Topological Materials Synthesis and Device Applications

Topological materials such as topological insulators (TIs) and Dirac and Weyl semimetals are an emergent class of quantum materials whose properties are protected by symmetry and topology of the bulk band structures. Therefore, these properties are robust against scattering, leading to near dissipationless carrier transport. In particular, in topological insulators, the timer-reversal symmetry protected surface states exhibit spin-momentum locking where the electron spin is locked to momentum, and hence an unpolarized charge current creates a spontaneous spin polarization.

The goals of this program is to synthesize topological materials by molecular beam epitaxy (MBE), and their heterostructures with magnetic materials, to demonstrate control and manipulations of spin and charge transport through electrical and optical means. Of particular interests are the exploration of device applications such as nonvolatile magnetic topological memory that utilize the current generated spins in TIs and Weyl semimetals to switch the magnetization of a ferromagnet via spin orbit torque. Physical processes such as spin transport at heterointerfaces and spin dynamics will be investigated to optimize efficiency and demonstrate prototype devices that are relevant in next generation low power electronics and spintronics, information processing, and in-logic memory.

Extensive facilities exist including a newly installed cluster system integrating MBE (equipped with ebeam sources), sputter, and SPECS angle-resolved photoemission spectroscopy (ARPES) system, with an Omicron INFINITY scanning tunneling microscope (STM) to be added in 2024. Electrical transport, magneto-optical and structural/magnetic characterization are also available, as well as a class 100 cleanroom for nanofabrication.

Reference:

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Key words:
Topological insulator, Dirac semimetal, Weyl semimetal, spintronics, spin-momentum locking, spin transport, molecular beam epitaxy, angle-resolved photoemission spectroscopy

Spin-Injection, Transport, and Localization in Graphene and Group IV Materials

This program addresses spin-dependent carrier properties in group IV materials (graphene, Si, Ge), accessed by transport, optical, or magnetic measurements. The principle objective is to develop a fundamental understanding of magnetoelectric phenomena in group IV nanostructures to enable sensing, information storage, and processing beyond Moore’s law. This effort will develop novel phenomena such as the inverse spin Hall effect to control spin-dependent processes, novel materials such as functionalized graphene for spin transport, and determine spin properties of high mobility Si-Ge two dimensional electron gas heterostructures.

We are interested in determining fundamental properties including spin lifetimes and scattering mechanisms, as well as in demonstrating prototype device concepts such as novel magnetic tunnel junctions (MTJ), spin-LEDs, or spin-RTDs. Our recent work has shown that 2D materials such as graphene can be used as a novel tunnel barrier in vertical transport MTJ structures, in all-graphene lateral spin-valves, or for spin injection and detection in silicon planar and nanowire structures.

One approach focuses on tunnel barrier injection from a ferromagnetic metal contact with detection accomplished by a second magnetic contact in a non-local spin valve geometry. A second approach focuses on polarization-dependent optical probe/analysis techniques. The transport channel may be graphene or another 2D material, or a conventional semiconductor such as silicon. Graphene is especially attractive as a transport channel due to the long spin lifetimes and diffusion lengths predicted by theory, although such values have proven a challenge to realize experimentally. One goal of this program is to understand and solve these issues. Functionalized graphene may be an important component, as it can serve as an insulating tunnel barrier, and also exhibits magnetic properties, suggesting its use as a spin injecting/detecting contact.

Extensive facilities exist for epitaxial growth, transport, magneto-optical studies, structural/magnetic characterization (e.g., AFM/MFM, magnetometry), and e-beam and photolithographic sample fabrication.

