FY2017 Annual Report

Quantum Dynamics Unit

Associate Professor Denis Konstantinov

Left to right: (top) Oleksiy Zadorozhko, Oleksandr Smorodin, Jiabao Chen, Jui-Yin Lin, Erika Kawakami, Shan Zou, Emil Joseph; (bottom) Shota Norimoto, Yuimaru Kubo, Petr Moroshkin, Denis Konstantinov, Alex Badrutdinov, Asem Elarabi, Jason Ball.

Abstract

In FY2017, the Quantum Dynamics Unit continued its experimental work on various quantum systems, including electrons on helium, coupled electron and nuclear spin systems in antiferromagnets, and impurity spins in diamond to explore new interesting quantum phenomena and look for their potential applications for quantum information technologies.

1. Staff

- Dr. Yuimaru Kubo, Staff Scientist/Group Leader
- Dr. Erika Kawakami, Postdoc Scholar
- Dr. Oleksiy Zadorozhko, Postoc Scholar
- Dr. Viacheslav Dvornichenko, Technician
- Morihiro Ohta, Part-time Research Assistant
- Yu Yamashiro, Intern Student

- Jason Ball, PhD OIST Student
- Jui-Yin Lin, PhD OIST Student
- Jiabao Chen, PhD OIST Student
- Taki Tazuke, Research Unit Administrator

2. Collaborations

2.1 Circular-Polarization-Dependent Study of MIRO in electrons on helium

- Description: Theory of the effect of circular polarization on Microwave-Induced Resistance Oscillations in electrons on helium
- Type of collaboration: Joint research
- Researchers:
  - Professor Yuriy Monarkha, Institute for Low Temperature Physics and Engineering, Ukraine

2.2 Capacitive detection of Rydberg state exciations in electrons on helium

- Description: Development of a sensitive cryogenic current amplifire for capacitive detection of the Rydberg states in elecrons on helium
- Type of collaboration: Joint research
- Researchers:
  - Dr. Oleksiy Rybalko, Institute for Low Temperature Physics and Engineering, Ukraine

2.3 Quantum transducer using impurity spins in diamond

- Description: Theoretical and experimental study of coherent conversion between optical and microwave photons using impurity spins in diamond
- Type of collaboration: Joint research
- Researchers:
  - Tokuyuki Teraji/NIMS/Japan
  - Jun-ichi Isoya/University of Tsukuba/Japan

3. Activities and Findings

3.1 Circular-Polarization-Dependent Study of MIRO in electrons on helium (O. Zadorozhko, in colloboration with Yu. Monarkha from Institute for Low Temperature Physics and Engineering, Ukraine) (link)

In FY2014, we reported the first observation of the conductivity photo-response in electrons on liquid helium at the harmonics of the cyclotron resonance (link). The orgin of this effect is similar to that of the Microwave-Induced Resistance Oscillations (MIRO) of 2DEG in semiconductors. An outstanding problem with the explanation of MIRO is their experimentally observed immunity to the direction of circular polarization. Since electrons on helium present an extremely clean and simple system, the study of MIRO in this system can provide important insight into this problem.

We had carreid our experiemntal study of circular-polarization-dependence of MIRO in electrons on helium and observed a strong dependence of MIRO amplitide on the microwave helicity, see Fig. 1.This is in sharp contrast with the similar studies in semiconductors, but is in good agrement with our theory of MIRO.

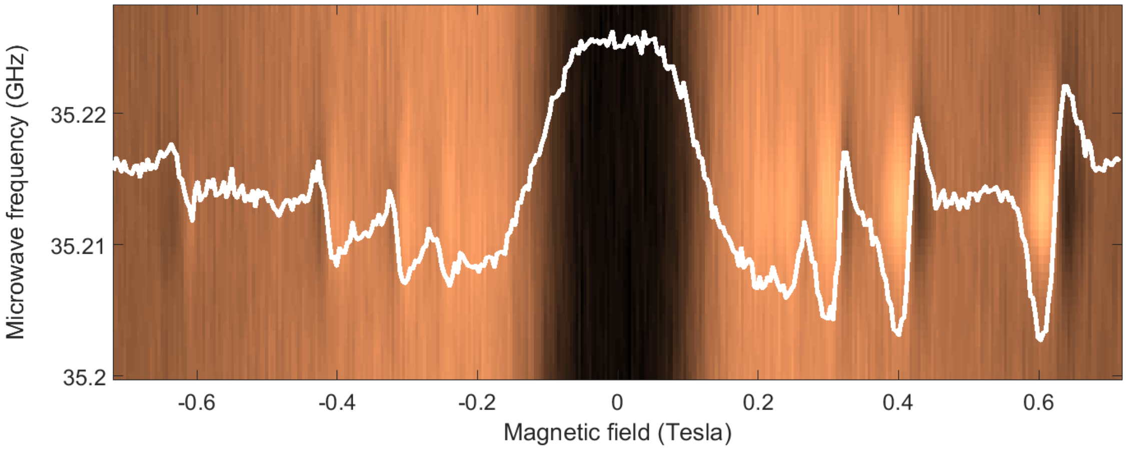


Figure 1: Photo-conductivity response of 2D electrons on liquid helium versus applied magnetic field B and microwave frequency f. The white trace is a slice at f=35.215 GHz showing MIRO which amplitide depends on the orientaion of B-field, therefore polarization of the microwaves.

