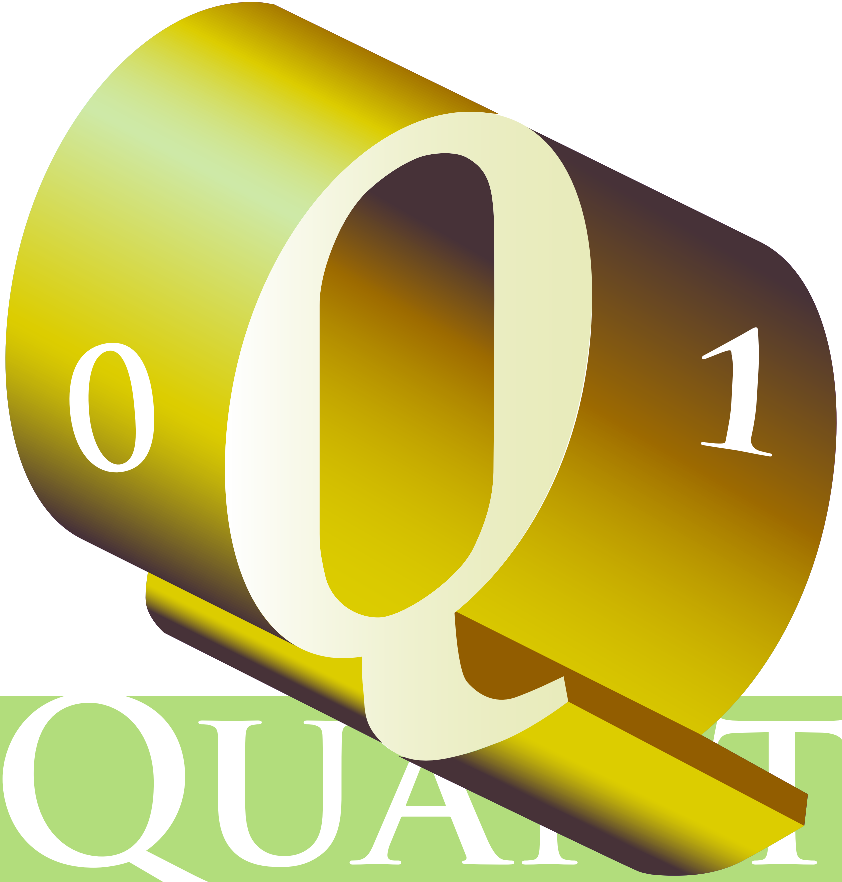

NEWS LETTER

Vol. 04

July 5, 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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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: 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)

Control-free control

Work in our group [1] was recently featured in a "News and Views" article [2] in Nature, on "Quantum Control". Below is a summary of our work [1].

Control techniques are applied in various areas of science and engineering. For example, when a device needs to be operated under certain conditions, but environmental fluctuations push it away from the optimal operation conditions, control techniques are applied in order to stabilize the device parameters and enhance its performance. This type of control is called closed-loop or feedback control. The basic structure of a closed-loop control system contains two steps: measurement and feedback control. In the first step, information is acquired about the state of the system and how far it is from the desired target state. In the second step, a "control" is applied to the system, i.e., a signal or force is applied, in order to change the state of the system and guide it toward the target state.

In classical physics, the measurement process only extracts information about the state of the system, but (under ideal circumstances) it does not change that state. This fact has been one of the basic principles in designing control systems over the past century. In quantum mechanics, this principle breaks down: the measurement itself will change the state of the system no matter how ideal it is. This fundamental difference between classical and quantum physics affects the design of control systems. One needs to treat quantum-control problems using a different frame of mind from that used when dealing with classical-control problems.

The most obvious approach to dealing with the unavoidable back-action of the measurement is to calculate the effected change and design the control signal accordingly. This approach has been used in most studies on quantum control, starting in the late nineteen eighties until the present. Another possibility, which might be conceptually more radical, is to use the change caused by the measurement as the sole means for manipulating the state of the system. In this case, closed-loop feedback control involves only the measurement step; the "control" is no longer needed. There have been a few studies exploring the possibility of measurement-only feedback control in the last few years. The first studies have generally assumed unlimited ability in the measurements that can be performed, and in many cases they applied either the standard theory of strong measurements or the alternative of very weak measurements. Reference [1] has taken these ideas further by utilizing the possible ability to tune the measurement strength as a controllable parameter that can be used enhance the performance of such control systems. Furthermore, they have shown that a single measurement setting can be used to prepare any desired target state, a concept that might have sounded impossible in the traditional thinking about control systems.

