Research Statement

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My research interests center on developing nanoscale epitaxial materials for spintronic device applications. Materials with strong spin-orbit coupling and conductive surface states, such as bismuth chalcogenide (Bi_2Te_3 and Bi_2Se_3) topological insulators, bismuth antimonide ($Bi_{1-x}Sb_x$) topological insulators, and quantum confined bismuth (Bi) thin films, are promising for emerging devices that require conversion between electrical charge currents and spin-polarized currents. Potential applications for these materials include the detection of electron spins in spin-based electronics, the efficient control of magnetization direction for non-volatile memory, and thermoelectrics based on the spin-Seebeck effect.

My Ph.D. research focuses on the growth of Bi and $Bi_{1-x}Sb_x$ thin films, their transfer to arbitrary substrates, and scaling these materials towards monolayer-scale thicknesses. Most recent spin injection experiments have utilized Bi_2Te_3 or Bi_2Se_3, which offer a relatively simple band structure and stoichiometric composition control, but are very sensitive to environmental doping. Bi and $Bi_{1-x}Sb_x$ thin films are interesting alternatives due to the extremely high mobility and long spin diffusion length of Bi, the tunability of the band structure through both the Sb concentration and the film thickness, and the potential to form allotropic crystal structures with distinct electrical properties during epitaxial growth. In my future research efforts, I plan to continue my work on crystal structure transitions in epitaxial Bi and $Bi_{1-x}Sb_x$, as well as to investigate the transport properties of Bi/$Bi_{1-x}Sb_x$ heterostructures and the role of quantum confinement in $Bi_{1-x}Sb_x$ thin films.

Epitaxial Growth and Transfer of Bismuth Thin Films

My initial Ph.D. research demonstrated that, unlike conventional films grown by molecular beam epitaxy (MBE), Bi films on silicon (Si(111)) exhibit weak adhesion to the growth substrate and may be easily transferred. The ability to transfer epitaxial Bi can facilitate integration with magnetic, transparent, and insulating substrates for measurements or device fabrication. Although bulk Bi is a semi-metal, films of Bi thinner than the critical thickness for quantum confinement have been previously shown to be semiconducting, with highly conductive, spin-split surface states. Using MBE, I optimized the growth parameters to produce highly crystalline (001)-oriented Bi thin films between 8-50 nm, which demonstrated thickness-dependent electrical properties characteristic of quantum confinement. To characterize the crystalline orientation, thickness, surface roughness, and semiconducting nature of the films, I used a combination of X-ray diffraction (XRD), X-ray reflectivity (XRR), atomic force microscopy (AFM), and temperature-dependent sheet resistance measurements.

The first transfer of the Bi films utilized a double cantilever beam (DCB) setup previously created by a group in the U.T. Austin Department of Aerospace Engineering to transfer graphene. This allowed us to measure the adhesion energy of the Bi/Si(111) interface, which we found to be unexpectedly low. This weak adhesion enabled us to demonstrate the first dry transfer of a thin film grown by MBE using the simple epoxy-based DCB method.

To expand the substrate materials and geometries the Bi films could be transferred to, I developed a process to directly transfer the Bi films to arbitrary substrates using thermal release tape. Using this method, the Bi films were transferred to glass, SiO_2 and yttrium iron garnet (YIG) substrates without requiring an intermediate epoxy layer. I am currently collaborating with external research groups to facilitate spin-Seebeck, magnetotransport, and phonon dynamics measurements on the transferred Bi films.

Bismuth Antimonide Thin Films and Heterostructures

The similarity of the Bi and Sb bulk crystal structures suggests that $Bi_{1-x}Sb_x$ grown on Si(111) may also be easily transferrable. Unlike bulk Bi, bulk $Bi_{1-x}Sb_x$ alloys between 7–22% Sb are semiconducting, with topological surface states that are protected from backscattering. By growing $Bi_{1-x}Sb_x$ films with varying thicknesses and compositions, I found that while 8 nm films had a crystalline orientation consistent with Bi(001) across all Sb concentrations studied, 20 nm films with relatively high Sb concentrations were oriented in the (012) direction. Futhermore, although both the (001) and (012)-oriented 20 nm $Bi_{1-x}Sb_x$ films could be easily transferred, the (012)-oriented films converted to the (001) orientation after removal from the Si(111) substrate.

These results suggest that strain significantly influences the crystal structure of epitaxial $Bi_{1-x}Sb_x$, and therefore potentially influences the topological surface states. As the (012) and (001) surfaces of $Bi_{1-x}Sb_x$ exhibit distinct surface state dispersions, understanding the role of strain in forming these structures is essential to realize topologically insulating $Bi_{1-x}Sb_x$ films on Si(111), as well as on a wider variety of substrates through transfer. Interestingly, 20 nm $Bi_{1-x}Sb_x$ films grown on a thin buffer layer of Bi on Si(111) did not experience changes in orientation either before or after transfer. Instead, the $Bi_{1-x}Sb_x$ layer appeared to be strained to the underlying Bi layer, maintaining a (001) crystalline orientation even at high concentrations of Sb. Bi/$Bi_{1-x}Sb_x$ heterostructures could therefore be a useful component in fabricating epitaxial $Bi_{1-x}Sb_x$(001), as well as an exciting platform for studying the effects of variables such as period thickness and quantum confinement effects on topological surface states in $Bi_{1-x}Sb_x$.

Monolayer-Scale Growth of Bismuth and Bismuth Antimonide

The growth of monolayer-scale epitaxial films is becoming increasingly important due to scaling trends in the microelectronics industry. Bi has been previously shown to initially form a puckered-layer allotrope on Si(111), followed by a transition to the bulk-like crystal structure after several monolayers of growth. The thinner puckered-layer structure is expected to exhibit distinct electrical properties from bulk-like Bi, and is also a potential candidate for spintronic device applications. However, this phase tends to form isolated nanoscale islands rather than a continuous film, raising measurement challenges. I am currently investigating how epitaxial growth parameters and Sb concentration affect the morphology of the puckered-layer Bi islands, with the goal of improving the continuity and crystalline quality in order to better facilitate characterization.