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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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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)

- Flux Noise Spectroscopy from Rabi oscillation in a Strongly Driven Flux Qubit

The power spectral density (PSD) of flux fluctuation has been studied in superconducting flux qubit. The spectrum typically follows 1/f frequency dependence. The accessible frequency range of the PSD measurement was limited up to around 10 MHz by spin-echo measurements and was extended to a few tens of MHz using Carr-Purcell-Meiboom-Gill (CPMG) pulse sequences.

On the other hand, from decay of Rabi oscillation in flux qubits, PSD of flux fluctuations at the Rabi frequency is obtained. To measure fast Rabi oscillations, large amplitude of oscillating magnetic flux in the superconductor loop of the flux qubit is necessary. Usually, large amplitude of oscillating magnetic flux results in exciting unwanted and unknown environmental degrees of freedom.

To have fast Rabi oscillations without significant decoherence, we prepare a flux qubit with strong inductive coupling to a microwave line (10 times stronger than usual). The flux qubit can be driven strongly with relatively small amplitude of microwave current, and Rabi oscillations in a wide range of Rabi frequency from 2.7 MHz to 1.7 GHz were measured. The PSD of flux fluctuations at each Rabi frequency is evaluated. We find that (1) the PSD decreases up to 300 MHz and (2) the PSD has a Lorentzian with its shoulder at 30 MHz.

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)

- Fabrication of four quantum dots toward for qubits

We have fabricated triple and four GaAs quantum dots (Fig.1) to achieve a multi-qubit technology, and confirmed that we can control the electronic states as a function of gate voltages. Tunnel-coupled four-quantum dot system is the first demonstration. In a triple quantum dot system by adjusting the gate voltages, we have demonstrated to initialize the (1,1,1) state, one electron in each quantum dot, which is required state for three qubits. In future, we will mount micro-magnets on the three- and four- quantum dots system, and execute electron spin resonance experiments with three and four spin qubits.

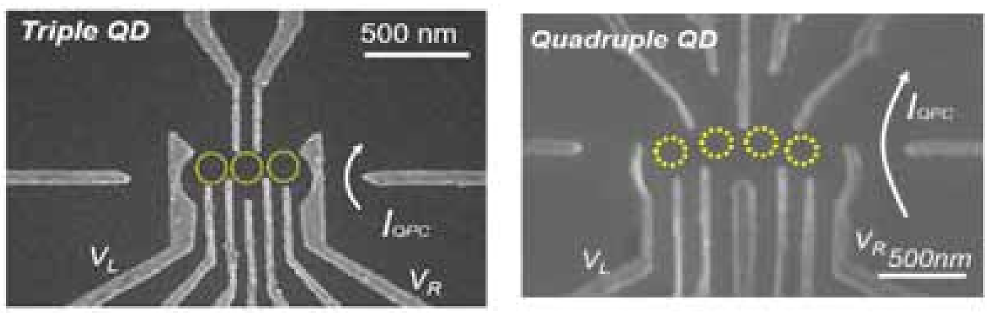


Fig.1 Scanning electron micrograph images of fabricated triple (left) and four (right) quantum dots.

- Fabrication of low-noise devices

It is well-known that the charge and spin qubits fabricated from GaAs/AlGaAs hetero-structures are strongly affected by charge noise, which shakes the quantum levels and hence introduces strong decoherence and gate errors. Previous reports had clarified that the charge noise is enhanced with negatively increasing the applied gate voltage, and is originated by the charge tunneling from the surface Schottky gate via trap sites in the device. We have evaluated the noise level in the current through quantum point contact (QPC) with fabricating QPC devices from GaAs/AlGaAs wafer. We have fabricated devices with changing the wafer layer structures and devices fabrication processes to clarify the origin of the noise. As in the previous reports, the gate-voltage sensitive charge noise is only observed for the devices fabricated with higher damaging process, but the noise is almost gate insensitive, independent of wafer layer structure and doping, for the devices fabricated with lower damaging process. Moreover, we found that the noise is insensitive to the gate voltage even for the devices with higher damaging process, when we insert GaAs/AlAs superlattice structure in the AlGaAs barrier layer. These results show that the charge noise is not intrinsic to the wafer, but is related to the fabrication processes, and superlattice structure prevents the trap sites in the device.

