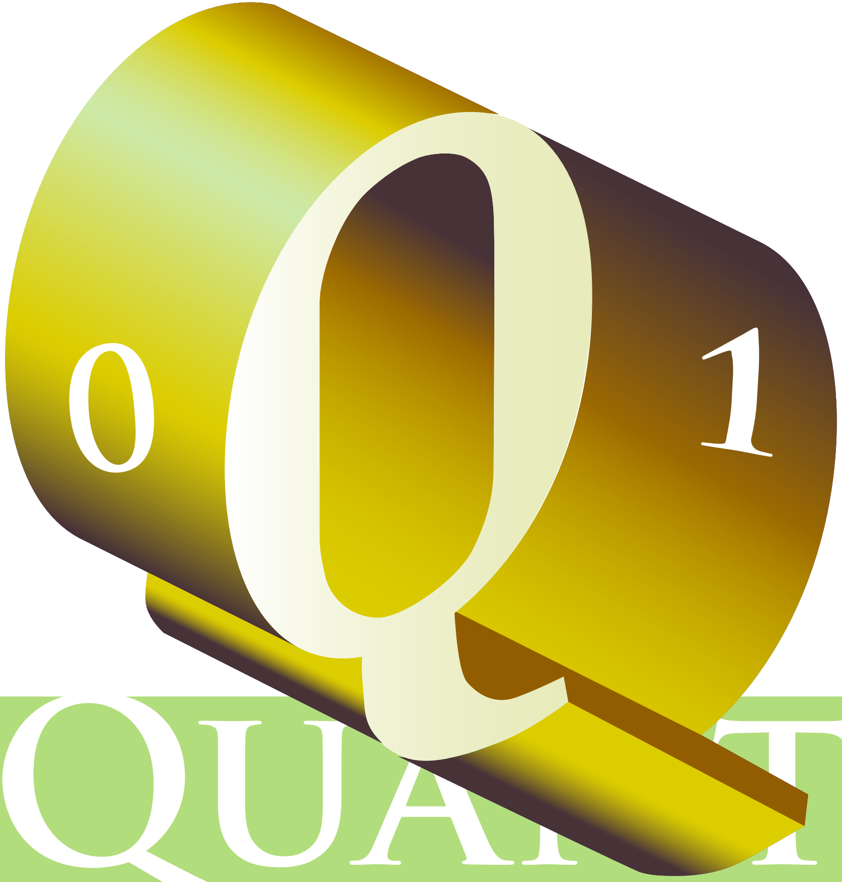

NEWS LETTER

Vol.05

November 18, 2011

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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Research topic: Solid-state device quantum cybernetics
Proposed research A01: Study of superconducting quantum cybernetics

Project Leader: Jaw-Shen Tsai (Team Leader, RIKEN; Senior Researcher, NEC Nanoelectronics Laboratory)

Coherent quantum phase slip - Josephson effect's complete conjugate

We are carrying out studies of coherent quantum phase slip (CQPS) effect which is the exact quantum mechanical conjugate to the Josephson effect. It is a phenomenon involving coherent tunneling of magnetic flux across a thin superconducting wire, just like tunneling of Cooper-pair across thin insulator in the Josephson tunnel junction. The existence of CQPS was recently proposed theoretically. The tunneling probability of CQPS is proportional to sin(2q/e), where q is the difference in charge between the two ends of the thin wire.

This is analogous to the tunneling probability of the Josephson junction that is proportional to sin(f) where f is the phase difference in the macroscopic wave functions between the two sides of the junction. By utilizing CQPS, it is expected that many unique quantum devices conjugate to the Josephson devices can be realized. For example, quantum current standard conjugate to the Josephson voltage standard, superconducting quantum charge detector conjugate to the superconducting quantum flux detector (SQUID) and so on should be realized.

We have initiated experiments toward the detection of CQPS by utilizing several superconducting materials.

Recently, in spectroscopy of superconducting circuits involving thin wire structures, we have detected first evidences of the CQPS.

