

SYMPOSIUM EP06

TUTORIAL: Introduction to Quantum Spintronics
November 25 - November 25, 2018

* Invited Paper

TUTORIAL Introduction to Quantum Spintronics

Sunday Afternoon, November 25, 2018
Hynes, Level 2, Room 204

Quantum spintronics is an emerging field of spin coherence and spin correlations at or near room temperature, and their effects on a wide range of properties, including spin dynamics and light emission from color centers in solids, spin and charge transport in organic materials, spin-dependent transport in tunnel junctions, dynamic nuclear polarization, and animal sensing of magnetic fields. Room-temperature quantum spintronic systems can be much more sensitive to external perturbations than sensors that must be very near thermal equilibrium. Applications include sensing of magnetic fields in biological systems (e.g. color centers in diamond and other wide-band-gap semiconductors and insulators), control of light emission intensity from organic light emitting diodes (e.g. thermally-activated delayed fluorescence), spin injection, spin dynamics, and coherent optical interactions with single spins (color-center photonics). Highly sensitive room-temperature spin systems also feature prominently in proposals for very low power electronic logic.

This tutorial will provide an introduction to the materials and operating regimes that tend to exhibit room-temperature spin coherence and spin correlations, methods of calculating and measuring these properties, areas of initial application and critical open questions.

1:30 PM

Theory of Quantum Spintronics Michael E. Flatté; The University of Iowa

The theoretical criteria for a stable, room-temperature quantum coherent system will be described, and several examples will be presented. Methods of calculating the response of a quantum coherent system to external fields and perturbations will be presented, including density matrices, stochastic Liouville equations, and master equations. Recent progress in predicting specific quantum coherent systems, such as density functional theory for new color centers in wide-gap semiconductors, will be surveyed. The ideal performance of quantum spintronic devices will be compared with other sensors or information processing approaches.

2:15: PM

Quantum Spintronics of Organic Semiconductors Christoph Boehme; The University of Utah

Organic semiconductors provide a varied set of materials that exhibit quantum spintronic phenomena. The effects of spin coherence on charge conductivity in organics will be described, along with large room-temperature responses to magnetic fields. Resonant manipulation of spins in organic materials, detected by transport, will be introduced as a mechanism for a sensitive magnetometer. Spin-charge correlations in the spin Hall Effect and spin pumping will also be presented.

3:00 PM BREAK

3:30 PM

Optical Coupling to Quantum-Coherent Spins David D. Awschalom; The University of Chicago

Coherent coupling of light to spin coherent systems, especially for color centers in diamond and silicon carbide, will be described in detail. Nonequilibrium polarization/pumping, manipulation of the spin state, and efficient detection will be presented, along with criteria for pulse shaping that can be used for low-error manipulation of the spin state of a quantum coherent system.

4:15 PM

Photonics and Quantum Spintronics Evelyn Hu; Harvard University

The design, fabrication, and measurement of photonic devices that efficiently integrate a quantum coherent spin with a cavity will be described. Methods of manipulating the quantum spin to bring it into resonance with the cavity, such as through acoustic oscillations or electrical gates, will be presented. The figures of merit for spin-photon coupling will be derived and compared with state-of-the-art coupling of other quantum coherent systems.

SYMPOSIUM EP06

Coherent Electronic Spin Dynamics in Materials and Devices
November 26 - November 28, 2018

Symposium Organizers

Michael Flatté, University of Iowa
Evelyn Hu, Harvard University
Hideo Ohno, Tohoku University
Bernhard Urbaszek, CNRS

Symposium Support

Springer Nature

* Invited Paper

SESSION EP06.01: Novel State Manipulation of Coherent Defects in Diamond

Session Chair: Michael Flatté

Monday Morning, November 26, 2018

Hynes, Level 2, Room 204

8:15 AM *EP06.01.01

The Dawn of Quantum Networks Ronald Hanson; QuTech, Delft University of Technology, Delft, Netherlands.

Entanglement – the property that particles can share a single quantum state - is arguably the most counterintuitive yet potentially most powerful element in quantum theory. The non-local features of quantum theory are highlighted by the conflict between entanglement and local causality discovered by John Bell. Decades of Bell inequality tests, culminating in a series of loophole-free tests in 2015, have confirmed the non-locality of Nature.

Future quantum networks may harness these unique features of entanglement in a range of exciting applications, such as distributed quantum computation, secure communication and enhanced metrology for astronomy and time-keeping. To fulfill these promises, a strong worldwide effort is ongoing to gain precise control over the full quantum dynamics of multi-particle nodes and to wire them up using quantum-photon channels.

Diamond spins associated with NV centers are promising building blocks for such a network as they combine a coherent electron-optical interface with a local register of robust and well-controlled nuclear spin qubits.

Here I will introduce the field of quantum networks and discuss ongoing work with the specific target of realizing the first multi-node network wired by quantum entanglement.

8:45 AM *EP06.01.02

Spin and Orbital Resonance Driven by a Mechanical Resonator Gregory Fuchs; Cornell University, Ithaca, New York, United States.

Creating and studying coherent interactions between solid-state quantum systems is a challenge at the intersection of atomic physics, condensed matter physics, and engineering. Efforts to create hybrid quantum systems are appealing because they enable the exploration of coherent interactions between a physical qubit and non-traditional degrees of freedom. For instance, there is a growing interest in mechanical motion as a “plastic” degree of freedom for coupling solid-state qubits, with the potential to form a coherent interface between them, and with light. This has motivated intense research into the coherent interactions between mechanical resonators and qubits formed from photons, trapped atoms, superconducting circuits, quantum dots, and nitrogen-vacancy (NV) centers in diamond, to name a few. I will describe our experiments to drive coherent resonance of NV center spins using gigahertz-frequency mechanical resonators through dynamic crystal lattice strain. In high-quality diamond mechanical resonators, we demonstrate coherent Rabi oscillations of NV center spins driven by mechanical motion instead of an oscillating magnetic field.^{1,2} We show that the mechanical resonator is a resource to prolong the NV center’s spin coherence.³ We also examine how strain can be used to control NV centers through their excited-state, either to control the spin at room temperature⁴ or the orbital states at low temperature.⁵ In particular, using resonant optical spectroscopy of an NV center coupled to a driven mechanical resonator, we demonstrate very-strongly driven orbital states. This includes the observation of coherent Raman sidebands out to nine orders, and multi-phonon Rabi coupling between two orbital states.

1. E. R. MacQuarrie et al., *Phys. Rev. Lett.* **111**, 227602 (2013).

2. E. R. MacQuarrie et al., *Optica* **2**, 233 (2015).

3. E. R. MacQuarrie et al., *Phys. Rev. B* **92**, 224419 (2015).

4. E. R. MacQuarrie et al., *Nat. Commun.* **8**, 14358 (2017).

5. H. Chen et al., *Phys. Rev. Lett.* **120**, 167401 (2018).

9:15 AM EP06.01.03

Using Microwaves to Study Charge State in NV Diamond Diana Prado Lopes Aude Craik^{1,3}, Pauli Kehayias^{1,2}, Andrew S. Greenspon³, Xingyu Zhang³, Matthew Turner^{1,2}, Erik Bauch¹, Jennifer Schloss^{4,5}, Connor Hart^{1,2,4}, Ronald Walsworth^{1,2,4} and Evelyn Hu³; ¹Department of Physics, Harvard University, Cambridge, Massachusetts, United States; ²Harvard-Smithsonian Center for Astrophysics, Harvard University, Cambridge, Massachusetts, United States; ³John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, United States; ⁴Center for Brain Science, Harvard University, Cambridge, Massachusetts, United States; ⁵Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

We present a novel, microwave-based technique for determining charge state of nitrogen-vacancy (NV) ensembles in diamond. The technique isolates, in situ, the spectral shape of the fluorescence contribution from neutral (NV⁰) and negatively-charged (NV⁻) defects, producing sample-specific results which

take into account the effects of experimental conditions (such as illumination intensity and wavelength) and material properties (such as local strain and electric fields). Using this technique, we explore how ensemble charge state is affected by experimental and material parameters, and study the physics of NV ionization from the negative charge state. The method can also be applied to determine relative concentrations of other solid-state defects which exhibit a spin-dependent fluorescence contrast.

9:30 AM EP06.01.04

Surface Engineering for Shallow Nitrogen-Vacancy Centers in Diamond with Long Coherence Times Sorawis Sangtawesin and Nathalie P. de Leon; Princeton University, Princeton, New Jersey, United States.

Nitrogen vacancy (NV) centers in diamond are point defects that exhibit excellent spin coherence at room temperature. When placed close to the surface, they can have strong interactions with other molecules, enabling a new form of nanoscale spectroscopy. However, surface defects can give rise to noise, and shallow NV centers exhibit rapid decoherence. We demonstrate a method for creating a well-ordered, oxygen-terminated surface that results in an improvement of NV spin coherence and magnetic field sensitivity by up to an order of magnitude. Careful control over surface morphology enables reversible and reproducible chemical termination, which we characterize using complementary surface spectroscopy tools: NV-based nanoscale spectroscopy to probe the nature of noise, and X-ray and electron spectroscopy to probe structure and chemical state. We find that the dominant contribution to NV decoherence is broadband magnetic noise arising from disorder at the surface.

9:45 AM BREAK

SESSION EP06.02: Novel Spin Centers in Wide-Gap Semiconductors

Session Chairs: Ronald Hanson and Evelyn Hu

Monday Morning, November 26, 2018

Hynes, Level 2, Room 204

10:15 AM *EP06.02.01

Controlling Defect Spin States with Photons, Magnons and Phonons Brian Zhou¹, Paolo Andrich¹, Samuel Whiteley¹, F. Joseph Heremans² and David Awschalom^{1,2}; ¹University of Chicago, Chicago, Illinois, United States; ²Argonne National Laboratory, Argonne, Illinois, United States.

There is a growing interest in exploiting the quantum properties of electronic and nuclear spins for the manipulation and storage of quantum information. Current efforts embrace materials with incorporated point defects, whose unique quantum mechanical electronic and nuclear spin properties allow a fundamentally different means to process information. Here we focus on recent developments in manipulating and connecting spins in both silicon carbide (SiC) and diamond. We find that defect-based electronic states in SiC can be isolated at the single spin level [1] with surprisingly long spin coherence times and high-fidelity control within a wafer-scale material operating at near-telecom wavelengths. Similarly, the spin-photon interface in diamond offers an opportunity to implement all-optical, geometrically protected quantum spin gates [2] for quantum information processing. Moreover, we present pathways for connecting isolated electronic spins using magnons and phonons. Exploring a hybrid qubit-magnon system, we use surface-confined spin-wave modes in YIG thin films to perform long-range coherent control of spins in diamond nanoparticles [3]. The magnon modes amplify the oscillating field of the microwave source by more than two orders of magnitude, thereby efficiently driving remote spin states. In addition, fabricated surface acoustic wave resonators exploit both the piezoelectric and isotropic phonon properties of SiC to create Autler-Townes splittings and mechanically drive coherent Rabi oscillations between arbitrary ground-state spin levels, including magnetically forbidden spin transitions [4].

[1] D. J. Christle, et al., Phys. Rev. **X** *7*, 021046 (2017).

[2] B. B. Zhou, P. C. Jerger, V. O. Shkolnikov, F. J. Heremans, G. Burkard, D. D. Awschalom, Phys. Rev. Lett. **119**, 140503 (2017).

[3] P. Andrich, et al., npj Quantum Information **3**, 28 (2017).

[4] S.J. Whiteley *et al.*, arXiv:1804.10996.

10:45 AM EP06.02.02

Photoluminescence Characterization of Precisely Located Si Vacancies in 4H-SiC Created via Li⁺ Implantation Shojan P. Pavunny¹, Edward Bielejec², Sam Carter¹, Hunter Banks¹, Rachael Myers-Ward¹, Paul Klein³, Mathew DeJarld¹, Allan Bracker¹, Evan Glaser¹ and D. Kurt Gaskill¹; ¹U.S. Naval Research Laboratory, Washington, District of Columbia, United States; ²Sandia National Laboratories, Albuquerque, New Mexico, United States; ³KeyW Corp., Arlington, Virginia, United States.

Silicon vacancies (V_{Si}) in SiC are of interest for future applications in quantum information and quantum sensing mainly due to the long electronic spin ($S = 3/2$) coherence times at room temperature. A key requirement for many applications is the precise placement of V_{Si} in a photonic crystal cavity (PhC) as the resulting Purcell enhancement improves the emission rate (brightness) of the photoluminescence (PL) as well as increases photon indistinguishability. Here we show that Li⁺ ions, implanted with energy 100 keV using a maskless focused ion beam technique (~25 nm diameter spot positioned with ~25 nm accuracy and having an ion travel depth of ~400 nm), create V_{Si} in the material. To facilitate PL characterization, arrays of locations were implanted into epitaxial 4H-SiC with doses ranging from $10^{12} - 10^{15}$ Li⁺ cm⁻². Epitaxial SiC is chosen as we have shown it has no measurable V_{Si} . Using a 745 nm excitation source, we find that the PL in the range of 860 to 975 nm is dominated by the V_1' , V_1 and V_2 lines of V_{Si} . Furthermore, the PL saturates at an excitation intensity of ~1 mW focused to a diameter of ~1 μ m. The PL intensity of V_1' for a high implantation dose is found to be constant on a time scale of many hours. Additionally, the V_1' intensity is linear with implantation dose. Moreover, we will describe data that indicates single V_{Si} formation at the lowest doses. Lastly, given the encouraging results to-date, we will discuss utilizing this approach with a PhC.

