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14. ABSTRACT

We report significant achievements, including the world's first observation of proximity-induced superconductivity in mesoscopic Josephson-junction devices that were fabricated using $Pb_{.5}Sn_{.5}Te$ topological crystalline insulators that were grown by molecular beam epitaxy (MBE) at the US Army Research Laboratory. Other achievements include growth, characterization, and theory of thin layers semiconductor tin and a new magneto-terahertz response technique to isolate real topological signatures of bulk states in Dirac and Weyl semimetals. Significant progress has been made toward the MBE growth of stanene.

15. SUBJECT TERMS

topological insulators, Weyl semimetals, Dirac fermions, molecular beam epitaxy, semiconductor

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1. Introduction

The objectives of the investigation of the unique electronic states between topological insulators (TIs) and superconductors are 1) molecular beam epitaxy (MBE) growth of PbSnTe and PbSnSe and verification that they are topological crystalline insulators (TCIs); 2) MBE growth of a thin layer of semiconductor tin (α-Sn) and 2-D tin (stanene) and verification that they are a 3-D TI and a 2-D TI, respectively; and 3) growth and characterization of tin-based TI/high-temperature superconductor heterostructures.

2. Accomplishments

A paper reporting the collaboration between US Army Research Laboratory (ARL) researchers and the University of Maryland Physics department has been submitted to *Physical Review Letters*. This collaboration led to the world's first observation of proximity-induced superconductivity in many mesoscopic Josephson-junction devices (JJ) that were fabricated using $Pb_{.5}Sn_{.5}Te$ topological crystalline insulators that were grown by MBE at ARL. Reviewers' comments to date suggest that it will be accepted for publication.

We have improved the quality of the thin layers of single crystal epitaxial semiconductor tin (α-Sn) grown by MBE on (111) cadmium telluride (CdTe) substrates, as evidenced by X-ray diffraction and Raman scattering measurements, which confirm that the thin layers of α-Sn are slightly strained. Using the envelope function approximation, theoretical calculations of the effects of quantum confinement on CdTe(111)/α-Sn and CdTe(001)/α-Sn quantum wells (QWs) were carried out. We show that CdTe/α-Sn QWs possess a rich variety of topological behaviors. As one increases the α-Sn thickness, CdTe/α-Sn transitions through the following phases: 2-D trivial insulator, effective 2-D topological insulator, 3-D topological insulator, and 3-D Dirac semimetal. We determined the critical thicknesses of α-Sn at which these transitions occur. The critical thickness between the 3-D topological insulator and Dirac semimetal phases is strongly dependent on the strain of the α-Sn layer and the orientation of the CdTe substrate. We also explored the impact of Rashba spin orbit coupling on the helical edge states of 2-D topological insulator CdTe(111)/α-Sn QWs and find their Dirac point to be electric field-dependent. Experiments aimed at observing the predicted topological phase transitions and confirming TI behavior are ongoing.

Thin layers of single crystal epitaxial semiconductor tin α-Sn were grown by MBE on a monolayer of hexagonal BN (h-BN), which was grown on a copper foil and then transferred onto a gallium arsenide substrate. This is an important milestone because it confirms that the Van der Waals MBE technique can grow cubic α-Sn on BN and possibly graphene. The structure used for the Van der Waals growth of α-Sn is shown in Fig. 1. X-ray diffraction (Fig. 2) and Raman scattering measurements (Fig. 3), and X-ray photoelectron spectroscopy measurements (Fig. 4) confirm that the thin layers of α-Sn are strained. More importantly, it strongly suggests that our collaborative investigation of the growth of stanene on h-BN or on graphene is likely to succeed. We plan to do in-situ growth and scanning tunneling microscopy characterization of stanene on graphene at the University of California, Santa Barbara, and transport studies of stanene on h-BN at ARL.

