NEWS LETTER Vol.09

February 15, 2013

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)

－Single-shot readout for superconducting flux qubit using Josephson parametric amplifier

Dispersive readout using a LC resonator is widely used to readout the state of superconducting qubits in fast and nondestructive fashion. This technique utilizes the fact that the resonance frequency of the resonator, to which the qubit is dispersively coupled, depends on the state of the qubit. Its usefullness has been already demonstrated in a variety of experiments of cavity quantum electrodynamics using superconducting circuits.
One of the problems of the dispersive readout, however, is its low signal to noise ratio (SNR). In this technique, in order to minimize the backaction on the qubit, one has to detect small signal of order of a single photon in a time scale much shorter than the life time of the qubit (~1 us, typically). Therefore, low-noise and wide-band amplifiers are indispensable, and cryogenic HEMT amplifiers have been commonly used so far. However, even with the best one with a noise temperature around 5 K, SNR is usually much smaller than 1. This necessiates an average of many trials to discriminate the state of the qubit, although single-shot readout is desirable if we consider its application to the quantum information processing.

Recently, many groups are trying to solve this problem by using low noise amplifiers based on superconducting circuits. We also have developed flux-driven Josephson parametric amplifiers (JPA) since 2008 [1]. In addition to the fact that its band center frequency is controllable by an external magnetic field, flux-driven JPA has an advantage that it does not require additional microwave to cancel strong pump tone. This is because the pump frequency is twice different from that of the signal in flux-driven JPA, which is not the case for the previous experiments using current-driven JPA [2]. Recently, we have incorporated the flux-driven JPA as a preamplifier in our setup for the dispersive readout for the superconducting flux qubit [3]. This led to dramatic improvement of SNR and enabled us to achieve single-shot readout and observation of quantum jumps.

[1] T. Yamamoto *et al.*, Appl. Phys. Lett. **93** 042510 (2008).
[2] R. Vijay *et al.*, Phys. Rev. Lett. **106** 110502 (2011).
[3] K. Inomata *et al.*, Phys. Rev. B **86** 140508(R) (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)

－Quantum interference induced by Landau-Zener transitions in a one-electron double quantum dot

NTT Basic Research Laboratories　Takeshi Ota

Recently, Landau-Zener (LZ) transitions have received renewed interest as an alternative approach to control single-qubit states. LZ transitions occur when a system is adiabatically passed through an avoided crossing that arises from quantum mechanical coupling of two levels, where the transition probability is determined by the velocity. Successive sweeps through the avoided crossing back and forth thus induce multiple LZ transitions, resulting in the interference between the superposition states generated on the incoming and outgoing passages. The effect, known as the Landau-Zener-Stückelberg (LZS) interference, has been demonstrated for both superconductor [1] and semiconductor [2] qubits.

We focus on charge states in a one-electron DQD in order to study such quantum coherent oscillations involved in the charge states. Since a single electron occupies either left (|L>) or right (|R>) dot in a one-electron DQD, the charge states |R> and |L> are relevant in the Rabi-type coherent oscillations and LZS interference. Figure 1(a) schematically shows the device structure and the experimental setup. High-frequency voltage pulses with amplitude V_p, applied to the drain electrode of the DQD. Figure 1(b) shows the pulse-induced dot current as a function of detuning ε at the pulse duration of 0.32 nsec. The oscillation patterns are apparently observed for $\varepsilon > 0$ as indicated by arrows. By comparing experiment and numerical simulations, we show that there is a significant enhancement in the oscillation amplitude of the final state probability due to LZS interference in the region away from the resonance between the left and right dot levels ($\varepsilon = 0$).

[1] For example, S.N. Shevchenko, et al., Physics Reports 492, 1 (2010).
[2] J. R. Petta, et al., Science 327, 669 (2010).