11:00 AM EP06.02.03

Spectrally Stable Defect Qubits for Quantum Communication with No Inversion Symmetry Péter Udvarhelyi^{1,2} and Adam Galí^{2,3}; ¹Eötvös Loránd Science University, Budapest, Hungary; ²Wigner Research Centre for Physics, Hungarian Academy of Science, Budapest, Hungary; ³Budapest University of Technology and Economics, Budapest, Hungary.

In this paper, we show that the inversion symmetry is not a prerequisite criterion for a spectrally stable defect quantum emitter. An ideal quantum emitter does not couple to the stray electric fields upon optical transition but the optical transition dipole moment should be strong for bright emission. These two conditions can be simultaneously satisfied for such defect quantum emitters that exhibit identical electron density in the ground and excited state to eliminate the coupling to the stray electric fields but the sign of the corresponding wavefunctions alters accordingly to maximize the optical transition

dipole moment. These properties can be principally manifested for defect qubits without inversion symmetry.

We demonstrate by means of density functional perturbation theory calculations that the so-called V1 optical center, i.e., negatively charged Si-vacancy, in 4H silicon carbide (SiC) tends to possess such favorable properties where 4H SiC can only host defects without inversion symmetry. Furthermore, this defect has favorable Debye-Waller factor with a ZPL emission in the near infrared region that can be efficiently converted to the telecom wavelengths. Our results imply that materials without inversion symmetry can be a subject to host defect qubits for quantum communication.

The support from NKFIH (Grant Nos. 2017-1.2.1-NKP-2017-00001, NVKP_16-1-2016-0043 and NN127902) and the EU Commission is acknowledged.

11:15 AM *EP06.02.04

Coherence Properties of Shallow Donors in ZnO Xiayu Linpeng¹, Maria Viitanieni¹, Aswin Vishnuradhan³, Y. Kozuka^{3,4}, Cameron Johnson¹, Masashi Kawasaki³ and Kai-Mei Fu^{1,2}; ¹University of Washington Dept. of Physics, Seattle, Washington, United States; ²Electrical Engineering, University of Washington, Seattle, Washington, United States; ³Applied Physics and Quantum-Phase Electronics Center, The University of Tokyo, Tokyo, Japan; ⁴PRESTO, JST, Kawaguchi, Japan.

Defects in crystals are leading candidates for photon-based quantum technologies, but progress in developing practical devices critically depends on improving defect optical and spin properties. Motivated by this need, we study a new defect qubit candidate, the shallow donor in ZnO. We demonstrate all-optical control of the electron spin state of the donor qubits and measure the spin coherence properties. We find a longitudinal relaxation time T_1 exceeding 100 ms, an inhomogeneous dephasing time T_2^* of 17 ns, and a Hahn spin-echo time T_2 of 50 μ s. The magnitude of T_2^* is consistent with the inhomogeneity of the nuclear hyperfine field in natural ZnO. Possible mechanisms limiting T_2 include instantaneous diffusion and nuclear spin diffusion (spectral diffusion). These results are comparable to the phosphorous donor system in natural silicon, suggesting that with isotope and chemical purification long qubit coherence times can be obtained for donor spins in a direct band gap semiconductor.

11:45 AM EP06.02.05

Room-Temperature Magneto-Optical Signatures of Defect Spins in Hexagonal Boron Nitride Annemarie L. Exarhos^{2,1}, David A. Hopper^{2,3}, Raj N. Patel², Marcus W. Doherty⁴ and Lee Bassett²; ¹Physics, Lafayette College, Easton, Pennsylvania, United States; ²Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, Pennsylvania, United States; ³Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania, United States; ⁴Research School of Physics and Engineering, Laser Physics Centre, Australian National University, Canberra, Australian Capital Territory, Australia.

Optically addressable spins associated with defects in wide-bandgap semiconductors have emerged as leading platforms for diverse applications in quantum information science and other quantum technologies, where spin-dependent inter-system crossing (ISC) transitions facilitate optical spin initialization and readout. Recently, the van der Waals material hexagonal boron nitride (h-BN) has emerged as a robust host for quantum emitters (QEs). Compared to traditional three-dimensional semiconductors like diamond and silicon carbide, h-BN promises unique capabilities for applications where defects couple to an external environment, such as sensing or nanophotonics, since defects exist at or very near atomically flat surfaces.

An outstanding question, however, has been whether h-BN can host QEs with an accessible spin degree of freedom, which could be used as qubits similar to the diamond nitrogen vacancy center. We report* on recent observations of a room-temperature magneto-optical response from select QEs in h-BN where the strongly anisotropic photoluminescence (PL) patterns as a function of applied magnetic field are markedly different from well-known spin defects in diamond and silicon carbide. We explore the anisotropic PL response due to an applied magnetic field through studies of an emitter's spectral, polarization, and photo-dynamic responses. Using a theoretical approach based on simple symmetry considerations, analytical molecular orbital theory, and semiclassical simulations, we show that the field-dependent variations in the steady-state PL and photon emission statistics are consistent with an electronic model featuring a spin-dependent ISC between triplet and singlet manifolds, indicating that optically-addressable spin defects are present in h-BN, a versatile two-dimensional material promising efficient photon extraction, atom-scale engineering, and the realization of spin-based quantum technologies using van der Waals heterostructures.

This work is supported by the Army Research Office (W911NF-15-1-0589) and the Australian Research Council (DE170100169).

* arXiv:1804.09061 [quant-ph] (2018)

SESSION EP06.03: Coherent Magnonics in Magnetic Insulators I
Session Chairs: Michael Flatté and Gregory Fuchs
Monday Afternoon, November 26, 2018
Hynes, Level 2, Room 204

1:30 PM *EP06.03.01

Freestanding YIG Magnon Nanoresonators with Ultra-Low Damping Georg Schmidt^{1,2}; ¹Institut für Physik, Universität Halle, Halle, Germany; ²Interdisziplinäres Zentrum für Materialwissenschaften, Universität Halle, Halle, Germany.

Nano electromechanical systems are interesting candidates for quantum information processing technology. Typical examples are the transfer of energy between mechanical and electromagnetic oscillators [1,2], but also spin wave excitations, so called magnons, can be used. An ideal material in this respect is Yttrium Iron Garnet. It combines long lifetimes as well for spin waves (magnons) as for mechanical waves (phonons) and a coupling mechanism for both (magnetoelastic coupling or magnetostriction). In the case of magnon resonances the coupling of a single Qbit to a magnon mode in a YIG sphere has already been demonstrated and also coupling of magnons to phonons in YIG spheres of diameters of a few hundred micron has already been published[3]. However, these experiments are still limited to macroscopic YIG spheres which forbid the integration of thousands or even hundreds of thousands of devices which may ultimately be necessary if a useful quantum computer shall be realized. So making true 3D YIG nanoresonators would open up a new field of applications for nanooscillators and create new options for quantum computation. However, up to now no method was available to shape three dimensional nanostructures from monocrystalline YIG.

We have developed a process to fabricate high quality monocrystalline freestanding 3D YIG nanostructures which can be designed for example as suspended bridges or cantilevers [4]. But also suspended optical ring resonators or disks for optical whispering gallery modes or more complex structures are possible. For the fabrication we use an electron beam lithography based process which was originally designed to realize metallic air bridges by

evaporation and lift-off [5]. A newly developed deposition process for YIG using pulsed laser deposition at room temperature [6] allows for the fabrication and lift-off of amorphous structures. Surprisingly subsequent annealing leads to monocrystalline bridges even if the length of the span is as large as several micrometers.

The structures were investigated using transmission electron microscopy indicating high crystalline quality. Detailed investigation of spin dynamics was done using time and spatially resolved Kerr microscopy. Here we see various standing spin waves including Damon Eshbach Modes and Backward Volume Modes. The minimum linewidth in ferromagnetic resonance at 8 GHz is as small as 140 μ T while the intrinsic linewidth at zero field is 75 μ T. Based on measurements at various frequencies the damping for a single resonator could be determined to $\alpha < 2 \times 10^{-4}$. The modes observed can be nicely reproduced in 3D micromagnetic simulations.

- [1] Y. Chu et al. Science **358**, 199 (2017)
- [2] A. D. O'Connell et al. Nature **464**, 697 (2010)
- [3] Xufeng Zhang et al. Science Advances **2**, (2016) e1501286
- [4] F. Heyroth et al. cond-mat.1802.03176
- [4] T. Borzenko et al. Microelectronic Engineering **75**, 210 (2004)
- [5] C. Hauser et al. Scientific Reports **6**, 20827 (2016)

2:00 PM *EP06.03.02

Bose-Einstein Condensates of Magnons in Optical Cavities Tianyu Liu; Tianjin Key Laboratory of Low Dimensional Functional Material Physics and Producing Technology and Department of Physics, Tianjin University, Tianjin, China.

Magnonics, a newly developing field of spintronics, has attracted much attention in the past decade. However, due to its large number of thermally excited magnons, most of experiments on magnonics remain in the classical regime, where incoherent magnons play an important role. By virtual of optical cavity, laser cooling of the magnon mode has been a potential step towards the quantum regime. Instead of preparing the magnon-vacuum state, here, we propose to form a macroscopically quantum coherent state of magnons--the magnon Bose-Einstein condensate (BEC)--in optical cavities made of magnetic solids. Our previous study has predicted that parametric pumping of magnons can be achieved in such a cavity with control light blue detuned from the cavity resonance. In this work, we study the dynamics of magnons excited by the optical cavity modes, and quantitatively estimate the requisite for preparing magnon BEC. By resolving magnon number states through spectroscopic measurements of cavity photons, the proposed method here may open up new directions for all-optical manipulation of quantum magnon states.

2:30 PM EP06.03.03

Spin Current Drive by Thermal Nonequilibrium Kevin S. E. Olsson, Kyongmo An, Jianshi Zhou, Li Shi and Xiaoqin E. Li; Univ of Texas-Austin, Austin, Texas, United States.

A central goal in spintronics is to develop devices that rely on the transfer of spin rather than charge. In magnetic insulators, magnons, quanta of collective spin excitations, carry a pure spin current and offer energy efficient information transport and processing. Several methods have been explored to generate spin currents in magnetic insulators, including spin pumping, the magnon Hall effect, and the spin Seebeck effect. Spin current is not a conserved quantity and may reduce via scattering processes involving angular momentum exchange. The spin relaxation extracted from earlier studies on YIG has yielded a value on the order of ~ 10 μ m, which is rather different from the energy relaxation length. A spin current can be introduced by a large temperature gradient introduced by a heating laser. We quantify such as a thermally driven spin current and magnon-phonon nonequilibrium in YIG using spatially resolved Brillouin light scattering technique. We obtain information on nonequilibrium spectral density and demonstrate that low-energy magnons have a longer spin relaxation length than that of high-energy magnons.

2:45 PM EP06.03.04

Coherent Magnonics in Vanadium Tetracyanoethylene Ezekiel Johnston-Halperin¹, Michael Chilcote¹, Harberts Megan¹, Bodo Fuhrmann², Katrin Lehmann², Franson Andrew¹, Yu Lu³, Howard Yu¹, Na Zhu⁴, Hong Tang⁴ and Georg Schmidt²; ¹The Ohio State University, Columbus, Ohio, United States; ²Institute für Physik, Martin-Luther-Universität-Halle-Wittenberg, Halle, Germany; ³Chemistry, The Ohio State University, Columbus, Ohio, United States; ⁴Yale University, New Haven, Connecticut, United States.

The exploration of quantum magnonics relies implicitly on the ability to excite and exploit long lived spin wave excitations in a magnetic material. That requirement has led to the nearly universal reliance on yttrium iron garnet (YIG), which for half a century has reigned as the unchallenged leader in high-Q, low loss magnetic resonance and spin wave excitation despite extensive efforts to identify alternative materials. Recent work has identified the organic-based ferrimagnet vanadium tetracyanoethylene (V[TCNE]₂) as the first credible alternative to YIG. In contrast to other organic-based materials V[TCNE]₂ exhibits a Curie temperature of over 600 K with robust room temperature hysteresis, sharp switching to full saturation, and magnetic resonance linewidths as low as 0.5 Oe at 9.86 GHz (quality factor $\sim 8,000$). Further, since V[TCNE]₂ is grown via chemical vapor deposition (CVD) at 50 C it can be conformally deposited as a thin film on a wide variety of substrates. Here we will discuss the coherent coupling of distinct magnon modes within a V[TCNE]₂ film that is templated by growth on a corrugated substrate. The resulting array of nanowire structures exhibits uniform ferromagnetic resonance (FMR) as well as a variety of exchange and dipole coupled standing wave modes defined by the lateral boundaries of the individual nanowires. Further, as the orientation of a DC applied magnetic field is varied between induced easy and hard magnetic axes we observe anticrossing behavior among these modes that indicates the constituent magnons are interacting in the strong coupling regime. In combination with low temperature CVD synthesis, these results demonstrate the unique ability to pattern on-chip high-Q magnonic structures with implications for emerging applications ranging from microwave electronics to quantum information systems.

