

**Poster Abstracts****Session A: Friday May 29**
Session B: Saturday May 30

A

Light-Matter Interaction in Quantum Dots with 2D/3D Photonic Crystal Nanocavity*Y. Arakawa, S. Iwamoto, M. Nomura, A. Tандаechnurat, D. Guimard*
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Following Esaki's pioneering work on super-lattices and quantum wells, the concept of quantum dots was proposed by Arakawa et al. in 1982 for application to semiconductor lasers together with the theoretical prediction of temperature-insensitive threshold current characteristics¹. The three-dimensional confinement of electrons in the quantum dots has brought up unique features of artificial atoms, such as discrete energy states and quantum correlation due to spin/charging effects.

The confinement of photons in an extremely small volume is led to a strong interaction between light and matter. In particular, quantum dots embedded in photonic crystal nanocavity systems² exhibit characteristic physics that can be described by cavity quantum electrodynamics, including vacuum Rabi splitting^{3,4} in the strong-coupling regime and highly efficient lasing in the weak-coupling regime.

In this paper, we discuss recent advances in excitation-photon interaction in single quantum dot with 2D photonic crystal nanocavity, showing successful demonstration of single quantum dot laser operation (i. e., single artificial atom lasers)³. Moreover, we report on an experimental demonstration of coupling of quantum dots with a point-defect nanocavity in woodpile 3D photonic crystal with the highest Q factor among those for 3D photonic crystal cavities by micromachining technique^{4,5}. The Q factor of more than 8,600 was so far achieved by stacking 25 layers by optimizing the size of the square-shaped defect cavity to tune the cavity mode to the midgap frequency of the complete photonic bandgap.

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References

1. Y. Arakawa and H. Sakaki: Appl. Phys. Lett., 40, 939 (1982)
2. E. Yablonovitch, Phys. Rev. Lett. 58, 2059 (1987).
3. M. Nomura, N. Kumagai, S. Iwamoto, Y. Ota and Y. Arakawa: unpublished
4. K. Aoki, D. Guimard, M. Nishioka, M. Nomura, S. Iwamoto, and Y. Arakawa, Nature Photonics, 2, 688 (2008)
5. A. Tандаechnurat, S. Ishida, K. Aoki, D. Guimard, M. Nomura, S. Iwamoto, and Y. Arakawa, Appl. Phys. Lett. 94, 171115 (2009)

A

Chemical Vapor Deposition (CVD) of Manganese for Copper Interconnections in Microelectronics*Y. Au, Y. Lin, H. Bhandari, H. Kim*
Harvard University

Metallic manganese (Mn) can be deposited by chemical vapor deposition (CVD) using a Mn amidinate precursor. Mn metal reacts with silica-containing surface of dielectric materials to form a manganese silicate (MnSi_xO_y) layer that has excellent barrier properties against diffusion of copper (Cu), water, and oxygen. The MnSi_xO_y barrier exceeds the ITRS requirements for future microelectronic devices. This CVD-Mn process can be applied to cap interconnect structures after chemical-mechanical polishing (CMP). Mn that is initially dissolved in the upper surface of Cu can diffuse back during subsequent deposition of an insulator capping layer, which enhances the adhesion between Cu and the capping layers and improves the electromigration reliability of the interconnect structures.

A

Detection of Single Photons and Single Photo-Generated Electron Spin in Lateral Quantum Dots

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Quantum state transfer between a single photon and a single electron spin will provide a large breakthrough in the development of long distance communications which may establish a global quantum network and act as a core technique for a quantum repeater. This will also give us a chance to gain an insight into the physics of the spin coherence. Recently, the principle behind the quantum state transfer between photons and spins has been proven in the case of the ensemble optical measurements in a quantum well [1]. To extend it into the quantum information communications, we aim to realize the quantum state transfer between single quanta using a quantum dot. In this presentation we show the single-shot single photon detection in lateral quantum dots using a charge detection technique in a time scale shorter than the typical electron spin relaxation time. We stress that single electrons generated by single photons are trapped in the quantum dots and can be reset in the electrically-controlled manner. We also study the detection of the spin state of single electrons generated by single photons using spin-resolved edge states formed in the leads coupled to the quantum dot in the presence of a perpendicular magnetic field. The results obtained suggest that the spin-dependent tunneling due to the edge states is a good measure of the photo-generated electron spins. This will be useful for the experiments of angular momentum transfer between single photons and single electron spins as the next step.

[1] H. Kosaka et al., Phys. Rev. Lett. 100, 096602 (2008); Nature 457, 07729 (2009).

A

Energy Levels and Hyperfine Tensors of Nitrogen-Vacancy Defect in Diamond from *ab initio* Calculations

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Nitrogen-vacancy (NV) center in diamond is one of the most promising candidates for realization of solid state qubits at ambient temperature. The electron and nuclear spins in the system are manipulated by optical excitations and applied magnetic field. Particularly, the entanglement between the electron and nuclear spins was achieved via hyperfine coupling. While NV-center has been successfully applied as qubit registers, ultra-sensitive magnetometers or biomarker, still the detailed knowledge about the process of optical excitation and recombination is not clear, and little is known about the hyperfine tensors of approximate $I > 0$ nuclei around the defect. By utilizing accurate *ab initio* plane wave supercell calculations we were able to calculate the spin-conserving excitations of the NV-center and explain the phonon contribution at different experimental conditions. In addition, we determined the hyperfine tensors of N and approximate ^{13}C atoms *both* in the ground and excited states. We were able to resolve some controversial issues regarding the sign and anisotropy of the hyperfine signals, and provide accurate picture about the energy levels in the case of level anti-crossing regime of the excited state. We believe that our results can significantly contribute to understanding the electronic structure and other properties of this very important defect.

