2012 Workshop on Innovative Nanoscale Devices and Systems

WINDS

Booklet of Abstracts

Edited by

Koji Ishibashi
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Hapuna Beach Prince Hotel
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December 2-7, 2012

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The **Workshop on Innovative Nanoscale Devices and Systems** (WINDS) is a 4½ day meeting with morning and evening sessions, and with afternoons free for *ad hoc* meetings and discussions among participants. WINDS follows the tradition and format of AHW (Advanced Heterostructure Workshop). In 2008, there was a transition as the workshop name morphed from AHW to AHNW to WINDS in order to attract more participation from industrial labs. The format of each session involves one or two overview presentations plus lively discussion (about 15 minutes for each paper) based on recent data. To ensure enough time for discussion, short presentation of data is encouraged. Each participant is expected to engage in these discussions and is strongly encouraged to bring three to four overhead transparencies or a PC with PowerPoint files showing most recent results that can be incorporated into the discussions. Titles, introductions, summary and acknowledgements are strictly discouraged. The total number of participants will be limited to around 80 to keep the discussions lively in the single session.

Conference Dedication and Special Session

This year's workshop is dedicated to Herb Goronkin, who was one of the founders of the original AHW in the 1980s. As part of the dedication of WINDS 2012 to Herb, there will be a special session in his honor during the workshop.

Conference Organization

General Chair
Koji Ishibashi, RIKEN, Japan
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US Co-Chair
Stephen M. Goodnick, Arizona State University, USA
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December 2nd (Sunday)

15:00-18:00 Registration (Breezeway-Kohala)

18:00-20:00 Welcome Reception (Poolside)

December 3rd (Monday)

8:50–9:00 Opening

Memorial Session for Herb Goronkin

10:30-11:00 Coffee Break

Topological Insulators

December 3rd (Monday) continued

December 4th (Tuesday)

Spintronics (2)

December 4th (Tuesday) continued

Spintronics (3)

December 5th (Wednesday)

Nanowires

Nanocarbon (1)

December 5th (Wednesday) continued

13:00-18:30 *Ad hoc* Session

18:30-21:00 Banquet (Courtyard)

December 6th (Thursday)

Transport Properties

Nanodevices (1)

Optical, Mechanical, and Interfacial Properties (1)

December 6th (Thursday) continued

December 7th (Friday)

Nanotube and Nanofabrication

Nanodevices (2)

Nanobio

Remembering Herb Goronkin

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Herb Goronkin and Motorola

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Herb Goronkin was one of the founders of the original AHW in the 1980s, and he was critical to its success over the years of its continual evolution into WINDS. Herb had a long and distinguished career at Motorola, where he was recognized with their highest technical honor, the Dan Noble Award in 1996. He served as Vice-President and Chief Scientist for Phoenix Corporate Research Labs until 2003, where he was a strong advocate and visionary for nanotechnology and its applications. After his retirement from Motorola in 2003, he continued to play a pivotal role in the nanotechnology community, working as a venture partner with Lux Capital investing in emerging companies.

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Challenges in Green Nanoelectronics: Growing Expectations for the Tsukuba Innovation Arena in Japan

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Our project is being assigned by Cabinet Office, Government of Japan, to develop core technologies for reducing the power consumption of LSI by a factor of 1/10, and eventually by a factor of 1/100. Collaborative Research Team Green Nanoelectronics Center (GNC) was newly established in AIST, in April 2010, to execute the project, where about 30 corporate researchers and another 20 AIST researchers are getting together to concentrate on the project, collaborating with distinguished professors and researchers of universities, NIMS, and SPring-8 in Japan. GNC accelerates research by taking advantage of the large-scale research infrastructure available at Tsukuba Innovation Arena for Nanotechnology and works together with other related nanoelectronics projects.

After describing good memories of Herb Goronkin, this presentation will introduce the research topics and current status of our project, focusing on development and application of nanocarbon materials such as CNT via and multiple graphene layers for three dimensional interconnections for low voltage operation of LSIs, 300 mm diameter single graphene growth technology, and new transport-gap opening technology for transistor applications.

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Biological Assembly for GaAs, Graphene, and Topological Insulator Nanoscale Devices

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The ability to to precisely assemble nanoparticles into programmable geometries could open a door to new physical systems and novel nanoscale devices. Biology offers an exotic yet elegant key to this door. In this talk, I will describe our work toward using DNA scaffolding to explore a new realm of many-body physics and new electronic devices based on arrays of ferromagnetic nanoparticles coupled via a two-dimensional electron gas in a GaAs-, graphene- or topological insulator-based structure.

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Topological Surface States in Topological Insulators, Superconductors, and Beyond

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Bulk Topological Insulators are a new phase of electronic matter which realizes a non-quantum-Hall-like topological state in the bulk matter and unlike the quantum Hall liquids can be turned into superconductors. In this talk, I will first briefly review the basic theory and experimental probes that reveal topological order. I will then discuss experimental results that demonstrate the fundamental properties of topological insulators (at the level of M.Z.Hasan and C.L. Kane, Rev. of Mod. Phys., 82, 3045 (2010)). I will then discuss the possible exotic roles of broken symmetry phases such as superconductivity and magnetism in doped topological insulators and their potential device applications in connection to our recent results as well as briefly outline the emerging research frontiers of the field as a whole from nanoscale device applications.

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Electrons on Surfaces of Topological Insulators: Coherence and Spin-Polarization at Room Temperature

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Scattering of electrons on crystal imperfections represents the ultimate limit on how good a material is for conducting the electrical currents. In topological insulators, the electronic states at material's boundaries scatter in a fundamentally different way than electrons in conventional materails. These states do not bounce back if they hit a potential barrier, a property that makes them ideal candidates for spintronics and quantum computing applications. However, magnetic impurities should cause back scattering and induce losses. In addition, inelastic scattering on phonons should introduce dissipation and de-coherence in a conventional way. In our Angle-Resolved Photoemission Spectroscopy (ARPES) studies, we reveal that, contrary to the expectations, the topological surface states are not affected by magnetic impurities and are extremely weakly coupled to phonons. In addition, these states remain fully spin-polarized, even at ambient temperatures. Our findings show that topological insulators have a potential to serve as a basis for room-temperature electronic devices.

This work is supported by the US Department of Energy.

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Point Group Symmetric Topological Insulators

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The discovery and classification of topological phases in condensed matter systems is a very active area of physics. To date, the vast majority of 2D and 3D topological materials that have been discovered are those which preserve time-reversal invariance. In principle, it is possible to find many additional topological systems each containing distinct physical observables characterized by the underlying symmetries that they preserve. In this sense, non-trivial topological systems possessing crystallographic point group symmetries (PGS) are of great interest because PGS universally exist in solids and may encompass materials that possess broken symmetry ground states.

In this talk, I will discuss a complete and general classification of all two-band k•p theories at high-symmetry points in 3D crystals containing C_n PGS. By applying this classification to 3D semimetals, we may classify all band crossings points by knowing the symmetry representations of the conduction and valence bands along high-symmetry lines in the Brillouin zone. We discuss the application of this theory to the 3D semimetal $HgCr_2Se_4$ in the ferromagnetic phase to show that it is a double Weyl metal whose bulk Weyl nodes are stabilized by C_4 rotational symmetry. We conclude by discussing the use of quasiparticle interference patterns in scanning tunneling microscopy experiments to experimentally classify PGS topological materials.

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Supercurrents in Time-Reversal Invariant Topological Insulator Josephson Junctions

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The coupling of 2D surface states with s-wave superconductivity is predicted to harbor the much-desired Majorana quasiparticle excitations. While superconductivity has been demonstrated in Josephson Junctions on the surface of 3D topological insulators (TIs), the nature and behavior of the resultant supercurrent remains largely unexplored. Here, we report critical current measurements in a DC biased TI Josephson junction as a function of chemical potential. We show, for the first time, the coupling of topological surface current with s-wave superconductivity as the chemical potential is shifted into the bulk band gap. We find that despite the presence of significant bulk density, a large majority of the critical current flows via surface states. We compare this with 3D quantum transport simulations to show that the injection into the surface states is due to the topology of the bands and is robust against time-reversal symmetric disorder provided the disorder does not hybridize the bulk bands with the topological surface states. We find that once disorder is sufficient to mix the bands, the topological nature is lost and bulk injection occurs. This work provides a crucial step towards understanding the necessary and sufficient conditions required to observe non-Abelian excitations in TI Josephson Junctions.

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Magneto-electric and Superconducting Properties of Doped Topological Insulators

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The recent prediction and experimental discovery of topological insulators has ignited a new field of condensed matter physics. Many of the unique features of topological insulators require that the bulk be completely insulating to be observed, yet most material samples are intrinsically doped and dominated by bulk carriers. In this talk we will describe two phenomena that distinctly identify topological insulators even when doped: a topological magneto-electric effect and a vortex phase transition in superconducting topological insulators (such as Cu-Bi_2Se_3). We will also show how materials design can optimize these effects so that they can be observed in experiments.

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Observation of Fractional AC Josephson Effect: The Signature of Majorana Particles

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Topological superconductors which support Majorana fermions are thought to be realized in one-dimensional semiconducting wires coupled to a superconductor. Such excitations are expected to exhibit non-Abelian statistics and can be used to realize quantum gates that are topologically protected from local sources of decoherence. I will report the observation of the fractional ac Josephson effect in a hybrid semiconductor/superconductor InSb/Nb nanowire junction, a hallmark of topological matter. When the junction is irradiated with a radio-frequency f in the absence of an external magnetic field, quantized voltage steps (Shapiro steps) with a height hf/2e are observed, as is expected for conventional superconductor junctions, where the supercurrent is carried by charge-2e Cooper pairs. At high magnetic fields the height of the first Shapiro step is doubled to hf/e, suggesting that the supercurrent is carried by charge-e quasiparticles. This is a unique signature of Majorana fermions.

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Design and Formation of Multiple Asymmetric Potential in a GaAs-Based Nanowire for Electron Brownian Ratchet

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Biological systems are considered to obtain coherent force from fluctuating molecules utilizing Brownian ratchet mechanism. To implement this mechanism electronically, periodic asymmetric potential is necessary, which work as a ratchet for electrons. We present design and formation of periodic asymmetric potential in GaAs-based nanowire channel with wedge-shaped wrap gate array. The formation of asymmetric potential is confirmed by three-dimensional potential simulation and current-voltage characteristics at 10K in a single gate device. In flashing ratchet operation, a fabricated multiple asymmetric gate device shows current, whereas a symmetric gate device does not show.

