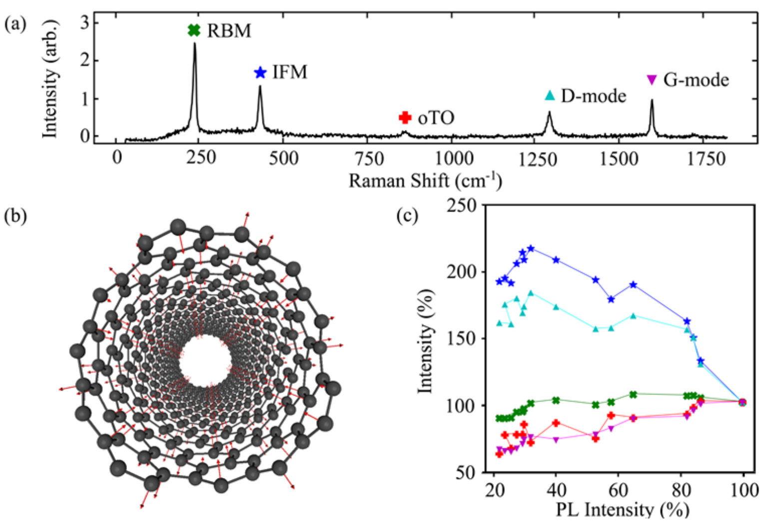

Fig. 1 (a) Raman spectrum of suspended (11,3) SWCNT.
(b) Illustration of atomic deformation vectors for IFM of (11,3) SWCNT.*
(c) Relationship between Raman and PL intensities.

Thermal Conductivity Measurements of Chirality Assigned Single-Walled Carbon Nanotubes

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Single-walled carbon nanotubes (SWCNTs) are expected to have high thermal conductivity along the tube axis. Although many experimental measurements of the thermal conductivity have been reported, the SWCNT structure was not characterized sufficiently. In particular, the chirality was not assigned, and it was not confirmed whether the SWCNT was isolated or not.

Here, we measured the thermal conductivity of chirality assigned SWCNTs, which were individually suspended, by using photoluminescence (PL) imaging spectroscopy. The crystallinity of SWCNTs were evaluated by Raman spectroscopy. The temperature distribution along the tube axis was obtained, and the temperature dependence of the thermal conductivity was measured in a wide-temperature range (from 350 to 1000 K). For (9, 8) SWCNTs with 10−12 μm in length, the thermal conductivity was 1166 ± 243 W/(m·K) at 400 K.

The proposed PL imaging spectroscopy enables to measure the thermal conductivity of SWCNTs with high precision and without any contacts. The method is based on the combination of single suspended SWCNT formation technology and high-sensitivity resonance spectroscopy and enables non-contact measurement of thermal conductivity with high precision. SWCNTs provide a hybrid system of electrons, photon, and phonon, and understanding the basic physical properties of phonons such as thermal conductivity contributes to the development of hybrid quantum technology.

Reference: K. Yoshino, T. Kato, Y. Saito, J. Shitaba, T. Hanashima, K. Nagano, S. Chiashi, and Y. Homma, "Temperature Distribution and Thermal Conductivity Measurements of Chirality-Assigned Single-Walled Carbon Nanotubes by Photoluminescence Imaging Spectroscopy", ACS Omega, 3, 4352 (2018). DOI: 10.1021/acsomega.8b00607

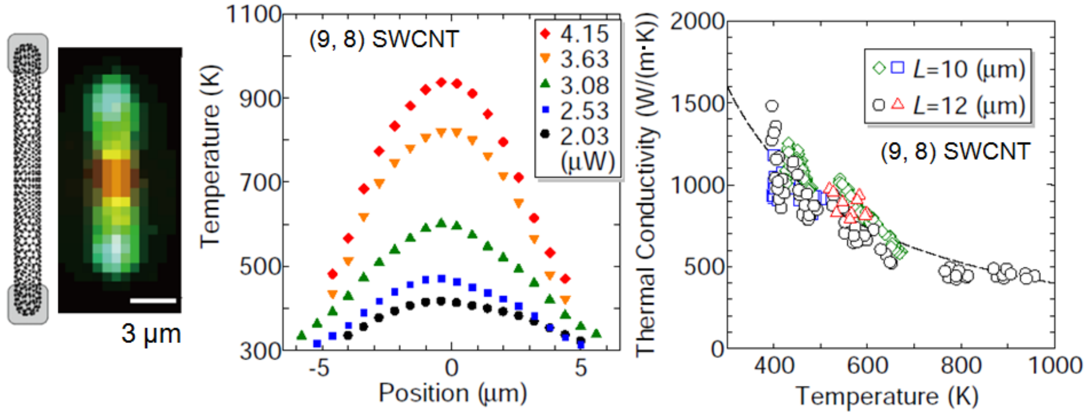

Fig. 1 Temperature distribution along the tube axis was measured by spectroscopic imaging of a suspended (9, 8) SWCNT under laser irradiation with different powers. The temperature dependence of the thermal conductivity was obtained from the temperature distributions for (9, 8) SWCNTs with different lengths (L)

Observation of band-like transport from defect-repaired graphene oxide film

-Towards scalable production of highly crystalline graphene thin film-

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Department of Applied Physics, Graduate School of Engineering, Osaka University

Graphene oxide (GO) is a nanocarbon material which can be produced in a scalable manner from bulk graphite. In this work, the crystallinity is successfully improved by thermal treatment at high temperature above 1100°C in a reactive atmosphere. The improved crystallinity unveils the original electrical properties of graphene from the reduced GO films, resulting in observation of band-like transport for the first time [1].

GO is attracting attention as a starting material for mass synthesis of graphene, which can be formed by the reduction of GO. However, defects formed during synthesis remain even after usual reduction processes by chemical treatment or heating. The carrier transport properties of the graphene thin film produced by such methods are not the band-like conduction caused by excellent physical properties of graphene, but reflect variable-range hopping (VRH) conduction in which electrons were localized due to defects. Therefore, the carrier mobility is limited to several cm^2/Vs at most, and it has been an issue to improve the crystallinity and approach the properties of high-quality graphene.

Recently, our research group has been investigating the process to produce graphene by heating and reducing GO thin films at high temperatures in an ethanol atmosphere. Raman and TEM study confirmed that the defects are drastically repaired by the thermal treatment above 1100°C. The remarkable improvement in crystallinity results in very high carrier mobility (~ 210cm^2 / Vs) which is top-level data observed from reduced GO (rGO) thin films. Furthermore, we analyzed the temperature dependence of conductance in the high-mobility rGO thin film and found that the conductance exhibits a non-linear change in the range from room temperature to 40K, indicating a change of transport mechanism from hopping to band-like conduction. This behavior reflects the original electronic structure of graphene and is the first case to be observed from a graphene thin film derived from GO. As for the rGO obtained by the lower temperature process at ~ 900C, a lot of defects remain as reported and the VRH conduction was observed. These behaviors of the transport measurements indicate that the improvement in crystallinity reduces to disconnect the electronic band structure and causes the change from hopping to band-like conduction. The band-like conduction was also supported by the electronic structure analysis of X-ray absorption fine structure spectroscopy and photoelectron spectroscopy.

The result shown here has opened up the possibility of scalable production of highly crystalline graphene thin films, enabling various applications such as electronic devices and sensors using graphene. Furthermore, various progress based on this work is expected as future research, such as nuclear spin control by introducing ^{13}C into the graphene lattice using the defect repair process, the modulation of local electronic structure by intentionally formed defects, and their application to quantum devices.

[1] R. Negishi, M. Akabori, T. Ito, Y. Watanabe and Y. Kobayashi, "Band-like transport in highly crystalline graphene films from defective graphene oxides", Sci. Rep. 6, 28936(2016). DOI: 10.1038/srep28936

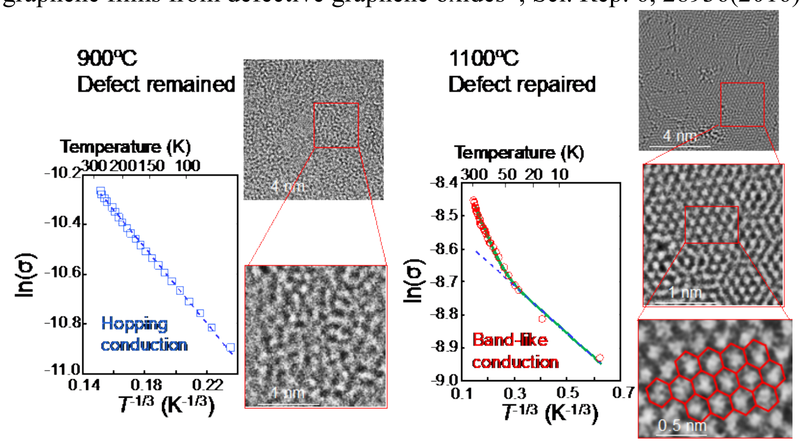

Fig. 1 TEM images and carrier transport characteristics (conductance σ vs temperature T) observed from rGO film formed by thermal processes at 900 and 1100°C.

Monte Carlo Simulation of Mobility Enhancement in Graphene

N. Mori[1], S. A. Mojtahedzadeh[1], L. Turyanska[2], O. Makarovsky[2], L. Eaves[2], and A. Patanè[2]
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[2] School of Physics and Astronomy, The University of Nottingham

To date, the high room-temperature carrier mobility of the exfoliated graphene is not reproduced in single layer graphene (SLG) grown by scalable large area methods. This mobility reduction is usually attributed to the presence of crystalline defects and scattering of free carriers by charged impurities on the substrate. Understanding the processes that control and limit the carrier mobility of graphene is a challenging research field that has potential to accelerate the technological readiness of large area SLG. We demonstrate theoretically and experimentally that the spatial correlation of charges in surface-functionalized graphene can provide a means to control the carrier mobility of SLG.

We performed Monte Carlo simulation of carrier dynamics in SLG decorated with a surface layer of colloidal PbS quantum dots (see Fig. 1). The spatial correlation between the charged impurities on the substrate and the localized charges in a capping layer is modeled with a correlation length r_{max}. Strong spatial correlation (small r_{max}) smooth out the electrostatic potential (Fig. 2), thus enhancing carrier mobility. The Monte Carlo simulations are in good agreement with experiments (Fig. 3). The control of the carrier mobility could prove to be a useful tool for fundamental studies of charge correlation phenomena and for application of graphene in devices requiring a high mobility.

[1] L. Turyanska, O. Makarovsky, L. Eaves, A. Patanè, and N. Mori, "Mobility enhancement of CVD graphene by spatially correlated charges," 2D Materials, Vol. 4, 025026 (1-6), 2017, DOI: 10.1088/2053-1583/aa55b4

[2] O. Makarovsky, L. Turyanska, N. Mori, M. Greenaway, L. Eaves, A. Patanè, M. Fromhold, S. Lara-Avila, S. Kubatkin, and R. Yakimova, "Enhancing optoelectronic properties of SiC-grown graphene by a surface layer of colloidal quantum dots," 2D Materials, Vol. 4, 031001 (1-7), 2017, DOI: 10.1088/2053-1583/aa76bb

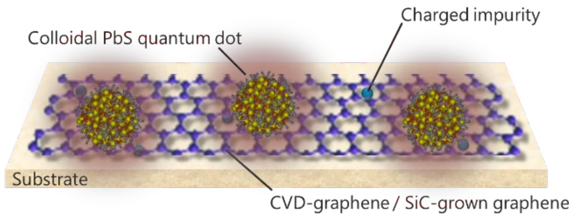
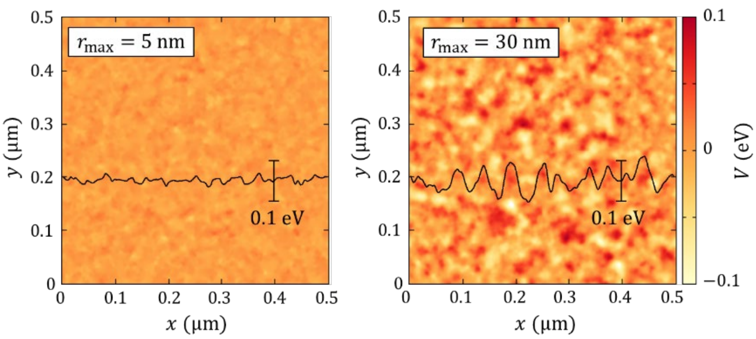


Fig. 1 Illustration of a single-layer graphene decorated with a surface layer of colloidal PbS quantum dots (QDs) which act as electron donors. Impurities are located on the substrate.