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Friedman AL, et al: Hydrogenated Graphene as a Homoepitaxial Tunnel Barrier for Spin and Charge Transport in Graphene, ACS Nano 9: 6747, 2015

Keywords:
Spin injection; Spin transport; Magnetoresistance; Graphene; Silicon; Magnetic tunnel junction; Tunnel barrier; Spin valve;

Magnetic and Structural Characterization of Magnetic / Semiconductor Interfaces

This research focuses on the growth and characterization of magnetic/semiconductor heterostructures in order to understand the role of the interface in mediating such properties as magnetic film anisotropy, spin-polarized charge transport, and magneto-optical effects. Knowledge of the evolving physical and chemical structure of both the interface and magnetic film is important in understanding these systems. Samples are prepared utilizing a variety of thin-film growth facilities, including a multiple growth chamber molecular beam epitaxy (MBE) machine, which permits the study of magnetic films deposited directly on MBE-grown surfaces of II-VI or III-V semiconductor epilayers. These epilayers offer a wide variety of controllable surface reconstructions and chemistry, enabling us to systematically study the role of the interface in determining the macroscopic properties of these technologically important heterostructures. Each chamber includes either reflection high-energy electron diffraction or low-energy electron diffraction with video data acquisition equipment. Post-growth characterization facilities include x-ray diffraction, magnetometry (superconducting quantum interference device and vibrating sample), magneto-optics, transport, ferromagnetic resonance, and extensive computer modeling programs of the electron forward scattering data.

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Keywords:
Electron scattering; Heterostructures and heterojunctions; Interfaces; Magnetic films; Metal films; Molecular beam epitaxy;

Ferromagnetic Semiconductors: An Emerging Spintronic Materials Technology

Ferromagnetic semiconductors are an exciting class of materials in which ferromagnetism and semiconducting properties coexist and are intimately connected. These materials combine the key aspects of two dominant technologies: the *nonvolatile character* inherent in magnetic materials, and the optical and band-gap engineering properties of current semiconductor devices. In addition, they are both lattice-matched and band structure-matched to a host semiconductor family, and open many new opportunities for spintronic device structures. The discovery of ferromagnetism in III-Mn-V compounds such as $Ga_{1-x}Mn_xAs$ is especially notable, and provides the ingredients for a potential spintronic device technology in the technologically dominant GaAs/AlAs system.

The more recent discovery of single monolayer direct gap semiconductors in the transition metal dichalcogenide (TMD) family, such as MoS2 and WS2, provides exciting new platforms in which to realize magnetic behavior through doping with elements such as Mn or Cr. In addition, theory predicts magnetic order to exist in single monolayer ScX2 (X = O,S,Se,Te) samples and other materials which have yet to be synthesized. Thus the TMD family and other 2D materials beyond graphene offer exciting new opportunities for achieving ferromagnetically ordered semiconducting materials.

Such ferromagnetic semiconductors may serve as either the source of spin polarized carriers (the spin injector) or the semiconducting transport medium. As a class of materials, ferromagnetic semiconductors are in their infancy; a number of issues exist which must be addressed prior to realizing their expected potential. The broader goals of this research are (1) to improve and understand these materials, (2) to develop new ferromagnetic semiconductor compounds based on new hosts such as the TMDs, and (3) to develop efficient electrical spin injection/transport methods and demonstrate proof-of-concept quantum spin devices based on these materials.

Extensive facilities exist for the growth (MBE, CVD) and characterization of these materials, including Raman, photoluminescence, magneto-optic, transport (charge and spin), structural/magnetic (e.g., AFM/MFM, x-ray diffraction, magnetometry) and clean room processing (e-beam and photolithography).

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Keywords:
Ferromagnetic; Magnetoelectronics; Quantum spin electronics; Semiconductors; Spin injection; Spin transport; Spintronics;

2D Materials and van der Waals Heterostructures

The objective of this research is to fabricate single- to few-layer samples of materials which exhibit a layered character in the bulk or are theoretically predicted to be stable as single layers, and determine their fundamental properties. Just as graphene exhibits dramatically different properties than graphite, theory and initial experiment indicate that the properties of other single monolayer materials will be strikingly different from their bulk counterpart. For example, single layer MoS_2 is a direct gap semiconductor with strong room temperature luminescence, while two-layer and bulk MoS_2 are indirect gap semiconductors. Theory has predicted similar dramatic property evolution in many other single layer transition metal dichalcogenide materials (e.g., WS_2, $MoSe_2$, VTe_2) that include metals, insulators, semiconductors, ferromagnets, and even potential superconductors, but the basic science is not well understood.

