

# Frontiers in Nanoscale Science and Technology

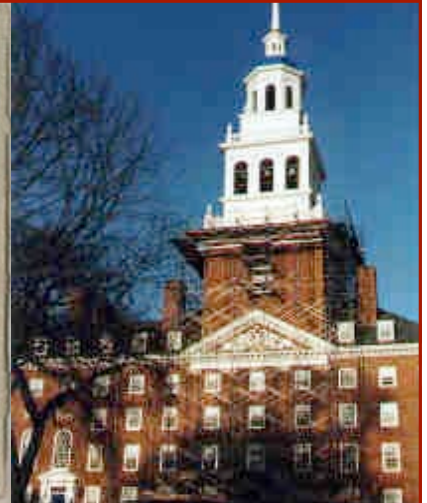
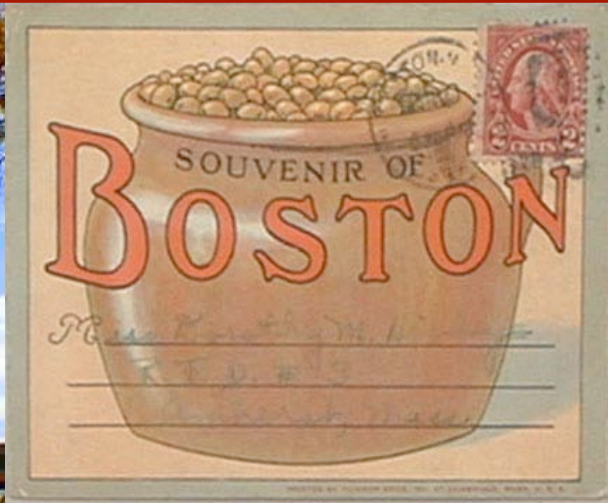
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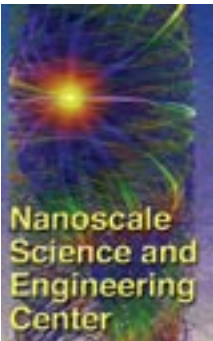
*Coherent Electronics*  
*Quantum Information Processing*  
*Quantum Optoelectronics*

## Abstracts



**October 25–26, 2004**  
**Harvard University**





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Frontiers in Nanoscale Science and Technology

**Coherent Electrons**  
**Quantum Information Processing**  
**Quantum Optoelectronics**

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Hiroyuki Sakaki, IIS, University of Tokyo, Japan

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The Center for Imaging and Mesoscale Systems at Harvard University (CIMS)



**Coherent Electronics**  
**Quantum Information Processing**  
**Quantum Optoelectronics**

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**ABSTRACTS OF TALKS**

**Optical Control of Single Charge and Spin in Self-Assembled Semiconductor  
Quantum Dots\***

*Gerhard Abstreiter*

**Walter Schottky Institut, University of München**

The control of individual charge and spin with novel semiconductor nanodevices based on self-assembled InGaAs quantum dots will be discussed. Such achievements are prerequisites for future semiconductor based quantum information technology.

Selected nanodevices will be presented including charge and spin storage in quantum dots, realization and measurement of long spin lifetimes, coherent control of a single dot photodiode, as well as controlled coupling of self-assembled dots.

\*In close collaboration with Jonathan Finley, Max Bichler, Yann Ducommun, Hubert Krenner, Miro Kroutvar, and Dieter Schuh. This work is financially supported by DFG (SFB 631) and BMBF.

**Progress and Prospects of Quantum Dots for Nanophotonic Device  
Applications**

*Yasuhiko Arakawa*

**Research Center for Advanced Science and Technology  
University of Tokyo**

Considerable research has been devoted to realizing the predicted potential of zero-dimensional quantum-confined structures, quantum dots which were first proposed by Arakawa and Sakaki in 1982. Because of their unique electronic states, the quantum dots are expected to have various useful properties for electronic and photonic device applications.

In this talk, we present our recent progress in physics and technology of the quantum dots for nanophotonic devices. The discussion includes growth of GaN quantum dots with a unique optical property of bi-excitons, manipulation of  $g$ -factor of InAs quantum dots and enhanced light emission from InAs quantum dots with photonic crystal. Moreover, we will survey the current state-of-the-art of quantum dots lasers and single photon emitters with our recent results on single photon emitters at the telecommunication wavelength and achievement of single blue-photon emission from GaN quantum dots.