References:

[1] S. Ashhab and F. Nori, Control-free control: manipulating a quantum system using only a limited set of measurements, Phys. Rev. A 82, 062103 (2010).
http://dx.doi.org/10.1103/PhysRevA.82.062103

[2] Howard M. Wiseman, Quantum control: Squinting at quantum systems, Nature 470, 178 (2011).
http://www.nature.com/nature/journal/v470/n7333/pdf/470178a.pdf
http://www.nature.com/nature/journal/v470/n7333/full/470178a.html

Figure:

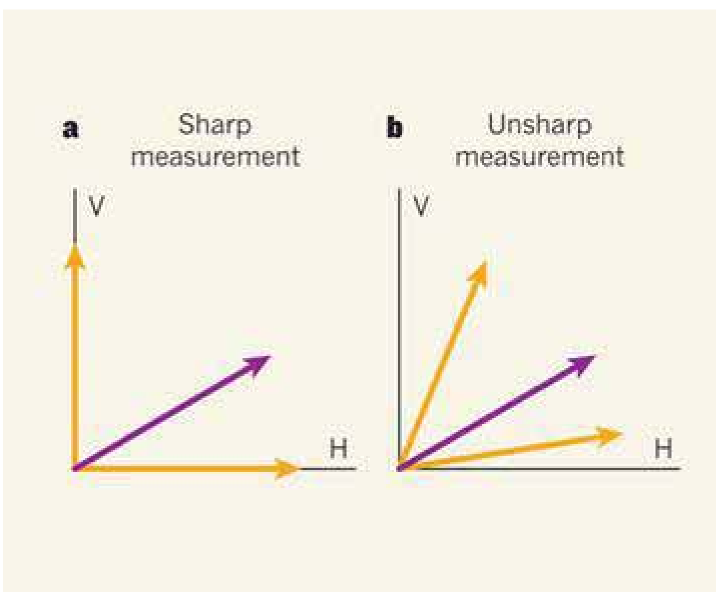


Figure taken from Ref. [2].

The purple arrow in this figure schematically shows the initial pure quantum state of a two-dimensional quantum system, for instance the polarization of a photon. Here, the direction V represents a vertically polarized state while H represents a horizontally polarized state. The initial state (the purple arrow) is a particular superposition of these (but nearer to H than V). After a sharp or strong (projective) measurement of polarization, shown in (a), the photon is in either the V-polarized state or the H–polarized state (orange arrows). After an unsharp or weak measurement ('squinting'; here with a sharpness or strength of 50%), as shown in (b), the photon is still in a superposition, but the 'H' result puts the state (lower orange arrow) much closer to an H–polarized state than the 'V' result puts it to a V–polarized state (upper orange arrow). Reference [1] show that by tuning the strength of the measurement to the right value, the measurement–induced change in the state can be optimized.

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)

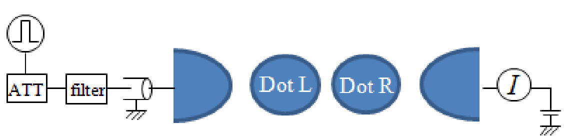
Coherent manipulation of a charge in a one-electron double quantum dot

Quantum coherence of a single electron spin/charge has been demonstrated using a semiconductor double quantum dot (DQD). In our group, we have focused on a charge qubit using a DQD. We have succeeded in controlling the coherence of the charge states in the DQD (one-qubit operation) [1]. A recent experiment on a coupled DQD has demonstrated correlated coherent oscillations of two electrons, which serves as a two-qubit SWAP operation [2]. In this work, we demonstrate coherent manipulation of a charge in a DQD containing only a single electron [3]. One of the advantages of a one-electron DQD is that the large energy spacing between the ground and excited states ensures that for each charge configuration only one orbital state is relevant, which makes the system more ideal as a quantum two-level system. This is in contrast to the previous charge qubit devices in which the coherent manipulation was performed on a single excess electron in a DQD containing a few tens of background electrons [1, 2]. In such multi-electron DQDs, not only the ground state but also excited states could be involved in the measurement. In our charge qubit, a single electron occupies either left ($|L\rangle$) or right ($|R\rangle$) dot of the DQD and its charge state is coherently manipulated via high-frequency voltage pulses.

Figure 1(a) schematically shows our experimental setup. A DQD is formed in a two-dimensional electron gas at the interface of a GaAs/AlGaAs heterojunction by applying negative voltages to the surface Schottky metal gates. High-frequency voltage pulses applied to the drain electrode of the DQD allow for a fast control of the dot energy levels with 80-ps time resolution. Figure 1(b) shows the measured DQD current as a function of the pulse duration, demonstrating coherent oscillations of a charge between $|R\rangle$ and $|L\rangle$.