A second objective is to develop a new paradigm for heterostructures unconstrained by lattice match by systematically stacking single monolayers of these two dimensional materials in a sequence of our choosing to form a **van der Waals heterostructure**. We will determine and understand the new electronic and optical properties these heterostructures exhibit, and develop a predictive capability to fabricate them with a property set of our design. The weak interlayer bonding enables a new approach for materials by design through van der Waals epitaxy of non-lattice matched 2D materials, an avenue not possible with traditional epitaxial approaches dominated by out-of-plane bonding. This represents a bottom up approach towards design and fabrication of new materials that do not exist in nature, and a new class of atomic-scale heterostructures that are expected to exhibit properties and functionality beyond the limits of their bulk counterparts.

In this research, single layer and van der Waals heterostructure samples will be fabricated either by exfoliation from bulk material or by direct synthesis using techniques such as chemical vapor deposition or molecular beam epitaxy, and a wide spectrum of experimental techniques employed to determine the fundamental properties. Extensive instrumentation exists for structural, transport (charge and spin), and optical characterization. Because each constituent atom participates in electron transport while also being a surface atom, these monolayer materials are particularly sensitive to their environment and are obvious candidates for gas/chemical sensors or surface functionalization for biological applications.

Through combined fabrication and theory efforts, this program will enable discovery of materials with new properties and provide avenues to tune the fundamental excitations. The scientific goals have relevance to low-power electronics, information processing, chemical/biological sensors, photo-detection, and energy harvesting.

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Jonker B: Graphene and Monolayer Transition-Metal Dichalcogenides: Properties and Devices, Journal of Material Research JMR-2015-0727.R1; Focus Issue Review Article: Two-Dimensional Heterostructure Materials, 2016

Keywords:
Transition metal dichalcogenides; 2D materials; van der Waals, Beyond graphene; Spintronics;

Spin dynamics of charge to spin conversion in topological insulators.

The objective of this research is to understand the spin dynamics of charge to spin conversion in topological insulators. Charge to spin conversion is expected to be ultrafast, since it relies on band structure details as opposed to spin dependent scattering in heavy metals. Little is known about the spin dynamics of topological insulators.

You will participate in a group effort to experimentally observe spin dynamics of topological insulators, using optical and electrical means.

A second objective is to combine the ultrafast spin dynamics of topological insulators with antiferromagnets. Here the goal is to switch the Neel vector of an antiferromagnetic material at near THz frequencies.

Through combined fabrication, characterization and theory efforts, this large program at NRL will enable topological devices. The scientific goals have relevance to maximize efficiency in the next generation of low power computing technology, information processing, on chip THz communication, in-logic memory.

Keywords:
Topological insulator; Antiferromagnet; Spin dynamics; Spintronics; Spin torque; THz; Nano oscillator

Metamagnetic Transitions as a Route Towards Fully Controllable Magnetism

FeRh is a unique material that changes its intrinsic magnetic order at an ambient temperature of 360 K; no other similar cases are known so far. This highly unusual metamagnetic transition suggests a possibility to switch between the two magnetic states by external perturbation, such as strain, potentially offering completely new avenues in device design.

Our preliminary results have proven that this magnetic phase transition can be further tuned with ion implantation. Nonetheless, very little is known about the basic properties or nanoscale effects of these phenomena.

You will be working in a group of experimental and theoretical scientists to study the fundamental physics of the metamagnetic transition of FeRh.

The outcome of the project will be a fundamental understanding of the physics that underlies the strain-imposed metamagnetic phase transition, the role that structural confinement has on these properties, and, eventually, an electrostatically controlled magnetic material that achieves logical switching efficiencies that exceed current electronic device technologies.

Keywords:
Metamagnetic transition, strain, FeRh, spintronics, antiferromagnet, ferromagnetism.