\*The work was done in collaboration with Professor Y. Yamamoto's group, Stanford University.

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## **Novel Filamentary Structures Discovered in the Quantum Hall Liquid Using Scanning Charge Accumulation Imaging**

*Raymond Ashoori*

**Massachusetts Institute of Technology**

We present Scanning Charge Accumulation (SCA) imaging data measuring novel spatial structure in the Quantum Hall effect in a GaAs two-dimensional electron gas (2DEG) 100 nm beneath the sample surface.

SCA measures the local charging of materials using a scanning metallic tip. A small AC excitation in the 10 kHz to 2 MHz range is applied to the sample and the tip scans 10 nm above the sample surface. Attached to the tip is a charge detector with an extremely high sensitivity ( $0.01 \text{ electrons}/\sqrt{Hz}$ ). Measurement of the phase and amplitude of the image charge induced on the tip directly reflects charging in the 2DEG, permitting us to extract the local density of states and the local resistivity of the 2DEG.

We use the SCA probe to study the local properties of the Quantum Hall effect (QHE). Under application of large magnetic fields (10 Tesla) at very low temperatures (300 mK), the 2DEG is expected to show rich local structure. In the presence of disorder, the 2DEG will break up spatially into compressible and incompressible regions. Theorists also predict that at certain magnetic fields the 2DEG will spontaneously form ordered bubble and stripe structures.

In this talk, we present recent and very striking images obtained using our technique. The images display an unexpected and intricate network of filaments. The filaments appear only in a narrow range of magnetic fields near integer filling factors and evolve continuously as the magnetic field and tip bias are varied. The observed structure is entirely reproducible upon returning to the same experimental parameters.

The filamentary pattern is formed when a bias is applied to the tip that pushes the local density under the tip towards a filled Landau level. This forms a “bubble” of a compressible region under the tip that is separated from the rest of the 2DEG by an incompressible strip that acts as a tunnel barrier to charge moving in and out of the bubble. This tunnel barrier slows down the rate at which the enclosed area under the tip can be charged and discharged. This results in an overall darkening of the image at positions where this strip forms. The filaments then appear as sharp and bright lines penetrating this dark region.

The filaments also have an extreme aspect ratio, being often several microns long, but with widths down to the magnetic length (15 nm), the smallest length scale in the physics of the 2DEG. This is considerably smaller than our expected resolution, which should be limited by the 100 nm depth of the 2DEG below the surface. Equally puzzling is the spatial structure of the filaments. They show no well-defined periodicity, but have a strong orientational selectivity, following preferential directions along crystallographic axes of the host GaAs crystal.

The data suggest that interactions between the tip and the 2DEG greatly enhance the resolution of the probe. We present ideas for how this occurs and conjectures for the origin of these astonishing features.

## Excitons and Multiexcitons in Semiconductor Nanocrystal Quantum Dots: Single Dots, Many Dots, Applications

*Moungi Bawendi*

Massachusetts Institute of Technology

Nanocrystals of semiconductors (quantum dots) such as CdSe access the regime of strong exciton confinement where exciton and multiexciton energetics and time scales differ markedly from the bulk and quantum wells. In this talk we will review recent work probing the energetics and dynamics of multiexcitons at both the single dot and the ensemble regime. We show that optically pumped stimulated emission and lasing can be generated from both biexcitons and triexcitons. We also show at the single dot level that a photon cascade can be generated with ordered photons from the triexciton, biexciton, and finally the exciton. We also demonstrate how long time dynamics at the ensemble level reflect underlying dynamics at the single dot level.

## Local Probes of Spin-Charge Separation

*Leonid Glazman*

University of Minnesota

Scanning tunneling microscopy (STM) and scanning probe microscopy (SPM) are two techniques that are sensitive to the coherence of electron propagation in a solid.

Scanning tunneling microscopy allows one to measure the local density of states at the position of the STM tip. The density of states carries information about the electron interference. An electron scattering off an obstacle forms a standing-wave pattern around it. Such patterns were observed in the STM images of surfaces of bulk metals [1], where the elementary excitations are Fermi quasiparticles characterized by their spin and charge. In contrast, in one-dimensional conductors—quantum wires—the spin and charge modes propagate independently, which is known as spin-charge separation. The existence of two modes with different propagation velocities modifies the spatial pattern of the STM spectra around a scatterer [2,3]. Further modification of the STM spectra comes from the interaction of these modes with the Friedel oscillation of the average electron density around the scatterer. The resulting pattern of spatial oscillations of the tunneling density of states depends strongly on the bias voltage applied to the STM tip. This dependence provides information about the electron-electron interaction in a quantum wire.