[1] T. Hayashi *et al.*, Phys. Rev. Lett. **91**, 226804 (2003).
[2] G. Shinkai *et al.*, Phys. Rev. Lett. **103**, 056802 (2009).
[3] unpublished.

(a)



(b)

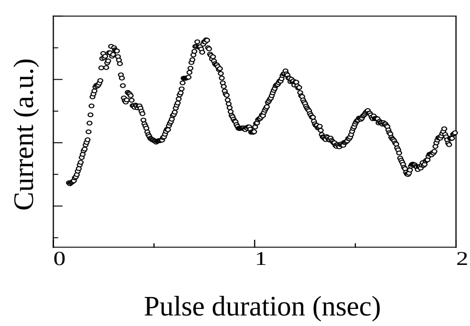


Fig. 1(a) Schematic illustration of the experimental setup. (b) Coherent oscillation of the charge state.

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)

Scalable spin amplification

A magnetic moment of a single nuclear spin is so small that its induction signal is buried under thermal noise. If information of a single nuclear spin is quantum-logically copied and transferred to a large number of spins, a spin component can be amplified. This scheme is called spin amplification, which enables non-demolition measurement of spin states and can be used for readout of quantum computers. However, it is difficult to perform quantum gate operations for the copy and transfer of a rare spin component to the surrounding abundant spins. Until now, a gain as low as four has been demonstrated with nuclear spins. In this work, we propose a new scalable implementation of spin amplification in a broader sense, which utilizes the spin diffusion phenomenon and magnetic-field cycling technique. We have demonstrated a gain of 140 in a solid-state nuclear spin system hyperpolarized with dynamic nuclear polarization using photoexcited triplet electron spins. We show that the spin amplification in a broad sense has non-trivial applications to improve the sensitivity of quantum state tomography, magnetic resonance spectroscopy, and quantum metrology. A factor of 140 spin amplification in conjunction with the modern magnetic resonance force microscopy (MRFM) technology, which is expected to detect a hundred nuclear spins in the near future, may open the door to the detection of a faint signal from a single nuclear spin. The proposed implementation has good scalability and will enable a higher gain. Scalable spin amplification will enable practical applications of NMR spectroscopy to rarely-existing nuclear spins in infinitesimal bulk samples which have been concealed by thermal noise. The demonstrated spin amplification in a broad sense can be straightforwardly modified to the scalable version of the spin amplification for non-demolition measurement. The breakthrough in the gain of spin amplification will be an important step for quantum information science.

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. In addition, we successfully performed a hole-burning spectroscopy and observed the very narrow excitation spectrum which is limited by the finite laser linewidth. Furthermore, we successfully detected the strong dependence of collisional shift on the magnetic sublevel.

In the quantum simulation using cold atoms in an optical lattice, we successfully applied Pomeranchuk cooling to cool the Yb atoms by making use of the spin degrees of freedom of SU(6). In addition, we newly realized a quantum degenerate mixture of alkali and Yb atoms, and find new possibilities including quantum magnetism.

Moreover, 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 also discuss the meaning of this process from the viewpoints of quantum information.

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

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

Single qubit operation using STIRAP

In almost all quantum gate experiments done so far in atomic systems, dynamic evolution arising from the system's Hamiltonian is employed to implement the desired operations. Such methods depend on pulse areas of excitation pulses or the details of frequency control, and may suffer directly from fluctuation of intensity or frequency and spatial intensity inhomogeneity. By replacing such methods with adiabatic ones, gate operations may be performed robustly, and large-scale state preparation including preparation of multi-partite entangled state may be realized with less effort. We realized single-qubit gate operations by means of purely geometrical phase factors for the first time in ionic systems, using two dark states in a tripod system comprising of three upper states and one lower state in single $^{40}Ca^{+}$ ion. The dark states were adiabatically manipulated by using stimulated Raman adiabatic passage. We confirmed population variation with contrast exceeding 0.9 in Z or X rotation experiments.

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)

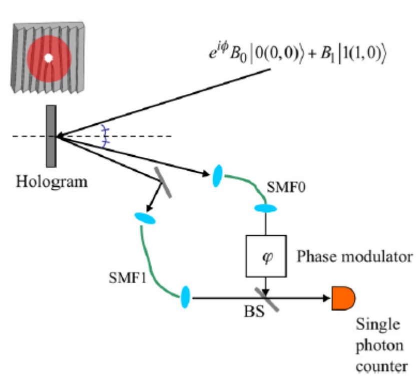
Preserving high-transmittance of nano optical fiber for photonic quantum devices, and new method to detect photons in a superposition of different orbital angular momentum.

