AFOSR Nanoelectronics Program Review Abstracts

Monday, October 24, 2016

Nanoscale Magnetic Imaging of Condensed Matter Systems Using Diamond Spins

Ania Bleszynski Jayich, UCSB

The nitrogen vacancy (NV) center in diamond, an emerging quantum technology, is an atom-sized defect in diamond that is a remarkably versatile sensor of fields (magnetic, electric, strain), offering nanoscale spatial resolution, minimal back action, and operation over a wide range of temperatures. In this talk, I present a novel, state-of-the-art NV-based imaging tool we have developed. With this tool we have magnetically imaged vortices in an iron pnictide superconductor as well as skyrmion structures in Ta/CoFeB/Pt/MgO/Ta multilayers. Magnetic skyrmions are topologically stabilized magnetization structures with a number of properties that make them appealing for use in future high-density, low-power memory and logic devices. We use our images to reconstruct the skyrmion magnetization structure and importantly the nature of the domain walls, with important implications for the functionality of skyrmions in real devices, in particular the topological stability of the skyrmions and the current density required for their manipulation. I shall also describe our exploration of skyrmion pinning effects and discuss the relevance of these effects for manipulating skyrmions. Lastly, we have demonstrated NV-based conductivity imaging and benchmark the sensitivity and resolution of our conductivity probe using silver nanopatterned structures.

Spatiotemporal Magnetic Imaging at the Nanometer and Picosecond Scales

Greg D. Fuchs, Cornell

Research advancement in magnetoelectronics is challenged by the lack of a table-top magnetic imaging tools with the simultaneous temporal and spatial resolution that is necessary for characterizing magnetization dynamics in devices of interest. Although magneto-optical microscopy provides superb temporal resolution, its spatial resolution is fundamentally limited by optical diffraction. To address this challenge, we use heat rather than light as a vehicle to stroboscopically transduce a magnetic moment into an electrical signal while retaining picosecond temporal resolution. Based on this concept, we developed a spatiotemporal magnetic microscope using the time-resolved anomalous Nernst effect (TRANE) and the time-resolved longitudinal spin Seebeck effect (TRLSSE). We perform phase-sensitive magnetic imaging of both charge current density and local dynamic magnetization in magnetic metal (CoFeB) and a magnetic insulator (YIG) samples with submicron resolution. These dynamic imaging studies are quantitative and vector-resolved, providing new insights into spin torques exerted by the spin Hall effect. Finally, I will discuss our recent progress in achieving sub-100 nm spatial resolution using a scanned plasmonic antenna as a near-field heat source.

Quantum Control of Single Spins in Semiconductors

David D. Awschalom, Chicago

There is a growing interest in exploiting the quantum properties of electronic and nuclear spins for the manipulation and storage of information in the solid state. Such schemes offer new scientific and technological opportunities by leveraging elements of traditional electronics to precisely control coherent interactions between electrons, nuclei, and electromagnetic fields. Although conventional electronics avoid disorder, recent efforts embrace materials with incorporated defects whose special electronic and nuclear spin states allow the processing of information in a fundamentally different manner because of their explicitly quantum nature. Here we present recent developments that exploit precise quantum control techniques to explore coherent spin dynamics and interactions. In particular, we manipulate and measure the geometric (Berry) phase of a single spin in diamond using all-optical control techniques, and investigate the robustness of this control pathway to noise as well as its viability for implementations of photonic networks of quantum states. Separately, we find that defect-based electronic states in silicon carbide can be isolated at the single spin level with surprisingly long spin coherence times, can achieve near-unity nuclear polarization and be robustly entangled at room temperature. Finally, we identify and characterize a new class of optically controllable defect spin based on chromium impurities in the wide-bandgap semiconductors silicon carbide and gallium nitride.