The scanning probe microscopy reveals the electron wave interference by measuring the response of sample conductance to a locally-induced potential which scatters electrons. In the SPM technique, conductance of a junction is measured as a function of the position of an electron scatterer placed at some distance away from the junction [4]. Applied to a quantum wire, SPM measurements may allow one to observe the spin-charge separation. The existence of two modes leads to a specific oscillatory pattern in the junction differential conductance as a function of the position of the scatterer and of the bias applied across the junction [5]. For realistic interaction strength, the structure of oscillations is relatively simple. It has a clear Moire pattern, associated with the difference between the velocities of the spin and charge modes.

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## Spin, Spin-Orbit Coupling, and Transport in 2-D Electron Systems

*Bertrand I. Halperin*  
Harvard University

Spin-orbit coupling is of interest for devices based on electron spins in semiconductors, both from a negative point of view as a source of unwanted spin relaxation, and from a positive point of view as a possible way to manipulate spins using electric, rather than magnetic fields. It has been shown that relaxation due to spin-orbit coupling may be greatly suppressed in small quantum dots, and at least in principle, ac electric fields can be used to do spin resonance manipulations. There has been much recent discussion of a spin Hall effect, in which spin currents are produced by an applied electric field, without an applied magnetic field or injection from a ferromagnetic. I will discuss some recent theoretical results on the spin Hall effect and electric-field induced spin polarization in two-dimensional electron systems.

## Coherent Charge Manipulation in a Semiconductor Double Quantum Dot\*

*Toshiaki Hayashi*  
NTT Basic Research Laboratories, Japan

Semiconductor double quantum dots (QDs) can be considered as a quantum two-level system (charge Qubit) in which charge is located in either of the two QDs ( $|L\rangle$  state and  $|R\rangle$  state). We introduced short voltage pulse trains to the drain electrode of the device to modify the energy configuration of the system and induce a coherent state. Thus, the initialization and coherent gate-manipulation on the Qubit are carried out electrically. Then, the observation of its final state is performed through transport measurements. In this way, we have demonstrated rotation gate operations and phase-shift gate operations on the charge Qubits. The advantage of this semiconductor charge Qubit is the high accessibility of its quantum state. In addition, the charge Qubit has great potential for the integration of a large number of Qubits because its technology is based on advanced semiconductor electronics.

A semiconductor lateral double QD used for this experiment is fabricated in a GaAs/AlGaAs heterostructure (Fig. (a)). The tunneling rate  $\Gamma_{L/R}$  of the left/right tunnel barrier can be controlled individually by the gate voltage  $V_{L/R}$ , respectively, and the coupling energy  $\Delta$  between the two QDs can be tuned by the gate voltage  $V_C$  applied to the center gate ( $G_C$ ). The pulse shape for the rotation gate operation is shown in Fig. (b). The abrupt change in source-drain voltage  $V_{sd}$  leads to the change in the energy bias  $\epsilon$  because of the mutual capacitive coupling between the two QDs. At initialization (Fig. (c)), the two localized states  $|L\rangle$  and  $|R\rangle$  are off-resonance ( $\epsilon = \epsilon_0$ ). The inelastic current associated with phonon emission (emission rate:  $\Gamma_i$ ) flows through the double QD.  $\Gamma_L$  and  $\Gamma_R$  are adjusted so that  $\Gamma_L, \Gamma_R \gg \Gamma_i$ . Thus, the system is prepared to be in  $|L\rangle$  as an initial state. At  $t = 0$ , the source-drain voltage is set to zero and the Fermi levels of the left and right electrodes are aligned with each other (Fig. (d)). The electron trapped in the left QD oscillates back and forth between the two QDs coherently for pulse length  $t_p$ . During the oscillation, the quantum two-level system is isolated from the source and drain electrodes because of the Coulomb blockade. At  $t_p$ ,  $V_{sd}$  becomes  $V_H$  (Fig. (e)). If the electron is located in the right QD at this moment, it can tunnel out to the right electrode and contribute to the pulse-modulated current (projective measurement: Fig.

