2016 Workshop on Innovative Nanoscale Devices and Systems

WINDS
Booklet of Abstracts

Edited by

Berry Jonker
Wolfgang Porod
Viktor Sverdlov
Kazuhiko Matsumoto
Siegfried Selberherr
Stephen M. Goodnick

Hapuna Beach Prince Hotel
Kohala Coast, Hawaii, USA

December 4-9, 2016

WINDS
Booklet of Abstracts

Hapuna Beach Prince Hotel
Kohala Coast, Hawaii, USA

December 4-9, 2016

The **Workshop on Innovative Nanoscale Devices and Systems** (WINDS) is a 4½ day meeting with morning and evening sessions, and with afternoons dedicated to *ad hoc* meetings and discussions among participants. WINDS follows the tradition and format of the Advanced Heterostructure Workshop (AHW) as the workshop name morphed in 2008 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 based on recent data. To ensure enough time for discussion, short presentations of data are encouraged. Each participant is expected to engage in these discussions and is strongly encouraged to display only a few slides showing most recent results. Introductions, summary, and acknowledgements are strictly discouraged. All contributions are by invitation only. The total number of participants is limited to around 80 to keep the discussions lively in the single session. This year the WINDS program includes joint sessions with a special Workshop on Frontiers of Topological Superconductivity, beginning on Thursday morning with a tutorial on Majorana physics. Dedicated sessions on Topological Superconductivity will continue on Thursday afternoon, Friday afternoon and Saturday morning, and are open to all attendees.

Conference Committee

General Chair
Berry Jonker, NRL, USA
berry.jonker@nrl.navy.ml

US Co-Chair
Wolfgang Porod, University of Notre Dame, USA
porod@nd.edu

Europe Co-Chair
Viktor Sverdlov, TU Wien, Austria
sverdlov@iue.tuwien.ac.at

Japan Co-Chair
Kazuhiko Matsumoto, Osaka University, Japan
k-matsumoto@sanken.osaka-u.ac.jp

Publication-Chair
Siegfried Selberherr, TU Wien, Austria
Selberherr@TUWien.ac.at

Local Arrangements-Chair
Stephen M. Goodnick, Arizona State University, USA
stephen.goodnick@asu.edu

December 4th (Sunday)

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

18:00-20:00 Welcome Reception (Lower Lawn Area)

December 5th (Monday)

8:45-9:00 Opening

Nanowires (Henning Riechert, Paul-Drude Inst.)

10:30-11:00 Coffee Break

Spintronics I (Siegfried Selberherr,TU Wien)

December 5th (Monday) continued

13:00-19:00 *Ad hoc* Session

2D Materials (Berry Jonker, NRL)

December 6th (Tuesday)

December 6th (Tuesday) continued

December 7th (Wednesday)

Novel Devices (Dave Ferry, ASU)

10:45-11:15 Coffee Break

December 7th (Wednesday) continued

Spintronics II (Viktor Sverdlov, TU Wien)

13:15-18:30 *Ad hoc* Session

18:30-21:00 Banquet (Courtyard)

December 8th (Thursday)

December 8th (Thursday) continued

December 9th (Friday)

Direct Observation of the Acoustic Phonon Spectrum Modification in Individual Free-Standing Semiconductor Nanowires

Fariborz Kargar[1], Bishwajit Debnath[1], Kakko Joona-Pekko[2], Antti Säynätjoki[2,3], Harri Lipsanen[2], Denis Nika[1], Roger Lake[1], and <u>Alexander A. Balandin</u>[1]

[1] Department of Electrical and Computer Engineering, UC Riverside, Riverside, CA 92521, USA
Tel: +1-951-827-2351   Fax: +1-951-827-2425
email: balandin@ece.ucr.edu

[2] Department of Micro and Nanosciences, School of Electrical Engineering
Aalto University, 00076 Aalto, Finland

[3] Institute of Photonics, University of Eastern Finland, 80101 Joensuu, Finland

A possibility of changing acoustic phonon spectrum in individual nanostructures via spatial confinement would bring tremendous benefits for controlling phonon-electron interaction and thermal conduction at nanoscale. However, despite strong scientific and practical importance, experimental evidence of acoustic phonon confinement in individual free-standing nanostructures, e.g. nanowires, is still missing. The length scale, at which phonon dispersion undergoes changes, is also not established. In this work, we demonstrate experimentally the confined acoustic phonon dispersion branches using a set of specially designed GaAs nanowires with different diameters and large inter-nanowire distances. The measurements were conducted with Brillouin – Mandelstam spectroscopy. Surprisingly, it was found that the acoustic phonon spectrum is confined in nanowires with diameters as large as ~128 nm, i.e. at length scale, which exceeds the "grey" phonon mean-free path by an almost an order of magnitude [1]. The obtained results can lead to more efficient nanoscale control of acoustic phonons, with benefits for thermal management of nanoelectronic circuits, thermoelectric energy conversion, and novel spintronic technologies.

1. F.Kargar, B.Debnath, J.-P.Kakko, A.Saynatjoki, H.Lipsanen, D.L Nika, R.K. Lake and A.A. Balandin, Nature Communications (2016); DOI: 10.1038/ncomms13400

Wigner Modelling of Quantum Wires

Paul Ellinghaus[1], Mihail Nedjalkov[1], <u>Josef Weinbub</u>[2], and Siegfried Selberherr[1]

[1] Institute for Microelectronics, TU Wien
[2] Christian Doppler Laboratory for High Performance TCAD at the
Institute for Microelectronics, TU Wien
Gußhausstraße 27-29, 1040 Wien, Austria

Tel: +43-1-58801-36053   Fax: +43-1-58801-36099
email: Josef.Weinbub@TUWien.ac.at

Aggressively scaled More Moore devices such as FDSOI FETs, FinFETs, and nanowire transistors are designed around the concept of spatial confinement, which challenges basic notions of electron transport, originally derived under the assumption of a bulk crystal. Confined electrons do not have a well-defined three-dimensional momentum and a continuous energy spectrum. Physical models with confined electrons usually identify a transport direction, separating the problem into transport and eigenvalue tasks. We have investigated quantum wires, where the transverse plane of confinement is characterized by a quantization into energy sub-bands and a lack of a well-defined momentum in accordance with the uncertainty relations. The Wigner function approach has proven to be well suited to model quantum transport in nanowires, where effects of confinement are naturally incorporated in the initial Wigner state and the scattering mechanisms. We critically consider the assumption for homogeneous conditions, which is inevitable when identifying a transport direction. The evolution of periodically injected coherent Wigner states into ideal and non-homogeneous nanowires has been investigated. In our results we observe differences in the behaviour of currents and densities, which are analyzed in Wigner function terms.

1. D.K. Ferry, IOP Publishing, doi: 10.1088/978-0-7503-1103-8 (2015).
2. M. Nedjalkov, D. Vasileska, D.K. Ferry, C. Jacoboni, C. Ringhofer, I. Dimov, V. Palankovski, Phys.Rev.B 74, 035311, doi: 10.1103/PhysRevB.74.035311 (2006).

Realistic Determination of Spin-orbit Coupling Effects in Nanowires

Tiago de Campos, Paulo E. Faria Junior, Martin Gmitra, Jaroslav Fabian, and
Guilherme M. Sipahi

Instituto de Física de São Carlos, Universidade de São Paulo
Av. Trabalhador são-carlense, 400, 13566-590 São Carlos SP, Brasil

Tel: +55-16-3373-9856   Fax: +55-16-3373-9879
email: sipahi@ifsc.usp.br

The study of spin-orbit coupling in nanowires is usually carried out by a two-band model due to its simplicity. Although they have been successful in determine some physical properties, a more realistic description of the spin-orbit coupling of interacting energy bands is required to further investigate quantum confined systems. In this study, we use multiband **k.p** Hamiltonians, including spin-orbit coupling [1-2], to determine the band structure of zincblende InSb and wurtzite InAs nanowires under a transverse electric field. We analyze the effects of the lateral quantum confinement, for different cross-section geometries, and growth directions in the energy bands and extract the pertinent parameters that can be used in two-band models. We found that the electric field boosts the spin split near the Brillouin zone center for both crystal structures and can be highly tunable. Without electric field, the zincblende InSb spin split is driven by the change of the quantum confinement and the wurtzite InAs by the change of the growth direction. Using our developed model, we performed a systematic investigation of spin-orbit coupling in NWs for experimentally achievable configurations.

1. R. Winkler. Spin-Orbit Coupling Effects in Two-Dimensional Electron and Hole Systems. Springer-Verlag Berlin Heidelberg: Springer Berlin Heidelberg, 2003.
2. P. E. Faria Junior, T. Campos, C. M. O. Bastos, M. Gmitra, J. Fabian, G. M. Sipahi. Phys. Rev. B **93**, 235204 (2016).

Impact Ionization and Ultrafast Relaxation Processes in Semiconductor Nanowires

Raghuraj Hathwar, Marco Saraniti, and Stephen M. Goodnick

School of Electrical Computer and Energy Engineering, Arizona State University
Tempe, AZ 85287, USA

Tel: +1-480-965-9572
email: stephen.goodnick@asu.edu

Impact ionization plays a critical role for high energy electrons and holes such as at high fields or during photoexcitation. Impact ionization nanowire multiple-gate-field-effect-transistors (I-MuGFET) have reported subthreshold swings of sub-5 mV/dec at room temperature while multi-excitation generation in nanowire solar cells has the potential for exceeding the single gap limits for photovoltaic devices. Here we investigate the role of impact ionization in nanowires using an atomistic tight binding representation of the nanowires, and calculating the full multi-subband impact ionization rate from perturbation theory. The high field transport of carriers in nanowires and the short time carrier dynamics in nanowires under varying photoexcitation conditions are investigated using a full band Cellular Monte Carlo (CMC) simulation based on an atomistic representation [1]. The CMC also includes the scattering rates due to optical and acoustic phonons that tend to the bulk material scattering rates for larger nanowire widths. The effect of impact ionization is shown to be prominent at larger electric fields for smaller width nanowires due to the increase in the band gaps as the nanowire width decreases. The percentage of electrons undergoing an impact ionizing event, thereby creating new electron hole pairs, is also shown to drastically increase as the photoexcitation energy is increased beyond twice the bandgap of the nanowire.

1. R. Hathwar, M. Saraniti and S. M. Goodnick, "Modeling of Multi-Band Drift in Nanowires using a Full Band Monte Carlo Simulation," *Journal of Applied Physics 120*, 044307 (2016).

High Breakdown Current Density in BN-Capped Quasi-1D TaSe$_3$ Metallic Nanowires: Prospects of Interconnect Applications

Maxim A. Stolyarov[1], Guanxiong Liu[1], Matthew A. Bloodgood[2], Ece Aytan[1], Chenglong Jiang[1], Rameez Samnakay[1], Tina T. Salguero[2], and Alexander A. Balandin[1]

[1] Department of Electrical and Computer Engineering, UC Riverside
Riverside   CA 92521, USA
Tel: +1-951-827-2351   Fax: +1-951-827-2425
email: balandin@ece.ucr.edu

[2] Department of Chemistry, University of Georgia, Athens, GA 30602, USA

We report results of investigation of the current-carrying capacity of nanowires made from the quasi-1D van der Waals metal tantalum triselenide capped with quasi-2D boron nitride. The chemical vapor transport method followed by chemical and mechanical exfoliation were used to fabricate TaSe$_3$ nanowires with lateral dimensions in the 20 nm to 70 nm range [1]. Electrical measurements establish that TaSe$_3$/h-BN nanowire heterostructures have a breakdown current density exceeding 10 MA/cm^2 — an order-of-magnitude higher than that in copper. Some devices exhibited an intriguing step-like breakdown, which can be explained by the atomic thread bundle structure of the nanowires. The quasi-1D single crystal nature of TaSe$_3$ results in low surface roughness and the absence of grain boundaries; these features potentially can enable the downscaling of these wires to lateral dimensions in the few-nm range. These results suggest that quasi-1D van der Waals metals have potential for applications in the ultimately downscaled local interconnects [2].

1. M. Stolyarov et al., Nanoscale, 8, 15774 (2016); DOI: 10.1039/c6nr03469a
2. G. Liu, et al., Nano Letters (2016); DOI: 10.1021/acs.nanolett.6b04334

Spin Current and Spin Hall Effect in Half-Metallic Ferromagnets

Yuichi Ohnuma, Matsuo Mamoru, and Sadamichi Maekawa

Advanced Science Research Center, Japan Atomic Energy Agency
Tokai, 319-1195, Japan

ERATO, Japan Science and Technology Agency
Sendai, Miyagi, 980-8577, Japan

Tel: +81- 29-284-3507   Fax: +81- 29-282-5939
email: ohnuma.yuichi@jaea.go.jp

A half-metallic ferromagnet, where the conduction electrons are completely spin polarized, is regarded as a candidate material for a spin injector in magnetic memories. The spin polarization of a half-metallic ferromagnet has been investigated theoretically [1]. Unlike the spin polarization, however, spin transport in half-metallic ferromagnets has yet to be studied. In this talk, we will show our results on theoretical investigation of spin transport with the electron-electron correlation in half-metallic ferromagnets [2]. Extrinsic spin Hall conductivity is calculated and it is shown that at finite temperatures, minority-spin electrons contribute to spin Hall conductivity owing to thermally excited magnons. The efficiency of the pure spin injections into a half-metallic ferromagnet is also discussed. The temperature dependence of spin Hall conductivity and spin polarization is compared, and it is shown that while spin Hall conductivity drastically increases with temperature the spin polarization remains mostly constant. This suggests that the observation of spin Hall conductivity may become a new method for studying the minority-spin state in a half-metallic ferromagnet.

1. R. A. de Groot et al., Phys. Rev. Lett., 50, 2024 (1983).
2. Y. Ohnuma, M. Matsuo, and S. Maekawa, Phys. Rev. B, (in press).

Universal Dependence of the Spin Lifetime in Silicon Films on the Spin Injection Direction

Viktor Sverdlov[1], Joydeep Ghosh[2], and Siegfried Selberherr[1]

[1] Institute for Microelectronics, TU Wien
Gußhausstraße 27-29, 1040 Wien, Austria
Tel: +43-1-58801-36033   Fax: +43-1-58801-36099
email: {sverdlov|ghosh|selberherr}@iue.TUWien.ac.at

[2] Department of Electrical Engineering, Indian Institute of Technology Bombay
Mumbai 400076, India

Recent spectacular experimental demonstrations of SpinFETs [1] and Spin MOSFETs [2] bring semiconductor spintronics closer to applications. However, in contrast to the electron charge, the total spin of an ensemble of injected spin-polarized carriers is not conserved. The spin relaxation in silicon is due to the Elliott-Yafet mechanism [3,4]. Because of the spin-orbit interaction, the wave function is not a pure spin state, so at every scattering event there is a final probability of a spin flip. In SOI MOSFETs the electron-phonon and surface roughness scattering must be considered. The spin relaxation is determined by the hot spots defined by the degeneracy of the two subbands originating from the two [001] valleys. The spin-orbit field is the strongest at the hot spots [5]. Because this field is in-plane, the spin relaxation should depend on the spin injection orientation. By performing numerical calculations in thin silicon films, we find a universal behaviour of the spin lifetime on the spin injection orientation. This behaviour is preserved for every scattering mechanism and is strain-independent [6] guaranteeing a spin lifetime enhancement by a factor of two [3,7] for in-plane injection as compared to the injection orthogonally to the film.

