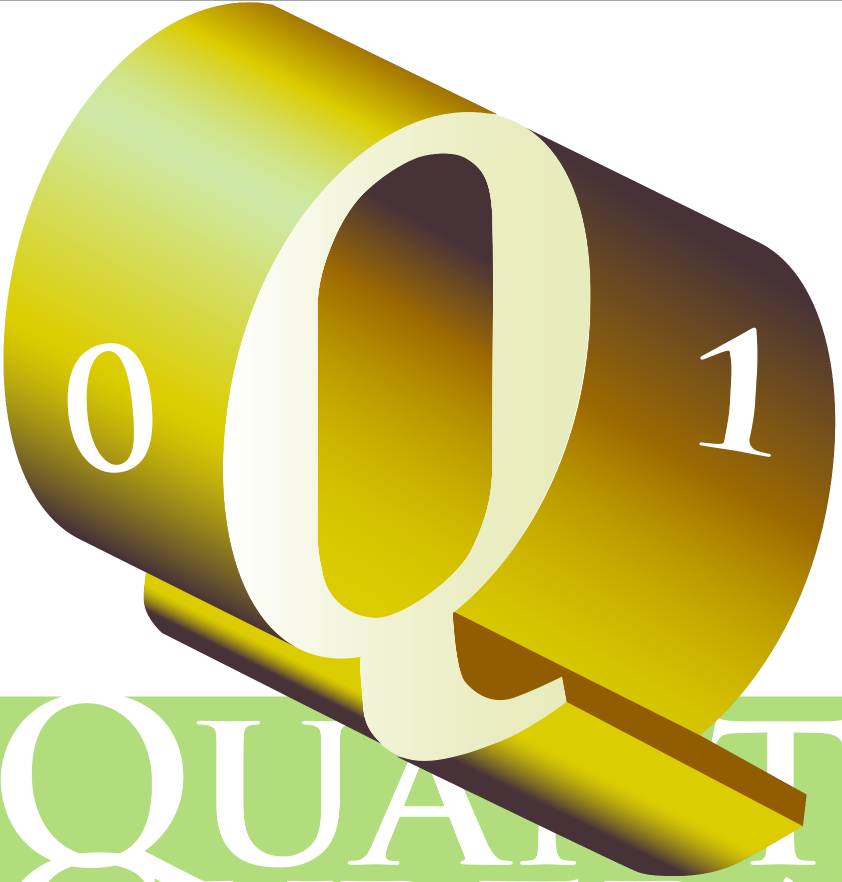

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Science Research Grants from the Ministry of Education, Culture, Sports, Science and Technology
— 2009 Grant-in-Aid for Scientific Research on Innovative Areas (Proposal-Based Research)

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

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Science Research Grants from the Ministry of
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「Quantum cybernetics — Interdisciplinary research on quantum control and its application to quantum computation」

5-year Research Summary

Research topic A: Solid-state device quantum cybernetics

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

During the 5-year period of the Quantum Cybernetics research, many important results were achieved.

The new field of quantum optics with superconducting artificial atom was pioneered. It is a field that has been dominated by interplay of natural atoms and photons, however, we have achieved many important results using superconducting artificial atom. As a solid state device, superconducting artificial atom has many advantages over natural atoms, such as freedom in design and means of control. In this research direction, we have demonstrated lasing [***Nature***, 449, 588, 2007], resonance florescence [***Science***, 327, 840, 2010], single atom quantum amplification [***Phys. Rev. Lett.*** 104, 183603, 2010] and other effects.

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. We demonstrated the CQPS, for the first time, in InOx nanowires [***Nature*** 484, 355 (2012)]. We also demonstrated the exponential dependence of the CQPS energy on its wire width [***Phys. Rev. B*** 88, 220506(R) , 2013].