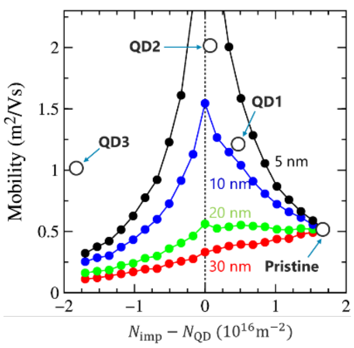


Fig. 2 [left, center] Simulated potential profiles for different correlation lengths, r_{max}.
Fig. 3 [right] Mobility as a function of carrier density. Open circles are data points for measured devices with QDs with different capping molecules (QD1, QD2, and QD3) and a device without QDs (Pristine). Closed circles correspond to Monte Carlo simulations with different r_{max}.

Isotope control in graphene phononic crystal

–Towards phonon transport control in graphene–

Takayuki Arie and Seiji Akita
Osaka Prefecture University

Graphene is a potential candidate for next generation electronic devices due to its unique electronic and mechanical properties. Since the main heat carrier in graphene is phonon, we aimed to control the phonon transport properties in graphene by introducing the interface of graphene composed of ^{12}C (^{12}C-graphene) and ^{13}C (^{13}C-graphene). This enables us to control the thermal conductivity of graphene, resulting in the higher thermoelectric performance of graphene devices.

Graphene was grown by chemical vapor deposition (CVD) using CH_4 as a source gas and Cu foils as a catalyst. As a top-down process, graphene isotopic heterostructures, ^{12}C-graphene and ^{13}C graphene, were synthesized by CVD and O_2 plasma etching. As a bottom-up process, on the other hand, we synthesized graphene heterostructures by continuously switching $^{12}CH_4$ and $^{13}CH_4$ repeatedly during CVD process to form isotopic superlattices in graphene hexagonal single crystals.

The isotopic interface grown by the top-down process (Fig. 1) shows significant increase in the thermal resistance, possibly due to the phonon frequency mismatch between ^{12}C-graphene and ^{13}C-graphene. For graphene grown by a bottom-up process, on the other hand, Raman spectral mapping from single-crystal graphene shows that each graphene has Raman peaks corresponding to ^{12}C-graphene or ^{13}C-graphene, indicating that the heterointerfaces were repeatedly fabricated. The apparent thermal resistance of the devices with respect to the interface number indicates that the resistance increases linearly as the interface number less than 4. The interfacial thermal resistance was estimated as 125 μm^{2}K/W. In the device with 4 interfaces, however, the resistance increases more significantly. As the distance between interfaces is approximately 600 nm in this device, which is shorter than the reported mean free path of phonon in graphene at room temperature, the heat transport in the device more likely changes from diffusive to quasi-ballistic regime, leading to a dramatic increase in the interfacial thermal resistance.

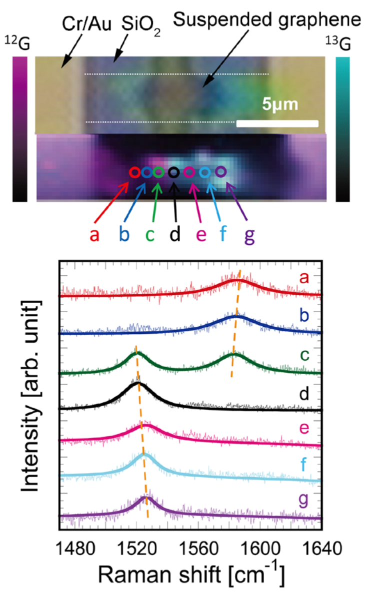


Figure 1 Isotopic heterostructures (top) and Raman spectra from each position in graphene (bottom).

References : Y. Anno, K. Takei, S. Akita, T. Arie, “Artificially controlled synthesis of graphene intramolecular heterojunctions for phonon engineering” Phys. Status Solidi RRL **8**, 692 (2014) /DOI 10.1002/pssr.201409210.

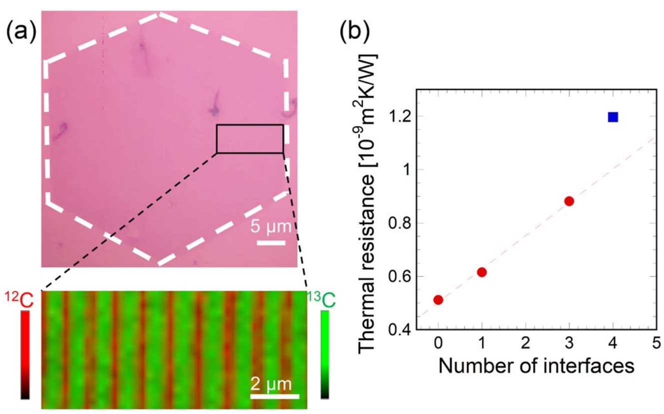


Figure 2 (a) Isotopic superlattice in single-crystal graphene and Raman spectral mapping of ^{12}C (red) and ^{13}C (green). (b) Thermal resistance of graphene isotopic heterostructures with respect to the interface number.

Controlling phonon propagation of monolayer graphene by structural defects

–Phonon control for enhancing thermoelectric device performance–

Takayuki Arie and Seiji Akita
Osaka Prefecture University

Graphene is one of the potential candidates for thermal management devices. Since phonon is the main hear carrier in graphene, the thermal conductivity can be controlled by the structural modifications into graphene networks. In particular, reducing the thermal conductivity of graphene without changing its electrical conductivity leads to the application as high efficient thermoelectric devices. We have been investigating the control of phonon transport by introducing isotope atoms in graphene. The phonon scatters at the interface between graphene composed of ^{12}C and ^{13}C due to the phonon frequency mismatch, resulting in the significant reduction in the thermal conductivity. Here, we investigate the change in thermal and thermoelectric properties of graphene by controlling defect densities.

The defects introduced into graphene by O_2 plasma are classified into 2 stages; sp^3-type defects at the lower defect density (stage 1) and vacancy-type defects at the higher defect density (stage 2). Raman spectra from graphene with each defect density show that D' band originating from defects begins to appear at the stage 2 (Fig. 1(a)). From Ioffe's semiclassical approximation of the thermoelectric properties, we found that at the stage 1 phonons are pre-dominant source of carrier scattering, while the scattering is mainly caused by charged impurities at the stage 2 (Fig. 1(b)). This corresponds to a transition in defect population from sp^3-type (stage 1) to vacancy-type defects (stage 2).

We also measured the thermal conductivity of graphene with various amounts of defects. Increase in the defect density were evaluated by the ratio between Raman D band and G band intensities (I_D/I_G). When $I_D/I_G \approx 2.4$, the thermal conductivity was dramatically reduced (150 W/mk) compared to that of as-prepared graphene (2,670 W/mK). At this stage, the density of defects was estimated to be 0.1%. This suggests that such a small amount of defect effectively modifies the phonon transport, leading to the great reduction in graphene thermal conductivity. Thus, the thermoelectric device performance can be enhanced by precisely controlling the stage of defects that are introduced into graphene.

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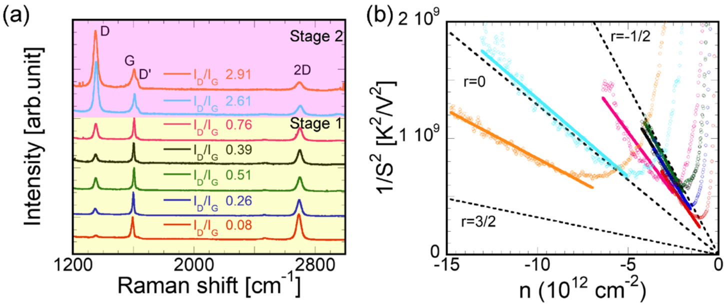

Figure 1 (a) Raman spectra with respect to the defect density. The defect stage is the stage 1 ($I_D/I_G \leq 0.76$) and stage 2 ($I_D/I_G > 2.61$). (b) The carrier scattering derived from the thermoelectric measurement.

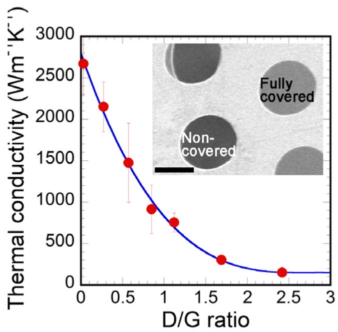

Figure 2 Thermal conductivity as a function of the defect density.

Directional heat flux and heat focusing

Roman Anufriev, Aymeric Ramiere, Jeremie Maire, and Masahiro Nomura
Institute of Industrial Science, The University of Tokyo

In the past few years, ballistic heat transport has been demonstrated experimentally in the bulk, thin-films and various nanostructures. Yet, practical use of this phenomenon remains challenging, because thermal phonons tend to travel in almost random directions. We used μTDTR experiments and Monte-Carlo simulations to show the in-plane ballistic heat transport in silicon phononic crystals and a possibility to use them for directional thermal emission and heat focusing.

First, our simulations demonstrated that aligned lattices of holes in a thin plate or periodic corrugations in a nanowire (Fig. 1) could form directional phonon fluxes from initially random phonon gas. In a series of μTDTR experiments, we demonstrated that membranes with an aligned lattice of holes have higher thermal conductivity than membranes with staggered lattice, indicating that aligned lattices indeed has directional heat fluxes between the holes.

Such phononic structures can act as sources of directional heat rays emitted in the desired directions. Thus, this phenomenon opens various possibilities of heat manipulations based on the ballistic transport of phonons, in contrast to traditional phononic manipulations based on wave interference of phonons.

To illustrate a practical application of this effect, we proposed a thermal lens structure that can focus the thermal energy in a spot. Using Monte Carlo simulations, we demonstrated the formation of a hot spot of 115 nm in a thermal lense structure (Fig. 1). Moreover, our μTDTR experiments showed experimental evidence of the heat focusing effect. These results motivate the concept of ray-like heat manipulations at the nanoscale and form a new paradigm of heat manipulations that we call ray phononics.

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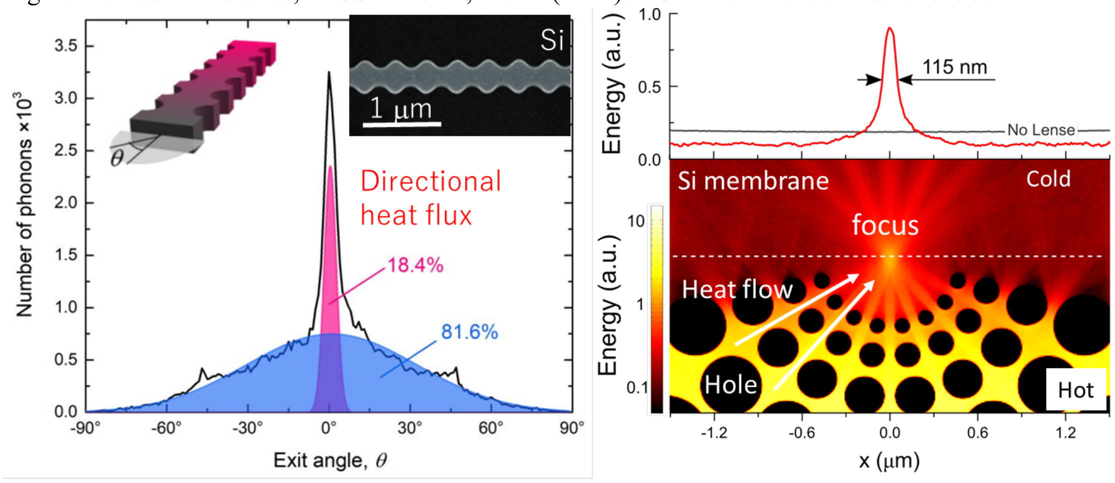


Fig. 1. (Left) Directionality predicted by Monte Carlo simulations in a corrugated nanowire. (Right) Heat focusing effect in a thermal lense structure predicted by Monte Carlo simulations.

Thermal conduction enhancement by surface phonon polaritons

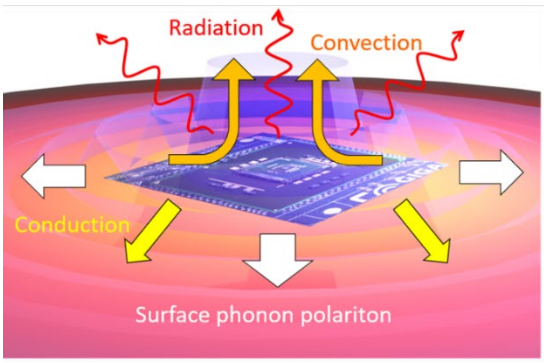
Yunhui Wu[1], Roman Anufriev[1], Sebastian Volz[1,2], and Masahiro Nomura[1,2]
[1] Institute of Industrial Science, The University of Tokyo、[2] LIMMS-IIS UT, CNRS

As the semiconductor devices scale down into thin film structure, phonons frequently scattered by the surface of the film into random directions to hinder the heat transport, resulting in a significant decrease in thermal conductivity. In addition, phonons scatter more often as the temperature of devices rises, leading the thermal conductivity further decreases. Modern semiconductor devices are highly integrated and large amount of electrical power is localized. Thus, intensive heat generation and reduction in thermal conductivity make heat dissipation difficult.