1. P. Chuang et al. Nature Nanotechnology, 10, 35 (2015).
2. T.Tahara et al., Appl.Phys.Express, 8, 113004 (2015).
3. J. L. Cheng et al., Phys. Rev. Lett., 104, 016601 (2010).
4. P. Li and H. Dery, Phys. Rev. Lett., 107, 107203 (2011).
5. D. Osintsev et al., Solid-State Electronics, 112, 46 (2015).
6. J..Ghosh et al., J. Nano Research, 39, 34 (2016).
7. H. Dery et al. Appl. Phys. Lett., 99, 082502 (2011).

Spin-charge Conversion in Graphene and Carbon Nanotube

<u>Yuichiro Ando</u>, Sergey Dushenko, and Masashi Shiraishi

Department of Electronic Science and Engineering, Kyoto University
Katsura, Kyoto 615-8510, Japan

Tel: +81-75-383-2274   Fax: +81-75-383-2275
email: ando@kuee.kyoto-u.ac.jp

The small spin-orbit interaction of carbon atoms in graphene and carbon nanotube promises a long spin lifetime and potential for the creation of a spin transport devices. However, for this reason, graphene and carbon nanotube were largely overlooked as possible spin-charge interconversion materials. In this study, we demonstrated spin-charge conversion in a single-layer graphene and a single-walled carbon nanotube mat (SWCNT mat). A pure spin current were generated in graphene / yttrium iron garnet (YIG) or SWCNT mat / YIG bilayers by using spin pumping. The spin current, flowing in the normal direction, was converted into an in-plane charge current. Clear electromotive forces due to spin-charge conversion were detected for both samples at room temperature. From electric gate tuning of the electromotive force in the single-layer graphene, we showed the dominance of the conventional inverse spin Hall effect over the inverse Rashba-Edelstein effect despite of two dimensional nature[1]. We also revealed that the SWCNT mat exhibits negative spin Hall angle[2], the first discovery of organic materials with negative spin Hall angle.

1. S. Dushenko et al, Phys. Rev. Lett. **116**, 166102 (2016).
2. E. Shigematsu et al., submitted.

Quantum Photon-spin Interface Consisting of Gate-defined Quantum Dots and Surface Plasmon Structure

Rio Fukai, Haruki Kiyama, Tomohiro Nakagawa, and Akira Oiwa

Institute of Scientific and Industrial Research, Osaka University
8-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan

Tel: +81-6-6879-8405   Fax: +81-6-6879-8405
email: oiwa@sanken.osaka-u.ac.jp

Quantum state conversion from a photon polarization to a single electron spin provides a way to realize entanglement distribution among distant nodes indispensable for long distance quantum communication [1]. Recently, the angular momentum conversion from single photons to single electron spins in gate-defined double quantum dots (QDs) has been realized [2]. Thus, the increase of the coupling efficiency between photons and electron spins in the QDs is strongly needed for practical applications of quantum communication. In this paper, we propose to combine QDs with a bull's eye (BE) structure, which is known as a surface plasmon structure inducing local electric field enhancement [3].

We simulated the electric field induced by incident light in a BE structure on a GaAs/AlGaAs quantum well with/without metallic gate electrodes forming a lateral double QD using FDTD method. The electric field at the position of the QD with BE is enhanced about nine times of that without BE. We also find that the polarization of the transmitted light is slightly distorted. The minute electrodes for QD may affect the excitation and distribution of the surface plasmon. We will discuss the fabrication of the QDs combined with BE structures.

1. E. Yablonovitch et al., Proceedings of the IEEE, 91 761 (2003).
2. T. Fujita et al., arXiv:1504.03696.
3. H. J. Lezec et al., Science 297, 820 (2002).

Parametric Oscillators as Mechanical Analogue of Spin-1/2 Systems

Imran Mahboob and Hiroshi Yamaguchi

NTT Basic Research Laboratories
3-1 Morinosato-Wakamiya, Atsugi, Kanagawa 243-0198, Japan

Tel: +81-46-240-3475   Fax: +81-46-240-4317
email: yamaguchi.hiroshi@lab.ntt.co.jp

A parametric oscillator is the harmonic resonator in which the oscillations are driven by modulating the force constant at the frequency that differs from the resonance. One of the simplest examples is the child swing and nowadays they are used in many experiments such like microwave amplifier and optical wavelength convertors.

In degenerate parametric oscillators, the modulation is made at twice the resonance frequency and two different phase states appear in the oscillation reflecting the half-period time translational symmetry. The bistability can be regarded as a classical spin-1/2 system and the implementation using electromechanical oscillator can simulate the Zeeman splitting and spin-spin coupling. In this talk, we will present our recent results that demonstrated the analogy between parametric resonators and spin-1/2 systems using GaAs/AlGaAs piezoelectric mechanical resonators.

1. I. Mahboob, C. Froitier, and H. Yamaguchi, Appl. Phys. Lett. 96, 213103 (2010).
2. I. Mahboob, H. Okamoto, H. Yamaguchi, Sci. Adv. 2, e1600236 (2016).

Coherence of the Photo-generated Spins and Effective Bell Measurement

Yasuhiro Tokura, Yuta Ohyama, and Taichi Furuya

Faculty of Pure and Applied Sciences, University of Tsukuba
Ibaraki, 305-8571, Japan
NTT Basic Research Laboratories, NTT Corporation, Atsugi 243-0198, Japan

Tel: +81-29-853-6147   Fax: +81-29-853-5924
email: tokura.yasuhiro.ft@u.tsukuba.ac.jp

Quantum coherence of single photon states is manifested by the superposition of two polarization states, which would be transferred to electron spin coherence with using the selection rule of semiconductor system. After a photon generates electron-hole pair, the electron spin is trapped to an electrostatically defined quantum dot (QD), while the accompanying hole is rapidly escaping from QD-region. It is quite important to quantify the effect of the exchange interaction between the electron and hole, which might contaminate the purity of the final electron spin state. Previously, this problem had been studied in a QD defined by heterostrucures[1]. We study this phenomenum in a finite electric field of QD's confinement potential. Moreover, the coherence of the generated electron spin under the influence of non-Markovian environment is studied[2]. Finally, a new scheme to make an entanglement of two electron spins is proposed[3] and possible application to more efficient Bell measurement is argued.

1. Y. Rikitake, H. Imamura, and H. Kosaka, J. Phys. Soc. Jpn., 76, 114004 (2007).
2. Y. Ohyama and Y. Tokura, "Pseudomode quantum jump and memory effect of non-Markovian dynamics", Resonance and non-Hermitian Quantum Mechanics 2016, Osaka, Aug. 3-5, (2016).
3. T. Furuya and Y. Tokura, "Entanglement dynamics in simultaneously coupling system: Toward the Bell Measurement", The 9th Int. Conf. on Quantum Dot (QD2016), Jeju, Korea, May 22-27, (2016).

Heterojunctions for Atomically Thin 2D Semiconductors Based on Two-dimensional Transition Metal Dichalcogenides

Kazuhito Tsukagoshi

WPI Center for Materials Nanoarchitectonics (WPI-MANA)
National Institute for Materials Science (NIMS), Tsukuba, Ibaraki 305-0044, Japan

Tel: +81-29-860-4894
email: Tsukagoshi.kazuhito@nims.go.jp

Growth of a uniform oxide film with a tunable thickness on two-dimensional transition metal dichalcogenides is of great importance for electronic and optoelectronic applications in next generation atomically-controlled hetero semiconducting structure. Here we demonstrate homogeneous surface oxidation of atomically thin WSe_2 with a self-limiting thickness from single- to trilayers.

Exposure to ozone (O_3) below 100 °C leads to the lateral growth of tungsten oxide selectively along selenium zigzag-edge orientations on WSe_2. With further O_3 exposure, the oxide regions coalesce and oxidation terminates leaving a uniform thickness oxide film on top of unoxidized WSe_2. [1]

The WO_x-covered WSe_2 is highly hole-doped due to surface electron transfer from the underlying WSe_2 to the high electron affinity WO_x. The dopant concentration can be reduced by suppressing the electron affinity of WO_x by air exposure, but exposure to O_3 at room temperature leads to the recovery of the electron affinity. Hence, surface transfer doping with WO_x is virtually controllable. Transistors based on WSe_2 covered with WO_x show only p-type conductions with orders of magnitude better on-current, on-off current ratio, and carrier mobility than without WO_x, suggesting that the surface WO_x serves as a p-type contact with a low hole Schottky barrier. [2]

Our findings point to a simple and effective strategy for creating heterojunction semiconducting electronics based on two-dimensional transition metal dichalcogenides with controlled dopant concentrations.

1. M.Yamamoto, S.Dutta, K. Wakabayashi, M. S. Fuhrer, K.Ueno, K.Tsukagoshi, Self-limiting surface oxidation of atomically thin WSe_2, Nano Letters 15 (3) 2067 (2015).
2. M. Yamamoto, S.Nakaharai, K.Ueno, K. Tsukagoshi, Surface Oxides on Single- and Few-layer WSe_2 as Controlled Dopants and Low-Barrier Contacts, Nano Letters16 (4) 2720 (2016).

Engineering the Structural and Electronic Phases of MoTe$_2$ through W Substitution

D. Rhodes[1,2], D. A. Chenet[3], R. M. Osgood, Jr.[4], A. M. Lindenberg[5], P. Y. Huang[6], A. N. Pasupathy[7], M. Dubey[8], J. Hone[3], and L. Balicas[1]

[1] National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA
Tel: +1-850-644-4201   Fax: +1-850-644-5038
email: balicas@magnet.fsu.edu

[2] Department of Physics, Florida State University, Tallahassee, FL 32306, USA

[3] Department of Mechanical Engineering, Columbia University, New York, NY 10027, USA

[4] Department of Applied Physics and Applied Mathematics, Columbia University, New York NY 10027, USA

[5] Department of Materials Science and Engineering, Stanford University, Stanford CA 94305, USA

[6] Department of Mechanical Science and Engineering, University of Illinois at Urbana Champaign, Urbana, IL 61801, USA

[7] Department of Physics, Columbia University, New York, NY 10027, USA

[8] Sensors and Electronic Devices Directorate US Army Research Laboratory Adelphi MD 20723, USA

MoTe$_2$ is an exfoliable transition metal dichalcogenide (TMD) which crystallizes in three symmetries; the semiconducting trigonal-prismatic $2H$−phase, the semimetallic $1T'$ monoclinic phase, and the semi-metallic orthorhombic T_d structure. The $2H$−phase displays a band gap of ~ 1 eV making it appealing for flexible and transparent optoelectronics. The T_d−phase is predicted to possess unique topological properties which might lead to topologically protected non-dissipative transport channels. Recently, it was argued that it is possible to locally induce phasetransformations in TMDs through chemical doping or local heating, to achieve ohmic contacts or to induce useful functionalities such as electronic phase-change memory elements. The combination of semi-conducting and topological elements based upon the same compound, might produce a new generation of high performance, low dissipation optoelectronic elements. Here, we show that it is possible to engineer the phases of MoTe$_2$ through W substitution by unveiling the phase-diagram of the Mo$_{1-x}$W$_x$Te$_2$ solid solution which displays a semi-conducting to semi-metallic transition as a function of x. We find that only ~ 8 % of W stabilizes the T_d−phase at room temperature. Photoemission spectroscopy, indicates that this phase possesses a Fermi surface akin to that of WTe$_2$.

Growth of Two-dimensionally Bonded Materials –
Fiction, Facts and Some Surprises

H. Riechert, J.E. Boschker, V. Bragaglia, R.N. Wang, K. Perumal, A. Giussani, L.A. Galves, T. Flissikowski, J.M.J. Lopes, and R. Calarco

Paul-Drude-Institut für Festkörperelektronik
Hausvogteiplatz 5-7, 10117 Berlin, Germany

Tel: +49-30-20377-365   Fax: +49-30-20377-201
email: riechert@pdi-berlin.de

Surface sensitive in-situ techniques make MBE an ideal tool to study the growth of two-dimensionally (van der Waals-) bonded materials. We use this approach to monitor e.g. the rotational registry of such layers in order to revisit the promises stated in some of the early, pioneering work[1] where it was assumed that lattice matching does not play an important role. The basis of the present work are graphene and Sb_2Te_3 , the latter being a 2D material consisting of blocks of quintuple layers. We grow Sb_2Te_3 on graphene layers of various thickness and on surfaces of Si(111), which are prepared in situ to obtain different amounts of surface bonds. In this way, we can tune or perturb the character of interfacial bonding between layered materials and/or the substrate. Based on both reflective high energy electron diffraction (RHEED) and Φ-scans in X-ray diffraction, our findings show that even in an ideal case of pure van der Waals-bonding, lattice mismatch is important for determining in-plane rotational order. Most surprisingly, surface reconstructions can be robust enough to determine the rotational orientation in the process of heteroepitaxy on Si(111). Our studies open up a way to understand and control the interaction of van der Waals-bonded layers. Finally, we will address the issue of strain caused by interactions between such layers in a more general context.

1. A. Koma et.al. Journal of Crystal Growth 201/202 p.236 (1999).
2. J.E. Boschker et al. Nano Letters 14 (6), 3534 (2014).
3. J.E. Boschker et.al. Scientific Reports 5:18079 (2015).

Atomic Layer Deposition of 2D MoS$_2$ on Si/SiO$_2$ and Quartz Substrates

Arturo Valdivia and John F. Conley, Jr.

School of Electrical Engineering and Computer Science, Oregon State University
Corvallis, OR 97330, USA

Tel: +1-541-737-9874
email: john.conley@eecs.oregonstate.edu

The synthesis of high quality monolayer 2D MoS$_2$ on large area substrates remains challenging. Mechanical exfoliation produces high quality material, but it is limited to small areas, requires transfer to the device substrate, and is impractical for manufacturing. Chemical vapor deposition is limited by non-uniform electrical properties, poor process stability, and high deposition temperature (>600°C). A natural method for the synthesis of 2D materials is atomic layer deposition (ALD), in which alternating, purge separated, self-limiting surface reactions allow for precise thickness control, high conformality, and scalability to large surface areas. Although reports of ALD MoS$_2$ are beginning to emerge, ALD of *single layer* MoS$_2$ has typically required specialty sapphire substrates and high temperature (800°C) post deposition anneals and/or has been limited to small diameter wafers.

We demonstrate low temperature ALD of single to few monolayer MoS$_2$ uniformly across 150 mm diameter patterned SiO$_2$/Si and quartz substrates using MoCl$_5$ and H$_2$S at temperatures ranging from 375°C to 475°C.[1] Raman scattering shows clear in-plane (E$^1_{2g}$) and out-of-plane (A$_{1g}$) modes, indicating the presence of mono- to few layer MoS$_2$. H$_2$S and sulfur annealing produces a sharpening of the E$^1_{2g}$ and A$_{1g}$ peaks and the appearance of the band edge PL and spin orbit splitting peaks – an indication of the presence of monolayer MoS$_2$. Transmission electron microscopy confirms the presence of monolayer to bilayer MoS$_2$ films. X-ray photoelectron spectroscopy indicates that a sub-stoichiometric S/Mo ratio in the as-deposited films is increased to the stoichiometric S/Mo ratio after annealing in H$_2$S at 600°C and above.