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Second-harmonic Generation Using $\bar{4}$-quasi-phasematching in a GaAs Microdisk Cavity

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The $\bar{4}$ crystal symmetry in materials such as GaAs can enable quasi-phasematching for efficient optical frequency conversion without poling, twinning or other engineered domain inversions. $\bar{4}$ symmetry means that a 90° rotation is equivalent to a crystallographic inversion. Therefore, propagation geometries where light circulates about the $\bar{4}$ axis, as in whispering-gallery-mode microdisk resonators, produce effective domain inversions that are useful for quasi-phasematching. Microdisk resonators also offer resonant field-enhancement and excellent spatial overlap, resulting in highly efficient frequency conversion in micrometer-scale volumes. These devices can be integrated in photonic circuits as compact sources of radiation or entangled photons. Efficient second-order frequency conversion is a new functionality for semiconductor microdisk resonators, which have been previously explored for all-optical circuits as switches, signal routers and optical logic gates. Here, we present the first experimental observation of efficient second-harmonic generation in a microdisk cavity utilizing $\bar{4}$-quasi-phasematching.

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The Spin-Seebeck Effect in Semiconductors

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The spin-Seebeck effect (SSE) is due to perturbations of magnetic ordering in an applied temperature gradient ∇T. The gradient drives the spin-polarized particles out of thermal equilibrium. This generates a spin flux that is converted into a voltage in a non-polarized adjacent material, typically Pt, by the inverse spin-Hall effect. First discovered on thin permalloy films in 2008 by the research group of E. Saitoh [1], the SSE has been measured on ferromagnetic insulators [2] and semiconductors [3]. The effect is small (on the order of ≤ 1μVK^{-1}) in ferromagnets, although phonon-drag has been shown to increase it 5-fold [4]. However, a giant spin-Seebeck effect [5] has been observed at cryogenic temperatures in a bulk non-magnetic semiconductor, n-type InSb, where it reaches values (~ 8mVK^{-1}) comparable to the highest classical thermopower. The conduction electrons in InSb, when subject to a quantizing magnetic field are confined to Landau levels. At high field *B,* the last Landau level is split by the Zeeman effect into spin-polarized spin-up and spin-down levels. Applying a ∇T creates a strong out-of-equilibrium distribution of electrons between these two levels by a combination of phonon-drag and strong spin-orbit interactions in InSb itself. Although such effect has so far only been observed at cryogenic temperatures, we suggest that the spin-Seebeck effect opens the way to a new class of spin-thermal energy converters, which, with much future research, may prove superior to classical thermoelectric converters. In particular, the 8mVK^{-1} mentioned above arises across a Pt bar which has high electrical conductivity, giving it a power factor *P* many orders of magnitude larger than that of conventional thermoelectrics.

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Dynamical Generation of Spin Currents

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Spin current, a flow of electrons' spins in a solid, is the key concept in spintronics that will allow the achievement of efficient magnetic memories, computing devices, and energy converters. I here review phenomena which allow us to use spin currents in insulators [1]: inverse spin-Hall effect [2,4], spin pumping, and spin Seebeck effect [4-6]. We found that spin pumping and spin torque effects appear at an interface between an insulator YIG and Pt. Using this effect, we can connect a spin current carried by conduction electrons and a spin-wave spin current flowing in insulators. We demonstrate electric signal transmission by using these effects and interconversion of the spin currents [1]. Seebeck effect (SSE) is the thermal spin pumping [5]. The SSE allows us to generate spin voltage, potential for driving nonequilibrium spin currents, by placing a ferromagnet in a temperature gradient. Using the inverse spin-Hall effect in Pt films, we measured the spin voltage generated from a temperature gradient in various ferromagnetic insulators.

This research is collaboration with K. Ando, K. Uchida, Y. Kajiwara, S. Maekawa, G. E. W. Bauer, S. Takahashi, and J. Ieda.

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Voltage Control of Magnetic Anisotropy in Ultrathin FePd and FeCo, and Coherent Magnetization Switching Using Voltage Pulses

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Voltage control of magnetization has been achieved in many systems, such as ferromagnetic semiconductors [1], magnetostrictive/piezoelectric bilayers [2], multiferroic materials [3], ferromagnetic metal films sintered in a liquid electrolyte [4,5], and ultra-thin ferromagnetic layers embedded in solid-state junctions [6-11]. Voltage driven actuation is attracting much interest as it is potentially faster and more energy efficient than current based techniques.
We have investigated the voltage response of epitaxial magnetic tunnel junctions with either an ultrathin $L1_0$ FePd(001) or an FeCo(001) layer adjacent to the MgO barrier. Application of a voltage to the junction modulates the perpendicular magnetic anisotropy of the magnetic film, which can be measured through DC magnetoresistance measurements. Clear material dependent effects were observed, such as opposite changes of anisotropy in FePd and FeCo, and voltage non-linearity in the case of FePd.
Nanosecond voltage pulses were then used to excite the magnetization dynamics in FeCo. By changing the easy axis from in-plane to out-of-plane, the voltage causes the magnetization to precess in the plane of the film. By determining the appropriate pulse length, the precession results in a two-ways toggle switching of the magnetization [10]. In this presentation, we will discuss the sensitivity of precessional switching on the length and amplitude of the voltage pulses. We will also point out the differences between voltage torque and spin transfer torque, and ways to distinguish between them.

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Electric Field Control of Ferromagnetism in Ultra-thin Metals

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Electrical control of magnetism adds a new dimension to the future spin based information processing methods. A use of not electric current but of electric field [1-10] is expected to realize ultra low power driving devices. In this talk we show electric field effects on Curie temperature, coercivity, magnetization, and domain wall (DW) velocity in Co and Fe ultra-thin films [7-10].

We thank K. Shimamura, M. Kawaguchi, S. Ono, S. Fukami, N. Ishiwata, M. Yamanouchi, F. Matsukura, H. Ohno, K. Kobayashi, and T. Ono for their help. This work was partly supported by the PRESTO program of JST, a Grant-in-Aid for Young Scientists (A) from MEXT, a Grant-in-Aid for Scientific Research (S) from JSPS, and JSPS through its "Funding Program for World-Leading Innovative R & D on Science and Technology" (FIRST Program).

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Reversible Electrical Switching of Spin Polarization in Multiferroic Tunnel Junctions

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Ferromagnetic tunnel junctions consist of an insulating barrier sandwiched between two ferromagnetic electrodes. In those junctions the magnetization alignment of the electrode is read by the electrical resistance of the junction. Spin-polarized transport in ferromagnetic tunnel junctions, characterized by tunnel magnetoresistance (TMR), has already been proven a high application potential in the field of spintronics and in magnetic random access memories. Until recently, in such a junction the insulating barrier played only a passive role, namely to facilitate electron tunneling between the ferromagnetic electrodes. However, new possibilities emerged when ferroelectric materials were used for the insulating barrier, as these possess a permanent dielectric polarization switchable between two stable states. In a tunnel junction with a ferroelectric tunnel barrier, called ferroelectric tunnel junction, the polarization direction of the ferroelectric barrier influences the resistance of the junction. A junction with magnetic electrodes and a ferroelectric barrier is called multiferroic tunnel junctions. By combining the two different magnetization alignments of the electrodes and the two polarization directions of the barrier four non-volatile states are therefore possible in such multiferroic tunnel junctions.

Due to the potential coupling, a magnetoelectric interaction, between magnetization and ferroelectric polarization at the interface between the electrode and barrier of a multiferroic tunnel junction, the magnetization of the electrodes is expected to be influenced by the ferroelectric polarization. Here, we show that the spin polarization of the tunneling electrons can be reversibly and remanently inverted by switching the ferroelectric polarization of the barrier. Selecting the spin direction of the tunneling electrons by short electric pulses rather than by an applied magnetic field yields new possibilities for spin control in spintronic devices.

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Electron Nuclear Feedback in the Pauli Spin Blockade Regime of a Double Quantum Dot

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Coherency of electron spins in GaAs quantum dots is significantly degraded by random orientation of the nuclear spins. Electron nuclear feedback is expected to reduce the fluctuation of nuclear spins. In this work, we study how the nuclear spin polarization develops under constant (without sweeping) dc voltages on the gates of a double quantum dot device in the Pauli spin blockade regime. We prepare nominally unpolarized nuclear spins and investigate transient current through the dots. At the beginning, the transport is blocked by the long-lived triplet state, showing the lowest current level. Flip-flop process gradually builds up the polarization more efficiently in one dot, and the inhomogeneous polarization is confirmed by stepwise increase of the current. Then, DNP process becomes more efficient to increase the polarization until the system reaches the feedback condition, which is evidenced as second stepwise increase of the current. This feedback condition may be effective in stabilizing the nuclear spin polarization.

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Single-atom Spin Qubits in Silicon

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The idea of using the spin of a single donor atom in silicon to encode quantum information goes back to the Kane proposal [1] in 1998. The proposal appeared ambitious and visionary and the time, and relied upon the assumption that the progress in the fabrication of classical silicon devices could be harnessed to pursue quantum information goals. We have now resolved the technical challenges involved in the readout and control of the electron and nuclear spin of a single dopant in silicon, while utilizing standard MOS fabrication techniques such as ion implantation [2] and metal gates fabricated on top of high-quality SiO_2 [3]. The key breakthrough was the development of a device structure where the donor is tunnel-coupled to the island of an electrostatically-induced single-electron transistor [4]. This device allowed the single-shot readout of the electron spin with visibility > 90% and 3μs readout time [5]. The single-shot readout device has been integrated with a broadband microwave transmission line to coherently control the electron and nuclear spins. The resonance frequency of the electron is found by monitoring the excess spin-up counts while sweeping the microwave frequency. At any time, one of two possible frequencies is found to be in resonance with the electron spin, depending on the state of the ^{31}P nuclear spin. Alternately probing the two frequencies yields the (quantum nondemolition) single-shot readout of the nucleus, with fidelity > 99.99%.

Then we demonstrate the coherent control (Rabi oscillations) of both the electron [5] and the ^{31}P nucleus, both detected in single-shot mode. The π-pulse fidelity is ~ 60% for the electron and ~ 99% for the nucleus. Hahn echo and multi-pulse dynamical decoupling sequences allow us to explore the true coherence of the qubits, yielding T_{2e} ~ 200μs for the electron, and T_{2e} ~ 60ms for the ^{31}P nucleus. These results are fully consistent with the bulk values for donors in a natural Si sample. Further improvements in qubit coherence can be expected by moving to isotopically pure ^{28}Si substrates.