We have developed low noise flux-driven Josephson parametric amplifiers (JPA) since 2008. Recently, we have incorporated the flux-driven JPA as a preamplifier in our setup for the dispersive readout for the superconducting flux qubit [***New J Phys.*** 16, 015017 (2014)]. This led to dramatic improvement of SNR and achieved single-shot readout and observation of quantum jumps [***Appl. Phys. Lett**.* 103, 132602(2013)]. We also reconstructed the Wigner function of squeezed vacuum in JPA, squeezed thermal and squeezed coherent sates with our dual-path method [***New J Phys.*** 15, 125013 (2013)].

We also carried out theoretical study of superconducting qubits, resulted with many fruitful outcomes. The total number of the paper published was about 170, among them, 13 papers were selected as the top 1% papers.

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

This research team aims to establish the control technology, communication technology and measurement technology of the quantum information realized in semiconductor nanostructure having high design flexibility. [Control] We focused the quantum information realized with electron spins in quantum dots and investigated the properties and its controllability of spin-orbit interaction. Moreover, using micromagnet technology, we have realized single- and two-qubit operations by fast modulating gate operations. We are continuing our efforts to realize qubit system more than two. The main obstacle of the coherence of electron spin is the nuclear spins. We have argued the details of the dynamical nuclear spin pumping and compared the experimental hysteresis behaviors. [Transfer] Designing one-dimensional electron wave-guides, we have demonstrated universal single operations orbital-qubit. Moreover, for better coherence of electrons, encapsulated flying qubit realized by surface acoustic wave had been demonstrated, which enables coherent transfer of electrons (spins) between remote quantum dots. [Measurement] Charge detector realized in the semiconductor devices has now fast operating speed and very high sensitivity. In the quantum capacitance measurement, beside usual Landau-Zener tunneling effect, a new characteristic frequency was observed, which is related to the coherent coupling between electron spins and nuclear spins. Precise measurement of system charge state unavoidably induces back-action to the system. In contrast to the conventional quantum point contact based charge detector, we have shown that the quantum dot based charge detector has very much different back-action to the system. Throughout these five-year collaborations within/between the team members, we have indebt for valuable new ideas and findings.
We sincerely appreciate to all the people, especially to our project manager, Dr. Jaw-Shen Tsai.

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)

Molecular Spin Quantum Control research group has been studying control of nuclear and electron spins in molecules for five years to establish a new research area "Quantum Cybernetics". We have studied two approaches; "designing" the Hamiltonian of spin system by designing and synthesizing molecules or supra-molecules, and, "modifying" the Hamiltonian of spin system by designing the pulse waveforms of the resonant magnetic field. For the latter purpose, we have studied how to apply resonant magnetic field strongly and precisely to spins and how to design waveform of the resonant magnetic field. We have also studied the functionalities to be realized by controlling molecular spins; initialization, amplification, decoupling, selective averaging, coupling with other quantum system, quantum simulations, topological quantum error correction, and spin squeezing. We list the methodologies we have obtained through our research below.

We have developed an efficient numerical optimization method for designing magnetic resonance pulse waveforms by unifying the average Hamiltonian theory and the optimal control theory, and designed high-performance decoupling and selective averaging pulse waveforms. We have realized scalable spin amplification by globally controlling more than a hundred spins in molecular crystal, and also realized quantum non-demolition spin amplification by designing and synthesizing a custom molecule. We have achieved the highest nuclear spin polarization at room temperature by dynamic nuclear polarization using photo-excited triplet electron state by regioselective deuteration of molecules. We have designed and synthesized molecules with triplet ground state suitable for coupling to superconducting qubit. We have proposed a method for surface code quantum error correction without projective measurement, which are suitable for molecular spin qubits.

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.

Firstly, we successfully achieved the results such as the realization of the single layer of quantum gas of ytterbium (Yb) atoms and the loading into the 2D and 3D optical lattice, development of a fluorescence imaging system with the sensitivity of almost one atom, construction of magnetic resonance imaging system with the spatial resolution of almost one optical lattice constant, development of optical spectral imaging method for a 2D quantum gas, and the ultra -stable excitation laser with the linewidth of about 3Hz.

