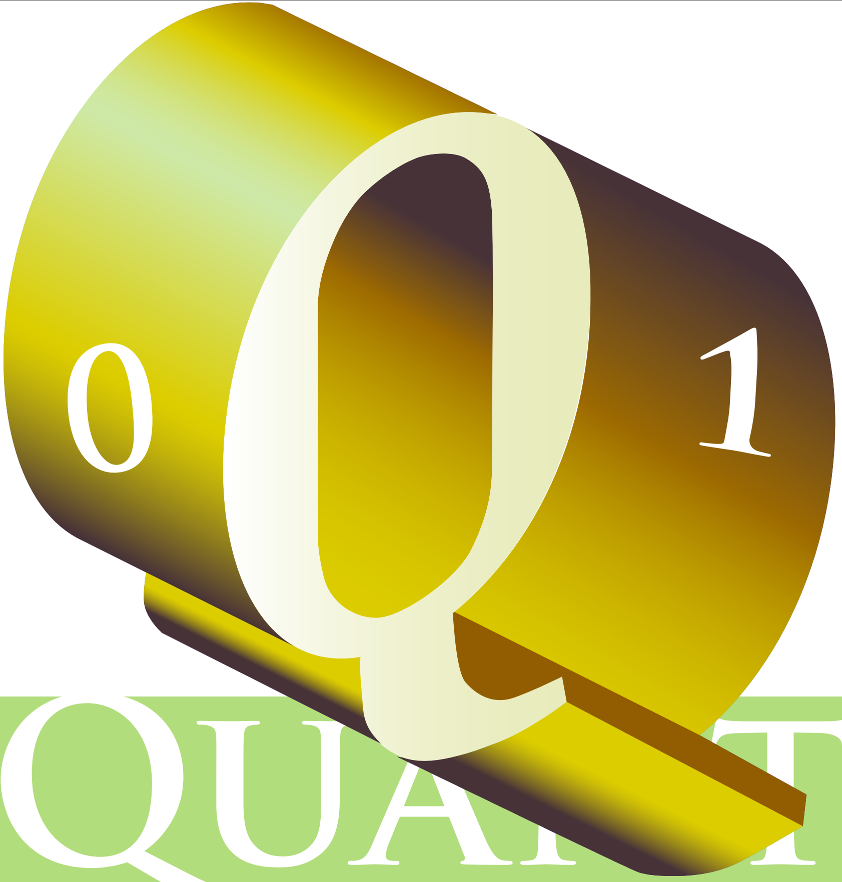

NEWS LETTER

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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
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「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)

―Coherent quantum phase slips: more evidences

We are investigating experimentally the coherent quantum phase slip (CQPS) effect, a phenomenon that involves coherent tunneling of quanta of magnetic flux across a thin and narrow superconducting wire. It is dual to the Josephson effect in which Cooper pairs of electrons tunnel across a thin insulating barrier separating two superconducting electrodes. There are hopes of constructing various unique CQPS-based quantum devices conjugate to conventional structures relying on Josephson tunnel junctions. Examples include a current standard conjugate to the Josephson voltage standard for quantum metrology, and a superconducting quantum charge detector conjugate to the Superconducting QUantum Inerference Device (SQUID) flux sensor.

Following our initial observation of CQPS in InO_x nanowires [1], we are studying the behavior of the flux tunneling amplitude as a function of the wire width, typically between 10 and 50 nanometers, and its reproducibility in the disordered superconductors NbN and TiN [2]. The phenomenon is revealed as a superposition of flux states in a superconducting loop with the nanowire acting as an effective tunnel barrier for the magnetic flux. We couple the two-level systems to a coplanar waveguide resonator, and characterize them using microwave spectroscopy. As a result, we obtained an exponential dependence of the CQPS energy on the wire width, as predicted by theory. In addition, coherent oscillations are revealed in time-domain measurements. Besides nanowires fabricated from these highly disordered superconductors with large kinetic inductance, we observe two-level system behavior also in purposely-made short and narrow constrictions in both NbN and TiN films.

[1] O. V. Astafiev et al., Nature **484**, 355 (2012).
[2] J. T. Peltonen et al., arXiv:1305.6692 (2013).