Figure 1(a)

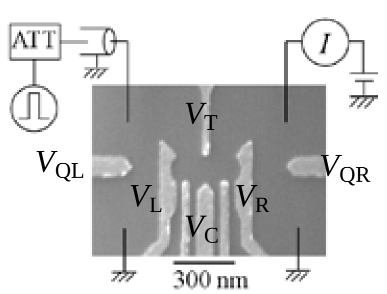


Figure 1(b)

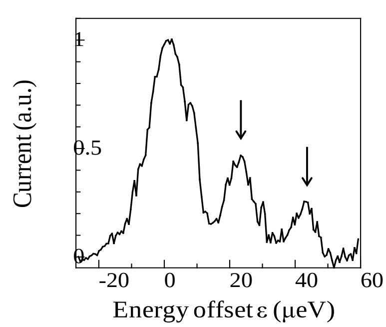


Fig. 1(a). Device structure and the experimental setup, (b) Pulse-induced dot current as a function of detuning ε at the pulse duration of 0.32 nsec.

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)

—A synthetic two-spin quantum bit: g-Engineered exchange-coupled biradical designed for controlled-NOT gate operations.

Reported by T. Takui, Group of “Control of Molecular Spins”

The last decade has witnessed that a rapidly developing field of quantum computing and quantum information processing is linked to chemistry in spite of the fact that molecular electron spin qubits are the latest arrival among many physical qubits.

We have designed a two-qubit biradical **1** designed as a fundamental unit of quantum computing that can afford CNOT gate operations, which are essentially important gates to constitute a universal set of quantum gates together with well-defined single qubit operations. [1] Biradical **1** is 2,2,6,6-tetramethylpiperidin-N-oxyl-4yl) {(2,2,6,6-tetramethylpiperidin-N-oxyl-4-yl) 3,5-dimethylbenzoate-4-yl}terephthalate (IUPAC nomenclature), in which extremely weak exchange-coupling is anticipated and the *g*-tensors at the NO sites of the TEMPO groups are non-equivalent, as the principal axes of the *g*-tensors pointing in different directions (*g*-tensor engineering); TEMPO = tetramethyl-piperidine-1-oxyl. The distance between the NO sites of the TEMPO units is designed so as to be about 2.0 nm, which corresponds to about 10 MHz of the electron spin dipolar interaction. The value of 10 MHz in the order of magnitude is required to manipulate electron spin qubits in molecular spins in terms of spin technology. The choice of the linker between the two TEMPO moieties is important in terms of crystal-engineering and synthetic feasibility in addition to the targeted *g*-tensor engineering. The introduction of two methyl groups into one of the phenylene rings is effective to make a large angle between the z-axes of the *g*-tensors. The angle between the *z*-axes is 57.5 degrees in the host lattice. ^{15}N-isotope labelling is essential to simplify fine-structure/hyperfine ESR (Electron Spin resonance) transitions whose number greatly depends on the nuclear spin quantum numbers involved in the ESR allowed transitions. Vanishing quadrupolar interactions of ^{15}N nuclei are highly favourable to reduce the ESR line width. Biradical **1** satisfies all these requirements for two-spin qubits, exemplifying the first synthetic electron spin qubits for molecular-spin based quantum computing.

[1] Shigeaki Nakazawa,* Shinsuke Nishida, Tomoaki Ise, Tomohiro Yoshino, Nobuyuki Mori, Robabeh D. Rahimi, Kazunobu Sato,* Yasushi Morita,* Kazuo Toyota, Daisuke Shiomi, Masahiro Kitagawa, Hideyuki Hara, Patrick Carl, Peter Hoefer, and Takeji Takui* “A Synthetic Two-Spin Quantum Bit: g-Engineered Exchange-Coupled Biradical Designed for Controlled-NOT Gate Operations”, *Angew. Chem. Int. Ed*., 51, 9860 – 9864 (2012).
http://onlinelibrary.wiley.com/doi/10.1002/anie.201204489/abstract
DOI: 10.1002/anie.201204489

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 installed a objective lens with NA=0.75 from the previously used one with NA=0.5 and also successfully constructed the imaging system with magnification with 200, which enables us to collect much more fluorescent photons. In addition, we successfully observed a Moire pattern with 532nm optical lattice and 556nm optical molasses, which is close to the goal of single atom detection.