Proposed research A02: Study of the control, measurement, and transfer of quantum information using a semiconductor nanoassembly

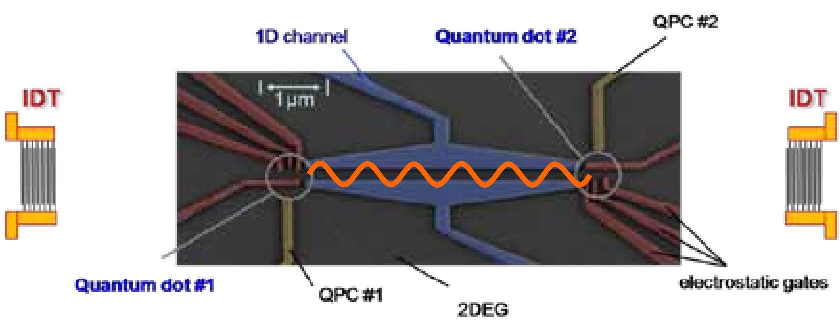
Project Leader: Yasuhiro Tokura (Executive Manager, NTT Basic Research Laboratories)

We have fabricated inter-digital transducer on GaAs substrate to generate surface acoustic wave (SAW). We irradiated SAW to a depleted quantum wire and observed the quantized wire current, indicating that SAW is actually accompanying electrostatic potential wave with one electron in each wave. Then we have succeeded for the first time in confirming a single electron confined a quantum dot being transferred to another quantum dot via one-dimensional wave-guide by SAW. This is the fundamental technology to build quantum network between quantum dots via wave-guides.[1]

We have accurately estimated the strength of the spin-orbit interaction (SOI) by measuring differential conductance of the current through an InAs quantum dot between source and drain contacts. Then we have demonstrated for the first time that the strength of SOI can be largely controlled by the side-gate. This is an important result since we can fast coherent control of electron spin by AC electric field with large SOI, while we can have a long coherence time of electron spin by reducing the strength of SOI.[2]

[1] S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A.D. Wieck, L. Saminadayar, C. Bäuerle, and T. Meunier, Nature, 477, 435 (2011)

[2] Y. Kanai, R.S. Deacon, S. Takahashi, A. Oiwa, K. Yoshida, K. Shibata, K. Hirakawa, Y. Tokura, and S. Tarucha, Nature Nanotechnology, 6, pp511–516 (2011).



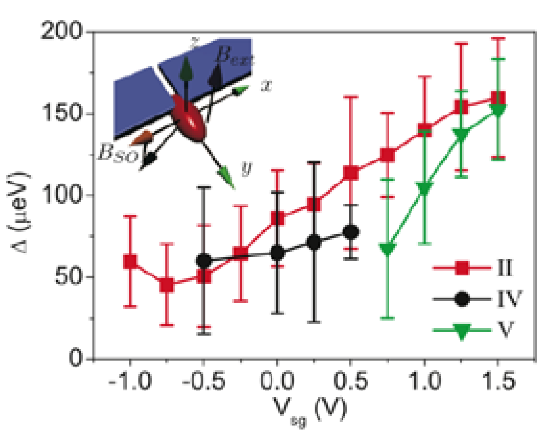
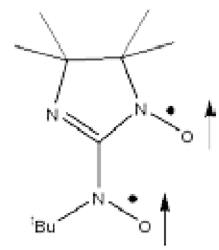


Figure (upper) Two quantum dots are coupled with a depleted wave guide. SAW transfers single electron between these quantum dots. (lower) The strength of SOI, Δ, controlled by a side gate. Inset shows the InAs quantum dot (red) sandwiched with electrodes.