Finally, we have been able to read out and coherently control an individual ^{29}Si nuclear spin, strongly coupled to the electron. The ^{29}Si spin is addressable after a bath narrowing protocol, and exhibits coherence and relaxation times comparable to those observed in bulk samples.

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Semiconductor Isotope Spintronics

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Ever since our proposal of using isotopes in semiconductor silicon as qubits [1], we have been conducting a wide variety of experiments to demonstrate application of such semiconductor spintronics. This presentation introduces three successful examples of spin manipulation based in isotope engineering:

1) successful entanglement formation and detection between phosphorus electron spins and ^{31}P nuclear spins in isotopically enriched ^{28}Si [2],

2) coherent transfer of quantum information between photoexcited oxygen-vacancy spin triplet electron states and the nearest neighbor ^{29}Si nuclear spins [3], and

3) the successful placement of single NV centers in a 5nm thick, isotopically enriched ^{12}C diamond layer for quantum metrology applications [4].

This work has been performed in collaboration with John Morton's group at University College of London, Stephen Lyon's group at Princeton University, Mike Thewalt's group at Simon Fraser University, Shinichi Shikata's group at AIST, Charles Santori's group at HP Labs, and Junko Hayase's group at Keio University.
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Spintronics Devices for Nonvolatile Memory and Logic

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Spintronics devices which implement a magnetic tunnel junction (MTJ) element are a promising solution for the serious issues of current large-scale integrated circuit (LSI) technology. We have developed two kinds of spintronics devices: two-terminal and three-terminal devices. Here, recent progress and future challenge of these devices will be presented.

The two-terminal device utilizes current-induced magnetization switching and is preferred for relatively high-density memory, e.g. replacement for DRAM. For the practical application, small switching current, large tunnel magnetoresistance (TMR) ratio, and large thermal stability should be obtained at the same time. We have satisfied these requirements by employing a CoFeB/MgO-based MTJ with perpendicular easy axis.

The three-terminal device utilizes current-induced domain wall motion and is preferred for relatively high-speed memory, e.g. replacement for SRAM. Co/Ni or CoFeB-MgO was found to be a good candidate for the material of the three-terminal devices. Especially, we have demonstrated the high-speed capability and high reliability by using the Co/Ni multilayer.

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Geometry Dependence of the Switching Time in MTJs with a Composite Free Layer

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Magnetoresistive random access memory with spin transfer torque (STT-MRAM) is a promising candidate for future universal memory. Perpendicular MTJs with an interface-induced anisotropy show potential, but still require damping reduction and thermal stability increase. Thus, finding alternative architectures for MTJ structures is of considerable importance for the success of STT-MRAM. Previously a MTJ with a composite free layer (C-MTJ) was proposed. The free magnetic layer of such a structure consists of two equal parts of half-elliptic form separated by a non-magnetic spacer. C-MTJs demonstrate a substantial decrease of the switching time and switching current.

We have investigated the switching statistics dependence on the geometry of the composite layer. We find that in C-MTJs with an elongated short axis the width of the switching time distribution is almost ~2000 times narrower than that in MTJs with a monolithic free layer. To find an explanation for this distribution narrowing, we analyze the switching process in detail. Each half of the free layer generates a stray magnetic field which influences the dynamics of the other half. This stray field increases with increasing short axis, which leads to the switching times distribution narrowing. Therefore, the investigated C-MTJ offers great potential for performance optimization of STT-MRAM devices.

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Half-metallic Heusler Alloy Thin Films for Spintronic Devices

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The creation of a highly spin-polarized current is essential for spintronic devices. One of the most suitable types of spin source materials for spintronic devices is half-metallic ferromagnets (HMFs) because of their complete spin polarization at the Fermi level. Among HMFs, Co-based Heusler alloys (Co_2YZ, where Y is usually a transition metal and Z is a main group element) are especially promising due to their high Curie temperatures, which are well above room temperature.

We have recently investigated the effect of defects in Heusler alloy Co_2MnSi thin films on spin-dependent tunneling characteristics. We found that fully epitaxial $Co_2MnSi/MgO/Co_2MnSi$ MTJs (Co_2MnSi MTJs) with Mn-rich Co_2MnSi electrodes exhibited high tunnel magnetoresistance (TMR) ratios of 1135% at 4.2K and 236% at 290K, exceeding those of MTJs with Co_2MnSi electrodes having an almost stoichiometric composition [1]. The observed lower TMR ratios for MTJs with Mn-deficient Co_2MnSi electrodes were explained by the formation of Co_{Mn} antisites that lead to minority-spin in-gap states around E_F as theoretically predicted by Picozzi et al. [2]. Consistent with this, the observed higher TMR ratio for MTJs with Mn-rich Co_2MnSi electrodes was explained by suppressed Co_{Mn} antisites, which caused a reduced density of minority-spin in-gap states around E_F [1].

To further clarify the key factors that influence the spin-dependent tunneling characteristics of Heusler alloy/MgO-based MTJs, we investigated how improved interfacial structural properties affect the TMR characteristics of Co_2MnSi MTJs. Giant TMR ratios of up to 1995% at 4.2K and up to 354% at 290K were obtained for Co_2MnSi MTJs with Mn-rich Co_2MnSi electrodes and featuring a reduced lattice mismatch in the MTJ trilayer obtained by introducing a thin Co_2MnSi lower electrode deposited on a $Co_{50}Fe_{50}$ buffer layer [3]. The obtained giant TMR ratios can be explained by the enhanced contribution of coherent tunneling originating from the increased misfit dislocation spacing at the lower and upper interfaces with a MgO barrier along with the half-metallicity of Co_2MnSi electrodes. Our experimental findings suggest that the in-gap states can be reduced by appropriate control of defects through the film composition, enabling the full utilization of half-metallic Heusler alloy thin films in spintronic devices.

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The Giant Spin Hall Effect and New Approaches for Spin Torque Devices and Circuits

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Spin-polarized currents can be used to apply torques to magnetic moments by direct transfer of spin angular momentum, enabling manipulation of nanoscale magnetic devices using currents much lower than required for magnetic-field-based control. Until recently the only way to generate spin currents strong enough for spin torque (ST) reversal or excitation of nanomagnets in practical applications has been to send an electron current through a magnetic polarizing layer, with the result that the most promising device geometry for applications has been the two-terminal magnetic tunnel junction (MTJ), consisting of a ferromagnetic layer (FM)/tunnel barrier/FM structure. While it has been known for some time that an electrical current density J_e in non-magnetic materials can generate a transverse spin current $[\hbar/(2e)]J_S$ by the spin Hall effect (SHE), where spin-orbit coupling causes electrons with opposite spin orientation to deflect in opposite directions, the strength of this effect has been generally reported as being weak. Recently we have reported the discovery of a giant SHE in the high resistivity form of tantalum (β–Ta) with $\theta_{SH}^{Ta} =$ 0.12-0.15, where $\theta_{SH} \equiv J_S / J_e$. Subsequently we found an even larger SHE in β–W with $\theta_{SH}^{W} \approx$0.30. We have employed this effect to implement a novel three-terminal device geometry in which the SHE-ST produces current-induced switching of an in-plane polarized FM layer, with read-out using a MTJ. This 3-T SHE-ST device is straightforward to fabricate and can have comparable efficiency to conventional two-terminal MTJs while providing greatly improved reliability and output signal levels, and therefore offers a powerful new approach for ST-MRAM. We have also shown that the SHE-ST can be combined with another recent discovery, voltage controlled magnetic anisotropy, to achieve new functionality: gate-voltage-modulated spin torque switching. This gating makes possible both more energy-efficient switching and also improved architectures for memory applications, including a simple approach for making magnetic memories with a maximum-density cross-point geometry that does not require a control transistor for every MTJ. In this presentation I will summarize our current understanding of the giant SHE in these material systems, and discuss aspects of SHE-ST relevant to various spintronic device and circuit applications.

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Device Modeling and Circuit Simulation of Spin-Transfer-Torque MRAM Considering Variability

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Spin-Transfer-Torque Magnetic Random Access Memory (STT-MRAM) is one of the most promising candidates for the next generation non-volatile memory with high speed and high reliability. For further increasing memory capacity, the miniaturization of the magnetic tunnel junction (MTJ) element is essential. In this study, we report on the investigations of the read and write characteristics of MTJ cells based on non-equilibrium Green's function method and Landau-Lifshiz-Gilbert (LLG) micromagnetic simulation. The impact of various variation sources (e.g., oxide film thickness, cell area, and thermal fluctuation) in the scaled MTJ cells on the MRAM circuit characteristics will be discussed.

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Physics and Applications of Current-induced Domain Wall Motion in Magnetic Nano-wires

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Electrical displacement of a domain wall (DW) is a prospective method for information processing in new type of magnetic non-volatile memories and logic devices[1-4]. Such novel spintronic devices require a low DW drive current and a high DW de-pinning field for stable information retention. We show that Co/Ni multilayer with perpendicular magnetic anisotropy is a promising material that satisfies these requirements. An electric current can drive a DW in one direction regardless of the polarity of a magnetic field in a Co/Ni nano-wire with perpendicular magnetization, i.e., the current can drive a DW against a magnetic field. Furthermore, both the DW velocity and the threshold current density for the DW motion show almost no dependence on the external magnetic field. These counter-intuitive behaviors can be interpreted as the consequence that the intrinsic pinning mechanism determines the threshold current, and the adiabatic spin torque dominates the DW motion in this system [5-11]. The established field-insensitivity of the electrical DW motion is promising for future spintronics applications based on the DW motion.

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Reconfigurable Array of Magnetic Automata (RAMA)

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RAMA represents a new paradigm for memory and logic based on a self assembled array of magnetic nanopillars embedded in a piezoelectric matrix. The magnetization direction in these pillars can be changed with electric fields applied to the matrix immediately surrounding the nanopillars. We have demonstrated this principle using a hybrid fabrication approach for this structure and are characterizing the switching behavior and will report on the status of this project at the WINDS conference.

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Bipolar Magnetic Junction Transistors for Spin Logic

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Bipolar magnetic junction transistors and diodes have been developed for spin logic circuits that operate at room temperature. We have investigated the effect of magnetic field strength and temperature on the operating characteristics of bipolar magnetic semiconductor heterojunction devices. Both InMnSb and InMnAs dilute magnetic semiconductor heterojunctions were studied. For an InMnAs p-n-p transistor magneto amplification was observed where the gain of the transistor decreases with magnetic field strength [1]. The magneto amplification was attributed to the positive junction magnetoresistance associated with the heterojunction between InMnAs and InAs. The magnetoresistance is attributed to spin-selective conduction. The magnitude of the junction magnetoresistance depends on the effective Landé g-factor. A large g-factor leads to a high degree of spin polarization. Measurements indicate that the effective g factor depends on temperature and Mn concentration. The existence of magnetic semiconductor heterojunction devices potentially enables the creation of new computer logic architectures that operate at room temperature [2]. We have recently proposed an emitter-coupled spin-transistor logic that potentially results in circuits with enhanced speed, smaller area and much improved power- delay product.

