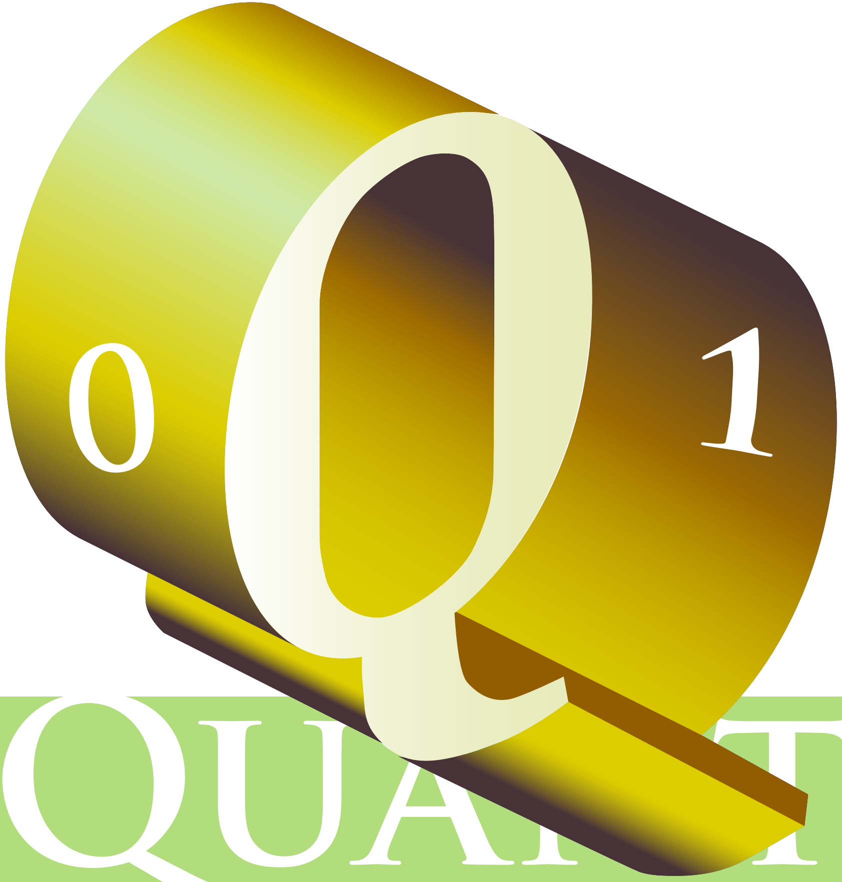

NEWS LETTER
Vol. 08
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Science Research Grants from the Ministry of Education, Culture, Sports, Science and Technology
— 2009 Grant-in-Aid for Scientific Research on Innovative Areas (Proposal-Based Research)

Project manager : Jaw-Shen Tsai, RIKEN

QUANTUM CYBERNETICS

Quantum cybernetics

Interdisciplinary research on quantum control and its application to quantum computation

http://www.riken.jp/Qcybernetics/index.html

QUANTUM CYBERNETICS

Contents

Science Research Grants from the Ministry of
Education, Culture, Sports and Science Technology
Scientific Research on Innovative Areas
「Quantum cybernetics — Interdisciplinary research on quantum control and its application to quantum computation」

Research topic A: Solid-state device quantum cybernetics

Proposed research A01: Study of superconducting quantum cybernetics
Project Leader: Jaw-Shen Tsai (Team Leader, RIKEN; Senior Researcher, NEC Smart Energy Laboratory)

- The followings are the recent results obtained by Nori Franco's group at RIKEN.

Speed limits for quantum gates in multiqubit systems

We use analytical and numerical calculations [1] to obtain speed limits for various unitary quantum operations in multiqubit systems under typical experimental conditions. The operations that we consider include single-, two-, and three-qubit gates, as well as quantum-state transfer in a chain of qubits. We find in particular that simple methods for implementing two-qubit gates generally provide the fastest possible implementations of these gates. We also find that the three-qubit Toffoli gate time varies greatly depending on the type of interactions and the system's geometry, taking only slightly longer than a two-qubit controlled-not (cnot) gate for a triangle geometry. The speed limit for quantum-state transfer across a qubit chain is set by the maximum spin-wave speed in the chain.