In this study, we experimentally investigated the heat conduction of surface phonon polaritons (SPhP). We observed that the heat conductivity increases as the temperature rises in dielectric thin film and the thinner the films have greater the effect of SPhP to enhance heat conductivity. The heat conduction was measured in four thin film samples: 30, 50, 100 and 200 nm at temperature between room temperature and 500 degree Celsius. In general, thermal conductivity decreases as the temperature of a substance increases, which is observed in 100 and 200 nm thin film (green and blue dots). The 200 nm thin film diminished with the square of the temperature, indicating that acoustic phonons, as well as sufficiently thick materials, are primarily responsible for heat conduction. However, it was observed that the decreasing tendency diminished in the thin film with a thickness of 100 nm, the thermal conductivity increased in the thin films with the thickness of 30 and 50 nm (black and red dots). This is a clear sign that SPhP is an important carrier of heat conduction in thin films. It was also found that the SPhP has the mean free path in millimeter range. This is because phonons form a mixed state with light, resulting a faster and less lossy propagation. It was found that thin films with thickness of 30 and 50 nm are equivalently double the phonons heat conduction.

The results of this research show that SPhP contribute significantly to heat conduction in a thin film structure, which can be the main heat dissipation mechanism. In addition to conduction, convection, and radiation, it paves the way as a fourth heat dissipation mechanism by phonons with the help of light. We expect to overcome the heat dissipation problem in semiconductor devices that have become highly integrated and miniaturized, furthermore, to be applied widely in the semiconductor field. It is expected that heat will be dissipated by using heat conduction of surface phonon polaritons to conduct the localized and intensive heat, which will contribute to further improve the performance of the devices.

Reference： Y. Wu, J. Ordonez-Miranda, S. Gluchko, R. Anufriev, D. De Sousa Meneses, L. Del Campo, S. Volz, and M. Nomura, "Enhanced thermal conduction by surface phonon-polaritons," Sci. Adv. 6, eabb4461 (2020). DOI: 10.1126/sciadv.abb4461



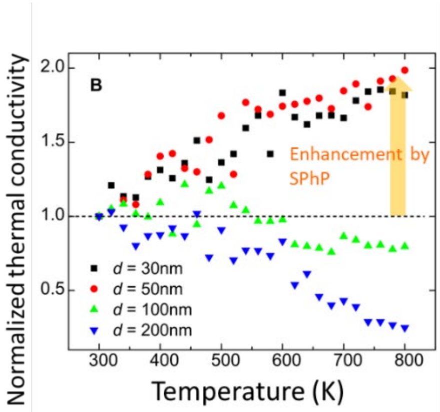


Fig. 1. Surface phonon polaritons in a semiconductor thin film can be a heat dissipation mechanism besides conduction, radiation, and convection. The temperature dependence of thermal conductivities is normalized with the ones at room temperature (300 K).

Heat conduction control based on the wave nature of phonons

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Heat conduction control using nanostructures attracts much attention since 1990’s. Phononic crystal (PnC) is one of the most attracting structure due to not only the ballistic phonon transport but also its possibility of band engineering by the periodic structure. A single-crystalline Si is often used for the playground due to its long phonon mean free path. We fabricated 145-nm-thick single-crystalline Si porous membranes by conventional top-down approach using electron beam lithography and measured thermal conduction in the nanostructures by a custom-built micro-time-domain thermoreflectance system. We compared heat dissipation time through various nanostructures of interest between 4 K and 295 K to investigate that heat conduction can be tuned by wave nature of phonons via heat wave interference.

We demonstrate that thermal conduction can be tuned by controlling the short-range order in PnC nanostructures at low temperature. Thermal decay rates were compared with a perfect PnC with a periodicity of 300 nm and disordered phononic structures [Fig. 1(a)]. The disorder was added to the spatial position of holes from the perfect periodic position. Thermal conduction is decreased as the structure approaches to the perfect crystal at 4 K. This result can be attributed to the group velocity reduction caused by the band-folding effect induced by the periodicity. However, this trend disappears around 15 K due to more incoherent phonon scattering process at higher temperature. The temperature limit to observe this coherent tuning can be increased by downsizing the phononic crystal structures, but too much downsizing will be suffered from the surface roughness of the holes. We also simulated thermal conduction in the diffusive regime and Monte-Carlo method, but the experimentally observed behavior shows opposite trend. Then, we constructed a simple model to explain the thermal decay rate reduction as the short-range order approaches to the perfect crystal. We adopted a cut-off frequency to distinguish the coherent and incoherent regimes. We assumed that the contribution of thermal phonons in the coherent regime is negligible due to the strong group velocity reduction and incoherent thermal phonons mainly contribute to the thermal conduction. The surface roughness play an important role in the coherent heat conduction. The simulation curve with a surface roughness of 1.5 nm reproduces experimental data points, and the roughness value shows a good agreement with the obtained value by a high-resolution scanning electron microscope.

Reference: J. Maire, R. Anufriev, A. Ramiere, R. Yanagisawa, S. Volz, and M. Nomura, “Heat conduction tuning by wave nature of phonons,” Sci. Adv. 3, e1700027 (2017). DOI: 10.1126/sciadv.1700027

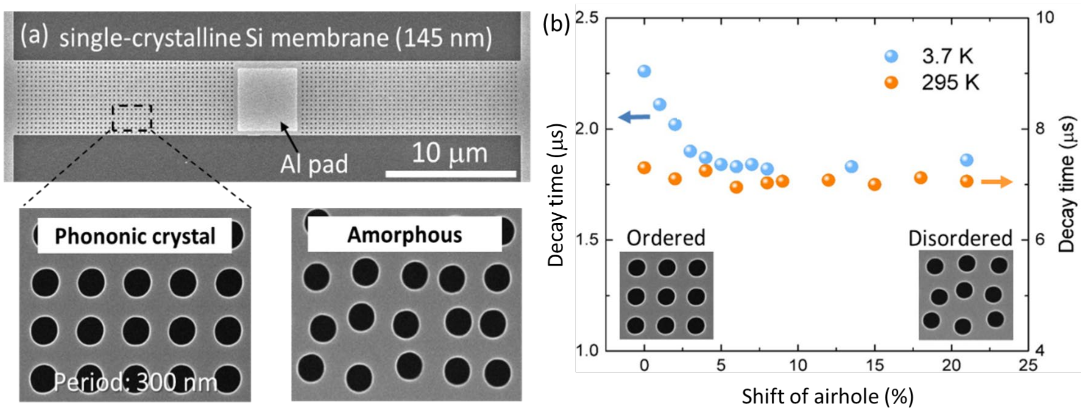

Fig. 1. (a) SEM images of suspended Si phononic structures (period: 300 nm). Position of holes are shifted in random directions for disordered structures. (b) Disorder dependence of thermal decay time at 3.7 and 295 K. The heat conduction can be controlled by the disorder in the phononic crystals at low temperature.

Ultrasonic pulse compression in a phononic crystal waveguide

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When a bell is hit, it resonates at a specific frequency which depends on its shape and size. A structure that has resonance with respect to mechanical vibration is called a mechanical resonator. A tiny mechanical resonator created using cutting-edge nano-fabrication technology has high resonance frequency in ultrasonic regime since resonance frequency inversely depends on its size. Latest smart phones can send and receive information through surface acoustic filters and oscillation devices which utilize high-frequency mechanical oscillations.

NTT research group has developed an acoustic artificial crystal, called a phononic crystal, which is fabricated by using nano-fabrication techniques and proceeded with the research of ultrasonic wave manipulation by using this phoninic crystal. The phononic crystal has thin and long membrane structure, called a waveguide, which transfers small mechanical oscillation as shown in Fig 1. The ultrasonic mechanical oscillation is generated by applying pulsed AC voltage at the metal electrode located at one end of the waveguide because this device is composed of piezoelectric GaAs/AlGaAs heterostructure. The ultrasonic mechanical pulses travel along the waveguide and are detected optically by Doppler interferometer at another end of the waveguide. In this way we have investigated the frequency dependence of ultrasonic pulses in a phononic crystal waveguide, i.e. group velocity dispersion (GDV).

In general, pulse shape broadens during propagation since a pulse contains different frequencies and a different-frequency wave travels at different velocity due to GVD. This effect is unfavorable for efficient wave guiding. However, we have utilized this disadvantage to demonstrate temporal focusing of the ultrasonic pulse. Instead of using unchirped pulses, chirped pulses are injected to cancel out the effect of GVD. As a result, the traveling pulses are temporally focused and the peak amplitude was amplified (Fig. 2). This pulse manipulation technique enables the timing and location of focusing to be controlled by changing the excitation frequency, input pulse width and chirp parameters, which pave the way to achieve the miniaturization and high integration of communication devices.

In this research, we have realized the temporal and spatial focusing of ultrasonic elastic waves in a phononoic crystal waveguide. Furthermore, this device is composed of GaAs/AlGaAs heterostructures, which is expected to be applied to hybrid structure with electron, spin and photon systems.

References M. Kurosu, D. Hatanaka, K. Onomitsu, and H. Yamaguchi, "On-chip temporal focusing of elastic waves in a phononic crystal waveguide", Nature Communications 9, 1331 (2018). DOI: 10.1038/s41467-018-03726-7

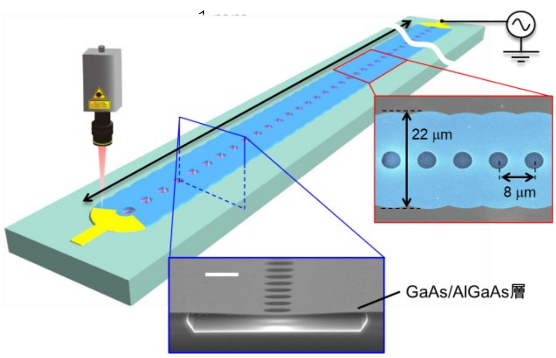

Fig. 1: A schematic of a phononic crystal waveguide.

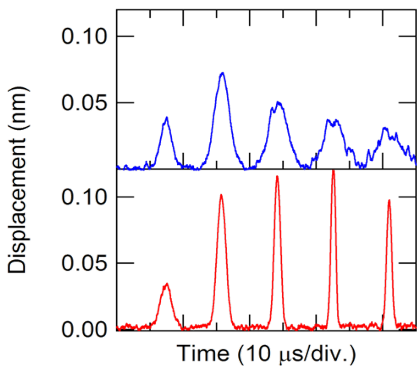

Fig. 2: Temporal evolution of ultrasonic waves.

Topological localized state of elastic wave in one-dimensional phononic crystal

Ingi Kim[1,2], Yasuhiko Arakawa[3], and Satoshi Iwamoto1[-3]
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Topology is an important concept in modern condensed matter physics. The concept of band topology also offers an intriguing route for controlling the flow of classical waves such as light, sound, and elastic wave. Generating topological states for such waves is the first step towards innovative devices based on topology. In this study, we realized a topological state of elastic wave in a continuous medium having a complete phnonic bandgap for the first time.

In a continuous medium, longitudinal-, transversal-waves as well as their mixed wave co-exist. This makes it difficult to obtain a topological state isolated within a complete phononic bandgap in general. We designed a quasi-one-dimensional phononic crystal (PnC) that have a complete phononic bandgap.The unit structure of the PnC is composed of two cuboids with different sizes. We found two types of structures possessing a common bandgap with different topology by tuning the area and thickness of each cuboid. A topological localized state for elastic wave is formed at the boundary between these two topologically distinct structures (Fig. 1). The presence of such a state is deterministically predicted from the bulk-edge correspondence. We fabricated the connected structure with quartz glass (Fig. 1) and experimentally verified the presence of the topological state by measuring the transmission of elastic wave through the structure. The measured transmission spectrum is shown in Fig. 2 (blue curve). The result shows good agreement with the calculation (black curve in Fig. 2). A sharp transmission peak at around 200 kHz with a *Q*-factor of ~5,700 is originated from the topological localization mode. We also succeeded in visualizing the spatial distribution of the topological state by photoelastic imaging, confirming the strong confinement of elastic wave at the boundary. The frequency of the topological elastic state can be increased simply by scaling the size of the structure. Such high-frequency topological elastic states can be applied to high-speed acoustic devices for signal processing and opto-mechanical devices, which can function as quantum transducers between photons and phonons.

The paper reporting the results was selected as one of the 2018 Spotlight papers in Appl. Phys. Express.