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)

- Synthetic ground-state triplet biradicals with the ZFS constants sizable enough to couple to SC flux qubits: Molecular design, synthesis and identification of their spin properties.

The quest for quantum memory entities capable of coupling to macroscopic superconducting(SC) flux qubits has been an important issue in the implementation of quantum information processing（QIP）systems. An attempt to couple SC qubits to electron spin ensemble of 30 million NV centers in diamond has successfully been carried out,[1] demonstrating that the NV center is a promising candidate for quantum memory devices in SC circuit technology. We have recently designed and synthesized ground-state triplet biradicals, nitroxide-Substituted nitronyl ntroxide **1** and iminonitroxide **2**, which have sizable zero-field splitting(ZFS) constants.[2] Biradical **1** and **2** have compact molecular structures which underlie the sizable ZFS constants. The ZFS of **2** ranges from 2 to 4 GHz in the absence of the static magnetic field. The ZFS's are tunable with respect to their molecular quantized axes and suitable models for coupling between SC qubits and molecular electron spin ensemble systems composed of organic biradicals. Both biradicals are extremely stable under ambient conditions, and they are robust down to liquid helium temperatures. In order to identify possible coupling schemes or microscopic mechanisms, we have characterized the experimentally determined ZFS constants by invoking sophisticated quantum chemical calculations for the ZFS tensors of biradical **1** and **2**. We have separately estimated contributions from spin-spin interactions and spin–orbit interactions. Coupling experiments to SC qubits by using single crystals of **1** are underway. We have designed and synthesized diamagnetic molecules capable of incorporating each biradical at any desired concentration, and the preparation of magnetically diluted single crystals is also underway.

[1] S. Suzuki, T. Furui, M. Kuratsu, M. Kozaki, D. Shiomi, K. Sato, T. Takui, and K. Okada, "Nitroxide-Substituted Nitronyl Nitroxide and Iminonitroxide", *J. Am. Chem. Soc.*, **132**, pp.15908-15910 (2010). (DOI: 10.1021/ja107769z)
[2] X. Zhu, S. Saito, N. Mizuochi, K. Semba et al., "Coherent coupling of a superconducting qubit to an electron spin ensemble", *Nature,* 478, 221-224 (2011).

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 successfully observed a two-dimensional superfluid-Mott insulator transition for a two-dimensional ytterbium Bose-Einstein condensate created right below an objective lens with high numerical aperture and tightly confined along the vertical direction which is superimposed with an optical lattice in the horizontal plane. In addition, we successfully observed fluorescence through the objective lens form the ytterbium atoms in an optical molasses operated with the strong electric dipole allowed transition and weak spin-forbidden transition.

Furthermore, it can be said that control of inter-atomic interaction is an important requisite for quantum simulation. Since a two-electron atom of an ytterbium atom which we use in our project has no hyperfine structure in the ground state, we cannot expect so called magnetic Feshbach resonance. Recently, we discovered the magnetic Feshbach resonance phenomena between the ground state and the metastable excited state induced by the anisotropic interaction both for 170Yb and 174Yb. This was made possible by the detailed analysis of the spectral shifts obtained by a high resolution laser spectroscopy of doubly occupied sites in a Mott insulating state of Bose-Einstein condensate of ytterbium atoms loaded into an optical lattice. Since this mechanism will similarly work for other isotopes including the fermions and also the metastable state of ytterbium and the ground state of lithium atom, we will search for the resonance and apply this effect to various studies.