3:00 PM BREAK

SESSION EP06.04: Dynamics and Magnetic Structure of Thin Magnetic Films
Session Chairs: Tianyu Liu and Georg Schmidt
Monday Afternoon, November 26, 2018
Hynes, Level 2, Room 204

3:30 PM *EP06.04.01

Observation of Anomalous Magneto-Optical Kerr Effect in SrRuO₃ Luyi Yang^{1,2} and F. Michael Bartram¹; ¹Physics, University of Toronto, Toronto,

Ontario, Canada; ²Physics, Tsinghua University, Beijing, China.

We report the observation of anomalous magneto-optical Kerr effect in ferromagnetic strontium ruthenate (SrRuO₃) thin films. We measure the polar Kerr signals as a function of an applied magnetic field. Apart from conventional hysteresis loops, the Kerr signals show additional hump features at small applied magnetic fields in certain thicknesses of the thin films. Similar to topological Hall effect, these hump features indicate the formation of topological spin textures (e.g. Skyrmions) possibly induced by the gradient of the strain.

4:00 PM EP06.04.02

Current-Induced Magnetic Domain Wall Motion in Compensated Ferrimagnet Saima A. Siddiqui, Jiahao Han, Joseph Finley, Caroline A. Ross and Luqiao Liu; Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Antiferromagnetic materials show promises compared to ferromagnetic materials for spintronic devices due to their immunity to external magnetic fields and their ultra-fast dynamics. However, difficulties in controlling and determining their magnetic state are limiting their technological applications. At the compensation point, the two antiparallel sub-lattices in a ferrimagnet have the same magnetic moment and the material is an antiferromagnet. Compensated ferrimagnets are expected to exhibit fast magnetic dynamics like an antiferromagnet and yet their magnetic state can be manipulated and detected like a ferromagnet, and therefore, have been pursued as a candidate system for ultrafast spintronic applications. Previously, it was demonstrated that current-induced spin orbit torque could provide an efficient switching mechanism for a compensated ferrimagnet. However, limited by the quasi-static measurement technique, the nature of the switching dynamics in these experiments are yet to be revealed. In this work, we provide the first experimental proof of current-induced fast domain wall (DW) motion in a compensated ferrimagnet.

Using a magneto optic Kerr effect microscope, we determine the spin orbit torque-induced DW motion in Pt/Co_{1-x}Tb_x microwires with perpendicular magnetic anisotropy. The DW velocity is determined as a function of applied current amplitude. A large enhancement of the DW velocity is observed in angular momentum compensated Pt/Co_{0.74}Tb_{0.26} microwires compared to single layer or multi-layer ferromagnetic wires. Using analytical model, we also find that near angular momentum compensation point, the domain walls do not show any velocity saturation unlike ferromagnets or uncompensated ferrimagnets since both the effective gyromagnetic ratio and effective damping diverge at this composition. Moreover, by studying the dependence of the domain wall velocity with the longitudinal in-plane field, we identify the structures of ferrimagnetic domain walls across the compensation points. The high current-induced domain wall mobility and the robust domain wall chirality in compensated ferrimagnets open new opportunities for spintronic logic and memory devices.

4:15 PM EP06.04.03

Non-Volatile Control of Anti-Ferromagnetic Néel Vector in α -Fe₂O₃ Through Hydrogen Doping Hariom Jani^{1,3}, Jiajun Linghu⁵, Rajesh Chopdekar⁴, Sonu Devi¹, Yonghua Du⁶, Changjian Li⁸, Ping Yang⁶, Sreetosh Goswami^{1,3}, Soumya Sarkar^{1,3}, Siddhartha Ghosh¹, Elke Arenholz⁴, Mike Coey⁷, Yuan Ping Feng⁵ and Thirumalai V. Venkatesan^{1,3,2}; ¹NanoCore, Singapore, Singapore; ²ECE, National University of Singapore, Singapore, Singapore; ³NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore, Singapore; ⁴Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, California, United States; ⁵Physics, National University of Singapore, Singapore, Singapore; ⁶Singapore Synchrotron Light Source, National University of Singapore, Singapore, Singapore; ⁷CRANN, Trinity College, Dublin, Ireland; ⁸MSE, National University of Singapore, Singapore, Singapore.

α -Fe₂O₃ hosts *in-plane* Antiferromagnetism (AFM) at room temperature, possessing spin canting due to the Dzyaloshinskii-Moriya interaction. Just 10⁰C below zero, bulk α -Fe₂O₃ undergoes *Morin transition* where the AFM spins re-orient colinearly along the *out-of-plane* symmetry axis. This first-order transition emerges due to the competition between magnetic-dipolar and single-ion magnetic anisotropies which have different magnitudes and temperature dependences.

We have developed a catalytic process for doping hydrogen into the α -Fe₂O₃ lattice, which allows non-volatile tuning of the AFM Néel vector and the accompanying spin canting. We discover that hydrogen doping also increases the electronic conductivity of α -Fe₂O₃ by three orders of magnitude. Moreover, owing to the light mass of a hydrogen atom, our H-doping process can be performed post-growth and is also reversible.

We characterize the new α -Fe₂O₃H_x phase via Reciprocal Space Mapping, Raman and UV-Vis Spectroscopy, Scanning Tunneling Electron Microscopy and X-Ray Magnetic Linear Dichroism. We use Elastic Recoil Detection Analysis to prove that hydrogenation indeed causes incorporation of H atoms in the α -Fe₂O₃ lattice. X-Ray Absorption Near Edge Structure and ab-initio calculations reveal that the hydrogenation induced magnetic and electric modulations in α -Fe₂O₃ are concomitant with electron doping and not due to any structural changes of the lattice. This Electronic doping plays a crucial role in tuning the relative magnitude of the single-ion anisotropy with respect to the magnetic-dipolar counter-part, causing the modulation of the Morin transition. Our approach opens new avenues for control of anti-ferromagnetism in oxide systems.

4:30 PM EP06.04.04

The Role of Mn and Si Co-Doping on the Ferromagnetic and Optical Properties of MOCVD GaN Layers for Spintronic Applications N Ben Sedrine¹, Vishal Saravade², Amirhossein Ghods², C. Zhou² and I. T. Ferguson²; ¹Departamento de Física e I3N, Universidade de Aveiro, Aveiro, Portugal; ²Missouri University of Science and Technology, Rolla, Missouri, United States.

Wide bandgap dilute magnetic semiconductors (DMS) have increasing interest due to their room temperature (RT) ferromagnetism. DMS can be integrated into existing electronic and optoelectronic devices, and are expected to support the transport and storage of spin for the next generation of electronic devices. RT ferromagnetic hysteresis has been observed in GaN doped with transition metal or rare earth ions, and that it can be controlled by different parameters such as: doping concentration, Si co-doping, and annealing. However, the mechanism behind the ferromagnetism is not well understood and needs further investigation for spintronic applications.

In this work, Mn and Si co-doping effects in GaN layers are investigated. Un-doped GaN, Ga_{1-x}Mn_xN and Mn and Si co-doped GaN layers grown on sapphire by MOCVD, with different Mn and Si concentrations, are studied using magnetometry measurements. Ferromagnetic hysteresis was recorded in the Ga_{1-x}Mn_xN layers at 300 K. However, for Si-doped Ga_{1-x}Mn_xN layers, the magnetization is found to decrease when Si concentration increases. It seems that Si compensates or shifts the acceptor levels in Ga_{1-x}Mn_xN, which are introduced by Mn-doping and contribute to the ferromagnetism [1]. Photoluminescence (PL) studies were performed as a function of temperature and excitation power, from ultraviolet (UV) to the near-infrared energy regions. In Ga_{1-x}Mn_xN layers, 14 K PL emissions exhibit well resolved near band edge (NBE) emission, UV luminescence (UVL), and a yellow luminescence (YL) band, while for Mn and Si co-doped layers, noticeable changes in the NBE and a suppression of the UVL were observed. For the same experimental conditions, overall PL intensity increases with increasing Mn concentration, but drastically decreases for the Mn and Si-co-doped samples. For the highest Mn concentration, the 14 K NBE emission exhibits several sharp peaks, while, Mn and Si co-doping induces a broadening of the NBE. Detailed investigation of these optically active defects in Ga_{1-x}Mn_xN and Ga_{1-x}Mn_xN:Si and their comparison with un-doped GaN will be performed.

Understanding of defects in GaN and their effects on the ferromagnetic and optical properties is a crucial step towards using GaN for spintronics.

M. Kane, S. Gupta and I. Ferguson, "Transition metal and rare earth doping in GaN", *Rare Earth and Transition Metal Doping of Semiconductor Materials: Synthesis, Magnetic Properties and Room Temperature Spintronics*, p. 338-340, 2016

4:45 PM EP06.04.05

Electronic Transport in Ballistic InSb Nanowires with Ferromagnetic Contacts Zedong Yang¹, Yifan Jiang², Sasa Gazibegovic³, Ghada Badawy³, Paul Crowell¹, Sergey Frolov², Erik P. Bakkers³ and Vlad Pribiag¹; ¹University of Minnesota, Minneapolis, Minnesota, United States; ²University of Pittsburgh, Pittsburgh, Pennsylvania, United States; ³Eindhoven University of Technology, Eindhoven, Netherlands.

InSb semiconductor nanowires (NWs) are a versatile semiconductor platform that has enabled investigations of Majorana bound states [1,2] and spin-based qubits [3]. Among their remarkable properties are large mobilities (up to ~20,000 cm²/Vs), very large Landé g-factors (up to ~50) and strong spin-orbital coupling (SOC). The large SOC and quasi-1D nature makes InSb nanowires interesting for all-electrical control of single spins, as demonstrated previously [4], and also offers the possibility to control electrically spin currents (as yet undemonstrated).

We fabricated InSb nanowire devices with ferromagnetic contacts (FM) to investigate spin transport. Conductance quantization plateaus in the back-gate sweep measurement demonstrate quasi-one-dimensional ballistic transport in these FM/NW/FM structures. We observe hysteretic features when varying the applied magnetic field, which could indicate spin injection from the FM contacts and transport in the quasi-1D InSb channel.

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SESSION EP06.05: Poster Session: Coherent Electronic Spin Dynamics in Materials and Devices

Session Chairs: Michael Flatté and Bernhard Urbaszek

Monday Afternoon, November 26, 2018

8:00 PM - 10:00 PM

Hynes, Level 1, Hall B

EP06.05.01

Photomagnetic Behavior and Infrared Spectroscopy of Rare-Earth Doped La_{0.7}Sr_{0.3}MnO₃ Ricardo Martinez Valdes³, Nitu Kumar³, Hannu Huhtinen¹, Wojciech M. Jadwisieniak² and R Palai³; ¹Department of Physics and Astronomy, University of Turku, Turku, Finland; ²School of Electrical Engineering and Computer Science, Ohio University, Athens, Ohio, United States; ³Department of Physics, University of Puerto Rico, San Juan, Puerto Rico, United States.

Trivalent rare earths (REs) exhibits fascinating spectroscopic, luminescent, and magnetic properties. REs have higher magnetic moment (Er³⁺ = 9.59 mB and Yb³⁺ = 4.5 mB) than transition metals. La_{0.7}Sr_{0.3}MnO₃ (LSMO) is a highly spin polarized materials with room temperature ferromagnetism. In the present work, we report the effect of RE co-doping (Er³⁺ and Yb³⁺) on photomagnetic behavior and infrared spectra of LSMO. In order to study the multifunctional effect, LSMO was co-doped with different concentrations of RE (1%, 2% and 3%) at the La-site. The microstructure, phase separation, electric and magnetic properties of LSMO was using energy dispersive x-ray spectroscopy (EDXS), scanning electron microscopy (SEM), X-Ray diffraction (XRD) and a physical properties measurement system (PPMS). The electronic states of the dopants are investigated by -ray Photoelectron Spectroscopy (XPS). Magnetic and photomagnetic measurements were carried out using SQUID magnetometry with visible and infrared excitation. Measurements of magnetoresistance at room temperature showed that Er³⁺ and Yb³⁺ ions have also great influence on the magnetic and electric ordering of LSMO under the influence of UV light and they can effectively enhance the magnetotransport properties of LSMO.

EP06.05.02

Dipole-Exchange Regime of the Spin Waves in Ferromagnetic Honeycomb Lattice Marcio d. Tavares^{3,4}, Samir S. Coutinho⁴, Edvan Moreira³ and David L. Azevedo^{1,2}; ¹Physics, Instituto de Física, Universidade de Brasília - UnB, Brasília, DF, Brazil, Brasília, Brazil; ²Materials, Faculdade UnB Planaltina - FUP, Universidade de Brasília - UnB, Área Universitária, Planaltina, DF, Brazil, Planaltina, Brazil; ³Physics, Universidade Estadual do Maranhão, São Luís, Brazil; ⁴Physics, Instituto Federal do Maranhão, São Luís, Brazil.

Many papers have been published in planar systems with honeycomb [1-2] and hexagonal [3] structures which has revealed magnetic behavior via doping and/or atomic adsorption processes, for this reason, the study of propagation of magnetic excitations (magnons) is a relevant issue. In this work, we investigate the effects of the dipolar-exchange effects on the spin waves in ferromagnetic honeycomb lattice.

The analytical calculations were performed in the context of the second quantization, via the creation and annihilation of the quasi-particles magnons, starting from the Heisenberg's Hamiltonian subjected to the Holstein-Primakov approximation. Then, we solved these equations numerically and we analyzed graphically the results.