Reference : I. Kim, S. Iwamoto, and Y. Arakawa, "Topologically protected elastic waves in one-dimensional phononic crystals of continuous media", Appl. Phys. Express 11, 017201 (2018). DOI: 10.7567/APEX.11.01720

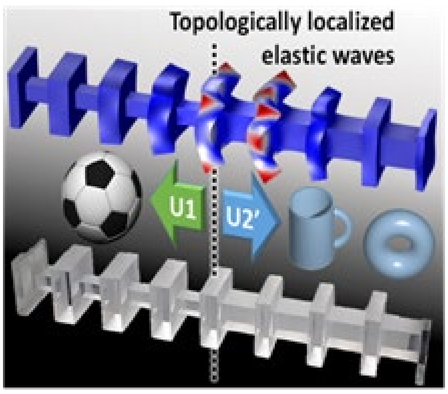

Fig. 1 One-dimensional phononic crystal made of quartz (bottom) and calculated distribution of displacement field of the topological localized state

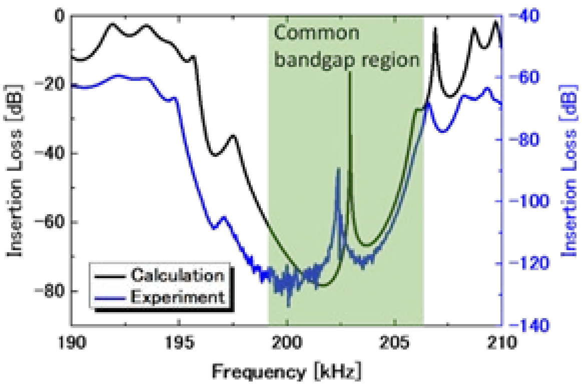

Fig. 2 Measured (blue) and calculated (black) transmission spectra of elastic wave

Control of Spin-Phonon Interaction and Photon Excitation in Asymmetric Artificial Lattices

Hiroyasu Yamahara[1], Md Sarker Shamim[1], Munetoshi Seki[1] and Hitoshi Tabata[1]
[1] Graduate School of Engineering, The University of Tokyo

Rare-earth iron garnets (RIGs) are ferrimagnetic insulators whose chemical formula is $R_3Fe_5O_{12}$ (R : rare-earth elements). They have been industrially available for optical devices such as optical isolators since they show large magneto-optical effect. On the other hand, they are unlikely to show remnant dielectric polarization in bulk, because their crystal structures are centrosymmetric cubic. If remnant magnetization and dielectric polarization co-exist in RIGs, simultaneous ordering of dipole and spin are expected in addition to the magneto-electric correlation (ME-effect), which is promising material for future application on spintronics devices. In this research, we demonstrate the coexistence of remnant magnetization and dielectric polarization in $Sm_3Fe_5O_{12}$ (SmIG) films grown on $Gd_3Ga_5O_{12}$ (GGG) substrates. The lattice mismatch between film and substrate is −1.17%, so that the critical thickness where misfit dislocation occurs is estimated to be 60 nm. SmIG films grown on GGG show tetragonal, strain-gradient, and cubic structures from the interface to the surface due to the epitaxial strain and the lattice relaxation. In the strain-gradient region, the inhomogeneous strain can generate flexoelectric polarization, $P=\mu(\partial u/\partial x)$, where μ and $(\partial u/\partial x)$ are flexoelectric tensor and strain-gradient, respectively. The presence of dielectric polarization in the strain-gradient region is confirmed by a scanning nonlinear dielectric microscopy. Negatively polarized local domains, whose size is 30 nm corresponding to the density of stacking-fault, exist in strain-gradient phase. We conclude that remnant magnetization and dielectric polarization co-exist in strain-gradient SmIG film. Moreover, we fabricate spin wave devices using an ultra-low damping $Y_3Fe_5O_{12}$ thin films and demonstrate a dynamic spin wave modulation using electric current. An additional Pt stripe connected to dc current source was integrated between a pair of coplanar waveguides to demonstrate the spin wave resonance frequency and amplitude modulations. Electric current applied through the Pt stripe generates local joule heating that modifies magnetic properties of the $Y_3Fe_5O_{12}$ film, which modulates the frequency and the amplitude of the spin wave spectra. This study presents a more convenient technique using simple DC current, which can be extended to thermal mapping for more complex spin wave devices.

Reference : Md S. Sarker, H. Yamahara, H. Tabata, "Current-controlled magnon propagation in Pt/$Y_3Fe_5O_{12}$ heterostructure", Appl. Phys. Lett. *Accepted.* Md S. Sarker, H. Yamahara, H. Tabata, "Spin wave modulation by topographical perturbation in $Y_3Fe_5O_{12}$ thin films", AIP Adv., 10, 015015 (2020).

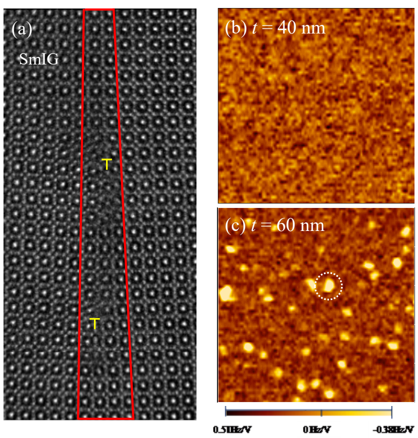

Fig. 1 (a) STEM image of strain-gradient SmIG film. (b,c) SNDM image for tetragonal (c) and strain-gradient (b) SmIG films. Bright-color indicates negative polarization.

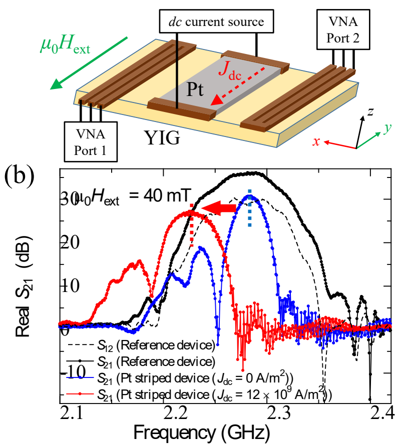

Fig. 2 (a) Schematic image of spin wave device. (b) S_{21} spectra of the reference device (black), and Pt/YIG bilayer device without (blue) and with (red) DC current through the Pt layer.

Highly sensitive motion detection in a mechanical resonator using a gate-controlled quantum dot

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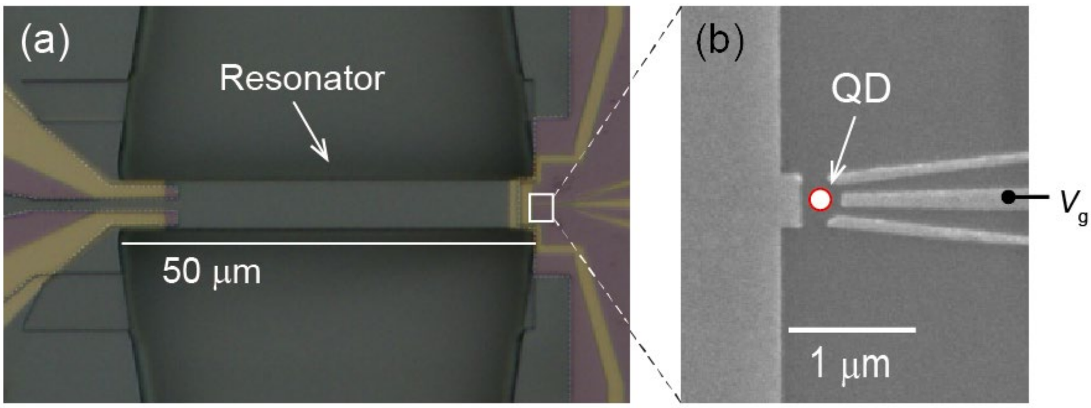
NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation

A mechanical resonator built into a GaAs/AlGaAs heterostructures is a promising hybrid quantum system, which can open new avenues for coherent coupling between macroscopic mechanical motion and wide variety of electron states formed in semiconductor quantum structures. The critical element in such a demonstration is an interface between the tiny mechanical motion of the resonator and the electronic degrees of freedom in the quantum structure. A semiconductor quantum dot (QD) is a potential candidate for this purpose, but the experimental realization of such systems is still in its infancy. Here we demonstrate highly sensitive displacement transduction of a doubly clamped mechanical resonator using a QD.

In our device (Fig.(a)), the QD is formed at one of the clamping points of the resonator using negatively-biased top gates (Fig. (b)). The motion of the fundamental flexural mode of our resonator is detected through power spectral measurements of the QD's current. By analyzing the temperature dependence of thermally-driven mechanical vibrations, the minimum detectable displacement of the QD transducer at a temperature of 80 mK is determined to be 63 fm/Hz$^{1/2}$. From the results, the position resolution is estimated to be 170 fm, which is about 70 times the zero-point quantum fluctuation for this resonator. Furthermore, the single electron transport in the quantum dot induces a backaction onto the mechanical motion, where the control of gate voltage enables the damping and even current-driven amplification of the mechanical motion. The result takes the first step toward the coherent coupling between mechanical resonator and electronic states, which pave the way to transfer the microscopic quantum phenomena in low-dimensional electron systems into macroscopic mechanical objects.

Reference : Y. Okazaki, I. Mahboob, K. Onomitsu, S. Sasaki and H. Yamaguchi, "Gate-controlled electromechanical backaction induced by a quantum dot", Nature Communications, 7, 11132 (2016). DOI: 10.1038/ncomms11132



Figs. (a) Optical and (b) electron micrograph of our device. A doubly-clamped mechanical resonator of 50 μm length is fabricated from GaAs/AlGaAs heterostructure. QD are defined at the clamping point of the resonator.

Nuclear spin control by a mechanical oscillator

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[1]NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation
[2]National Institute of Advanced Industrial Science and Technology

Nuclear spin is a kind of rotation of an atomic nucleus, and under a magnetic field, it shows a precession. The precessional motion is widely detected as nuclear magnetic resonance (NMR) and is recently promising to the application in various quantum technologies, such as highly sensitive magnetic field sensors and quantum memory. We developed a novel architecture using a compound-semiconductor nanostructure device to manipulate nuclear spins with a micromechanical oscillator.

The mechanical oscillator consists of a doubly clamped beam structure and is fabricated using a piezoelectric GaAs/AlGaAs heterostructure. The piezoelectric transduction electrically actuate the mechanical vibration. The motion generates periodic strain at the clamping point and the strain modifies the quadrupole interaction between nuclear spins in the strained region. In the experiments, we observed strain-induced NMR frequency shift as well as the sideband resonances, where the resonance was detected at two sideband frequencies. The numerical calculation showed a good agreement with the experimental results, indicating that the phenomenon is induced by the effect of mechanical oscillation.

Reference: Y. Okazaki, I. Mahboob, K. Onomitsu, S. Sasaki, S. Nakamura, N. Kaneko, and H. Yamaguchi, "Dynamical coupling between a nuclear spin ensemble and electromechanical phonons", Nature Commun. 9, 2993 (2018). DOI: 10.1038/s41467-018-05463-3

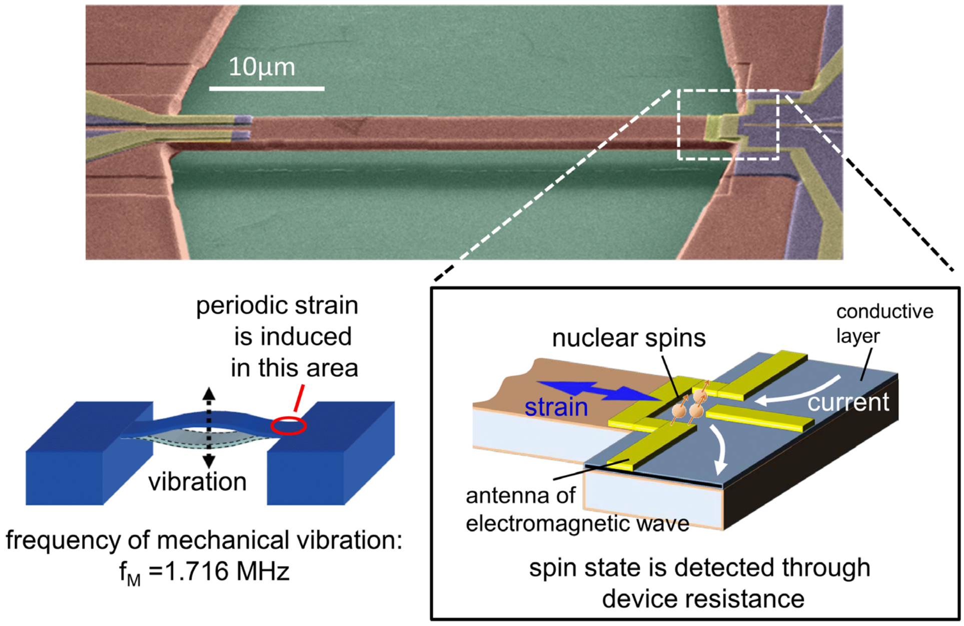

Fig. 1 A mechanical resonator used for controlling nuclear spins.