Research topic: Molecular spin quantum cybernetics
Proposed research B01: Molecular spin quantum control

Project Leader: Masahiro Kitagawa (Professor, Graduate School of Engineering Science, Osaka University)

Synthetic electron spin qubits for the hybridization/coupling with superconducting qubits



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Recently, the hybrid superconducting qubit systems coupled with ensemble spin qubits using ruby (Al_2O_3:Cr^{3+}) or N-V center of diamond have been reported [1-3]. In macro/microscopic hybrid systems, rapid quantum operations are made by the sperconducting qubits and the quantum informaton is stored in the spin qubits with the relatively longer decoherence time. Highly compact and chemically stable nitoroxide-substituted iminonitroxide **1** was designed and synthesized[1], which serves for not only a building block for organic molecular magnetic materials but also a molecular electron spin-qubit for quantum memory coupled with the circuit of superconducting qubits. Synthetic electron spin species **1** is in the triplet ground state with a large zero-field splitting constant (*D* value) of −0.0639 cm^{-1}(= -1.92 GHz), the second largest among the nitroxide triplet systems documented so far. The X-ray crystal structure analysis was completed, and both the theoretical zero-field splitting tensor and g tensor of **1**, calculated by sophisticated quantum chemical methods, agreed with the experimental ones. The use of the triplet species **1** allows us to tune the fine-structure energy with or without the static magnetic field.

[1] D.I. Schuster, A.P. Sears, E. Ginossar, L. DiCarlo, L. Frunzio, J.J.L. Morton, H. Wu, G.A.D. Briggs, B.B. Buckley, D.D. Awschalom, and R.J. Schoelkopf, *Phys. Rev. Lett.* 2010, 105, 140501.

[2] Y. Kubo, F.R. Ong, P. Bertet, D. Vion, V. Jacques, D. Zheng, A. Dreau, J.-F. Roch, A. Auffeves, F. Jelezko, J. Wrachtrup, M.F. Barthe, P. Bergonzo, and D. Esteve, *Phys. Rev. Lett.,* 2010, 105, 140502.

[3] X. Zhu, S. Saito, A. Kemp, K. Kakuyanagi, S. Karimoto, H. Nakano, W.J. Munro, Y. Tokura, M.S. Evertitt, K. Nemoto, M. Kasu, N. Mizuochi, and K. Semba, *Nature*, 2011, 478, 221-224.

[4] S. Suzuki, T. Furui, M. Kuratsu, M. Kozaki, D. Shiomi, K. Sato, T. Takui, and K. Okada, *J. Am. Chem. Soc.* 2010, 132, 15908-15910.

Research topic: Atomic and ionic system quantum cybernetics
Proposed research C01: Quantum control using cold atoms

Project Leader: Yoshiro Takahashi (Professor, Atomic Physics, Kyoto University Graduate School of Science)

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.

In the effort towards realization of optical lattice quantum computer, we successfully load the Bose-Einstein condensate created in a thin glass cell region into a 3D optical lattice, and investigated the superfluid-Mott insulator transition by high-resolution laser spectroscopy, which turns out to offer very important insights to the quantum critical behavior. In addition, we analyzed the spectroscopic data on the resonance shifts of doubly and triply occupied sites based on the formalism of so called confinement-induced resonance, and we found this corresponds to a new mechanism of control of inter-atomic interaction different from the Feshbach resonance. Furthermore, we found the unique possibility to study the universal three body bound states with this resonance shifts.

In the quantum simulation using cold atoms in an optical lattice, we successfully studied Pomeranchuk cooling by direct comparison of the cases of SU(2) and SU(6) with Yb atoms, and found a significant difference between the two cases, highlighting the importance of the spin degrees of freedom.

Moreover, while we realized quantum feedback control of nuclear spin ensemble, and successfully created a squeezed spin state deterministically in spite of using the measurement process, we could also perform multiple feedback cycles and observe quantum trajectories. We also discuss that this process corresponds to the quantum version of Maxwell demon.

Proposed research C02: Quantum information processing using an ion trap system

Project Leader: Shinji Urabe (Professor, Osaka University Graduate School of Engineering Science)

In the geometric-phase quantum gate that we reported previously, we used sublevels in a metastable excited state of calcium ions as the qubit states. Recently we extended this scheme to one employing an optical-transition qubit which is more widely used in quantum information processing experiments using trapped ions. To realize this, we used a radio-frequency (RF) transition in place of one of the relevant three transitions. We performed X- and Z-rotation gate operations in the Bloch sphere, and observed population oscillation by varying the rotation angles with visibility ~0.9, which is similar to those observed in the case of using only optical transitions. Furthermore, for a similar physical system, we studied the possibility of generating entangled states of RF qubits directly by combining RF dressed states and entangling operations.