A

Hybrid Integrated Circuit / Microfluidic Chips

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We present the development of a versatile platform for performing biology and chemistry experiments on a chip, using the integrated circuit (IC) technology of the commercial electronics industry. This work represents an important step towards miniaturizing the complex chemical and biological tasks used for diagnostics, research, and manufacturing into automated and inexpensive chips. Hybrid IC / microfluidic chips are developed to simultaneously control many individual living cells and small volumes of fluid. The hybrid chip consists of a custom IC that is fabricated in a commercial foundry and a fluid chamber that is built directly on top of it. Taking inspiration from cellular biology, phospholipid bilayer vesicles are used to package pL volumes of fluid on the chips. The chips can be programmed to trap and position, deform, set the temperature of, electroporate, and electrofuse living cells and vesicles. The fast electronics and complex circuitry of ICs enable thousands of living cells and vesicles to be simultaneously controlled on the chip, allowing many parallel, well-controlled biological and chemical operations to be performed in parallel.

A

Sidegate Control of InAs Quantum Dots Coupled to Superconducting Leads

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Transport through single quantum dots laterally coupled to superconducting nanogap leads exhibits the novel interplay between the superconductivity and Kondo screening¹. We study a single InAs self-assembled quantum dot (SAQD) coupled to aluminum leads in which the supercurrent is tunable with an electrostatic backgate². An additional sidegate electrode is utilized to tune the dot-lead tunnel coupling, because it imposes an additional but anisotropic electrostatic potential to the dot, depending on the geometry of the QD and sidegate. In regions with appropriate energy scales we find that the sidegate can strongly suppress the junction critical current. We attribute this to reduction of the Kondo temperature. Observation of suppressed critical current is complemented by the study of dissipative subgap transport, where we observe strong enhancement of the 1st-order resonant Andreev transport channel for high Kondo temperatures. These results suggest that the junction is tuned from a 0-junction in which the supercurrent is dominated by Kondo physics to a p-junction in which the magnetic moment is unscreened and critical current is suppressed.

[1]. C. Buizert et al., Phys. Rev. Lett. **99**, 136806 (2007).

[2]. Y. Kanai et al., Journal of Physics Conference Series **150**, 022032 (2009).

A

Study of Leakage Current Mechanisms In Ballistic Deflection Transistors

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In this paper, the Ballistic Deflection Transistor (BDT) is reviewed for variations in performance of the device including leakage with respect to geometry modifications. Monte Carlo and Silvaco modeling tools are used to study current leakage mechanism in BDT. Low power selection criteria and theory behind position of deflector in the device are examined. Since ballistic conduction is not dissipative, power loss should be low. Leakage can be reduced by placing deflector at about 25% of its own length lower than the exact centre of the device. Current leakages that occurred during device operation are compared with each other and with the output current. It is observed that magnitude of leakage current is distinct at different ports of the device. For a specific set of parameters, leakage is comparable to the output which essentially motivates to choose optimum device architecture.

A

A Method for Coupled Quantum Mechanics/Molecular Mechanics Simulations of Surface Chemistry Applied to Epoxide Adsorption on Al₂O₃

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Simulating the chemistry between organic molecules and solid surfaces requires the quantum mechanical treatment of the electrons of surfactant and surface to be able to correctly describe the formation and breaking of bonds. However, such electronic structure methods are very computationally involved and practical calculations are limited to very small surface sections, containing at most a few hundred atoms. At the same time, it is known that changes in the electronic structure are limited to a short range around the reaction site. Therefore it is beneficial to only treat atoms within this influence range quantum mechanically and model the influence of a larger portion of the surface by simpler molecular mechanics methods. This approach is widely employed in biochemistry and polymer science, but polar solids like metal oxides give rise to special problems that cannot be solved by the approaches used in organic chemistry. We present a coupling scheme that allows us to couple the density-functional based tight-binding (DFTB) QM method to MM modeling of the surrounding surface. We employ this method to explore how surface water and excess hydrogen emanating from the condensation of molecules of a model epoxide adhesive on native alumina influence subsequent adsorption reactions. Our results show that careful control of byproducts of the adsorption reactions can help to improve the strength and stability of the link between organic adhesives and metal-oxide substrates.

A

Toward Integrated Control and Single Shot Read-Out in Laterally Gated Quantum Dots

*M. Laforest, K. C. Nowack, G. Prawiro-Atmodjo, L. M. K. Vandersypen
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Qubits formed from the electron spins of singly charged laterally gated quantum dots hold promises toward the implementation of quantum information processing. To date, single shot readout on single spin has been realized for single dots. Also, magnetic and electric single spin coherent control have been performed on double dot systems using readout methods sensitive only to the spin parity of the two electrons. Unfortunately, the control and read-out experiments occurred in different regimes of magnetic field. In order to implement small scale quantum information processing experiments, these two requirements must be integrated in the same regime. To perform the readout, a large Zeeman energy splitting (i.e. large magnetic field) is needed to overcome thermal broadening, which in turn implies that resonant control of the spin state of the single electrons will occur for excitation frequencies larger than 20GHz, which is technically challenging and has not been previously implemented in such systems.