(e). If the electron is in the left QD, the electric state after the pulse is the same as the state before the pulse and does not give any current. We repeat this pulse sequence with repetition frequency  $f_{\text{rep}} = 100$  MHz and pulse length  $t_p = 0.08 - 2$  ns. The experiments were done at low temperature ( $< 100$  mK) and in a magnetic field normal to the sample plane (0.5 T).

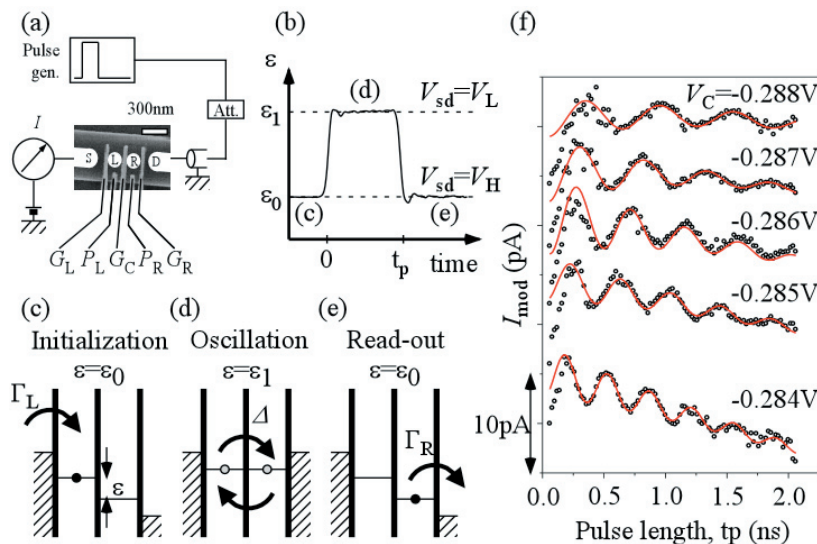


Figure (f) shows the  $t_p$  dependence of the current difference ( $I_{\text{mod}}$ ) with or without the voltage pulse for some  $V_C$ . Clear oscillations of  $I_{\text{mod}}$ , which can be roughly taken as the averaged number of electrons in the right QD at measurement, were observed as a function of  $t_p$ . They are all fitted with damped cosine functions (solid lines). Furthermore, the oscillation frequency, which is related to  $\Delta$ , can be changed by changing the gate voltage  $V_C$ .

\*This work was done in collaboration with T. Fujisawa and Y. Hirayama, NTT Basic Research Laboratories, Japan.

### Manipulation of Nuclear Spins in GaAs Based Hetero- and Nanostructures

*Yoshiro Hirayama*

NTT Basic Research Laboratories, Japan

Interactions between electron and nuclear spins and their control in GaAs-based hetero- and nanostructures will be discussed in this presentation.

In the fractional quantum Hall regime, such as  $\nu = 2/3$ , different composite-fermion Landau-levels with different spin states degenerate at a certain magnetic field. An extremely interesting phenomenon observed at this degenerate point is a novel interaction between electron and nuclear spins. Nuclear spins are polarized by a current flow, resulting in resistance enhancement and hysteretic characteristics [1–4]. On the other hand, nuclear spin relaxation is strongly influenced by the spin properties, especially the spin fluctuations, of the two-dimensional electrons in the GaAs quantum well. Extremely fast relaxation is observed on either side of  $\nu = 1$ , reflecting the electron spin texture called Skyrmion [2,3]. The spin-orbit interaction induced by the asymmetric confinement potential also enhances the nuclear-spin relaxation [5]. These features suggest the possibility of all-electrical control of nuclear spin polarization and relaxation in GaAs quantum wells [2,3].

We have applied these findings to manipulate nuclear spins in nanoscale semiconductor

systems. We prepared a point contact where a  $\nu = 2/3$  edge channel passed through the constriction. Nuclear spin polarization is realized by flowing appropriate current, which polarizes nuclear spins only in the point contact region. Nuclear spin polarization, which induces backscattering from the inhomogeneous Zeeman fields, is detected as the enhanced point-contact resistance. The coherent control of nuclear spin polarization is achieved by flowing radio-frequency pulse current along a microstrip line near the point contact and the coherent oscillations are detected by the resistance readout [6]. Coherent oscillations are measured for all quadrupolar splitted transitions, which are well resolved by the effectively improved uniformity in nanoscale NMR (Nuclear Magnetic Resonance).