Single Color Center Engineering in Nanodiamond for Quantum Key Distribution

Luke J. Bissell and Michael H. Check, AFRL/RXAN

Efficient quantum key distribution (QKD) requires a stable, room temperature single-photon source (SPS). Diamond color centers are defects substituted in the diamond lattice. They work as nearly ideal SPSs, having high emission rates at room temperature, and excellent photostability. We will fabricate diamond color centers at precise locations that can be harnessed as a robust, room-temperature SPS for QKD applications. A challenge to implementing diamond SPSs is the precise incorporation of a single color center in the crystal lattice. A bottom-up approach could be advantageous compared to top-down strategies by offering higher efficiency and robust control. We are developing molecular seed clusters capable of: (1) efficiently nucleating diamond nanocrystals, and (2) stoichiometric incorporation of single nitrogen atoms in the diamond lattice. We are accomplishing this by exploring seed induced nucleation. We have built a unique vertical plasma chemical vapor deposition (CVD) chamber to explore various nucleation seeds; in parallel we are using a commercial diamond CVD system. The wide range of functional groups that can be attached to seed clusters could provide a chemical means to incorporate single defects into nanodiamond. We are performing molecular dynamics modeling of diamond nucleation and vacancy diffusion to augment the experimental effort.

This approach can also controllably synthesize many other color centers that have infrared emission. An infrared SPS will allow device implementation in current telecom and free-space channels. Diamond color centers can also be used in quantum computing, magnetic sensing, and biotagging, thus supporting AF needs in computing, communication and human performance monitoring.

Manipulation of Electrons to Improve Thermoelectric Transport

Mona Zebarjadi, UVA

Thermoelectric (TE) devices can either convert heat directly into electricity or use electricity to pump heat. Despite their environmentally friendly operation, these devices are currently used only in niche applications. The main limiting factor for TE devices is their low efficiency limited by the TE figure of merit of known bulk materials. In this talk we look at two ideas to improve thermoelectric transport in different contexts. We first look at design of dopants invisible to conduction electrons in order to enhance electron mobility and thus the thermoelectric power factor for energy conversion and for refrigeration applications. Second, we introduce the active cooling mode of operation which is useful for electronic cooling applications. In this mode of operation, high power factor and high thermal conductivity materials are essential. We report record power factor observed in graphene based devices. Graphene’s large power factor and thermal conductivity, makes it an ideal candidate for electronic cooling applications. We discuss the effect of substrate on graphene thermoelectric properties and ways to improve its performance.

Transverse Thermoelectric Performance and Characterization: Towards Scalable Integrated Thermoelectrics

Matthew Grayson, Northwestern

By driving Peltier heat flow perpendicular to an applied current, transverse thermoelectric materials can achieve integrated thermal management at arbitrarily small length scales. Key advantages of transverse thermoelectrics arise due to their single-leg nature, which allow for thin-film thermoelectric coolers, tapered thermoelectric cryogenic coolers, and other unconventional geometries not possible with standard thermoelectrics. Since the differential equations that govern transverse thermoelectric heat flow are different from that of standard thermoelectrics, key performance metrics remained uninvestigated. This talk will show the first calculations of the coefficient of performance (COP) for transverse thermoelectrics (ratio of cooling power to input electrical power). It will also introduce a mobility spectrum analysis method that can rapidly determine the transport characteristics of these ambipolar materials that simultaneously exhibit electron and hole conduction.

Electronic, Thermal, and Unconventional Applications of 2D Materials

Eric Pop, Stanford

Two-dimensional (2D) materials have applications in low-power electronics and energy-conversion systems. These are also rich domains for both fundamental discoveries as well as technological advances. This talk will present recent highlights from our research on graphene, BN, and transition metal dichalcogenides (TMDs). We have studied graphene from basic transport measurements and simulations, to the recent wafer-scale demonstration of analog dot product nanofunctions for neural networks. We are also growing and evaluating the electrical, thermal, and thermoelectric properties of TMDs including MoS2, MoSe2, HfSe2, and WTe2. Recent results include imrpovements in contact resistance, enabling quasi-ballistic transport in ~10 nm scale transistors. We have also examined the anisotropic thermal conductivity of these materials, for unconventional applications to thermal switches and thermal routing. If time permits, I will discuss "bottom up" thermal management starting at dimensions comparable to the electron and phonon mean free paths (~100 nm), where quasi-ballistic heat flow effects dominate. Our studies reveal fundamental limits and new applications that could be achieved through the co-design and heterogeneous integration of 2D nanomaterials.

