Quantum Materials for Communication, Computing, and Storage

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Primary CNF Tools Used: Autostep 2000 I-Line stepper, JEOL 6300, AJA sputter, Vecco AFM, DISCO dicing saw

Abstract:

The integration of new material properties into electronics devices creates new possibilities for device performance, architecture, and function. We therefore investigate the fabrication and applications of materials with exceptional properties, including superconductivity, ferromagnetism, ferroelectricity, and topologically non-trivial electronic states.

Summary of Research:

Two-dimensional (2D) materials, which allow the extreme scaling down of transistors with their atomically thin structure, are a promising candidate for the next generation electronics. One of the challenges for these applications is complementary metal oxide semiconductor (CMOS) devices. For CMOS, there should be a complementary pair of n-type and p-type field effect transistors (FETs) whose mobility and threshold voltage are well matched. There have been many studies about n-type 2D materials that make n-type field effect transistors (FETs), but p-type 2D materials with sizable band gap have not been well explored. For a pMOS option, we have investigated tungsten diselenide (WSe_2). WSe_2 is a good candidate for CMOS applications since it shows ambipolar behavior as well as relatively high hole mobility. We have been making p-type FETs using exfoliated WSe_2 flakes. The Autostep stepper is used to make the substrate for 2D material transfer, the JEOL 6300 is used to define patterns for metal contacts, and the AJA sputtering system is used to deposit metals. The I-V characteristics of representative device is shown in Figure 1(a) and 1(b). Maximum drive current reaches more than 20 µA/µm, the on/off current ratio is more than seven decades, and the upper bound of contact resistance is around 75 kΩ·µm, which is comparable to some of the best results in literature [1].

Spin-orbit torque (SOT) is a physical phenomenon where a material with large spin-orbit coupling can exert a torque on the magnetic moment of an adjacent ferromagnet (FM). This effect is applicable to magnetic memory, where information can be stored in the magnetization direction of the FM, and SOT can be used to control that magnetization direction. The efficiency of magnetic manipulation by SOT is dependent on the types of materials used and the quality of the interface between them. Topological insulators (TI) are a class of materials with strong spin-orbit coupling, an inversion of the band structure, and surface states where the spin and momentum of electrons are interdependent. These attributes can lead to more efficient SOTs and make FM/TI bilayers very promising for magnetic memory devices [1]. However, in many reports, at least one material of the FM/TI bilayer is sputtered [1-3]. To further enhance the performance of FM/TI bilayer, we grow FM/TI structures using molecular beam epitaxy (MBE) in one shot without exposure to air. Here, we report our advances in the MBE growth and characterization of TIs and FMs bilayers that are applicable to SOT devices.

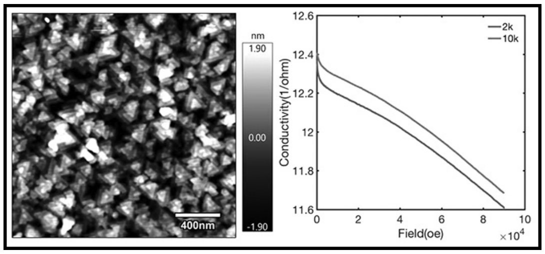

Figure 1: AFM surface height map of Bi_2Se_3 grown on GaAs, showing < 1 nm RMS roughness (left) and magnetoresistance of Bi_2Se_3 grown on GaAs (right).

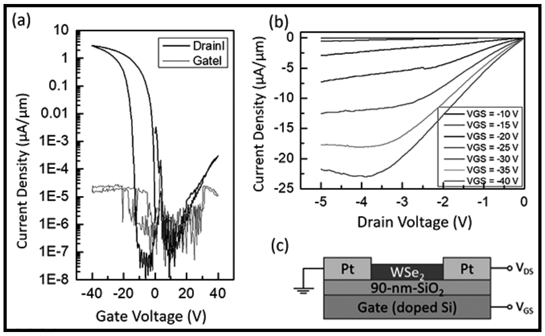

Figure 2: (a) Transfer curve of WSe_2 pFET, (b) Output curve of WSe_2 pFET, and (c) Cross-sectional image of WSe_2 pFET.