3.2 Strong couping of 2D electron ensemble to a single-mode microwave cavity resonator (O. Zadorozhko, J. Chen) (link)

Previously, we reported observation of the strong coupling between the cyclotron motion of an ensemble of 2D electrons and a single-mode microwave cavity resonator (link). One of the unexpected results was observation of an additoinal weak resonance corresponding to the "passive" cavity mode (see FY2016 Annual Report).

In our new study, we carried out an experiment using a high-quality factor 35 GHz Fabry-Perot resonator. In a new setup, we clearly obsereved existance of the additinal resonace, see Fig. 2. To elucidate its origine, we carried out a detailed theoretical analysis of our experiement using both classical and full quatum treatments. We showed that both treatments of this lienar system give identical results. Moreover, we elucidate origin of the additional resonace as arising from the conversion of the "passive" mode to the mode with opposite circular polarization due to boudary condiations at the conducting walls of the experimental cell. Our numerical simulations turned out to be in comlete agrement with our experimental results, see Fig. 3.

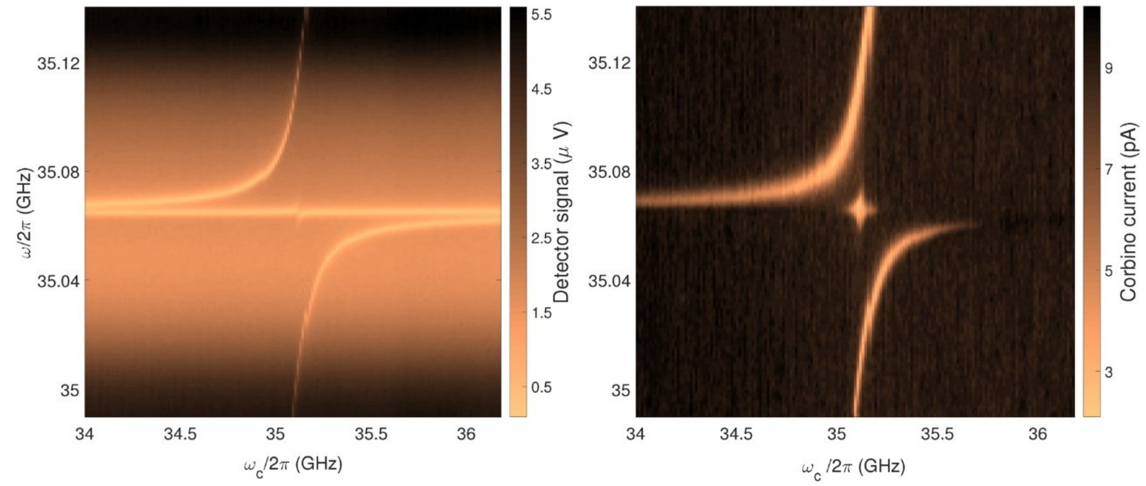


Figure 2: Power reflection from te cavity (top) and photo-conductivity response of electrons (bottom) versus the cyctron frequency and frequency of microwave pump. Additional resonace is clearly observed at the "passive" mode.