We verified that the dipole interactions influence in the energy increment of the modes mainly in the magnetostatic region, thus promoting effects of coalescence in the energy spectrum in the edge regions of the first Brillouin zone. We also observe a break in reciprocity of energy for positive and negative values of wave vectors q_x . In addition, we show that the breakdown of the linearity of the energy near the high symmetry point K , which stays very clear in the behavior of the magnetic density of states, so that the absence of plateaus of energy are not favored with the increase of the dipole interactions.

We investigated the effects of the dipolar-exchange contribution to the energy of the ferromagnetic honeycomb system, where we observed the breakdown of energy reciprocity and the absence of degenerate magnetic modes.

ACKNOWLEDGMENTS

The authors are grateful for the support given from the UEMA, IFMA, FAPEMA.

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EP06.05.03

Spin Wave Propagation Properties in Strain Introduced Yttrium Iron Garnet Films Takuya Yoshimoto¹, Taichi Goto^{1, 2}, Bungo Iwamoto¹, Yuichi Nakamura¹, Hironaga Uchida¹, Caroline A. Ross³ and Mitsuteru Inoue¹; ¹Toyohashi University of Technology, Toyohashi, Japan; ²JST PRESTO, Kawaguchi, Saitama, Japan; ³Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Magnonics is an emerging research field for the realization of low-power signal processing by taking advantages of spin waves (SWs). Recently we demonstrated SW logic gate having the functionalities of XNOR or AND/OR based on the interference of the forward volume (FV) SW propagating in a 10 μm thick yttrium iron garnet (YIG) film. This thin YIG film is desirable for an integrated SW device because the thinner YIG propagates the shorter-wavelength SW which dictates device scalability. However, thin YIG film tends to magnetized in-plane because of the dominant out-of-plane demagnetization field, causing an increase of the required field for excitation of FV SW.

To decrease the saturation magnetic field of YIG film, we modulated magnetoelastic anisotropy in epitaxial growth of YIG films on gadolinium gallium garnet (GGG), rare-earth substituted GGG (SGGG) and neodymium gallium garnet (NGG) substrates. These substrates have the same garnet structure but different lattice constants, so YIG films on these substrates received different in-plane stresses and magnetoelastic anisotropies. YIG films were deposited by using pulsed laser deposition technique. The thicknesses were 93, 104 and 115 nm on GGG, SGGG and NGG substrate respectively. In-plane and out-of-plane spacing was extracted from the reciprocal space mapping around the asymmetric (336) peaks. The strain states of the YIG films were calculated from lattice spacing on the assumption of rhombohedral distortion of YIG.

To measure a field dependence of propagation properties of FV SW (spin wave spectroscopy: SWS) coplanar waveguides (CPWs) were fabricated by using electron beam lithography and liftoff technique. A distance of two CPWs were 64 μm . CPWs and vector network analyzer were connected via micro-probe to measure scattering parameters. The prominent signals in SWS shifted to the field by the gyro magnetic ratio was observed and it can be attributed to the signal of FV SW. The zero-crossing point of FV SW signal indicates minimum required field for FV SW excitation and these were 2290, 1390 and 1310 Oe on GGG, SGGG and NGG substrates respectively. The value of YIG on NGG was about two times smaller than that of YIG on GGG. FV SW dispersion curve taking account of magnetic anisotropy was calculated by using obtained strain states and showed good agreement with especially in YIG on GGG and SGGG. The differences between experiment and calculation might originate from differences in calculation parameter such as magnetocrystalline anisotropy constant, magnetostriction constant, and shear modulus.

The size of the permanent magnet needed to apply the required field to excite FV SW was calculated using a charge model. A neodymium iron boron magnet having a residual magnetic flux density of 12600 G was assumed. In this case, the volume of the magnet can be 2.53 times smaller for a device made from YIG on NGG than from YIG on GGG. These results contribute to the realization of integrated SW device.

EP06.05.04

Influence of Effective Mass on Flying Qubit Coupling for Heterostructure-Based Qubit Implementations Gaurab Panda⁷, Haozhi Dong⁷, Kan Xie¹, Virginia M. Ayres⁷, Harry Shaw⁶, Deborah Preston⁵, Volkan Tiryaki⁵, Han Chen³, David Shreiber³, Ijaz Ahmed³ and SK Bay⁴; ¹University of Maryland, College Park, Maryland, United States; ³Rutgers, The State University of New Jersey, Piscataway, New Jersey, United States; ⁴Bahcesehir University, Istanbul, Turkey; ⁵Siirt University, Siirt, Turkey; ⁶NASA Goddard Space Flight Center, Greenbelt, Maryland, United States; ⁷Michigan State University, East Lansing, Michigan, United States.

Initial solid-state qubit implementations have shown great promise but currently suffer from non-robust qubit generation and significant active cooling requirements. Flying qubit designs have emerged as an approach for adding dynamic control to solid-state qubit implementations. The flying qubit approach utilizes surface acoustic (SAW) wave interaction(s) for the capture and transport of a single or few electron(s) from a reduced dimensionality electron pool. Electron transport between quantum dots over a several-microns distance has been experimentally demonstrated [1] and theoretical investigations for spin-entangled electron qubits show promise [2]. In previous work, we investigated the effect of the SAW wave longitudinal component modelled as perturbation to the k-space momentum in the transport direction for a heterostructure based finite width 1D channel using the lowest energy level of an infinite potential well for the transverse electron confinement [3]. In the present work, the infinite potential well is replaced with a more realistic parabolic confinement in the transverse direction. Derivation of a new expression for number density enables first-time investigations of quantum channel accessibility and number density allowed occupations as a function of semiconductor effective mass. Results for devices with gallium arsenide versus gallium nitride as the confinement layer are presented.

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EP06.05.05

Phase-Transition Induced Magnetism Modulation and Logic Implementation in NiFe/VO₂ Heterostructure Guodong Wei¹, Xiaoyang Lin¹, Zhizhong Si¹, Xinhe Wang^{1, 2}, Kai Liu², Kaili Jiang², Yanxue Chen³ and Weisheng Zhao¹; ¹Beihang University, Beijing, China; ²Tsinghua University, Beijing, China; ³Shandong University, Jinan, China.

With more degree of freedom to manipulate information, multi-field control of magnetic and electronic properties may trigger various potential applications in spintronics and microelectronics. [1, 2] However, facile and efficient modulation strategies which can simultaneously response to different stimuli are still highly desired. Here, the strongly correlated electron system VO₂ is combined to realize efficient control of the magnetism in NiFe by

phase-transition. The NiFe/VO₂ bilayer is prepared by pulsed laser deposition (PLD) and magnetron sputtering. VO₂ is chosen as a representation of strongly correlated electron system, which exhibits complex property change as it transforms from a monoclinic insulator into a rutile metal at the critical temperature around 340K. [3] With the phase-transition happens, the heterostructure features appreciable modulations in the coercivity (60%), saturation magnetic strength (7%) and magnetic anisotropy (33.5%). To further confirm that the magnetism variation is indeed related to the phase-transition of VO₂, we also measured the temperature dependence of the film magnetization. With the phase-transition, a magnetization increasing could be detected owing to the coercive field shrinking. With further analysis, a conclusion could be drawn that the magnetism modulation is mainly attributed to the interfacial strain coupling of the heterostructure system.

These appreciable effects in heterostructures may further enable emerging device applications with capability of multi-field modulation. As a demo, a phase-transition anisotropic magnetoresistance device (PTAMR device) is fabricated. The coercivity change from about 500e to less than 100e and resistance drops more than 10% with illumination applied. Utilizing this feature, the PTAMR device provides an opportunity to achieve multi-resistance states, under multiple controls of the magnetic field and light illumination. Furthermore, this phase-transition spintronic device also shows a potential to construct programmable logic gates with multi-field inputs.

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EP06.05.06

The Linear Relationship of Spin Pumping in a La:YIG/Pt Heterostructure Used as a Microwave Rectifier Yiheng Rao, Huaiwu Zhang, Dainan Zhang, Lichuan Jin, Zhiyong Zhong, Qinghui Yang and Mingming Li; University of Electronic Science and Technology of China, Chengdu, China.

LPE technique YIG films have been grown on (1 1 1) GGG substrates with thickness of 300nm as a basic material for ISHE device fabrication. A 10nm Pt thin film as a non-magnetic material with a large spin hall angle was used as a spin detect layer sputtered on the YIG film. We investigated the dependence of the spin pumping effect on the power and frequency of the excitation microwaves in the YIG/Pt bilayers by measuring the ISHE. We demonstrated that the area under the ISHE curve (S_{ISHE}) across a wide power range had a nearly linear correlation with the input microwave power (P_{in}). The parameter S_{ISHE} can thus not only be used to describe the spin current energy in a Pt layer, but can also be applied as a microwave rectifier that works based on spin pumping.

SESSION EP06.06: Coherent Magnonics in Magnetic Insulators II
Tuesday Morning, November 27, 2018
Hynes, Level 2, Room 204

8:15 AM EP06.06.01

Level Attraction—Magnon-Photon Coupling Takes a New Form Can-Ming Hu; University of Manitoba, Winnipeg, Manitoba, Canada.

Cavity Spintronics [1] (also known as Spin Cavitronics) is a newly developing interdisciplinary field that brings together microwave cavity community with researchers from spintronics. This field started around 2014 when it was found that ferromagnets in cavities hybridize with both microwaves and light via light-matter interaction [2-6]. Since then, the emergence of this field has attracted broad interests. It connects some of the most exciting modern physics, such as quantum information and quantum optics, with one of the oldest science on the earth, the magnetism.

So far, at the center stage of this new field is the coherent magnon-photon coupling, which leads to level repulsion by producing a quasi-particle called cavity magnon polariton (CMP) [5-7]. In this talk, I will report our latest experiment that reveals magnon-photon level attraction [8]. Based on dissipative magnon-photon coupling, this effect is distinct from traditional level repulsion, resulting in the coalescence of hybridized modes at zero detuning in contrast to the Rabi gap observed in CMP systems. The experimental features of these new hybridized states can be accounted for by the magnetization back action which exists inside the cavity, and are revealed by our experiments due to the ability to control such a cavity Lenz effect. Exploiting this capability, we observe the transition between attraction and repulsion behavior, revealing the sharp transition which exists between the two effects. As observation of coherent magnon-photon coupling has spawned the field of cavity-spintronics, this new form of magnon-photon coupling may open up new avenues for exploiting the light-matter interactions using cavity spintronic approach.

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8:30 AM EP06.06.02

Selection Rules for Cavity-Enhanced Brillouin Light Scattering from Magnetostatic Modes James A. Haigh¹, Nicholas Lambert², Sanchar Sharma³, Yaroslav Blanter³, Gerrit Bauer³ and Andrew Ramsay¹; ¹Hitachi Cambridge Laboratory, Cambridge, United Kingdom; ²Cavendish, University of Cambridge, Cambridge, United Kingdom; ³Delft University of Technology, Delft, Netherlands.

We present measurements of enhanced Brillouin light scattering from magnons in yttrium iron garnet spheres. Optical whispering gallery modes confined at the surface by total internal reflection are coupled to the ferromagnetic resonance modes via the Faraday effect. Our experiments on optical coupling in this manner have demonstrated an enhancement in magnon Brillouin light scattering when the system is tuned to a triple-resonance point [1]. This occurs when both the input and output optical modes are resonant with those of the whispering gallery resonator, with a separation given by the ferromagnetic resonance frequency. Extending the measurements to higher order magneto-static modes [2], we have confirmed recent theoretical predictions [3] of the selection rules for scattering, dependent on the mode indices of the optical and magnetic modes. We give experimental evidence that the opto-magnonic

coupling to non-uniform magnons can be higher than that of the uniform Kittel mode, due to the better spatial overlap with the optical modes.

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SESSION EP06.07: Coherent Spin Dynamics in 2D Materials
Session Chairs: Ezekiel Johnston-Halperin and Bernhard Urbaszek
Tuesday Morning, November 27, 2018
Hynes, Level 2, Room 204

8:45 AM *EP06.07.01

Intrinsic Exciton Valley Dynamics in Semiconductor Monolayers and Heterostructures [Xiaoqin E. Li](#); Univ of Texas-Austin, Austin, Texas, United States.

Monolayer transition metal dichalcogenides (TMDs) have a hexagonal lattice structure in which the extrema (i.e., valleys) of the energy-momentum dispersion curves appear at two degenerate K and K' points at the boundary of the Brillouin zone. Time-reversal symmetry dictates that the electron spins in the K and K' valleys have opposite signs, effectively locking the spin and valley DoF. Valley pseudospin has been proposed and pursued as an alternative information carrier to charge. Optical manipulation of the valley index via excitons (neutral and charge exciton) requires the knowledge of valley polarization and valley coherence dynamics. Nonlinear resonant spectroscopy studies reveal intrinsic valley ultrafast dynamics inaccessible via simple linear spectroscopy measurements such as photoluminescence. We report valley decoherence measurements associated with excitons and trions in monolayers. We also discovered an exceptionally long valley polarization time associated with intra-valley excitons. Finally, we discuss our most recent studies on interlayer excitons in TMD vertical heterostructures.