1. A. Valdivia, D.J. Tweet, and J.F. Conley, Jr., J. Vac. Sci Tech A **34**, 021515 (2016).

Progress in 2D Semiconductor Optoelectronics

Xiaodong Xu

Department of Physics, Department of Materials Science and Engineering
University of Washington, Seattle, WA 98105, USA

Tel: +1-206-543-8444   Fax: +1- 206-685-0635
email: xuxd@uw.edu

Two-dimensional transition metal dichalcogenides (TMDs) are a recent addition to the 2D electronic materials family. They have shown outstanding electrical and optical properties for new optoelectronic device concepts[1]. In this talk, we will discuss our recent progress in understanding the optoelectronic properties of monolayer and heterostructures of TMDs. I will first talk about hybrid monolayer/photonic crystal cavity devices[2,3]. Both electroluminescence and photoluminescence show coupling with the cavity mode. Signature of lasing will be discussed. I will then present light emission from single defects in both monolayers and heterostructures[4]. Electrically driven single defect light emitting diodes will also be discussed[5].

1. J R Schaibley et al., Nature Reviews Materials. Article Number: 16055 (2016).
2. S Wu et al., Nature. 520, 69 (2015).
3. S Wu et al., 2D Materials 1, 011001 (2014).
4. Y He et al., Nature Nanotechnology 10, 497 (2015).
5. G. Clark et al., Nano Letters 16, 4738 (2016).

Magneto-spectroscopy of Excitons in Semiconducting 2D Transition-metal Dichalcogenides

Dmitry Smirnov

National High Magnetic Field Laboratory
Tallahassee, FL 32310, USA

Tel: +1-850-644-5399   Fax: +1-850-644-0534
email: smirnov@magnet.fsu.edu

Monolayer transition metal dichalcogenides (ML TMDs) have recently emerged as a new class of direct bandgap 2D semiconductors with valleys at the $\pm K$ points in the Brillouin zone. Due to the broken inversion symmetry, this valley degree of freedom can be selectively addressed by optical helicity. At zero magnetic field, the two valleys are degenerate, however, their corresponding magnetic moments have opposite signs. In this work, we apply a magnetic field to selectively tune the valley energies and use circularly polarization resolved photoluminescence (PL) to probe neutral exciton, X0, and negatively charged trion, X-, in $MoSe_2$ and WSe_2. In a perpendicular field, the PL energies of both X0 and X- in $MoSe_2$ experience a linear shift. The direction of the shift is reversed for photons with opposite circular polarization, clearly demonstrating the lifting of the valley degeneracy, the valley Zeeman effect [1]. Similar valley Zeeman shifts in $MoSe_2$ and WSe_2 indicate that the valley Zeeman splitting is fundamental to semiconducting ML TMDs. However, an opposite change of the X- PL intensity with the magnetic field is consistent with different configuration for the ground state trion in $MoSe_2$ and WSe_2. In addition, we report the quadratic diamagnetic shift in these materials as well as field-induced brightening of dark excitons in WSe_2.

1. Y. Li et al. Phys. Rev. Lett. **113**, 266804–5 (2014).

Current-Injection Terahertz Lasing in Graphene-Channel Field Effect Transistors

Gen Tamamushi[1], Takayuki Watanabe[1], Alexander Dubinov[2], Tetsuya Suemitsu[1], Akira Satou[1], Maxim Ryzhii[3], Victor Ryzhii[1,4], and Taiichi Otsuji[1]

[1] Research Institute of Electrical Communication, Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan
Tel: +81-22-217-6104 Fax: +81-22-217-6104
email: otsuji@riec.tohoku.ac.jp
[2] Institute for Physics of Microstructures, RAS, Lobachevsky State University of Nizhny Novgorod, Nizhny Novgorod 603950, Russia
[3] Department of Computer Science and Engineering, University of Aizu
Aizu-Wakamatsu 965-8580, Japan
[4] Institute of Ultra High Frequency Semiconductor Electronics
Russian Acedemy of Science, Moscow 111005, Russia

Graphene, a monolayer carbon-atomic honeycomb lattice crystal, has attracted attention due to its superior carrier transport properties owing to the massless and gapless energy spectrum. Optical and/or injection pumping of graphene can exhibit negative-dynamic conductivity in the terahertz (THz) spectral range. In the graphene structures with p-i-n junction, the injected electrons and holes have relatively low energies compared with those in optical pumping, so that the effect of carrier cooling can be rather pronounced, providing a significant advantage of the injection pumping in realization of graphene THz lasers [1,2]. We implemented a forward-biased graphene structure with lateral p-i-n junctions in a distributed-feedback dual-gate graphene-channel field effect transistor (DFB-DG-GFET) and experimentally observed a single mode emission at 5.2 THz at 100K [3]. The device exhibits a nonlinear threshold-like behaviour with respect to the current-injection level. The observed spectral linewidth agrees well with the modal gain analysis. The observed emission is interpreted as THz lasing in population-inverted graphene by carrier-injection.

1. M. Ryzhii, and V. Ryzhii, Jpn. J. Appl. Phys. **46**, L151 (2007).
2. T. Otsuji et al., IEEE J. Sel. Top. Quantum Electron. **19**, 8400209 (2013).
3. G. Tamamushi et al., CLEO Tech. Dig. SM3L.7, Sa Jose, CA, USA (2016).

Intrinsic Ion Sensitivity of Graphene Field-effect Transistors

Yasuhide Ohno, Takanori Mitsuno, Yoshiaki Taniguchi, and Masao Nagase

Graduate School of Science and Technology, Tokushima University
2-1 Minamijousanjima, Tokushima 770-8506, Japan

Tel: +81-88-656-7439   Fax: +81-88-656-7439
email: ohno@ee.tokushima-u.ac.jp

Graphene has been expected for highly sensitive biosensors owing to its outstanding electrical and mechanical characteristics [1]. To realize practical sensor applications, it is important to understand the fundamental sensitivities of graphene FETs to ions, proteins, and so on. However, typical sensing characteristics include many environmental effects such as resist residues, contact resistance and ion impurities in SiO_2 substrate. To investigate the intrinsic sensitivity of graphene, these effects have to be eliminated in the sensing system to establish standard of the sensors. In this work, intrinsic ion sensitivity of graphene field-effect transistor (FET) using large-scale epitaxial graphene film on a SiC substrate was investigated.

Single crystalline graphene film was synthesized on a 4H-SiC(0001) substrate. Hall-bar pattern was formed by the stencil mask lithography and air plasma treatment. And we prepared two kinds of pH-adjusted buffer solution. One consists of 10 mM phthalate (pH 4), phosphate (pH 7), and borate (pH 9)-buffered solution. And the other was 10 mM pH-adjusted phosphate-buffered solution. As results, electrical characteristics were not changed by pH change but slightly changed by concentration change of the phthalate buffer solution, indicating that graphene FET with bare graphene channel cannot detect ions except ions with benzene ring.

1. Y. Ohno et al., Nano Lett. 9, 3318 (2009), & J. Am. Chem. Soc. 132, 18012 (2010).
2. T. Aritsuki et al., Jpn. J. Appl. Phys. 55, 06GF03 (2016).

Graphene Strain Engineering for Band Gap Opening

Rineka Hiraide[1], Hikari Tomori[2], and Akinobu Kanda[1]

[1] Division of Physics and TIMS, University of Tsukuba
Tsukuba, Ibaraki 305-8571, Japan
Tel: +81-29-853-5081   Fax: +81-29-853-4345
email: kanda@lt.px.tsukuba.ac.jp

[2] PRESTO, Japan Science and Technology Agency
Kawaguchi, Saitama 332-0012, Japan

Strain engineering is a promising but unexplored method of inducing transport/band gaps in graphene. Theories tell that spatial variation of lattice strain produces pseudo magnetic field. Local or periodic pseudo magnetic fields can be used to open a band/transport gap in graphene without degradation of transport properties.[1,2] So far, strain-induced band gap has been observed only in scanning tunnel spectroscopy studies, while it has not been confirmed in field effect devices. Here, we present novel device fabrication methods by which we are able to tailor the spatial variation of lattice strain in field effect devices. The observed transport/band gaps are ~ 2 meV for graphene with periodic uniaxial strain, and ~ 5 meV in graphene with local uniaxial strain. These values are quite small, but an important step toward graphene device applications.

1. V. M. Pereira and A. H. Castro Neto, Phys. Rev. Lett. 103, 046801 (2009).
2. F. Guinea et al., Nat. Phys. 6, 30 (2010).

An Integrated 1T-TaS$_2$ – *h*-BN – Graphene Oscillator: A Charge-Density-Wave Device Operating at Room Temperature

Guanxiong Liu[1], Bishwajit Debnath[2], Timothy R. Pope[3], Tina T. Salguero[3], Roger K. Lake[2], and <u>Alexander A. Balandin</u>[1]

[1] Department of Electrical and Computer Engineering, UC Riverside
Riverside, CA 92521, USA
Tel: +1-951-827-2351   Fax: +1-951-827-2425
email: balandin@ece.ucr.edu

[2] Department of Chemistry, University of Georgia, Athens, GA 30602, USA

The charge-density-wave (CDW) phase is a macroscopic quantum state consisting of a periodic modulation of the electronic charge density accompanied by a periodic distortion of the atomic lattice in metallic crystals. Several layered transition metal dichalcogenides, such as 1T-TaSe$_2$ and 1T-TaS$_2$ exhibit unusually high transition temperatures to different CDW symmetry-reducing phases. These transitions can be affected by environmental conditions, film thickness and applied electric bias [1]. However, device applications of these intriguing systems at room temperature or their integration with other 2D materials have not been explored. Here, we demonstrate room temperature current switching driven by a voltage controlled phase transition between CDW states in sub-10 nm films of 1T-TaS$_2$ [1]. We exploit the transition between the nearly-commensurate and the incommensurate CDW phases, which has a transition temperature of 350 K, and it gives an abrupt change in the current accompanied by hysteresis. An integrated graphene transistor provides a voltage tunable, matched, low-resistance load enabling precise voltage control of the circuit. The 1T-TaS$_2$ film is capped with hexagonal boron nitride to provide protection from oxidation. The integration of these three disparate two-dimensional materials, in a way that exploits the unique properties of each, yields a simple, miniaturized, voltage-controlled oscillator suitable for a variety of practical applications.

1. G. Liu, B. Debnath, T.R. Pope, T.T. Salguero, R.K. Lake and A.A. Balandin, Nature Nanotechnology, 11, 845 (2016); DOI: 10.1038/NNANO.2016.108

Density Dependence of the High Field Transport and Velocity Saturation in Graphene

D. K. Ferry

School of Electrical, Computer, and Energy Engineering, Arizona State University
Box 875706, Tempe, AZ 85287-5706, USA

Tel: +1-480-965-2570
email: ferry@asu.edu

Recent experiments on graphene transistors have shown a strong density dependence to the saturated velocity, and indicating that the latter may *exceed* the band limited Fermi velocity at low density [1]. We study the density dependence of the scattering in graphene and compute the velocity-field characteristics via an ensemble Monte Carlo process. We find only weak density dependence of the "saturated" value of the velocity near 4×10^7 cm/s. We discuss several reasons why transistor estimates in graphene may over-estimate the real values of the saturated velocity.

1. Ramamoorthy H *et al.,* Nano Letters **16,** 399 (2016).

Quantum Transport in van der Waals Junctions of Graphene and 2D Materials

Tomoki Machida[1], Sei Morikawa[1], Satoru Masubuchi[1], Naoto Yabuki[1], Rai Moriya[1],

Kenji Watanabe[2], and Takashi Taniguchi[2]

[1] Institute of Industrial Science, University of Tokyo, Komaba, Tokyo 153-8505, Japan
Tel: +81-3-5452-6742   Fax: +81-3-5452-6743
email: tmachida@iis.u-tokyo.ac.jp

[2] National Institute for Materials Science, Tsukuba 305-0044, Japan

Recent advances in transfer techniques of atomic layers have enabled one to fabricate van der Waals junctions of two-dimensional (2D) crystals such as graphene, hexagonal boron nitride (h-BN), and transition-metal dichalcogenides (TMDs). Here, we present our recent experiments on quantum transport in graphene/2D crystal van der Waals junctions. First, we discuss ballistic/coherent carrier transport in graphene npn junctions. In particular, we demonstrate a quantum Hall edge-channel interferometer in a high-quality graphene pn junction under high magnetic field. Next, we show that high-quality Josephson junctions can be built by connecting two exfoliated crystal flakes of a layered 2D superconductor, $NbSe_2$. Current-voltage measurements show characteristic features of Josephson effect, and an in-plane magnetic field induces a periodic modulation of the critical current due to the phase shift in supercurrent, Fraunhofer pattern. The results suggest that a superconducting 2D material can be included as a new element to inject supercurrent into van der Waals superlattices of various 2D materials.

1. S. Morikawa, S. Masubuchi, R. Moriya, K. Watanabe, T. Taniguchi, and T. Machida, Appl. Phys. Lett. **106**, 183101 (2015).
2. S. Morikawa, Z. Dou, S. -W. Wang, C. G. Smith, K. Watanabe, T. Taniguchi, S. Masubuchi, T. Machida, and M. R. Connolly, Appl. Phys. Lett. **107**, 243102 (2015).
3. S. Morikawa, S. Masubuchi, K. Watanabe, T. Taniguchi, and T. Machida, J. Jpn. Appl. Phys. **55**, 100305 (2016).
4. S. Morikawa, Q. Wilmart, S. Masubuchi, K. Watanabe, T. Taniguchi, B. Plaçais, and T. Machida (submitted).
5. N. Yabuki, R. Moriya, M. Arai, Y. Sata, S. Morikawa, S. Masubuchi, and T. Machida, Nature Commun. **7**, 10616 (2016).

Stability of Fractional Quantum Hall States with Non-Zero Width, Landau Level Mixing, and Temperature

Kiryl Pakrouski[1], Peter Raum[2], Micheal R. Peterson[3], Thierry Jolicoeur[4], Vito Scarola[1], Chetan Nayak[5,6], and Matthias Troyer[1]

[1] ETH Zurich
Theoretaische Physik, 8093 Zurich, Switzerland

[2] Virgini Tech
Physics Department, 850 W. Campus Dr. Blacksburg, VA 24061,USA
Tel: +1-540-231-8757   Fax: +1-540-231-7511
email: scarola@vt.edu

[3] California State University Long Beach
Department of Physics and Astronomy, Long Beach, CA 90840, USA

[4] CNRS and Université Paris-Sud,
Laboratoire de Physique Théorique et Modèles Statistiques, 91405 Orsay, France

[5] Department of Physics, UC Santa Barbara, CA 93106, USA

[6] Microsoft Research, Station Q
Elings Hall, UC Santa Barbara, CA 93106, USA

Fractional quantum Hall states, e.g., the Abelian Laughlin state or the non-Abelian Moore-Read Pfaffian state, are sensitive to changes in model parameters. We numerically diagonalize a comprehensive effective Hamiltonian describing the fractional quantum Hall effect of electrons under realistic conditions in GaAs semiconductors [1]. The effective Hamiltonian takes into account Landau-level mixing, the nonzero width of the quantum-well, and sub-band mixing. We observe that both Landau-level mixing and nonzero width suppress the excitation gap, but Landau-level mixing has a larger effect in this regard. Our findings have important implications for the identification of non-Abelian fractional quantum Hall states.   In a separate work, we study the thermal stability of Laughlin states [2]. We construct and validate an ansatz for computing thermodynamic functions, e.g., the heat capacity, to identify the onset of Laughlin correlations. Future work will examine the thermodynamics of non-Abelian states.