In addition, we have achieved the results on quantum simulation such as the creation of strongly –interacting Bose-Fermi mixed Mott insulators, creation of SU(6) Mott insulator by Pomeranchuk cooling, development of site-resolving laser spectroscopic method for superfluid-Mott insulator transition, realization of Alkali-Yb mixed atomic quantum gases and the loading into 3D optical lattice for the impurity quantum simulator, observation of magnetic Feshbach resonance between different electronic orbitals and the direct optical creation of Feshbach molecules, development of optical Feshbach resonance method for controlling s-wave and p-wave inter-atomic interaction, implementation of spin-orbit interaction, realization of optical Lieb lattice, precise measurement of collisional stability of metastable states of Yb atoms, and creation and observation of long-lived molecules in a 3D optical lattice.

Furthermore, we could successfully create spin-squeezed states of a nuclear spin ensemble of cold Yb atoms by quantum-nondemolition measurement, and achieved its fast quantum feedback control.

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

We developed a multi-segmented planar trap and performed transportation of Ca^+ ions between different trapping regions by controlling applied voltages. This technique enables us to control a large number of ions in scalable quantum information processing. Based on this trap design, we fabricated a novel trap for generating spin-spin-interaction via Coulomb interaction, which is useful for gate operation and quantum simulation. A high magnetic field gradient of several ten T/m at trapped ion is expected by integrating small permanent magnets in the planar trap, which realizes a large spin-spin interaction. We are currently measuring the magnetic field at several positions by observing Ca^+ ion spectra. As a novel system of trapped ions and light, we proposed coupling trapped ions and evanescent light of an optical nanofiber. We are performing evaluation of electric characteristics of the optical nanofiber with trapped microparticles.

In experiments of quantum gate and entanglement generation for quantum information processing, we can perform such experiments in a robust manner by using adiabatic or geometrical methods. We succeeded in entanglement generation with 2 to 4 ions using adiabatic methods. Moreover, we performed for the first time single qubit operations using geometric methods with adiabatic control. The latter can be a building block for holonomic quantum computation which realizes quantum computation by means of purely geometric phase factors. As an approach for quantum simulation, we have performed experimental demonstration of the Jaynes-Cummings-Hubbard (JCH) model for the first time using two trapped ions. The JCH model is a variant of the Hubbard model that is a model for interacting electrons in solid state systems, and is related to the Bose-Hubbard model which has been extensively studied using neutral atoms. We have realized a quantum rotor by using three trapped ions and by cooling their rotational motion to its ground state. We have shown that the rotor transfer itself between macroscopically distinguishable two configurations via a tunneling effect, and that it can be controlled by the Aharonov-Bohm effect originated from an applied magnetic field. In addition, we have continuously addressed such subjects as narrowing of the excitation laser, and have succeeded in stabilizing a ring titanium sapphire laser at 729 nm to Hertz-order linewidth.

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.

As a result of novel interdisciplinary collaboration, we have succeeded in the realization of the world's first `adaptive quantum state estimation [1],' which was mathematically proposed by Prof. Fujiwara's group. This method can be used to estimate the state of polarization of faint light most accurately and will be also useful in other areas including life science. We also realized a novel method to distinguish a small deviation of quantum states harnessing new concept `data mining' with Prof. Washio's goup[2]. About the photonic quantum circuit for quantum control, we have realized photonic quantum circuit for heralded controlled-NOT operation for the first time [3].

For the interface between photons and artificial atoms, we have realized a highly efficient coupling of photons from a single quantum dot [4] and a diamond nano-crystal [5] into a nano optical fibers. We also advanced collaboration with Prof. Urabe's group and Prof. Mizuochi's group on the interface of photons with ions and diamond NV centers respectively.

We are also very grateful for the support from Japan Society for the Promotion of Science, and to related collaborators and all persons concern.

