Search for Topological Phases in Ultrathin Sb Films

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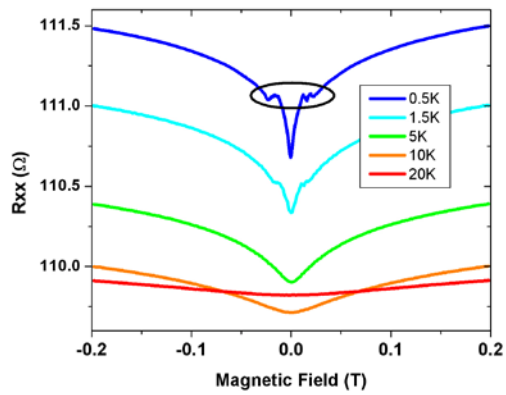
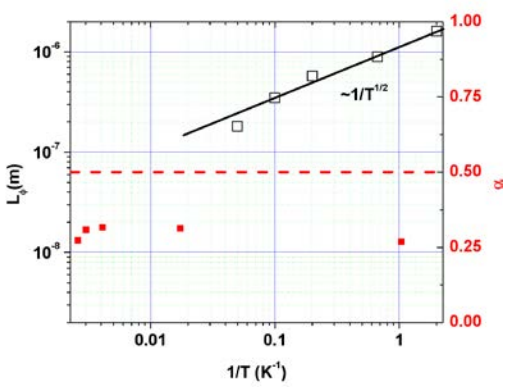
Introduction

Elemental Sb has gained attention recently as calculations indicate that the inherently large spin-orbit coupling enables topological insulator (TI) behavior [1]. TIs are a new class of materials that are electrical insulators in their bulk interior, but electrical conductors at their surfaces. These conducting surface states are topologically protected from elastic backscattering[2], unlike those found in ordinary two-dimensional (2D) electron systems. Elemental bulk Bi and Sb are semimetals, however particular alloy concentrations of BiSb are semiconducting and these alloys were the first materials identified as three-dimensional (3D) TIs. While the semimetallic states in bulk Sb preclude TI behavior, recently topo-electronic phase transitions in Sb films as a function of film thickness have been predicted[1]. A semimetal-to-3D TI transition induced by quantum confinement is expected at a critical thickness of ~7.8nm and a 3D TI-to-2D quantum spin Hall state transition at a critical thickness of ~2.7nm with a trivial semiconductor state for films thinner than ~1nm. The search for these topological phases has motivated our recent studies of atomically flat, ultra-thin Sb films.



Results and Discussion

We have developed a molecular beam epitaxy procedure to realize ultra-thin films of Sb with good crystalline quality on semi-insulating GaAs (111)A substrates with GaSb buffer layers. Our growth rate of 0.1nm/sec provides excellent control over final film thickness. Magneto-transport data for a 2.9nm thick film is shown on the right for five temperatures ranging from 0.5 to 20K. A shallow resistance minimum is observed in the vicinity of 12K and for temperatures below 15K weak anti-localization (WAL) induces a strong resistance minimum at zero field. The WAL behavior of a TI is expected to follow the conventional form for systems with strong spin-orbit coupling predicted Hikami, Larkin and Nagaoka[3] modified with infinite spin-orbit coupling (i.e. fully suppressed backscattering). This form provides an excellent fit to the Sb data with two fitting parameters (the phase coherence length and a pre-factor indicative of the number of channels contributing to the WAL) as shown on the left. The phase coherence length in our sample exceeds 1μm below 1K and decreases with increasing temperature as $1/T^{1/2}$ as expected for systems limited by electron-electron scattering. The prefactor α however is less than 0.5 expected of a single conducting channel; far below the expected value of 1 for two uncoupled TI surface states. We speculate that residual bulk Sb states may couple the surface states and work to reduce the bulk conductivity is ongoing. An unexpected addition to the WAL signal below 1.5K, is highly reproducible resistance fluctuations (shown circled in the figure on the left). While resembling universal conductance fluctuations for micron-sized samples, it remains a puzzle as to why they appear in our mm-sized sample. Preliminary data on 2nm thick films are comparable and also display the reproducible fluctuations at the same fields and temperatures. Additionally these thinner films display linear magneto-resistance at higher fields, a potential signature of TI behavior.



Acknowledgements

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References

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[2] M. Z. Hasan *et al.*, Rev. Mod. Phys. **82**, 3045 (2010).
[3] S. Hikami *et al.*, Prog. Theo. Phys, 63, 707 (1980).