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Magnonic Logic Devices: Current Status and Perspectives

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Modern logic circuits consist of a large number of transistors fabricated on a surface of a silicon wafer and interconnected by metallic wires. In the past sixty years, a straightforward approach to functional throughput enhancement was associated with the increase of the number of transistors, which is well known as the Moore's law. Decades of transistor-based circuitry perfection resulted in the Complementary Metal–Oxide–Semiconductor (CMOS) technology, which is the basis for the current semiconductor industry. Unfortunately, CMOS technology is close to the fundamental limits mainly due to the power dissipation problems. The latter stimulates a big deal of interest to the post-CMOS technologies able to overcome the current constrains. Magnonic logic circuits exploiting magnetization as a state variable and spin waves for information transmission and processing is one of the possible solutions. The utilization of waves for data transmission makes it possible to code logic 0 and 1 in the phase of the propagating wave, make use of waveguides as passive logic elements for phase modulation and exploit wave interference for achieving logic functionality. In this work, we review the recent progress in magnonic logic devices development and discuss the perspectives of this approach.

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Giant Enhancement of Spin Accumulation and Long-distance Spin Precession in Lateral Spin Valves

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The non-local spin injection in lateral spin valves (LSVs) has provided not only scientific interests to study spin transport in a nanowire but also potential spintronic device applications. The non-local method involves no charge-current flow but spin accumulation in the nonmagnetic wire. In order to increase the output signal, related to the spin accumulation splitting for electrochemical potential, efficient spin injection into the nonmagnet from the ferromagnet as well as high applied current are indispensable. Although a low junction resistance is preferred for applying high current, the spin resistance mismatch between the ferromagnet and the nonmagnet needs to be overcome to achieve efficient spin injection by inserting high interface resistance such as tunnel barrier. In this talk, I will discuss a guideline to design the LSVs. The interface resistance of around 0.1Ωμm^2, several orders of magnitude smaller than that of a typical tunnel junction, can effectively overcome the spin resistance mismatch in the metallic system [1] and leads to the giant spin accumulation signal over 200μV in LSVs with NiFe/MgO/Ag junctions [2]. The Hanle effect measurements demonstrate a long-distance 2π spin precession along the 10μm long Ag wire. In the diffusive pure spin transport, the spin precession decoheres due to broadening of the dwell time distribution in the channel between the injector and the detector. The coherency in the spin precession is summarized in a universal behavior as a function of the normalized channel length in material-independent fashion for metals and semiconductors including graphene [3].

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Graphene as a Tunnel Barrier: Magnetic Tunnel Junctions and Spin Injection into Silicon

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Graphene has been widely studied for its high in-plane charge carrier mobility and long spin diffusion lengths. In contrast, the out-of-plane charge and spin transport behavior of this atomically thin material have not been well addressed. Tunnel barriers are the basis for many spintronic devices, and to date have relied upon oxides which often exhibit defects, trap states and interdiffusion which compromise performance and reliability. We show here that while graphene exhibits metallic conductivity in-plane, it serves effectively as an insulator for transport perpendicular to the plane. The transport occurs by quantum tunneling perpendicular to the graphene plane and preserves a net spin polarization of the current from a ferromagnetic (FM) contact.

The graphene was grown by chemical vapor deposition on copper foil and incorporated as the tunnel barrier by physical transfer and standard lithographic processes to form NiFe / graphene / Co magnetic tunnel junctions (MTJs) 20-40μm in diameter [1]. Non-linear *IV* curves and weak temperature dependence of the zero-bias resistance provide clear evidence for tunneling. These structures exhibit tunneling magnetoresistance to 425K, in good agreement with theory [2], which decreases monotonically with both bias and temperature, typical of MTJ behavior.

Single-layer graphene also successfully circumvents the classic issue of conductivity mismatch between a metal and a semiconductor for electrical spin injection and detection, providing a highly uniform, chemically inert and thermally robust tunnel barrier. We demonstrate electrical generation and detection of spin accumulation in silicon above room temperature, and show that *(a)* the corresponding spin lifetimes correlate with the silicon carrier concentration, confirming that the spin accumulation measured occurs in the silicon and not in the graphene or interface trap states, and *(b)* the contact resistance–area products are two to three orders of magnitude lower than those achieved with oxide tunnel barriers on silicon substrates with identical doping levels. Our results identify a new route to low resistance–area product spin-polarized contacts, a key requirement for semiconductor spintronic devices that rely on two-terminal magnetoresistance, including spin-based transistors, logic and memory [3].

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Efficient Spin Transport in Graphene

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Spintronics is a paradigm focusing on spin as the information vector. Ranging from quantum information to zero-power non-volatile magnetism, the spin information can also be translated from electronics to optics. Several spintronics devices (logic gates, spin FET, etc) are based on spin transport in a lateral channel between spin polarized contacts. However while spin is acclaimed for information storage, a paradox is that efficient spin transport as remained elusive.

We will present magneto-transport experiments on epitaxial graphene multilayers on SiC [1] connected to cobalt electrodes through alumina tunnel barriers [2]. The spin signals are in the MΩ range in terms of $\Delta R = \Delta V/I$ [3]. This is well above the spin resistance of the graphene channel. The analysis of the results in the framework of drift/diffusion equations leads to spin diffusion length in graphene in the 100µm range (as high as 285µm) for a series of samples having different lengths and different tunnel resistances. In the best case, the spin transport efficiency of epitaxial graphene is found to be of 75% of the ideal channel [3].

In conclusion, graphene, could turn out as a material of choice for large scale logic circuits and the transport/processing of spin information. Understanding the mechanism of the spin relaxation, improving the spin diffusion length and also testing various concepts of spin gate are the next challenges.

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Spintronics with Graphene-passivated Ferromagnetic Electrodes

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Magnetism is today the main technology in use for data storage, with expected further growth coming from the blooming of giant data centers which support online cloud computing. Spintronics is at the heart of this information storage revolution [1], with ferromagnets acting as fundamental building blocks: spin sources or analysers. However, these ferromagnetic metals (e.g. nickel, cobalt…) are easily prone to oxidation, detrimental to their performances. In turn, this limits their processability, e.g. with low cost wet processes, and their integrability, e.g. with organic molecules or chemically derived nanostructures. These limitations impede in particular the development of the promising, but still young, organic spintronics. Graphene-metals systems appear as interesting interfaces for organic-based processes [2]. However, the potential of graphene in vertical spintronics devices has been limited as its integration relied so far on ambient or wet transfer steps [3], [4].
Here, we present graphene-passivated ferromagnetic electrodes (GPFE) as novel oxidation-resistant spin sources. Nickel lines are coated with graphene in a direct and scalable chemical vapor deposition step. An in-situ X-ray photoelectron spectroscopy study shows that the resulting GPFE are reduced during the growth process and remain resistant to oxidation upon air exposure. The GPFE spin polarisation properties are then measured through a complete vertical spin valve structure based on a standard Al_2O_3/Co spin probe. It appears that GPFE not only retain a spin polarisation, but also present a particular majority spin filtering effect, which eventually leads to the reversal of the its spin polarisation. Our results open new promising pathways for organic-based spintronics devices.

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Reduction of Surface Roughness Induced Spin Relaxation in Thin Silicon Films

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In order to integrate contemporary electronics with spin-based devices three issues must be solved: spin injection, spin transport, and spin detection. We focus on a particular issue in spin transport, namely on spin relaxation due to surface roughness scattering in thin (001) silicon films.

To accurately describe the band structure of silicon in the presence of the intrinsic spin-orbit interaction we generalize the perturbative two-band k•p approach to include the spin degree of freedom. Due to the spin-orbit interaction the spin-up and spin-down functions are not the eigenfunctions of the Hamiltonian resulting in a finite probability of spin-flip during scattering. Surface roughness scattering is taken proportional to the product of the subband function derivatives at the interfaces squared. An accurate inclusion of the spin-orbit interaction results in a large mixing between the spin-up and spin-down states along the [100] and [010] axes resulting in spin “hot spots”. The origin of these “hot spots” lies in the unprimed subband degeneracy in a confined electron system. Shear strain splits the otherwise degenerate unprimed subbands. This energy splitting removes the origin of the spin “hot spots”, which should substantially improve the spin lifetime in thin silicon films.

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Dynamical Generation of Spin Currents

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In this work, we experimentally demonstrate efficient spin injection into semiconductors through ohmic and Schottky contacts using dynamical spin injection: spin pumping. In a ferromagnetic metal/semiconductor (FM/SC) junction, the spin-angular momentum of precessing magnetization in the FM layer is transferred to the carriers in the SC layer via dynamical spin-exchange coupling, inducing a pure spin voltage, the potential acting on spins not on charges, in the SC layer. This enables spin injection into both p- and n-type GaAs from NiFe through both ohmic and Schottky contacts in a NiFe/GaAs interface even at room temperature. Furthermore, we demonstrate that the spin exchange interaction can be controlled electrically by applying a bias voltage across a NiFe/GaAs interface, enabling electric tuning of the spin-pumping efficiency [1]. The dynamical spin injection can be used to explore the physics of spin currents in high resistivity materials. A spin current is coupled with a charge current through the spin-orbit interaction in solids. This coupling enables conversion from spin currents into charge currents: the inverse spin Hall effect, providing a route for electric detection of spin currents. However, so far, the inverse spin Hall effect has only been accessible in limited materials, excluding a wide range of indirect-bandgap semiconductors, which precludes further development. Notable in this group is Si, the most fundamental material in the current electronic chips. Accessing the inverse spin Hall effect in Si has been believed to be difficult because of the very weak spin-orbit interaction. Here we show that the dynamical spin injection allows access to the inverse spin Hall effect in Si at room temperature.

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Spin Lasers and Spin Communication

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Practical paths to room-temperature spin-controlled devices are typically limited to magnetoresistive effects, successfully employed for magnetically storing and sensing information. However, spin-polarized carriers generated in semiconductors by circularly polarized light or electrical injection, can also enhance the performance of lasers, for communication and signal processing [1]. While in the steady-state such spin-lasers already demonstrate a lower threshold current for the lasing operation [2] as compared to their conventional (spin-unpolarized) counterparts, the most exciting opportunities come from their dynamical operation. We reveal that the spin modulation in lasers can lead to an improvement in the two key figures of merit: enhanced bandwidth [3] and reduced parasitic frequency modulation—chirp [4]. The principles of spin modulation may also enable high-performance spin interconnects exceeding by orders of magnitude the information transfer available in conventional metallic interconnects [5].