Research topic: 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)

Realization of a Knill-Laflamme-Milburn controlled-NOT photonic quantum circuit combining effective optical nonlinearities

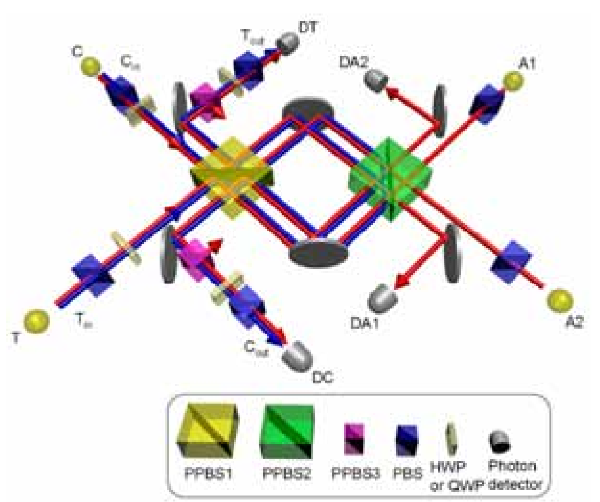
Photons have excellent controllability and are easily interfaced with naturally occurring atoms and molecules as well as artificial atoms. Our planning team aims to control photonic quantum state and explore new concepts in terms of quantum cybernetics. We also aim to achieve quantum state control between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

The lack of interaction between photons was a major obstacle for quantum information science. In a breakthrough, Knill, Laflamme and Milburn (KLM) showed that the "non-linear switch" working at single photon level can be realized using the quantum interference on a half mirror. They also proposed a heralded controlled-NOT (CNOT) gate for scalable quantum computation using a photonic quantum circuit to combine two such nonlinear elements. However, the KLM CNOT gate was not realized for 10 years after the proposal because of the technical difficulties: the high quality quantum interferences on half mirrors and the optical path lengths alignment with an accuracy of 1/(1 million) meter.

We improved the performance of our photon source and developed a stable architecture combining a ultra-Sagnac interferometer and special half mirrors (Figure). Then, we demonstrated the KLM CNOT gate for all-optical quantum computation. The average gate fidelity we obtained was 0.82 which proved the high quantumness of our gate. This result should be useful for on-demand entanglement generation and purification. Optical quantum circuits combining giant optical nonlinearities may find wide applications in quantum information processing, communication and sensing.

This work was in collaboration with Prof. Jeremy L. O'Brien in Bristol Univ. and Holger F. Hofmann in Hiroshima Univ.

[1] R. Okamoto, J. L. O'Brien, H. F. Hofmann, S. Takeuchi, Proc. Natl. Acad. Sci. 108, 10067 (2011).