In this poster, we will present the strategy to perform integrated control and single-shot readout in a single quantum dot system. We will also discuss the single-shot readout of all four spin states of a double quantum dot system as well as other possible future directions, such as integrated universal control and readout of two quantum dots.

A

Cavity Quantum Electrodynamics with Quantum Dot in H1-type Photonic Crystal Nanocavity

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Combinations of atom-like quantum states in semiconductor quantum dot (QD) and photonic crystal (PhC) nanocavity with small mode volume (V) and high quality factor (Q) are one of the best platforms for studying light-matter interaction in the context of cavity quantum electrodynamics (QED). Strong coupling regime, where QD's excitons and cavity photons coherently exchange their energies, are considered to be a key component of quantum information technology and have been recently reported [1]. Since the first demonstration, observations of strong coupling phenomena with QD and PhC cavities have been limited only for L3-type cavities which are composed of three missing air holes in two dimensional triangular PhC lattice.

In this poster, strong coupling phenomena between a H1-type PhC nanocavity and a single InAs QD are discussed [2]. H1-type PhC nanocavities are consisting of one missing air hole and possess several distinguished features such as doubly degenerated cavity modes and small V that boosts the coupling strength between QD and cavity photon. First, we investigated strong coupling of a single QD to the originally doubly degenerated cavity modes and found anti-crossing around both QD-cavity resonances. We will show how the information of the coupling can be utilized for estimating the QD location in the cavity. Then we studied excitation power dependence of a QD-cavity coupled system with large coupling constant of $\sim 100\text{meV}$ and found a transient behavior from doublet to triplet emission as increasing the power.

[1] T.Yoshie, *et al.*, Nature **432**, 200 (2004). [2] Y. Ota, *et al.*, Appl. Phys. Lett. **94**, 033102 (2009)

A

Two-Electron Spin Manipulation by Photon Assisted Tunneling

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Electron spins in a gate-defined double quantum dots formed in a GaAs/(Al,Ga)As 2DEG are promising candidates for quantum information processing as coherent single spin rotation [1,2] and spin swap [3] has been demonstrated recently.

In this system we investigate the two-electron spin dynamics in the presence of microwaves (5 GHz to 20 GHz) applied to one side gate. The charge state of the zero-biased double quantum dot is read out by a nearby quantum point contact (QPC). During microwave excitation we observe characteristic photon assisted tunneling (PAT) peaks in the QPC current close to the (1,1) to (0,2) double dot charge transition. We analyze the PAT pattern as a function of the detuning of the double dot potential, of the microwave frequency and of the in-plane magnetic field (0 T to 4 T). Some of the PAT peaks can be attributed to multi-photon tunneling events between the singlet S(0,2) and the singlet S(1,1) states.

Surprisingly, other PAT peaks stand out by their different magnetic field dependence, which indicates that they correspond to tunneling between a S(0,2) and a T₊(1,1) or T₋(1,1) state. At fixed microwave frequency, the excited triplet state can be selected by adequate detuning of the double dot. The full spectrum of the observed PAT lines is captured by simulations. The underlying mechanism for the spin flip could be spin orbit interaction or the inhomogeneous magnetic field of a Co micro magnet placed next to the electric gates.

1. F. H. L. Koppens *et al.*, Nature **442**, 766 (2006)
2. K. C. Nowack *et al.*, Science **318**, 1430 (2007)
3. J. R. Petta *et al.*, Science **309**, 2180 (2005)

A

Technique to Transfer Metallic Nanoscale Patterns to Small and Non-Planar Surfaces: Fiber Optic Device for Surface Enhanced Raman Scattering Detection

*E. Smythe, M. Dickey, G.M. Whitesides
Harvard University*

We present a method of transferring patterns of micro- and nanoscale metallic features to substrates that are difficult to pattern using lithographic techniques. We use a thin polymer film to strip features from large substrates and transfer them to unconventional substrates. The transferred patterns have a variety of geometries, high feature resolution and no residual ion implantation doping. We transfer dense and sparse patterns of isolated and connected gold features ranging in size from 30nm to 1 μ m to an optical fiber facet and a silica microsphere. A fiber-based Surface Enhanced Raman Scattering probe created with this transfer method is presented.

A

Highly Stretchable Polyimide-Supported Ceramic Island Arrays

*J.Y. Sun, N. Lu, J. Yoon, K. H. Oh, J. Vlassak, and Z. Suo
Harvard University*

Organic and inorganic materials have to be integrated together to build flexible electronic devices. While polymers can be highly deformable, ceramic films usually fail by brittle fracture at very small strains. The only approach to prevent rupture of ceramic films is to reduce the strain they are subjected to. Instead of using blanket films that rupture at very small deformations, we have patterned ceramic films into periodic island arrays on polyimide substrates. Finite element simulations along with a shear lag model show that a very soft interlayer between the islands and the underlying polyimide substrate reduces the strain in the islands by orders of magnitude. Using this approach, arrays of 200 μ m x 200 μ m large SiN_x islands supported by polyimide substrates were stretched beyond 20% without mechanical failure.