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Evidence of Strong Coupling Between Electron and Nuclear Spin Systems in Two-dimensional Quantum Wells

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The ν= 2/3 spin phase transition (SPT) peak well reflects nuclear polarization and its spatial distribution in GaAs quantum systems [1-3]. This SPT peak measurement is applied to study electron and nuclear spin interactions in single and bilayer GaAs quantum wells. When nuclear spins are spatially inhomogeneously polarized by current flow and subsequently exposed to two-dimensional systems, most of the case, the time evolution of the SPT peak can be explained by a conventional nuclear relaxation with different time constant. The surprising phenomena appear in the nuclear spin systems exposed to the bilayer canted spin (CS) state where one can expect many-body coherent electron-spin state. The SPT peak evolution clearly indicates a drastic enhancement of in-plane nuclear diffusion, suggesting an existence of the novel coupling between electron and nuclear spin systems. This interesting feature weakens with increasing temperature from 70mK to 200mK, supporting contribution of the coherent electron state. Although less prominent, the similar phenomena appears for the single layer Skyrmion state at very low temperatures.

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GaN Nanowires: Growth, Optical Properties, and the Route Towards LED Applications

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We are investigating GaN nanowires both, to study the underlying growth processes and to test their potential as building blocks for nanoscale devices. In this talk we will discuss group-III nitride nanowires with respect to their possible impact on realising high quality material on Si, in particular for LED applications.

We grow such nanowires by molecular beam epitaxy (MBE) on bare Si surfaces without any aid by prestructuring or coverage by foreign materials. We will at first illustrate the factors that govern the nucleation process and the formation of the initial nanowire diameter on Si.

In order to assess the usefulness of such structures, some results on structural and luminescence properties will be presented. They will illustrate that despite the high surface-to-volume ratio, the luminescence of GaN nanowires can be very efficient, but also shows some features that are unusual compared to planar GaN layers.

In order to prepare test devices, we have grown p-i-n structures and processed these into arrays of LEDs and I will show results on electroluminescence as well as an analysis of their efficiency.

Looking into the future, it has to be questioned if the statistical nucleation process can be sufficiently controlled in order to lead to a viable technology. To address this issue, we will present promising results of our efforts to achieve a controlled positioning of GaN nanowires by selective area growth.

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Tailoring Photonic Properties in Hierarchical, Branched Arrays of Nanowires.

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Arrays of semiconductor nanowires are of potential interest for applications including photovoltaic devices and IR detectors/imagers. While nominally uniform arrays have typically been studied, arrays containing nanowires with multiple diameters and/or random distributions of diameters, could allow tailoring of the photonic properties of the arrays. In this study, we demonstrate the growth and optical properties of hierarchical, branched InSb nanowire arrays. The structure consists of three vertically stacked regions, with average diameters of 20, 100 and 150nm. Reflectance and transmittance have been performed in the visible and IR ranges, and absorbance has been calculated from these measurements. The structures show low reflectance over the full wavelength range and a roll-off in the absorbance spectra at wavelengths well below the bulk cut-off of ~ 7μm. We have also developed a model considering the diameter-dependent photonic coupling (at a given wavelength) and random distribution of nanowire diameters. The wavelength-dependent absorbance in the IR region is attributed to diameter-dependent photonic coupling, and randomness is observed to broaden the absorbance response. Varying the average diameters would allow tailoring of the wavelength dependent absorption within various layers, which could be employed in photovoltaic devices or wavelength dependent-IR imagers.

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Dissipative Transport in Nanowire FETs

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We will discuss fullband Monte Carlo simulation of nanowire FETs. Here we have implemented a full atomistic approach based on the empirical tight binding method using a sp3d5s* basis. The full quasi-1D scattering rates (intra- and intersubband) calculated using this basis for the various phonon scattering processes (including the full bulk phonon dispersion) are stored in a lookup table and used in the Cellular Monte Carlo algorithm. Application to the modeling of realistic n and p-MOS device structures currently under development will be discussed.

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Transport Characteristics of Gate-All-Around InAs Nanowire FETs

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Semiconductor nanowires (NWs) are promising candidates as building blocks for future electronic devices beyond conventional CMOS technology. NWs of narrow band gap materials, such as InAs, are of particular importance due to the intrinsic high electron mobility in view of application to high-performance field-effect transistors (FETs). We fabricate InAs NW lateral FETs with a gate-all-around (GAA) geometry enabling improved electrostatic control. We adopt a two-step gate electrode formation method where a NW, conformally coated with 6nm of Al_2O_3 gate dielectric, is sandwiched between the lower and upper gate metals. This method allows us to make the gate electrode overlap the source/drain electrodes, where the NW channel is completely encapsulated inside the gate stack. The fabricated GAA FETs exhibit a high on-current comparable with the best values previously reported in NW FETs. This may be attributed to the enhanced electron mobility due to surface passivation by the gate metal, as well as to an elimination of the parasitic resistance near the source/drain electrodes. We also investigate ac magneto-conductance of the GAA FETs down to 1.5K, and observed clear weak-anti-localization characteristics arising from Rashba spin-orbit interaction. We discuss advantage of using radial electric field generated by GAA structure from a view point of application to spintronics devices.

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Vertical Si Nanowire Array High Sensitivity Photodetectors and Retinal Prosthetic Devices

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This abstract is not printed due to the authors' request.

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QED Interfacial Heat Conductance in Nanocarbon Thermal Interconnects

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Heat management solutions are critical nowadays in multiple fields and applications, from nanoelectronics to spacecrafts. Interfacial thermal barrier is known to be one of the largest problems that modern nanomaterials were aimed to overcome. Nanocarbons in various forms have been suggested to serve as a cheap and excellent thermal interconnect material, though their interface heat conductance has not been completely understood so far. We show that the bulk heat conductance of the nanocarbons (graphene and nanotubes are studied in details) is unlikely to be a bottleneck for thermal applications. It is rather the thermal interfacial conductance mechanism which will be of critical importance. On the basis of atomistic quantum models and fluctuational electrodynamics we studied the QED thermal conductance across the interface between a nanocarbon material and a dielectric/semiconductor/metal substrate. Extremely high and potentially controllable thermal conductance was found and the physics of the effect was explained in terms of the near-field radiative heat transport. Both analytical models and useful empirical fits will be presented to guide the design of well-tempered nanocarbon thermal interconnects.

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Carbon Nanotube Field Effect Transistors with Graphene Contacts

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Carbon nanotube field effect transistors (CNT-FETs) with graphene contacts which were formed by using solid-phase epitaxy of graphene on the CNT were fabricated. The CNT-FETs showed p-type conduction in air. However, the conduction type has changed to ambipolar in a vacuum after annealing at 200^{o}C. This suggests that the p-type conduction in air is attributed to the adsorbed oxygen. The barrier heights at the graphene/CNT contacts in vacuum were ~400meV for electrons and ~310meV for holes. These values suggest that the Fermi level of graphene contacts is located at slightly below the midgap of the CNTs in vacuum.

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Graphene Based Integrated Electronic, Photonic, and Spintronic Circuit

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We demonstrate theoretically how using size, shape, and edge engineering of graphene one can implement the three functionalities of an integrated carbon based circuit: electronics, photonics and magnetism. We demonstrate single electron transistor action in a gated graphene quantum dot, show that it interacts with light, and discuss existence of magnetic moment in nanostructures with broken sublattice symmetry. We focus on three unique features of graphene quantum dots: (a) magnetic field tunability of bandgap, (b) erasure of magnetic moment with a gate and restoration with a photon, and (c) electric field switching of magnetic moment in bi-layer quantum dots.

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Electric Transport and Spectroscopic Studies on CVD Graphene Transistors Fabricated by Using Oxide Passivations

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Graphene has attracted attention as a channel material for future high-speed field-effect transistors (FETs) because of the high mobility. For fabricating graphene FETs at low cost, chemical vapor deposition (CVD) is recognized as a powerful technique to produce large-area graphene on metal catalysts. Graphene grown by CVD on metals must be transferred to insulating substrates, when applying it to a FET channel. In the conventional graphene transfer process, resist polymer layers are used to support graphene while the metal is chemically etched. However, after removing the resist, polymer residues robustly remain on the graphene surface and induce the extrinsic carrier doping into graphene as well as the deterioration in transport characteristics. Here, we report on a newly developed CVD graphene transfer and FET fabrication processes with oxide passivation layers (Al_2O_3, Cr_2O_3, TiO_2, and NiO), which prevents polymer residues from being directly adsorbed on the graphene surface. The efficacy of each oxide passivation has been examined by spectroscopic and four-probe electric transport measurements. It has been found that the Al_2O_3- and Cr_2O_3-passivations are effective to suppress the contaminations from polymer residues on the graphene surface. Meanwhile, the TiO_2- and NiO-passivations are not suitable since the Ti− or Ni−C chemical bonding states induce the reduction of the mobility.

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The Case Against Graphene

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Graphene is often suggested as the next, best thing with which to make semiconductor devices. Here, we review the transport properties of graphene on various substrates, and show that it is unlikely to be better than Si for FETs, and worse than Si in most cases.

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Antidot Lattices in Graphene

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Antidot lattices – regular nanoperforations - defined on graphene can be used to create a band-gap in graphene, thereby allowing for a multitude of device applications. Since the theoretical proposal by our group in 2008 a number of experimental techniques have been devised to fabricate these structures, e.g., by using block co-polymer etch masks, or e-beam lithography. I review the physics of graphene antidot lattices, discuss some recent device proposals, and give an update of the experimental progress made at Technical University of Denmark, and present some very recent transport data.

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Tunneling Spectroscopy of Graphene Using Planar Pb Probes

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Tunneling spectroscopy is an important method used to study the electronic properties of materials, as it has the capability of probing both the electronic density of states (DOS) and energy distributions. We have developed techniques to create lithographically-fabricated planar tunnel junctions on carbon nanostructures such as graphene [1,2]. Such probes have the advantage of high configurability within a standard measurement set up at low temperatures and with high fields. However, there has been limited use of planar tunnel junctions in graphene, likely because of the difficulty in creating the thin, insulating barriers required. We show that Pb deposited directly on graphene forms robust, high quality tunnel junctions, and show that, compared to similarly-fabricated junctions of Al-graphene, Au-graphene, and Pb-Au, only the Pb-graphene junctions are suitable for reproducible tunneling experiments [3]. We demonstrate the flexibility of the Pb tunnel junctions by utilizing them for low-temperature, magnetic and electric field-dependent spectroscopy of the graphene, and discuss energy-dependent features reminiscent of quasiparticle scattering resonances and interference. The superconducting properties of the Pb probes can also be utilized to determine new physics, for example, by determining the spectroscopy of Andreev bound states [4].