Furthermore, while we have so far performed the optical lattice quantum simulation experiments, we could not independently control the onsite interaction. Recently we have successfully observed the signature of the Feshbach resonance between the ground and metastable states. In addition, we have successfully implemented the spin-orbit interaction between the ground and metastable states.

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 an optical trapping with the new setup. In particular, we successfully optically trap the 171Yb atoms which are used in the squeezing experiments.

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)

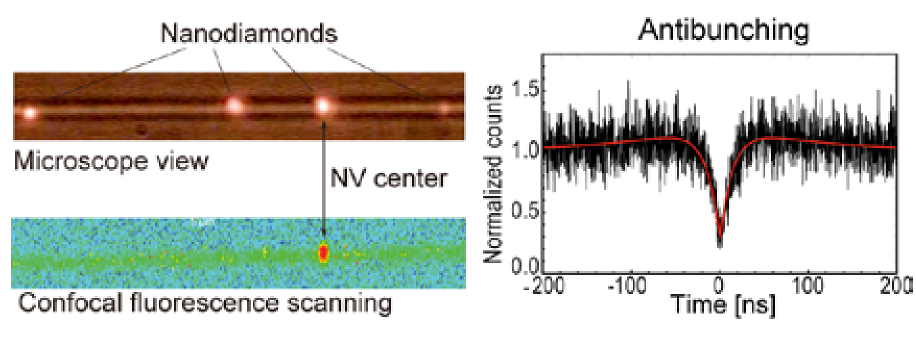
―A nanodiamond-tapered fiber system with high single-mode coupling efficiency

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.

Coupling fluorescence of nanoemitters, such as quantum dots (QDs), to single mode fibers is very important for developing quantum cryptography network in future secure communication networks. So far, we succeeded in coupling 7.4 % of the total emitted photons from single CdSe/ZnS QDs to single mode fibers by placing those QDs on the surface of our optical tapered nanofibers whose tapered diameter was only 300 nm [1]. This value of 7.4 % is almost 7 times higher than the conventional fluorescence collection method using microscope objectives. However, CdSe/ZnS QDs have notorious drawbacks for applications to single photon sources, i.e. fluorescence intermittency and broad spectral emission line.

To overcome these difficulties, we have employed nitrogen vacancy (NV) centers in nanodiamonds. NV centers are very promising nanoemitters showing blinking-free emission and life-time limited very narrow emission line. The NV-coupled nanofiber has provided 689,000 Hz single photon emission rate in the single mode fiber, which is the highest value ever reported [2].

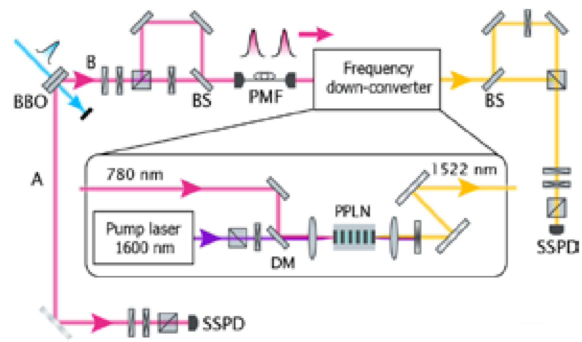
[1]M. Fujiwara, K. Toubaru, T. Noda, H.-Q. Zhao, S. Takeuchi, Nano Lett. **11**, 4362-4365 (2011).
[2] T. Schröder, M. Fujiwara, T. Noda, H.-Q. Zhao, O. Benson and S. Takeuchi, Opt. Express **20**, 10490-10497 (2012).