A

Triple Quantum Dots with Micro-Magnets Specially Designed for Implementing Three Spin Qubits

T. Takakura, M. Pioro-Ladrière, T. Obata, Y. S. Shin, R. Brunner,
K. Yoshida, T. Taniyama
University of Tokyo

Since the proposal [1] of electron-spin-based quantum computation, many experimental challenges have been performed to coherently manipulate electron spins in quantum dots (QDs). Electron spin resonance (ESR) is the fundamental concept of electron spin qubits, and has been demonstrated in several ways. ESR usually requires two magnetic field components of a static dc field and an ac field, which are normal to each other with the ac field frequency equivalent to the dc field induced Zeeman energy. Manipulation of single electron spins can be achieved by making the ac field local to a QD holding just one electron in the presence of a global dc magnetic field. However, to handle individual electron spins in a multiple QD or to make more than one spin qubits, it is necessary to set up the ESR condition of both magnetic fields local to each QD. We have recently demonstrated a new technique of electrical ESR using a micro-magnet (MM) to facilitate such an ESR condition [2]. An ac magnetic field is generated by ac electric field driven oscillations of an electron in a QD under a gradient of the *out-of-plane* stray field, which is imposed by a MM located above. This MM can bring about an *in-plane* stray field also local to the QD. This technique, therefore, allows us to address single spins in multiple QDs with ESR at different resonance frequencies or external magnetic fields, which has been demonstrated for two individual electrons in a double QD [3].

The next step is to extend the above technique to triple QDs (TQDs) aiming at manipulating three individual electrons. However, there are just a few previous reports on fabrication and characterization of TQDs themselves because of the difficulty in fabrication. In this work we initially design a realistic TQD for the MM technique to optimize the stray magnetic field distribution across the three dots. We then fabricate the TQD device but without MMs, and measure the transport property to derive the stability diagram with tunable numbers of electrons in each dot, which is predicted from calculations of the electrostatic potential to confine the electrons in the TQD. And we propose a next design of TQD and MMs considering the effect of spin-orbit interaction, which also gives an effective ac magnetic field.

1. D. Loss and D. P. DiVincenzo, Phys. Rev. A **57**, 120 (1998).
2. Y. Tokura, W.G. van der Wiel, T.Obata, and S. Tarucha, Phys. Rev. Lett. **96**, 047202 (2006).
3. M. Pioro-Ladrière, T. Obata, Y. Tokura, Y.-S. Shin, T. Kubo, K. Yoshida, T. Taniyama, and S. Tarucha, Nature Physics **4**, 776 (2008).

A

Scanning Microwave Microscope

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We have developed a Scanning Microwave Microscope (SMM) that uses a microwave stimulus from a network analyzer applied to the tip. The said approach, using a conductive AFM tip and AC stimulus, can concurrently image topography, material electrical properties and dopant density in semiconductors. The microwave-based measurement of materials at the nanoscale poses difficulty in measuring small changes of a large reflected signal. We have overcome this problem via a microwave interferometer design.

The said new nanoscale measurement technology is capable of measuring electrical material properties below the surface (the depth of measurement depend on the tip diameter). This allows new sample characterization that has not been available previously available.

The SMM can image a variety of materials and can be used to measure the dopant profile of semiconductors, the electrical properties of polymers (eg. dielectric constant and glass transition) as well as cellular structure, viruses, and other biological materials. This new measurement technology will accelerate the development of nanomaterials and nanodevices, cell analysis and imaging, and polymer science.

A

Nuclear Spin Pumping in Asymmetrical Double Dots

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Current rectification by Pauli spin blockade (P-SB) in a series double quantum dot is a milestone for precise initialization and detection of individual spins localized in quantum dots and is now extensively applied for spintronics and quantum information technology using electron spins. The 'dark state' realized in the P-SB opens a new channel of the electron spins to couple with ubiquitous nuclear spins in GaAs-based devices. The physical details of the hyperfine interaction are very important for understanding recent ESR experiments conducted in such systems by the groups of Harvard, Delft and ours and also provides interesting new research fields. Originally, P-SB was found in a double dot system with one electron in each dot. However, similar effects can be expected and actually observed in many other systems with other combinations of electron numbers in each dot. We will explain some of these examples with a simple analysis. More important fact in these asymmetric double dot systems is the way of hyperfine interaction can be quite different from that of original P-SB. We argue possible mechanisms of nuclear spin pumping in these systems.

A

Gate Voltage Control of a Flying Charge Qubit and Observation of Transmission Phase Shift in an Aharonov-Bohm Ring

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Aharonov-Bohm (AB) effect is known as one of the most spectacular interference phenomena of coherent electrons, where an electron wave propagating through two paths acquires different phases and interferes with itself. Although a number of experiments have been performed since its discovery, observation of purely intrinsic phase shift between the two paths has been rather elusive. This is because linear conductance measured in a two-terminal geometry suffers from the phase rigidity resulting from multi-scattering in which the phase is reconstructed to satisfy the boundary condition imposed by the contacts.

