Production and Characterization of Topological Insulators

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Abstract:

Topological insulators (TIs) represent a novel category of material whose bulk insulates, but whose surface conducts. The ability to produce topological insulators would be of great interest, because electron states can cross the insulating band gap, as well as surface conduction and spin-locking properties [1]. Bismuth selenide (Bi_2Se_3) is one of the best candidates for three dimensional (3D) TIs. Our project focuses on developing a method to produce undoped and doped Bi_2Se_3 via vapor-liquid-solid (VLS) deposition. Upon examination with a scanning electron microscope (SEM), energy dispersive x-ray spectroscopy (EDS) and x-ray diffraction (XRD), we found that both nanoribbons and nanowires about 5 μm in length formed; the doped sample with 61.4% selenium, 33.30% bismuth, 5.66% antimony by atomic percentage, and the undoped sample with 61.62% selenium and 38.38% bismuth. Being able to produce these doped and undoped topological insulators opens up exciting new avenues of research into their properties and possible applications.

Introduction:

In the last few years a new electronic crystal state was discovered, the topological insulator (TI). It is a unique state in which normal insulating states exist in conjunction with spin-momentum locked electronic states. These extra electronic states are the source of much interest due to the fact that they cross the electronic band gap, as shown in Figure 1; leading to various interesting properties [1]. However, these states are difficult to examine due to the fact that they only exist on the crystal's surface, and therefore could be masked by bulk conduction from unintentional doping. To eliminate this effect, nanostructures, such as wires and ribbons that have large surface-to-volume ratio, are the ideal structure to find these topologically insulating states.

In order to create the best TIs, we must choose the correct material. The material we chose in this case was bismuth selenide (Bi_2Se_3), due to the fact that it can exist as a nano-structured crystal, has a very simple band structure, is easily obtained, and can be doped with antimony [2].

Doping is the process where atoms in a crystal are substituted with similar atoms. In this case antimony substituted the bismuth atoms, which opened a band gap in the topological insulating states [3].

Our objective was to produce and characterize both antimony doped and undoped Bi_2Se_3 nanostructures in order to test TI properties.

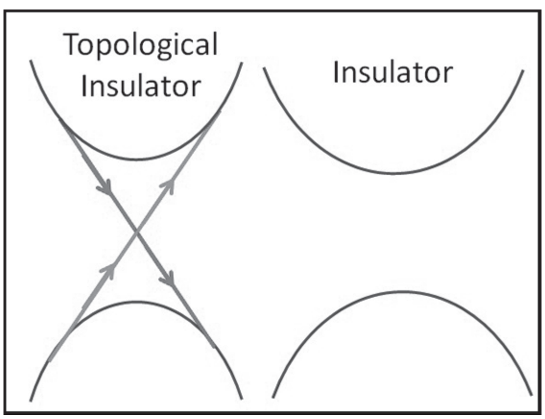

Figure 1, above: Band diagram of an insulator and a TI. The arrows represent spin-momentum locking.

Figure 2, right: Our tube furnace setup where the growth took place, the crucible with Bi_2Se_3 at the center of the glass tube.

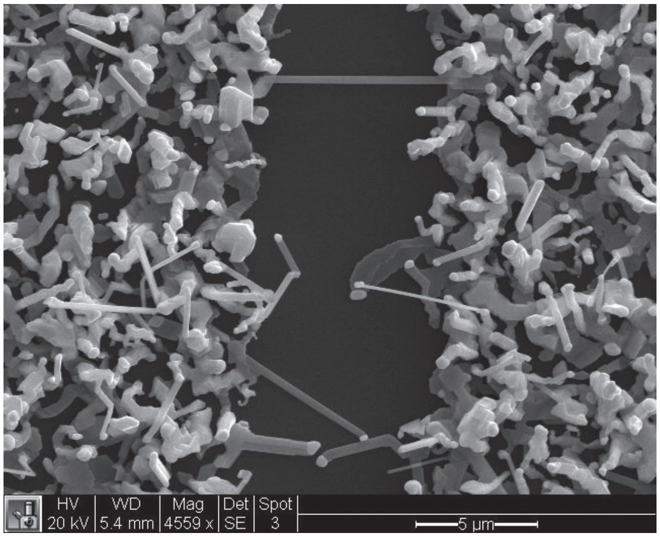

Figure 3: SEM image of Bi_2Se_3 wires 5-10 µm in length on a silicon substrate.

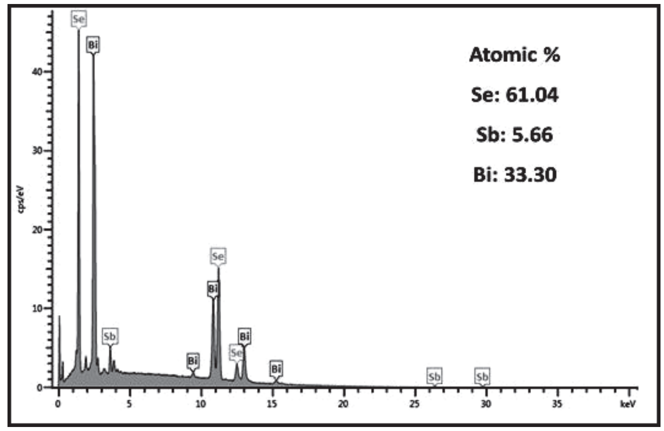

Figure 4: EDS graph on the atomic percentages of bismuth, selenium and antimony in a doped sample of Bi_2Se_3.

Methodology:

We went about producing the Bi_2Se_3 nanostructures via vapor-liquid-solid growth (VLS). In this process, the Bi_2Se_3 source material was heated up and then carried to the substrate by an inert carrier gas. The substrate itself was coated with a 20 nm gold film prior to growth, and also heated so that the film melted and beaded up. These gold droplets catalyzed crystal formation as the vapor Bi_2Se_3 deposited on the silicon substrate [4]. Our specific growth process used a tube furnace and argon as a carrier gas, as shown in Figure 2. The Bi_2Se_3 source was placed at the center of the furnace, while the substrate was placed 9-11 inches away (380°C ~ 450°C). The furnace was pumped down to 500 mtorr and heated to 490°C for 2.5 hours. The argon source was at a pressure of 12 psi.

Results:

Our growth resulted in many nanowires and some nanoribbons forming that were 5-10 μm in length, as shown in Figure 3. The characterization with XRD showed that the crystal structure matched up with Bi_2Se_3 rather than other compounds containing bismuth and selenium. SEM and EDS verified that our bismuth selenium ratio was at 37.09% of bismuth and 62.91% of selenium, which was close to the expected 2:3 stoichiometry. Samples with antimony doping were characterized by EDS with atomic percentages of 33.30% bismuth, 61.04% selenium and 5.66% antimony, as shown in Figure 4, which agrees with direct substitution of bismuth with antimony.

Discussion and Future Work:

The production of these topological insulators was successful and matched our expectations. Now what is left to be done in this project is to perfect the drop casting method where the nanostructures are transferred from the silicon substrate to an insulating substrate in order to create electronic devices for testing.

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