[1] S. Ashhab, P.C. de Groot, F. Nori, Phys. Rev. A 85, 052327 (2012).

Selective darkening of degenerate transitions for implementing quantum controlled-NOT gates

We present a theoretical analysis [2] of the selective darkening method for implementing quantum controlled-NOT (CNOT) gates. This method, which we have recently proposed and demonstrated, consists of driving two transversely coupled quantum bits (qubits) with a driving field that is resonant with one of the two qubits. For certain driving conditions, the evolution of the two-qubit state realizes a CNOT gate. The gate speed is found to be limited only by the coupling energy J, which is the fundamental speed limit for any entangling gate. We conclude that this method is competitive with existing schemes for creating entanglement, with the added advantages of being applicable for qubits operating at fixed frequencies (either by design or for the exploitation of coherence sweet-spots) and having the simplicity of microwave-only operation.

[2] P.C. de Groot, S. Ashhab, A. Lupascu, L. DiCarlo, F. Nori, C.J.P.M. Harmans, J.E. Mooij, New J. Phys. 14, 073038 (2012).

Two-qubit gate operations in superconducting circuits with strong coupling and weak anharmonicity

We theoretically study the implementation of two-qubit gates in a system of two coupled superconducting qubits [3]. In particular, we analyze two-qubit gate operations under the condition that the coupling strength is comparable with or even larger than the anharmonicity of the qubits. By numerically solving the time-dependent Schrödinger equation under the assumption of negligible decoherence, we obtain the dependence of the two-qubit gate fidelity on the system parameters in the case of both direct and indirect qubit–qubit coupling. Our numerical results can be used to identify the 'safe' parameter regime for experimentally implementing two-qubit gates with high fidelity in these systems.

[3] X.-Y. Lu, S. Ashhab, W. Cui, R. Wu, F. Nori, New J. Phys **14**, 073041 (2012).

Landau-Zener-Stückelberg interferometry of a single electron charge qubit

We perform Landau-Zener-Stückelberg interferometry [4] on a single electron GaAs charge qubit by repeatedly driving the system through an avoided crossing. We observe coherent destruction of tunneling, where periodic driving with specific amplitudes inhibits current flow. We probe the quantum dot occupation using a charge detector, observing oscillations in the qubit population resulting from the microwave driving. At a frequency of 9 GHz we observe excitation processes driven by the absorption of up to 17 photons. Simulations of the qubit occupancy are in good agreement with the experimental data.

[4] J Stehlik, Y. Dovzhenko, J.R. Petta, J.R. Johansson, F. Nori, H. Lu, A.C. Gossard, Phys. Rev. B 86, 121303 (2012).

Strong coupling of a spin qubit to a superconducting stripline cavity

We study electron-spin-photon coupling in a single-spin double quantum dot embedded in a superconducting stripline cavity. With an external magnetic field, we show that either a spin-orbit interaction (for InAs) or an inhomogeneous magnetic field (for Si and GaAs) could produce a strong spin-photon coupling, with a coupling strength of the order of 1 MHz. With an isotopically purified Si double dot, which has a very long spin coherence time for the electron, it is possible to reach the strong-coupling limit between the spin and the cavity photon, as in cavity quantum electrodynamics. The coupling strength and relaxation rates are calculated based on parameters of existing devices, making this proposal experimentally feasible.

[5] X. Hu, Y.X. Liu, F. Nori, Phys. Rev. B **86**, 035314 (2012).