Mechanical engineering of excitons in semiconductor

－Demonstration of strain-mediated coupling between dark and bright states－

Ryuichi Ohta, Hajime Okamoto, Takehiko Tawara, Hideki Gotoh, and Hiroshi Yamaguchi
NTT Basic Research Laboratories, NTT Corporation,

Electron-hole pairs (excitons) in semiconductor efficiently convert electrons to photons and thus have been applied to various opto-electro devices, such as light sources, detectors, modulators and amplifiers. The optical properties of excitons obey the selection rule based on their spin configurations, which results in the two different states. One is called as the bright state which is allowed to be optically addressed, and the other is called as the dark state which is not available to be optically addressed. Although the dark state is of great interest owing to its long-lived nature indicating the potential for quantum information and spintronic applications, its optical inaccessibility limits its practical usage. Magnetic field enables the coupling between dark and bright states and has been used to allow the optical access to dark state via bright state. However, dynamic control of their coupling is technically challenging by magnetic field because strong magnetic field does not rapidly change. Here, we demonstrate a new scheme to couple the dark state to bright state allowing the optical addressing the dark state by means of time-varying strain of a micromechanical resonator. The uniaxial strain induced by the mechanical motion breaks the symmetry of the crystal field and mixes dark and bright excitons via deformation potential. In contrast to the magnetic approach, this scheme has an advantage of high-speed switching of the coupling, which will lead to the memory and logic applications based on the dark excitons.

We fabricated a mechanical resonator from GaAs/AlGaAs heterostructures containing excitons (Fig. 1). To investigate the strain effect for excitons, we continuously drove the mechanical resonator and applied pulse laser whose repetition synchronized to the driving frequency. By changing the relative phase of pulse, we could obtain the spectra at arbitral timing of the mechanical motion. As shown in Fig. 2(a), the mechanical strain modulated the exciton energies, and caused avoided-crossing between dark and bright states, which is sign of the coupling between them. The photoluminescence from the dark state was originally zero, but was enhanced by the strain-mediated coupling to the bright state. It indicates that the optical access to the dark state became possible via the bright state. This experimental result was well reproduced by numerical analysis based on semiconductor band modes (Fig. 2(b)).

Reference： R. Ohta, H. Okamoto, T. Tawara, H. Gotoh, and H. Yamaguchi, "Dynamic control of the coupling between dark and bright excitons with vibrational strain", Physical Review Letters, 120, 267401. (2018). DOI：10.1103

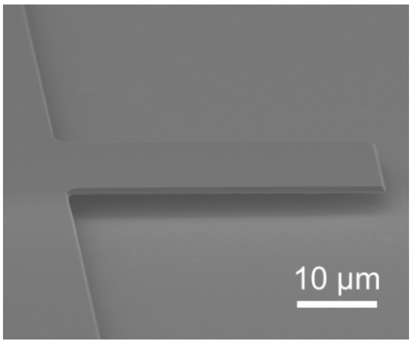

Fig.1 Scanning electron microsopy image of the mechanical resonator based on the GaAs/AlGaAs heterostructure.

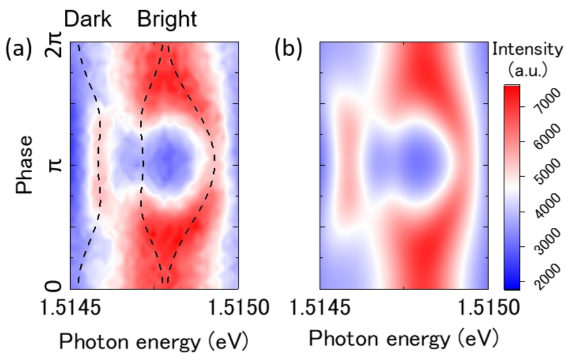

Fig.2 (a) Experimental and (b) numerical stroboscopic photoluminescence spectra with mechanical motion.

Ising spin coupling in electromechanical resonators

I. Mahboob, H. Okamoto, and H. Yamaguchi
NTT Basic Research Laboratories, Nippon Telegraph and Telephone Corporation

A parametric oscillator is the harmonic resonator in which the oscillations are driven by modulating the force constant at the frequency that differs from the resonance. One of the simplest examples is the child swing and nowadays they are used in many experiments such like microwave amplifier and optical wavelength convertors. In degenerate parametric oscillators, the force constant modulation is made at twice the resonance frequency and two different phase states appear in the oscillation reflecting the broken half-period time translational symmetry. The bistability can be assigned to a classical spin-1/2 system and it is proposed to use a mutually coupled resonator network for numerial calculation. This coupled resonator system is called as "Ising machine", and used for efficiently obtaining the solution of optimization problems.

In this work, we demonstrated the Ising coupling between two electromechanical parametric oscillation modes. We fabricated a coupled GaAs/AlGaAs piezoelectric beam resonators and investigated the correlation of phase states between two flexural vibration modes. Fig. 1(a) shows the schematic illustration of experimental setup. Two alternate voltages at $2\omega_S$ and $2\omega_A$ are applied to excite parametric oscillation in two modes. The pump voltage at ω_p is applied to induce the coupling. Fig. 1(b) shows the correlation coefficient for phase states between two modes. By changing the phase of pump voltage, the phase of coupling can be continuously controlled from antiferromagnetic to ferromagnetic.

Reference: I. Mahboob, H. Okamoto, and H. Yamaguchi, "An electromechanical Ising Hamiltonian", Sci. Adv. 2 : e1600236 (2016). DOI: 10.1126/sciadv.1600236.

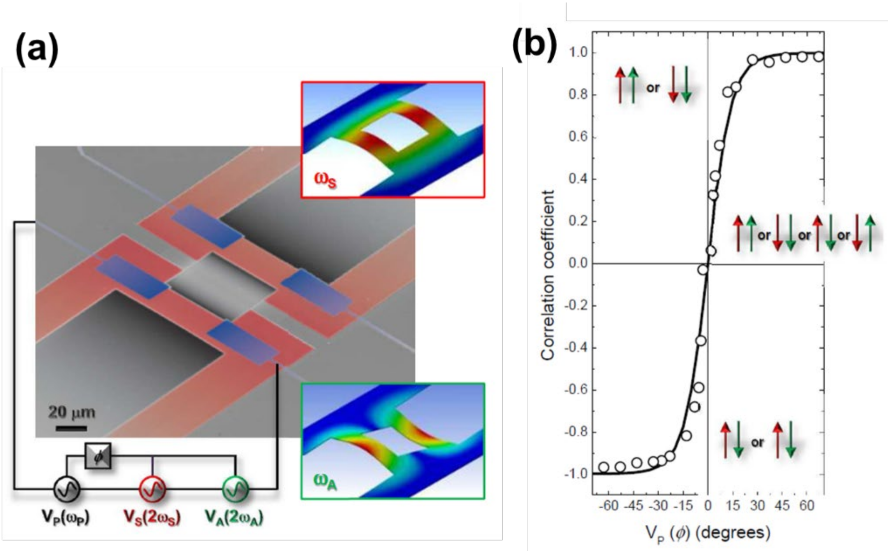

Fig. 1 (a) A schematic illustration of experimental setup. The symmetric and antisymmetric vibration modes are both parametrically excited by $V_S(2\omega_S)$ and $V_A(2\omega_A)$ and the pump voltage $V_P(\omega_P)$ is also applied for their coupling. (b) The correlation coefficient measured between two modes as a function of the phase of pump voltage.

Fast and Sensitive Bolometric Terahertz Detection at Room Temperature through Thermomechanical Transduction

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[1] Institute of Industrial Science, University of Tokyo, [2]INQIE, University of Tokyo

Terahertz (THz) electromagnetic waves interact with various substances and are suitable for investigating their structures and functions. In general, broadband THz detectors use detection elements which once convert THz radiation into heat and then read out the temperature rise of the detection element as a signal (bolometers). However, in order to obtain high sensitivities, bolometers are often cooled down to extremely low temperatures. Therefore, for wider applications of THz technologies, the development of uncooled, high-sensitivity, and high-speed THz detectors is necessary.

Microelectromechanical system (MEMS)-based resonators are very attractive for sensing applications. High quality (Q)-factors of the MEMS resonators even at room temperature are advantageous for detecting small changes in resonance frequency. It has been demonstrated that shifts in resonance frequencies can be used to detect mass, charge, spin orientation, temperature, and infrared radiation.

In this work, we have proposed and demonstrated a very sensitive, room temperature thermistor that consists of a doubly clamped GaAs MEMS beam resonator. It detects a temperature change by measuring a shift in its resonance frequency induced by thermal expansion of the beam. The MEMS thermistor senses a temperature change by measuring a shift in the mechanical resonance frequency and can detect a temperature change as small as ~1 μK (noise equivalent temperature difference ~1 μK/√Hz) even at room temperature. This unprecedented temperature sensitivity of the MEMS resonator is advantageous not only for realizing high sensitivity but also achieving high-detection speed in the order of several kHz, which is more than 100 times faster than other uncooled THz thermal sensors. We have achieved an electrical noise equivalent power (NEP) as low as ~90 pW/√Hz, which is close to the fundamental limit set by the thermal fluctuation noise. Furthermore, we note that the dynamic range of the present MEMS bolometer is greater than 10^7. The present MEMS bolometers are fabricated by the standard semiconductor fabrication process and are well suited for making detector arrays for fast THz imaging.

Reference: Ya Zhang, Suguru Hosono, Naomi Nagai, Sang-Hun Song, and Kazuhiko Hirakawa, "Fast and sensitive bolometric terahertz detection at room temperature through thermomechanical transduction", Journal of Applied Physics **125**, 151602 (2019); https://doi.org/10.1063/1.5045256, etc.

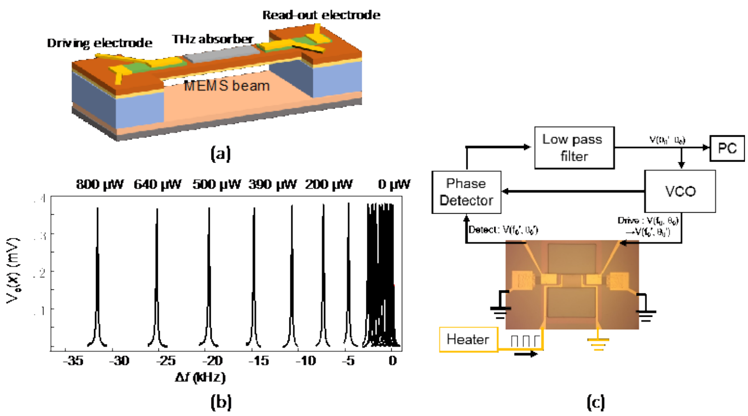

Fig. 1 (a) MEMS double-sided beam structure manufactured using a GaAs / AlGaAs semiconductor heterostructure, (b) shift of resonance frequency with respect to input power to the MEMS beam, and (c) phase-locked loop (PLL). Signal readout circuit

Focusing Terahertz Radiation on a Single Molecule by Nanogap Electrodes and Observation of Enormous Terahertz Field Enhancement Effect

Kenji Yoshida[1], Kenji Shibata[1], and Kazuhiko Hirakawa[1,2]
[1] Institute of Industrial Science, University of Tokyo, [2]INQIE, University of Tokyo

The use of molecules to electronic devices has great potential. We have fabricated extremely small transistors (Fig. 1(a)) with a single molecule as an active region and investigated how electrons are transferred through such a single molecule. In particular, we have been working on the elucidation and control of the electron dynamics using terahertz (THz) radiation.

Since the wavelength of THz radiation is typically as long as 100 μm, we have a problem that the interaction between the THz radiation and a single molecule is extremely small. By using the source/drain electrode of the single molecule transistor structure as an antenna, we have successfully focused the THz radiation on a single C_{60} fullerene molecule, exceeding the diffraction limit by 100,000 times.

Figure 1(b) shows a color map of the conductivity of a C_{60} single molecule transistor. When the sample was illuminated with a THz laser light with a wavelength of 119 μm, we observed that, in addition to the tunnel conduction through an ordinary molecular orbital, equally spaced new conduction channels are formed above and below it by integer multiples of the THz photon energy (10 meV). When the quantum level in the molecule is shaken by a strong THz electric field, the level is split into equally spaced photon side bands, forming new conduction channels (photon-assisted tunneling). Furthermore, the formation of photon sidebands means that the single C_{60} molecule sandwiched between the nanogap electrodes feels a very intense THz electric field in the order of hundreds of kV/cm. In this experiment, the THz electric field outside the sample is only about several V/cm, which means that the THz electric field is enhanced by 100,000 times by the nanogap electrode.

In this study, we have shown that nanogap electrodes are suitable for clarifying the THz dynamics of nm-scale nanostructures and that they can create a huge electric field enhancement effect in the order of 100,000 times. Nanogap electrodes provide a valuable opportunity to explore new physics in atomic-scale systems.