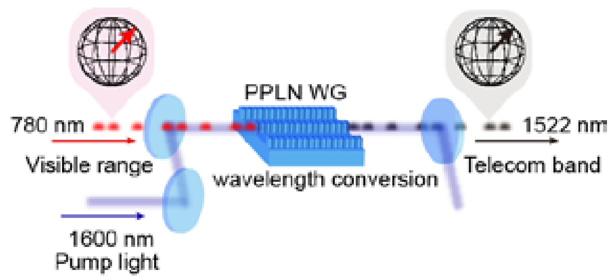


Schematic of experimental setup

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

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

Quantum interface for converting quantum information into telecomm-band photons



A lot of emerging techniques for storage and manipulation of quantum information tend to be very selective in the wavelengths, which are often in the visible range, when they are linked to optical carriers of information. On the other hand, near-infrared photons in telecommunication bands are required for long-distance quantum communication, which necessitates an optical quantum interface enabling the transfer of quantum information across the gap in the wavelengths. We developed a quantum interface of frequency down-conversion from visible to telecom bands by using difference-frequency generation (DFG) in a nonlinear crystal, and demonstrated conversion of a pico-second visible photon at 780 nm to a 1522-nm photon. Intensity correlation measurement on the converted light confirmed that the non-classical nature of the input single photon is retained over the down-conversion process. We further investigated the case where the input photon is entangled to another photon and confirmed that the entanglement survived after the down-conversion, which shows that quantum information is really transferred in our interface. The DFG process with the quasi-phase-matching techniques allows us to convert a wide range of visible wavelengths to telecommunication ones with a wide acceptable bandwidth, which makes it a useful tool toward realization of long distance quantum communication.

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2010 Selected research subjects and project managers

Proposed research 01: New development of quantum estimation theory in quantum cybernetics

Project Leader: Akio Fujiwara (Professor, Department of Mathematics, Osaka University)

In collaboration with Takeuchi group (Hokkaido/Osaka University), we are demonstrating experimentally the strong consistency and asymptotic efficiency in an adaptive quantum estimation scheme (J. Phys. A: Math. Gen., **39** (2006) 12489). Based on the experimental setup reported in the previous News Letter, we have made a series of quantum optical experiments to estimate the true value ϕ_0 of the direction of photon polarization for $\phi_0 = 0°, 30°, 60°, 78.3°$, and have given a statistical analysis of the experimental data. We found that 1) according to the χ^2-test, the distribution of the estimated values seemed to converge to a theoretical normal distribution even for a rather small number n of photons, say $n = 300$ that 2) the estimated value of the variance was in good agreement with the true value, i.e., the inverse of the Fisher information of the model for each ϕ_0, and that 3) the estimated value of the angle parameter deviated from the true value ϕ_0 by an angle between ±0.17 ～ ±0.43 degrees. Since the width of an estimated confidence interval (99% significance level) is narrower than ±0.1 degrees, the last observation suggests the existence of a systematic error in the experiment. Currently we are devoting ourselves to resolve this difficulty.

Proposed research 03: Theoretical study on quantum coherence generating from coupling between quantum dot and superconductor

Project Leader: Michiyasu Mori (Senior Assistant Researcher, Japan Atomic Energy Agency)

In this project, we have studied quantum coherence generated from coupling between the phase degree of freedom of superconducting order parameter (Josephson phase) and electron spins, bearing several applications such as precise measurement on magnetism in mind. From this viewpoint, the superconductor/ferromagnet/superconductor junction, called ferromagnetic Josephson junction (FJJ), is also one of important target, since it has analogy of spins in the quantum dot, and can be applied to measure the magnetic domain wall motion used in the magnetic random access memory (MRAM). The equivalent circuit model composed of Josephson current, resistance, and condenser is useful to study the current-voltage (I-V) characteristics in FJJ. So far, we have shown that the ferromagnetic resonance produces the stepwise I-V characteristics in FJJ by supposing a single magnetic domain in the ferromagnet. The stepwise structure originates from the coherent motion of electron spins and Josephson phase[1]. The damping factor on each degree of freedom appears in the I-V characteristics differently[2]. On the other hand, it becomes important to measure precisely the magnetic domain wall motion. However, the domain wall motion driven by current or magnetic filed is quite complicated[3], and must be measured precisely by some experimental techniques. Hence, we have examined to extent our previous results into the FJJ with the magnetic domain wall as shown in Fig. 1. By adopting a simple model on the magnetic domain wall, we have successfully obtained an analytical formula for the Josephson current[4]. Now, we try to solve numerically the equivalent circuit model including our analytical formula, and to find conditions in which the I-V characteristics shows some special features such as stepwise ones. In the remaining period of this project, we will try to find a way to control a quantum phase coherence generated in the hybrid system of superconductor and quantum dot.