In this work, we studied electron transport through a parallel coupled-wire combined with an AB ring hybrid structure. An electron coherently propagating between the two wires acts as a flying qubit, which is defined as superposition of two quantum states: an electron existing in one of the two wires. In this geometry, phase rigidity no longer exists as there are two output contacts which equally collect coherent electrons. The inter-wire tunnel coupling allows flipping between the two quantum states, i.e. rotation about the x-axis of the Bloch sphere, and the evolution of AB phase - the relative phase shift between the two states - is translated into rotation about the z-axis. In our experiment, we defined the initial qubit state by injecting electrons into only one of the two wires, and detected the output state by measuring the two output currents. The output state oscillates as a function of perpendicular magnetic field with the AB oscillation period, whose amplitude becomes maximal when the two tunnel couplings are tuned so that they work as ideal 50-50% beam splitters, i.e. $\pi/2$ rotation about the y-axis. We observed that the shift of k-vector in one of the two wires induced by the gate voltage works equivalently as the shift of the perpendicular magnetic field. This is a direct observation of the phase shift $\Delta\theta = \Delta k \cdot L$.

A

Optically Pumped Nanowire Lasers

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A systematic study of the various properties of nanowire lasers as they evolve from the regime of amplified spontaneous emission to laser oscillation above threshold is presented. The key dependence of the laser threshold on nanowire diameter is demonstrated. A "head on" detection geometry is used to measure the far-field profile of a nanowire laser and thus identify the modes responsible for lasing.

B

Quantitative Measurements of Individual Gold Nanoparticle Scattering Cross Sections

*L. Anderson, K. M. Mayer, S. Lee, Y. Yang, R. Fraleigh and J. H. Hafner
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I have investigated the relationship between Dark-field Microscopy (DFM) contrast and gold nanoparticle scattering. By comparing the differential scattering cross sections of spherical gold nanoparticles given by Mie theory to the CCD count rate measurements from DFM, a spectral scaling constant, $K(\lambda)$, relating the two was obtained. Using this constant, I was able to extrapolate the scattering cross sections of differently shaped nanoparticles from DFM measurements. My results show that angular scattering dependence is of great importance. According to Mie and Gans theories, elongated particles have larger total scattering cross sections than spherical particles of the same volume. Contrary to this prediction, elongated particles are consistently dim in the DFM. Because of azimuthal asymmetry the differential scattering cross section for the angle range of the dark field detector is less for elongated particles than for spheres. I have compared these cross sections and discuss the angular dependence that comes into play when measuring anisotropic particle scattering using DFM.

B

A Single-Photon Source Based On Diamond Nanowires

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The Nitrogen-vacancy color center (NV center) in diamond is a remarkable source of single photons for photonic quantum information processing and quantum cryptography applications. It has nearly ideal optical properties, including room-temperature operation, photo-stability, and potential for integration into solid-state devices. Nanophotonic structures in particular could be used to engineer the optical properties of embedded NV centers via: (1) enhanced photon collection, (2) modification of NV center lifetime via the Purcell effect in the weak coupling regime, and (3) coherent photon exchange between a cavity mode and a NV center in the strong coupling regime. These would represent a new class of practical quantum communication devices with high single photon emission rate and yield.

Recently, we have fabricated diamond nanowire waveguides in a commercially available bulk diamond crystal. Coupling between embedded NV centers and the nanowire waveguide mode facilitates collection and results in a bright photon source. This is a dramatic improvement over studies of NV centers in the bulk, where the majority of photons are lost to total internal reflection.

Top-down nanofabrication processes were used to fabricate nanowire waveguides in bulk single crystal diamond. E-beam lithography was first used to define circular masks made of flowable oxide FOx (spin-on glass) on the diamond surface. Next, an ICP RIE tool with Oxygen chemistry was used to selectively etch and transfer the mask pattern into the diamond. A HF wet etch was then used to remove the mask and leave the diamond nanowires. Finally, the diamond was cleaned with a mixture of nitric, perchloric, and sulfuric acids (1:1:1). With this technique, both the mask diameter and etch time were controlled independently, and diamond nanowires structures with diameters ranging from 100-500nm and lengths up to 2.2 μ m long have been fabricated.

In order to realize diamond nanowires with single embedded NV centers, the devices used in this experiment were fabricated in Nitrogen rich type 1b diamond. These crystals, which were the subject of early studies of NV centers, are already known to contain NV centers that can be optically addressed. Using standard confocal microscopy techniques, we have observed dramatically different count rates between NV centers in different nanowires over the bulk. This is due to different coupling strengths between NV centers, randomly located at different positions within the nanowire cross-section, and the waveguide mode. Moreover, photoluminescence studies indicate that the photon emission is from NV centers in the nanowire structure. Finally, strong photon antibunching is observed and we may conclude that single NV centers are present in the devices.

B

Imaging Universal Conductance Fluctuations in Mesoscopic Graphene

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Harvard University*

We spatially map the effect of a movable scatterer on coherent diffusive transport through a graphene device. In this mesoscopic regime, the conductance exhibits fluctuations determined by the interfering contributions of all diffusive carrier trajectories through the sample. We scan a charged tip above the surface of the sample, inducing a perturbation to the charge density that locally scatters these electron or hole trajectories. The resulting conductance image yields a spatial “fingerprint” of the conductance fluctuations for a particular arrangement of scatterers at a given Fermi energy. We calculate correlations between these images as a function of the Fermi energy, and the spatial correlations of the fluctuations within an image. We find that the spatial fluctuations scale with the Fermi wavelength, providing a direct view of the interferometric nature of mesoscopic diffusive transport.