The obtained results will open the way to using nuclear spins in semiconductors for spintronics and Qubits.

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**Manipulation of Spin Effects in Coupled Quantum Dots  
Single Spins in 1-D Nanowires and Tubes**

*Leo Kouwenhoven*  
**Delft University of Technology**

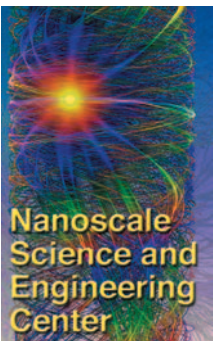
We have studied quantum dots defined in semiconductor nanowires (based on InP and InAs materials) and in carbon nanotubes. We observe regular Coulomb blockade effect which is the starting point for identifying spin states. In carbon nanotubes we have used particularly tuned spin states to observe an SU(4) Kondo effect and a purely-orbital Kondo effect.

**Decoherence and Relaxation of Spin Qubits in Quantum Dots**

*Daniel Loss*  
**University of Basel, Switzerland**

Quantum dynamics and decay of a single electron spin confined to a GaAs quantum dot will be discussed. Coupled arrays of such systems are considered as promising candidates for a scalable solid-state implementation of a quantum computer. The most important sources of spin decay are hyperfine interaction with  $N$  nuclear spins [1,2] and the spin-orbit interaction coupling spins to phonons [1]. The hyperfine interaction leads to non-exponential decay laws (due to memory effects in the nuclear spin system) on a scale of microseconds, but the amount of decay can be efficiently suppressed by applying magnetic fields (comparable to the Overhauser field) and/or by dynamically generating a finite polarization  $p$  of the nuclear spins, with the mild requirement that  $p > 1/\sqrt{N}$  [2]. The detailed dynamics of the nuclear spins is very rich and can be obtained in a systematic approach in terms of a generalized master equation for a wide physical parameter range [2], thereby generalizing exact results we have obtained for full polarization  $p = 1$  [1]. The decay due to phonons [3] is described





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in terms of an effective Hamiltonian (obtained via Schrieffer-Wolf transformation) which couples the electron spin to phonons or any other fluctuation of the dot potential. It is shown that the spin decoherence time  $T_2$  is as large as the spin relaxation time  $T_1$ , under realistic conditions. For the Dresselhaus and Rashba spin-orbit couplings, we found [3] that, in leading order, the effective magnetic field can have only fluctuations transverse to the applied magnetic field. As a result,  $T_2 = 2T_1$  for arbitrarily large Zeeman splittings, in contrast to the naively expected case  $T_2 \ll T_1$ . The spin decay is drastically suppressed for certain magnetic field directions and values of the Rashba coupling constant. Finally, for the spin coupling to acoustic phonons, we have shown that  $T_2 = 2T_1$  for all spin-orbit mechanisms in leading order in the electron-phonon interaction. The theoretical values for  $T_1$  are in the range of milliseconds (for  $B = 8T$ , and at low temperatures), and agree well with recent experiments by the Delft group.

## References:

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## Coherent Optoelectronics for Quantum Communication and Quantum Networks

*Mikhail Lukin*

**Harvard University**

Quantum communication holds promise for transmitting secure messages via quantum cryptography, and for communicating quantum information. However, extending quantum communication techniques to long distances represent a conceptual and technological challenge: on the one hand photon losses fundamentally limit the range of direct communication, on the other hand quantum signals cannot be amplified without adding noise. The so-called quantum repeater techniques provide a potential solution to this problem. Implementation of these techniques requires coherent light-matter interface including quantum memory nodes for photon state storage and the means for generation and purifying quantum entangled states. This talk will describe our progress toward developing the new tools and techniques required for constructing quantum repeaters. Two specific approaches based on atomic and solid-state systems will be described.

## Spin and Charge Manipulation in Few Electron Quantum Dots\*

*Charles Marcus*

**Harvard University**

This talk reviews recent experiments on coherent charge and spin manipulation in few electron quantum dots and double quantum dots, including measurement of  $T_1$  and  $T_2^*$  for coherent charge oscillations in a double quantum dot, photon-assisted charge transfer in an isolated double dot, and spin  $T_1$  measurements at arbitrary magnetic field. These new results are made possible by a combination of pulsed gate control, high-bandwidth gating, and integrated capacitive charge sensing.