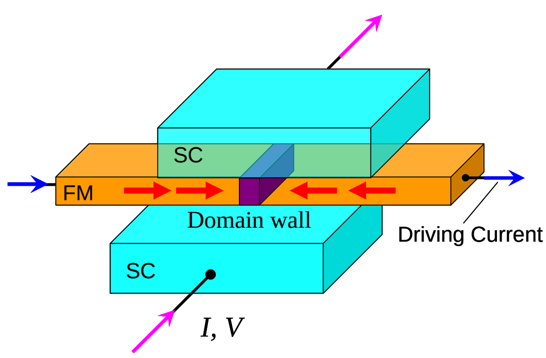

Figure 1

[1] S. Hikino, M. Mori, S. Takahashi, and S. Maekawa, Supercond. Sci. Technol. 24, 024008 (2011).

[2] S. Hikino, M. Mori, S. Takahashi, and S. Maekawa, J. Phys. Soc. Jpn, 80, 074707 (2011).

[3] S. S. P. Parkin, M. Hayashi, and L. Thomas, Science 320, 190 (2008).

[4] M. Mori, S. Hikino, W. Koshibae, and S. Maekawa, in preparation.

Proposed research 04: Study of single NV center in diamond toward scalable multi-qubit system

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

In this project, we develop the single NV center in diamond toward the multi-qubits. By using the confocal laser scanning microscopy combined with magnetic resonance system, we can control and optically detect the single spin. So, it is expected as good quantum bit system.

Recently, we have demonstrated strong coupling between a solid-state quantum processing unit (a flux-qubit) and a dedicated quantum memory (NV centers in diamond) [1]. These results indicate that quantum information manipulated in flux qubits can be stored to and retrieved from an ensemble of NV centers. A quantum memory is an essential component for quantum communication and information processing. Our work demonstrated that diamond is a promising candidate for a future quantum memory. This is a significant step forward in the development of a quantum computer and additionally to an interface between the microwave and optical worlds.

This work has been realized at NTT Basic Research Labs in cooperation with National Institute of Informatics and with us (Osaka Univ.).

[1] X. Zhu, S. Saito, A. Kemp, K. Kakuyanagi, S. Karimoto, H. Nakano, W. J. Munro, Y. Tokura, M. S. Everitt, K. Nemoto, M. Kasu, N. Mizuochi, K. Semba, "Coherent coupling of a superconducting flux-qubit to an electron spin ensemble in diamond" ***Nature***, 478, 221-224 (2011).

Proposed research 05: <u>Manipulation of electron spin and nuclear spins in hetero-g-factor double quantum dot</u>

Project Leader: Keiji Ono (Low Temperature Physics Laboratory, RIKEN)

Spin blockade with 3 electron spins

Spin blockade (SB) has been used to polarize and detect nuclear spins in quantum dots. In double dot system such as source-dot1-dot2-drain, SB manifest itself as one electron on each dot whose spins are parallel (spin triplet) each other. The source-drain current is blocked unless the spin-state changes. In order to the current to flow, an electron in the dot1 has to move to the dot2, shearing the same site of dot2. Because the only antiparallel spin (spin singlet) is allowed for this state due to Pauli's exclusion principle, current is blocked as soon as parallel spin is injected to dot1 from the source.

This can be, although for only two spins, a unique method to generate polarized spins. SB mechanism captures the preferred spins in the dots from the current of unpolarized spins, and unneeded spins are released to the drain, and leads to local "ferromagnet" in non-equilibrium steady state. There are no needs for electron-electron interaction (necessary for ordinary ferromagnetic state), or injection of spin angular momentum from outside of the system (necessary for optical pumping or spin injection). Can we make this "catch-and-release" ferromagnet for larger number of electrons? Yes, in principle it is possible to align N electrons if we have properly controlled N quantum dots connected in series. Reentry we have realized the three electron-spins (spin quartet) catch-and-release ferromagnet. Instead of using 3 quantum dots, we used a different orbital state of dot2 of the double dot and use it as a three-site system. We also find the interaction between the three electron spins and nuclear spins in the quantum dots.