—The results obtained by Nori Franco's group at RIKEN : click here

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)

—Non-linear dependence of Rabi frequency on microwave amplitude

We have been studying coherent electron spin control (electric dipole spin resonance, EDSR) using oscillating microwave electric field and micro-magnet. Initially, we could observe Rabi frequency of several MHz. Recently the group of Univ. Tokyo is realizing more than 100MHz Rabi frequency by improving the design of micro-magnets and increasing the microwave amplitude. In the perturbation theory of EDSR on the microwave and magnetic field gradient, it had been shown that the Rabi frequency is linearly proportional to the microwave amplitude. Recently, we have shown that for any microwave amplitude, the Rabi frequency should be linear in microwave amplitude when the confinement potential of the quantum dot is harmonic, rotating-wave approximation is applicable, and real orbital excitations are negligible. We had extended our analysis to anharmonic potential, double well potential, and found the non-linear behavior of the Rabi frequency for large microwave amplitudes.

Y. Tokura, T. Kubo and W. J. Munro, arXiv:1308.0071.

—Possibility of multiple spin initializations

Unconditional initialization of two electron spins into spin triplet states is realized using Pauli-spin blockade phenomena in a series double quantum dots (QDs) under finite bias. This is also useful to the detection of the spin. We have examined new current blockade mechanism and possibility of spin initialization in three-QD system under finite bias. In particular, we studied (1,2) configuration, with one QD coupled to the source lead and two QDꞌs to the drain lead and (2,1) configuration, with two QDꞌs coupled to the source and one QD to the drain. When the total electron number is one or two, we can expect current blocking when the energies of the parallel two QDs are equal. The spin is initialized to triplet state for (1,2) configuration, but the spin is not initialized for (2,1) configuration. This is because of the current blocking process by the coherent population trapping (CPT), which is independent of spin. When the total electron number is two or three, the spin is initialized to quadruplet state for (1,2) configuration.

Research topic B: Molecular spin quantum cybernetics

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

―Strongly driven electron spins using a Ku band stripline resonator

Precise control of qubits is required to build a fault tolerant, scalable quantum computer. To achieve such precise control on a quantum computer using electron spins, we have to implement fast spin rotations, which is much shorter than spin decoherence time, and design pulses, which suppress systematic errors. We have constructed a Ku-band electron spin resonance spectrometer with an arbitrary waveform generator, which can suppress systematic errors.

For fast spin rotations, resonators are often used to generate strong microwave magnetic field. Taking into account the strengths of couplings between electron spins, a wideband (low Q factor) resonator is needed. We developed a wideband stripline resonator, which can strongly drive electron spins. We constructed a small U-shape at the center of stripline where the magnetic flux can be concentrated and the strong irradiation can be applied (Fig.1 (a)). We achieved a Rabi frequency of 210 MHz at 1 W at room temperature (Fig.1 (b)) and the Q factor was 85 (bandwidth 200 MHz).

Unpaired electron spins in a molecule have to be initialized by cooling to temperatures below 1 K. Our developed stripline resonator is useful for experiments under such conditions because fast spin rotation can be applied with low microwave power.

[1] Y. S. Yap, H. Yamamoto, Y. Tabuchi, M. Negoro, A. Kagawa, M. Kitagawa, J. Magn. Reson., 232, 62-67 (2013).