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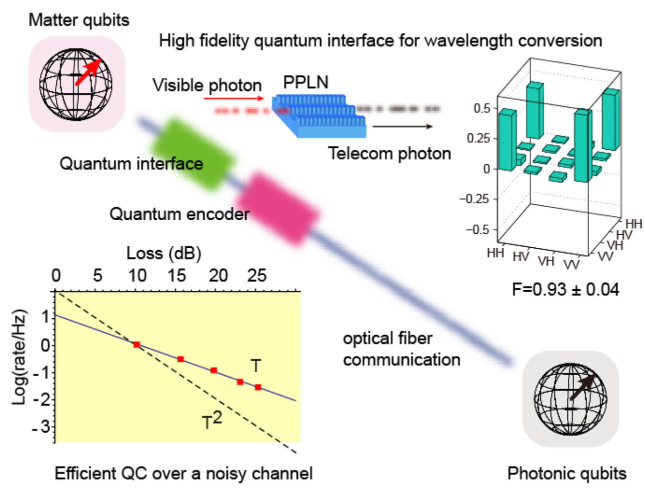
Project Leader: Masato Koashi (Professor, Photon Science Center of the University of Tokyo)

－Manipulation of light as a carrier of quantum information in communication



Among various physical systems, photons play a unique role as the only physical system that can be used as a carrier of quantum information in the communication between two remote parties. This means that any physical system must be coherently connected to photons for communication, and the issues occurring during the communication must be solved by exploiting the properties of photons. Under such a motivation, we have developed quantum interface to change the wavelength of the photons while preserving quantum properties of light and the quantum information it carries, and achieved a conversion fidelity over 90%. This interfeace is a vital tool when one wants to transmit the quantum information in various physical systems to a remote place through telecom fibers. We have also developed a very efficient method of protecting quantum information from collective noises in communication channels, exploiting the bosonic nature of photons. Our experimental demonstration has shown that the new method achieves an efficency two orders of magunitude higher than the conventional method.

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 focused on complex, realistic hardware models for quantum repeaters. We developed a design using three types of qubits. Nitrogen vacancy (NV) centers in diamond as the transceiver qubits, superconducting flux qubits for logic elements, and bismuth in silicon centers as long-term memory. Other researchers have designed NV-flux heterogeneous hardware with a focus on computation, in which the rate of interaction between the two qubits is of primary importance, leading to the use of a large number of NV centers. In our design, the focus is on minimizing the stray thermal excitations in order to increase the fidelity of the photons emitted by the NV center qubit. Interaction rate is less important, allowing us to reduce the number of NV centers used. Simulation of the complete design is still pending.

We have also studied double-selection purification, and found that it is an appropriate tool for heterogeneous hardware. We have proposed a more complete network model, featuring well-defined protocol roles based on classical network design principles.

Proposed research 02: Classical Compilers for Topological Quantum Information Processing

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

During the quantum cybernetics project we have made great advances in the development of classical optimisation and compilation techniques for large scale computation. This includes the first accurate resource estimation for topological quantum algorithms, published in Nature (Communications), the development of the framework for topological circuit synthesis and verification published in the IEEE conference on Nanotechnology and the IEEE conference on Design and Testing in Europe. We have successfully implemented an alpha version of a game called meQuanics to offer the general public the chance to help us optimise quantum algorithms and we have given numerous presentations, including a Google TechTalk in 2013 and an an invited special session on quantum compilation at the 2012 IEEE Asian Test Symposium. We have successfully laid the groundwork for significant advances in quantum compilation and optimisation which is desperately required given the accelerated advance of Hardware systems for quantum computation.

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)

Spins in semiconductors are expected to be used for quantum information processing as highly integrated quantum bits in the solid state and quantum memory. Long spin coherence of localized electrons in semiconductors allows the fast and multiple quantum operation and long spin quantum memory well matching light, flying qubit, for long-distance quantum communication. In this study initialization and relaxation of spins in localized electrons were studied through coherent spin manipulation of trions by ultrashort light pulses.

