Frontiers in Quantum Materials and Devices Workshop

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ABSTRACTS

Dynamics of Magnetic Skyrmions - Toward Skyrmionics -

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Nature and dynamics of magnetic skyrmions have been investigated for chiral magnets, correlated oxide films and ferromagnetic topological insulators in terms of real-space observation by Lorentz transmission electron and magnetic force microscopies, topological transport properties, and micromagnetic simulations. Key functions toward skyrmionics are discussed.

Spintronic Nano-Devices for Nonvolatile VLSIs

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I review physics and materials science of nanoscale spintronic devices being developed for nonvolatile VLSI [1]. VLSIs can be made high performance and yet standby-power free by using magnetic tunnel junction, a two-terminal spintronic device, in combination with current CMOS technology. The scalability of perpendicular magnetic tunnel junctions utilizing CoFeB-MgO [2] is passing the 20 nm dimension; the smallest and well characterized ones now reaching 11 nm [3, 4]. Another important entity is three terminal devices utilizing current-induced domain wall motion [4] and its recent variants using spin-orbit torque [5]. In the end, I will discuss electric-field switching of magnetization in perpendicular CoFeB-MgO magnetic tunnel junctions [6].

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Sculpting Nanostructures with Electrons for Nano And Biotechnology

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In 400 BC, Democritus hypothesized that matter is made of atoms that are miniscule quantities of matter. Today, we have transistors at the size scale of several atoms soon to be integrated into everyday computer chips. Understanding, shaping and manipulating matter at atomic scale remains one of the major contemporary challenges in science and technology. In this respect, electron beams constitute the power tools to shape materials with atomic resolution inside a transmission electron microscope (TEM). I will describe experiments where we push the limits of device size to atomic scale, and expand their function and precision, while addressing fundamental questions about structure and properties at nanometer and atomic scales. Experiments are performed *in situ or ex situ TEM*. *In situ TEM* experiments include the study of electrons flow in nanowires in novel two-dimensional materials as a function of their structure as they are nanosculpted down to zero width. We reveal the electrical current scaling with size and atomic structure and develop methods to realize pristine and highly conducting sub-10-nm-wide wires. *Ex situ TEM* include the ultrafast, all-electronic detection and analysis of biomolecules or nanoparticles by threading them through tiny holes – or nanopores – in thin membranes, including efforts towards mapping a human genome under 10 minutes. As particles are driven through nanopores in solution, they block the current flow resulting in current reductions from which particle's physical and chemical properties are inferred. Measurements of DNA, proteins, microRNA and other biomolecules as well as solid-state particles will be highlighted, where we improved the temporal and spatial resolution and sensitivity. I will also describe alternative uses of nanopores such as electrically controllable chemical nanoreactors, and explore the use of nanopores in two-dimensional nanowires to highly localize and probe molecules.

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Properties of 2D Materials in the Ultraclean Limit

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Two-dimensional materials offer a wide range of outstanding properties but are highly sensitive to disorder from the environment. We have developed techniques to stack 2D materials on top of each other to create 'van der Waals Heterostructures' with nearly perfect interfaces, and to achieve high-quality contacts to the one-dimensional edge of buried layers. These techniques provide an ideal platform to study 2D materials in the ultraclean limit. Recent results in this area will be discussed, including: 1. Near-ideal performance in graphene and applications in plasmonics, photonics, and light emission; 2. Greatly improved measurements of the electrical transport in semiconducting MoS_2; 3. Measurements of air-sensitive 2D materials including phosphorene, TaS_2, and $NbSe_2$.

System-Level Applications of Two-Dimensional Materials: *Challenges and Opportunities*

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Two dimensional materials represent the next frontier in advanced materials for electronic applications. Their extreme thinness (3 or less atoms thick) give them great flexibility, optical transparency and an unsurpassed surface-to-volume ratio. At the same time, this family of materials has tremendously diverse and unique properties. For example, graphene is a semimetal with extremely high electron and hole mobilities, hexagonal boron nitride forms an almost ideal insulator, while MoS_2 and other dichalcogenides push the limits on large area semiconductors.

The growth of these materials over large areas has allows their use in numerous system-level demonstrators. For example, the zero bandgap of graphene and its ambipolar has been used in a wide variety of rf and mixed applications, including frequency multipliers, mixers, oscillators and digital modulators. At the same time, the wide bandgap of MoS_2 in combination with advanced fabrication technology has enabled its use in memory cells, analog to digital converters and ring oscillators with orders of magnitude better performance than other materials for large area applications. These and other examples will be discussed to highlight the numerous new opportunities of 2D materials.