9:15 AM EP06.07.02

Defects in 2D Materials from First Principles for Applications in Quantum Information Science [Chris Ciccarino](#)^{1,2}, Dan Wang³, Ravishankar Sundaraman³, Dirk R. Englund⁴ and Prineha Narang¹; ¹John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, United States; ²Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts, United States; ³Department of Materials Science and Engineering, Rensselaer Polytechnic Institute, Troy, New York, United States; ⁴Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Recent decades have seen tremendous progress towards low-dimensional electronic structures in solids that exhibit atom-like properties. While this progress was largely confined to 3D crystals and to molecules, new types of atom-like emitters were recently discovered in 2D layered materials. These 2D material hosts open new possibilities, including atom-by-atom imaging, atomic-scale structuring, their integration with optoelectronic 2D heterostructures, and applications in high-density and tightly-integrated quantum computers. However, there are many open questions concerning the origin and nature of atom-like defects in 2D materials, and experimental investigation has thus far been challenging. Here, we leverage first principles methods to investigate defects in 2D materials, including the wide band gapped hexagonal Boron Nitride. Our methods determine both zero phonon line excitation energies as well as vibrational effects, such that we capture not only expected emission energies but also important spectral properties including the Debye-Waller factor. We combine these techniques with accurate, 2D-tailored charge correction schemes to determine defects which both are optically promising and have charge stability. Given the large number of unexplored defects possible for 2D systems, we aim to use these efficient computational techniques to explore this defect parameter space and identify promising defect center/host combinations for single photon emission. By identifying promising candidates, we can provide a guide for future experimental investigation of defect centers in 2D materials.

9:30 AM EP06.07.03

Spin Relaxation in 2D Semiconductors with an Elliptic Band Structure [Seyed Mohammad Farzaneh](#) and Shaloo Rakheja; New York University, Brooklyn, New York, United States.

Coherent spin distribution can be used to transport information through semiconductors. The relaxation dynamics of the spin distribution is key in analyzing experimental data and enabling spin-based device applications. For most spin transport applications, a long spin relaxation time is desirable. Two-dimensional (2D) materials, such as monolayer black phosphorus (BP), have a weak intrinsic spin-orbit interaction and are expected to have long spin relaxation times, which could allow spin-encoded information to travel macroscopic distances in these materials. Moreover, an external electric field perpendicular to the plane of the 2D materials is an effective method to tune their spin-transport characteristics. Monolayer BP has a highly anisotropic band structure with an elliptic Fermi contour due to its puckered honeycomb structure. The anisotropy in the band structure leads to anisotropic momentum relaxation, anisotropic Rashba spin-orbit coupling, and, therefore, anisotropic spin relaxation. The goal of this work is to theoretically investigate spin relaxation in 2D semiconductors that have intrinsic anisotropy as well as other 2D materials in which mechanical strain results in ellipticity of the band structure. Two major relaxation mechanisms, namely D'yakonov-Perel' (DP) and Elliot-Yafet (EY), are taken into account to calculate the spin relaxation time. Within the DP theory, spin relaxation occurs due to the scattering-induced motional narrowing of spin precession about the Rashba spin-orbit field which is the result of broken inversion symmetry in the presence of an external electric field. Per the EY mechanism, which is present in centro-symmetric structures like BP, spin flipping at momentum scattering events causes nonequilibrium spin population to relax. We model the elliptic band structure using the effective mass approximation and quantify the impact of effective mass anisotropy on the spin relaxation anisotropy. More specifically, we demonstrate how fast a spin ensemble relaxes for a given initial polarization. The results from the DP and EY mechanisms are compared to determine the dominant spin relaxation mechanism in experimental samples. Finally, the results are used to predict the impact of mechanical strain on spin relaxation.

9:45 AM EP06.07.04

Spin Relaxation in Quasi-1D GaAs Nanowires - Spin Noise Spectroscopy and Electric Field Dependence Stefania Castelletto³, Deborah L. Gater¹, T. Alkhalid¹ and [Abdel F. Isakovic](#)^{1,2}; ¹KUST, Abu Dhabi, United Arab Emirates; ²CNF, Cornell University, Ithaca, New York, United States; ³RMIT University, Melbourne, Victoria, Australia.

In the last 20 years, several optical and electrical methods have been used to demonstrate how change in the dimensionality of a GaAs-based semiconductor system (bulk - 3D, quantum well - 2D, quantum dot - 0D) affects the spin relaxation rate over the broad range of technologically relevant doping levels (N_d above 10^{14} cm^{-3} and below 10^{19} cm^{-3}), and temperature ranges ($\sim 1\text{K} - 300\text{K}$). This work represents advances in the use of Spin Noise Spectroscopy (SNS) [1,2] aiming to understand the level of control over the spin relaxation rate in two cases: (a) varied dimensionality of GaAs based spintronic devices with the focus on differences between the available ranges of spin relaxation values driven by the changing dimensionality of GaAs systems, and, more specifically (b) voltage and geometry control of spin relaxation rate in quasi-1D nanowires. Compared to bulk (3D), quantum wells (2D) and quantum dots (0D), there have been comparatively fewer studies that focused on spin relaxation in two other systems: (a) 1D (quantum wires), and (b) quasi-1D semiconducting nanowires. Our interest in such systems stems from the belief that quantum wires and nanowires will play important role as interconnects in future quantum devices, especially in hybrid photonic-electronic spintronic quantum devices. To this end, we fabricated the semiconductor nanowires with controllable dimensionality, so that the cross section of the NWs is in the range (10-100 nm x 10-50 nm), with length in micrometer range. We report on the spin relaxation range between 20 and 300 ns, depending on temperature, magnetic field and doping. We also report on some qualitative differences between the behavior of spin relaxation rate for quasi-1D systems on one side, and 2D and 0D systems on the other. Two additional facets of this work are: (1) electric field dependent studies, and (2) nanowire aspect ratio studies. Electric field dependence is studied after the contacts were nanopatterned at the end of nanowires, using end contacts technology [3]. It is shown that the change of the applied voltage within 1.5 V range may affect the spin relaxation rate by more than 40%, for selected values within that range. Additionally, the voltage dependent study is then conducted for a variety of controllable external conditions. Changes in aspect ratio (width-to-thickness) of GaAs nanowires also affect the spin relaxation rate, pointing towards the need to optimize the NW dimensions prior to quantum spintronic devices implementation. A part of this work was supported by US DoE Office of Basic Sciences at Brookhaven National Laboratory. We acknowledge support from GRC-SRC, and partial support from 2012 KUIRF-Level 1, and 2015 ADEC-A2RE grants.

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10:00 AM BREAK

SESSION EP06.08: Advances in Sensing Enabled by NV Diamond
 Session Chair: Maria Vladimirova
 Tuesday Morning, November 27, 2018
 Hynes, Level 2, Room 204

10:30 AM *EP06.08.01

Exploring Condensed Matter Systems Using Diamond Magnetometry Amir Yacoby; Harvard University, Cambridge, Massachusetts, United States.

NV magnetometry has become a powerful tool for exploring magnetic properties of novel electronic systems. In this talk I will give an overview of some of the recent work we have done to use NV center magnetometry to image skyrmions in thin magnetic films, measure the spin chemical potential in magnetic insulators, and image hydrodynamic electron flow in graphene.

11:00 AM *EP06.08.02

Exploring Magnetism at the Nanoscale with a Single Spin Microscope Vincent Jacques; Laboratoire Charles Coulomb, UMR 5221, CNRS and Université Montpellier, Montpellier, France.

In the past years, it was realized that the experimental methods allowing for the detection of single spins in the solid-state, which were initially developed for quantum information science, open new avenues for high sensitivity magnetometry at the nanoscale. In that spirit, it was proposed to use the electronic spin of a single nitrogen-vacancy (NV) defect in diamond as an atomic-sized magnetic field sensor [1,2]. This approach promises significant advances in magnetic imaging since it provides non-invasive, quantitative and vectorial magnetic field measurements, with an unprecedented combination of spatial resolution and magnetic sensitivity under ambient conditions.

In this talk, I will show how scanning-NV magnetometry can be used as a powerful tool for exploring exotic spin textures in thin magnetic materials focusing on (i) domain walls and magnetic skyrmions in ultrathin ferromagnets [3,4] and (ii) cycloidal antiferromagnetic order in multiferroic materials [5].

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11:30 AM *EP06.08.03

Diamond Electronics for Quantum Sensing Mutsuko Hatano and Takayuki Iwasaki; Tokyo Institute of Technology, Tokyo, Japan.

Nitrogen-vacancy(NV) centers in diamond have superior physical properties at room temperature for quantum sensing of the magnetic field, electronic field, temperature, and pressure enabling scalable applications from atomic-scale to macroscopic range.

We would like to introduce our recent progress on materials, devices, and protocols;

- Materials: Selectively-aligned (> 99%) NV ensemble formed by distinctive CVD-growth with precise depth control for scalable applications [1-3].

- Sensing devices: Charge state control of NV centers

by band-gap engineering using pn junctions [4,5].

-Protocols: The iterative Qdyne protocol for wide field NMR imaging with mHz frequency resolution and nT sensitivity

For applications, we will introduce biological imaging, nano-scale NMR [3], macro-scale magnetometer [6] and its portable prototype, and internal device sensing [7].

This work was supported in part by JST-CREST Grant No. JPMJR1333, KAKENHI (17H01262 and 18H01472), and JSPS Bilateral Open Partnership Joint Research Projects.

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SESSION EP06.09: Coherent Dynamics from Nuclear and Ionic Spins in Semiconductors

Session Chairs: Vincent Jacques and Amir Yacoby

Tuesday Afternoon, November 27, 2018

Hynes, Level 2, Room 204

1:30 PM *EP06.09.01

Nuclear Spin System in GaAs—Cooling, Relaxation and Spin Temperature Concept [Maria Vladimirova](#)¹, Steve Cronenberger¹, Denis Scalbert¹, Mladen Kotur², Roslan Dzhioev², Ivan Ryzhov³, Valerii Zapasskii³, Gleb Kozlov³, Aristide Lemaître⁴ and Kirill Kavokin^{3,2}; ¹Laboratoire Charles Coulomb, CNRS-University of Montpellier, Montpellier, France; ²Ioffe Institute, St Petersburg, Russian Federation; ³Spin Optics Laboratory, St-Petersburg State University, St Petersburg, Russian Federation; ⁴Centre de Nanosciences et de nanotechnologies, CNRS, Université Paris-Saclay, Université Paris-Sud, Marcoussi, France.

Cooling of nuclear spins in doped semiconductors via their dynamic polarization by optical pumping is a powerful method for harnessing ubiquitous fluctuations of nuclear spin, which constitute a well-known decoherence channel for the electronic spins. The idea of spin cooling is based on the hypothesis of spin temperature, which states that nuclear spin system (NSS) reaches an internal thermal equilibrium long before it comes to equilibrium with the external bath (crystal lattice). Although thermodynamic framework has been successfully employed for the description of a variety of the experimental data, a rigorous check of this concept in semiconductors was impossible until recently, in particular at low magnetic field. The reason for that is the lack of experimental techniques allowing nonperturbative optical control over adiabatic transformation of the NSS.

We have recently developed such methods, based on off-resonant Faraday rotation and spin noise spectroscopy [1, 2]. Using these techniques, combined with dark-interval photoluminescence spectroscopy, we established a comprehensive picture of the nuclear spin relaxation efficiency, its magnetic field, temperature, and carrier concentration dependence in doped GaAs, a model system in the field of nuclear spin physics in semiconductors [3-5]. We also analyzed the interplay between four relevant relaxation mechanisms: hyperfine interaction, quadrupole interaction, spin diffusion and Korringa mechanisms.

Understanding of field dependence of NSS dynamics allowed us to obtain a new insight into the NSS thermodynamics, and verify the spin temperature concept in GaAs bulk material and microcavities [6]. We have demonstrated, that NSS exactly follows the predictions of the spin temperature theory, despite the quadrupole interaction that was earlier reported to disrupt nuclear spin thermalization in quantum dots [7]. Our results open a way for the deep cooling of nuclear spins in semiconductor structures, with the prospect of realizing nuclear spin-ordered states for high-fidelity spin-photon interfaces.

This work is supported by a joint grant of the Russian Foundation for Basic Research (RFBR, Grant No. 16-52-041301-4 and National Center for Scientific Research (CNRS, PRC SPINCOOL No. 148362)

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2:00 PM EP06.09.02

Electrically Tunable Dynamic Nuclear Spin Polarization in GaAs Quantum Dots at Zero Magnetic Field Marco Manca¹, Gang Wang¹, Takashi Kuroda², [Shivangi Shree](#)¹, Andrea Balocchi¹, Pierre Renucci¹, Xavier Marie¹, Mikhail Durnev³, Mikhail Glazov³, Kazuaki Sakoda², Takaaki Mano², Thierry Amand¹ and Bernhard Urbaszek¹; ¹LPCNO - INSA - CNRS - UPS, Toulouse, France; ²National Institute for Materials Science, Tsukuba, Japan; ³Ioffe Institute, St. Petersburg, Russian Federation.

The spin coherence of carriers in semiconductor quantum dots is limited by interactions with the nuclear spin bath fluctuations because the carrier and nuclear spins are efficiently coupled through the hyperfine interaction especially in III-V nano-structures with Ga, Al and In where 100 % of nuclei have non-zero nuclear spin.

On the other hand, the stable nuclear spins themselves can potentially be used as a resource for quantum information storage. Semiconductor quantum dots allow manipulating a mesoscopic ensemble of several thousand nuclear spins by optical manipulation of a single carrier spin, but commonly nuclear spin polarization manipulation is achieved in applied magnetic fields of several Tesla, a major drawback for practical applications.