Time-resolved Kerr rotation spectroscopy was applied to observe coherent spin precession of electrons in InP quantum dots doped by one electron and Ga-doped ZnO and the initialization, coherent spin precession and dephasing of the spins were studied.

In InP quantum dots doped by one electron, long spin coherence time of T_2*=2ns restricted by the fluctuating nuclear magnetic field produced by ^{115}In and ^{31}P was observed. Under the weak excitation, fast spin dephasing arose due to its coherent radiation emission newly proposed. 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 observed the long spin coherence time, T_2*=12ns, of localized electrons in ZnO under the trion resonant excitation of sharp D^0X formed by an electron doped by a Ga donor, Ga^+ and a photogenerated electron-hole pair. Small natural abundance (4.1%) of ^{67}Zn (I=5/2) gives the electron spin relaxation time of 13ns in consistency with the observed time of 12ns. In both InP quantum dots doped by one electron and Ga doped ZnO, electron spins are initialized by the formation of the electron-trion coherent superposition resonantly excited by the laser pulses.

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 designed and fabricated silicon QD devices and succeeded in fabricating stable silicon QD devices in a few-electron regime. In addition, we performed high-frequency voltage operation for spin manipulation in silicon QDs.

We studied silicon double QDs coupled in series with a QD charge sensor by transport measurement as well as by simulation. Devices are lithographically-defined silicon QDs with the top gate (TG) for tuning carrier density and the side gates for controlling QD-potentials. A non-doped silicon-on-insulator (SOI) wafer instead of a heavily-doped n-type SOI wafer was used in order to avoid localized states due to fluctuation of dopant potentials. By simulation study, we analyzed the local magnetic field generated by the ferromagnets integrated in the vicinity of the silicon QDs for controlling electron spins. Frequency of electron spin resonance is estimated as faster ~1 order of magnitude than similar QDs device in GaAs. By measuring the double QD device with ferromagnet, we observed blockade phenomena of inter-dot tunneling. Magnetic field dependence of the leakage current in the blockade region indicates that inter-dot tunneling is suppressed by valley blockade. By applying microwave, we observed the current peak probably due to electron spin resonance, at finite magnetic field where the valley blockade is lifted

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, “the fluctuation theorem” has been discovered. The theorem is formulated based on the distribution of 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, these experiments were still in the “classical” regime. The aim of this project is to extend them to the quantum regime.

The fluctuation theorem, which is a simple detailed balance relation for the probability distribution out of equilibrium, is nontrivial when we try to demonstrate experimentally in the quantum regime. A method to measure the full probability distribution and effects of hidden environment are yet to be investigated. In this project, we theoretically investigate (1) a measurement method for the probability distribution of the quantum work, (2) effects of external environments and (3) an experimental setup to demonstrate the quantum fluctuation theorem.

For the first topic (1), we have proposed to use a classical LC circuit to measure the work done to a quantum conductor. For the second topic (2), we analysed the full-counting statistics of a quantum dot coupled to a single-mode phonon environment. We also investigated a temperature probe terminal as an environment. We have revealed that the environment will not violate the fluctuation theorem if the system and the environment reach a steady state. For the third topic (3), we are developing the full-counting statistics of the heat emitted to a bath coupled to a two-level system. We are now investigating the fluctuation theorem and the selection of states and 1/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 have fabricated a quantum dot LED with a side-gate, which is designed to control the electronic states as in single electron transistor. The device is packaged in flip-chip packages to extract photons from bottom (substrate) side because the top surface of the device is covered by electrodes for the current injection and the side-gate. The position of the pillars with diameters of 300-1000 nm is obtained by measuring reflectance using 1.5 μm laser for which the substrate is transparent. By using the technique, we have successfully observed a single dot electroluminescence from the side-gate structure.