1. K. Pakrouski, P. Raum, M. R. Peterson, T. Jolicoeur, V. W. Scarola, C. Nayak, and M. Troyer PRX 5, 021004 (2014).
2. P. Raum and V.W. Scarola, in preparation (2016).

Transport through InSb Self-assembled Quantum Dots Coupled to Nanogap Metal Electrodes

Kenji Shibata[1], Masato Ohmori[2], Hiroyuki Sakaki[2], and Kazuhiko Hirakawa[3]

[1] Tohoku Institute of Technology, 35-1 Kasumicho, Taihaku-ku, Sendai 982-8577, Japan
Tel: +81-22-305-3217   Fax: +81-22-305-3217
email: kshibata@tohtech.ac.jp
[2] Toyota Technological Institute, 2-12-1 Hisakata, Tempaku-ku, Nagoya 468-8511, Japan
[3] IIS and INQIE, University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

InSb quantum dots (QDs) exhibit large orbital quantization energies, large electron g-factors, and strong spin-orbit interactions. These properties have attracted considerable attention not only as an ideal environment to study single spin-based physics but also for their applications to spin-based quantum information technology. However, so far, only a few experimental works have been reported concerning the electron transport through InSb quantum dots [1], due to technology challenges in the growth and device fabrication. In this work, we have grown self-assembled InSb QDs on (001)-oriented GaAs substrates and investigated electron transport through single InSb QDs by using metal electrodes with a narrow gap [2]. The fabricated samples exhibited very low but finite differential conductances and staircase like pattern at 4.2 K, indicating successful fabrication of the single electron transistors using single self-assembled InSb QDs. In the presentation, possible future applications of our InSb QD transistors based on the manipulation of single electron charge/spin states using electric/magnetic field, THz photon [3] and phonon [4] will be discussed.

1. H. A. Nilsson, et al, Nano Lett. 9, 3151 (2009).
2. M. Jung, et al., Appl. Phys. Lett. 86, 033106 (2005).
3 K. Shibata, et al, Phys. Rev. Lett. 109, 077401 (2012).
4. E. A. Zibik, et al., Phys. Rev. B 77, 041307R (2008).

Photonic Quantum Information and Quantum Metrology

Shigeki Takeuchi

Department of Electronic Science and Engineering
Kyoto University, Kyoto 615-8510 Japan

email: takeuchi@kuee.kyoto-u.ac.jp

Quantum information science has been attracting significant attention recently. It harnesses the intrinsic nature of quantum mechanics such as quantum superposition, the uncertainty principle, and quantum entanglement to realize novel functions. Recently, quantum metrology is emerging as another appealing application of quantum information science. In this talk, we will report our recent progresses on the development of novel quantum entangled-photon sources [1] and application to quantum measurements, including an entanglement enhanced microscope [2] beating the standard quantum limit [3], and application to quantum optical coherence tomography[4].

1. S. Takeuchi, Jpn. J. Appl. Phys. 53, 030101 (2014).
2. T. Ono, R. Okamoto, and S. Takeuchi, Nature Communications 4, 2426 (2013).
3. T. Nagata, R. Okamoto, J. L. O'Brien, K. Sasaki and S. Takeuchi, Science 316, 726 (2007).
4. M. Okano, H. H. Lim, R. Okamoto, N. Nishizawa, S. Kurimura and S. Takeuchi, Sci. Rep. 5, 18042 (2015).

Atomic Silicon Quantum Dots Enable an All-silicon Quantum Annealing Machine

Robert Wolkow
Department of Physics, University of Alberta
Edmonton, Alberta T6G 2J1, Canada

Tel: +1-780-641-1725   Fax: +1-780-492-0714
email: rwolkow@ualberta.ca

Our proposal that diverse ensembles of atomic silicon quantum dots can embody the passive and active elements of ultra-low power classical electronics as well as quantum electronics such as a quantum annealing machine have been further substantiated in our work over the past year. New atomic force microscopy (AFM) techniques, experiment and theory, have been applied to reveal the first atom resolved images of H terminated silicon while doing so with far less perturbative effects than scanning tunneling microscopy (STM). It is shown for the first time that AFM can image bonds, not only the radial exponentially decaying character of atom centers. The technique is also used to effectively see and controllably position single electrons and to demonstrate that an ideal binary "bit energy", of order 1 eV, can be achieved with the atom scale fabricated electronics being made by Quantum Silicon Incorporated. In another project, the first all-electronic pump-probe STM measurements of silicon are shown to be capable of simultaneous atom scale spatial and nanosecond temporal images of single electron dynamics. As an example, a new understanding of gated bulk to surface transport will be shown. A third project shows the first multi-silicon atom artificial molecules. Spatially and energetically resolved density of states maps reveal the newly emergent electronic states. Crucially, these are gap states, a central and enabling feature of our atomically defined electronics. Controlled, reversible perturbation of electronic structure will be shown and the importance of that to signal propagation will be explained.

Rectifying Current-Voltage Characteristics of Single Molecular Junctions

Keigo Minode, Mariko Yamaguchi, Shunpei Nobusue, Tatsuhiko Ohto, Ryo Yamada, and Hirokazu Tada

Graduate School of Engineering Science, Osaka University
1-3 Machikaneyama, Toyonaka 560-8531, Japan

Tel: +81-6-6850-6430   Fax: +81-6-6850-6430
email: tada@molectronics.jp

The concept of "molecular rectifier" proposed by Aviram and Ratner in 1974 [1] has motivated many researchers to prepare electronic devices based on single molecules. The break-junction method established in 2000s has enabled us to carry out the quantitative measurement not only of electrical conductivity of single molecules inserted between metal electrodes, but also of transport properties of spins and heat in single molecular junctions.

We have installed a mechanically controllable break junction (MCBJ) device in a low-temperature cryostat, which makes it possible to trace the I-V characteristics of the molecular junctions as a function of the gap spacing between electrodes with the resolution of 0.01 nm. It was found that the reproducible I-V characteristics were mostly observed for the junctions with the molecule elongated just before losing the contact. We have investigated the I-V characteristics of molecules having a permanent dipole moment. The low-temperature MCBJ measurements revealed that the molecules showed clear rectification behaviors. The rectification ratio became larger with an increase of the molecular length by the sequential stacking of the dipole unit. The first-principles transport calculations indicated that the electric field between the electrodes during the I-V measurements induces the deformation of the highest occupied molecular orbital, which causes the asymmetric electronic coupling between the molecule and the electrode. The guiding principle for preparation of molecular rectifiers will be discussed.

1. Aviram, A. and Ratner, M. A. Chem. Phys. Lett. 29, 277 (1974).

Nanofluidic Ionic Devices

Weihua Guan[1,2], Xin Li[3], and Mark A. Reed[4]

[1] Department of Electrical Engineering, Yale University
New Haven, CT 06520, USA
email: mark.reed@yale.edu

[2] Department of Electrical Engineering, Pennsylvania State University
State College, PA 16801, USA

[3] Department of Physics, Yale University,
New Haven, CT 06520, USA

[4] Department of Applied Physics, Yale University,
New Haven, CT 06520, USA

Solid-state nanofluidic devices have proven to be ideal systems for studying the physics of ionic transport at the nanometer length scale. When the geometrical confining size of fluids approaches the ionic Debye screening length, a number of new transport phenomena occur, which have wide ranging implications to diverse areas such as biological ion channels, desalination, and energy storage and conversion. We have demonstrated a variety of nanofluidic ionic devices which utilize controllable ion selectivity, allowing us to realize ionic diodes and field effect transistors [1]. These devices have remarkable analogies to their semiconductor counterparts, but with some important differences.

One of the most intriguing implications of nanofluidic ionics is the ability to construct artificial ion channels. We have demonstrated [2] that we can create membrane potentials similar to cellular systems, with the additional ability to tune the ion selectivity ratio. The detailed dynamics of the transport allows us to identify relevant relaxation times and mechanisms, which could enable engineering of faster ionic and neural systems.

The study of nanofluidic ionic systems has primarily used monovalent ion systems. However, divalent ions comprise some of the most important ion channels in biological systems. We have investigated divalent nanofluidic ion transport, and have observed charge inversion at the channel/fluid interface [3]. The observation of charge inversion has important implications to the theory of a strongly correlated liquid (SCL) and biological permselectivity.

1. W. Guan, R. Fan, and M.A. Reed, *Nature Comm.* **2**, article # 506 (2011).
2. W. Guan and M.A. Reed, *Nano Lett.* **12**, 6441 (2012).
3. X. Li, W. Guan, B. Weiner, and M.A. Reed, *Nano Lett.,* **15**, 5046 (2015).

Electrical Detection of Dissociation Process of Virus Using Sugar Chain Modified Graphene FET

Kazuhiko Matsumoto, Kaho Kamada, Yasushi Kanai, and Takao Ono

Institute of Scientific & Industrial Research, Osaka University
Mihogaoka 8-1, Ibaraki-shi, Osaka-fu, Osaka 567-0047, Japan

Tel: +81-6-6879-8410   Fax: +81-6-6879-8414
email:k-matsumoto@sanken.osaka-u.ac.jp

We formed a bio-platform by modified the surface of graphene FET using the sugar chain, which emulates a biological surface of human cell, and succeeded in detecting electrically the dissociation process of virus from the sugar chain.

Human cells are covered with sugar chains, and viral infection is via this sugar chain. Virus can penetrate into the cell by attaching the hemagglutinin tip of the virus to the the sialic acid that is at the top of the sugar chain. After the growth in the cell, virus released from the cell to another cell and continues the infection. At that time, neuraminidase of the virus tip dissolves the sialic acid of the sugar chain where the hemagglutinin is attached. However, there was no approach to the physical measurement of the status of this dissociation process until now.

In the present research, we introduced the neuraminidase to the system of sugar chain modified graphene FET. The neuraminidase dissolves sialic acid that is at the top of the sugar chain, and the negative charge of the carboxyl group of the sialic acid is removed. Then, the induced positive charge in the graphene channel by this negative charge of the carboxyl group is decreased, and we have first succeeded in observing the shifts of the Dirac point in the negative direction.

This is the first time result that captures the dissociation process and dissociation time constant of virus from sugar chain by electrical method. By introducing the viral drug of e.g., Relenza and Tamiflu, etc., the time constant of the dissociation of the virus may be delayed and the effect of the viral drug will be evaluated quantitatively.

Electrochemical Micro-Electrode Arrays for Measurement of Transient Concentration Gradients of Hydrogen Peroxide

David Janes, Siddarth V. Sridharan, Jose F. Rivera, Xin Jin, James Nolan, Hannah Kriscovich, Sarah Libring, Jenna L. Rickus, and Muhammad A. Alam

Purdue University
1205 W State St., West Lafayette, IN 47906, USA

Tel: +1-765-494-9263   Fax: +1-765-494-0811
email: janes@purdue.edu

In a number of biological processes, there is interest in measuring dynamic concentration gradients of selected analytes. Prior measurements of gradients/transients using electrochemical sensors include spatially-moving single electrode approaches (e.g. self-referencing) or arrays of electrodes with cells immobilized on the arrays. In general, it has been difficult to achieve high spatial and temporal resolution simultaneously using these approaches. In the current study, amperometric measurement of transients and gradients with fast response time and high spatial resolution are obtained using an on-chip array of micro-electrodes that can be positioned in the vicinity of a natural or artificial source/sink of analyte (e.g. a 2-D/3-D culture of cells).   The target analyte, hydrogen peroxide (H_2O_2), is a species of interest both as a reactive oxidative species and as a signalling molecule. In addition, peroxide is the redox-active species generated in enzymatic layers used to provide selective response to analytes at electrode surfaces (e.g. glucose with glucose oxidase for glucose detection) and can be used determine intrinsic electrode response times. Measurements using a large-area electrode as a sink of peroxide show that spatial resolution below 30 µm and temporal resolution sufficient to capture 150 ms transients can be achieved simultaneously.   The presentation will also discuss functionalization of the electrodes surfaces, including nanostructured coatings and selective enzymatic layers.

Wearable and Implantable Bio-signal Monitoring Systems

Shusuke Yoshimoto, Teppei Araki, Takafumi Uemura, and Tsuyoshi Sekitani

The Institute of Scientific and Industrial Research, Osaka University
8-1, Mihogaoka, Ibaraki, Osaka 567-0047, Japan

Tel: +81-6-6879-8400   Fax: +81-6-6879-8404
email: sekitani@sanken.osaka-u.ac.jp

We will present the recent progresses and future prospects of ultra-soft, conductive gel electrodes, and wearable and implantable electronic sensors for bio-medical applications [1-9]. Ultrasoft gel electrodes consist of highly-conductive nano-conductive materials including Ag-based nanowires and flakes, carbon nanowires and nanocomposites, and bio-compatible gels. The conductive gel composite shows conductivity greater than 10,000 S/cm, and can be stretched more than 100% without any damages in electrical and mechanical performances, so that it can spread over arbitrary curved surfaces even on the ultrasoft brain. With integrating the ultrafsoft gel electrodes, ultraflexible amplifier, Si-LSI platform consisting of wireless data-transmission module and analog-to-digital converter, Li-ion-based thin-film battery, and information engineering, here we would like to demonstrate the applications of wearable and implantable bio-compatible active sensors. Our patch-type electroencephalogram (EEG) sensor will be presented with a diagnosing tool for Alzheimer's disease using frequency domain analysis.

1. Shusuke Yoshimoto, et al., Proc. of IEEE EMBC, pp. 6286-6289, (2016).
2. Shusuke Yoshimoto, et al., Proc. of IEEE BioCAS, pp. 476-479, (2016).
3. Tsuyoshi Sekitani, et. al., Nature Communications Vol. 7, 11425 (2016).
4. Martin Kaltenbrunner, Tsuyoshi Sekitani, et. al., Nature Vol. 458, pp. 499-463 (2013).
5. Tsuyoshi Sekitani, et. al., Nature Materials Vol. 9, pp. 1015-1022 (2010).
6. Tsuyoshi Sekitani, et. al., Science Vol. 326, pp. 1516-1519 (2009).
7. Tsuyoshi Sekitani, et. al., Nature Materials Vol. 8, pp. 494-499 (2009).
8. Tsuyoshi Sekitani, et. al., Science Vol. 321, pp. 1468-1472 (2008).
9. Tsuyoshi Sekitani, et. al., Nature Materials Vol. 6, pp. 413-417 (2007).

Magnetoresistance in Organic Materials

Takeshi Kamiya, Chihiro Miyahara, Marine Fayolle, Toan Song Pham, Tatsuhiko Ohto, Ryo Yamada, and Hirokazu Tada

Graduate School of Engineering Science, Osaka University
1-3 Machikaneyama, Toyonaka 560-8531, Japan

Tel: +81-6-6850-6430   Fax: +81-6-6850-6430
email: tada@molectronics.jp

Magnetic field effects onto electrical resistance in organic materials (OMs) become of interest because of their potential applications to non-volatile memories and sensors on flexible substrates. The studies are classified into two categories according to device structures with or without ferromagnetic (FM) metal electrodes. The former devices give the information about the spin injection and transport behaviors in organic materials, while using the latter ones we can discuss about the dynamics of bipolarons and excitons. We have prepared sandwich structures consisting of FM/OMs/FM to study the spin diffusion length, as well as of ordinary metal/OMs/ordinary metal to study the mechanism of magnetoresistance (MR) induced by the formation of bipolarons and/or excitons. We have prepared spin-valve characteristics of single crystals of molecular conductor with a nonlocal geometry, in which the electric current is separated from the spin cur-rent. The nonlocal MR decayed with increasing the gap spacing between FM electrodes, indicating diffusive spin transport. The spin diffusion length and the spin relaxation time at 2.5 K were evaluated to be 1.1 μm and 3 ns, respectively. These values are one order of magnitude larger than those of ordinary metals. Concerning the intrinsic MR in OMs, we studied bipolarons-induced and excitons-induced MR in OMs sandwiched between ordinary metals. Impedance spectroscopy of OMs has revealed that the localized states at the metal-organic interfaces play an important role to determine the sign and/or magnitude of MR.