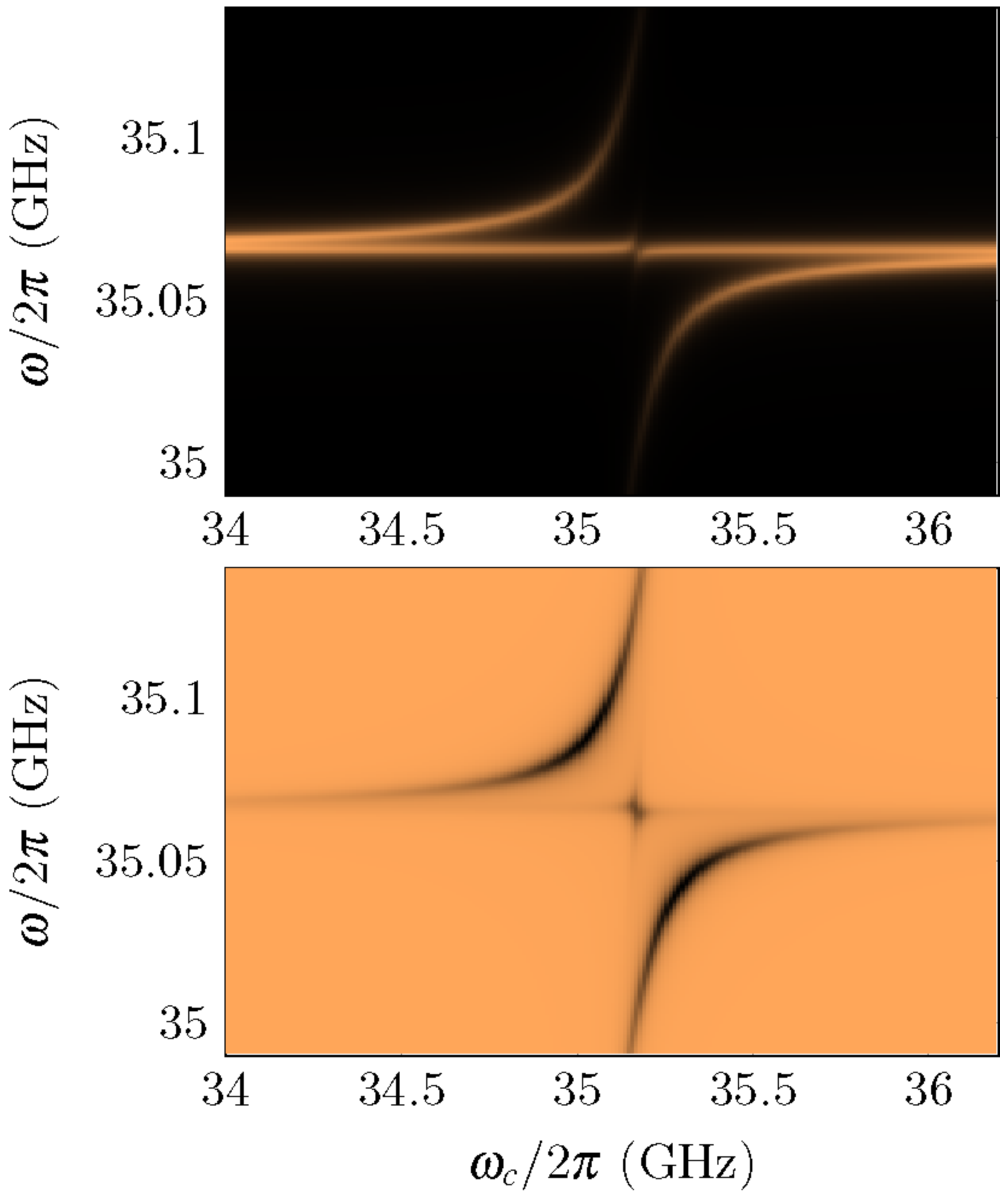
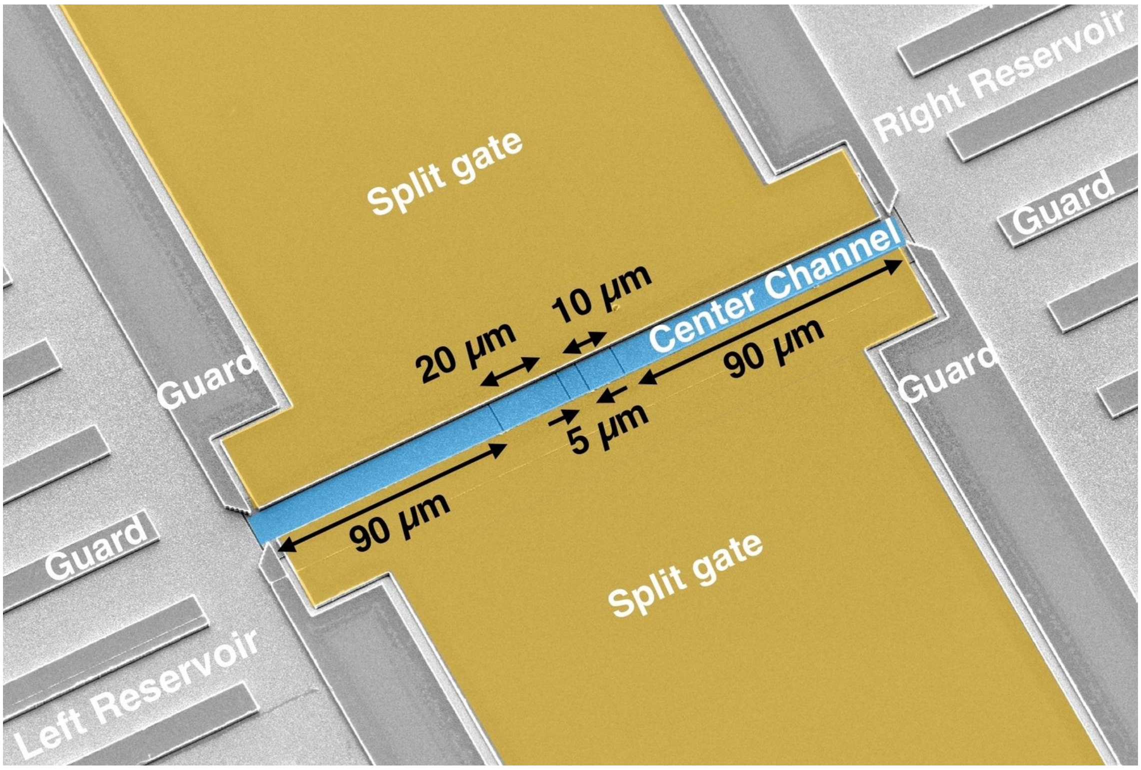