Proposed research A02: <u>Study of the control, measurement, and transfer of quantum information using a semiconductor nanoassembly</u>
Project Leader: Yasuhiro Tokura (Professor, Graduate School of Pure and Applied Science, University of Tsukuba)

―Gate-controlled inhomogeneous magnetic field and fast Rabi oscillation

Aiming at increasing operation speeds of single electron spins inside quantum dots (QDs), we improved the magnetic field property of micro-magnets, which are utilized for electrical control of spins. We carried out electron spin resonance experiments using a double QD device on shallow 2DEG wafer with thick magnets. The observed interdot magnetic field difference is roughly 5 times larger (80 - 100mT) than in previous devices. We confirmed that 10mT change in the local field is accessible electrically by combining spatially distributed magnetic fields and gate control of QD position. Furthermore, Rabi oscillations with 75MHz spin rotations are observed from microwave-power-sweep experiments, which is nearly one order of magnitude faster than previously reported.

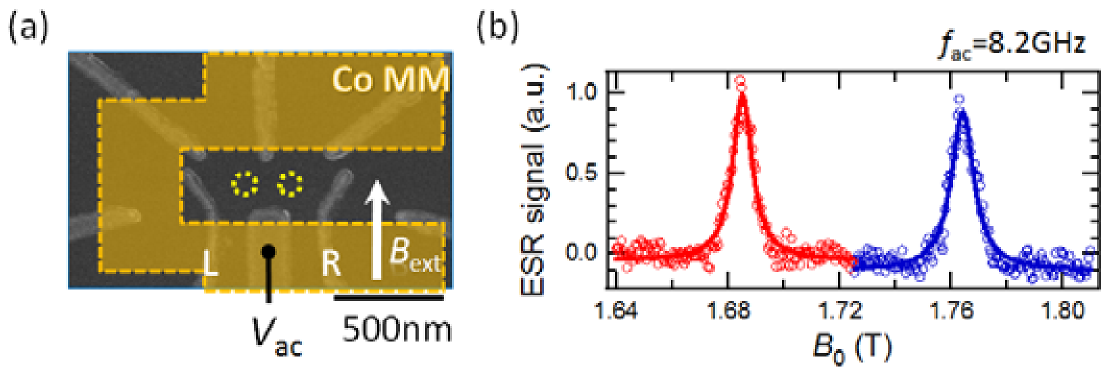


Fig. (a) An SEM picture of a double QD device with Co magnet colored orange. (b) Electron spin resonance spectra. Two peaks correspond to left and right QDs.

―Current induced dynamics of dynamical nuclear spin pumping

It is well-known that all the nuclei in the GaAs device has spin 3/2 and are the serious source of the decoherence to the electron spin as a qubit. Since the Zeeman energy of the nuclear spins are so small that the temperatures in dilution refrigerator is still 'high' and their statistical character is negligible. Recently, cooling mechanisms of the nuclear spins by the process of dynamical nuclear spin pumping (DNP) by current had been pointed out. We have studied the dynamics of this electron-spin-nuclear-spins hybrid system theoretically, especially paying special attention to the large difference between the dynamics of the electron spin and nuclear spins. We have found that the difference of the nuclear polarization in two quantum dots depends on the bias applied to the system.

Research topic B: Molecular spin quantum cybernetics

Proposed research B01: Molecular spin quantum control
Project Leader: Masahiro Kitagawa (Professor, Graduate School of Engineering Science, Osaka University)

For dynamical decoupling between a qubit system and its environment, multiple pulse sequences (MPS), which were originally-developed for NMR spectroscopy, are often used in molecular qubit system as well as impurity qubit system like NV center and superconducting qubit system. The modulated pulses which are numerically optimized based on the optimal control theory (OCT) can also provide efficient dynamical decoupling. Using numerical simulation, we show that the decoupling efficiencies of MPS and numerically-optimized pulses degrade due to the pulse transient inside a resonator and the compensation technique which we developed can appreciably improve these efficiencies [1].

The OCT-based design approach can take into account the experimental constraints such as the finite pulse width effect, whereas the MPS approach is not as flexible. The MPS approach does not require the detailed information of the system and does not depend on the system size. On the other hand, the OCT-based approach requires the detailed information and computational resources scale up exponentially with the system size and the lack of the detailed information. We present the integrated approach which takes these advantages and overcomes the drawbacks [2]. In order to fully exploit the symmetry of a system, the cost function for the numerical optimization is defined in Lie algebra, and therefore, we can alleviate the growth of computational complexity as a system becomes larger.