Staircase and Homojunction Avalanche Detectors in InAlAsSb

Scott Maddox[1,*], Min Ren[2,*], Maddy Woodson[2], Ann-Kathryn Rockwell[1], Joe C. Campbell[2], and Seth R. Bank[1]

[1] University of Texas at Austin
10100 Burnet Rd., Austin, TX 70758 USA
Tel: +1-512-471-9669
email: sbank@ece.utexas.edu

[2] University of Virginia, Charlottesville
351 McCormick Rd, Charlottesville, VA 22904 USA

Since the initial proposal by Capasso[1] of the staircase avalanche photodiode (APD) – the solid-state implementation of the photomultiplier tube – experimental realization has been hampered by the lack of a well-controlled material system with sufficiently large band offsets and intervalley energy separations. We have demonstrated a working single step staircase APD that exhibits a gain of 2x over a wide range of bias, excitation wavelength, temperature, etc,[2] enabled by the development of AlInAsSb growth, lattice-matched to GaSb, over its entire direct-bandgap compositional range.[3] Perhaps more puzzling, simple p-i-n homojunction APDs of AlInAsSb exhibit low excess noise, making it the first low noise III-V APD alloy family to date.[4] The cutoff wavelength is tunable with the composition, enabling separate absorption and multiplication APDs operating out to 1.55, with noise comparable to silicon and high gains.[5] These detectors could revolutionize quantum and conventional fiber-based communication systems, as well as emerging imaging applications such as 3-D laser radar.

1. F. Capasso, IEEE Trans. Nucl. Sci. 30, 424 (1983).
2. M. Ren, et al., Appl. Phys. Lett. 108, 081101 (2016).
3. S. Maddox et al., ACS JCGD, 16, 3582 (2016).
4. M.E. Woodson, et al., Appl. Phys. Lett. 108, 081102 (2016).
5. M. Ren, et al., Appl. Phys. Lett. 108, 191108 (2016).

*Contributed equally to the work.

Scanning Nano-SQUID Microscope for Investigations of Properties of Two-dimensional Layer of Semiconductors and Superconductors

S. Nomura[1], Y. Shibata[1], H. Kashiwaya[2], S. Kashiwaya[2], R. Ishiguro[3], Y. Nago[4], and H. Takayanagi[4]

[1] Division of Physics, University of Tsukuba, Tsukuba 305-8571, Japan
Tel: +81-29-853-4218   Fax: +81-2-853-6618
email: nomura.shintaro.ge@u.tsukuba.a.jp
[2] National Institute of Advanced Industrial Science and Technology
Tsukuba 305-8561 , Japan
[3] Department of Mathematical and Physical Sciences, Japan Women's University
Tokyo 112-8681, Japan
[4] Department of Applied Physics, Tokyo University of Science, Tokyo 162-0825, Japan

Nano-superconducting quantum interference devices (SQUIDs) have been recognized to be the most sensitive magnetic field and flux detectors. Recently, nano-SQUIDs have been actively investigated to facilitate nano-scale applications. Weak-link Dayem Josephson junction nano-SQUIDs are favourable to reduce the size of the SQUID loop, however, hysteresis is often observed in current-voltage characteristic [1] that hinders application to scanning microscope. Here we report on a weak-link nano-SQUID scanning microscope with a Nb nano-SQUID probe that can be operated as magnetic flux to voltage transducer due to its small hysteresis in current-voltage curve [2]. We have successfully reconstructed current densities in two-dimensional electron gas in GaAs single heterojunction by mapping magnetic field distribution [2]. We have revealed reduction of magnetic field on superconducting Nb/Au and FIB-deposited tungsten-carbide wires in an external magnetic field [3]. Scanning nano-SQUID microscopes offer great advantages of direct measurement of magnetic fields and have wide applications in investigations of nanoscale devices and materials.

1. T. Matsumoto et al., Physica C **471**, 1246 (2011).
2. Y. Shibata et al., Sci. Rep. **5**, 15097 (2015).
3. Y. Shibata et al., Supercond. Sci. Technol. **29**, 104004 (2016).

Uncooled, Very Sensitive Bolometer using a Doubly Clamped Microelectromechanical Beam Resonator for Terahertz Detection

Ya Zhang[1], Yasuyuki Watanabe[1], Suguru Hosono[1], Naomi Nagai[1], and
Kazuhiko Hirakawa[1,2]

[1] Institute of Industrial Science, University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
Tel: +81-3-5452-6260   Fax: +81-3-5452-6262
email: hirakawa@iis.u-tokyo.ac.jp

[2] Institute for Nano Quantum Information Electronics, University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

We propose a room temperature, all electrical driving and detecting, very sensitive thermometer structure using a microelectromechanical (MEMS) resonator for bolometer applications. We have fabricated a GaAs doubly clamped MEMS beam resonator whose oscillation can be excited and detected by piezoelectric effect [1]. When a heating power is applied to a NiCr film deposited on the MEMS beam surface, internal thermal stress is generated in the beam, leading to a reduction in the resonance frequency. The present device detects the shift in resonance frequency caused by heating and works as a very sensitive thermometer [2]. When the resonator was driven by a voltage slightly below the threshold for the nonlinear, hysteretic oscillation, the thermometer showed a voltage responsivity of about 3,300 V/W, while keeping a low noise spectral density of about 60 $nV/Hz^{1/2}$, demonstrating a noise equivalent power of < 20 $pW/Hz^{1/2}$ even at room temperature. The observed effect can be used for realizing high-sensitivity terahertz bolometers for room-temperature operation [2].

1. I. Mahboob and H. Yamaguchi, Nat. Nanotechno. **3**, 275 (2008).
2. Y. Zhang, Y. Watanabe, S. Hosono, N. Nagai, and K. Hirakawa, Appl. Phys. Lett. 108, 163503 (2016).

Antenna-Coupled Single-Metal Nanothermocouples for THz Wave Detection

Gergo P. Szakmany, Alexei O. Orlov, Gary H. Bernstein, and Wolfgang Porod

Department of Electrical Engineering, Center for Nano Science and Technology
University of Notre Dame, Notre Dame, IN 46556, USA

Tel: +1-574-631-6376
email: porod@nd.edu

We present THz wave detectors based on antenna-coupled single-metal nano-thermocouples (NTCs). The top panel of the figure shows the Au dipole antenna and the Ni thermocouples. The thermocouples are placed at the center of the dipole antenna where maximum heating occurs due to the radiation-induced antenna currents. In order to increase the detector signal, the NTCs were connected in series to form thermopiles. The bottom part of the figure shows 9 thermocouple junctions connected in series to form a thermopile. The resonant antenna length for 600 GHz radiation was determined by COMSOL simulations. We present the measured polarization-dependent response of antennas with thermopiles of various lengths. The devices exhibit a cosine-square polarization response, and they follow the thermocouple addition rule, confirming that the detection mechanism is based on the heating of the "hot" NTC junctions by the radiation-induced antenna current.
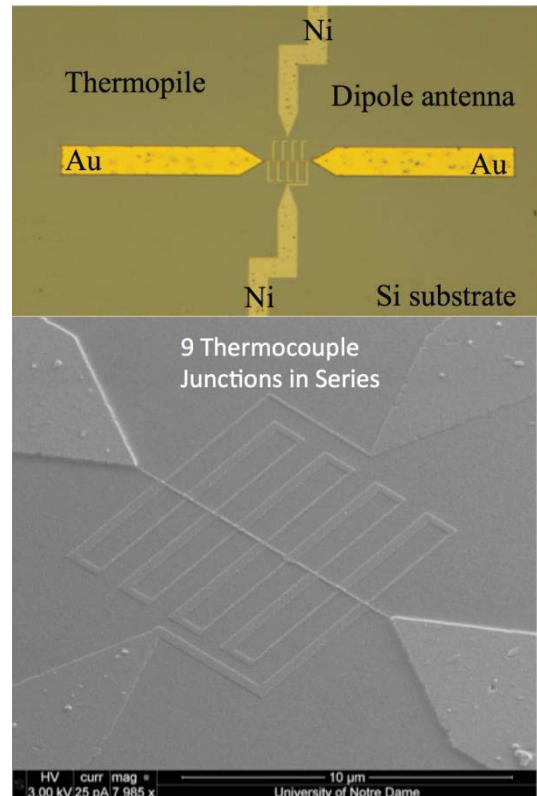
Infrared and Terahertz Detectors based on Graphene - van der Waals Heterostructures

Victor Ryzhii[1,2], Maxim Ryzhii[3], Taiichi Otsuji[1], Dmitry Svintsov[4],
Vladimir Leiman[4], Vladimir Mitin[1,5], and Michael S. Shur[6]

[1] Research Institute of Electrical Communication, Tohoku University
2-1-1 Katahira, Aoba-ku, Sendai 980-8577, Japan
Tel: +81-242-222-379
email: v-ryzhii@riec.tohoku.ac.jp
[2] Institute of Ultra High Frequency Semiconductor Electronics
Russian Academy of Sciences, Moscow 117105, Russia
[3] Department of Computer Science and Engineering, University of Aizu
Aizu-Wakamatsu 965-8580, Japan
[4] Laboratory of Optoelectronics of Two-Dimensional Materials
Moscow Institute of Physics and Technology, Dolgoprudny 141701,Russia
[5] Department of Electrical Engineering, University at Buffalo
Buffalo, NY 14260, USA
[6] Department of Electrical, Computer, and System Engineering
Rensselaer Polytechnic Institute, Troy, NY 12180, USA

We propose and evaluate the detectors of infrared and terahertz radiation based on van der Waals (vdW) heterostructures with the radiation absorbing graphene layers (GLs). The operation of these GL-vdW detectors is associated   with the electron photoexcitation from the GL valence band to the continuum states above the inter-GL barriers (either via tunneling of the photoexcited electrons or via the direct their transitions to the continuum states). Using the developed device model, we calculated the photodetector characteristics (spectral, voltage, and so on) as functions of the heterostructure parameters. We show that due to relatively large probability of the electron photoexcitation and low capture probability of the electrons propagating over the barriers GL-vdW detectors can exhibit elevated photoelectric gain, detector responsivity and other characteristics.

Interaction of Surface Acoustic Waves with a 2D Wigner Crystal in High-Mobility n-GaAs/AlGaAs

I. L. Drichko[1], I. Yu. Smirnov[1], A. V. Suslov[2], Y. M. Galperin[3,1], L. N. Pfeiffer[4], and K. W. West[4]

[1] A. F. Ioffe PTI of Russian Academy of Sciences, 194021 St. Petersburg, Russia
[2] National High Magnetic Field Laboratory, Tallahassee, FL 32310, USA
Tel: +1-850-644-6788   Fax: +1-850-644-0534
email: suslov@magnet.fsu.edu
[3] Department of Physics, University of Oslo, 0316 Oslo, Norway
[4] Department of Electrical Engineering, Princeton University, Princeton, NJ 08544, USA

Absorption and velocity of surface acoustic waves (SAWs) propagating in vicinity of high-mobility 2D n-GaAs/AlGaAs channel have been measured in magnetic fields B up to 18 T at temperatures T = (40 ÷ 340) mK and SAW frequencies f = (30 ÷ 300) MHz. The complex ac conductance, $\sigma^{AC}(\omega) \equiv \sigma_1(\omega) - i\sigma_2(\omega)$ and its dependences on frequency, temperature, and the amplitude of the SAW-induced electric field were calculated. We demonstrated that at low temperatures at some magnetic fields the electronic system forms pinned Wigner crystal (WC), the so-called Wigner glass. We estimated that the correlation (Larkin) length of the Wigner glass is of about 3 μm. At a certain temperature T_m, the temperature dependences of both components of the complex conductance get substantially changed: from the dielectric behavior at $T < T_m$ to the metallic one at $T > T_m$. We proved that this change of the conduction mechanism is due to melting of the WC. The dependence of the so-defined melting temperature on the electron filling factor was further studied. In fact, our observations show that magnetic field can be used to control the attenuation and velocity of surface acoustic wave in a hybrid WC/SAW device.

Spin Wave Reversible Logic Gates

Michael Balinskiy[1], Howard Chiang[1], Alexander Kozhevnikov[2], Yury Filimonov[2], and Alexander Khitun[1]

[1] Electrical Engineering Department, UC Riverside, Riverside, CA 92521, USA
Tel: +1-951-827-5816   Fax:+1-951-827-2425
email: akhitun@engr.ucr.edu

[2] Kotel'nikov Institute of Radioengineering and Electronics of Russian Academy of Sciences, Saratov Branch, Saratov 410019, Russia

We discuss the possibility of building spin wave logic gates for reversible computing. The gates consist of passive elements: waveguides, cross-junctions and phase shifters. Logical 0 and 1 are encoded in the propagating spin wave packets. The gates contain several possible trajectories for each packet to propagate from the input to the output. Re-direction of the spin wave packets among the possible trajectories is due to the interference in the magnetic cross-junctions. We present experimental data obtained on the cross junction made of $Y_3Fe_2(FeO_4)_3$. The obtained data demonstrate efficient spin wave re-direction at Room Temperature. The proposed gates may potentially provide a route to magnetic reversible logic circuitry with power dissipation less than kT per operation.

Quantum Algorithms without Quantum Entanglement: Data Processing with Magnonic Holographic Memory

Michael Balinskiy[1], Howard Chiang [1], Alexander Kozhevnikov[2], Yuri Khivintsev[2], Yury Filimonov[2], and Alexander Khitun[1]

[1] Electrical Engineering Department, UC Riverside, Riverside, CA 92521, USA
Tel: +1-951-827-5816   Fax: +1-951-827-2425
email: akhitun@engr.ucr.edu

[2] Kotel'nikov Institute of Radioengineering and Electronics of Russian Academy of Sciences, Saratov Branch, Saratov 410019, Russia

Magnonic Holographic Memory (MHM) is a type of holographic device which exploits spin wave interference[1]. One of the appealing properties of MHM is utilization of phase in addition to amplitude for data processing. The latter makes it possible to implement some of the algorithms developed for quantum computers with classical waves but without using quantum entanglement. We will present experimental data obtained on the $Y_3Fe_2(FeO_4)_3$ prototypes showing MHM capabilities for *pattern recognition*, *parallel database search* and *prime factorization*. According to the estimates, magnonic holographic devices may provide data processing rates higher than 1×10^{18} bits/cm^2/s while consuming only 0.15mW. Technological challenges and fundamental physical limits of this approach will be also discussed.

1. Khitun, A. Magnonic holographic devices for special type data processing. *JOURNAL OF APPLIED PHYSICS* **113**, doi:16450310.1063/1.4802656 (2013).