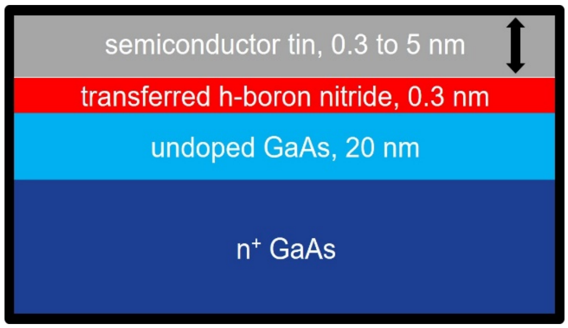

Fig. 1 α-Sn/h-BN/GaAs structure

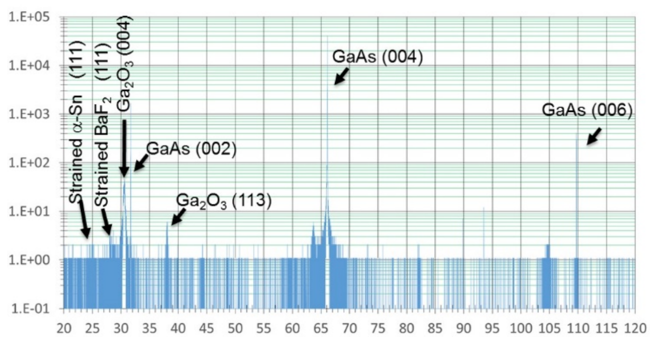

Fig. 2 XRD of α-Sn/h-BN/GaAs

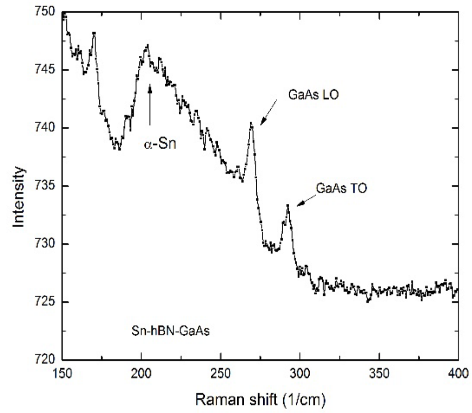

Fig. 3 Raman scattering α-Sn/h-BN/GaAs

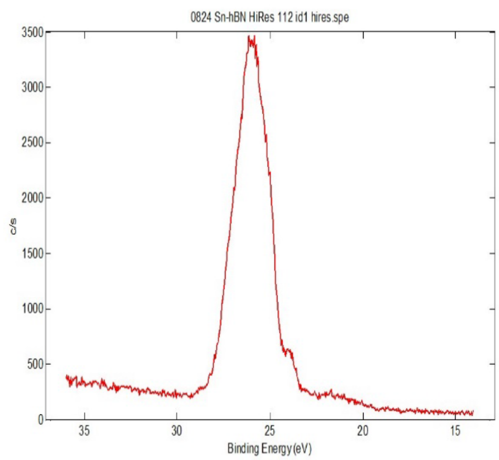

Fig. 4 XPS of α-Sn/h-BN/GaAs

Conductance fluctuations in mesoscopic $Pb_{1-x}Sn_xTe$ devices are currently being investigated. Resistivity and magnetoresistance measurements as a function of temperature on some α-Sn layers show the existence of a thin disordered metallic layer at the α-Sn layer/CdTe substrate interface. The disordered metallic layer exhibits superconductivity at a critical temperature $T_c = 3.9$ K – 5 K, which is being investigated. We are also investigating transport across a $Pb_{.5}Sn_{.5}Te$/high-temperature superconductor interface that was fabricated by exfoliating a bismuth strontium calcium copper oxide layer in-situ, followed by MBE growth of $Pb_{.5}Sn_{.5}Te$.

3. Conclusion

We conclude by pointing out that ongoing Director's Research Initiative research over the next 6 months could yield significant results that will be reported in another final report.

4. Manuscripts Submitted or in Preparation for Journal Publication

Folkes P, Taylor P, Rong C, Nichols B, Hier H, Gao T, Ong M N-P. Molecular beam epitaxy growth and characterization of thin layers of semiconductor tin. Neupane will be submitted to Thin Solid Films.

Snyder R, Trimble C, Rong C, Folkes P, Taylor P, Williams J. Josephson junctions with weak links of topological crystalline insulators. Submitted to Physical Review Letters.

de Coster G, Folkes P, Taylor P, Vail O. Effects of orientation and strain on topological characteristics of CdTe/ α-Sn quantum wells. Submitted to Physical Review B.

Cheng B, Taylor P, Folkes P, Armitage N P. Magneto-terahertz response and giant Faraday rotation from massive Dirac fermions in the topological crystalline insulator $Pb_{.5}Sn_{.5}Te$. Submitted to Physical Review Letters.

Presentations

Vail O, Taylor P, Nichols B, de Coster G, Rong C, Hewitt A, Folkes P. Transport properties of thin film α-Sn. American Physical Society Conference; March 2018; Los Angeles, CA.

Snyder R, Trimble C, Deitemyer S, Rong C, Folkes P, Taylor P, Williams J. Mesoscopic fluctuations of conductance topological crystalline insulators. American Physical Society Conference; March 2018; Los Angeles, CA.

Vail O, Taylor P, Nichols B, de Coster G, Folkes P. Growth and Characterization of α-Sn Thin Films. 34th Annual International Conference on the Physics of Semiconductors; July 2018; Montpellier, France.

Collaborators: Prof. Williams (Univ. MD), Prof. Palmstrøm (UCSB), Prof. Armitage (Johns Hopkins), Prof. Ong (Princeton), Profs. Fu, Gedik, Nelson Soljacic MIT ISN-4 Project No. 3.4.

List of Symbols, Abbreviations, and Acronyms

α-Sn	semiconductor tin
ARL	US Army Research Laboratory
CdTe	cadmium telluride
h-BN	hexagonal BN
MBE	molecular beam epitaxy
QW	quantum well
TCI	topological crystalline insulator
TI	topological insulator

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