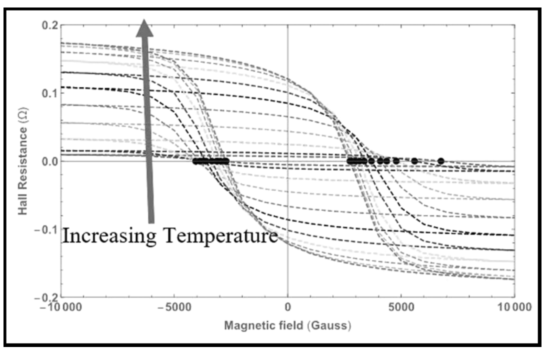

Figure 3: Temperature-dependent AHE measurement from 10K - 300K for Mn_4N film on MgO (001). The saturation Hall resistance increases with temperature. (Find full color on pages xiv-xv.)

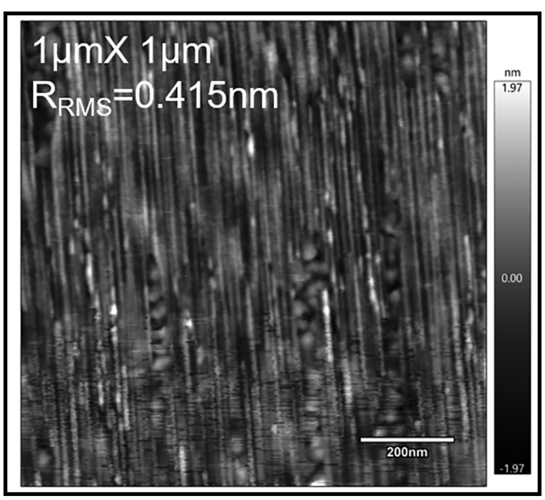

Figure 4: AFM surface height map of NbN/AlN/NbN heterostructure grown on 6H-SiC by MBE.

Recently, room temperature switching of the magnetization of a FM using Bi_2Se_3 as the TI have been reported [2,3], revealing the merits of using Bi_2Se_3 in FM/TI structures. We are now optimizing growth condition of Bi_2Se_3 on different substrates including GaAs and sapphire. Thanks to the weak VdW interaction between Bi_2Se_3 and substrates, high quality single crystal Bi_2Se_3 have been successfully grown on both substrates with smooth surface (RMS < 1 nm), as shown in the atomic force microscopy (AFM) image shown in Figure 1. However, it is found that bulk states exhibit metallic electrical transport characteristics, as shown by the temperature-dependent resistance in Figure 2. Topological insulators should be insulating in the bulk, so the metallic behavior indicates that the Fermi level is not in the bulk band gap of Bi_2Se_3. Tuning the Fermi level into the bulk bandgap of Bi_2Se_3 by electrostatic gating or doping the film could also lead to higher SOT efficiency.

For the ferromagnetic layer in our FM/TI structure, we are exploring Mn_4N, one of the few known magnetic nitride materials. We are optimizing the MBE growth of Mn_4N on various substrates such as MgO, STO and GaN. Through measurement techniques such as vibrating sample magnetometry and anomalous Hall effect (AHE) measurements, we have confirmed perpendicular magnetization and low saturation magnetization which are both beneficial for magnetic memory device applications. To make our samples suitable for these measurements, we use the dicing saw and metal deposition systems such as the CHA thermal evaporator. The shape of the AHE signal, as shown in Figure 3, nearly forms a parallelogram and is indicative of perpendicular magnetic anisotropy, which is desirable for higher-density magnetic memory.

The phenomena of superconductivity and the integration of superconducting materials with normal state materials are utilized in applications such as quantum computing and single flux quantum computing. We investigate the possibility of realizing epitaxial integration of III-N semiconductors with metallic superconducting materials such as NbN through the growth of thin film heterostructures by molecular beam epitaxy. We have demonstrate that epitaxial NbN/AlN/NbN heterostructures can be grown on 6H-SiC substrate with RMS roughness less 0.5 nm. Measurements to observe the Josephson effect in these structures are ongoing.

References:

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[3] Han, Jiahao, et al. "Room-temperature spin-orbit torque switching induced by a topological insulator." Physical review letters 119.7 (2017): 077702.

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