Reference : K. Yoshida, K. Shibata, and K. Hirakawa, Phys. Rev. Lett. **115**, 138302 (2015); DOI: https://doi.org/10.1103/PhysRevLett.115.138302

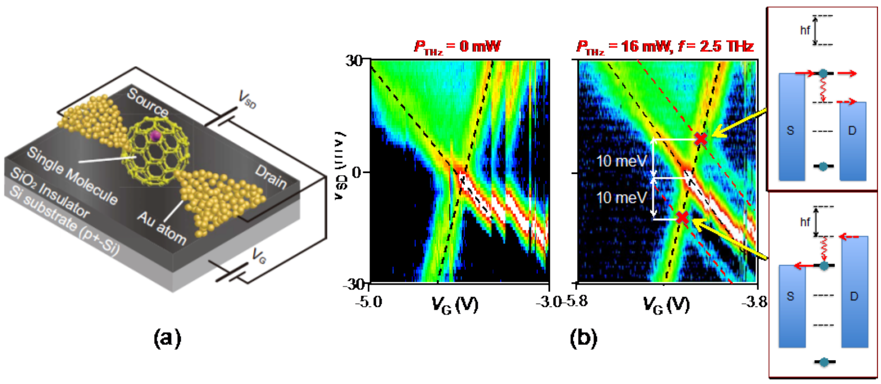

Fig. 1 (a) Schematic illustration of a single molecule transistor structure, (b) Coulomb stability diagram of a single C_{60} molecule transistor when terahertz radiation is off (left) and on (right)

Observation of Ultrafast Motion of a Single Molecule by Terahertz Spectroscopy

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Terahertz (THz) spectroscopy has been developed as a powerful tool for clarifying vibrational dynamics of various kinds of molecules. Because of the long-wavelength nature of the THz electromagnetic waves (typically, ~100 μm), however, spectral information was obtained only for an ensemble average of a huge number of molecules. It has been a formidable challenge to by far exceed the diffraction limit and focus the THz radiation on single molecules. Furthermore, the number of mobile charges that can absorb THz radiation in a single molecule is very few, which makes THz absorption extremely small.

Here, we report on the THz spectroscopy of single molecules by using the single molecule transistor (SMT) geometry. The SMT is a structure in which a single molecule is captured in a sub-nm gap created between the source and drain metal electrodes fabricated on a field plate. Using the source and drain electrodes separated by a sub-nm gap as a THz antenna, we focus THz radiation onto a single fullerene molecule trapped in the nanogap electrodes. Furthermore, we can detect a very small absorption by measuring the THz-induced photocurrent by the same electrodes.

We have studied the dynamics of a single C_{60} (fullerene) molecule with a THz radiation using this SMT structure. We could detect ultrafast motion of a single molecule on a time scale of about psec. Such THz measurements have become possible only when both atomic-level ultrafine fabrication technology and ultrahigh-speed time-domain terahertz measurement technology become available. Furthermore, we have found that the observed THz peaks are finely split into two, reflecting the difference in the van der Waals potential profile experienced by the C_{60} molecule on the metal surface when the number of electron on the molecule fluctuates between N and N+1 during the single electron tunnelling process. Such an ultrahigh-sensitivity to the electronic/vibronic structures of a single molecule upon charging/discharging a single electron has been achieved by using metal source-drain electrodes separated by a sub-nm gap as a THz antenna and detecting the THz-induced photocurrent. This novel scheme provides a new opportunity for investigating ultrafast THz dynamics of sub-nm scale systems.

Reference: S.Q. Du, K. Yoshida, Y. Zhang, I. Hamada, and K. Hirakawa, "Terahertz dynamics of electron-vibron coupling in single molecules with tunable electrostatic potential", Nature Photonics, **12**, 608–612 (2018), https://doi.org/10.1038/s41566-018-0241-1

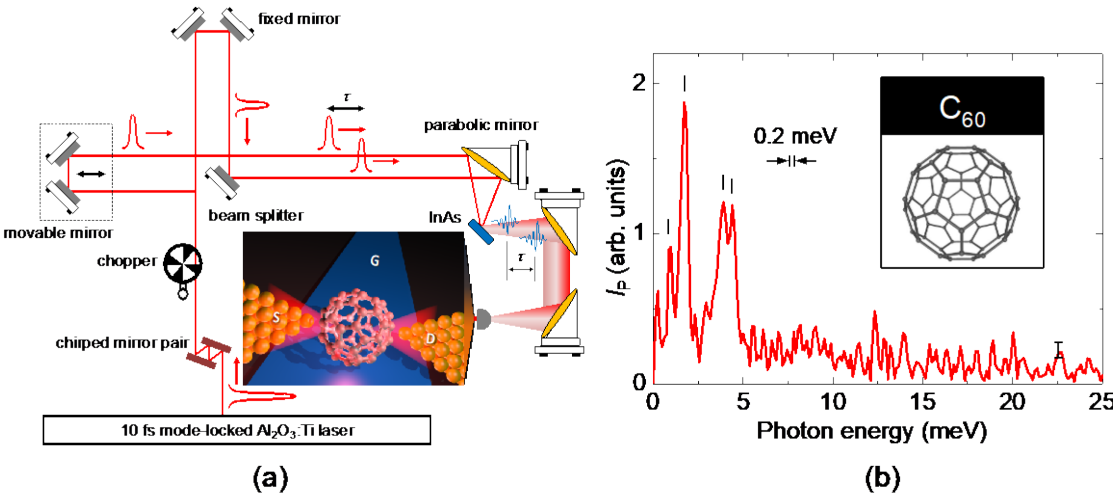

Fig. 1 (a) Single molecule terahertz spectrum system using nanogap electrode and femtosecond laser pulse, (b) Molecular vibration spectrum in which C60 molecule moves its center of gravity on a gold electrode

THz-field-induced Macroscopic Ionic Flow in a Superionic Conductor Na^+ β-Alumina

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Recent advances in terahertz (THz) technology have provided possibilities for novel nonperturbative and nonlinear processes in solids with ultimate spatiotemporal resolutions. However, most of these processes are dominated by the ultrafast electron dynamics, and the nonlinear responses of ions have rarely been investigated because of the greater mass of ions compared to that of electrons.

In the present study, we show that a field-driven ionic motion is induced by applying single-cycle intense THz fields, generating a macroscopic current that depends on the polarity of the applied THz fields. We used stoichiometric crystalline Na^+ β-alumina, which is a superionic conductor wherein Na^+ ions move in the two-dimensional space between the spinel layers perpendicular to the *c* axis (Fig. 1). The ionic conductivity of Na^+ β-alumina is as large as 1 S/m at room temperature.

By applying single-cycle THz pulses with a peak field strength ranging from 15 to 300 kV/cm, we could observe the THz-induced macroscopic direct current using a conventional ammeter at high electric field strengths, indicating that the motion of Na^+ ions transfers from the vibration mode to the conduction mode (Fig. 2). We believe that our finding — macroscopic current flow in a superionic conductor driven by single-cycle THz pulses — may pave the way for future ultrafast ionics.

Reference: Y. Minami, B. Ofori-Okai, P. Sivarajah, I. Katayama, J. Takeda, K. A. Nelson, and T. Suemoto, Physical Review Letters, 124, 147401 (2020). DOI: 10.1103/PhysRevLett.124.147401

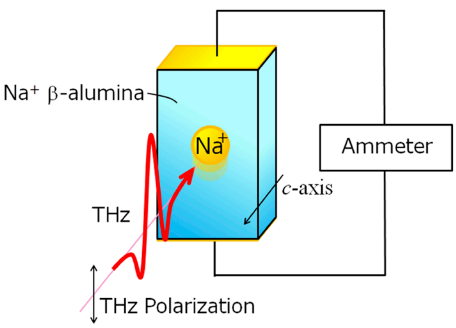

Fig. 1 Setup used for measuring the THz-field-induced ionic current using an ammeter.

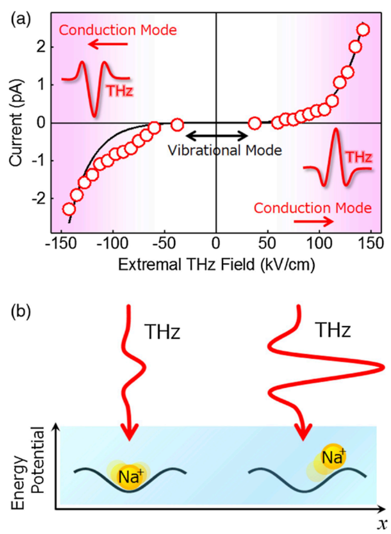

Fig. 2 (a) THz intensity dependence of the ionic current measured using an ammeter. (b) Configuration of the ion and local potential in real space for Na^+ β-alumina at room temperature. The intense THz electric field leads to the ionic configuration from the vibration mode to the conduction mode.

Terahertz Spectroscopy of a Single Carbon Nanotube

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Carbon nanotubes (CNTs) are unique electronic materials of one-dimensional character and have been extensively studied as promising materials for optoelectronic devices. When potential barriers at two locations are introduced, they behave as quantum dots. We formed source and drain electrodes with a 100 nm-gap on a single metallic carbon nanotube grown from a catalyst and fabricated a single carbon nanotube quantum dot (QD) transistor (Fig. 1(a)). Figure 1(b) is the color-coded differential conductivity of this sample as a function of the gate voltage and the source-drain voltage. From the observed diamond-shaped patterns called Coulomb diamonds, we can tell that this sample works as a single electron transistor.

This sample is illuminated with terahertz radiation and the photocurrent spectra induced by the THz radiation are shown in Fig. 1(c). By using this method, we have successfully detected THz spectral signals from individual CNTs.

We have found that sharp resonant peaks appear in the THz spectra and their energies are quantitatively in agreement with the sublevel energy spacing expected from the linear band dispersion in metallic CNTs, which indicates that the observed peaks originate from the intersublevel transitions between two neighboring quantized orbitals in the CNT-QDs. The linewidth of the photocurrent peaks is as narrow as 0.3 meV, which is consistent with the tunnel escape time from the CNT-QDs to the electrodes. The linewidth of the photocurrent peaks is governed by the tunnel coupling with the electrodes, suggesting that electrons in the CNT QD have a scattering time comparable to or longer than 10 ps. The observation of a sharp absorption peak at the bare quantization energy was not consistent with the Tomonaga-Luttinger liquid theory.

Reference: Takuma Tsurugaya, Kenji Yoshida, Fumiaki Yajima, Maki Shimizu, Yoshikazu Homma, and Kazuhiko Hirakawa, "Terahertz Spectroscopy of Individual Carbon Nanotube Quantum Dots", Nano Letters, **19**, 242–246 (2019), https://doi.org/10.1021/acs.nanolett.8b03801

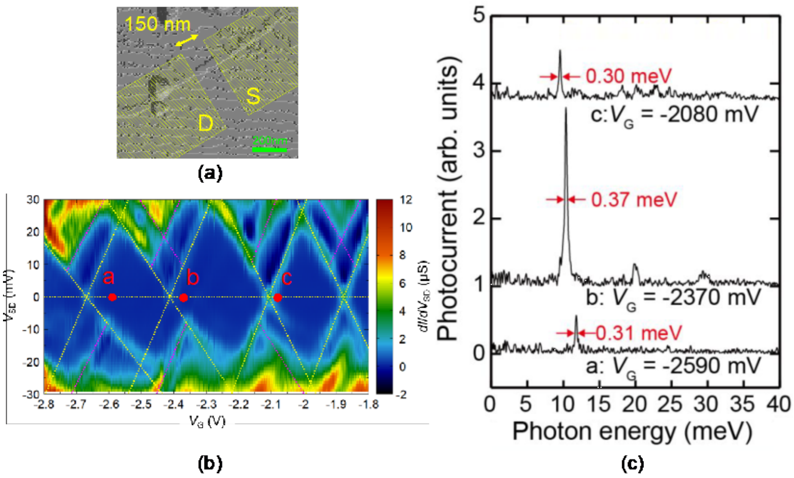

Fig. 1 (a) AFM image of a sample in which nanogap electrodes are formed on metallic single carbon nanotubes, (b) color mapping of conductivity of single carbon nanotube transistors, (c) measured terahertz excitation light. Current spectrum

Phase-controlled THz-field-driven Scanning Tunneling Microscopy

－Ultrafast electron manipulation with tailor-made single-cycle THz near fields－

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Light-field-driven processes occurring under conditions far beyond the diffraction limit of the light can be manipulated by harnessing spatiotemporally tunable near fields. A tailor-made carrier envelope phase (CEP) in a tunnel junction formed between nanogap electrodes allows to precisely manipulate these processes. Here, we demonstrate that desirable phase-controlled near fields can be produced in a tunnel junction via terahertz scanning tunneling microscopy (THz-STM) with a broadband THz phase shifter (Fig. 1). Measurements of the phase-resolved sub-cycle electron tunneling dynamics revealed an unexpected large CEP shift between far-field and near-field single-cycle THz waveforms, which stems from the wavelength-scale feature of the tip-sample configuration. By using a dual-phase double-pulse scheme (Fig. 2), the electron tunneling was coherently manipulated over the femtosecond timescale. Our new prescription — in situ tailoring of single-cycle THz near fields in a tunnel junction — will offer unprecedented control of electrons for ultrafast atomic-scale electronics and metrology.