Figure 3: Numerical simulations of the experiment which completely reproduce our experiemntal results shown in Fig. 2.

3.3 Effect of finit size of an elecron crystal on its sliding from polaronic deformations on the surface of liquid helium (J.-Y. Lin, in collaboration with Alex Badrutdinov from Research Support Team, OIST) (link)

At sufficiently low temperatures and high electron densities 2D electrons on helium crystalize into the Wigner Solid (WS) phase. The electrical transport of WS shows some facinating features such as self-trapping into polaronic deformations of the liquid surface (the Bragg-Cherenkov scattering), as well as sliding from these deformations at sufficiantly large driving electric fields.

We proposed that, for sufficiently small WS, the sliding threashold should strongly depend on size of the electron crystal due to radiative loss of ripplons through the crystal boundary. To test this idea, we fabricated a device which allowed us to study the effect of the crystal size on the slding threshold, see Fig. 4 (top). Using this device we confirmed that the thershold strongly decreases when the size of WS becomes less than ~20 microns, the damping length of the ripplons due to their interaction with phonons in the liquid, which is in good agreement with our theoratical model, see Fig. 4 (bottom).



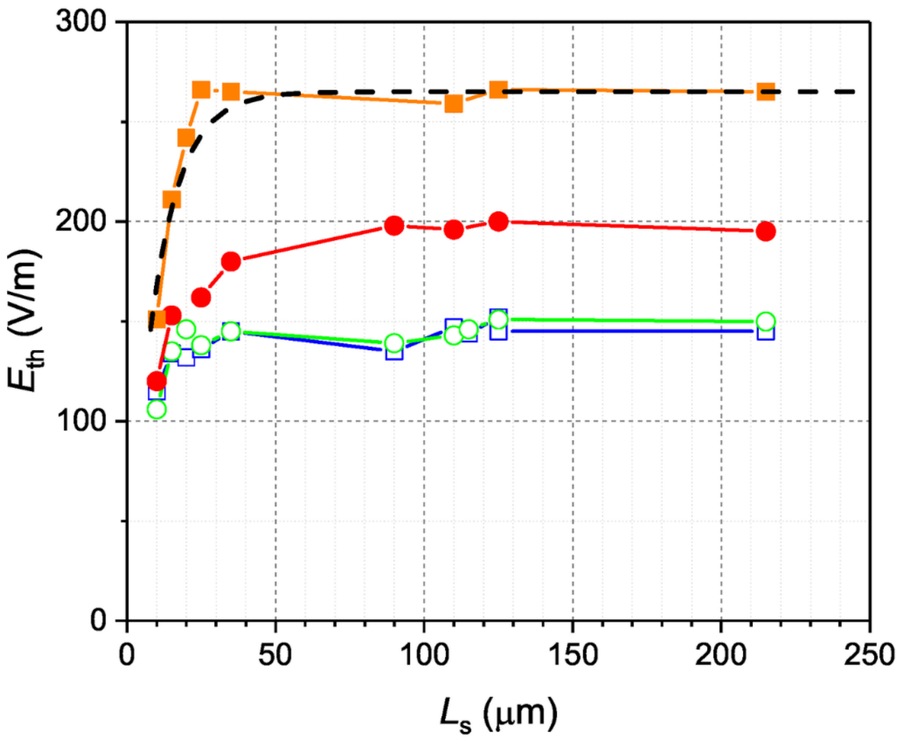


Figure 4: (top) Micrograph of our fabricated sample consisting of two reservoirs for electron storage connected by a 10 micron-wide and 1 micron-deep central channel. The bottom of the channel consists of a set of electrodes of virable size, which determine the size of the electron crystal in the channel. (bottom) Experimental values of the driving electric field at the sliding threshold versus the size of the crystal. Dashed line is the predication of our theoretical model.