[1] Y. Tabuchi, M. Negoro, K. Takeda, M. Kitagawa, "Total compensation of pulse transients inside a resonator", *Journal of Magnetic Resonance*, **204**, 327 (2010).
[2] Y. Tabuchi, M. Kitagawa, "Design method of dynamical decoupling sequences integrated with optimal control theory", arXiv:1208.5218.

Research topic C: Atomic and ionic system quantum cybernetics

Proposed research C01: <u>Quantum control using cold atoms</u>
Project Leader: Yoshiro Takahashi (Professor, Atomic Physics, Graduate School of Science, Kyoto University)

In this proposed research, we aim at achieving coherent quantum control with cold atoms such as a realization of quantum computer and quantum simulator using ultra-cold atoms in an optical lattice, quantum metrology, and quantum feedback using a nuclear spin ensemble.

First, realizing a single site addressing and detection in an optical lattice brings a new possibility of research. We have successfully made progress towards this goal. Firstly, we applied so called dual optical molasses to the two-dimensional Mott insulator state of ytterbium Bose-Einstein condensate created right below an objective lens with high numerical aperture and tightly confined along the vertical direction, and we successfully observed fluorescence through the objective lens form the ytterbium atoms with an optical molasses operated with the strong electric dipole allowed transition and weak spin-forbidden transition. We confirmed about 5 s –long lifetime of the atoms in the optical lattice, and observed the effect of light-assisted collision as well as the standing wave effect of the molasses beams.

Furthermore, while we have so far performed the optical lattice quantum simulation experiments using the standard cubic lattice, we recently extend the possibility by developing an optical super-lattice with optical lattice lasers with two different wavelengths. The successful formation of the optical super-lattice is confirmed by the behaviors of the interference of the matter waves of the released Bose-Einstein condensate. We also made progress to prepare a novel, so called Lieb lattice by stabilizing the optical path lengths with an optical interferometer.

Towards the quantum feedback using a nuclear spin ensemble, we significantly revised the vacuum chamber from that with magneto-optical trap alone into that with long-lifetime optical trapping capability under the high-vacuum condition. So far, we successfully achieved a magneto-optical trapping with the new setup.

Proposed research C02: Quantum information processing using an ion trap system
Project Leader: Shinji Urabe (Professor, Graduate School of Engineering Science, Osaka University)

We have succeeded in generation of a Dicke state of 4 ions. Although generation of a six-partite Dicke state in a photonic system has been reported, generation of a Dicke state in atomic systems with excitation numbers exceeding 1 has not realized so far. Dicke states along with GHZ states are representative classes of multipartite entangled states, and they are expected to be used in precision frequency measurements. In the method that we propose and demonstrate, two-color laser beams nearly resonant to blue- and red-sideband transitions of ions are used. The amplitudes of the two-color beams are independently modulated to induce multi-level STIRAP (Stimulated-Raman Adiabatic Passage). This operation can be shown to correspond to a unitary spin-squeezing operation, and therefore Dicke states which are among maximally squeezed states can be generated using this operation. This method does not require individual addressing to each ion and have such robustness that the generated states do not sensitively depend on the details of amplitude modulation. The actual fidelity in the experiment was above 0.84.