(Left) Diamond NV center placed on the nanofiber and (right) its single photon emission to the fiber, characterized by antibunching photon correlation.

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

ーHigh-fidelity photonic quantum interface for wavelength conversion



Wavelength conversion of a photon while preserving the encoded quantum information is actively studied for linking the distantly located matter qubits, such as atoms, trapped ions and solid states, through photonic quantum communications. Recently we demonstrated such a quantum interface for converting visible to telecom bands by using difference frequency generation via a periodically-poled lithium niobate (PPLN) crystal, but the observed fidelity of the two-photon state after the frequency conversion to a maximally entangled state was about 0.75. The degradation of the fidelity was mainly caused by background photons from the Raman scattering and dark counts of the detectors. In order to suppress these effects and obtain a high fidelity, we used newly developed superconducting single photon detectors (SSPDs) and properly adjusted the pump strength. The resulting enhancement of the signal-to-noise ratio enabled us to achieve a higher fidelity of 0.93 ± 0.04 after the wavelength conversion. The high performance quantum interface will become a useful tool toward realization of long distance quantum communication.

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)

This project is focusing on complex, realistic hardware models for quantum repeaters. We are developing detailed simulations of networks of repeater nodes, simulating both the physical node design and the communication protocols used. We will use the specific design of superconducting qubits coupled to nitrogen-vacancy diamond ensembles, and simulate the rate of generation of usable entangled links within the network for a range of parameters. The results of the simulation will enable us to evaluate the medium-scale performance of these existing small-scale technologies, laying out a specific roadmap for experimental improvement that will lead to network deployment.

Our initial step in this project has been studying entanglement purification protocols adapted for the proposed hardware scheme. We found the double-selection purification scheme of Fujii and Yamamoto [PRA 80, 2009] to be an attractive fit due to its robustness against local gate errors, which are expected to be common in early experimental demonstrations. Our detailed simulations, however, have found that operation of the protocol is not robust; it is very sensitive to conditions on the network. If one communication session is forced to wait due to the activity of another, the throughput of double-selection fares poorly. Moreover, double-selection is very sensitive to the availability of resources. Thus, although it is attractive, it must be used with care in order to benefit the network performance.

Proposed research 02: Classical Compilers for Topological Quantum Information Processing

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

－Developments in Resource optimisation for topological quantum computing

Resource optimisation in large scale quantum computing is of huge importance to the construction of a large-scale, commercially viable quantum computer. Solving quantum problems, intractable to classical supercomputers, requires a very large number of physical qubits and a large amount of computational time. Coupled with the necessity of quantum error correction, the number of qubits necessary to factor large prime numbers or simulate classically intractable quantum systems could easily reach one billion.

Recent results (Devitt et. al. arXiv:1212.4934) has illustrated that the biggest hurdle to reducing the total number of physical resources for a large scale architecture may have little to do with the actual quantum hardware and more to do with exactly how we compile and execute fault-tolerant quantum algorithms. The *classical* problem of quantum circuit compilation and compactification has the potential to reduce physical demands on large scale computer significantly. More importantly, the manner in which we implement large scale computation (namely through the model of topological computation) divorces the classical problem of circuit compilation from the underlying physics of a quantum computer.

For this reason we have actively been engaging with the classical computer science community in an attempt to solve this problem. Not only have we found new methods for topological circuit compilation (Fowler and Devitt, arXiv:1209.0510, Fowler, Devitt and Jones, arXiv:1301.7107) but we have been actively engaging the computer science community by introducing these ideas within their community (Palar, Devitt, Nemoto, Polian, Proc. NanoArch'12), (Devitt and Nemoto, Proc. ATS'12), including a special session on programming quantum computers held this year at the Asian Test Symposium in Niigata (ATS'12).

We feel that continued engagement with classical computer scientists will open up a new range of possibility that will help reduce the resources for a large scale computer and bring quantum computing one step closer to reality.