3.4 Capacitive detection of the Rydberg state exciation in electrons on liquid helium (E. Kawakami, in collaboration with O. Rybalko from Institute for Low Temperature Physics and Engineering, Ukraine)

We proposed and experimentally demonstrated a new method for detection of excitation of the Rydberg states of electrons on liquid helium. In our experiment, 2D electron system is placed between two plates of a parallel-plate capacitor, see Fig. 5 (on the left). As electrons are excited from the ground state (n=1) to the first excited state (n=2) of orbital motion perpendicular to the surface, the image charge induced by each electron at the top (bottom) plate is changed by q ($-q$), which is a small fraction of the elementary charge e. The corresponding image current from many electrons (~1,000,000) induced at each plate is detected, see Fig. 5 (on the right), and shows a characteristic 1-2 transtion resonance.

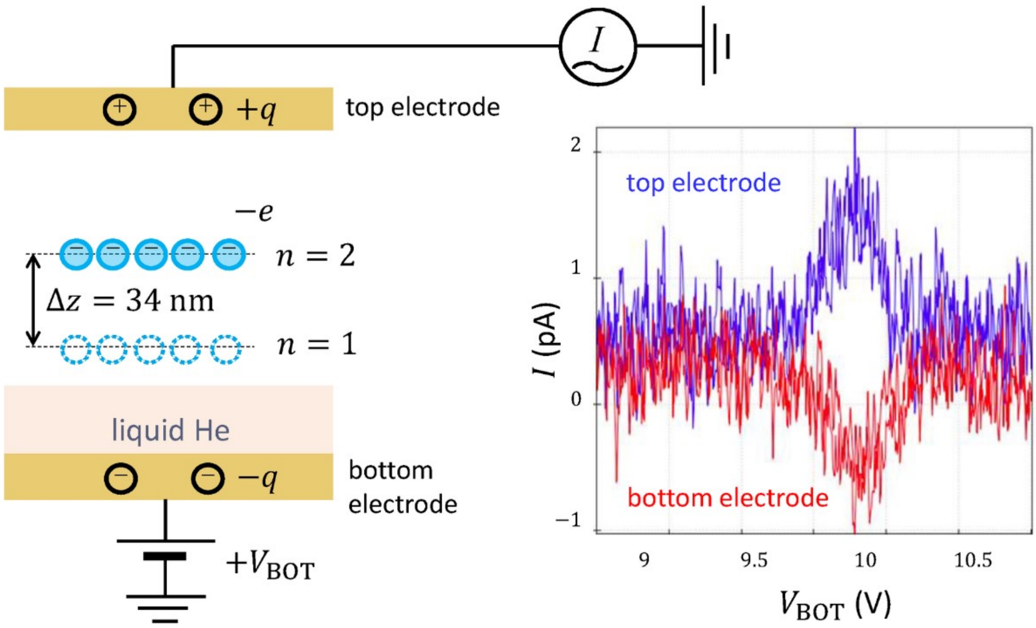


Figure 5: (left) Schematic diagram of the capacitive detection of the first excited Rydberg state population. Excited electrons are elevate about 35 nm above the liquid helium surafce and change the amount of the image charge induced at the top and bottom plates of the capacitor. (right) Image current at the capacitor plates detected during excitation of electrons with applied microwaves.

In our future experiments, we aim to increase sensitivity of our detection method by employing sensitive cryogenic amplifies.

3.5 Coupling of spin ensembles in diamonds to a 3D loop-gap resonator

We designed a loop-gap microwave resonator for applications of spin-based hybrid quantum systems and tested it with impurity spins in diamond. Strong coupling with ensembles of nitrogenvacancy (NV) centers and substitutional nitrogen (P1) centers was observed, as seen in Fig. 6 below.