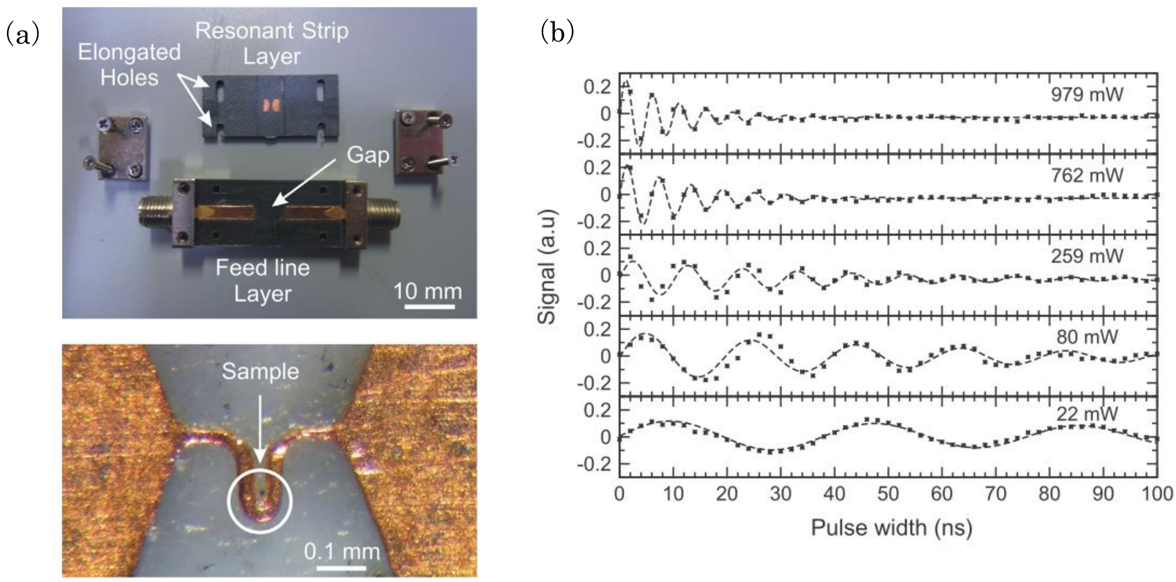


Fig.1: (a) stripline resonator, (b) Rabi oscillation.

Research topic C: Atomic and ionic system quantum cybernetics

Proposed research C01: Quantum control using cold atoms
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. The recent achievements are in the followings.

The control of inter-atomic interaction is an important requisite for quantum simulation as well as quantum computation. Since a two-electron atom of an ytterbium atom which we use in our project has no hyperfine structure in the ground state, we cannot expect so called magnetic Feshbach resonance. While we discovered the magnetic Feshbach resonance phenomena between the ground state and the metastable excited state induced by the anisotropic interaction both for 170Yb and 174Yb, we recently confirmed the Feshbach resonance for fermionic isotope of 171Yb at about 3G and 6G by measuring the relaxation rate. With this observation we can pursuit the novel BEC-BCS crossover physics.

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 a non-standard lattice of an optical Lieb-lattice. The successful formation of the optical Lieb-lattice is confirmed by the behaviors of the interference of the matter waves of the released Bose-Einstein condensate. We also confirmed the successful loading of ultracold SU(6) Fermi gas into a flat-band of the Lieb lattice by measuring the band populations. This realization is encouraging us to study the flat-band ferromagnetism and super-solid phase and so on.

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

We experimentally realized the Jaynes-Cummings-Hubbard (JCH) model using two trapped ions, and observed a quantum phase transition of polaritonic excitations. Recently the JCH model, which is the model for an interconnected array of Jaynes-Cummings systems each comprising of a two-level atom and an optical mode, is attracting theoretical interests. The model is related to the efforts to realize artificial strongly correlated systems using optical cavities. JCH systems are expected to undergo in certain conditions a superfluid-to-Mott-insulator transition arising from a competition between interactions and quantum fluctuations. This time we experimentally realized the JCH model for the first time using the internal states and radial phonon modes of two trapped ions. In the JCH system using trapped ions, internal excitations and phonons interchange via JC interactions, and hence their combinations, referred to as polaritonic excitations, become the conserved particles. This time we succeeded in observing a quantum phase transition from a localized insulator phase of the polaritonic excitations to a delocalized superfluid phase of them [1].

Trapped ions and photons are one of the candidates for quantum networks composed of stationary qubits and flying qubits. We are trying to couple trapped ions and the evanescent components of the light field of an optical nanofiber. The important parameter in such system is the distance between the ions and the fiber, which is affected by electric properties of the fiber surface. To evaluate the surface charge, we have assembled an optical nanofiber in a linear Paul trap, made trapped microsphere with the diameter of 3 εm close to the fiber under normal pressure, and estimated the line charge density from the equilibrium position of the microsphere. This is a collaborative research with Prof. Takeuchi's Lab of Hokkaido University.

[1] Kenji Toyoda, Yuta Matsuno, Atsushi Noguchi, Shinsuke Haze, Shinji Urabe, 'Experimental realization of a quantum phase transition of polaritonic excitations', arXiv:1308.3295

Research topic D: Optical system quantum cybernetics

Proposed research D01: Realization of quantum cybernetics using photonic Quantum circuits

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.

Toward the realization of the quantum state control between the dissimilar quanta, we study microcavity system coupled with single nitrogen vacancy (NV) center in diamond. Nanofiber-coupled microspherical cavities (shown in figure) are one of the most promising microcavities for ultra-high Q factor ($Q > 10^8$) and high input-output efficiency. We controlled the nanofiber-coupled microspherical cavity at cryogenic temperature (7 K) and succeeded in a cavity-induced phase shift transition due to the change of coupling condition and 0.8 GHz frequency tuning of the cavity resonance [1].