Proposed research 03: **<u>Study of the initialization of an electron spin</u>**

Project Leader: Yasuaki Masumoto (Professor, Graduate School of Pure and Applied Science, University of Tsukuba)

ー Long coherence time of electron spins in Zn

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. Non-zero nuclear spins of constituent atoms in ZnO are smallest in the natural abundance among II-VI semiconductors, 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 consisting of Ga^+, two electrons and a hole, 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 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 13ns in consistency with the observed time of 12ns.

Proposed research 04: Development of element technologies and elucidation of physics toward realization of silicon quantum bits

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 continued characterizing silicon double QDs coupled in series with the single-electron transistor charge sensor. We applied a positive voltage to the top-gate for inducing electrons to silicon layer and then measured the source-drain current while sweeping the two side gates. As a result, we obtained a honeycomb-like charge stability diagram, which is typical for double QDs coupled in series. 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 more negative voltages to the side gates, we realized pinch-off of two QDs. Next step is to study spin- and valley-related transport properties of few-electron silicon double QDs in detail and then to compare the characteristics with those of GaAs double QDs

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 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, "the fluctuation theorem" 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 "classical" regime. The aim of this project is to extend them to the quantum regime.

For now, we have theoretically analyzed several issues, which should be clarified in order for the verification of the quantum fluctuation theorem. For the problem, how to measure the "quantum" work 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 analyzed 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 analyze the environmental effect using the full-counting statistics and consider the experimental setups to test the quantum fluctuation theorem.

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)

Very recently, spin-photon entanglement, which is the first crucial step to realize the spin-spin entanglement of two remote devices, has been demonstrated by Prof. Yamamoto group (FIRST program) in a quantum dot coherently excited by short laser pulses. In this project, we aim to achieve the spin-photon entanglement in a compact and practical device based on an electrically excited quantum dot.

For demonstrating the spin-photon entanglement, coherent spin rotation is an important prerequisite. In an optically excited quantum dot, the spin is rotated by a combination of stimulated-Raman transitions and Larmor precession under an external magnetic field oriented in the Voigt geometry. On the other hand, in an electrically excited quantum dot, we suggest that a promising candidate for spin-controlled photon emission is two-electron spin system in a double quantum dot under an external magnetic field oriented in a Faraday geometry. A single electron transport measurement has demonstrated coherent spin rotation by rapid electrical control of the exchange interaction with the help of random hyperfine fields. The Faraday geometry allows for spin initialization. Our device is designed to generate entangled states between the frequency of an outgoing photon emitted from the double dot system and a two electron spin state. The two-electron spin states correspond to the final states after photon emission of X^{2-} exciton. Because the two-electron spin states are split by the exchange coupling, the photon will be frequency-entangled with the spin state of the remaining electrons. We have fabricated some prototype devices to achieve appropriate band alignment, effective gate operation, and efficient photon extraction.

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)

The primary energy conversion steps of photosynthesis involve a series of light-induced electron-transfer reactions which occur in specific membrane-bound proteins, the so-called reaction centers. A radical pair with a pure singlet state is created in the charge-separation. There are coherences between the eigenstates of the radical pair, which can 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. A lot of researcher has attracted how can quantum coherence last long enough to be useful in photosynthesis. High-frequency (>94GHz) time-resolved EPR is a powerful technique to detect entangled electron spins. 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. In our experiment, using the deuterated and ^{15}N-substituted cyanobacteria, its coherence time could be improved up to hundreds of nanoseconds. We are also constructing electrically detected EPR based on high-time resolution and high-frequency pulse techniques in order to realize manipulate 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. Recently, we have demonstrated electrically driven single photon emission by using single NV center in diamond at room temperature. Our results prove that it provides new opportunities for integrating single-photon sources based on diamond defects into electronic control circuitry and for spintronic applications for quantum communication and processing. Furthermore, we investigate the dynamics of electrical excitation. We continue the research for further development for electrical control of qubit by a NV center in diamond.