Electrically Controlled Surface Magnetism

Peter A. Dowben, Christian Binek, Takashi Komesu, Mike Street, and Shi Cao

Department of Physics and Astronomy, University of Nebraska-Lincoln
Theodore Jorgensen Hall, 855 North 16th Street, Lincoln, NE 68588-0299, USA

Tel: +1-402-472-9838   FAX: +1-402-472-6148
email: pdowben1@unl.edu

Manipulation of magnetically ordered states by electrical means is among the most promising approaches towards novel spintronic devices [1-4]. Indeed, voltage control of magnetism is a "holy grail" of spintronics. Electric control of the exchange bias can be realized when the passive antiferromagnetic pinning layer, in an exchange bias system, is replaced by a magneto-electric antiferromagnet [3]. In a magneto-electric material, an applied electric field induces a net magnetic moment. Surprisingly, this net magnetic moment, at the surface of a magneto-electric antiferromagnet, can be observed in spin-polarized photoemission [3], spin-polarized inverse photoemission [4], X-ray circular dichroism [4] and spin polarized low energy electron microscopy [5], when the antiferromagnetic single domain state is selected in a magneto-electric annealing process. In the single domain antiferromagnetic state of $Cr_2O_3(0001)$, a magnetic surface moment evolves which is robust against surface roughness. This has led to revived interest in the prototypical magneto-electric Cr_2O_3, where spontaneous ferroelectric order is absent, but a specific surface magnetic order enables electric control of a net spin polarization of the $Cr_2O_3(0001)$ surface. Some ideas will be provided on how magneto-electrics might be implemented into voltage controlled nonvolatile spintronic devices.

1. Ch. Binek, B. Doudin, *J. Phys. Condens. Matter* **17**, L39 (2005).
2. P.A. Dowben, Ch. Binek, and D.E. Nikonov, "Potential of nonvolatile magnetoelectric devices for spintronic applications", Chapter 11 in *Nanoscale Silicon Devices*; edited by Shuni Oda and David Ferry; Taylor and Francis (London), pp 255-278, ISBN 9781482228670 (2016).
3. Xi He, Yi Wang, N. Wu, A.N. Caruso, E. Vescovo, K.D. Belashchenko, P.A. Dowben and Ch. Binek, *Nature Materials* **9**, 579-585 (2010).
4. N. Wu, Xi He, A. Wysocki, U. Lanke, T. Komesu, K.D. Belashchenko, Ch. Binek and P.A. Dowben, *Physical Review Letters* **106**, 087202 (2011).
5. Shi Cao, X. Zhang, N. Wu, A. T. N'Diaye, G. Chen, A. K. Schmid, X. Chen, W. Echtenkamp, A. Enders, Ch. Binek, P. A. Dowben, *New Journal of Physics* **16**, 073021 (2014).

Influence of the Free Layer Alignment on the Reliability of a Non-Volatile Magnetic Shift Register

Thomas Windbacher[1], B. Gunnar Malm[2], Viktor Sverdlov[1], Mikael Östling[2], and Siegfried Selberherr[1]

[1] Institute for Microelectronics, TU Wien
Gußhausstraße 27-29, 1040 Wien, Austria
Tel: +43-1-58801-36010   Fax: +43-1-58801-36099
email: Selberherr@TUWien.ac.at

[2] School of Information and Communication Technology, KTH
Electrum 229, 16440 Kista, Sweden

Due to physical limitations and financial constraints a reduced progress rate through CMOS scaling is foreseeable for the near future. Among the smorgasbord of possible successor technologies, spin-based electronics (spintronics) shows considerable potential. Spintronic devices feature non-volatility, fast switching, high endurance, and CMOS compatibility. First competitive MRAM circuits are already commercially available and more applications will for sure follow soon [1]-[4]. Although promising logic CMOS/spintronic hybrids already exist, they cannot compete with respect to the integration density - one of the keys of success of CMOS technology. In order to enable a higher integration density, we proposed to omit the extra transistors required for the communication between the CMOS and the spintronic circuit parts and shift as much as possible of the CMOS functionality into the spintronic domain. The results are an extremely small non-volatile magnetic flip flop [5], a very compact buffered logic gate grid [6], and a dense shift register [7]. We will present our most recent results related to these novel structures, particularly the reliability of the devices, where the influence of free layer alignment variations appears to be of major importance.

1. Everspin Technologies. http://www.everspin.com/pub (2016).
2. Chabi et al., IEEE Trans. Circuits and Systems I, 61 6, 1755 (2014).
3. Deng et al., IEEE Trans. Circcuits and Sysems I, 62 7, 1757–1765 (2015).
4. Deng et al., IEEE Trans. Nanotechnology 14(1), 169–177 (2015).
5. Windbacher et al., in Proc. SISPAD, 368–371 (2013).
6. Windbacher et al., ECS Trans., 66 (4) 295-303 (2015).
7. Windbacher et al., in Proc. NANOARCH, 36-37 (2013).

Spin Josephson Effects in Exchange Coupled Ferromagnets and Antiferromagnets

Yizhou Liu[1], Gen Yin[1*], Jiadong Zang[2], Yafis Barlas[1,3], and Roger K. Lake[1]

[1] Department of Electrical and Computer Engineering, UC Riverside, CA 92521, USA
Tel: +1-951-827-2122
email: rlake@ece.ucr.edu
[2] Department of Physics and Materials Science Program, University of New Hampshire
Durham, NH 03824, USA
[3] Department of Physics and Astronomy, UC Riverside, CA 92521, USA

One exotic method to transport pure spin currents exploits the ground states of easy-plane ferromagnets (FMs) or antiferromagnets (AFMs). Such systems support metastable spin spiral states that can transfer spin angular momentum without dissipation giving rise to spin super-currents and spin superfluidity. We explore the analogy of the Josephson effect in a lateral spin valve heterostructure with two AFM insulators (AFMIs) separated by a thin metallic spacer. A spin chemical potential difference between the two AFMIs perpendicular to the direction of the Néel vector field drives THz oscillations of the spin current. This spin current also has a non-linear, time-averaged component that can be detected by the inverse spin-Hall effect in the metal spacer with large spin-orbit coupling providing a clear signature of spin superfluidity. Establishing the spin chemical potential difference requires the injection of pure spin into one of the AFMIs, which can be accomplished using the spin-Hall effect. The physics described above also applies to easy-plane ferromagnetic insulators. These results may provide a new approach for experimental verification of spin superfluidity and realization of a terahertz spin oscillator. Very recently, we have found that the spin-Josephson analogy can be extended to include Shapiro steps.

*Current address: Department of Electrical Engineering, University of California Los Angeles

Signal Processing by Spin-Wave Interference

Adam Papp, György Csaba, and Wolfgang Porod

Department of Electrical Engineering, Center for Nano Science and Technology
University of Notre Dame, Notre Dame, IN 46556, USA

Tel: +1-574-631-6376
email: porod@nd.edu

By means of micromagnetic simulations we demonstrate that spin-wave interference can be used to decompose a microwave signal into its spectral components. In particular, we show that a spin-wave based realization of the Rowland geometry is possible. The Rowland circle [1] is well established in X-ray spectroscopy. Its main element is a patterned, reflecting surface, acting as a combination of a diffraction grating and a concave mirror. In this geometry, waves are first diffracted by the grating, depending on their wavelength, and then subsequently focused by the mirror on different points of the Rowland circle.

Different wavelengths correspond to different foci. A spin-wave-based implementation for the Rowland geometry is shown in Fig. 1. This shows an actual micromagnetic simulation an approx. 3 x 2.5 micrometer size permalloy film. The bottom of the film is patterned in such a way that it performs both the diffracting and focusing functions. The resulting structure is significantly simpler than our earlier proposal for a spin-wave lens [2], as it requires no non-uniform magnetic fields for the manipulation of spin waves.
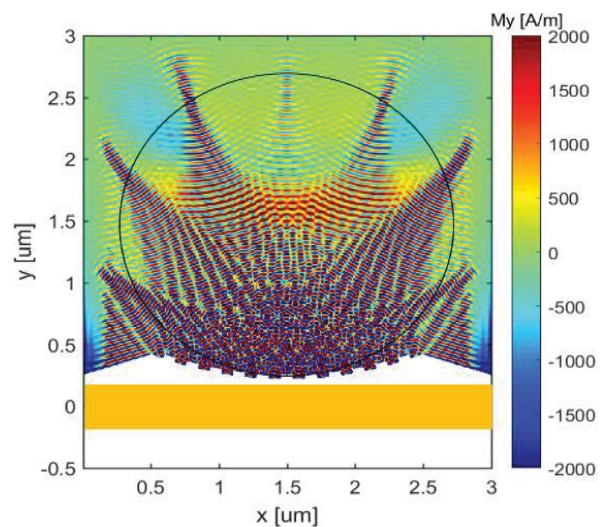

Figure 1 Figure 1: Micromagnetic simulation of the spin-wave device. The colormap shows a magnetization snapshot of the magnetic film. Along the Rowland circle different diffraction orders of one frequency component can be seen.

1. M. C. Hutley, Diffraction Gratings (Academic Press, London ; New York, 1982).
2. G. Csaba, A. Papp, and W. Porod, J. Appl. Phys. 115, 17C741 (2014).

Steep Slope Devices Combining Two Subthermionic Switching Principles

Adrian M. Ionescu, Wolfgang Vitale, and <u>Montserrat Fernández-Bolaños</u>

Nanoelectronic Devices Laboratory, NANOLAB.
École Polytechnique Fédérale de Lausanne (EPFL)
STI IEL Station 11 1015 Lausanne, Switzerland

Tel: +41-21-693-3973   Fax: +41-21-693-3640
email: montserrat.fernandez-bolanos@epfl.ch

Many disruptive innovations in science and technology originated in the discovery of new materials or in the way their unique properties have been smartly exploited. Today CMOS technology is facing both scaling and power limitations that require more fundamental innovations compared to the traditional Dennard scaling supported by various technology boosters at nanoscale. New materials and device principles for making more energy efficient low power electronic switches are required. Among them, the steep slope switches are forming a particular class of devices capable of switching between *off* and *on* states with a subthreshold slope smaller than 60mV/decade at room temperature; impact ionization devices, tunnel FETs, negative capacitance FETS, NEM switches and phase change switches are just a few examples of such emerging devices, exploiting a sub-thermionic switching principle.

In this talk we will present some special classes of hybrid steep-slope devices that can achieve a very small subthreshold swing by combining in a single device architecture two abrupt switching mechanisms: (i) *phase-change Tunnel FETs*, exploiting the metal-insulator transition (MIT) in VO_2 materials integrated in the gate or the source of tunnel FETs and (ii) *tunnel FETs exploiting the negative capacitance* effect in PZT gate stacks, as performance booster. We will illustrate our talk with explanations of the device principles and with experimental results.

1. W. A. Vitale, C. F. Moldovan, M. Tamagnone, A. Paone, A. Schuler, and A. M. Ionescu, *IEEE Electron Device Lett.*, vol. 36, no. 9, pp. 972–974, (2015).
2. A.Saeidi, F. Jazaeri, I- Stolichnov, A.M. Ionescu, *IEEE Transactions on Electron Devices*, Volume: 63, Issue: 12, pp. 4678 - 4684 (2016).

Novel Energy-efficient Transistors with 2D Materials

Rajib Rahman

Network for Computational Nanotechnology (NCN), Purdue University
207 S. Martin Jischke Dr., DLR 441-3, West Lafayette, IN 47907, USA

Tel: +1-765-496-6884, Fax: +1-765-496-6026
email: rrahman@purdue.edu

Emerging two-dimensional materials provide new opportunities to design post-Moore's Law devices due to their atomically thin dimensions, layer dependent band gaps and effective masses, large density of states, and exotic band structures. Novel designs for energy efficient steep subthreshold swing transistors are investigated in 2D materials, highlighting the material and device properties that optimize the On-currents and energy-delay products. Based on atomistic non-equilibrium Green's function simulations, the device characteristics of various 2D material based tunnel field effect transistors (TFET) [1] are compared. Design principles for TFETs with chemical and electrical doping are both explained. A new design for an electrically doped 2D TFET, which uses a combination of high and low k dielectrics to achieve high On-currents, is presented [2]. It is also shown that few-layer Phosphorene optimizes TFET characteristics among chemically doped 2D TFETs. Finally, a novel design for a Phosphorene TFET is presented which uses its anisotropy of effective mass to improve On-currents and suppress Off-state leakage [3]. Such a TFET also helps dimension scaling down to 1nm channel lengths [4].

1. H. Ilatikhameneh et al, IEEE J-EDS Vol. 4, Issue 5, 260-265 (2016).
2. H. Ilatikhameneh et al, IEEE EDL Vol. 36, No. 10, 1097-1100 (2015).
3. T. A. Ameen et al, Scientific Reports 6, 28515 (2016).
4. H. Ilatikhameneh et al, Scientific Reports 6, 31501 (2016).

Quantum Tunneling in Vertically Stacked Quasi-2D Heterojunctions Enabled Multifunctional Optoelectronic Devices

Wei-Chun Tan, Chia-Wei Chiang, Mario Hofmann, and <u>Yang-Fang Chen</u>

Department of Physics, National Taiwan University
No. 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan

Tel: +886-2-33665125   Fax: +886-2-23639984
email: yfchen@phys.ntu.edu.tw

The advent of 2D materials integration has enabled novel heterojunctions where carrier transport proceeds through different ultrathin layers. We here demonstrate the potential of such heterojunctions on graphene/dielectric/semiconductor vertical stacks that combine several enabling features for optoelectronic devices. Efficient and stable light emission was achieved through carrier tunneling from the graphene injector into prominent states of a luminescent material. Graphene's unique properties enable fine control of the band alignment in the heterojunction. This advantage was used to produce vertical tunneling-injection light-emitting transistors (VtiLET) where gating allows adjustment of the light emission intensity independent of applied bias. This device was shown to simultaneously act as a light detecting transistor with a linear and gate tunable sensitivity. In addition, a new light emitting memory has been developed, which enables to read the encoded signal both electrically and optically. This facilitates the capability for a parallel reading process and raises the transmission rate of the signal dramatically. The ON/OFF ratio can be extremely large, based on optical detection with low applied bias. The presented development of electronically controllable multifunctional light emitter, light detector, memory, and transistor can open up a new route for future optoelectronics.

1. Yi-Rou Liou, Yang-Fang Chen et al, Adv. Opt. Mater. DOI: 10.1002/adom.201600298 (2016).
2. Wei-Chun Tan, Yang-Fang Chen et al, Sci. Rep. 6, 31475 (2016); Adv. Mater. (under revision).

Graphene/TMDC Heterostructures for Spintronic Applications

Jaroslav Fabian

Department of Physics, University of Regensburg
93040 Regensburg, Germany

Tel: +49-941-943 2031   Fax: +49-941-943 4382
email: jaroslav.fabian@ur.de

Graphene and novel 2d materials offer new perspectives for spintronics [1]. Graphene can reach spin lifetimes of 1-10 ns, limited currently by spin flips off magnetic moments [2]. However, graphene has no band gap, so its spintronic applications will be limited as a highly efficient spin transfer channel. Heterostructures of graphene and two-dimensional transition-metal dichalcogenides (TMDC) are emerging as systems in which both orbital and spin properties can be controlled by gating, thus offering a materials basis for spintronic applications, such as bipolar spin devices [3]. We have proposed that graphene on TMDCs can be used in optospintronics [4], since the direct gap of TMDCs allows optical spin orientation, with the successive transfer of spin into graphene. But these van der Waals stacks also yield interesting fundamental physics. We have recently shown that graphene on WSe_2 exhibits an inverted band structure, which leads to the quantum spin Hall effect in graphene nanoribbons on WSe_2 [5], with a bulk spin-orbit gap of about 1 meV, which is giant when compared to 24 micro eV in pristine graphene. In the talk I will also mention our most recent results on engineering the proximity exchange in graphene and TMDCs in tunnel junctions with ferromagnetic metals.