B

Interacting Electrons in a Quantum Dot

*M. F. Borunda, E. J. Heller, E. E. Boyd, H. J. Trodahl, and R. M. Westervelt
Harvard University*

Few-electron quantum dots have many applications in nanoelectronics, spin electronics, and quantum information processing. Scanning probe microscopy (SPM) makes it possible to image and control the electronic properties of systems with unprecedented control. We present simulations of two-electron InAs quantum dots formed in a nanowire heterostructure and study the influence of the conducting tip of the SPM. Our interest lies in the study and time control of coherent phenomena in this type of quantum dots.

B

Imaging of the Zeeman Effect in InAs/InP Nanowire Quantum Dots

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Harvard University, Lund University*

Nanowires are promising contenders for applications in novel spintronic and nanoelectronic devices. Using a liquid He-4 cooled scanning gate microscope (SGM), the energy states of an electron in a quantum dot defined in an InAs/InP heterostructure nanowire can be probed and manipulated [1]. Confinement of electrons within nanowires allows charge to be manipulated at relatively high temperatures, while the large g-factor of InAs eases the task of manipulating electron spins. The SGM tip acts as a movable gate and capacitively couples to the quantum dot. We model this system in the presence of a perpendicular magnetic field, and show the associated ring patterns for zero and finite source-drain bias. By sweeping the magnetic field strength, the effect of the field on the electron’s energy in the confined structure can be imaged.

[1] Bleszynski-Jayich, A.C., et al., *PRB* **2008**, 77, 245327.

B

Fluorescence of Semiconductor Quantum Dots and their Ensembles

*T. Dadosh, S. Wang
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The fluorescence properties of core-shell CdSe/ZnS semiconductor nanorods on thin silicon-nitride membranes were studied. The use of marked membrane substrates enables the unique combination of fluorescence measurements and transmission electron microscopy that allows correlating the fluorescence with its source of signal (the number of nanorods) 1, 2. The time-dependent cluster fluorescence was correlated with the particle number by direct particle counting. With increasing particle number, the cluster fluorescence increases in intensity and the relative fluorescence fluctuations decrease.

1. Querner, C.; Wang, S.; Healy, K.; Fairfield, J. A.; Fischbein, M. A.; Drndic, M., Fluorescence Dynamics of Semiconductor Nanorod Clusters Studied by Correlated Atomic Force, Transmission Electron, and Fluorescence Microscopy. *Journal of Physical Chemistry C* **2008**, 112, (50), 19945-19956.
2. Wang, S.; Querner, C.; Fischbein, M. D.; Willis, L.; Novikov, D. S.; Crouch, C. H.; Drndic, M., Blinking Statistics Correlated with Nanoparticle Number. *Nano Letters* **2008**, 8, (11), 4020-4026.

B

Photoconductivity in Quantum Dot Nanogap Devices

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Assemblies of semiconducting quantum dots and the optoelectronic devices based on them are of great general interest, and can be used to make solar cells, light-emitting diodes, and photodetectors. In this work, the photocurrent response of CdSe-ZnS core-shell nanocrystals in gold electrode gaps which are 20-30 nanometers in size has been measured. These gaps are much smaller than most of those which have been investigated in the literature, and correspond to less than 10 nanocrystals needed to bridge two electrodes. Nanocrystal thin-film photocurrent dependence on illumination intensity, illumination wavelength, temperature, and annealing temperature is characterized.

B

Quantum Dots Coupled to Photonic Crystal Cavities: Physics and Applications

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Quantum dots coupled to optical modes in photonic crystals provide an efficient platform for controlling the flow of light in future nano-photonics networks for classical and quantum information science. Recent progress in local control of quantum dots coupled to photonic crystal cavities led to devices where the transmission function of the cavity can be controlled at the most fundamental level using a single quantum dot. We demonstrate that these systems exhibit large optical nonlinearities at the single photon level – photon blockade and photon-induced tunneling – that can be exploited for on chip generation of non-classical light, as needed for quantum information processing devices. For classical information processing, we show that an electrically controlled quantum dot can induce modulation of the cavity transmission function up to 150MHz (limited by the driving electronics). This switch is predicted to operate at speeds up to 10GHz and energy per switching operation of 1fJ/bit, orders of magnitude lower than current state of the art electro-optic modulators.

B

Surface-Emitting THz-QCL Source Based on Intracavity-Difference Frequency Generation

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A surface-emitting terahertz source based on intracavity difference-frequency generation in dual-wavelength midinfrared quantum cascade lasers with integrated giant second order nonlinear susceptibility is improved. The terahertz light is coupled out of the waveguide by a second-order grating etched into the laser ridges. In contrast to sources where the difference-frequency radiation is extracted from the facet, this approach enables extraction of the terahertz emission from the whole length of the device even when the coherence length is small. This results in increased power and directionality. Detailed studies revealed disadvantageous behavior of the two midinfrared pump beams, as higher order transversal modes are present. This is explained by mutual interaction of the midinfrared lasers, resulting in local gain depletion for one of the lasers. To address the challenge of coupling the generated light out efficiently, a method for modeling high absorption terahertz-waveguides including phase mismatch in the source is developed and applied to the actual device. Results explain characteristics of actual devices and provide understanding of the outcoupling mechanisms.