\*This work was carried out primarily by Jason Petta and Alex Johnson, and was supported in part by DARPA, NSF-NSEC, and Harvard CIMS. We acknowledge collaboration with Amir Yacoby, Misha Lukin and Jacob Taylor.

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**Ballistic Electro-Photonics**  
**Venkatesh (Venky) Narayanamurti**  
**Harvard University**

The ballistic transport of hot electrons in semiconductors has long been a subject of interest. Over the last decade enormous progress has been made in the study of such transport by use of tunneling based hot electron (or hole) injectors [1,2]. In this talk, I will present several exciting new results which have broad implications for the study of new semiconductor nanostructures including the transport of spin. These are:

- A) Ballistic Electron Emission Luminescence [3,4] (BEEL) which allows the simultaneous monitoring of electron transport and luminescence for quantum dot structures placed below the surface.
- B) Demonstration of several new types of hot electron based devices involving the monitoring of spin transport. Examples include luminescent spin valve transistors [5] and spin valve photodiodes [6].
- C) Transport and luminescence studies of semiconductor nanowires such as ZnO [7].
- D) A new type of BEEM instrument using dual tips to study transport in nanowire structures [8].

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**Single Molecule Transistors**  
**Hongkun Park**  
**Harvard University**

In this presentation, I will describe the fabrication and characterization of single-molecule transistors that incorporate individual transition-metal complexes. Examples to be discussed include: (i) The observation of the internal vibrational motion of ferrocene induced by single-electron hopping, (ii) the observation of Kondo resonance in single-divanadium-molecule transistor caused by correlated spin screening, and (iii) the electroluminescence from a single CdSe-nanorod transistor. These examples demonstrate that single-molecule transistors provide a powerful new tool to investigate correlated electronic motion in nanoscale systems as well as the coupling between electronic motion and molecular degrees of freedom.

## Optoelectronic Manipulation of Spins in Quantum Wells: Harnessing Local Magnetic Interactions\*

*Martino Poggio*

University of California, Santa Barbara

A semiconductor quantum information processor based on spin will require the coherent control of local states. In this vein, understanding electron spin dynamics in semiconductor nanostructures and their magnetic interactions with local moments will be crucial to the design of any practical device. Due to the ease with which charge can be controlled in these systems, it is natural to use conduction electrons as intermediaries in manipulating local spins. Here we will discuss the electrical control of electron spin coherence in GaAs/AlGaAs quantum wells [1], the use of conduction electrons to locally manipulate lattice nuclear spin [2], and touch on the possibility of harnessing local magnetic interactions in magnetically doped GaAs QWs [3].

Electron spin dynamics of optically excited carriers confined in square, parabolic, and coupled QWs are investigated through time resolved Faraday rotation experiments. Spin coherence can be manipulated in specially designed structures through the application of electric fields.

The shaping of nuclear spin polarization profiles and the induction of nuclear resonances are demonstrated within a parabolic QW using an externally applied gate voltage. Voltage control of the electron and hole wave functions results in nanometer-scale 2-D sheets of polarized nuclei positioned along the growth direction of the well. RF voltages across the gates induce resonant spin transitions of selected isotopes. This depolarizing effect depends strongly on the separation of electrons and holes, suggesting that a highly localized mechanism accounts for the observed behavior.

\*In collaboration with R.C. Myers, N.P. Stern, A.C. Gossard, and D.D. Awschalom. This work is supported by DARPA and NSF.

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## Recent Advances in Quantum Dots, Quantum Wires and Related Nanostructures: Summary Report of Collaborative Research Project on Quantum Dots at the University of Tokyo

*Hiroyuki Sakaki*

Institute of Industrial Science, University of Tokyo

Research activities at the University of Tokyo in the field of nanophysics and nanoelectronics have a rather long history. A pioneering theoretical work of R. Kubo on metal nanoparticles, for example, dates back to 1962. A series of works on two-dimensional (2-D) electrons gas in silicon MOS structures were started around 1968; they led in the early 1970s to seminal theoretical studies of T. Ando and Y. Uemura on 2-D electron transport under strong quantizing magnetic fields and also to early experimental work of H. Sakaki and T. Sugano that clarified

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roles of gate-field-induced quantization of electrons in the room temperature operation of MOS FETs. This research has laid the foundation for interdisciplinary interactions across campus, in which the scope of research has been expanded to cover quantum wells (QWs) and superlattices (SLs), quantum wires (QWRs) and nanotubes, quantum dots (QDs) and rings, and other nanostructures.