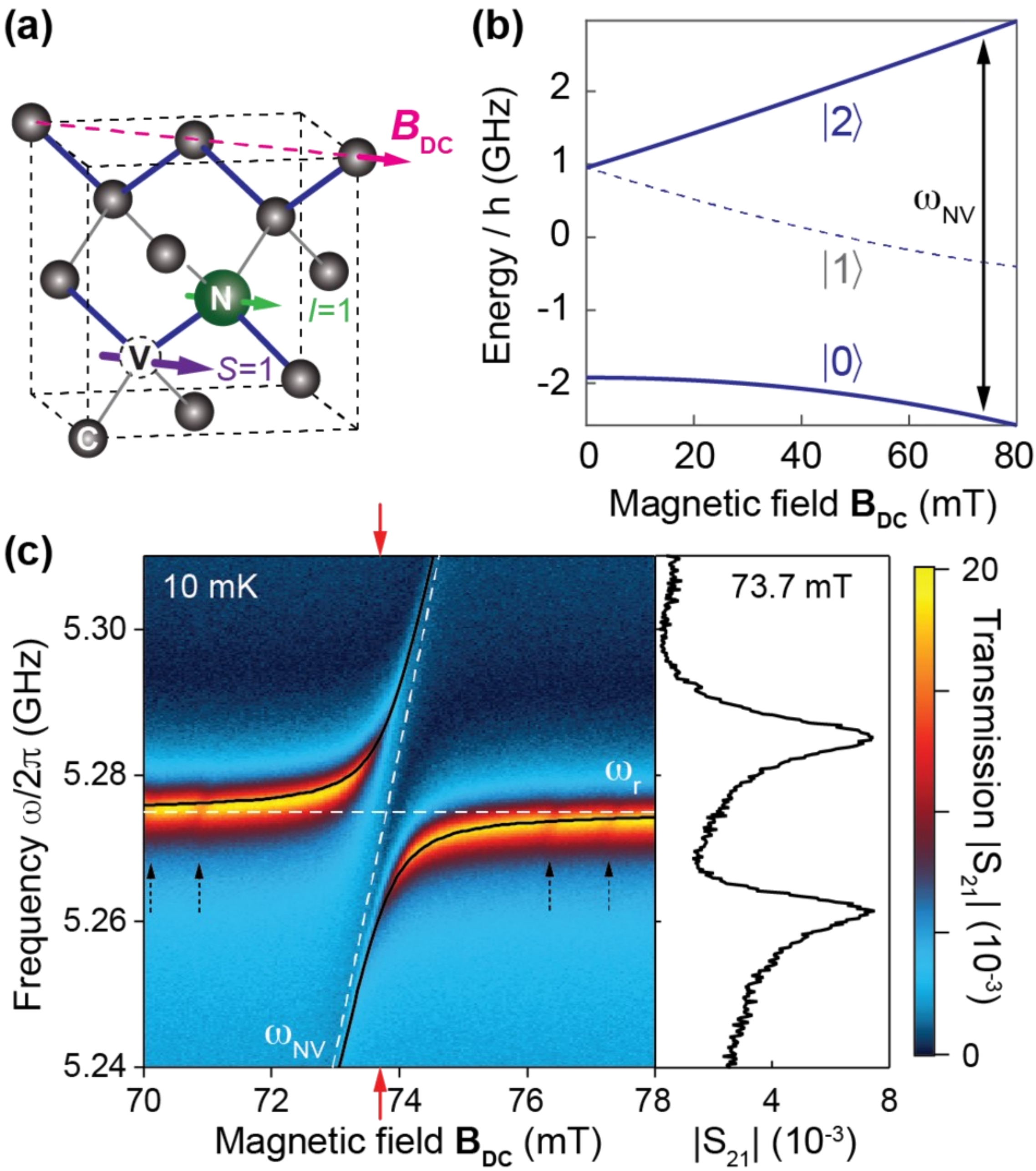


Figure 6: Schematic of an NV center in a diamond crystal with the orientation of the external constant magnetic field B_{DC} || 110 . In this configuration, there are two possible orientations of NV center with respect to B_{DC}: orthogonal ones (bonds drawn in gray) and non-orthogonal ones (thick blue). (b) Energy levels of the non-orthogonal NV centers. The transition investigated in this work is between the lowest |0> and the highest |2> states, which are drawn in solid blue curves. (c) Transmission spectra color plot of the diamond sample (left) and the spectrum at 73.7 mT (right). The white dashed lines are the original eigenfrequencies of the NV centers and the loop-gap resonator. The dotted arrows on the left panel highlight the other spin transitions due to the hyperfine coupling to ^{13}C nuclei.

These results show that loop-gap resonators are viable in the prospect of spin-based hybrid quantum systems, especially for an ensemble quantum memory or a quantum transducer. We next plan to incorporate an optical setup into our dilution refrigerator to demonstrate coherent microwave-to-optical frequency conversion.

4. Publications

4.1 Journals

1. M. I. Dykman, K. Kono, D. Konstantinov, M. J. Lea, "Ripplonic Lamb shift for electrons on liquid helium", Phys. Rev. Lett. 119, 256802, https://doi.org/10.1103/PhysRevLett.119.256802 (2017).
2. L. V. Abdurakhimov, M. A. Borich, Yu. M. Bunkov, R. R. Gasizulin, D. Konstantinov, M. I. Kurkin, A. P. Tankeyev, "Nonlinear NMR and magnon BEC in antiferromagnetic materials with coupled electron-nuclear spin precession", Phys. Rev. B 97, 024425, https://doi.org/10.1103/PhysRevB.97.024425 (2018).
3. A. A. Zadorozhko, Yu. P. Monarkha, "Circular-polarization-dependent study of microwave-induced conductivity oscillations in a two-dimensional electron gas on liquid helium", Phys. Rev. Lett. 120, 046802, https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.120.046802 (2018).
4. E. Kawakami, "Toward the realization of a quantum computer using single electron spins in Si quantum dots", 川上 恵里加, 最近の研究から 「Si 量子ドット中の単一電子スピンを用いた量子コンピューターの実現へ向けて, Japan Physical Society, 72, 5, pp. 334-338, https://doi.org/10.11316/butsuri.72.5_334 (2017).