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

We generated three partite Dicke states and evaluated them with trapped ions. Dicke states, which are in a class of entangled state, have such properties as robustness against measurements and particle losses, and are expected to be applied to precision measurements. Not only their generation process but also their evaluation is under discussion. Dicke states are highly symmetric, and therefore the evaluation in which only global observables are used such as total angular momentums may provide a clearer insight and reduce experimental costs. In the previous experimental studies of Dicke states, their evaluation has been done using quantum tomography that requires individual rotations and measurements. This time we derived inequality representing the upper and lower limits of the Dicke-state (W-state) fidelity for three particles, and analyzed experimentally the generated states using this inequality. As a result, we were able to conclude that the generated states were a Dicke state. In a multi-segmented planar trap, we are preparing two novel experiments in which we transport ions between different trapping regions. One experiment is coupling the evanescent wave around a nano-optical fiber to trapped ions, the other is generation of spin-spin interaction via Coulomb interaction under large magnetic field gradient which is achieved by integrating small permanent magnets in a planar trap.

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)

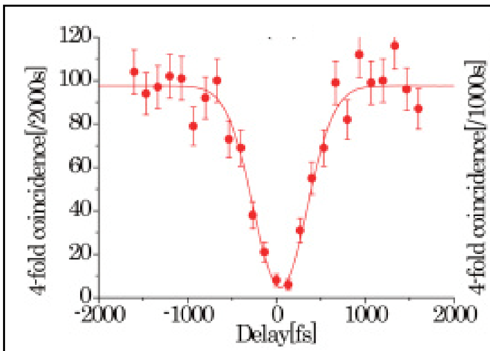
- Highly indistinguishable heralded single-photon sources using parametric down conversion

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.

In linear optics quantum computation, quantum interference between photons, called “two photon quantum interference”, plays a central role. In the phenomenon, two indistinguishable photons, incident on the two ports of a half beam-splitter, always emerge as a pair, exiting randomly from one port or the other since two processes “both photons are reflected” and “both photons are transmitted” are destructively interfered. This phenomenon is also very important for quantum repeater which will largely extend the distance of quantum cryptography and quantum metrology. For these applications, it is very important to develop a heralded single photon source which can achieve high two photon interference

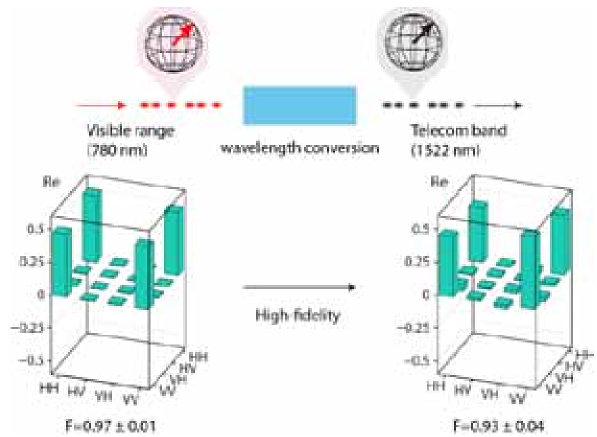
We theoretically and experimentally investigated the conditions for realizing highly indistinguishable heralded single-photon sources using spontaneous parametric down conversion. In a previous analysis of the same conditions, photon pairs were assumed to be uniformly generated in a crystal; i.e., the conversion efficiency was assumed to remain constant as the pump pulse propagates through the crystal. We extended the theory by considering that the number of photon pairs increases linearly as the pump propagates within the crystal. We showed that this effect becomes significant for crystal lengths of about 1.5 mm or longer, which have been commonly used in previous experiments. We also experimentally investigated the effect of group velocity mismatch in crystals. As a result, numerical calculations based on our extended theory agree well with the experimental results. We also succeeded in obtaining a high-visibility of 95.8 ± 2%. To the best of our knowledge, this visibility equals the highest visibility ever reported, but in our case the coincidence rates were higher by a factor of 4. By using this photon source, optical quantum circuit for quantum control would achieve lower errors.