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Ballistic Transport in Graphene/h-BN Mesoscopic Wires

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We study magnetotransport in ballistic graphene mesoscopic wires where the charge carrier mean free path exceeds the wire width. The graphene/h-BN mesoscopic wires are fabricated using conventional mechanical exfoliation and transfer technique of single-layer graphene on hexagonal boron nitride crystal. The device exhibits high carrier mobility over 70,000cm2/Vs at 4K and the mean-free path of charge carriers reached ~1μm. Magnetoresistance shows characteristic peak structures, which is attributed to diffusive boundary scattering and magnetic commensurability effect in ballistic graphene. The peak magnetic field scales with the ratio of cyclotron radius R_c and wire width W as W/R_c = 0.9. The proportionality constant of the magnetic commensurability effect is different from that of a semi-classical two-dimensional electron system in semiconductor where W/R_c = 0.55. We also discuss the anomalous Hall effect and the carrier focusing effect in ballistic graphene four-terminal cross junctions.

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Transport Properties of a Single Nanocrystalline Silicon Quantum Dot between Nanogap Electrodes

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We experimentally study transport properties of a single nanocrystalline silicon quantum dot between nanogap electrodes. We obtain the device by depositing nanocrystalline quantum dots directly into ~10 nm gap using a VHF plasma cell. We clearly observe Coulomb diamond at a temperature of 4.5 K. The diamond size depends on the number of electron. Charging energy is estimated as ~12 meV and consistent with the size of the nanocrystalline silicon quantum dot. Perpendicular magnetic field dependence of Coulomb diamonds shows Zeeman splitting as well as orbital energy evolving.

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Adiabatic Motion of Electrons on Cylindrical Surfaces; Curvature Drift and Centrifugal Forces

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We study adiabatic motion of electrons on curved surfaces which were fabricated by self-rolling of thin, pseudo morphologically strained semiconductor bilayer systems based on epitaxial heterostructures grown by molecular-beam epitaxy. One dominant modification of motion of electrons on cylindrical surfaces is the related gradient of the magnetic field, which leads to trochoid- or snake-like trajectories.

The special feature in our samples is that the low-temperature mean free path of electrons is comparable to the radius of curvature of the tube. As a result while moving adiabatically on the cylinder surface the electrons are forced to bend by more than 60°, thereby being enforced to change their momentum direction. Here we discuss two physical consequences of the adiabatic motion of electrons on curved surfaces. First, an anomalous Hall effect (AHE) appears in tangential magnetic fields from induced axial magnetic dipole moments. We will show that this AHE may be interpreted as a topological Hall effect when during adiabatic motion the electrons in their rest frame experience a varying magnetic field. Secondly, an additional drift arises from centrifugal forces of the curved adiabatic motion of electrons in a magnetic field.

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Theoretical and Experimental Results for Information Transfer at the Nanoscale: The Information Ratchet

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A discussion of the thermodynamic constraints on chemical information transfer in catenane and rotaxane systems, with an emphasis on the constraints of microscopic reversibility will be given.

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Electron Transport Properties of a GaAs/AlGaAs Quantum Well with Self-assembled InAs Dots

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In recent years, self-assembled quantum dots have attracted the attention of researchers for application in optoelectronics and quantum computing. When inserted into a two dimensional (2D) electron system the quantum dots form random repulsive scattering centers and reshape the scattering potential from ionized donors. It has been reported that variable range hopping of electrons can take place when applying a large negative gate voltage, and Landau quantization and localization can coexist in this system.

In this work we study the weak localization (WL) effect of a sample (D1) with embedded quantum dots by applying a modest positive gate voltage and compare it with the results from a reference sample in which, apart from the absence of the dots, all other conditions, such as wafer growth sequence and sample geometry, are the same. WL has been studied in various 2D GaAs systems; and in a previous paper concerning the electron transport properties of the 2D gas with embedded InAs dots, WL features had been observed, but no detailed analysis was presented. The WL effect originates from the enhanced backscattering probability due to quantum interference in a weakly disordered system. The application of a magnetic field introduces a phase difference for interfering electrons and thus suppresses the WL effect. Study of WL is very useful in understanding the scattering processes accounting for electron dephasing. These processes can be inelastic electron–electron/electron–phonon scattering, or scattering from magnetic impurities.

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Multi-Electron Wave Packet Dynamics with Long-range Coulomb Interaction

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We have theoretically studied the effect of Coulomb interaction in one-dimensional periodic nanoscale structure using multi-electron wave packet approach, which has crossover nature between particles and waves. We have taken long-range Coulomb interaction into account by time-dependent Hartree-Fock equation. To carry out the time evolution, we solved the equation numerically with fourth-order Taylor expansion. We changed the strength of Coulomb interaction and the number of electrons up to 30. Without Coulomb interaction, electrons spread all over the system, generating plane wave state. With strong Coulomb interaction, electrons repel each other and stay separately, like Wigner crystal like state. What we'd like to note is the weak Coulomb interaction case. With weak Coulomb interaction, electrons show crossover nature between plane wave and Wigner crystal like state. Electrons make clusters, which we call multi-electron wave packets; each of them consists of finite number of electron. Our result suggests three different phases in electron transport: plane wave, Wigner crystal and multi-electron wave packet. In summary, we found that electrons have three different phases depending on long-range Coulomb interaction in nanoscale structure.

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Theoretical Studies on Current-voltage (I-V) Characteristics of Metal Containing Artificial DNA and Ni Complex Based Molecular Devices

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In this work, we theoretically investigate the current-voltage (I-V) characteristics between adjacent bases in two types of artificial metal-DNA (M-DNA) models, i.e., hydroxypyridone (=2-methyl-3-hydroxy-4-pyridone, H) and salen (=N,N-bis(salicylidene) ethylenediamine, S) complexes, using an elastic scattering Green's function method together with a density functional theory. In order to estimate quantitative behaviors of the I-V characteristics of the artificial M-DNAs, we considered I-V characteristics from the following viewpoints: the effect of spin states, the effect of backbone, and the effect of metal ions. We have found that the magnitude of the current of the H complex tends to become larger than that of the S complex. We also found that a difference in the spin states drastically changes the I-V characteristics. These behaviors suggest the possibility of the control of the I-V characteristics in the artificial M-DNA by an external magnetic field. Moreover we also apply the same methods to estimate the I-V characteristics of Ni complex with a one-dimensional chain structure.

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Accuracy of Single-electron Transfer in Si Nanowire MOSFETs

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Single-electron (SE) transfer devices will be key elements for electrical current standards in metrology and SE sources for future electronics and circuits. Especially, it is a potential candidate to realize a new ampere based on a fixed value of the elementary charge in recently proposed “new SI definitions”. We evaluated the accuracy of tunable-barrier SE turnstiles composed of Si nanowire MOSFETs. The measurement was made in a dilution refrigerator at a base temperature of 30mK. The error rate was directly measured by electron counting scheme, where the transferred electron was detected by a charge sensor nearby the SE turnstile. The obtained error rate was 100ppm, which suggests that the actual device temperature was elevated above 1K due to the heating by the pulse voltages to the transfer gate. The heating effect was then studied by reducing the pulse amplitude and investigating the shape of the staircases in the turnstile current. We found that the shape of the current staircases showed a transition which indicates that the transfer mechanism changes from thermal equilibrium to non-adiabatic process. Theoretical analysis shows that the error rate as low as 10ppb will be possible with optimized conditions, suggesting a potential of this device for metrological application.

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Defect Detection and Subthreshold Single Electron Charging in Nanoscale Si Single-electron Transistors by RF Impedance Analysis

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The ability of a Single Electron Transistor (SET) to detect very small charge variations enables a uniquely precise way of characterization of CMOS-relevant materials (e.g. gate stacks containing novel dielectric materials). Most well known method of individual trap detection near nanoscaled SETs is quasi static low frequency (DC) single-electron spectroscopy where differential conductance, G, is measured for slowly changing V_g and V_{ds} ("Coulomb diamonds plot"). The deviation from ideal diamonds enables detection of single impurities and electron traps in and near the SET barriers through comparison with electrostatic models. However, the ability to detect conductance using DC small signal measurement technique is limited by 1/f noise to a level of ~1nS. Therefore, only charging events affecting SETs that are above that minimal conductance can be probed by this method. A different approach for investigation of charging mechanisms in ultra small SETs is by means of Radio Frequency (RF) transport characterization. By analyzing the full impedance of the SET configured as RF reflectometer we study single-electron charging events completely obscured for DC spectroscopy. We present several new effects discovered in nanoscaled MOSSETs using this approach and discuss possible applications and limits of this technique.

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Quantum Transport Simulation for Cross-Technology Comparisons of Beyond-CMOS Nanodevices

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We will present our effort to predict and compare performances of different beyond-CMOS nanodevice paradigms (Si MuGFETs, III-V MuGFETs, tunneling FETs, 2D-material transistors) that can serve as the foundation for exascale computing.

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Antenna-Coupled Thermocouples for Infrared Detection

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We show that antenna-coupled thermocouples function as infrared detectors in the long-wave IR regime. The operating principle is based on the heating of one thermocouple junction by radiation-induced antenna currents, and the subsequent detection of this heating through the thermoelectric Seebeck effect. We will present experimental results of the IR response for various thermocouple metal combinations.

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Coherent Oscillations in a Mechanical System

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Coupled mechanical oscillations have attracted attention for both practical applications and fundamental studies. However, a key obstacle to the further development of the coupled mechanical oscillators is the ability to coherently manipulate the mechanical oscillators. This limitation arises as a consequence of the usually weak coupling between the constituent mechanical elements which cannot be adjusted in-situ due to it being hardwired at the device fabrication stage. To overcome this, we have fabricated parametrically coupled electromechanical oscillators in which the coupling can be dynamically adjusted by periodically modulating the stress between them via a piezoelectric transducer. The parametric control enables the coupling rate between the two oscillators to be made so strong that it exceeds their intrinsic dissipation rate. This strong coupling can be exploited to coherently transfer phonon populations, namely phonon Rabi oscillations, between the two oscillators. This works suggest that the presented technique can also be extended to the quantum regime by preparing phonon-number states. Consequently exciting possibilities for preparing novel non-classical states become available including the prospect of entangling a single phonon between two distinct macroscopic mechanical objects.

