Dear Students,

The Madhavan laboratory is currently looking to take on two graduate students in the Summer/Fall. In the following paragraphs I describe our current materials of interest and some details about the lab. Please do not hesitate to get in touch if you have questions.

Regards,

Vidya Madhavan

**Introduction to Topological Materials**

In 2007, in an important scientific breakthrough, three-dimensional topological insulators (3D-TIs) were theoretically predicted and almost simultaneously experimentally discovered\(^1\),\(^2\),\(^3\),\(^4\),\(^5\). Topological insulators (TIs) are semiconductors with strong spin-orbit (SO) coupling. As we go across the periodic table to heavier elements, the strength of SO coupling increases which influences bulk band structure. Eventually the positions of the bulk valence and conduction bands get inverted in energy (band inversion), leading to a topologically non-trivial material. This non-trivial band topology dictates the presence of surface states (SS) with unique characteristics where electrons behave like zero mass (massless), relativistic fermions. A key element in the discovery of TIs was the application of the ideas of topology and symmetry to condensed matter systems.

The idea of viewing physical systems from the perspectives of symmetry and topology is not new. Half a century ago, the mathematician Roger Penrose applied the arguments of topology to cosmology and proved that black holes could originate from the collapse of very massive stars. The essence of the topological perspective is that the existence of certain elements or states in a geometric object (existing in Euclidean or Hilbert spaces) is dictated purely by the topology of that geometric object. This is beautifully exemplified by the well-known `hairy ball' theorem, which states that it is impossible to comb the hair flat on a ball without incurring at least one cowlick. Interestingly (similar to the behavior of other topological invariants) the hairy-ball theorem applies to any shape that can be obtained by continuously (adiabatically) deforming a sphere. The application of the ideas of topology to condensed matter systems is also not new. Thoules and others\(^6\),\(^7\) used the topological framework to describe the integer and fractional quantum Hall effects. However, with the discovery of symmetry protected topological states in TIs, these ideas have entered the mainstream terminology of condensed matter physicists. Using the concepts of topology, we have been able to discover new phases in old materials that we did not know existed.

The most interesting aspect of topologically non-trivial materials such as 2D and 3D-TIs is that they are required to have special states at their boundaries, which act as a bridge between the topologically non-trivial bulk and the trivial outside. For two-dimensional (2D) TIs these boundary modes would be 1D edge states and for 3D-TIs the boundaries would host 2D surface states. These 1D and 2D states have extraordinary properties. They have linear Dirac dispersion (the electrons behave like massless relativistic Fermions i.e., Dirac Fermions) and they have chiral spin texture (the spin of the electron is locked perpendicular to its momentum). Due to spin-momentum locking, Dirac electrons can carry spin-currents and are prohibited from back scattering by normal impurities that preserve time reversal symmetry. These properties combine to make topological materials fascinating both for their unique and fundamentally different states as well as their potential for use in applications ranging from spin-plasmonics and spintronics to quantum computation.
The discovery of TIs set off a flurry of experiments on topological phases of matter. Most of the initial experiments were done on the Z2 class of 3D-TIs which host an odd number of Dirac cones protected by time-reversal symmetry. In 2011, a new class of topological materials (TM)s were discovered\textsuperscript{8,9,10} which while trivial according to the Z2 classification, are however topologically non-trivial with a distinct non-trivial mirror Chern number of ±2. Similar to TIs, band inversion results in exotic SS. Unlike TIs however, the Dirac nodes are protected by a crystalline symmetry (such as mirror symmetry) and this class of TMs has therefore been dubbed topological crystalline insulators (TCIs). This discovery has opened up a whole new category of TMs which host Dirac surface states and together, TIs and TCIs have the potential to not only help us realize exotic particles like Majorana fermions but also to bridge the gap between TMs and applications.

One of the most interesting directions for this field is the possibility of discovering and exploring complex phases with non-trivial topology. Similar to the case of non-interacting systems, applying the perspectives of topology to materials with correlations is predicted to reveal fundamentally new ground states and phenomena. Topological superconductivity, Majorana modes, and Weyl semimetal phases are all examples of novel states predicted to occur in TMs under special circumstances. The experimental realization and investigation of these complex phenomena has only just begun with only a few initial reports of observations of a subset of these phases.

\textit{Lab information:}

We have published extensively in the areas of superconductivity as well as topological materials. A few publications are attached. The lab’s capabilities include advanced low temperature scanning tunneling spectroscopy as well as Molecular beam epitaxy growth. With these capabilities we can build strain and gating devices and well as thin film heterostructures (TI and superconductor, TI and ferromagnet) and study the resulting physics at the nanoscale. We are currently interested in exploring the next generation of topological materials and has openings in the following projects:

1. \textit{Topological Superconductivity}
2. \textit{Proximity induced superconductivity and Majorana Fermions}
3. \textit{Topological superconductivity in 3D Dirac and Weyl Semimetals}
4. Controlling topological materials at the nanoscale with in-situ strain
5. Correlated, spin-orbit coupled oxides

This summer and Fall (2015) will be an exciting time to join the group. We will be setting up a brand new laboratory in the basement of MRL. We expect to be assembling the scanning tunneling microscopes as well as the MBE system. This phase will only last one or two months and presents a unique opportunity for students to see the details of how instruments are put together. We expect to start growing thin films and measuring thin films and single crystals by October 2015.

This summer and fall, the lab will have two students and two post-docs. I am currently looking to take on two more students. Interested students can contact me directly by email: \texttt{vm1@illinois.edu}. I will be interviewing students in the middle of March so please contact me before that if you are interested. I look forward to hearing from you!