1. W. Han, R. Kawakami, M. Gmitra, and J. Fabian, Nature Nanotechnology 9, 794 (2014).
2. D. Kochan, S. Irmer, M. Gmitra, and J. Fabian, Phys. Rev. Lett. 115, 196601 (2015).
3. I. Zutic, J. Fabian, and S. Erwin, IBM journal of research and development 50, 121 (2006).
4. M. Gmitra and J. Fabian, Phys. Rev. B 92, 155403 (2015).
5. M. Gmitra, D. Kochan, P. Högl, and J. Fabian, Phys. Rev. B 93, 155104 (2016).

Intervalley Scattering and Velocity Saturation in MoS$_2$

D. K. Ferry

School of Electrical, Computer, and Energy Engineering, Arizona State University
Box 875706, Tempe, AZ 85287-5706, USA

Tel: +1-480-965-2570
email: ferry@asu.edu

The velocity at high electric fields is an important aspect of transistors for both logic and microwave applications, as it determines both the delay time and cutoff frequency. Recent studies of transistors in MoS$_2$ have estimated the saturated velocity to be near 3×10^6 cm/s [1,2], a value below the estimated phonon-limited value [3]. MoS$_2$ is a complicated material and has a direct gap only in the monolayer form. Hence, the residual of the indirect gap lies only about 0.2 eV above the K point minima, so that multiple valleys are important in high field transport. We use an ensemble Monte Carlo procedure to study the high electric field transport in this material. We include the non-parabolicity of the bands and the dominant phonons, and show that the expected velocity is closer to the phonon-limited value. We discuss why experiments may give a lower value.

1. G. Fiori *et al*., Appl. Phys. Lett. **103**, 233509 (2013).
2. G. He *et al.,* Nano Lett. 15, 5052 (2015).
3. H. Chandrasekar *et al*., IEEE Electron Dev. Lett. **63**, 767 (2016).

Topological Quantum Computation with Majorana Zero Modes

Roman M. Lutchyn

Station Q, Microsoft Research, Santa Barbara, CA 93106-6105, USA

email: rolutchy@microsoft.com

Research in quantum computing has offered many new physical insights as well as the potential of exponentially increasing the computational power that can be harnessed to solve important problems in science and technology. The largest fundamental barrier to building a scalable quantum computer is errors caused by decoherence. Topological quantum computing evades this barrier by exploiting topological materials which, by their nature, limit errors. In this talk, I will discuss how to engineer topological superconductors at the interface of a conventional superconductor and a one-dimensional semiconductor with spin-orbit interaction [1,2]. I will show that such a topological state emerging at the interface hosts Majorana zero modes. The defects binding these modes obey exotic (non-Abelian) exchange statistics. I will review recent experimental efforts in realizing and detecting Majorana zero-energy modes in one-dimensional nanowires [3,4], and will discuss the progress towards building the first topological qubit [5].

1. R. M. Lutchyn, J. D. Sau, and S. Das Sarma, Phys. Rev. Lett. 105, 077001 (2016).
2. Y. Oreg, G. Refael, F. von Oppen, Phys. Rev. Lett. 105, 177002 (2016).
3. V. Mourik, K. Zuo, S. M. Frolov, S. R. Plissard, E. P. A. M.Bakkers, and L. P. Kouwenhoven, Science 336, 1003 (2012).
4. S. M. Albrecht, A. P. Higginbotham, M. Madsen, F. Kuemmeth, T. S. Jespersen, J. Nygard, P. Krogstrup, and C. M. Marcus, Nature (London) 531, 206–209 (2016).
5. T. Karzig, C. Knapp, R. M. Lutchyn, P. Bonderson, M. Hastings, C. Nayak, J. Alicea, K. Flensberg, S. Plugge, Y. Oreg, C. Marcus, M. H. Freedman, arXiv:1610.05289 (2016).

Wireless Majorana Bound States: From Magnetic Tunability to Braiding

Igor Zutic, Geoffrey Fatin, Alex-Matos Abiague, and Benedikt Scharf

Department of Physics, University at Buffalo, Buffalo, NY 14260, USA

Tel: +1-716-645-6599   Fax: +1-716-645-2507
email: zigor@buffalo.edu

In condensed-matter systems Majorana bound states (MBS) are emergent quasi-particles with exotic non-Abelian statistics and particle-antiparticle symmetry. However, important and widely stu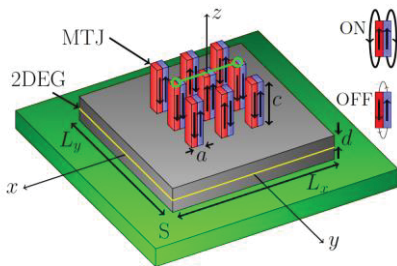died 1D semiconductor nanowires with proximity-induced superconductivity preclude simple braiding (exchange of MBS), the key to demonstrate non-Abelian statistics and fault-tolerant quantum computing. To address these challenges, we propose a novel platform to realize MBS (Fig. 1) and enable their braiding in 2D systems without the need for wire networks [1]. This proposal seemingly contradicts prior knowledge. In semiconductor wires the energetically isolated MBS do not survive the transition to 2D, but rather evolve into edge states

Fig. 1. Two-dimensional electron gas (2DEG) next to an s-wave super-conductor and an array of magnetic tunnel junctions (MTJs) which produce a magnetic texture (fringing fields), tunable by magnetization (arrows) switching of individual MTJs [1].

with increasing wire width. Here we show that in a properly designed magnetic texture acting on a 2D electron gas with proximity induced s-wave superconductivity can support localized MBS. The effect of the magnetic texture is twofold: (i) it drives local transitions to the topological regime and the emergence of MBS and (ii) it confines MBS by forming effective wires. The size, position, and shape of the effective wires can be modified by altering the magnetic texture, permitting exchange of the MBS. Remarkably, the required magnetic textures can be generated by an array of MTJs, similar to those used commercially. We discuss suitable materials and experimental progress in realizing our proposal.

1. G. Fatin, A. Matos-Abiague, B.Scharf, and I. Zutic, Phys. Rev. Lett. **117**, 077002 (2016).

Novel Phenomena in Quantum Tunnelling of Majorana Quasiparticles

Zhi Wang and Xiao Hu

International Center for Materials Nanoarchitectonics, National Institute for Materials Science, Tsukuba 305-0044, Japan

Tel: +81-29-860-4897   Fax: +81-29-860-4706
email: Hu.Xiao@nims.go.jp

In the very recent work [1], Albrecht et al. observe successfully two degenerate superconducting states characterized by even- and odd-number of electrons in a nanowire topological superconductor indicating clearly the existence of two end Majorana quasiparticles (MQs). This result is extremely important since it is known that the parity states composed by MQs can be exploited for topological qubit and robust quantum computation. However, ideas for manipulating Majorana qubit proposed so far are based on braiding operation, which is hard to be performed quickly and stably in practice, and furthermore, braiding itself does not provide a universal gate indispensable for quantum computation.

Here we propose a new way for manipulating Majorana qubits in nanowire systems [2]. The prototype setup consists of two one-dimensional topological superconductors coupled by a quantum tunnelling junction. We show theoretically that injecting current into the system induces a Landau-Zener-Stuckelberg interference between the parity states of Majorana qubit. Adjusting the current pulse and the gate voltage at junction, one can build a Landau-Zener-Stuckelberg interferometry as a universal gate for the Majorana qubit. This scheme is scalable, and the rotation of Majorana qubit can be monitored by analysing spectra of microwaves radiated from the system. Our work is expected to enhance the exploration of MQ physics [3] and eventually the implementation of topological quantum computation.

1. S. M. Albrecht et al., Nature 531, 206 (2016).
2. Z. Wang, W.-C. Huang, Q.-F. Liang and X. Hu, arXiv.1607.08491.
3. T. Kawakami and X. Hu, Phys. Rev. Lett. 115, 117001 (2015).

From the Parity Anomaly to a Majorana Fermion - Realization of the Ultra-relativistic Physics in Topological Insulators

Ewelina M. Hankiewicz[1], Laurens W. Molenkamp[2], and Shou-Cheng Zhang[3]

[1] Institute for Theoretical Physics and Astrophysics, University of Würzburg, Germany
Tel: +49-931-318-4998,   Fax: +49-931-318-5141
email: hankiewicz@physik.uni-wuerzburg.de
[2] Institute of Experimental Physics (EP3) University of Würzburg, Germany
[3] Department of Physics, Stanford University, CA 94305-4045, USA

A realization of the high energy ideas in the solid state physics lab, like the parity anomaly or Majorana fermions, is one of new directions of current research. Topological insulators are perfect materials to realize both of these phenomena. Topological insulators (TIs) have a bulk energy gap while the gapless energy electronic states that are protected by time reversal symmetry live at the edge (2D TIs) or surface (3D TIs) [1,2]. When doped with the magnetic impurities the TIs show the quantum anomalous Hall effect i.e. a single circulating chiral mode at the boundary of 2D TI. We prove theoretically that quantum anomalous Hall effect is directly related to the parity anomaly and discuss the experimental consequences [3]. On the other hand, a topological insulator in the proximity to an s-wave superconductor is the prefect platform to detect signatures of Majorana fermions [4,5]. S-wave superconductor on the top of the surface states of 3D TI generates s-wave and p-wave pairing mixture in the surface state due to the spin-momentum locking. We predict that in the Josephson junctions built on TIs, the existence of the p-wave component of superconductivity leads to novel features in transport like superconducting Klein tunneling i.e. the perfect transmission of hybridized Majorana states for normal incidence [5], the non-sinusoidal current phase relation [6] and unusual phase-dependent thermal conductance [7].

1. G. Tkachov and E. M. Hankiewicz, review in Phys. Status Solidi 250, 215 (2013).
2. C. Brüne, A. Roth, H. Buhmann, E. M. Hankiewicz, L. W. Molenkamp, J. Maciejko, X.-L. Qi, S.C. Zhang, Nature Physics 8, 486 (2012).
3. J. Böttcher and E. M. Hankiewicz, in preparation (2016).
4. L. Elster, C. Platt, R. Thomale, W. Hanke, and E. M. Hankiewicz, Nature Comm. 6, 8232 (2015).
5. G. Tkachov and E. M. Hankiewicz, Phys. Rev. B 88, 075401 (2013).
6. I. Sochnikov et al. Phys. Rev. Lett. 114, 066801 (2015).
7. B. Sothmann and E. M. Hankiewicz, arXiv:1603.08736 (2016).

New Approaches to Solar Energy Conversion Using Engineered Quantum Dots

Victor I. Klimov

Center for Advanced Solar Photophysics, Los Alamos National Laboratory
Los Alamos, NM 87545, USA

email: klimov@lanl.gov http://casp.lanl.gov, http://quantumdot.lanl.gov

Quantum-confined semiconductor nanocrystals, or "quantum dots," are promising materials for applications in a range of solar-energy technologies from low-cost solar cells to large-area luminescent solar concentrators (LSCs). In addition to solution processability, they feature size/shape-tunable optical spectra, as well as a variety of novel physical properties that can enable fundamentally new schemes of solar energy conversion. This presentation provides an overview of fundamental and applied studies of quantum dots conducted in the context of solar energy conversion with a focus on carrier multiplication (generation of multiple excitons by single photons) and LSCs. The specific topics will include charge transport properties of quantum dot assemblies evaluated via a novel technique of ultrafast photoconductivity, recent progress in understanding of carrier multiplication in quantum confined materials, and applications of engineered quantum dots in LSCs. The discussion of carrier multiplication will include spectroscopic versus photoconductive signatures of photogenerated multiexcitons, the effect of structural parameters such as particle size, shape, and composition on multiexciton yields, and recent demonstrations of increased carrier-multiplication efficiencies achieved by suppressing a competing process of intraband cooling. The LSC part of the presentation will overview recent efforts on reducing re-absorption losses via "Stokes-shift-engineering" in core-shell structures as well as demonstrations of high-performance LSCs based on heavy-metal-free I-III-VI$_2$ quantum dots

Predictive Modeling of CdTe Solar Cells for Higher Efficiency and Larger Reliability

Dragica Vasileska[1], Igor Sankin[2], Da Guo[1], Daniel Brinkman[3], Christian Ringhofer[4], Andrew Moore[5], and James R. Sites[5]

[1] School of Electrical, Computer and Energy Engineering, Arizona State University
Tempe, AZ 85287-5706, USA
email: vasileska@asu.edu

[2] First Solar, Perrysburg, OH 43551, USA

[3] Department of Mathematics, San Jose State University, San Jose, CA 95192, USA

[4] School of Mathematical and Statistical Sciences, Arizona State University
Tempe, AZ 85287-5706, USA

[5] College of Natural Sciences-Physics, Colorado State University, Fort Collins, CO 80523, USA

The record efficiencies of thin-film CdTe technology are still ten absolute percent lower than the Shockley-Queisser limit. As short-circuit current density (J_{SC}) is approaching the theoretical limit, both open-circuit voltage (V_{OC}) and fill factor (FF) are far below the theoretical limits for most devices. Although V_{OC} larger than 0.9V have been reported for single crystal (sx-) CdTe solar cells, low V_{OC} still limits the performance of polycrystalline CdTe devices.

Since V_{OC} is a strong function of the doping concentration in the absorber layer, better understanding of doping mechanisms and defects formation is a must. Like most common dopants in px-CdTe, Copper (*Cu*) forms multiple species of defects including interstitial donors (Cu_i), substitutional acceptors on *Cd* site (Cu_{Cd}) and tightly-bounded complexes such as Cu_i-Cu_{Cd} and Cd_i-Cu_{Cd}. Resulting amount of uncompensated acceptor impurities is usually three or four orders of magnitude smaller than the total atomic *Cu* concentrations, which limits the V_{OC} of *Cu*-doped CdTe solar cells significantly. Low V_{OC} of px-CdTe solar cells is also believed to be due to large defect density, and short minority carrier lifetime in the absorber layer. Not only carriers, the self-compensated active *Cu* dopants provide active defect (recombination centers) in CdTe material as well, which results in poor minority carrier lifetime, that once again connects *Cu* with the low V_{OC} presented in px-CdTe PV cells.

Although total Cu concentration profiles can be measured by the secondary ion mass spectrometry (SIMS) technique, the concentration of different species of Cu (mainly Cu_i and Cu_{Cd}) generally cannot be identified. Lacking a description of the transition process, theoretical concentrations of the related defects were estimated from charge neutrality equation with formation energies of defects obtained from First Principles calculations. Given this, gaining a better understanding of Cu migration in CdTe is of crucial importance in order to further enhance the performance of CdTe solar cells.

Moreover, PV modules (multiple solar cells electrically connected) are expected to function properly for more than 25 years, in order to provide electricity at proper cost. However, due to the fast diffusion rates of Cu atoms, the gentle balance between mutually compensating Cu impurities could be subject to temporal changes causing metastabilities observed in CdTe solar cells, which also makes the predictive simulation of device performance more important.

Thus, gaining a better understanding of mechanisms that govern formation and interactions between *Cu*-related defects is of crucial importance for further advancement of the CdTe photovoltaics.