[1] M. Tanida, R. Okamoto, S. Takeuchi, Optics Express 20, 15275 (2012).



Two photon quantum interference between different heralded single photon sources

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



Wavelength conversion of photons in a quantum regime has been actively studied as a quantum interface for applications of quantum information processing and communications. Such a conversion aiming at near-infrared photons in telecommunication bands is essential for transmitting quantum information over long-distance optical fiber networks. For this aim, nonlinear optical crystals with waveguide structure have practically desirable features as well as a wide bandwidth for high-clock-rate quantum information processing. But the achieved fidelity of the conversion had suffered greatly from degradation due to background noises caused by Raman scattering of a strong pump light. Here we achieved almost noiseless wavelength conversion through the aid of newly developed superconducting single-photon detectors (SSPDs) for visible and telecommunication wavelengths of the photons, in collaboration with NICT. The SSPDs have low dark count rates and small timing jitters, and especially the latter property enabled us to selectively observe well-defined temporal modes in which quantum information was stored, leading to a high fidelity beyond 90%.

2012 Selected research subjects and project managers

Proposed research 02: <u>Classical Compilers for Topological Quantum Information Processing</u>

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

– The Construction of Fault-tolerant Topological Circuits.

Large scale quantum computing architectures are essentially massive error correcting machines. While quantum algorithms are run on these machines, the majority of hardware resources are dedicated to correcting the inevitable errors occurring in the hardware. Programming such a machine is a complicated task and needs to be done effectively to reduce the number of devices needed for a large scale computer. The error correction method we utilize is that of topological cluster state codes. In this model, algorithms are represented as a large array of 3D geometric shapes. The way these shapes more around each other define the error corrected algorithm run on the computer. The goal of optimization is to compactify these structures into a smaller 3D space, reducing both the time required for computation and the number of qubits.

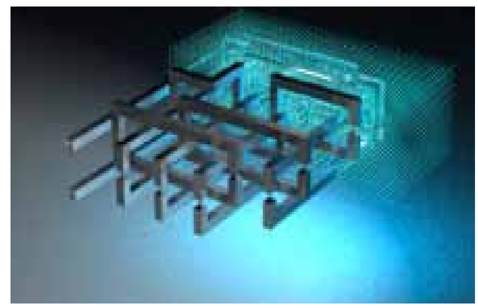


Illustration of a quantum algorithm in the Topological cluster model. The geometric shapes exist within a 3D space of qubits created by the quantum hardware.

Current version welcome screen for the puzzle game quantum blocks which converts our abstract optimization problem into a publicly downloadable game

QUANTUM BLOCKS: Our first attempt to provide a solution to this problem is to program and publicly release a puzzle game that the general public can download and use on their iPhone, iPad and desktop computer. This game will convert the abstract problem into something that can be understood by the general public and consequently may provide us with interesting solutions that would not be found using more standard techniques. Quantum Blocks is currently in the Alpha stage of development and will hopefully be released towards the end of 2012.

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)

Spins in semiconductor quantum dots are expected to be used for quantum information processing as highly integrated quantum bits in the solid state. Long relaxation time of electron spins localized in quantum dots allows high-speed multiple quantum operations. Electron spins in quantum dots and photons can easily exchange the quantum information in quantum communication. In this study initialization and control of spins in quantum dots will be especially developed through coherent spin manipulation of trions in quantum dots by ultrashort light pulses.

We have experimentally studied the spin dynamics of excitons, electrons, and trions in charge-tunable InP/InGaP quantum dots (QDs) excited by picosecond resonant laser pulses by observing the time-resolved Kerr rotation. In singly charged QDs, inversion of the spin polarization direction of doped electrons is found to be caused simply by variation in the pulse intensity, which is accompanied by an abrupt change of the spin coherence time. This phenomenon is reproduced by density-matrix calculations allowing for the reaction on the QD electron-trion four-level system during its coherent radiation emission. This result means that the optical coherence is another critical factor affecting electron spin coherence.