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Nano-Structures Probed by Tip-Enhanced Raman Scattering

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We report the nanometer-scale Raman mapping of Ge nanostructures, i.e., a single Ge nanowire (NW) and Ge/Si quantum dots (QDs), using Tip-Enhanced Raman Scattering (TERS) with a spatial resolution of less than 100 nm. The obtained results are as follows:

(a) We found that the TERS spectra of the Ge NW have two components originating from crystalline and amorphous Ge. The peak of the crystalline Ge shows downshift and asymmetric broadening due to the phonon confinement effect. We estimated the fraction of crystalline Ge as 0.8–0.95 from the integrated Raman intensities of the crystalline and amorphous Ge.

(b) From the TERS images of the QDs, we found that a large stress acts on the Si substrate around the dots. The Ge-Ge and Si-Ge modes in the Raman spectra were significantly enhanced only when the TERS probe was positioned on the QDs. The Ge content reduces as the dot size increases, which indicates larger Si intermixing within the dots. Furthermore, the Ge content reduced significantly in the central part of the dots. This result suggests that the dots consist of a Si-rich core and a Ge-rich shell.

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A Systematic Preparation and Investigation of Optical Properties of silica@gold Core-shell Nanocomposites for Using in Photothermal Therapy

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Metal nanoshells consists of a dielectric core surrounded by a thin noble metal shell, possess unique optical properties, including a strong optical absorbance that can be selectively tuned to any wavelength across the visible and infrared regions of the spectrum simply by adjusting the ratio of the dielectric core to the thickness of the metal overlayer. These features render nanoshells attractive for use in technologies ranging from conducting polymer devices to biosensing, drug delivery and photothermal therapy by absorbing light in NIR range in which human body has the most transparency. This paper reports a systematic investigation of the characterization and growth of small gold nanoparticles on the functionalized surface of larger silica nanoparticles. Monodispersed silica particles and gold nanoparticles were prepared by sol–gel method. The size of the particle could be altered by repeating the stage of reducing HAuCl4 on Au/APTES/silica particles, and the time for which they react. The nanocoreshell particles prepared were studied using scanning electron microscopy (TEM), UV–vis spectroscopy, Fourier transform infrared spectroscopy(FTIR) and PL spectrophotometer. It shows that By rowing gold nanoseeds over the silica cores a red shift in the maximum absorbance of UV-Visible spectroscopy is observed. furthermore, a remarkable intensification happens in the PL spectra of silica@Au NPs compared with that of bare silica nanoparticles, but the existence of gold nanoseeds on the silica particles surface does not change the peaks of these nanoparticles.

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Atomic Disorder Effects on Optical Absorption Spectra of Vertically Stacked InAs/GaAs Quantum Dots

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We have calculated optical absorption spectra of vertically stacked InAs/GaAs quantum dots (QDs). We use an empirical $sp^3d^5s^*$ tight-binding method to obtain the electronic states of InAs/GaAs QD superlattice (SL), whose atomic structure is relaxed by minimizing the elastic energy with the valence-force-field method. In the present study, we focus on effects of atomic disorder on the optical properties in vertically stacked InAs/GaAs QD SLs.

The intermediate-band solar cell (IBSC) is a promising device structure for increasing efficiency of solar cells. The IBSCs can be realized with vertically stacked InAs/GaAs QDs. Although the uniformity of the QDs is important for improving the efficiency of IBSCs, there should exist fluctuation and disorder in actual QDs. Here we present theoretical study of effects of atomic disorder on the optical properties in vertically stacked InAs/GaAs QD SLs.

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Managing Dislocations in Quantum-Confined Epitaxial Structures

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Quantum confinement in epitaxially formed nanostructures such as quantum dots (QDs) is known theoretically to offer significant improvements for optoelectronic device applications. However, lattice strain behavior with its associated dislocation and defect effects around QD structures has so far strongly challenged the complete implementation of this theoretical aspiration.

We report new data concerning lattice strain dynamics, dislocation mechanisms, and ways to manage and reduce dislocations and defects in epitaxially fashioned QD structures. Using various characterization tools and novel epitaxial growth procedures, we have investigated and analyzed the role played by lattice strain mechanisms as observed in *p-i-n* structures grown by molecular beam epitaxy using the Stranski-Krastanov growth mode. Specifically, $In_{0.15}Ga_{0.85}As$ based *p-i-n* devices with InAs QDs incorporated in the intrinsic region have been analyzed and compared with identical $In_{0.15}Ga_{0.85}As$ *p-n* devices without QDs. Using this new data, we show how a better understanding of lattice-strain decay mechanisms in the regions around epitaxially formed QDs can be obtained and used to achieve improved optoelectronic device performance.

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Fermi Level Pinning Issues in III-V Nanoscale Devices

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Increased surface to volume ratio in nano-scale devices makes them more prone to adverse effects of Fermi level pinning (FLP) caused by surface/interface trapping states. This paper addresses the basic FLP issue in III-V high-k MOS gate stacks often used in gate controlled nanodevices. Here, unlike the near ideal Si-SiO_2 interface, one is forced to live with higher values of the interface trap density (D_{it}) Thus, an accurate determination of the D_{it} distribution is essential for proper device analysis and design. However, according to recent publications on GaAs and InGaAs high-k MOS structures, D_{it} distributions measured by the capacitance method are very different from those by the conductance method. Namely, the capacitance method gives U-shaped D_{it} valleys with the D_{it} minimum lying at the charge neutrality level (CNL), while the conductance method gives inverse-V shaped near-midgap peaks. I explain this discrepancy on the basis of our disorder-induced gap state (DIGS) model [1] from the view point of extended state formation and time constant dispersion by inelastic tunneling. It is shown that the conductance method, which is the most preferred technique for D_{it} determination in the Si MOS community, is not directly applicable to III-V MOS structures. To get detailed information on D_{it}, a full admittance analysis over a wide frequency range is required.

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Control of Interface Charge of GaN MOS Devices when Using GaN Bulk Substrate

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We report the interface charge of GaN metal-oxide-semiconductor (MOS) devices for power applications. Control of interface charge between an insulator and a GaN layer is most important to realize stable normally-off operation even at high temperature.
In this study, we focused on the temperature dependence of the interface charge using CV measurements. Two different GaN bulk substrates, such as a polar c-plane (0001) substrate and a non-polar m-plane (1-100) substrate, were used to clarify the effect of polarization on the interface charge. An Al_2O_3 film was deposited on GaN substrates by atomic layer deposition (ALD). Anode electrodes were formed on Al_2O_3.
Consequently, it was found that there were the "negative" charges of 1.07×10^{12} cm^{-2} at the Al_2O_3/m-plane GaN interface, in contrast with the "positive" charges of $9.5\times10^{11}cm^{-2}$ at the c-plane interface. Negative charge formation of m-plane devices is preferable property to obtain normally-off operation. It was also found that the flatband voltage of m-plane devices shifted only 0.05V from 300K to 450K. On the other hand, that of c-plane devices shifted positively 0.5V. Stable temperature characteristics of m-plane devices might be attributed to no spontaneous polarization charges at the Al_2O_3/m-plane GaN interface.

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Nanoscale Band Profile Variations and Carrier Dynamics in AlInN/GaN HEMT Structures

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$Al_{0.83}In_{0.17}N$ is lattice matched to GaN relieving strain at the interface. This feature, along with the wide band gap and the strong interface charge density, makes AlInN/GaN heterostructure an attractive basis for HEMTs. However, properties of AlInN are still little explored and its potential for applications is far for being confirmed. For instance, a huge, up to 1eV, Stokes shift between absorption and emission of AlInN suggests a high density of localized states, which might have a severe influence on the HEMT channel width and the interface scattering.

In this work, energy spectra of AlInN localized states, their spatial distribution and related carrier dynamics have been studied by time-resolved photoluminescence and photoreflection, as well as by scanning near-field optical microscopy (SNOM). Carrier localization regions have been found to be dense and have dimensions below 100nm. They have been attributed to different In atom arrangements around N atoms creating spatial variations of the valence band potential. These potential fluctuations, through spatial variation of the interface charge density, should affect the channel width and the carrier scattering. Besides, SNOM has been found to be an efficient technique for direct nanoscale measurements of the HEMT channel potential variations.

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Semi-classical Klein Tunneling with Berry Curvature Effects in Graphene

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Both the Klein paradox, which refers to the unhindered transmission of relativistic Dirac particles through high and wide potential barriers, and Berry-phase related phenomena in graphene originate from the unusual conical energy dispersion at two special points of the graphene band structure. Here we study the transport dynamics of semi-classical electrons in graphene in the Klein tunneling regime by scattering wave packets off a potential step while taking the full graphene Hamiltonian into account. Besides establishing the general transmission characteristics for zigzag and armchair step edges, our numerical simulation also suggests that the wave packet dynamics is heavily affected by the Berry curvature, which is known to modify the semi-classical equations of motion in systems with broken time-reversal or inversion symmetry. We present and discuss our results.

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Controlling the Electron Flow through Graphene by Vacancies

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We have examined the possibility that vacancies in graphene sheet can allow us to control the electron pathway by simulating the electron motion in graphene with vacancies.

We use a tight-binding model that allows us to describe the total energy relationships of graphene sheet with vacancies and to estimate the probability amplitude response. Our model consists of the contact region and the graphene region. We add vacancies in the graphene region. We inject a two-dimensional Gaussian wave packet into the contact region as an initial input and investigate the time-dependent behavior of the wave packet in the graphene region by solving Schrödinger's time-dependent equation.

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Electron Transport in Graphene under Local Strain

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We investigate the gate voltage dependence of conductivity in graphene with one-dimensional local strain. Theories tell that such local strain leads to the appearance of the transport (energy) gap around the Dirac point, which is quite useful for the transistor application. We induced strain in graphene by inserting dielectric (resist) nanostructures between a graphene film and the substrate. As far as we know, this is the first report of the electron transport in artificially strained graphene films.

In contrast to the theoretical prediction, we did not see any transport gap in the back gate voltage dependence of the conductivity, σ(Vg). Instead, we found that the σ (Vg) curve was deformed in the low-conductivity region, when the spatial variation of the strain was remarkable. We will discuss the condition for observing a transport gap of graphene in experiments.