Research topic D: Optical system quantum cybernetics

Proposed research D01: <u>Realization of quantum cybernetics using photonic Quantum circuits</u>

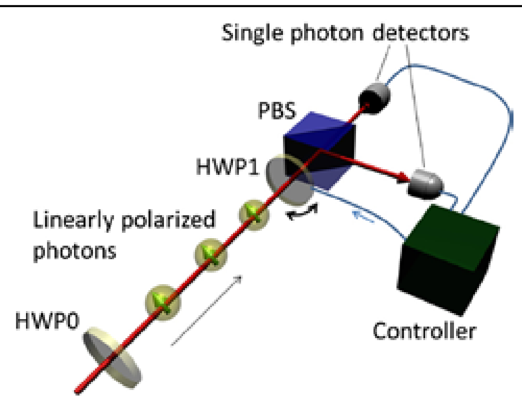
Project Leader: Shigeki Takeuchi (Professor, Institute for Electronic Science, Hokkaido University)

Photons have excellent controllability and are easily interfaced with naturally occurring atoms and molecules as well as artificial atoms. Our planning team aims to control photonic quantum state and explore new concepts in terms of quantum cybernetics. We also aim to achieve quantum state control between dissimilar quanta and to develop optical devices with built-in quantum control.

Unlike a classical particle, an electron or a photon can be in a "superposition" state of different states. When we measure the superposition state is measured only once, the measurement result is one of these states. Hence, there is no way to identify the "superposition state" with a single measurement. It is thus very important, not only for quantum state technology but also for faint light measurement, to accurately estimate a quantum state with the smallest number of measurements. To solve this problem, Prof. Hiroshi Nagaoka at the University of electro-communications advocated an adaptive estimation scheme where measurement method is optimized each time with the measurement results. Later, Prof. Akio Fujiwara at Osaka University, who is a selected researcher of this Grant-in-Aid for Scientific Research on Innovative Areas, theoretically proved its optimality (strong consistency and asymptotic efficiency).

We recently succeeded in demonstrating this "adaptive quantum state estimation" using photons for the first time as far as we know. Photons, which were generated from a heralded single photon source using parametric down-conversion, were prepared to be a specific linearly polarized state and the polarization angle of the photon was estimated using the method. A sequence was carried out with 300 input photons and the sequence was repeated 500 times. By analyzing the experimental data, we have exactly verified the optimality of the adaptive quantum state estimation (strong consistency, asymptotic efficiency). It has been found that the precision of the adaptive quantum state estimation outperforms the conventional state tomography. It is thus expected that the adaptive quantum state estimation will provide a useful methodology in the broad area of quantum information processing, communication, and metrology.

[1] R. Okamoto, M. Iefuji, S. Oyama, K. Yamagata, H. Imai, A. Fujiwara, and S. Takeuchi, Physical Review Letters109, 130404 (2012).



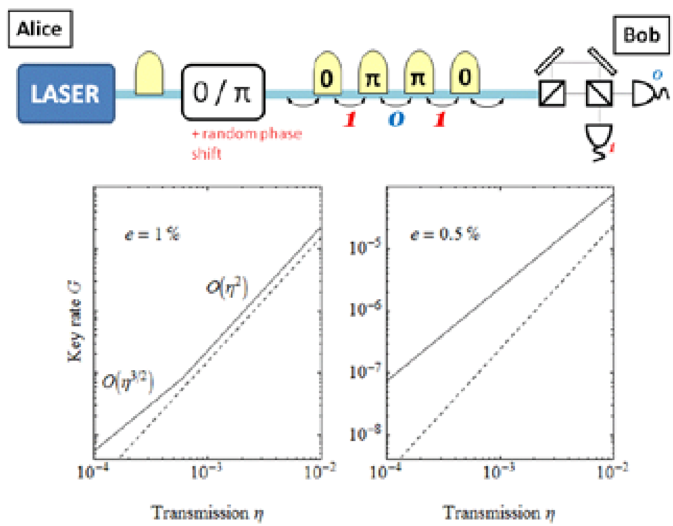
Adaptive quantum state estimation

Proposed research D02: Light-based multi-qubit quantum control

Project Leader: Masato Koashi (Professor, Photon Science Center of the University of Tokyo)

ー Proof of security for quantum cryptography based on phase-shifts in a pulse train

Differential-phase-shift (DPS) protocol is an advanced QKD (quantum key distribution) protocol in which the bit values are encoded on the relative optical phase shift between the neighboring pulses in a weak laser pulse train. Since a laser emits photons randomly, unavoidable events of multiple photon emission may be exploited by an eavesdropper. This threat tends to restrict the intensity of the source, leading to a poor scaling of secure key rate on the channel transmission. In this regard, the simple implementation used in the DPS protocol is expected to provide robustness against such an attack, only there was no security proof to assure that. Here we have presented a security proof that ensures that the DPS protocol indeed possesses the expected robustness. As a result, we achieved a secure key rate with a better scaling $O(\eta^{1.5})$ with channel transmission η, which should be compared with the scaling of $O(\eta^2)$ expected if there was no robustness.