Atomic-Level Control of Quantum Material Growth: From Quantized Anomalous Hall Effect to Interface-Enhanced High Tc Superconductivity

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Molecular beam epitaxy (MBE) has been well-known as a powerful technique for preparing semiconductors and heterostructures. Combining MBE with scanning tunneling microscopy (STM) and angle resolved photoemission spectroscopy (ARPES) can even push its power to an unprecedented level in material quality control. We apply MBE-STM-ARPES to topological insulators and high Tc superconductors, which have recently attracted extensive attention. We show how quantized anomalous Hall effect could be achieved by atomic-level control of band-engineered and magnetically doped topological insulators with MBE-STM-ARPES. We then show the discovery of interface enhanced high temperature superconductivity in single unit-cell FeSe films on $SrTiO_3$ using the same approach. Implications on exploring other exotic quantum phenomena such as Majorana fermions in topological insulators and on searching for new high temperature superconductors will be discussed.

Engineering Topological Quantum States: 1D and 2D case

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I will present results on exotic bound states in one-dimensional (Majorana fermions and parafermions) and two-dimensional (edge states in topological insulators) condensed matter systems that have attracted wide attention due to their promise of non-Abelian statistics believed to be useful for topological quantum computing. I discuss systems in which topological properties could be engineered per demand. For example, Majorana fermions can emerge in hybrid systems with proximity pairing in which the usually weak Rashba spin-orbit interaction is replaced by magnetic textures. Here, I will discuss candidate materials such as semiconducting nanowires [1-2], graphene nanoribbons [3], atomic magnetic chains or magnetic semiconductors [4]. One further goal is to go beyond Majorana fermions and to identify systems that can host quasiparticles with more powerful non-Abelian statistics such as parafermions in double wires coupled by crossed Andreev reflections [5,6]. In the second part of my talk, I will focus on 'strip of stripes model' consisting of weakly coupled one-dimensional wires [6-8], where interaction effects in the wires can be treatednon-perturbatively via bosonization. I will demonstrate that such systems can exhibit the integer or fractional quantum Hall effect [6], spin Hall effect [7], and anomalous Hall effect [8]. In the fractional regimes, the quasiparticles have fractional charges and non-trivial Abelian braid statistics.

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Revealing the Empty-State Electronic Structure of Single-Unit-Cell FeSe/SrTiO3

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When a single layer of FeSe is grown on a SrTiO3 substrate, its superconducting Tc is enhanced by a factor up to 10 or more. Furthermore, this heterostructure has been predicted to undergo a topological phase transition under some conditions. Understanding these remarkable mechanisms will depend crucially on knowledge of the band structure of both filled and empty states. We use scanning tunneling microscopy, and particularly quasiparticle interference imaging, to reveal the empty state band structure of single-layer FeSe/SrTiO3. We investigate the orbital structure of near-Fermi-level bands, and comment on their relationship to superconductivity.

MoS_2 and Dichalcogenide-Based Devices and Hybrid Heterostructures

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MoS_2 and transition metal dichalcogenides have opened numerous research directions and potential applications for this diverse family of nanomaterials. The combination of these 2D materials in heterostructures can result in a huge number of potentially interesting new materials. Most of the attention in this field is focused on heterostructures composed of different 2D materials. In my talk, I will present some of our recent efforts in this direction, oriented towards realizing combinations of 2D and 3D materials into van der Waals heterostructures. I will report on high-performance photodetectors based on 2D/3D heterostructures that can operate with internal gain and high sensitivity. Next, I will give an update on our efforts to realize high-performance electrical circuits based on TMD materials.

Quantum Information with Nuclear Spins in Diamond

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The nitrogen vacancy (NV) center in diamond is a promising candidate to realize extended quantum networks of nuclear spins. On the one hand, NV nodes can be linked over large distances by entangling their electron spins through an optical interface, as we recently demonstrated [1,2]. On the other hand the electron spin couples to nuclear spins in the environment making it possible to control multiple qubits within the nodes [3].

In this talk, I will discuss our latest progress in extending our control over such multi-qubit nodes. We exploit the NV electron spin to detect, polarize, and control multiple individual nuclear spins and construct non-destructive multi-qubit measurements. We then use these tools to realize quantum error correction by stabilizer measurements and fast feedback. Together with entanglement between remote NV centers, these results provide a basis for error-corrected quantum networks based on spins in diamond.

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The Battle to Control Diamond

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Diamond possesses remarkable physical and chemical properties, and in many ways is the ultimate engineering material, but its use until relatively recently has been limited by the lack of scalable techniques for manufacture, processing and integration. This paper will review and summarize key progress in fabrication techniques utilizing chemical vapour deposition (CVD), processing using mechanical and chemical methods and solutions for integration. It will present several case studies that include polycrystalline diamond for high power CO_2 optics for applications that include EUV to advanced cooling solutions for rf electronics and manipulation of optical signals at single-photon level in single crystal CVD diamond using nano-cavities and waveguides.