4.2 Books and other one-time publications

Nothing to report

4.3 Oral and Poster Presentations

1. Ball, J.R., Kubo, Y., Isoya, J., Konstantinov, D., 2018. Coupling impurity spins in diamond to a 3D loop-gap resonator: contributed talk at APS March Meeting, Los Angeles, USA.
2. Ball, J.R., Yamashro, Y., Isoya, J., Konstantinov, D., Kubo, Y., 2017. A loop-gap resonator for hybrid quantum systems: invited talk at the International Spins for Quantum Information Technologies, ISQIT2017, Onna, Okinawa, Japan.
3. Chen, J., 2018. Squeezed state and spin-squeezed state by adiabatic passage: invited talk at the International Workshop on Electrons and Ions in Quantum Fluids and Solids, Mishima, Japan.
4. Kawakami, E., 2017. Towards realization of a universal quantum computer using electrons on helium: invited talk at the International workshop Inmpurity Spins for Quantum Information and Technologies, Onna-son, Okinawa, Japan.

5. Kawakami, E., Konstantinov, D., 2017. Capacitive read-out of the Rydberg states of the surface electrons on helium: invited talk at the International Workshop on Electrons and Ions in Quantum Fluids and Solids, Toray Human Resources Development Center (Mishima, Japan).
6. Konstantinov, D., 2017. Ensemble of Electrons on the Surface of Liquid Helium in a Microwave Cavity: invited tal at the 28th International Conference on Low Temperatrure Physics LT-28, Gothenburg, Sweden.
7. Konstantinov, D., 2017. Photoconductivity responce at cyclotron-resonance harmonics in the electron-on-helium system: invited talk at the International Conference on Ultra-low Temperatrure Physics ULT-2017, Heidelberg, Germany.
8. Konstantinov, D., 2017. Ripplonic Lamb shift for electrons on liquid helium: invited talk at the International workshop Inmpurity Spins for Quantum Information and Technologies, Onna-son, Okinawa, Japan.
9. Kubo, Y., 2017. "Hybrid quantum systems with spins and superconductors (and photons)": invited talk at the 7th Summer School on Semiconductor/Superconducting Quantum Coherence Effect and Quantum Information, Shuzenji, Shizuoka, Japan.
10. Lin, J.-Y., 2018. Effects of finite size and periodic spatial modulation on transport of Wigner solid on liquid helium confined in a microchannel: poster presetnation at the International Workshop on Electrons and Ions in Quantum Fluids and Solids.
11. Kubo, Y., 2017. Quantum Information Science and Technology with Hybrid systems, アーブ滋賀 ed. Osaka University 5th Interactive Material Science cadet program Shiga, Japan.
12. Kubo, Y., 2018. Loop-Gap Microwave Resonator for Hybrid Quantum Systems, 早稲田大学、東京 ed. JSAP Spring Meeting, Waseda University, Tokyo.
13. Kubo, Y., 2018. Magnetic Resonance at the Quantum Limit: invited talk at the JPS Annual Meeting, Tokyo University of Science, Noda, Chiba.
14. Ball, J.R., Kubo, Y., Konstantinov, D., 2017. Investigating SiV centers in diamond for applications in quantum technology. Nanotechnology meets quantum information, San Sebastian, Basque Autonomous Community, Spain.
15. Ball, J.R., Yamashiro, Y., Sumiya, H., Onoda, S., Ohshima, T., Isoya, J., Konstantinov, D., Kubo, Y., 2018. Loop-gap resonator for hybrid quantum systems. Dynamics of Artificial Quantum Systems, University of Tokyo, Tokyo, Japan.
16. Kawakami, E., Konstantinov, D., 2017. Gate-based read-out of the Rydberg states of electrons on helium: poster presentation at the 28th International Conference on Low Temperatrure Physics LT-28, Gothenburg, Sweden.