Ferroelectric and Multiferroic Thin Films for Tunnel Junction Applications

Ram S. Katiyar, UPR

Magnetoelectric multiferroics combine ferromagnetism and ferroelectricity giving the possibility of controlling polarization P with a magnetic field H or magnetization M with an electric field E resulting in the realization of four-state logic devices. A way to exploit these properties is to use them in multiferroic tunnel junctions (MFTJs). We have recently discovered new single phase room temperature multiferroics by preparing solid solutions of PZT with other lead based perovskites. One such compound is Pb(Zr0.53Ti0.47)0.60(Fe0.5Ta0.5)0.40O3 (PTZFT) which is a promising single-phase room temperature multiferroic and we have grown thin films of it and that of PZT for tunnel barrier applications utilizing pulse laser deposition technique. Piezoforce microscopy measurements on all 3 -7 nm thick films showed clear and reversible out-of-plane phase contrasts, indicating ferroelectric character of ultra-thin films. The transport properties for Pt/PZT(7nm)/LSMO heterostructures showed a significant variation in tunneling electroresistance (TER) ratio with H, changing from 57 (at 0 G) to 110 under 10 kG. We attributed this enhancement near the PZT/LSMO interface under H. These and the tunneling experiments with multiferroic thin films will be presented.

Local Picoscale Disorder of Periodic Lattice Displacements in a Stripe-Ordered Manganite

Lena F. Kourkoutis, Cornell

Periodic lattice distortions (PLDs) and the coupled charge density wave (CDW) states are intertwined with high Tc superconductivity, colossal magnetoresistance, and metal-insulator type transitions in strongly correlated material systems such as cuprates, manganites, and 2D dichalcogenides. Phenomenologically, their interactions are varied, from competition with high Tc superconductivity, to spatially inhomogenous coexistence with magnetic phases, to mediation of electronic transitions. Direct observation of local symmetry, topology and disorder of PLDs is therefore paramount. Here, I will discuss our approach of combining aberration-corrected scanning transmission electron microscopy with a novel picometer-precision atomic tracking method to directly map the local picometer scale PLD structure of the hole-doped, stripe-ordered manganite Bi1-xCaxMnO3. We uncover intrinsic disorder in the form of topological defects and shear deformations of the displacement field, and characterize an attendant elastic response in both the phase and amplitude of the PLD. Further, we establish that close to Tc the modulation forms nanoscale domains which locally break the fourfold rotational symmetry of the underlying lattice, in spite of global rotational symmetry preservation.

<u>Probing the Atomic Origins of Electronic States in Low Dimensional Materials and Interfaces</u>

Pinshane Huang, UIUC

Recent advances in the synthesis, isolation, and manipulation of individual atomic layers has opened a new era of high quality electronic devices at molecular length scales. Devices based on 2D materials have attracted intense interest because their small size enables the miniaturization of electronics, as well as the creation of entirely new device technologies based on quantum physical phenomena. In systems only a few atoms thick, the location and interactions of every atom can impact device performance. A critical step in realizing the potential of molecular-scale electronics is therefore the development of methods to understand and control two-dimensional materials and their interfaces at the level of single atoms. Here, we propose to use state-of-the-art, quantitative methods in transmission electron microscopy and spectroscopy to develop a coherent framework for understanding and controlling the atomic origins of electronic states in 2D materials and devices. These electron microscopy techniques will allow us to simultaneously probe local band structure, composition, and bonding with nearly single atom precision; we will use these abilities to test new routes to design and engineer emergent properties in 2D materials through control of their phase structure and interfaces. The proposed research possesses transformative technological potential because it aims to transmute what is currently a major challenge: the ability of 2D materials to be strongly altered by changes in local structure and environment, yielding a honed tool to achieve new and tailored properties in molecular-scale devices. The successful completion of the proposed work will speed the development of new technologies based on molecular-scale materials, advance the rational design of emergent properties at materials interfaces, and hold high potential for discovery of novel physical phenomena. These goals tie directly into Air Force objectives that support the development of atomic and molecular-scale devices for ultra-dense, high-performance electronics.