In this work we show that both the sign and amplitude of optically generated dynamic nuclear polarization can be switched electrically in experiments at zero magnetic field, through the application of a bias voltage to our device based on charge tunable GaAs droplet dots grown by MBE on 111A substrates [1].

We demonstrate dynamic nuclear polarization (DNP) at zero magnetic field in a single quantum dot for the positively charged exciton X⁺ state transition. We tune the DNP in both amplitude and sign by variation of an applied bias voltage V_g. Variation of V_g on the order of 100 mV changes the nuclear spin polarization from -22% to +7% although the X⁺ photoluminescence polarization does not change sign over this voltage range. This indicates that absorption in the structure and energy relaxation towards the X⁺ ground state provide favorable scenarios for efficient electron-nuclear spin flip-flops,

generating DNP during the first tens of ps of the X+ life- time, which is on the order of hundreds of ps.

We also present Hanle spin depolarization experiments for electrons and nuclei in transverse magnetic fields, which confirm the dependence of dynamic nuclear spin polarization on the applied bias. First results on all electrical nuclear spin manipulation at zero magnetic field are discussed for a SpinLED device [2].

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2:15 PM EP06.09.03

Magneto-Optical Properties of Magnetically Doped Semiconductor Nanocrystals Controlled by Spin-Spin Interactions Efrat Lifshitz; Technion-Israel Inst of Tech, Haifa, Israel.

The control of individual spins in semiconductor nanocrystals is an emerging scientific field which undoubtedly play an important role in the development of new spin-based technologies. Generation of individual spins via incorporation of magnetic ions into colloidal nanocrystals became a hot topic in recent years. These diluted magnetic semiconductor (DMS) nanocrystals are subject to a size confinement on photo-generated carriers, which markedly enhances the mutual carrier-dopant spin-exchange interaction, consequently leading to a pronounced modification of the host's optical and magneto-optical properties.

Here we described the synthesis and characterization of DMS nanocrystals based on colloidal nanoplatelets, rods or spherical host semiconductor matrices, embedded with extremely low concentration of Mn^{2+} ions. This work includes host nanocrystals with a core/shell design (one semiconductor covered by another semiconductor) with dopant ions positioned either in the core or in the shell, using the layer-by-layer deposition. Thus, the work here discusses the influence of internal design on the magneto-optical properties of DMS colloidal nanocrystals. The research involved the use of magneto-photoluminescence (MPL) and optically detected magnetic resonance (ODMR) spectroscopy. The MPL spectra recorded at various temperatures and strength of magnetic field revealed the generation of giant magnetization (~ 30 Tesla) and g-factor (-4) of the exciton upon doping. The ODMR spectra of those samples designated a resonance line with a distinguished sextet related to the hyperfine interaction between the photo-generated electron and the surrounding nuclear spins of the dopants. The ODMR explored, for the first time, a control of nuclear spins on the magneto-optical properties of DMS nanocrystals. Furthermore, a time resolved ODMR experiment also revealed a shortening of the spin coherence time with respect to estimations, due to the hyperfine interaction. The carrier-nuclear spin may occur either directly, or mediated via the carrier-dopant electron spin (the sp-d interaction).

2:30 PM EP06.09.04

High Field Spin Resonance of Shallow Donors in Silicon Gemma Chapman¹, Konstantin Litvinenko¹, Dmytro Kamenskyi³, Viktoria Eles², Kamyar Saeedi Ilkhchy², Peter Christianen³ and Ben Murdin¹; ¹Advanced Technology Institute, University of Surrey, Guildford, United Kingdom; ²FELIX Laboratory, Radboud University, Nijmegen, Netherlands; ³High Field Magnet Laboratory, Radboud University, Nijmegen, Netherlands.

Single impurities in silicon are a key contender in the development of quantum technology applications. Donors can be placed and isolated within silicon with atomic resolution and have exceedingly long spin and orbital coherence times, leading to many potential spin-based quantum information architectures. High magnetic fields are an important tool for the control of impurity-based qubit structures. External fields manipulate the wave-functions of bound states allowing controlled modulation of the interaction between neighbouring impurities. Additionally, it has been shown that applying a gradient magnetic field can be used to read out the spin state of a bound donor. A potential quantum computing scheme could use magnetic fields to transfer quantum information along chains of qubits, before being manipulated and read out electrically through the external magnetic field. While spin dynamics at low field is well understood, knowledge of spin dynamics under high magnetic fields is limited.

Through the use of a tuneable microwave free electron laser and a helium-isolated bitter magnet, we have developed a scheme to investigate the spin dynamics of Group V donors in silicon in fields up to 25T. Real-time photoconductivity measurements of the bound-exciton have demonstrated incoherent control of the population of the ground state of phosphorous impurities and resolution of the relaxation dynamics of the system.

We acknowledge the support of the HFML, member of the European Magnetic Field Laboratory (EMFL) and the Engineering and Physical Sciences Research Council (EPSRC, UK) via its membership to the EMFL (grant EP/N01085X/1)"

2:45 PM EP06.09.05

Theory of the Circulating Current of a Single Magnetic Impurity in a Semiconductor Adonai R. Cruz¹ and Michael Flatté²; ¹Eindhoven University of Technology, Eindhoven, Netherlands; ²The University of Iowa, Iowa City, Iowa, United States.

The localized electron spin of a single impurity in a semiconductor is a promising system to realize quantum information schemes [1]. Coherent control of this spin depends on understanding the structure of the magnetic moment that couples the system with external fields. In this work we investigate the spin-orbit induced circulating current associated with the ground state of a single magnetic impurity in zincblende III-V semiconductor. This circulating current is dissipationless and represents an electron moving in a closed trajectory producing an orbital contribution to the magnetic moment [2]. We developed a formalism employing Green's functions obtained by the Koster-Slater technique [3] with a $sp^3d^5s^*$ empirical tight-binding Hamiltonian [4,5] to describe the host material.

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3:00 PM BREAK

SESSION EP06.10: Electrical Coherence of Localized Spin States
Session Chairs: Nathalie de Leon and Michael Flatté
Tuesday Afternoon, November 27, 2018
Hynes, Level 2, Room 204

3:30 PM *EP06.10.01

Electrically-Driven Spin Resonance of Surface Atoms Yujeong Bae^{1,2,3}, Kai Yang², Philip Willke^{1,2,3}, Andreas Heinrich^{1,3} and Christopher Lutz²; ¹Center for Quantum Nanoscience, Institute for Basic Science, Seoul, Korea (the Republic of); ²IBM Almaden Research Center, San Jose, California, United States; ³Physics, Ewha Womans University, Seoul, Korea (the Republic of).

Meticulous control of spin states is of central importance in spin-based information processing and spintronic devices. Electron spin resonance (ESR) combined with atom manipulation in a scanning tunneling microscope (STM) provides electrical access to spin structures constructed on a surface with atomic precision. In this talk, we demonstrate precise measurement and control of (i) the magnetic interactions between surface atoms and (ii) the hyperfine interaction of individual atoms.

The magnetic interactions between two spin-1/2 atoms on a surface were tailored via atom manipulation, resulting in a wide range of coupling strengths, extending from dipole to exchange interactions. We find that increasing the interaction strength between the spins of two atoms enhances the degree of the mixing of quantum spin states, enabling us to create robust singlet and triplet states. We show that a two level system composed of these singlet and triplet states is insensitive to local and global magnetic field noise, resulting in longer spin coherence times compared to single atoms.

We also measured the hyperfine interactions of individual atoms on a surface. Taking advantage of atom manipulation, we show that the hyperfine splitting strongly depends on the binding site of surface atoms as well as the proximity of other magnetic atoms. The observed hyperfine spectra enable us to deduce position-dependent information about the electronic ground state, the state mixing with neighboring atoms, and properties of the nuclear spin.

Our work provides a powerful probe of the quantum states of electron and nuclear spins for individual atoms and nanostructures. Magnetic structures built using spin-1/2 atoms may serve as the smallest component for assembling custom spin chains and arrays for the exploration of quantum phases, spintronic information processing, and quantum simulation.

4:00 PM EP06.10.02

Proposal for Measurement of Coherent Spin Dynamics of Individual Magnetic Dopants in a Semiconductor Using Low-Field Magnetoresistance of Spin-Polarized Scanning Tunneling Spectroscopy Stephen R. McMillan, Nicholas J. Harmon and Michael E. Flatté; The University of Iowa, Iowa City, Iowa, United States.

Individual magnetic impurities or small collections of magnetic impurities in III-V semiconductors can be identified via scanning tunneling microscopy (STM) [1,2], their exchange interaction can be measured [3], and they can have remarkably long spin coherence times [4]. Spin-1/2 impurities are able to be addressed individually and the eigenstates tailored allowing the construction of engineered spin networks [5]. We describe an approach to explore the coherent spin dynamics of a spin-1/2 defect coupled to an additional spin-1/2 defect via exchange interaction with a spin-polarized STM contact through low-field magnetoresistance. Our model utilizes a single site approximation and a stochastic Liouville equation allows for the calculation of steady state currents through the mediating defect. The inherent anisotropy [2,3,5,6] in conjunction with the applied magnetic field should allow one to describe a single spin Hanle curve. In addition, measurements of the spin coherence time and the local hyperfine interaction should be feasible. This analysis is then used to guide the examination of coherent spin-dynamics involving coupled Mn-hole complexes in III-V semiconductors.

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4:15 PM EP06.10.03

Spin Dependent Variable Range Hopping in a Highly Disordered Dielectric—Amorphous SiOC:H and SiOC:D Ryan J. Waskiewicz¹, Patrick Lenahan¹ and Sean King²; ¹The Pennsylvania State University, University Park, Pennsylvania, United States; ²Logic Technology Development, Intel Corporation, Hillsboro, Oregon, United States.

Leakage currents in low dielectric constant materials, such as SiOC:H, are important problems for microelectronic and nanoelectronic technology. Thus, a fundamental physical understanding of the point defects responsible for these leakage currents is a topic of significant interest. In this study, we utilize electrically detected magnetic resonance (EDMR) at multiple magnetic fields and frequencies to explore defect centers involved in electronic transport in these films. The EDMR is observed through changes in currents which are almost certainly due to spin dependent variable range hopping. The study includes extensive comparisons of the EDMR response as a function of voltage applied across thin films in metal-oxide-silicon structures. Comparisons of the EDMR versus voltage response and fairly well understood band diagrams provide information about the defect densities of states. We have exploited the fact that EDMR sensitivity is very nearly independent of the field and frequency at which the measurements are made. Comparison of EDMR measurements at high (9.5GHz) and low (about 100 MHz) frequencies help to deconvolute contributions to the spectra from hyperfine and spin orbit coupling. EDMR results also include comparisons with films in which hydrogen was replaced with deuterium. These comparisons also provide information about hyperfine interactions. In these hydrogen/deuterium comparisons, some structures were subjected to ionizing radiation, a process which considerably altered the defect structures. Our results allow some (somewhat tentative) conclusions to be drawn with regard to defect structure and also provide semiquantitative information about defect energy levels as well as defect-hydrogen interactions.

The project or effort depicted is sponsored by the Department of the Defense, Defense Threat Reduction Agency under grant number HDTRA1-16-0008. The content of the information does not necessarily reflect the position or the policy of the federal government, and no official endorsement should be inferred.

4:30 PM EP06.10.04

Blurring the Boundaries Between Topological and Non-Topological Phenomena in Dots Denis Candido¹, Michael E. Flatté² and José Carlos Egues¹; ¹Instituto de Física de São Carlos, Universidade de São Carlos, São Carlos, São Paulo, Brasil, Brazil; ²Department of Physics and Astronomy and Optical Science and Technology Center, The University of Iowa, Iowa City, Iowa, United States.

In this work we first predict using the $\mathbf{k}\cdot\mathbf{p}$ method and the valence band anti-crossing theory that the common III-V $\text{InAs}_{0.85}\text{Bi}_{0.15}$ / AlSb quantum well becomes a room temperature 2D topological insulator for well thickness $d_e < 6.9\text{nm}$. Second, we analytically solve the correspondent BHZ model for our TI by introducing a cylindrical confinement defining cylindrical quantum dots (QDs). Surprisingly, we find for the non-topological QDs “geometrically protected” discrete helical edge states, i.e., Kramers pairs with spin-angular- momentum locking, similar to the topological protected helical edge states within the gap in

the topological QDs. We calculate the circulating currents associated to both trivial and topological edge states and find no substantial difference between them. The two terminal conductance calculation for two pairs of edge states as a function of the QD radius and the gate controlling its levels with respect to the Fermi energy of the leads shows a double peak at $2e^2/h$ for both topological and trivial QDs. In conclusion, our results blur the boundaries between topological and non-topological QDs as for the protection of the helical edge states, their calculated circulating currents and their two terminal conductance measurements.

4:45 PM EP06.10.05

Charge State of Single and Ensemble Nitrogen Vacancy Center in Diamond n-i-n Junctions Maki Shimizu¹, Toshiharu Makino², Hiromitsu Kato², Masanori Fujiwara³, Takayuki Iwasaki⁴, Satoshi Yamasaki², Norikazu Mizuochi³ and Mutsuko Hatano⁴; ¹Tokyo University of Science, Shinjuku, Japan; ²National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan; ³Kyoto University, Uji, Japan; ⁴Tokyo Institute of Technology, Meguro, Japan.