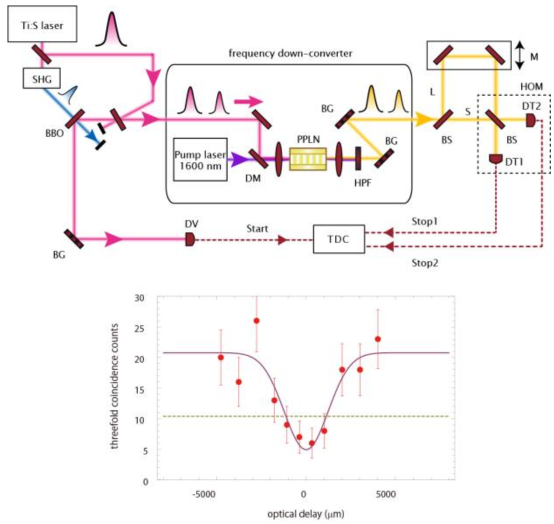
An entangled photon pair is also a fundamental resource of photonic quantum circuits. We realized the quantum entangled photon pair sources with broad frequency correlation. First, we proposed that the combination of multiple bulk nonlinear crystals enable us to broaden the bandwidth of the entangled photon pairs and demonstrated the broad bandwidth of 170 nm (the center wavelength of 808 nm) using two bulk crystals [2]. Next, we generated ultra-broadband entangled photon pairs whose correlation bandwidth spans from 790 nm to 1610 nm (a center wavelength of 1064 nm) using quasi-phase matched device whose poling periods is linearly chirped [3]. This bandwidth is world largest to our best knowledge. Our results can be useful for applications such as the quantum metrology and the photonic quantum circuits.

[1] M. Fujiwara, T. Noda, A. Tanaka, K. Toubaru, H. Zhao, and S. Takeuchi, Opt. Express **20**, 19545 (2012).
[2] M. Okano, R. Okamoto, A. Tanaka, S. Subashchandran, and S. Takeuchi, Opt. Express **20**, 13977 (2012).
[3] A. Tanaka, R. Okamoto, H. H. Lim, S. Subashchandran, M. Okano, L. Zhang, L. Kang, J. Chen, P. Wu, T. Hirohata, S. Kurimura, and S. Takeuchi, Opt. Express, **20**, 25228 (2012).

A microspherical cavity coupled with a thin tapered fiber at cryogenic temperature.

Proposed research D02: Light-based multi-qubit quantum control
Project Leader: Masato Koashi (Professor, Photon Science Center of the University of Tokyo)

—Observation of two-photon interference after conversion to telecom wavelength



Quantum interface for wavelength conversion of photons is an important building block for linking quantum information among different kinds of physical systems, such as atoms, trapped ions and solid states, through photonic quantum communications. Observation of non-classical interference between two photons at the telecommunication band converted from visible photons is a significant requisite for the quantum interface, for there are quantum repeater protocols which perform the Bell measurement based on two-photon detection in their elementary links. Here we observed Hong-Ou-Mandel (HOM) interference between two photons converted to a telecom wavelength via our quantum interface based on difference frequency generation in a periodically-poled lithium niobate (PPLN) crystal. The HOM interference shows up as a dip in the coincidence detection rate of the two photons, which stems from their inherent indistinguishability. The observed dip has a relative depth of 0.76±0.12, which is well above the classical limit of 0.5. The high-visibility interference is an important step for fiber-based quantum communications of photons generated from visible photon emitters.

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)**

In this project, we are investigating heterogeneous hardware architectures for quantum repeaters. Two of the most promising quantum information technologies are superconducting flux qubits and nitrogen vacancy centers in diamond. A third promising technology is bismuth vacancy centers in silicon. Our proposed approach is to combine these three into a complete repeater system. The flux qubit provides the logic element and the tunable coupling between the other two types of qubits. The NV qubit provides the optical transceiver, while the Si:Bi qubit provides long-lived memory. Because the coupling of a single NV center to the flux qubit is weak, we propose using a small ensemble of NV centers. The principal challenge in this approach is to be able to reliably emit a useful quantum optical state using this ensemble.

Proposed research 02: **Classical Compilers for Topological Quantum Information Processing**
Project Leader: **Simon Devitt (Assistant Professor, Quantum Information Science group, National Institute for Informatics)**

—**Compilation and Programming of quantum computers**

In the past year we released a preliminary version of a game that will be used to "crowd-source" the optimisation of large scale quantum algorithm. Named *meQuanics: The Quantum Computer Game* (www.mequanics.com), we have converted the problem of algorithmic optimisation into a elegant three dimensional puzzle. This game, when initially released, generated great response in Japan, generating over hundreds of tweets on Twitter. Our goal for the next year is to convert this game into a popular piece of software for iOS and Android platforms with the aim of competing with serious puzzle games.