Reference: K. Yoshioka, I. Katayama, Y. Arashida, A. Ban, Y. Kawada, K. Konishi, H. Takahashi, and J. Takeda, Nano Letters, 18, 5198-5204 (2018). DOI: 10.1021/acs.nanolett.8b02161

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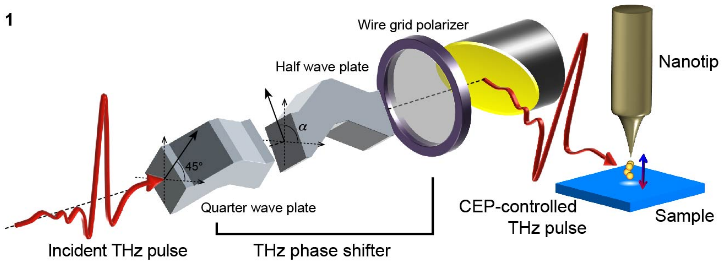

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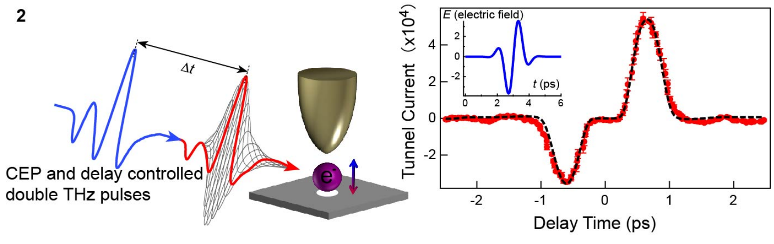

Fig. 1 Schematic of phase-controlled THz-STM with a broadband THz phase shifter composed by three optical elements: quarter wave plate, half wave plate and wire grid polarizer. By rotating the half-wave plate, the CEP of THz near fields can be precisely tuned from 0 to 2π.

Fig. 2 Schematic of ultrafast electron manipulation with CEP- and delay-controlled double THz pulses. By using sinusoidal THz near fields, the bidirectional tunnel current can be flowed on the femotosecond timescale.

Probing microscopic property of topological protection

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Topological materials, which are expected as materials for next-generation information processing devices, have the property that information carried by electrons is less to be disturbed by impurities than conventional materials. We succeeded in visualizing the special insulating region by disturbing the quantum Hall state, which is one of the topologically protected electronic states, with an excess current and observing with a scanning gate microscope. As shown in FIG. 1 (a), the quantum Hall insulating region (white and bright region) appears along the left-side the Hall bar edge, and moves to the interior of the Hall bar with bringing the electron filling factor ν closer to an integer value. By comparing the filling factor dependence of the position of this insulating region with the theoretical calculation (Fig. 1 (b)), it is demonstrated that the topologically protected microscopic state is maintained even under disturbance such as excess current. On the other hand, when a larger current is applied, the observed filling factor dependence (Fig. 2 (a) (b)) disappears (Fig. 2 (c) (d)) due to breakdown of the quantum Hall state.

These results provide a new method for exploring the microscopic state created by topological universality, and is expected to be applied to various topological quantum state observations in the future. It can contribute to the search for information processing device materials, which are more robust against disturbance.

Reference : K. Hashimoto, T. Tomimatsu, S. Taninaka, S. Nomura, and Y. Hirayama, "Probing the breakdown of topological protection: Filling-factor-dependent evolution of robust quantum Hall incompressible phases", Physical Review Research, 2, 013128. (2020). DOI : https://doi.org/10.1103/PhysRevResearch.2.013128

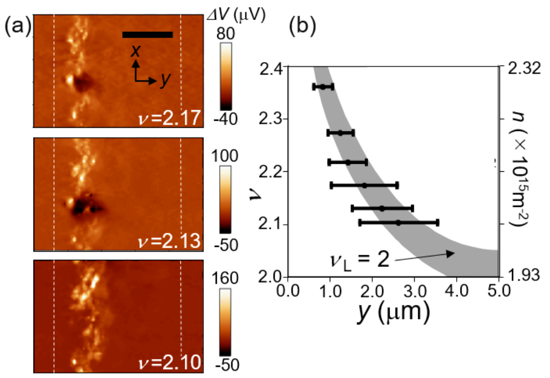

Fig. 1 (a) The electron filling factor dependence of the quantum Hall insulating region (bright white region) appearing at the hole bar edge (broken line). (B) Comparison of the center position (point) and width (horizontal line) of the insulating region with the one deduced by theoretical calculation。

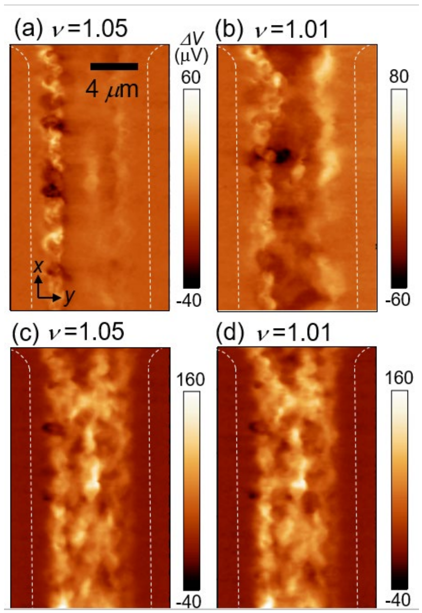

Fig. 2
The electron filling factor dependence (a) (b) of the quantum Hall insulating region observed by the current under the excess current (0.5-1.0 μA) disappears under the larger excess current (2.3-2.5 μA) (c) (d).

Scanning Nuclear Resonance Microscope

－Microscopic MRI of spin state in quantum structure－

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[1] Graduate School of Science, Tohoku University、[2]CSIS, CSRN, Tohoku University

MRI (Magnetic Resonance Imaging) has been widely used for diagnostic imaging of diseases in the medical field. To detect a small disease, it is necessary to display MRI with fine pixels, but it is currently difficult to perform high-resolution diagnosis in which the pixel spacing is tens of micrometers or less, which is smaller than that of hair. Even in semiconductor devices with quantum structures, nuclear spin resonance, which is the core technology of MRI, is used as a powerful tool for investigating the spin state of quantum structures. However, when using MRI for nano- to micron-scale confined structures such as semiconductor devices, in addition to the resolution problem described above, the question is how to extract nuclear spin resonance signals from quantum structures embedded in semiconductors.

In this work, we developed a scanning probe incorporated with a resistively detected nuclear resonance technique and succeeded in microscopically probing the nuclear resonance signal from a semiconductor quantum device. This was demonstrated using the quantum Hall state that emerges in the two-dimensional electron system confined in the semiconductor quantum structure with a strong magnetic field. From the nuclear spin resonance signal obtained at each point, we extracted not only the signal intensity, but also the shift of the resonance frequency called the Knight shift, which indicates the electron polarization around the nuclear spin to obtain spin information for both the nucleus and the electron. By mapping these signal strength and resonance frequency shifts, we succeeded in clearly observing the distribution of nuclear spin polarization that occurs in a semiconductor quantum structure with a thickness of several tens of nanometers (Fig. 1) and the spatial changes of electron spin polarization at a few microns range (Fig. 2). Figure 1 shows that the region where the nuclear spins are polarized changes significantly from one end of the hole bar sample to the center with changing the quantum Hall state. In addition, in the electron spin polarization distribution in Fig. 2, it was found that the spatial change in electron spin polarization became more severe as the current increased.

The results of this research provide a new technology that clearly reflects the distribution of electron and nuclear spins in quantum structures, and are expected to be applied to the spin states of various quantum structures and MRI diagnosis of quantum devices in the future.

Reference： K. Hashimoto, T. Tomimatsu, K. Sato, and Y. Hirayama, "Scanning nuclear resonance imaging of a hyperfine-coupled quantum Hall system", Nature Communications, 9, 2215. (2018). DOI : 10.1038/s41467-018-04612-y

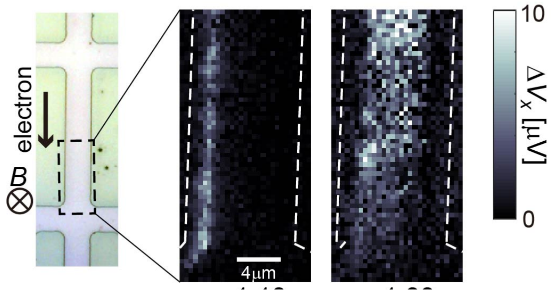

Fig. 1 Image of nuclear spin resonance signal intensity (right) in different quantum Hall states (shown below) obtained in the Hall-bar sample (left).

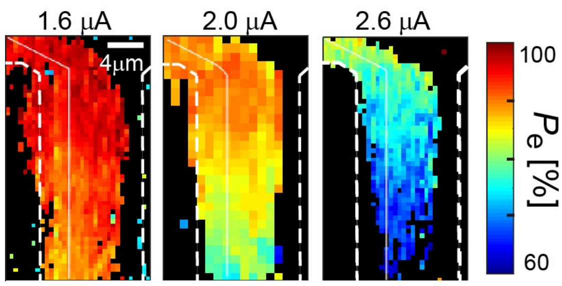

Fig. 2 Color scale images of electron spin polarization *P*e obtained at different electric currents (indicated above the images) flowing through the sample.

5 Achievements

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5-2 Major invited talks

International conference

2015

1. J. Hirotani, R. Matsui, S. Kishimoto and Y. Ohno, Large-scale characterization of carbon nanotube thin-film transistors, NT15 Satellite Symposia (Third Carbon Nanotube Thin Film Electronics and Applications Satellite), 2015
2. J. Ishi-Hayase, Orientation and Position-controlled Nitrogen-Vacancy Centers in CVD Diamond grown on Micropatterned (001) Sybstrate, Diamond Quantum Sensing Workshop 2015, 2015
3. J. Ishi-Hayase, H. Watanabe, K. M. Itoh, Control of position and orientation of nitrogen-vacancy centers in CVD-grown diamond thin film, 28th International Conference on Defects in Semiconductors (ICDS 2015), 2015
4. J. Ishi-Hayase, H. Watanabe, K. M. Itoh, Engineered nitrogen vacancy centers in diamond for quantum sensing, EMN Meeting on Vacuum Electronics, 2015
5. J. Ishi-Hayase, H. Watanabe, K. M. Itoh, Spatially selective creation of nitrogen-vacancy centers with preferential orientation in an isotopically-purified diamond thin film, XIV International Conference on Quantum Optics and Quantum Information (ICQOQ'2015), 2015
6. K. Akiba, S. Kanasugi, T. Yuge, K. Nagase, and Y. Hirayama, Optically induced nuclear spin polarization in the quantum Hall regime, International Workshop : Quantum Nanostructures and Electron-Nuclear Spin Interactions , 2015
7. Y. Ohno, Carbon nanotube thin films for flexible and formable electronics, 4th International Conference and Exhibition on Materials Science and Engineering, 2015
8. Y. Ohno, Carbon nanotube flexible devices for wearable healthcare electronics, 5th International Conference on Nanotek & Expo, 2015
9. Y. Ohno, Electronic and optoelectronic device applications of carbon nanotube thin films, Nanotechnology-2015, 2015
10. Y. Ohno, Wafer-scale investigation of electrical characteristics of carbon nanotube thin-film transistors, Pre-NT15 Workshop of Carbon Nanotubes and Graphene at U Tokyo, 2015
11. Y. Ohno, Carbon nanotube thin film-based transistors and biosensors for flexible healthcare devices, The 6th A3 Symposium on Emerging Materials Nanomaterials for Electronics, Energy, and Environment, 2015
12. Y. Ohno, Bio-electronics applications of carbon nanotube thin film, The International Chemical Congress of Pacific Basin Societies, PACIFICHEM, 2015
13. Y. Ohno, Flexible bio-electronics applications of carbon nanotube thin films, The International Conference on Small Science, 2015
14. Yoshiro Hirayama, Highly-sensitive Resistively-Detected Nuclear–Magnetic -Resonance in Compound Semiconductor Quantum Systems, 1st International conference on "Physics for sustainable development and Technology" (ICPSDT-2015) , 2015
15. Yoshiro Hirayama, Nuclear spin polarization and manipulation in semiconductor quantum systems, EMH HongKong Meeting, 2015
16. Yoshiro Hirayama, Nuclear spin polarization and detection in quantum Hall systems, Sweden-Japan QNANO Workshop, 2015
17. Yoshiro Hirayama, Nuclear spin polarization and manipulation in quantum Hall systems, The 2015 Gordon Godfrey Workshop on Spins and Strongcorrelations, 2015