In this talk, a summary report will be made to introduce several key results achieved in our five-year (2000–05) collaborative research project on quantum dots and related structures, supported as specially-promoted COE research by the Ministry of Education (MEXT).

We describe first recent advances in single-electron transistors (SETs) and planar SL FETs (originally proposed by the author in 1975), including the 300 K operation of Si SETs with an ultrasmall QD (less than 2 nm) (Hiramoto group), a novel SET with a self-organized InAs QD (Hirakawa group), and transport properties of novel planar SL structures (Iye-Katsumoto group). We discuss also electron transport in various systems, where neutral and charged QDs interact with neighboring 2-D and 1-D channels (Iye-Katsumoto, Hiramoto and Sakaki), including their possible uses in memory and other applications. We examine also recent advances on 1-D transport in QWR FETs (proposed by the author in 1980) and carbon nanotubes (Ando group).

As for optical properties of QDs and their photonic applications, recent developments of QD-based lasers (proposed by Arakawa and Sakaki in 1982) and a single-photon emitter (Arakawa group) will be briefly mentioned together with progress on QD-based photodetectors (Hirakawa and Sakaki).

Finally, several other exploratory studies will be described, including the interference and many-body effects in dot and ring structures (Katsumoto-Iye group), MEMS and scanning nano-probe studies of nanostructures (Fujita, Takahashi and Arakawa) and transport and FET studies of organic molecules (Someya group).

### **Circuit Quantum Electrodynamics: Doing Quantum Optics with Superconductors**

***Robert Schoelkopf***  
**Yale University**

I will describe recent experiments in which the strong coupling limit of cavity quantum electrodynamics has been realized for the first time using superconducting circuits. In our approach, we use a Cooper-pair box as an artificial atom, which is coupled to a one-dimensional cavity formed by a transmission line resonator. When the Cooper-pair box Qubit is detuned from the cavity resonance frequency, we perform high-fidelity dispersive quantum non-demolition readout of the Qubit state. Using this readout technique, we have characterized the Qubit properties spectroscopically, performed Rabi oscillations of the Qubit, and attained coherence times greater than 200 ns, indicating that this architecture is extremely attractive for quantum computing and control. In the case when the Qubit is tuned into resonance with the cavity, we observe the vacuum Rabi splitting of the cavity mode, indicating that the strong coupling regime is attained, and coherent superpositions between the Qubit and a single photon are generated.

## Manipulation of Spin Effects in Coupled Quantum Dots

*Seigo Tarucha*

The University of Tokyo, Hongo, Bunkyo, Tokyo, Japan

Manipulation of spin effects in semiconductor nanostructures is a key ingredient of quantum information technology. Electronic spin is a well-defined quantum number in quantum dots, and can be used for making Qubits in quantum computing. In addition, a novel concept of quantum storage arises from information conversion from electron spin to nuclear spin. In this talk I will discuss spin effects in coupled two quantum dot system, including interaction between two electron spins and hyperfine coupling of an electron spin to nuclear spin ensembles. Control over exchange coupling between two electron spins in two dots is a key concept for quantum gate operation, and the coupling strength depends strongly on the orbital and spin configurations just like the case for real molecules. I will first discuss such molecule-like properties of coupled two dot systems and schemes for manipulating two electron spins in two dots. Then, I will show that hyperfine interaction between a single electron spin and nuclear spin ensembles is tunable with magnetic field and bias voltage, and this enables electrical initialization and readout of nuclear spin polarization. We use the polarized or initialized nuclei to demonstrate memory and Qubit operation. I will show some improvement for high-speed manipulation of nuclear spin Qubits and electrical control of nuclear spin relaxation.

## Imaging a Single-Electron Quantum Dot\*

*Robert M. Westervelt*

Harvard University

Images of a single-electron quantum dot in a GaAs/AlGaAs heterostructure were obtained at liquid-He temperatures using a cooled scanning probe microscope (SPM). Single-electron quantum dots are building blocks for quantum information processing systems. The charged SPM tip shifts the energy of the electron ground state in the dot and creates a ring in the image corresponding to a peak in its Coulomb-blockade conductance. Fits to the lineshape of the ring determine the tip-induced shift of the energy state. SPM manipulation of electrons in quantum dots promises to be useful for understanding, building and manipulating dot and dot circuits.

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