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)

—Trion resonant Kerr rotation

Long spin coherence of electrons in semiconductors allows the fast and multiple quantum operation and spin quantum memory well matching light, flying qubit, for long-distance quantum communication. Spin coherence time of localized electrons in semiconductors is restricted by the fluctuating nuclear magnetic field produced by hyperfine interaction between electron spins and nuclear spins. Non-zero nuclear spins of constituent atoms in ZnO are smallest in the natural abundance among II-VI semiconductors, which lengthens the coherence time of localized electrons. We already observed the long spin coherence time, T_2*=12ns, of localized electrons in ZnO by means of femtosecond time-resolved Kerr rotation. In this study, we measured the picosecond time-resolved Kerr rotation in Ga-doped ZnO ($6x10^{17}cm^{-3}$) under the resonant excitation of sharp D^0X. An electron doped by a Ga donor, Ga^+ and a photogenerated electron-hole pair form a trion resonance, D^0X. Picosecond time-resolved Kerr rotation has not only time resolution of 2ps but also spectral resolution of 0.3meV, although femtosecond time-resolved Kerr rotation has better time-resolution and worse spectral resolution. With the change of the excitation photon energy near the resonance, Kerr rotation signal by electrons change the sign and the amplitude drastically. Because Kerr rotation angle is proportional to the difference between the refractive indexes for left and right circularly polarized light, the resonant Kerr rotation signal is expected to be described by the derivative of the refractive index spectrum and the 2nd derivative of the absorption spectrum.

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 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.

Hole spins in silicon QDs are expected to have longer coherence time than electron spins because hyperfine interaction is suppressed due to the *p*-orbital symmetry of the Bloch wavefunction. We successfully observe a single hole transport through p-type silicon double QDs. We fabricate double QDs and charge sensors on silicon-on-insulator (SOI) substrate by using dry etching and electron beam lithography. Boron is doped in source and drain regions using ion implantation. In transport measurement performed at 4.2 K. we observe a honeycomb-like charge stability diagram which is typical for double QDs. We also observe several charge triple points at positive source-drain voltage. By applying a negative source-drain voltage, current of one of the charge triple points is strongly suppressed. This result may indicate that we observe hole spin blockade in the p-type silicon double QDs.

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

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

Recently it became 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 and an exact relation valid in non-equilibrium regime, ñthe fluctuation theoremò has been discovered. The theorem is formulated based on the distribution of non-equilibrium fluctuations induced by a driving force. For now, measurements of probability distributions of current and work using single-electron transistors have been realized and the fluctuation theorem has been verified experimentally. However those experiments are still in the ñclassicalòregime. The aim of this project is to extend them to the quantum regime.

For now, we have theoretically analysed several issues, which should be clarified in order for the verification of the quantum fluctuation theorem. For the problem, how to measure the ñquantumòwork in a quantum conductor, we proposed to use a classical LC circuit and to perform projection measurements repeatedly. Then in order to understand the heating effect, we analysed the full-counting statistics of a quantum conductor in the presence the electron-phonon coupling. We investigated the analytic property of the cumulant generating function for the case of the single-mode phonon. Since this model is oversimplified, we now consider general models for the environment, the acoustic phonon bath and the voltage probe. We continue to analyse the environmental effect using the full-counting statistics and consider the experimental setups to test the quantum fluctuation theorem.

Until now, we have theoretically analysed several issues, which should be clarified in order for the verification of the quantum fluctuation theorem. In the last few months, we have been considering the effects of environments, such as a photon bath. By extending our previous work on the full-counting statistics of the quantum-dot coupled to a single-mode phonon bath, we are developing the theory of the full-counting statistics including a temperature probe, which is also working as an environment. For now, by accounting for the fluctuation of the energy inside the temperature probe electrode, we constructed the full-counting statistics of electrons satisfying the fluctuation theorem. We are also considering an experimental setup to test the quantum fluctuation theorem using a solid-state qubit. Especially we are interested in a protocol to be robust against the1/f noise.