Negatively charged nitrogen vacancy center (NV⁻) has attracted considerable interest over the past years since it is promising for magnetometer, quantum information science and biosensors. For these applications, controlling the charge state of NV center is essential, since NV⁻ center is sometimes unstable and may transition to NV⁰ in uncontrolled way.

Recently, we have demonstrated that the charge state is controlled in n-type-intrinsic-n-type (n-i-n) diamond junction[1][2]. In this method, NV centers were formed in the undoped i-layer where impurity concentration is very low and we can control Fermi energy (E_F) externally using standard band engineering techniques. Therefore, both the long spin coherence time (T_2) and the stabilization of NV⁻ centers can be obtained simultaneously. We showed that the E_F in the i-layer was controlled via the band bending at the two n-i junctions and the ratio of NV⁻ to NV⁰ centers was increased by reducing the width of the i-layer between the two n-layers. However, the spatial change of charge state of NV center in depletion region and neutral region near the n-i junctions were not examined in detail and the relationship between the measured photoluminescence (PL) spectra of ensemble of NV center and a single NV center are not clear.

In this study, we fabricated multilayer of n-i-n junction to investigate spacial change of the charge state of single and ensemble of NV centers along the junction. We measured the PL spectra of ensemble NV centers by continuous laser illumination which caused the stochastic charge state transitions between NV⁻ and NV⁰. We also measured the population of each charge state of single NV center by single shot measurement. The charge state depended on the band structure calculated by the Poisson equation in both of the measurements. The proportion of NV⁻ gradually increased in the vicinity of n-i junctions where it was considered to be depletion layer, and did not change at the center. This work was supported by JST CREST Grant Number JPMJCR1333, Japan

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SESSION EP06.11: Ensemble Spin Dynamics in Nonmagnetic Materials

Session Chairs: Ezekiel Johnston-Halperin and Bernhard Urbaszek

Wednesday Morning, November 28, 2018

Hynes, Level 2, Room 204

8:00 AM *EP06.11.01

Orbital Edelstein Effect and Phonon Edelstein Effect Taiki Yoda¹, Masato Hamada¹, Emi Minamitani³, Takehito Yokoyama¹, Motoaki Hirayama⁴ and Shuichi Murakami^{1,2}; ¹Department of Physics, Tokyo Institute of Technology, Tokyo, Japan; ²TIES, Tokyo Institute of Technology, Tokyo, Japan; ³The University of Tokyo, Tokyo, Japan; ⁴RIKEN, Wako, Japan.

In the Edelstein effect, a current in the crystal induces a spin polarization. It occurs in crystals without inversion symmetry, such as Rashba systems and surfaces of topological insulators. The spin polarization vanishes in equilibrium, but in the presence of the current, the electron distribution becomes off-equilibrium, giving rise to nonzero spin polarization, due to the spin-split band structure.

We propose an analogous effect for orbital angular momentum [1,2]. For example, in crystal with helical structure such as tellurium (Te) [3], we propose that a current along the helical axis induces an orbital magnetization [1,2] as well as spin magnetization. This effect is analogous to solenoids in classical electrodynamics. Within this analogy to solenoids, we quantify this effect by introducing a dimensionless parameter ξ , which represents a number of turns within the unit cell when regarded as a classical solenoid. Then we found that ξ is largely enhanced when the system is in the Weyl semimetal phase [1,2]. Here the Weyl semimetal phase [4] is allowed by broken inversion symmetry, and it is shown that Te becomes a Weyl semimetal at higher pressure [3,5]. There are other crystal structures that allow Edelstein effects, and we also demonstrate the orbital Edelstein effect for polar systems. Moreover, we propose a similar effect appears for phonons. In crystals, each phonon eigenmode has angular momentum due to rotational motions of the nuclei, but their sum is zero in equilibrium. Meanwhile a heat current in the Te crystal induces a nonzero total angular momentum [6]. We evaluate this effect for GaN and Te by ab initio calculation, and propose experiments to measure this effect.

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8:30 AM EP06.11.02

Anisotropic g-Factors of Bi_{1-x}Sb_x Alloys Cuneyt Sahin and Michael E. Flatté; Univ of Iowa, Iowa City, Iowa, United States.

Bismuth and bismuth-based materials with small band gaps and large spin-orbit couplings exhibit novel physical phenomena such as three-dimensional topological insulator phases [1] and giant spin Hall conductivities [2]. Furthermore, prediction [3] and a recent discovery of the Weyl semimetal phase [4] with the chiral anomaly in the Bi and Sb alloys demonstrate the rich physics of these materials. In this work, we calculate another spin-orbit interaction related term, the g-factor in the BiSb alloys. Early studies of the g-tensor with a two band k.p approach [5] are valid only for electrons, and a more recent multi-band k.p model [6] is accurate just for electrons and holes. The magnitude of g-factor may change dramatically in a crystal as a result of the crystal

potential and the spin-orbit interaction, which makes the g-factor a band structure dependent, an intrinsic property of the crystal. Additionally, g-factor is a direction dependent property in a crystal; therefore it is a rank two tensor.

Here we present a full Brillouin zone calculation of the g-factor using a 16 band tight-binding Hamiltonian of the BiSb alloys. To calculate effective g-factors of bismuth and antimony alloys, we model electronic bands and eigenfunctions using a Slater-Koster type tight-binding technique with parameters taken from a previous study [7] and investigate the behavior of conduction and valence band edges. In addition to the tight-binding Hamiltonian, we include a spin-orbit Hamiltonian with spin-orbit couplings of 1.5 eV and 0.6 eV for Bi and Sb respectively.

We calculate the electronic band structure from the tight-binding Hamiltonian for different concentration of antimony using the virtual crystal approximation. As the antimony concentration is increased the band overlap disappears and a semimetal-semiconductor transition occurs. Further increase in the antimony concentrations leads to a faster shift in the valence band than the conduction bands. Therefore, an indirect gap opens, leading to topologically insulating (TI) phase. BiSb alloys also display a Weyl semimetal with chiral anomaly within the range of the TI phase.

For bismuth, holes are located at the T point in the Brillouin zone whereas electrons are at the L point. As a result of the symmetry of the T point, g_z is the only non-zero g-factor element where z is along the trigonal axis. However, at the L point, we observe substantial g-tensor elements for both pure Bi and BiSb alloys that differ in magnitude. In conclusion, we show that bismuth, antimony and bismuth-antimony alloys exhibit giant anisotropic g-factors.

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8:45 AM EP06.11.03

Tuning Spin-Charge Interconversion with Quantum Confinement in Ultrathin Bismuth Films Matthieu Jamet¹, Carlo Zucchetti², Federico Bottegoni², Céline Vergnaud¹, Thomas Guillet¹, Alain Marty¹, Cyrille Beigne¹, Serge Gambarelli¹, Andrea Picone², Alberto Calloni², Gianlorenzo Bussetti², Alberto Brambilla², Lamberto Duo², Franco Ciccacci², Pranab Kumar Das³, Jun Fujii⁴, Ivana Vobornik⁴, Marco Finazzi² and Minh-Tuan Dau¹; ¹CEA Grenoble, Grenoble, France; ²Politecnico di Milano, Milan, Italy; ³National University of Singapore, Singapore, Singapore; ⁴Elettra, Trieste, Italy.

Bismuth exhibits a series of electronic properties that made it the subject of experimental and theoretical interest for decades, in particular in electronic-transport studies [Y. Fuseya et al., J. Phys. Soc. Jpn. **84**, 012001 (2015)]. With a lattice structure close to that of graphene and a very large spin-orbit coupling, bismuth may have the potential to be a topological semimetal or semiconductor [I. Aguilera et al., Phys. Rev. B **91**, 125129 (2015)]. In order to explore this possibility, we have grown by molecular beam epitaxy (MBE) ultrathin films of Bi on Ge(111). Indeed, MBE gives the opportunity to grow metastable allotropic phases of Bi or to induce strain into bulk Bi which may give topological properties to this material. Moreover, the growth of such phase on germanium opens new perspectives to use the electron spin in traditional microelectronics. In this study, we have grown a bismuth wedge (0-15 nm) on Ge(111) by MBE. Using structural characterization (RHEED and x-ray diffraction), we found a critical thickness of 5 nm below which Bi exhibits an allotropic pseudocubic phase. A careful angle-resolved and spin-resolved photoemission spectroscopy study using synchrotron radiation (ELETTRA, Italy) showed that the pseudocubic phase exhibits surface states with a quasi-linear band dispersion and a characteristic helical spin texture. We have then investigated the spin-to-charge interconversion at these surface states using 3 different techniques: magneto-optical Kerr effect to probe the Rashba-Edelstein effect (REE), inverse REE using optical spin orientation in the Ge film beneath and finally spin pumping from a ferromagnetic layer grown on top of Bi separated by an Al spacer. We found a clear signature of the strong spin-to-charge interconversion in these surface states only in the regime where Bi grows in the form of nanocrystals on Ge(111). We could demonstrate that this effect is the result of a strong quantum confinement in the Bi nanocrystals [C. Zucchetti et al., arXiv:1805.01841].

9:00 AM EP06.11.04

Epitaxial BaTiO₃ on Ge as a Tunnel Barrier for Charge and Spin Injection Yichen Jia, Cristina Visani, Charles H. Ahn and F. J. Walker; Yale University, New Haven, Connecticut, United States.

The epitaxial integration of functional oxides on conventional semiconductors opens new opportunities for coupling their unique properties with semiconductors for post-CMOS technologies. Here we demonstrate a spin-injection device based on epitaxial BaTiO₃ on Ge (001) heterostructures. We first show spin accumulation in the p-type Ge and measure a sizeable spin lifetime in the semiconductor. The magnitude of the spin injection signal can be quantitatively explained using a two-channel spin transport model with one channel due to spin injection into germanium and the other due to injection into interfacial localized states (ILS). We also demonstrate control of the spin signal by manipulating the band profile across the heterojunction, which modulates the charge transport between impurity-assisted conduction and quantum mechanical tunneling, effectively acting as a “switch” for spin injection.

9:15 AM EP06.11.05

Spin Injection into Epitaxially-Grown β -FeSi₂ in Lateral Structural Spin-Valves Hiroki Ishimoto¹, Tetsuo Tabei², Ken-ichiro Sakai³ and Tsuyoshi Yoshitake¹; ¹Applied Science for Electronics and Materials, Kyushu University, Kasuga-shi, Japan; ²Research Institute for Nanodevice and Bio Systems, Hiroshima University, Higashihiroshima, Japan; ³Control and Information Systems Engineering, Kurume College, Kurume-shi, Japan.

Since giant magnetoresistance (GMR) and tunnel magnetoresistance (TMR) effects were discovered, spintronics have received much attention from physical and scientific viewpoints. Spintronics is the fusion field of electronics and magnetism, which is utilizing not only the electrical charge but also electrical spin of an electron. GMR and TMR, which employ nonmagnetic metal and insulator as interlayers, respectively, have already been applied to magnetic heads and magnetic random access memories (MRAM). On the other hand, semiconductor spintronics employing semiconductor interlayer such as Si, Ge, and GaAs has actively been developed. Employing semiconductor has the following merits: (i) crystal growth and process techniques have been already matured; (ii) physical properties change significantly by control of carriers; and (iii) electronic devices and their large scale integration (LSI) techniques have been well-established. Therefore, Spin-devices comprising semiconductors have a potential compatible with present semiconductor devices. As fundamental preparation researches for such an application, we have studied spin injection into nanocrystalline FeSi₂ with vertical-type spin-valves. Since spin is easily scattered at grain boundaries, high purity of crystallinity is desired for the application of the spin-devices. Semiconducting β -FeSi₂ has been attracting much attention as a possible candidate compatible with Si technologies because β -FeSi₂ can be grown epitaxially on Si (111) substrates with small lattice mismatches of -5 to 2%. Furthermore, it has a large absorption coefficient of over 10⁵ cm⁻¹ at 1.5 eV, and it is a candidate semiconductor applicable to optoelectronic applications. Our laboratory has ever succeeded in the epitaxial growth of β -FeSi₂ films on Si (111) substrates at a substrate temperature of 600 °C by facing target direct current sputtering (FTDCS). So far, there have been few studies on the spin injection into β -FeSi₂. In this study, based on experimental techniques in the previous studies, lateral-type spin-valves comprising β -FeSi₂ films were fabricated, and spin injection and transport were experimentally studied. Lateral-type spin-valves were prepared by electron beam lithography combined with the deposition of semiconducting β -FeSi₂ films and ferromagnetic metal Fe films, and a mask method. The magnetoresistance (MR) curve in local-structure was measured at

room temperature by a vibrating sample magnetometer (VSM). From the measurement of MR curves, it was confirmed high and low electrical resistance values are owing to the antiparallel and parallel alignments of the Fe layers magnetization are clearly realized. It was experimentally demonstrated that β -FeSi₂ is applicable to interlayers of spin valves that work at room temperature. Further systematic experiments are conducted and results will be reported at the conference.

9:30 AM EP06.11.06

Non-Local Opto-Electrical Spin Injection and Detection in Germanium at Room Temperature [Matthieu Jamet](#)¹, Fabien Rortais², Carlo Zucchetti³, Lavinia Ghirardini³, Celine Vergnaud¹, Julie Widiez¹, Alain Marty¹, Laurent Vila¹, Jean-Philippe Attane¹, Henri Jaffres⁴, Jean-Marie George⁴, Michele Celebrano³, Giovanni Isella³, Franco Ciccacci³, Marco Finazzi³ and Federico Bottegoni³; ¹CEA Grenoble, Grenoble, France; ²University of Kyoto, Kyoto, Japan; ³Politecnico di Milano, Milan, Italy; ⁴Unité Mixte CNRS-Thales, Palaiseau, France.