2012 Selected research subjects and project managers

Proposed research 01: Heterogeneous Quantum Repeater Hardware
Project Leader: Rodney D. Van Meter（Associate Professor, Faculty of Environment and Information Studies, Graduate School of Media and Governance Keio University)

ーAQUA: Advancing Quantum Architecture

Our mission is to bridge the gap between theoretical algorithms and real-world experiments to accelerate the deployment of useful quantum information technology. Much of our work is directed at designing distributed quantum computing systems, a paradigm we expect to be critical to scalability and usability of quantum systems.

We work in six main areas, including: design of large-scale devices (in conjunction with Stanford University and others); principles of quantum computer architecture; software tools for programming quantum computers and visualizing their behavior; workload analysis, determining how to efficiently implement known quantum algorithms on prospective quantum architectures; and repeater networks, to tie them all together. The sixth main area, management of errors in quantum systems, drives all of the other areas.

Recent results include development of a layered approach to quantum computer architecture (Jones et al., Phys. Rev. X 2012), and an analysis of large-scale quantum repeater networks (Van Meter, IEEE Network 2012). Lattice surgery for surface code quantum computation (Horsman et al., New J. Phys., to appear) provides a new, resource-efficient mechanism for fault-tolerant operation, and is expected to impact near-term experimental work.

For the Quantum Cybernetics project, we are extending our work on repeater networks to heterogeneous hardware, simulating three types of physical qubits in the same repeater node.

Proposed research 02: Classical Compilers for Topological Quantum Information Processing

Project Leader: Simon Devitt (Assistant Professor, Quantum Information Science group, National Institute for Informatics)

– Quantum Blocks: A crowd-sourcing solution to programming a topological quantum computer

In 2005 a group of computer scientists at the University of Washington undertook a unique project to solve a necessary scientific problem through the general public; they created a video game. FoldIt (foldit.it) was designed to allow members of the general public to determine the unique was in which a long chain of amino-acids (the building blocks of proteins) fold up into a 3-dimensional shape. This problem, which is extremely difficult to calculate automatically, ultimately determines the function of proteins in the human body and consequently is of great interest to biologists and drug manufactures. This game was a great success, generating solutions that had baffled scientists for years with a registered user base (as of 2011) of over 250,000 members of the public.

Inspired by this work, we have begun a similar project, "Quantum Blocks". Quantum Blocks is a game targeted at members of the public, designed to optimise the circuits needed to implement fault-tolerant quantum information processing in the topological cluster state model. The game will be released on all major platforms and on Android and iOS devices. The current version of Quantum Blocks is currently an Alpha version and will be distributed to members of the physics community later this year. A full public release is expected in the winter of 2013 and will hopefully find better solutions to circuit optimisation in the topological model.

Proposed research 03: Study of the initialization of an electron spin
Project Leader: Yasuaki Masumoto (Professor, Graduate School of Pure and Applied Science, University of Tsukuba)