B

Transport and Charge-Sensing Measurements on a Few-Electron Quantum Dot

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We report on quantum transport and real time charge sensing measurements in a few electron GaAs lateral quantum dot. The experiments are performed with a device that can be tuned to both a single or a double quantum dot. An adjacent quantum point contact is used as a charge sensor, giving a signal change of about 5% per electron. From the real time data we extract the tunnelling rates onto and off the quantum dot, which allows us to do level spectroscopy. Our studies aim at investigating the magnetic field anisotropy of spin tunnelling as well as spin relaxation.

B

Low-Index Photonic Crystal Cavities

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In this work, we are pursuing the design, fabrication and experimental validation of low-index photonic crystal (PhC) nanobeam cavities for quantum information processing applications. In order to improve efficiency of quantum-emitters, it is important to enhance the photon production rate as well as the collection efficiency of emitted photons. This can be achieved by embedding quantum emitters within optical cavities. These cavities were designed to operate for emitters in the visible, particularly near 637nm, in order to strongly enhance the zero-phonon-line (ZPL) emission of the nitrogen-vacancy (NV) color center in diamond nanocrystals (NCs) while suppressing the emission into the phonon side-band. In spite of the low-indices of most visibly transparent materials, designs with quality (Q) factors of 1.4×10^6 and 1.6×10^6 and mode volumes of $0.78(\lambda/n)^3$ and $0.44(\lambda/n)^3$ have been respectively achieved in silicon nitride (SiNx) and titanium dioxide (TiO₂). Additionally, we have proposed the use of a flowable oxide (FOx-17), for which the index is 1.46, as a viable material system, by demonstrating theoretical Q's as high as 2.5×10^4 under such low-index contrast in air. Furthermore, simulation studies indicate that $Q > 1.4 \times 10^6$ could still be retained for a diamond NC embedded inside or on top of the cavity.

We show the fabrication of PhC cavities in FOx, TiO₂ and SiNx. Preliminary characterization of the latter using photoluminescence demonstrates Q's as high as 14000 without any diamond NC or other emitters such as quantum dots inside or near the cavity. The presented work is an important step towards the realization of diamond or colloidal quantum dot-based single-photon sources, including switches.

B

Size-Dependent Quantum Transport Effects in Graphene Quantum Dots

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We report on quantum transport measurements on three quantum dots of 40 nm, 60 nm and 80 nm diameter, fabricated on a mechanically exfoliated graphene flake using electron beam lithography and oxygen plasma etching. These dots are comprised of two narrow constrictions on each side of a nearly circular graphene island and can be tuned by adjacent graphene side-gates as well as a back-gate. At dilution refrigerator temperatures, large back-gate hysteresis and slow relaxation drifts are observed, which may be associated with a thin PMMA layer left on the device surface. However, at a temperature of 4K, the hysteresis and drifts are substantially reduced, resulting in quite stable and reproducible data.

The size of an apparent region of strongly suppressed conductivity – the transport gap – shows a clear dependence on dot size. Further, quantum transport features in the Coulomb blockade regime found within this transport gap also show a strong dependence on dot size, in general agreement with theory. In the smaller devices at appropriate barrier transparencies, excited states and cotunneling features become visible in Coulomb diamond measurements. Perpendicular and parallel magnetic fields are used to investigate orbital and spin-dependent effects of the quantum transport features.

B

Extracting Single Emitter Spectral Dynamics from Intensity Correlations in an Ensemble Fluorescence Spectrum

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We show that the single emitter linewidth underlying a broadened ensemble emission spectrum can be extracted from correlations among the stochastic intensity fluctuations in the ensemble spectrum. Spectral correlations can be observed at high temporal and spectral resolutions with a cross-correlated pair of avalanche photodiodes placed at the outputs of a scanning Michelson interferometer. As illustrated with simulations in conjunction with Fluorescence Correlation Spectroscopy, our approach overcomes ensemble and temporal inhomogeneous broadening to provide single emitter linewidths, even for emitters under weak, continuous, broadband excitation.

B

A Single Molecule Immunoassay by Localized Surface Plasmon Resonance

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Noble metal nanoparticles exhibit sharp spectral extinction peaks at visible and near-infrared frequencies due to the resonant excitation of their free electrons, termed localized surface plasmon resonance (LSPR). Since the resonant frequency is dependent on the refractive index of the nanoparticle surroundings, LSPR can be the basis for sensing molecular interactions near the nanoparticle surface. However, previous studies have not determined whether the LSPR mechanism can detect the presence of an individual molecule near the nanoparticle surface. Here we demonstrate single molecule LSPR detection by monitoring antibody-antigen unbinding events through the scattering spectrum of individual gold bipyramids. The unbinding times are consistent with antibody-antigen binding kinetics determined from previous ensemble experiments. LSPR sensing could thus be a powerful addition to the current toolbox of single molecule detection methods since it probes interactions on long time-scales and under relatively natural conditions.