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.

We investigated the cause of optical transmittance degradation in tapered fibers. Tapered optical fibers are promising tool to have tight coupling between photonic qubits and matter qubits. However, there has been a critical problem that the transmittance of the tapered fiber decreases to almost zero after several hours in atmospheric condition. We systematically investigated the effect of the dust-particle density and the humidity on the degradation dynamics. The results clearly show that the degradation is mostly due to dust particles and that it is not related to the humidity, as supposed before. We also succeeded in preserving the transmittance with a degradation of less than 2% over 1 week.

Orbital angular momentum states of photons are attracting attention for realizing a high-dimensional quantum space and will be useful for quantum info-communication. In previous experiments, measurements of photons in a superposition of different orbital angular momentum were done by shifting the hologram dislocation. But this method has the problem that various unneeded modes mix in the measurement basis. Here we have proposed a new method using a hologram and a path interferometer. We have also reported an experimental observation of non-classical correlation in the orbital angular momentum of photons by use of the proposed method. This new method will be useful for photonic quantum information processing using orbital angular momentum of photons.

[1] M. Fujiwara, K. Toubaru, S. Takeuchi, Opt. Exp. vol.19, 8596 (2011).
[2] Y. Miyamoto, D. Kawase, M. Takeda, K. Sasaki, S. Takeuchi, J. Opt. J. Opt. 13 064027 (2011).

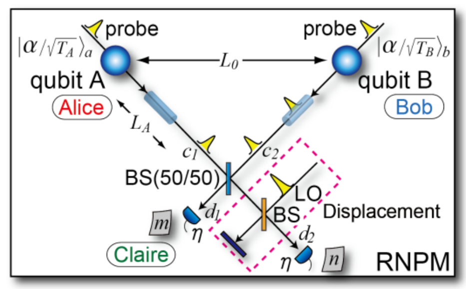


New method to detect a photons in a superposition of different orbital angular momentum.

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

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

A new road to quantum information processing via remote nondestructive parity measurement



Two-qubit gate operations are essential in quantum information processing (QIP). We need to let two qubits interact to each other for the gate operations, but the interaction must be turned off for the rest of the time in order to avoid decoherence. Good control over interaction among qubits thus plays a key role in implementations of QIP. Here we have proposed a novel protocol called `remote nondestructive parity measurement' (RNPM) that brings about interaction over two qubits spatially apart. The protocol is based on a basic interaction between a laser pulse and a matter qubit, and is applicable to various choices of media for the quantum memory. The protocol realizes various basic gate operations used in QIP, such as entanglement generation, Bell measurement, and parity-check measurement. In this protocol, the distance between two qubits are freely chosen: it is applicable to a qubit pair shared by a sender and a receiver far apart, as well as to the qubits placed sparsely on a single chip to avoid decoherece. We have shown that a long distance quantum communication with quantum repeaters is feasible even if we assume that the RNPM protocol is carried out with practical devices. The efficiency and distance of the communication will improve simply by the improvement of the devices used in the RNPM protocol. If a further improvement realizes the RNPM protocol with high fidelity, quantum computation will also be brought within the scope. We believe that our RNPM protocol paves a new route toward realization of QIP.

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)

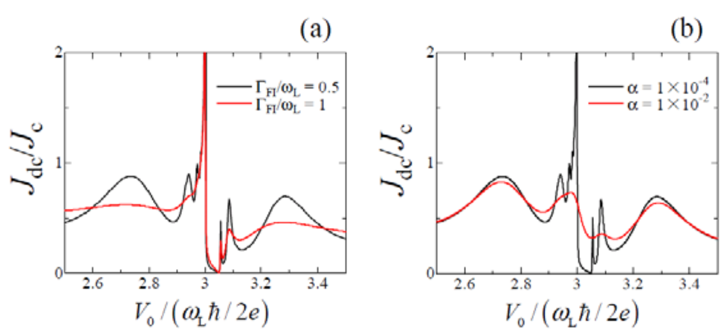
Quantum estimation theory is a branch of noncommutative statistics that addresses the problem of finding the best estimation procedure for an unknown quantum object by a physically feasible measuring process. In collaboration with Takeuchi group (Hokkaido/Osaka University), we are making an experimental demonstration of the strong consistency and asymptotic efficiency in an adaptive quantum estimation scheme (J. Phys. A: Math. Gen., **39** (2006) 12489). In particular, we aim to clarify whether, and how quick, the strong consistency and asymptotic efficiency are observed in estimating the direction of photon polarization. In order to design an actual experiment, we first made a series of numerical experiments, including tests of goodness of fit (χ2-test), and clarified that the distribution of the adaptive estimator converges to the theoretical Gaussian distribution even for a rather small number n of samples, say n = 100 ~ 300, at least 10% significant level. We are now analyzing the experimental data obtained by Takeuchi group from a statistical point of view.