ー Long coherence time of electron spins in II-VI semiconductors

Spin coherence time of electrons in semiconductors is restricted by the fluctuating nuclear magnetic field produced by hyperfine interaction between electron spins and nuclear spins. In III-V semiconductors, nuclear spins of most constituent atoms are half integer which restricts the coherence time of electrons up to a few nanosecond. In II-VI semiconductors, such as ZnO, on the other hand, non-zero nuclear spins of constituent atoms are small in the natural abundance which may lengthen the coherence time of electrons. In this study, we measured the spin relaxation of electrons in Ga-doped ZnO ($6x10^{17}cm^{-3}$) by means of the time-resolved Kerr rotation. Under the resonant excitation of D^0X, electron spin precession continues up to the laser repetition time of 12.2ns at 1.8K. Resonant spin amplification under the transverse magnetic field derives the spin coherence time T_2* of 12ns. At the elevated temperatures, the time-resolved Kerr rotation signal shows the two-component decay and the slower component survives at the higher temperatures. The slow spin relaxation is considered to be restricted by the fluctuation of hyperfine nuclear magnetic field of nuclear spins. We measured the Kerr rotation amplitude at the negative time delay of -250ps under the longitudinal magnetic field and found a narrow dip (half width at the half maximum of 1.3mT) at the zero magnetic field. Small natural abundance (4.1%) of ^{67}Zn (I=5/2) and low-density dopant ^{69}Ga (I=3/2) and ^{71}Ga (I=3/2) give the electron spin relaxation time of 14ns in consistency with the observed time of 12ns.

Proposed research 04: <u>Development of element technologies and elucidation of physics toward realization of silicon quantum bits</u>
Project Leader: Tetsuo Kodera (Assistant Professor, Quantum Nanoelectronics Research Center, Tokyo Institute of Technology)

Study of quantum computation using electron spins in quantum dots (QDs) has been led by GaAs systems so far. However, it needs to be expanded to silicon-based QD systems in the future when a problem of decoherence due to nuclear spins and the compatibility to the current technologies of electronics are taken into account. In order to advance more rapidly this research, it is essential to successfully apply the technologies and the findings which have been obtained in GaAs QD systems, to silicon QD systems. In this study, we design and fabricate silicon QD devices in a few-electron regime and characterize the transport properties. In addition, we aim spin manipulation and readout by high-frequency voltage operation on the basis of experiences in GaAs QDs.

We fabricated and characterized silicon double QDs in the vicinity of the single-electron transistor charge sensor. By measuring the source-drain current while sweeping the two side gates, we obtained a honeycomb-like charge stability diagram, which is typical for double QDs. We also succeeded in detecting the change in the number of electrons in the double QDs using the single-electron transistor charge sensor. By applying a negative voltage to the source electrode and the drain electrode of the single-electron transistor, we have also demonstrated operation of single-electron transistor working as the gate electrode for controlling the potential of the double QDs. This means that we gave single-electron transistors dual functions of charge sensing and gating, which is a useful technique for integration of silicon quantum bits.

Proposed research 05: Quantum non-equilibrium statistical physics and thermodynamics in the control and detection of quantum coherent processes

Project Leader: Yasuhiro Utsumi (Associate Professor, Department of Physics Engineering, Faculty of Engineering, Mie University)

Recently it become possible to control and detect coherent quantum systems, such as charge, flux and spin qubits. Independently, the statistical physics and the thermodynamics in mesoscopic systems have been progressed rapidly. The concepts playing key roles in this direction are the fluctuation theorem and the Jarzynski equality. In mesoscopic systems, the statistical physics is formulated based on the distribution function of non-equilibrium fluctuations induced by a time-dependent driving force. For now, the measurement of the probability distribution of current and work using single-electron transistors have been realized and the fluctuation theorem and the Jarzynski equality have been verified experimentally. However those experiments are still for "classical level" and the aim of this project is to extend them to quantum regime.

We continue preliminary investigations. One of problems in testing the Jarzynski equality using quantum systems is that the quantum work is not defined naively. Before, we theoretically consider a measurement of the work for electric circuits including a quantum conductor. Our model describes realistic experiments, in which projective measurements are repeated continuously. Then we suggested that to analyze coherent control and detection experiments, we have to consider many issues, such as heating effects and environments. Motivated by this observation, we considered the full-counting statistics of electron transport in the presence of electron-phonon coupling and investigated qualitative features of the cumulant generating function. We will continue to study effects of environments as well as possible experimental setups to test the fluctuation theorem in quantum regime.