Non-local charge carrier injection/detection schemes lie at the very foundation of information manipulation in integrated systems. The next generation electronics may operate on the spin instead of the charge and germanium appears as the best hosting material to develop such spintronics for its compatibility with mainstream silicon technology and long spin lifetime at room temperature. Moreover, the energy proximity between the direct and indirect bandgaps allows for optical spin injection and detection within the telecommunication window. In this presentation, we demonstrate injection of pure spin currents (i.e. with no associated transport of electric charges) in germanium, combined with non-local spin detection blocks at room temperature [C. Zucchetti et al., Phys. Rev. B **96**, 014403 (2017), F. Rortais et al. Appl. Phys. Lett. **111**, 182401 (2017)]. Spin injection is performed either electrically through a magnetic tunnel junction (MTJ) or optically, exploiting the ability of lithographed nanostructures to diffuse the light and create an in-plane polarized electron spin population. Pure spin current detection is achieved using either a MTJ or the inverse spin-Hall effect (ISHE) across a Pt stripe. These results first show that the spin diffusion length in low-doped germanium can be as long as 10 μ m and broaden the palette of tools available for the realization of opto-spintronic devices.

9:45 AM EP06.11.07

Electronic Raman Scattering in Ge Studied by Circular-Polarized Femtosecond Excitation Correlation Photoluminescence [Yuhsuke Yasutake](#) and Susumu Fukatsu; Graduate School of Arts and Sciences, University of Tokyo, Tokyo, Japan.

Germanium (Ge) has received the renewed interest in light of not only optoelectronic but also spintronic advantages. In fact, its relatively small offset between the indirect and direct valleys (ca. 140 meV) permits direct-gap optical transitions while crystal inversion symmetry, fewer nuclear spins and the fairly large spin-orbit splitting (ca. 290 meV) promise the manipulation of electron spin polarizations. Electronic Raman scattering (ERS) is a two-photon process that predominantly occurs in Ge involving the valence bands for above-gap excitations. Optical injection of spin-polarized electrons and near-direct-edge optical gain are some of the functions expected for ERS due to the split-off (SO) hole. Degenerate with the direct band-edge, however, it is difficult to discriminate such SO-ERS by means of linear spectroscopy. Here we attempt to do it by leveraging the ultrafast relaxation of carriers and spins that undergo intervalley scattering.

We used the circular-polarized femtosecond excitation correlation (FEC) technique. The same spot on the sample was excited by two femtosecond pulses (1030 nm, 200 fs), and the cross-correlation of photoluminescence intensities was taken as a function of the delay, t . Negative (positive) FEC signals were obtained for a nonlinear power growth curve of the emission intensity (I^n) such that $n < 1$ ($n > 1$). Direct-gap recombination (1250-1420 nm) showed largely positive FEC due to the Shockley-Read-Hall recombination ($n = 2$). In the vicinity of the SO-ERS (1400 nm), however, a negative FEC feature that monotonically varies with a time constant ($\tau = 1.2$ ps) was observed, which suggests the relevance of the intervalley scattering. On the other hand, circularly polarized FEC of n-Ge was obtained by monitoring the (σ^+)-polarized pump, (σ^-)-polarized probe, and circular-polarized photoluminescence. The time evolution of the circular polarization visibility was best fitted with a double exponential, from which different time scales were identified such that SO-ERS ≈ 4 ps and direct-gap ≈ 200 ps.

10:00 AM BREAK

10:30 AM EP06.11.08

Ab Initio Electronic T_1 Spin Relaxation Times in Silicon and Diamond [Jinsoo Park](#), Jin-Jian Zhou and Marco Bernardi; Department of Applied Physics and Materials Science, California Institute of Technology, Pasadena, California, United States.

Spin relaxation in crystals with inversion symmetry primarily occurs through the Elliott-Yafet mechanism, in which the injected spins are scattered by phonons or impurities. We present an efficient first-principles approach for computing the Elliott-Yafet electronic spin relaxation time T_1 in semiconductors and insulators. Our scheme combines ab initio electron-phonon scattering with a new approach to correctly treat degenerate electronic states. Application of our approach to silicon and diamond is discussed in this talk. Our computed spin relaxation times in silicon are in excellent agreement with experiment above 150 K, and we can also resolve the phonon modes that mainly contribute to spin relaxation. The temperature dependence of the spin relaxation times in silicon and diamond are analyzed, together with the contributions from intravalley and intervalley scattering. We show that intravalley scattering dominates at low temperature, and that intravalley and f-intervalley scattering becomes comparable at room temperature. Our work enables accurate ab initio calculations of the T_1 spin relaxation time in a range of materials, providing new microscopic insight into spin relaxation.

SESSION EP06.12: Novel Spin Centers in Diamond

Session Chair: Michael Flatté

Wednesday Morning, November 28, 2018

Hynes, Level 2, Room 204

10:45 AM *EP06.12.01

Engineering Coherent Defects in Diamond [Nathalie P. de Leon](#); Princeton University, Princeton, New Jersey, United States.

Engineering coherent systems is a central goal of quantum science and quantum information processing. Point defects in diamond known as color centers are a promising physical platform. As atom-like systems, they can exhibit excellent spin coherence and can be manipulated with light. As solid-state defects, they can be produced at high densities and incorporated into scalable devices. Diamond is a uniquely excellent host: it has a large band gap, can be synthesized with sub-ppb impurity concentrations, and can be isotopically purified to eliminate magnetic noise from nuclear spins. Specifically, the nitrogen vacancy (NV) center has been used to demonstrate basic building blocks of quantum networks and quantum computers, and has been demonstrated to be a highly sensitive, non-invasive magnetic probe capable of resolving the magnetic field of a single electron spin with nanometer spatial

resolution. However, realizing the full potential of these systems requires the ability to both understand and manipulate diamond as a material. I will present two recent results that demonstrate how carefully tailoring the diamond host can open new opportunities in quantum science.

First, currently-known color centers either exhibit long spin coherence times or efficient, coherent optical transitions, but not both. We have developed new methods to control the diamond Fermi level in order to stabilize a new color center, the neutral charge state of the silicon vacancy (SiV) center. This center exhibits both the excellent optical properties of the negatively charged SiV center and the long spin coherence times of the NV center, making it a promising candidate for applications as a single atom quantum memory for long distance quantum communication.

Second, color centers placed close to the diamond surface can have strong interactions with molecules and materials external to the diamond, which makes them promising for nanoscale sensing and imaging. However, uncontrolled surface termination and contamination can degrade the color center properties and give rise to noise that obscures the signal of interest. I will describe our recent efforts to stabilize shallow NV centers within 5 nm of the surface using new surface processing and termination techniques. Specifically, we are able to demonstrate reversible and reproducible control over the top layer of atoms. These highly coherent, shallow NV centers will provide a platform for sensing and imaging down to the scale of single atoms.

11:15 AM EP06.12.02

Group-IV Defects in Diamond from First Principles [Chris Ciccarino](#)^{1,2}, Matthew Trusheim³, Dirk R. Englund³ and Prineha Narang¹; ¹John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, United States; ²Department of Chemistry and Chemical Biology, Harvard University, Cambridge, Massachusetts, United States; ³Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts, United States.

Color centers in diamond have emerged as leading solid-state "artificial atoms" for a range of technologies from quantum sensing to quantum networks. Concerted research activities are now underway to identify new color centers that combine the favorable spin properties of the diamond nitrogen vacancy (NV⁻) with the spectral stability of the silicon vacancy (SiV⁰) center. Among the alternate color centers explored, the SiV⁰ and PbV⁻ centers, the latter of which we have investigated previously, are among the most promising candidates for application in spin-photon systems such as quantum repeaters and quantum networking. Characterizing these defect centers and their emission spectra remains an actively debated area of research. We use a combination of theory and experiment to study the PbV⁻, SiV⁰ and the previously unexamined GeV⁰ defects in diamond and determine the nature of these defect states. By leveraging theory to accurately predict vibrational effects as well as Jahn-Teller distortion, we capture experimentally accessible spectral features including the Debye-Waller factor and spin-orbit-quenched zero field splitting. Meanwhile, we identify potential experiments that can verify theoretical predictions and provide additional defect characterization data of interest, including the excited-state lifetime. Together with theory, these results provide new insight into the potential of these defect centers as single photon emitters for quantum information processing.

11:30 AM EP06.12.03

Diamond Color Centers Created by Implantation of Heavy IV-Group Elements of Tin and Lead [Takayuki Iwasaki](#)¹, Yoshiyuki Miyamoto², Takashi Taniguchi³, Petr Siyushev⁴, Mathias Metsch⁴, Fedor Jelezko⁴ and Mutsuko Hatano¹; ¹Tokyo Institute of Technology, Tokyo, Japan; ²AIST (National Institute of Advanced Industrial Science and Technology), Ibaraki, Japan; ³National Institute for Materials Science, Ibaraki, Japan; ⁴Ulm University, Ulm, Germany.

Quantum emitters in diamond are expected to be important components toward the realization of quantum network. Although nitrogen-vacancy (NV) centers have been most intensively studied, they suffer from the low fraction of zero phonon line (ZPL) in the total fluorescence and external noise leading to the unstable emission line. To solve these problems, color centers based on the IV-group elements have recently attracted attention because of the large ZPL and robustness of the emission line due to the inversion symmetry. Furthermore, a long spin coherence time over 10 ms has been reported for a silicon-vacancy (SiV) center at millikelvin temperatures [1]. It is expected that a heavier element with larger spin-orbit interaction can increase the ground state splitting to reduce the phonon-mediated decoherence. Thus, long spin coherence times can be expected at higher temperatures without a dilution refrigerator. In this study, we demonstrate the creation of a novel quantum emitter in diamond, called tin-vacancy (SnV) center [2], possessing a much larger ground state splitting than the SiV center, and we also discuss optical properties of diamond implanted with a heavier IV group element of lead (Pb). SnV centers were fabricated by ion implantation and subsequent high-pressure and high-temperature (HPHT) annealing over 2000 deg. Both single and ensemble SnV centers were formed. Pb ions were implanted into different diamond crystals, and the HPHT annealing was performed. The SnV center showed a sharp ZPL at 619 nm at room temperature, while it splits into four peaks at low temperatures, corresponding to split ground and excited states. The ground state splitting was estimated to be 850 GHz, which is 17 times higher than that of the SiV center. With this large value, we can expect a long spin coherence time for the SnV center in the kelvin regime. The first-principles calculations indicated the D_{3d} symmetry of the SnV center, same as the SiV and GeV center. Thus, the stable emission of the SnV center can be also expected. Optical properties of Pb implanted diamond crystals were investigated. Note that independent works on the Pb-implanted diamonds have been very recently reported [3,4]. We observed prominent peaks at 551, 556, and 591 nm. However, we found that these peaks also appeared in a Sn implanted sample. Thus, at present, we speculate that these peaks are not related with Pb, but probably vacancies created by the implantation of the heavy atoms. Further efforts will be discussed for the fabrication of the Pb-related color center in diamond.

This work was supported in part by JST-PRESTO Grant No. JPMJPR16P2, JST-CREST Grant No. JPMJR1333, and JSPS Bilateral Open Partnership Joint Research Projects.

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[2] T. Iwasaki, et al., Phys. Rev. Lett. 119, 253601, 2017.

[3] M. E. Trusheim, et al., arXiv:1805.12202.

[4] S. D. Tchernij, et al., arXiv:1806.01608.

11:45 AM EP06.12.04

Lead-Related Quantum Emitters in Diamond [Matthew Trusheim](#)¹, Noel Wan¹, Kevin Chen¹, Chris Ciccarino², Ravishankar Sundaraman³, Eric A. Bersin¹, Michael Walsh¹, Benjamin Lienhard¹, Hassaram Bakhru⁴, Prineha Narang² and Dirk R. Englund¹; ¹Massachusetts Institute of Technology, Cambridge, Massachusetts, United States; ²Harvard University, Cambridge, Massachusetts, United States; ³Rensselaer Polytechnic Institute, Troy, New York, United States; ⁴State University of New York Polytechnic Institute, Albany, New York, United States.

Quantum emitters in diamond are promising spin-photon interfaces, as they can possess both long-lived electronic spin states and coherent optical transitions. In particular, color centers based on Group IV impurities, such as the silicon vacancy center, have a crystallographic inversion symmetry that eliminates their static dipole moment and produces stable optical lines approaching the lifetime limit. This crystallographic structure, however, results in a pair of nearly degenerate orbital ground states that can scatter phonons, resulting in rapid spin dephasing for silicon- and germanium-vacancy centers at liquid helium temperatures. Here, we report on lead-related centers fabricated in ultrapure diamond following ion implantation and high temperature

annealing. Cryogenic photoluminescence measurements performed on single quantum emitters in nanofabricated pillars show several transitions, most notably a pair of lines around 520 nm. The splitting of this doublet, 2 THz, is the largest reported of any Group IV-vacancy emitter in diamond. These observations are consistent with our models of the negatively charged Pb-vacancy center, which is expected to have a combination of narrow optical transitions and stable spin states that make it a promising system for quantum networking applications.