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)

We theoretically study several possibilities to observe quantum coherence in a hybrid system of superconductor and quantum dot in order to realize the quantum bit. In particular, it must be important to control quantum states generating from the coupling between the superconducting phase and the electron spin. From this viewpoint, we examine the "ferromagnetic Josephson junctions", in which two superconducting electrodes are separated by a ferromagnet. The circuit model composed of Josephson current, resistance, and condenser is frequently adopted as a phenomenological model for the current-voltage characteristics of this system. In our study on ferromagnetic Josephson junction, the charging effect is ignored to focus on the coherence of electrons spins.

Applied the DC voltage to the ferromagnetic Josephson junction, in which a ferromagnetic insulator separates two superconducting electrodes, the AC Josephson current generated by the DC voltage induces the electromagnetic field inside the junction. In this case, the junction itself behaves as resonator. When the frequency of AC Josephson current matches to the resonance frequency of junction, the DC Josephson current is induced (Fiske resonance). In the case of ferromagnetic insulator, the multiple resonances appear due to the spin-wave excited by the electromagnetic field. As shown in the following figures, the spin coherence is manifest in those resonances[1]. If the ferromagnetic metal was inserted instead of the ferromagnetic insulator, those resonances would become unclear due to rather large damping on spin dynamics, and then one needs to insert an additional insulation layer between the ferromagnetic metal and superconducting electrode[2]. So far, we have supposed the ferromagnetic insulator to be a single domain. We have started to examine the magnetic domain wall and its dynamics and coherence[3]. Concerning the quantum dot as well, our study on the quantum coherence is running by including the charging effect, which becomes crucial in a small junction, and we are trying to propose and to control a quantum bit generating from the hybrid system of superconductor and quantum dot now.



The resonant state appears at the voltage, V_0, where one can observe the dc Josephson current, J_{dc}. (a) The red line is the case of larger damping from quasiparticle current. (b) This red line is the case of larger damping in rotational motion of spin.

[1] S. Hikino, M. Mori, S. Takahashi, and S. Maekawa, J. Phys. Soc. Jpn, 80 (2011) in press.
[2] A. F. Volkov and K. B. Efetov, Phys. Rev. Lett. 103, 037003 (2009).
[3] S. Hikino, M. Mori, 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 at room temperature. So, it is expected as good quantum bit system. For local coupling, we develop by using the coupling between nuclear spin and electron spin. Recently, we demonstrated the one of the important technique of quantum information processing for quantum network. At present, we evaluate and optimize the experimental condition.

One of the important characters of the NV center is that it has optical accessibility to spin. From this, the NV center is expected to be a resource to play a role of interface between single photon and single spin. For further development, we consider that the character of interface between charge and photon can be added to the NV center. As a first step, we investigate the single photon emission by current injection. At present, we analyze the mechanism and optimize the experimental condition.

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

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

Dynamics of polarized nuclei by pulsed-DC Voltage in quantum dot devices

We study electrical control of nuclear spins in quantum dots that can potentially be used as a quantum memory for spin qubits. We have reported in the previous letter that, the nuclear spins can be strongly polarized in either of two opposite directions and the nuclear spins in quantum dots are indeed long-lived quantum states with a coherence time of up to 1 millisecond. A paper summarizing this work is accepted for publication in Physical Review Letters.

In the work reported in the previous letter, we switch the DC source-drain voltage in a time scale of seconds. Now we switch the voltage in the order of millisecond to nanoseconds and study the dynamics of polarized nuclei. At the certain condition of the device, the nuclei in the dot is polarized to the direction that is parallel to the external field at the source-drain voltage Vp, and is polarized anti-parallel at the voltage Vap. Starting from fully polarized initial state at Vp, we apply a short DC pulse of Vap, and study how the initial state changes. Against our straightforward expectation that the polarization is gradually decreased and eventually reversed to the anti-parallel direction, we observed interesting behavior that the polarization stochastically takes two different value at the Vap-pulse of order milliseconds.