Proposed research 06: <u>Research on charge-state controlled single-photon device toward realizing long-distance transfer of electron spin state</u>

Project Leader: Toshihiro Nakaoka (Associate professor, Faculty of Science, Sophia University)

In this project, we aim to fabricate a quantum dot single photon source with a side gate and to develop the measurement setup to realize the spin-spin entanglement of two remote electronic devices.

For this purpose, we have recently developed a reflection-type laser scanning confocal microscope combined with an electrical measurement setup for efficient measurement of electrically injected single photons from our device covered with gate metals. Figure 1 (right) shows the device image obtained by scanning the laser light that is transparent to the substrate. The image is confirmed to be the same as the microscope image of our device reported in the previous News Letter (Fig. 1, left).

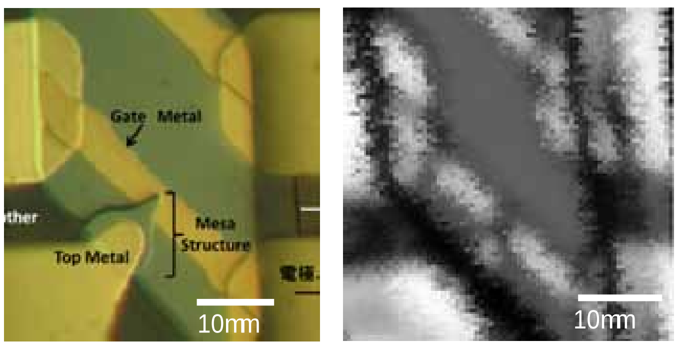


Figure 1：Device image taken by a conventional microscope（left）and the image obtained by the reflection-type laser scanning confocal microscope combined with an electrical measurement setup (right).

Proposed research 07: Toward Manipulation of Quantum Spin Information in Biomolecules

Project Leader: Hideto Matsuoka (Assistant Professor, Institute of Multidisciplinary Research for Advanced Materials, Tohoku University)

Recently, native photosynthetic systems have attracted much attention in the field of quantum information science because it was demonstrated that molecules involved in photosynthesis can remain entangled at room temperature. High-frequency (>94GHz) time-resolved EPR is a powerful technique to detect entangled electron spins. High-time resolution and high-frequency CW EPR spectrometer was constructed by incorporating a fast low-noise preamplifier (NF SA-230F5, bandwidth of 500 Hz to 140 MHz), leading to the improvement of the time resolution up to 5 ns. High-time resolution and high-frequency pulse spectrometer was also constructed by incorporating a pulse microwave bridge with a high power MW amplifier of 280 mW and a lab-made PC control system into a Bruker E600 spectrometer. We have performed high-frequency EPR measurements of spin correlated radical pairs in entangled states, which are ubiquitous intermediates in photosynthesis At 10 ns after the laser flash, fast initial oscillations were observed, which is attributed to quantum beats from the spin correlated radical pair, $P_{700}^{+}A_{1}^{-}$, in photosynthetic proteins. Toward manipulation of quantum spin information in photosynthesis, further improvements of the time-resolution are in progress. We are also constructing electrically detected EPR based on high-time resolution and high-frequency pulse techniques, which will be applied toward manipulating and measuring biological quantum information.

Proposed research 08: Research for electrical control of quantum information by NV center in diamond

Project Leader: Norikazu Mizuochi (Associate Professor, School of Engineering Science, Osaka University)

In this project, we investigate the single nitrogen vacancy (NV) center in diamond. By using the confocal microscopy combined with magnetic resonance system, the single spins can be controlled and optically detected at room temperature. So, it is expected as good quantum system. In addition, due to their outstanding photo-stability, it has been used as single photon source for quantum cryptography and single photon interference by laser excitation. The development of such a promising solid-state sources of single photons is a major challenge in the context of quantum communication, optical quantum information processing, and metrology. Recently, we have demonstrated electrically driven single photon emission by using single NV center in diamond at room temperature. We continue the research for further development for electrical control of quantum information by NV center in diamond.