InSb Double Quantum Dots Interacting with Electromagnetic Fields in a Superconducting Microwave Cavity

Rui Wang[1], Russel S. Deacon[1], Diana Car[2], Erik P. A. M. Bakkers[2], and
Koji Ishibashi[1]

[1] Advanced Device Laboratory, Center for Emergent Matter Science (CEMS), RIKEN
2-1, Hirosawa, Wako 351-0198, Japan
Tel: +81-48-467-9367   Fax: +81-48-462-4659
email: kishiba@riken.jp

[2] Department of Applied Physics, Eindhoven University of Technology
P.O. Box 513, 5600 MB Eindhoven, The Netherlands

To realize quantum mechanical coupling between qubits with various forms through a microwave cavity would be useful for a hybrid quantum computing system. The qubits can be a superconducting qubit, a spin qubit or others. The superconducting qubit has an advantage that it is easily accessed, while the spin qubit has a long coherence time, good for storing quantum information (quantum memory). However, it is difficult is to realize a strong coupling between the single spin and the cavity because the magnetic interaction between them is small. To overcome the problem, one possibility is to use a spin-orbit interaction through which electric field interacts with the spin. To test the possibility, we have fabricated the InSb double quantum dots embedded in a coplanar waveguide microwave cavity and measured transmission properties of the cavity in a dilution refrigerator temperature. The preliminary results in a large number of photon regime indicate that the cavity resonance (resonant frequency, peak width) depends on the charge states of the double dots[1]. We have not studied the spin effect, and the results are discussed in terms of possible charge-cavity interactions including effects of electrodes.

1. Rui Wang, Russell S. Deacon, Diana Car, Erik P. A. M. Bakkers, and Koji Ishibashi, Appl. Phys. Lett. 108, 203502 (2016).

Printing Technologies for Sensors and Other Electronic Components

Paolo Lugli

Institute for Nanoelectronics, Technical University of Munich
Arcisstraße 21, 80333 Munich, Germany

Tel: +49-89-28925332   Fax: +49-89-28925337
email: lugli@tum.de

Printing technologies could provide a valuable platform for various electronic, optoelectronic and sensing devices. The crucial characteristics of printing technologies are that they i) intrinsically guarantee low fabrication costs, since they are based on techniques e.g. spray coating or inkjet printing that requires rather simple and inexpensive equipment; ii) are mature as they have been used for a long time in other applications like coating; iii) work on basically any substrate, iv) can rely on a large variety of active materials which can be prepared from solution, and v) can be integrated with conventional technologies, e.g. CMOS. The talk will present some examples of the possible applications of printing techniques, focusing on the chemical and biosensors, optical sensors based on conductive polymers, pressure and strain gauge sensors based on CNT films, polymer layers and their combinations. For each application, the independence on the chosen substrate (e.g. silicon, glass, plastic, paper) will be demonstrated. On a more visionary level, the potential extension of such technologies to 3D printing will be addressed.

Intervalley Energy of GaN Conduction Band Estimated by Ultrafast Pump-probe Spectroscopy

Saulius Marcinkevičius[1], Tomas K. Uždavinys[1], James S. Speck[2], and Claude Weisbuch[2,3]

[1] KTH Royal Institute of Technology, Department of Materials and Nano Physics
Electrum 229, 16440 Kista, Sweden
Tel: +46-8-7904192
email: sm@kth.se

[2] Materials Department, UC Santa Barbara, CA 93106, USA

[3] Laboratoire de la Physique de la Matière Condensée, CNRS, Ecole Polytechnique
91128 Palaiseau, France

The energy difference between the lowest conduction band valleys is a fundamental semiconductor parameter affecting performance of electronic devices via the intervalley electron scattering. Surprisingly, the intervalley energy in GaN is still disputed. The value that is typically used in GaN-based high power electronic device simulations is >2 eV and was obtained by ab initio calculations.

In this work, we apply time-resolved transmission and reflection measurements on bulk GaN to evaluate the energy of the first conduction band satellite valley via the onset of the intervalley scattering. The measurements showed clear threshold-like spectra for transmission decay and reflection rise times. The thresholds were associated with the onset of the intervalley electron scattering. Transmission measurements with pump and probe pulses in the near IR produced the intervalley energy of 0.97 eV, about half of the currently accepted value. UV pump and IR probe reflection provided a similar intervalley energy. Besides, comparison of the transmission and reflection data provides information on the hole effective mass in the top most valence band. Analysis of reflection transients with rate equations allows estimating electron-LO phonon scattering times. These results should have a significant impact on simulations and design of GaN-based electronic devices.

.

Emerging Nonvolatile Memory and Logic Devices for Beyond-CMOS Applications

An Chen

SRC, 4819 Emperor Blvd, Suite 300 Durham, NC 27703, USA

Tel: +1-919-941-9400   Fax: +1-919-941-9450
email: an.chen@src.org

With CMOS scaling approaching the fundamental limit, significant investment has been made in beyond-CMOS device research in various programs including the Nanoelectronics Research Initiative (NRI). While no beyond-CMOS logic device has been found to surpass CMOS in overall performance, several novel non-volatile memories (NVMs) have emerged with promising characteristics, including phase change memory (PCM), magnetic random-access-memory (MRAM), resistive random-access-memory (RRAM), and ferroelectric field-effect-transistor (FeFET) memory. Built-in non-volatility is also a key characteristics of some novel beyond-CMOS logic devices with the potential to enable more efficient computing solutions. In the changing market trend toward energy-efficient, data-centric, intelligent, and secure applications, emerging NVM technologies and nonvolatile logic devices have become increasingly important. This presentation will review the progress of emerging NVM devices in terms of their advantages, challenges, and potential applications. Memory selector devices have important impact on memory array design. High-performance emerging NVM and nonvolatile logic devices may simplify memory and storage hierarchy, improve system power efficiency, and enable novel architectures. Some unique characteristics of emerging NVM devices can be utilized for novel applications beyond the memory space, e.g., neuromorphic computing, hardware security, etc. In the beyond-CMOS era, emerging nonvolatile memory and logic devices have the potential to enable more efficient, intelligent, and secure computing systems.

Enhanced Ferroelectric-Control of All-Oxide Mott Transistors via Interfacial Charge Engineering

Xuegang Chen[1], Xin Zhang[1], Mark A. Koten[1], Hanghui Chen[2], Zhiyong Xiao[1], Le Zhang[1], Jeffrey E. Shield[1], Peter Dowben[1], and Xia Hong[1]

[1] University of Nebraska-Lincoln,
Lincoln, NE 68588-0299, USA
Tel: +1-402-472-2779   Fax: +1-402-472-6148
email: xia.hong@unl.edu

[2] New York University-Shanghai, Shanghai 200122, China

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

Electrical Switching of an Antiferromagnet

Xavier Marti

Institute of Physics, Academy of Sciences of the Czech Republic
Cukrovarnicka 10, 16253 Prague, Czech Republic

Tel: +420-220318-471
email: xavi.mr@gmail.com

Louis Néel pointed out in his Nobel lecture that while abundant and interesting from theoretical viewpoint, antiferromagnets did not seem to have any applications. Indeed, the alternating directions of magnetic moments on individual atoms and the resulting zero net magnetization make antiferromagnets hard to control by tools common in ferromagnets. Strong coupling would be achieved if the externally generated field had a sign alternating on the scale of a lattice constant at which moments alternate in antiferromagnets. However, generating such a field has been regarded unfeasible, hindering the research and applications of these abundant magnetic materials. We have recently predicted that relativistic quantum mechanics may offer staggered current induced fields with the sign alternating within the magnetic unit cell which can facilitate a reversible switching of an antiferromagnet by applying electrical currents with comparable efficiency to ferromagnets. Among suitable materials is a high Néel temperature antiferromagnet, tetragonal-phase CuMnAs, which we have recently synthesized in the form of single-crystal epilayers structurally compatible with common semiconductors. We demonstrate electrical writing and read-out, combined with the insensitivity to magnetic field perturbations, in a proof-of-concept antiferromagnetic memory device which operates USB-powered at room temperature.

1. X. Marti et al., Nature Materials 13, 367 (2014).
2. J. Zelezny et al., Phys. Rev. Lett. 113, 157201 (2014).
3. P. Wadley et al. Science 351, 587 (2016).
4. T. Jungwirth et al., Nature Nanotech. 11, 231 (2016).
5. www.igsresearch.com/afm_spintronics.

Chiral Magnetic Effect in Condensed Matter

Tonica Valla

Condensed Matter Physics and Materials Science Department
Brookhaven National Lab, Upton, NY 11973, USA

Tel: +1-631-344-3530   Fax: +1-631-344-2739
email: valla@bnl.gov

The chiral magnetic effect (CME) is the generation of electric current induced by chirality imbalance in the presence of magnetic field - a macroscopic manifestation of the quantum anomaly in relativistic field theory of chiral fermions.[1] This phenomenon is currently under intense study at Relativistic Heavy Ion Collider at BNL and at the Large Hadron Collider at CERN, where it was predicted to induce the fluctuations in hadron charge asymmetry with respect to the reaction plane. Closely related phenomena are expected to play an important role in the Early Universe, possibly causing the generation of primordial magnetic fields. However, the interpretation in these cases is under debate due to lack of control over the produced chirality imbalance. The recent discovery of Dirac and Weyl semimetals opened a fascinating possibility to study this phenomenon in condensed matter experiments.[2,3] Magneto-transport in ZrTe5 shows a strong evidence for CME.[4] Our ARPES experiments show that this material's electronic structure is consistent with a highly anisotropic 3D Dirac semimetal. We observe a large negative magnetoresistance in parallel magnetic field, with the quadratic field dependence of the magneto-conductance - a clear indication of the CME.

1. S. L. Adler, Phys. Rev., **177**, 2426 (1969).
2. S. Borisenko et al, Phys. Rev. Lett., **113**, 027603 (2014).
3. Z. K. Liu et al, Science (New York, N.Y.), **343**, 864-7 (2014).
4. Q. Li et al, Nature Physics **12**, 550 (2016).

Direct Comparison of Current-induced Spin Polarization in Topological Insulator Bi_2Se_3 and InAs Rashba States

C. H. Li[1], O. M. J. van 't Erve[1], S. Rajput[2], L. Li[2,3], and B. T. Jonker[1]

[1] Materials Science and Technology Division, Naval Research Laboratory
Washington, DC 20375, USA
Tel: +1-202-404-8015
Email: jonker@nrl.navy.mil

[2] Department of Physics, University of Wisconsin, Milwaukee, WI 53211, USA
[3] Department of Physics and Astronomy, West Virginia University
Morgantown, WV 26506, USA

Three-dimensional topological insulators (TIs) exhibit time-reversal symmetry protected, linearly dispersing Dirac surface states with spin-momentum locking. Band bending at the TI surface may also lead to coexisting trivial two-dimensional electron gas (2DEG) states with parabolic energy dispersion. A bias current is expected to generate spin polarization in both systems, although with different magnitude and sign. Here, we compare spin potentiometric measurements of bias current-generated spin polarization in $Bi_2Se_3(111)$ where Dirac surface states coexist with trivial 2DEG states, and in InAs(001) where only trivial 2DEG states are present. We observe spin polarization arising from spin-momentum locking in both cases, with opposite signs of the measured spin voltage. We present a model based on spin dependent electrochemical potentials to directly derive the sign expected for the Dirac surface states, and show that the dominant contribution to the current-generated spin polarization in the TI is from the Dirac surface states [1].

1. C. H. Li, O. M. J. van 't Erve, S. Rajput, L. Li, and B. T. Jonker, to appear in *Nature Commun*. (2016).

.

All-Dielectric Topological Photonics

Xiao Hu

International Center for Materials Nanoarchitectonics (WPI-MANA)
National Institute for Materials Science, Tsukuba 305-0044, Japan

Tel: +81-29-860-4897   Fax: +81-29-860-4706
email: Hu.Xiao@nims.go.jp

We propose a new way to realize topological photonics with time-reversal symmetry purely based on dielectric material, such as silicon, GaN and so on [1]. Deforming the honeycomb lattice of dielectric cylinders in a certain way preserving C6v symmetry, we demonstrate theoretically the nontrivial topology by showing photonic band inversion, and counterpropagating electromagnetic waves at sample edge which are robust to lattice imperfections because of topological protection. Without requiring any complex material and external field, this topological photonic crystal can be fabricated easily and is compatible to electronics. This idea can be extended to many other systems include cold atoms, surface plasmon and polariton, and phonon, as well as electron [2, 3].

1. L.-H. Wu and X. Hu: Phys. Rev. Lett. 114, 223901 (2015).
2. L.-H. Wu and X. Hu: Sci. Rep. 6, 223901 (2016).
3. T. Kariyado and X. Hu, arXiv.1607.08706.

Understanding Topological Superconductivity in an Ultra-thin Magnetically-Doped Proximity-Coupled Topological Insulator

Youngseok Kim[1,3], Timothy M. Philip[1,3], Moon Jip Park[2,3], and Matthew J. Gilbert[1,2,3]

[1] Department of Electrical and Computer Engineering
[2] Department of Physics
[3] Micro and Nanotechnology Laboratory
University of Illinois, Urbana, IL 61801, USA

Tel: +1-217-333-3064
email: matthewg@Illinois.edu

As a promising candidate system to realize topological superconductivity, a system comprised of a 3D time-reversal invariant topological insulator (TI) grown on top of an s-wave superconductor has been extensively studied. To access the topological superconductivity experimentally the 3D TI must be thin enough to allow for Cooper pair tunneling to the exposed TI surface. The use of magnetically ordered dopants to break time-reversal symmetry may allow the surface of the TI to host Majorana fermions. In this talk, we will discuss our theoretical results on the phase diagram of a magnetically-doped, proximity-coupled ultra-thin 3D TI as a function of the relevant parameters: hybridization gap, Zeeman energy, and the chemical potential. In addition to providing a useful guide as to the proper combination of parameters to obtain topological superconductivity, we discuss why this interesting phase has not yet been experimentally observed.

Heterostructure Topological Polariton: On Existence of Exact Solution of Bosonic Coupled Dyson Equations

Slava V. Rotkin[1] and Alexey G. Petrov[2]

[1] Department of Physics, Lehigh University
16 Memorial Drive East, Bethlehem, PA 18015, USA
email: rotkin@lehigh.edu

[2] Ioffe Institute, 26 Polytekhnicheskaya, St. Petersburg 194021, Russia

A problem of strong coupling between bosonic (harmonic) fields has been in the focus of attention of physicists for decades. In condensed matter, such systems as plasmon-, phonon- and exciton-polaritons give vivid examples of the coupled fields.

Most recently, with development of plasmonic and nanophotonic structures, coupled modes were found between the polaritonic bulk and an optical-active object of lower dimensions. It was not noted before, however, what are the conditions under which such a coupled mode should exist. Neither a simple general solution was known for the strongly coupled case, outside of the "comfort zone" of perturbation theory.

We propose an efficient method of solving the coupled Dyson equations for (harmonic oscillator-like) bosonic fields and derive localized modes existing at the interface between systems of different dimensionality. Clear analytical result can be derived if the mode coupling mechanism has a high symmetry, *e.g.*, if some fundamental quantum numbers are conserved (along the interface). Such a solution, to the best of our knowledge, was not demonstrated before. As an example, we show mixing of a 2D phonon-polariton of a dielectric substrate with a 1D plasmon of a polarizable material (nanowire or nanotube) with conservation of the axial momentum. We emphasize on that the problem is solved non-perturbatively, presenting full solution, beyond weak coupling model. The method appears to be applicable to a large class of systems with mismatched dimensions and high enough symmetry of the interface.

Author Index