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Low Temperature Magneto-resistance in MWNT

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In order to study on nano scaled quantum transport in multi-walled carbon nano-tube (MWNT), a few experimental implementations have been performed to observe and analyze precisely on the low temperature magneto-resistance (MR). In our studies, AB flux cancellation and AB and/or AAS oscillations must be observed. Therefore, we discuss on the relationship between flux cancellation and weak localization appeared in the angular dependent CNT MR.

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Coherent Control of Exitons in Carbon Nanotube Quantum Dots

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AFM Characterization of poly(methyl methacrylate) and poly(ethylene glycol) Deposited by Ink-jet Printing

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Inkjet Printing (IJP) technique is one of the promising methods for organic electronics fabrication because its processing is compatible with organic materials and is mostly processed in liquid phase. This study reports atomic force microscope (AFM) characterization of amorphous PMMA and semi-crystalline PEG deposited by IJP. PMMA solutions were prepared by mixing PMMA in 91% isopropyl alcohol (IPA) with a concentration of 1:50 (w/w) and sonication. The solution was deposited by micropipette or IJP on the mica substrate, and cured on a hot plate at 80ºC for 30 minutes.

PEG solutions were prepared by mixing PEG in 91% IPA with a concentration of 1:50 and 1:10 (w/w) and deposited with micropipette and also printed on the mica substrate. After curing, PMMA and PEG droplets were then characterized with optical microscope (OM) and AFM.

The morphology structure at the outer-edge layer of PMMA dropped from micropipette suggested that it was formed under shear conditions. The AFM image of a thin film of 1:10 (w/w) PEG/91%IPA deposited by IJP showed many hillocks forming and crossing each other. This might indicated that each droplet initiated the crystallization process separately.

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Block Copolymer Self-assembly Based Device Structures for Nanoelectronic Applications

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The advances in information and communication technologies have been largely predicated around the increases in computer processor power derived from the constant miniaturization (and consequent higher density) of individual transistors. Transistor design has been largely unchanged for many years and progress has been around scaling of the basic CMOS device. Scaling has been enabled by photolithography improvements (i.e. patterning) and secondary processing such as deposition, implantation, planarization, etc. Perhaps the most important of the secondary processes is the plasma etch methodology whereby the pattern created by lithography is 'transferred' to the surface via a selective etch to remove exposed material. However, plasma etch technologies face challenges as scaling continues. Maintaining absolute fidelity in pattern transfer at sub-16nm dimensions will require advances in plasma technology (plasma sources, chamber design, etc) and chemistry (etch gases, flows, interactions with substrates, etc). In this paper, we illustrate some of these challenges by discussing the formation of ultra-small device structures from the directed self-assembly of block copolymers (BCPs) where nanopatterns are formed from the micro-phase separation of the system. The polymer pattern is transferred by a double etch procedure where one block is selectively removed and the remaining block acts as a resist pattern for silicon pattern transfer. Data are presented which shows that highly regular nanowire patterns of feature size below 20 nm can be created using etch optimization techniques and in this paper we demonstrate generation of crystalline silicon nanowire arrays with feature sizes below 8nm. BCP techniques are demonstrated to be applicable from these ultra-small feature sizes to 40nm dimensions. Etch profiles show rounding effects because etch selectivity in these nanoscale resist patterns is limited and the resist thickness rather low. The nanoscale nature of the topography generated also places high demands on developing new etch processes.

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Fabrication of One-dimensional Conductive Polymer Nanowires Using STM: A Key Step Towards Development of Molecular Devices

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We describe here a versatile technique to fabricate one-dimensional (1-D) conductive polymer nanowire at designated positions which is quite important towards fabrication of molecular devices. The process involves spontaneous chain polymerization initiated by a local single-molecule excitation using scanning tunneling microscope (STM) probe tip. The STM probe tip induced application of a certain voltage pulse to a self-assembled monolayer (SAM) of a diacetylene compound (DA; general formula R_1–C≡C–C≡C–R_2 where C≡C–C≡C is the diacetylene moiety, R_1 and R_2 are substituent groups) results the formation of polymer nanowire at designated positions. We have successfully carried out fabrication of conductive polydiacetylene (PDA; $(=R_1C–C≡C–CR_2=)_n$) nanowires on both highly oriented pyrolytic graphite (HOPG) substrate and semiconducting MoS_2 substrates. We further demonstrate the connection of a single molecule and isolated metal nanocluster using such fabricated polymer nanowire. The data represents a key step for future advancement of molecular electronics as well as studying physics in one-dimensional systems.

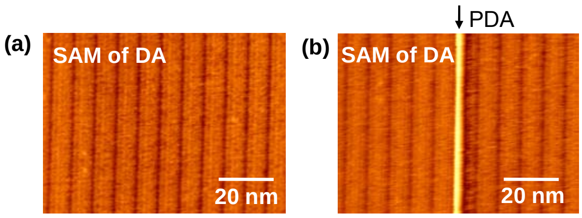

Figure 1. STM image of (a) a self-assembled monolayer (SAM) of a diacetylene (DA) compound, and (b) fabrication of a polymer nanowire using STM tip.

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Applications of Metal Oxide Memristors Beyond NVRAM

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Metal oxide memristors are best known as candidates for the next generation of nonvolatile memory devices and are currently under intense industrial development. Here we present recent data on devices and circuits which extend applications of memristors beyond memory into the domain of Boolean logic and gainful signal amplification. We discuss the directions that we are taking at HP Labs to address these applications and their associated opportunities and challenges.

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Zn Modified Hydroxyapatite Nanoceramic Ethanol Sensors

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The hydroxyapatite (Hap) nanoceramics is synthesized and characterized by means of XRD, SEM, FTIR, DT/TGA, so as to standardize the synthesis process. The nano-powder is then doped with varying concentrations of Zn compounds. The sensor device is fabricated in the form of thick films screen printed on insulating substrate. The Zn doped Hap is then subjected to Ethanol atmosphere of variable ppm level. The change in electrical parameter is sensed by the two-probe technique. The sensitivity percentage, response and recovery for Ethanol gas is determined. It is observed that the sensing temperature of these Zn doped Hap thick films sensors are much lower as compared to pure Hap thick films sensor. The surface changes upon exposure to gas is observed and characterized: The parameters are studied from the point of view of practical utility of these films as thick film gas sensors.

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DNA-translocation Through a Solid-state Nanopore Coated with a Functionally Switchable Self-assembled Monolayer

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Obtaining motion control over DNA-molecules as they translocate through solid-state nanopores is a core requirement of all nanopore-based next generation DNA sequencing technologies. We have investigated the impact of surface-property modulations inside coated nanopores on translocation dynamic behavior of DNA-molecules translocating through coated nanopores. We have custom-designed and synthesized an organic compound, which we used to coat a 5nm-diameter nanopore drilled into a 30nm-thick Si_3N_4 membrane. One end of the molecule can self-assemble onto the inside surface of the nanopore, and the other end can be changed *in situ* from hydrophilic to hydrophobic status. Within its hydrophilic functionality, the molecule can be switched between negative and neutral status with weak bases and dilute acids, respectively. We performed translocation experiments of 2Kbp dsDNA (at a concentration of 2nM in a 1M KCl solution) through the same solid-state nanopore endowed with three different functionalities. Translocation events were characterized and categorized for every surface charge state by monitoring blockade current, dwell time and blockade ratio (i.e., blockade current/open pore current) as well as the occurrence of DNA-sticking to the walls of the pore. The average blockade current at 300mV was the lowest (664.22 ± 30.92pA) for negative hydrophilic, intermediate (1199.78 ± 28.09pA) for the neutral hydrophilic and the largest (1529.40 ± 36.79pA) for the neutral hydrophobic pore surface states. The average dwell times were 9.87ms, 0.4ms, and 0.15ms for three states in the above sequence. The blockade ratio was 0.37 for the neutral hydrophobic state and 0.20 for the negative hydrophilic state. Long-time sticking events of translocating DNA-molecules to the pore were mostly observed in hydrophilic pores. Taken together, our results show that changing the surface state of the coated pore from hydrophilic to hydrophobic considerably reduces DNA-sticking events, thus enabling a smooth translocation behavior.

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Acoustofluidics: Manipulating Fluids at the Microscale and Nanoscale

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Though uncommon in most microfluidic systems due to the dominance of viscous and capillary stresses, it is possible to induce inertial transport at microscale and nanoscale dimensions using high frequency ultrasonic waves. In particular, microfluidic actuation and manipulation is particularly efficient when driven using surface acoustic waves (SAWs), which are nanometer order amplitude electroelastic waves that can be generated on a piezoelectric substrate. Due to the confinement of the high frequency acoustic energy to a thin localized region along the substrate surface and its subsequent leakage into the body of liquid with which the substrate comes into contact, SAWs are an extremely efficient mechanism for driving ultrafast microfluidics. We demonstrate that it is possible to generate a variety of efficient microfluidic flows using the SAW. For example, the SAWs can be exploited to transport liquids in microchannels or to translate free droplets typically one or two orders of magnitude faster than conventional electroosmotic or electrowetting technology. In addition, it is possible to drive strong microcentrifugation for micromixing and bioparticle concentration or separation. In the latter, rich and complex colloidal pattern formation dynamics have also been observed. Further, we show this functionality to be useful in inducing rapid rotation of millimeter dimension discs on which microchannels and other microfluidic structures can be patterned – a Lab-on-a-Disc that is a miniature counterpart to the Lab-on-a-CD but one that does not require a benchscale motor to drive the rotation. Finally, at large input powers, the SAW is a powerful means for the generation of jets and atomized aerosol droplets through rapid destabilization of the parent drop interface. In the former, slender liquid jets that persist up to centimeters in length can be generated without requiring nozzles or orifices. In the latter, a monodispersed distribution of 1–10 micron diameter aerosol droplets is obtained, which can be exploited for drug delivery and encapsulation, nanoparticle synthesis, and template-free polymer array patterning.

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Functionalised Nanowires: Chemical and Electronic Sensors for Nanobionics

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Recent reports have shown that silicon nanowires can be made into sensitive molecular and electrical sensors. In this talk CMOS compatible nanowires will be introduced that are either sensitive electrical sensors or when functionalized with monoclonal antibodies are chemical sensors capable of detecting femto molarconcentrations of antigens in real time. Antibodies conjugated to the surface of nanowires displace free carriers in the nanowire modifying the conductance, capacitance and inductance of the nanowire. When the antigen attaches to antibody, the net charged seen by the nanowire, changes and this modifies the electrical properties of the nanowire. These changes can be measured by on chip circuitry. When integrated with bionic devices, these sensors will provide a new capability to electrically and chemically sense the environment creating new and more capable bionic devices.

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