<u>Valley Magnetoelectricity in Single-layer MoS2</u>

Kin Fai Mak, Penn State

Magnetoelectric effect (MEE), the phenomenon of inducing magnetization by application of an external electric field or vice versa, holds great promise for magnetic sensing and switching applications. Studies of the MEE have so far focused on the control of the electron spin degree of freedom (DOF) in materials such as multiferroics and conventional semiconductors. In this talk we will discuss a new form of MEE based on the valley DOF in two-dimensional (2D) Dirac materials. By breaking the three-fold rotational symmetry in single-layer MoS2 via a uniaxial stress, we have demonstrated the pure electrical generation of valley magnetization in this material, and its direct imaging by the magneto-optical Kerr rotation microscopy. The dependence of the out-of-plane valley magnetization on magnetic field, current density, and current directions are fully consistent with a theoretical model of valley magnetoelectricity driven by Berry curvature effects. Furthermore, the effect persists at room temperature, opening possibilities for practical valleytronic devices.

NanoSQUID-on-a-tip for Scanning Magnetometry and Thermometry

Andrea F. Young, UCSB

Nanoscale scanning probes are an essential tool for probing quantum materials and devices, offering spatially resolved access to basic electronic properties. Of particular value are nanoscale probes which probe new observables, or old observables in new regimes. I will discuss ongoing efforts in my lab to develop scanning nanoSQUID-on-tip (nSOT) microscopy, which offers high magnetic, thermal, and topographic sensitivity at low temperatures and high magnetic fields. Using a self-aligned deposition at cryogenic temperatures, nanoSQUIDs are fabricated on the end of quartz pipettes, resulting in effective diameters between 40-200nm. Previous measurements have demonstrated single spin sensitivity and microkelvin local thermometry at 4K, which we intend to extend a further order of magnitude lower in temperature. Part of our plans include extending the practical sensitivity of nSOTs via robust topographic feedback.

Tuning Electronic Properties by Uniaxial Strain

Abhay Pasupathy, Columbia

Uniaxial strain when applied to a material causes changes to band gaps, effective masses and scattering rates. Strain also can cause the breaking of in-plane lattice symmetries and even change the structural phase of the material. Typical 3D solids are able to withstand only a percent or two of strain before fracturing, but two-dimensional materials such as graphene are able to withstand several percent strain before yielding. I will discuss strategies by which we can systematically apply tensile and compressive strain to various two-dimensional materials all the way to their yield point and monitor their response in optics, transport and scanned probe microscopy. I will demonstrate the new techniques on semiconducting transition metal dichalcogenides (where we can tune the band gaps significantly by large strain as monitored optically), topological semimetals (where we can tune Fermi surface properties using strain in transport) and superconductors (where we can break rotational symmetry and induce a nematic response by applied strain).

Paper and Circuits, only Atoms Thick

Jiwoong Park, Chicago

2D layered materials are like paper: they can be colored, stitched, stacked, and folded to form integrated devices with atomic thickness. In this talk, I shall discuss how different 2D materials can be grown with distinct electrical and optical properties (coloring), how they can be connected laterally to form patterned circuits (stitching), and how their properties can be controlled by interlayer rotation (twisting).