2016

18. Akihito Soeda, Universal controllization--its no-go and remedy for projective measurement of energy, Quantum Information Science Workshop, 2016
19. Daiki Hatanaka, Imran Mahboob, Koji Onomitsu, Hiroshi Yamaguchi, Electromechanical Phononic Crystal, 20th International Vacuum Congress (IVC-20), 2016
20. H. Yamaguchi, I. Mahboob, H. Okamoto, Two-mode nonlinear electromechanics, Opto- and Electro-mechanical Technologies 2016 (OET2016), 2016
21. Hiroshi Yamaguchi, Daiki Hatanaka, Yuma Okazaki, and Imran Mahboob1, Piezoelectric phonon manipulation in electromechanical resonators and waveguides, SPICE Workshop Quantum Acoustics, 2016
22. Jun Kobayashi , An ytterbium quantum gas microscope with narrow-line laser cooling, CEMS Topical Meeting on Cold Atoms, 2016
23. K. Hashimoto, T. Tomimatsu, S. Shirai, S. Taninaka, K. Nagase, K. Sato, and Y. Hirayama, Scanning nuclear electric resonance microscopy in a quantum Hall system, 33rd International Conference on the Physics of Semiconductors (ICPS2016), 2016
24. K. Hirakawa, Room temperature, very sensitive bolometer using doubly clamped microelectromechanical resonators, 5th Russia-Japan-USA-Europe Symposium on Fundamental & Applied Problems of Terahertz Devices & Technologies (RJUSE TeraTech-2016), 2016
25. K. Hirakawa, Terahertz spectroscopy of quantum nanostructures far beyond the diffraction limit, TERAMETANANO 2016, 2016
26. K. Hirakawa, S. Du, K. Yoshida, and Y. Zhang, Seeing single molecules with long wavelength terahertz radiation, Workshop University of Tokyo/ENS, 2016
27. Satoshi Iwamoto, Shun Takahashi, Ingi Kim, Takeyoshi Tajiri, Yasutomo Ota, and Yasuhiko Arakawa, Control of Light Polarization using Photonic and Phononic Crystals, Asia Communications and Photonics Conference (ACP) ACP2016, 2016
28. Satoshi Iwamoto, Shun Takahashi, Takeyoshi Tajiri, Yasutomo Ota, and Yasuhiko Arakawa, Control of Quantum Dot Light Emission by Chiral Photonic Crystal Structures , The 37th Progress in Electromagnetics Research Symposium (PIERS), 2016
29. Satoshi Iwamoto, Yasutomo Ota, Shun Takahashi, Takeyoshi Tajiri, Kazuhiro Kuruma, Masahiro Kakuda, and Yasuhiko Arakawa, Quantum-Dot Cavity Quantum Electrodynamics using 2D and 3D Photonic Crystal Structures, The 12th International Symposium on Photonic and Electromagnetic Crystal structures (PECS-XII), 2016
30. Satoshi Iwamoto, Yasutomo Ota, Shun Takahashi, Takeyoshi Tajiri, Kazuhiro Kuruma, Masahito Kakuda and Yasuhiko Arakawa, Quantum-Dot Cavity Quantum Electrodynamics using Photonic Crystals, German-Japanese Meeting on the Science of Hybrid Quantum Systems, 2016
31. T. Ushiyama, N. X. Viet, S. Kishimoto and Y. Ohno, Bio-electronics applications of carbon nanotube thin film, The Seventeenth International Conference on the Science and Applications of Nanotubes and Low-dimensional Materials, 2016
32. Takaaki Koga, Electric spin generation using a double quantum well based on the interband Rashba effect, EMN Quantum Meeting 2016, 2016
33. Takaaki Koga, Quantitative determination of the Rashba parameters in the InGaAs/InAlAs quantum wells and the proposal to use the double quantum wells to enhance the Edelstein effect, International Conference on Semiconductor Nanostructures for Optoelectronics and Biosensors (IC SeNOB), 2016
34. Takaaki Koga, Spin Blocking Device Using the Inter-Band Rashba Effect in Double Quantum Well, The 6th Annual World Congress of Nano Science and Technology-2016 (Nano S&T-2016), 2016
35. Y. Ohno, Bio-electronics applications of carbon nanotube thin film, The Fifith International Workshop on Nanocarbon Photonics and Optoelectronics, 2016
36. Yoshiro Hirayama, Resistively-detected nuclear based measurements in semiconductor quantum systems, China-Japan International Workshop on Quantum Technologies (QTech 2016) , 2016
37. Yoshiro Hirayama, Quantum Transport and Nuclear Related Phenomena in GaAs and InSb Systems, Recent Development in 2D Systems (RD2DS) , 2016
38. Yoshiro Takahashi, A quantum gas microscope for ytterbium atoms, 47th Annual Meeting of the APS Division of Atomic, Molecular and Optical Physics, 2016
39. Yoshiro Takahashi, Quantum simulation using ultracold atoms in an optical lattice, International Symposium on New Horizons in Condensed Matter Physics, 2016
40. Yosuke Takasu, Study of Non-Equilibrium Dynamics of Isolated Quantum Systems Using Ultracold Ytterbium Atoms in an Optical Lattice, NCTS Annual Theory Meeting 2016:Quantum Simulations and Numerical studies in Many-Boday Physics, 2016
41. 高橋義朗，トポロジカルポンピング現象の冷却原子を用いた新展開，第２回「トポロジーが紡ぐ物質科学のフロンティア」領域研究会, 2016

2017

42. Akinobu Kanda, Search for unusual Andreev reflection in a graphene/superconductor interface, Collaborative Conference on Material Science (CCMR 2017), 2017
43. D. Hatanaka, M. Kurosu, and H. Yamaguchi, Dynamic phonon propagation control in GaAs/AlGaAs phononic crystal wave guides, 6th International Workshop "Epitaxial Growth and Fundamental Properties of Semiconductor Nanostructures", 2017
44. D. Hatanaka, M. Kurosu, and H. Yamaguchi, GaAs/AlGaAs phononic crystal waveguide, Asia Pacific Society for Materials Reseach 2017 Annual Meeting (APSMR2017), 2017
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46. H. Tabata, Noble functionalities created by Yuragi/Fluctuation in strongly correlated electron compounds, 2017 Asia-Pacific Workshop on Fundamentals and Applications of Advanced Semiconductor Devices (AWAD 2017), 2017
47. H. Tabata, New electronic devices for low power consumption by learning from bio system, The 14th International Symposium on Sputtering and Plasma Processes (ISSP2017), 2017
48. H. Tabata, Oxide Electronics and Ferroelectrics – Their History and Relations –, The 34th Meeting on Ferroelectric Materials and Their Applications(FMA34), 2017
49. H. Tabata, Ferrite Oxide Engineering for Solar Energy Harvesting and Spin-based Electronics, The Core-to-Core Workshop, 2017
50. H. Tabata, M. Adachi, H. Yamahara, M. Seki, Spin Fluctuated Garnet Ferrites for Brain Mimetic Memory Devices, IUMRS-ICM 2017(the 15th International Conference on Advanced Materials), 2017
51. H. Yamaguchi, Electromechanical semiconductor quantum structures, SPIE Optics & Photonics annual meeting 2017, 2017
52. H. Yamaguchi, I. Mahboob, H. Okamoto, and D. Hatanaka, Parametric coupling and correlated fluctuation in multimode electromechanical resonators, Frontiers of Nanomechanical Systems 2017 (FNS2017), 2017
53. H. Yamaguchi, M. Kurosu, and D. Hatanaka, Acoustic phonon manipulation in GaAs/AlGaAs electromechanical systems, US-Japan Joint Seminar on Nanoscale Transport Phenomena, 2017
54. H. Yamaguchi, M. Kurosu, D. Hatanaka, GaAs/AlGaAs phononic crystal waveguide, International Workshop on Quantum Technologies (QTech2017), 2017
55. Hitoshi Tabata, Phonon and Magnon Properties of Gradient Strain Introduced Garnet Ferrite Oxide Thin Films, 18th US-Japan Seminar on Dielectric and Piezoelectric Ceramics, 2017

56. Hitoshi Tabata, THz-TDS Combined with Metamaterials for Detecting Hydration State of Bio Related System, MTSA 2017&TeraNano-8, 2017
57. J. Ishi Hayase, Improvement of photon-echo generation efficiency by adiabatic rapid passages with a pair of chirped pulses in an inhomogeneous quantum dot ensemble, XV International Conference on Quantum Optics and Quantum Information（ICQOQI'2017）, 2017
58. K, Hirakawa, S. Du, K. Yoshida, and Y. Zhang, Terahertz spectroscopy of single molecules and single atoms far beyond the diffraction limit, Russia-Japan-USA-Europe Symposium on Fundamental & Applied Problems of Terahertz Devices & Technologies (RJUSE TeraTech 2017), 2017
59. K, Hirakawa, S. Du, K. Yoshida, C.Tang, and Y. Zhang, Terahertz spectroscopy of single molecules and single atoms, 4th International Symposium on Microwave/Terahertz Science and Applications (MTSA 2017), 2017
60. K. Hashimoto, Scanning-probe imagning of nuclear/electron spin polarization in a quantum Hall system, The Collaborative Conference on Materials Research (CCMR) 2017, 2017
61. K. Hirakawa, Uncooled, sensitive, high-speed bolometers using doubly clamped microelectromechanical resonators, 2017 Sweden-Japan International workshop on quantum nanophysics and nanoelectronics, 2017
62. K. Hirakawa, Uncooled, sensitive, high-speed bolometers using doubly clamped microelectromechanical resonators, 2017 Sweden-Japan International workshop on quantum nanophysics and nanoelectronics, 2017
63. K. Hirakawa, Ultrafast nanomechanical oscillation of single C60 molecules investigated byterahertz spectroscopy, Japan-China International Workshop on Quantum Technologies (QTech 2017), 2017
64. Kae Nemoto, A Universal Quantum Module For Quantum Computation And Communication, 2017 CLEO Pacific Rim Conference, 2017
65. Kouichi Akahane, Carrier dynamics of InAs quantum dot with digital embedding method grown on InP(311)B substrate, 6th International Workshop Epitaxial Growth and Fundamental Properties of Semiconductor Nanostructures (SemiconNano2017), 2017
66. M. Nomura, Thin Si thermoelectric material by phonon engineering, IUMRS-ICA2017, 2017
67. M. Nomura, Heat transfer control by Si phononic nanostructures, PHONONICS2017, 2017
68. M. Nomura, Physics of Nanoscale Heat Transfer and Applications, The 9th International Electronics Cooling Technology Workshop, 2017
69. M. Nomura, Phononic Crystal Nanopatterning in Si and SiGe Thin Films for Thermoelectric A pplication, TMS2017, 2017
70. M. Nomura, Thermophononic crystals, Wave Phenomena and Phonon Thermal Transport Sientific School, 2017
71. Michael Hanks,　Nicolò Lo Piparo,　Michael Trupke, Jörg Schmiedmayer, William J. Munro, Kae Nemoto, A universal quantum module for quantum communication, computation, and metrology, SPIE. Optics+Photonics, 2017
72. Mio Murao, Higher order quantum operations of unitaries and their implications, The 17th Asian Quantum Information Science Conference, 2017
73. R. S. Deacon, E. Bocquillon, J. Wiedenmann,　F. Dominguez, T. Klapwijk, K. Ishibash, and L. W. Molenkamp, Topological States of Matter , The 20th International Conference on Electron Dynamics in Semiconductors, Optoelectronics and Nanostructures (EDISON20), 2017
74. Ryota Negishi and Yoshihiro Kobayashi, Bandlike-tranport in highly crystalline graphene films from defective graphene oxide, Collaborative Conference on Materials Research, 2017
75. S. Du, Y. Zhang, K. Yoshida, and K. Hirakawa, Terahertz spectroscopy of a single atom in a fullerene cage, 42 International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz 2017), 2017
76. T. Tomita, S. Nakajima, I. Danshita, Y. Takasu, Y. Takahashi, Controlling quantum many-body states and dynamics of strongly correlated bosons with an engineered dissipation, The 2nd Tokyo-Beijing Workshop on Ultracold Atoms, 2017
77. Takao Aoki, Nanofiber resonator for a cavity QED network, The 3rd Australia New Zealand Conference on Optics and Photonics (ANZCOP), 2017
78. Takashi Yamamoto, Motoki Asano, Sahin Kaya Ozdemir, Controlling group delay with passive and active microresonators, SPIE Photonic West 2017, 2017
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