Investigation of Magnetic-Field Effect on Topological Insulators Surface States

L. He, X. Kou, M. Lang, K.L. Wang (UCLA, Electrical Engineering); E.S. Choi (NHMFL, FSU)

Introduction

Topological insulators (TIs) have been predicted to have metallic edge or surface states with a linear, Dirac-like dispersion relation in addition to a normal bulk band structure. The most remarkable characteristic is that these edge or surface states remain robust against time reversal invariant disorders since the directions of the spin and the momentum are locked due to the strong spin-orbit interaction. Thus there are exciting opportunities for constructing novel electronic and spintronic devices that consume much less energy than the current CMOS technology.

Experimental

We have fabricated 3D topological insulators of $(Bi_xSb_{1-x})_2Te_3$ thin films with different doping concentration x and film thickness, by molecular beam epitaxy (MBE). Standard hall bar devices with top gate electrodes have been fabricated. We then measured the low temperature longitudinal resistance (R_{xx}) and Hall resistance (R_{xy}) as a function of two variables – the perpendicular magnetic field and the top gate bias voltage. We have used the superconductor magnet SCM2, and resistive magnets at cell 8 and cell 12.

Results and Discussion

First of all, for all doping concentration x, we have revealed an ambipolar effects in the longitudinal resistance (R_{xx}) with film thicknesses being fixed at 10 nm. And for Bi concentration x = 0.53 sample gives the lowest carrier concentration of 1.3×10^{12} cm^{-2} and a high Hall mobility of 3100 cm^2/Vs. More importantly, on this sample Shibnikov-de Haas (SdH) oscillations associated with the top and bottom surface states have been observed. And they can be selectively tuned by gate biases. The observation of the two surface states is an important step towards the implementation of TIs in spintronics.

Second, when we reduce the films below a critical thickness of 6 quintuple layers (QLs), the top and bottom surface states start to hybridize and form gapped surface states. This gapped surface state is evidenced through the observation of the competition between weak antilocalization (WAL) effect and weak localization (WL) effect at low magnetic field, when tuning the Fermi level across the Dirac point. This behavior is probably due to the change of the net Berry phase due to the gap. Furthermore, when the Fermi level is inside the surface gap of the ultrathin films, the overall unitary behaviors are revealed at higher magnetic fields, which are in contrast to the pure WAL signals obtained in thicker films. Our findings show an exotic phenomenon characterizing the gapped TI surface states and point to the future realization of quantum spin Hall effect and dissipationless TI-based applications.

Conclusions

Our results demonstrate the presence of top and bottom surface states in 3D TI thin films, and their hybridization below a critical thickness of 6 QLs. We also prove that these two surface states can be separately tuned. With top and bottom gated device structures based on our films, the quantum spin Hall effect in 3D topological insulators may be observed.

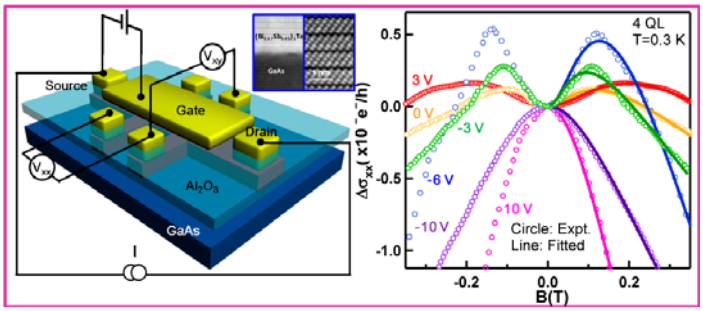

Figure 1. (Left): Schematic diagram of $(Bi_xSb_{1-x})_2Te_3$ on a highly resistive GaAs (111) top-gate Hall bar device structure with measurement setup. Inset: High resolution TEM picture indicates the five layer structure of TI, and the Van der Waals gap. (Right): Evolution of the Low field magneto-conductance as a function of gate voltages. It shows a competition between weak antilocalization (WAL) effect and weak localization effect.

Acknowledgements

We would like to thank the support from the Defense Advanced Research Projects Agency (DARPA) under the grant no. N66001-12-1-4034 and N66001-11-1-4105, NSF Cooperative Agreement No. DMR-1157490, the State of Florida, and the U.S. Department of Energy.

Publications

[1] He, L., *et al*., Sci. Rep. **3**, 3406 (2013). [2] Lang, M., *et al*., Nano Lett. **13**, 48-53, (2013).