The device can be applied for electrically driven quantum repeater by producing quantum entanglement between the spins of two remote devices. The spin-spin entanglement is expected to be achieved by the interference between two photons generated from each of spin-photon entangled states in the devices. One of the main obstacles for the electrically driven remote entanglement is a jitter problem for electrical injection of carriers. We have proposed a way to reduce the jitter using double dot system in this device structure. A preparation of initial emission state through indirect-direct exciton transition can reduce the jitter. Future fast gate pulse operation of the indirect-direct transition allows for quantum control of the population via a Landau-Zener-type process towards realizing more complicated hybrid quantum system.

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

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

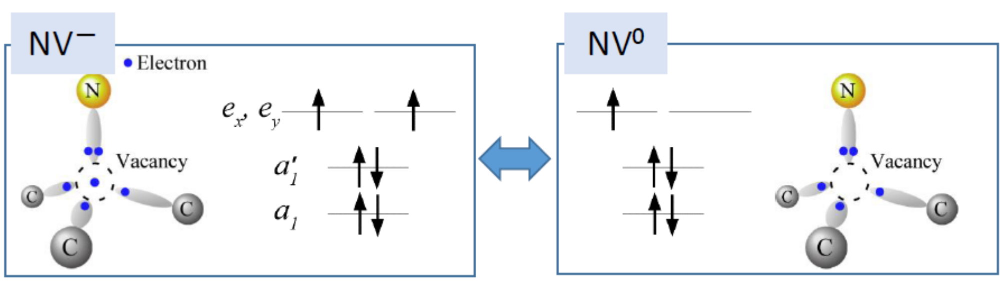
Several research groups have suggested that long-lived coherent dynamics may play an important role in photosynthetic highly-efficient energy transfer. In addition, very recently, synthetic heterodimer systems, which show long-lived electronic coherence in photo-excited states, were engineered as a model system to investigate that the coherence may increase energy transfer efficiency relative to strictly incoherent transfer mechanisms. We have also demonstrated that correlated radical pairs in a pure singlet state, which are generated by light-induced electron-transfer reactions in the primary energy conversion steps of photosynthesis, have a relatively long coherence even at room temperature. Our high time-resolution EPR (Electron Paramagnetic Resonance) experiments showed that the coherence time in the correlated radical pairs is mainly influenced by surrounding nuclear spins. EPR measurements performed for one of the two different electron-transfer pathways existing in each protein, indicating that the coherence time can be prolonged up to 1.2 μs from 600 ns at 100K by performing deuteration and ^{15}N-substitution. On the other hand, it was demonstrated that the spin pairs in the other electron-transfer pathway have half of the coherence time, though the chemical circumstances in the two pathways are almost identical. The result indicated that there exists another mechanism to attain the long-lived coherence even in the biological environment composed of thermally fluctuating water and amino acids. Engineering a model system using thiophene oligomers employed in solar cells as well as EPR characterization are in progress.

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.

Apart from applications in classical information processing devices, the electrical control of atomic defects in solids at room temperature will have tremendous impact on quantum devices that are based on such defects. In this study, we demonstrate the electrical manipulation of individual prominent representatives of such atomic solid-state defects, namely, the negative charge state of single nitrogen-vacancy defect centers (NV^-) in diamond. We experimentally demonstrate for the first time deterministic, purely electrical charge state initialization of individual NV centers. (Figure) [1] The NV centers are placed in the intrinsic region of a p-i-n diode structure that facilitates the delivery of charge carriers to the defect for charge state switching. The charge state dynamics of a single NV center were investigated by time-resolved measurements and nondestructive single-shot readout of the charge state. Fast charge state switching rates (from negative to neutrally charged defects), which were greater than $0.72 \pm 0.10\ \mu s^{-1}$ were realized. Furthermore, in no-operation mode, the realized charge states were stable for presumably much more than 0.45 s. We believe that the results obtained are useful not only for ultrafast electrical control of qubits, long T_2 quantum memory, and quantum sensors associated with single NV centers but also for classical memory devices based on single atomic storage bits working under ambient conditions.



Figure, Schematic representation of the negative and neutral charge state of nitrogen-vacancy defect centers (NV^-, NV^0), respectively.

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