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 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 develop a newly-designed silicon QD device. It would be suitable for spin manipulation by micro-magnet method, which has been demonstrated in GaAs QDs. We have no top gate to induce carriers in undoped silicon layer by applying a positive voltage, and then micro-magnet can be easily fabricated on top of the QDs. In this device, the carrier is induced in the silicon layer by the back gate.

Using lithographically-defined silicon QDs electrostatically-coupled in parallel, we measure current through each QD when we sweep a side gate voltage. Several kinks on the Coulomb peaks are observed. Each kink reflects a change in the electrostatic interaction when the number of electron in the other QD changes. As a result, we succeed in charge detection experiments using the silicon QDs where the carrier is induced with the back gate.

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 become possible to control and detect coherent quantum systems, such as charge, flux and spin qubits. Independently, the statistical physics/thermodynamics in mesoscopic systems, such as “the fluctuation theorem”, has been progressed rapidly. In mesoscopic systems, the statistical physics/thermodynamics is formulated based on the distribution function of non-equilibrium fluctuations induced by a time-dependent driving force. For now, the measurement of the probability distribution of single-electron tunneling current has been realized and the fluctuation theorem in the single-electron level has been verified. The aim of this project is to extend it to the quantum regime.

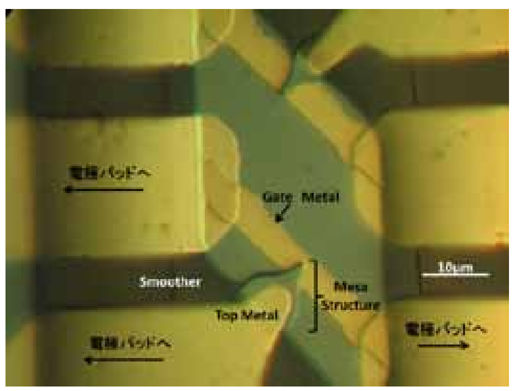
This project has been started from April. As a preliminary investigation, we have performed the full-counting statistics analysis of a quantum conductor coupled with a classical circuit. We have demonstrated that the probability distribution of current through the quantum conductor is measureable in principle as the probability distribution of work done to the classical circuit. Further we have proved that the fluctuation theorem is satisfied for this coupled system. We expect that our model properly describes real experimental setups, in which the projective measurements are repeated continuously. However, to analyze more sophisticated experiments on the control and detection of quantum systems, we have to extend our present model. Especially, in real experiments, there are many issues to be considered, such as the heating by external driving voltage. We are planning to analyze effects of environments including the heating effect.

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)

Generation of long-distance quantum entanglement between two remote devices is important for the development of quantum information technology including quantum communication and quantum computation, especially for quantum repeaters. In this project, we aim to develop a quantum dot single photon source with a side gate to realize the spin-spin entanglement of two remote electronic devices, which corresponds to a semiconductor-based distribution of EPR pairs.

We have designed and have fabricated a trial device structure as shown below. Although a bright photoluminescence from the quantum dots embedded in a p-i-n structure with a side gate is confirmed, an unexpected gate leakage current is observed by I-V measurement. Now, we are designing a modified structure to prevent the leakage. We are also developing a photon-detection method for extracting photons from the back-side of the device. We have succeeded in obtaining the sample image from the bake-side.