FY15 MURI: Foldable and Adaptive Two-dimensional Electronics

Han Wang, USC

Engineer folding of van-der-Waals materials and devices into flexible and conformal structures to enable mimicking of nature in its ability to use adaptable features and develop complex systems. Control folding of 2D materials to obtain antennas with unprecedented tunability. Build nano and microscopic 3D structures for advanced metamaterials, as well as flexible electronic systems with unprecedented robustness in the face of mechanical accelerations, deformations and vibration. Enable a new paradigm for the fabrication of the next generation of electronics systems, mimicking the complexity of biological cells to enable nanoscale electronic and photonic systems with functionalities impossible in planar systems.

Reconfigurable, Corrugated Graphene Plasmonics

SungWoo Nam, UIUC

Graphene plasmons are rapidly emerging as a technologically viable and significant platform for rapid electrical manipulation and subwavelength confinement of light. However, the key challenge in graphene plasmonics research has been that most of the currently available strategies are unable to excite plasmons at the near-infrared and visible wavelengths (i.e. higher energy regimes), which is needed for electro-optics applications. In this presentation, we report a tunable plasmon platform based on corrugated graphene which takes advantage of micro- to nano-scale graphene topographies to enable excitation of surface plasmon polaritons upon electromagnetic radiation. I will present our progress on controlled fabrication of corrugated graphene structures with precise dimensions and also atomic force microscopy-infrared imaging of corrugated graphene plasmons. I also shall share our computational and analytical models to underscore the fundamental physics of corrugated graphene plasmonics, and also discuss the mechanical reconfigurability of plasmonic resonance of corrugated graphene plasmonics. We believe that our new approach will yield a deeper understanding of the nature of plasmons in corrugated graphene and will produce a technique to generate low loss, tunable, near-infrared plasmons in graphene.

Quantum Transport and Optoelectronics with van der Waals Heterostructures

Pablo Jarillo-Herrero, MIT

Two-dimensional materials, such as graphene, hexagonal boron nitride (BN), and ultra-thin transition metal dichalcogenides (TMDs), exhibit a wide variety of electronic and optical phenomena that are very different from their bulk counterparts. The quantum size effect vastly alters the electronic band structure, leading to novel electronic properties and light-matter interactions. Moreover, the recent progress in the assembly of these 2D materials to form van der Waals (vdW) heterostructures with ultraclean interfaces has led to an emerging field in condensed matter physics focusing on versatile composite systems with distinct electronic and optoelectronic properties from their original constituents. In this talk I will describe our current efforts to investigate new physics and device principles in these vdW heterostructures. In particular I will focus on recent experiments on ultra-thin 1T-WTe2, a novel TMD which exhibits tunable magnetoresistance and a tunable semi-metal to metal transition with potentially interesting properties for nanoelectronics.

FY15 MURI: Atomically-Thin Systems that Unfold, Interact and Communicate at the Cellular Scale

Jiwoong Park, Chicago

The objective of this MURI program is the development, control and application of atomically thin, membrane-like integrated circuits and devices, which can fold, unfold, interact and communicate at the cellular/subcellular scale. Such ultrathin, substrate-free circuits will be over a 1,000 times more flexible and bendable than current flexible electronics, enabling folded, 3D structures with nanoscale features with previously unexplored mechanical, physical and surface properties. These novel properties offer revolutionary applications in health, biology, and remote and dispersable sensing with significant DoD relevance; examples include “wearable” and foldable electronics at the cellular and subcellular level and microscopic deployable structures whose surface area can increase by several orders of magnitude upon actuation. In order to pursue these goals, our MURI team explores and solves fundamental scientific and engineering challenges in the fabrication, transformation, communication and integration/deployment of systems constructed from atomically-thin, flexible, substrate-free films of 2D layered materials (2DLMs). We generate wafer-scale 2DLM building blocks and produce 2DLM-based integrated circuits and devices in large quantities. We develop a suite of general schemes, including Kirigami, optical & magnetic actuations and surface-induced self-folding, to reversibly and controllably bend and fold 2DLM structures into pre-programmed 3D structures at micron and nanometer length scales.