B

A Graphene-Based Double Quantum Dot Device

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The recent discovery of single- and few-layers graphene (FLG) has opened a door to a new area of low-dimensional physics. The low-energy physics of graphene is described theoretically by (2+1)-dimension. Dirac fermion, which leads to rich physics inherited from quantum electrodynamics (QED). From the application point of view, the ballistic transport and high mobility in graphene and FLG make it possible candidate for future nano-electronic quantum devices.

Here, we demonstrate double quantum-dot devices in a graphene-based two-dimensional semimetal, which exhibits single-electron transport of two lateral quantum dots coupled in series. Low-temperature transport measurements have been carried out in the double-dot device at the dilution refrigerator. The experimental results revealed the honeycomb charge stability diagrams from weak to strong interdot tunnel coupling regimes. Our results suggest an important step for the realization of the integrated quantum devices in graphene-based nanoelectronics.

B

Capacitance Spectroscopy of Vertical Wrap-Gate InAs Nanowire MOS Arrays

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Recent progress in vertically processed semiconductor nanowire (NW) devices with a cylindrically symmetric gate electrode, such as the wrapped insulator-gate field-effect transistor developed in Lund, has been promising, and the devices seem extremely apt for application in future highly scaled electronic devices. Besides the possibility of incorporating wrapped gates for improved gate control, NWs offer other intriguing possibilities not easily accessible to planar designs, such as inherent one-dimensionality as well as relaxed constraints in terms of combining highly lattice-mismatched materials along the NW channel due to radial relaxation of interface strain.

In order to facilitate the development of high performance electronic devices, it is important to be able to accurately characterize fundamental material properties, as well as interface properties of the system. Industrial Si-technology has long benefited from well developed capacitance-voltage (C-V) measurement schemes for device characterization. However, similar methods have so far been largely unavailable for NW devices due partly to the small capacitances involved. In this work, a scalable processing protocol is demonstrated which enables accurate C-V investigations of NW MOS arrays and routine inspection of different geometries and material combinations.

Arrays of NW seed particles are positioned using an electron beam lithography system, and grown using metal organic chemical vapor deposition. The NWs are capped using a high-k dielectric and a metallic gate electrode is deposited using sputtering. In order to decrease the capacitance between the gate electrode and the substrate, the gate is elevated from the substrate surface. By varying the gate voltage, we tune the Fermi-level position within the band structure and are able to accurately measure the metal-oxide-semiconductor capacitance between the NWs and the gate. From these measurements parameters such as semiconductor-dielectric interface state density and semiconductor doping level are extracted.

B **High-Sensitivity Measurements of the Persistent Current in Normal Metal Rings**

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A metal ring possessing a finite resistance can maintain a dissipationless, equilibrium current. This normal state persistent current results from constructive interference of the electron's wavefunction around the ring and so requires small rings and low temperatures to be observed. Early measurements reported unexpectedly large currents. For ensembles of rings, the low field susceptibility of the rings also had the opposite sign from that predicted by theory. While these results have not been fully explained, further theoretical work has shown that persistent currents form a good system for probing Kondo physics, quantum phase transitions, and electron decoherence. However, previous measurements of persistent currents to date have operated at the limits of measurement sensitivity and have not been able to explore these effects. We have developed a mechanical detection scheme for measuring persistent currents with good sensitivity over a large range of magnetic field and in a clean electromagnetic environment. We report measurements of persistent currents in aluminum rings which we have characterized as a function of size, temperature, and magnetic field magnitude and orientation. Our measurements are in good agreement with theory and promising for further study of persistent currents in normal metal rings.

B **Imaging Double Quantum Dots in Semiconductor Nanowire Heterostructures**

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Semiconductor nanowires are attractive candidates for applications in nanoscale electronics and optics. InAs/InP nanowires grown by chemical beam epitaxy are of particular interest, as heterostructures in the axial direction can be defined down to the nanometer scale. The incorporation of two InP segments in a nominally InAs nanowire forms a well defined quantum dot in the wire. Previously it has been shown that the charge state of such a single quantum dot can be manipulated with the use of a nearby charged scanning probe microscope tip [1]. Presented here are simulations of tip induced transport through a double quantum dot in an InAs nanowire formed by the incorporation of three InP segments. The effects of capacitive and tunnel coupling between two adjacent dots are taken into account, and the evolution from uncoupled to highly coupled dots is examined.

[1] Bleszynski-Jayich, A.C., et al., PRB 77, 245327 (2008)

B **Strong Photon Localization in Disordered Photonic Crystal Waveguides**

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Disorder is introduced into the design file for a 2D photonic crystal lattice by randomizing the shape of the elements that form the lattice. Line-defect waveguide devices fabricated with such disordered PhC templates exhibit spectral features that bear signatures of Anderson localization. Disorder-induced high-Q cavities are observed in a narrow frequency band close the guided modes cut-off. Spectrally distinct quasi-states with Qs up to 750,000 are distributed at random locations along the guide. A mechanism that relies on polarization mixing allows for the excitation of the cavities by TM polarized, index-guided waveguide modes. Light localization is observed in nanoscale modal volumes which can find applications in sensors and active devices.