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

Project Leader: Hideto Matsuoka (Assistant Professor, Institute of Multidisciplinary Research for Advanced Materials, Tohoku University)

Recently, native photosynthetic systems have attracted much attention in the field of quantum information science because it was demonstrated that molecules involved in photosynthesis can remain entangled at room temperature. In photosynthesis, two types of reaction centers can be distinguished, which are called Photosystem I and II (PSI and PSII). PSI is a supercomplex of a reaction centre and light-harvesting complexes, which includes the primary electron donor chlorophyll P_{700} and 5 electron acceptors as the electron transfer components: chlorophyll (A_0), phylloquinone (A_1) and three 4Fe-4S iron-sulphur centres. So far we have studied spin correlated radical pairs in entangled states, which are ubiquitous intermediates in photosynthesis, by high-time resolution and high-frequency EPR (Electron Paramagnetic Resonance) spectroscopy. In particular, we have focused on the radical pair $P_{700}^{+}A_1^{-}$, which is the first detectable intermediate by time-resolved EPR. Toward manipulation of quantum spin information in photosynthesis, the following experiments are in progress. First of all, we are trying to stabilize quantum coherence of the radical pairs by chemical modification of photosynthetic proteins. We also focus on development of electrically detected EPR based on high-time resolution and high-frequency pulse techniques, which will be applied toward manipulating and measuring biological quantum information.

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)

- Electrically driven single photon source at room temperature

Significant progress in highly efficient and entangled photons sources has recently been shown in semiconductor quantum dots; however, the requirement of cryogenic temperatures due to the necessity to confine carriers is a major obstacle. Here we show the realization of a stable room temperature electrically driven single-photon source based on a single neutral NV centre [1]. Efficient generation of electroluminescence (EL) from diamond single defects requires synthesis of electron (*n*-type) and hole (*p*-type) conducting materials along with an ultrapure intrinsic (*i*) layer in a *p*-*i*-*n* diode structure as shown in Figure 1. Diamonds are doped with a large amount of boron (B) and phosphorous (P) by microwave plasma-enhanced chemical vapour deposition (CVD) growth to create semiconducting properties. However, this leads to defects emitting EL in the visible spectral range. Therefore, we introduced an extremely high-quality undoped region, where the concentration of colour centres was reduced to <<0.1 ppb ($10^{13}/cm^3$) which is the upper limit for single colour centre microscopy.

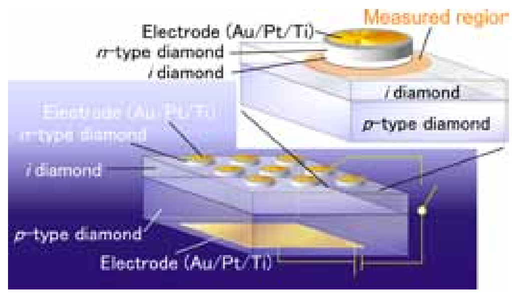


Figure 1, Schematic diagram of the single-photon-emitting diode. The thicknesses of the p-type, intrinsic and n-type layers of the device amount to 0.5 mm, 10 µm and 0.5 µm, respectively. The device was contacted on both interfaces using Ti(30 nm)/Pt(100 nm)/Au(200 nm) electrodes.

Antibunching measurements were performed in several NV centres. The second-order autocorrelation function $g^{(2)}(t)$ at t = 0 was less than 0.5, indicating that those were originated from single centres (Fig. 2). Remarkably, from the analysis of dynamics, it was revealed that the generation of electroluminescence follows fundamentally different kinetics than photoluminescence with intra-bandgap excitation. This suggests electroluminescence is generated by electron-hole recombination at the defect. 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. [1]

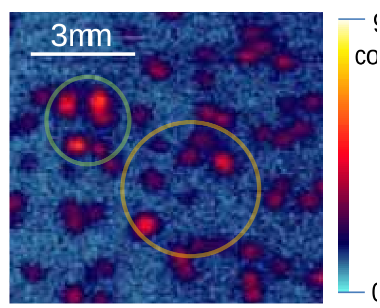


Figure 2, Microscopy images of electroluminescence (EL). Light with wavelengths longer than 560 nm were collected at room temperature.

[1] N. Mizuochi, T. Makino, H. Kato, D. Takeuchi, M. Ogura, H. Okushi, M. Nothaft, P. Neumann, A. Gali, F. Jelezko, J. Wrachtrup, S. Yamasaki, *Nature Photonics*, **6**, 299-303 (2012).