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 develop basic techniques for remote entanglement in a compact device based on an electrically excited quantum dots. We have successfully fabricated the quantum-dot light-emitting-diode (LED) structure with a side gate. The gate is designed to generate X^{2-} exciton states for producing entangled states between the frequency of an outgoing photon emitted from the double dot system and a two electron spin state. We note that the gate structure is very similar to vertical single electron transistor which provides fine controls of single electron states.

For efficient photon extraction from the device covered with source-drain and side-gate electrodes, we have developed a method for optical access from the substrate-side (backside). The substrate of the device was polished from 650 □m to 300 □m in thickness to allow for optical access from the substrate-side. The device was mounted in a PLCC-type package with through-holes. The package was set to to turn upside down. Through the hole, we focused a laser light on the backside of the sample to measure the reflectivity of the position. By scanning the reflectivity of the sample using a high precision translation stage, we have successfully access the LED structure with 500 nm in diameter from the backside of the device

We have also studied the jitter problem for electrical injection of carriers, which is one of the main obstacles for electrically driven remote entanglement. We have suggested a way to reduce the jitter problem by putting carriers into an indirect state in a double quantum dot system, and then transforming the state into a direct state with a fast recombination rate. Future fast gate pulse operation of the indirect-direct transition allows for quantum control of the population by a Landau-Zener-type process.

Proposed research 07: <u>Toward Manipulation of Quantum Spin Information in Biomolecules</u>

Project Leader: Hideto Matsuoka (Senior Scientist, Institute of Physical and Theoretical Chemistry, University of Bonn)

To interpret the mechanism of biological functions achieving high efficiency solar energy conversion has been a long standing issue in the field of photosynthesis. Recently, several research groups have demonstrated that quantum entanglement is employed in the electron- and charge-transfer processes of photosynthesis. Nobody has clarified yet how long-lived quantum coherence is attained in the biological environment composed of thermally fluctuating water and amino acids. In this work, high time-resolution ESR (Electron Spin Resonance) studies have been performed for a correlated spin pair (entangled state). Quantum coherence was created between the eigenstates of the correlated spin pair, which could manifest themselves as quantum beats in an EPR experiment with adequate time resolution. It should be notice that coherence effects are observed even at ambient temperatures. Coherence time was measured for the correlated spin pair in various experimental conditions. By performing deuteration and ^{15}N-substitution, coherence time could be improved up to 1.2 □s from 600 ns at 100K, meaning that the coherence time is normally influenced by surrounding nuclear spins. Compared to at 100K, the coherence time became half at room temperature, but it was still longer than expected under ambient conditions. Further experiments are in progress for model systems of photosynthetic protein.

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

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. Recently, the optical, chemical and electrical control of its charge state of NV center has been investigated because the control is essential for the stability and manipulation of the qubit. However, electrical manipulation of the charge state of a single NV^- centre and its dynamics have not yet been reported. Recently, we realized the electrical manipulation of the charge state of a single NV^-. Furthermore, we investigate the dynamics by time-resolved measurements. These results pave the way to the electrical control of the charge state of NV^-.

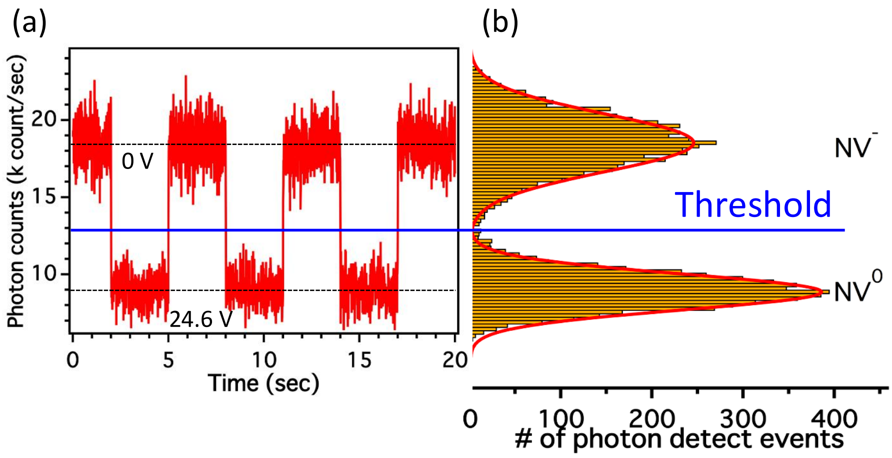


Fig. (a) Real-time trace of the fluorescence intensity with the switching of current between 0 and 70 µA. (b) The histogram of (a).