17. Kubo, Y., 2017. "Towards a quantum transducer with spins in diamond": invited talk at Impurity Spins for Quantum Information and Technologies ISQIT2017, Onna-son, Okinawa, Japan.
18. Lin, J.-Y., Smorodin, O., Badrutdinov, A., Konstantinov, D., 2017. FiniteSize Effects on Sliding of Wigner Solid on the Surface of Liquid Helium: poster presentation at the 28th Iternational conference on low temperature physics, Gothenburg, Sweden.
19. Konstantinov, D., 2017. Ensemble of Electrons on the Surface of Liquid Helium in a Microwave Cavity, invited seminar at CEMS-RIKEN, Wako, Japan.
20. Kawakami, E., 2017. Realization of a quantum computer using electron spins in a two-dimensional electron gas as quantum bits, invited talk at 産業技術綜合研究所つくばセンター ed, National Institute of Advanced Industrial Science and Technology.
21. Kubo, Y., 2017. Quantum Information Science and Technologies with Hybrid Systems, 岡山大学 ed, Okayama University, Okayama, Japan
22. Kawakami, E., Konstantinov, D., 2018. Towards realization of a quantum computer using electrons on the surface of helium, JPS Annual Meeting, Tokyo University of Science, Noda, Chiba.

5. Intellectual Property Rights and Other Specific Achievements

Nothing to report

6. Meetings and Events

6.1 OIST/Unit organized seminars

- Date: Septemebr 12, 2017
- Venue: OIST Campus Lab1, C016
- Speaker: Dr. Denis Vion (CEA-Saclay, France)
- Title: Quantum Zeno Dynamics in a 3D circuit-QED experiment
- Date: Septemebr 19, 2017
- Venue: OIST Campus Lab1, C016
- Speaker: Dr. Benjamin Pingault (Cambridge University, UK)
- Title: The silicon-vacancy centre spin in diamond for quantum information processing
- Date: December 1, 2017
- Venue: 15:30-16:30 OIST Campus, C016
- Speaker: Prof. Kohei Itoh (Keio University, Japan)
- Title: Silicon Quatum Computer
- Date: December 4, 2017
- Venue: OIST Campus Lab1, C016
- Speaker: Dr. Petr Moroshkin (CEMS-RIKEN, Japan)

- Title: Laser spectroscopy of Dy atoms in superfluid helium: Interaction of atomic nano-bubbles with phonons and rotons
- Date: December 18, 2017
- Venue: OIST Campus Lab1, C016
- Speaker: Dr. Kunihiro Inomata （National Institute of Advanced Industrial Science and Technology, Japan)
- Title: Single microwave-photon detector based on superconducting quantum circuits
- Date: February 16, 2018
- Venue: OIST Campus Lab1, C016
- Speaker: Dr. Shota Norimoto Osaka University, Japan)
- Title: Fast charging state detection and coherent transport of an artificial molecule

6.2 OIST/Unit organized workshops

ISQIT-2017: Impurity Spins for Quantum Information Technologies

- Date: September 15-17, 2017
- Venue: OIST Seeside House and OIST Main Cumpus
- Speakers:
    - Klaus Moelmer (Aarhus University, Denmark)
    - John Morton (University College of London, UK)
    - Patrice Bertet (CEA-Saclay, France)
    - Jarryd Pla (The University of New South Wales, Australia)
    - Renbao Liu (The Chinese University of Hong Kong, China)
    - Rose Ahlefeldt (Australian National University, Australia)
    - Dianna Serrano (Chimie ParisTech and CNRS, France)
    - Lucile Veissier (LAC University d'Orsay, France
    - Micheal Stern (Bar-Ilan University, Islael
    - Koji Usami (RCAST, The University of Tokyo, Japan)
    - Tokuyuki Teraji (NIMS, Japan)
    - Kukharchyk Nadezhda (University of Saarland, Germany
    - Philp Daniel Blocher (Aarhus University, Denmark)
    - Takayuki Iwasaki (Tokyo Institute of Technology, Japan)
    - Reinier Heeres (CEA-Saclay, France)
    - Denis Vion (CEA-Saclay, France)
    - Bartolo Albanese (CEA-Saclay, France)
    - Jessica Fermanda Barbosa (CEA-Saclay, France)
    - Benjamin Pingault (Cambridge University, UK)
    - Leonid Abdurakhimov (University College London, UK)

- James O'Sullivan (University College London, UK)
- Gavin Dold (University College London, UK)
- Christoph Zollitsch (University College London, UK)
- Alexander Barbaro (Oxford University,UK)
- Erika Kawakami (OIST, Japan)
- Jason Robert Ball (OIST, Japan)

7. The Category or Type of Funding, like External Funding, Awards, etc.

JST-PRESTO: “Coherent Bidirectional Conversion between Optical and Microwave Photons using Electron Spins in Solids” （固体中の電子スピンを用いた光ーマイクロ波のコヒーレント相互変換）

JST-PRESTO: “Towards realization of a universal quantum computer using electrons on the surface of helium” (ヘリウム表面上の電子を用いた万能デジタル量子コンピューターの実現へ向けて)