Final Technical Report

Institution: Yale University
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Title: One-Dimensional Topological Nanomaterials and Superconductivity
Sponsoring Program Office: Basic Energy Science, Experimental Condensed Matter Physics
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1. Abstract

The project synthesized and measured transport properties of topological nanomaterials, including topological crystalline insulator tin telluride (SnTe) nanowires, thin layers of topological semimetal molybdenum ditelluride ($MoTe_2$) and tungsten ditelluride (WTe_2), and topological semimetal molybdenum phosphide (MoP) nanowires.

The aim was to reveal and enhance the topological surface properties via transport measurements of topological nanomaterials, with a particular focus for realization of 1D topological superconductivity using SnTe nanowires as the model system.

2. Summary of Proposed Activities and Accomplishments

The central hypothesis of the proposed activities is that nanoscale topological materials will enhance the signature of the surface states in the transport properties due to the large surface to volume ratio. The proposal had a particular focus on trying to realize 1D topological superconductors based on SnTe nanowires.

We have revealed size-dependent transport properties using SnTe nanowires, which include diameter-dependent ferroelectric phase transition temperature, superconductivity induced by indium doping, and diameter-dependent Josephson junction behaviors. The Josephson junction measurements were done in collaboration with James R. Williams at the University of Maryland, College Park. His group found that the superconductivity induced in SnTe nanowires has broken time reversal symmetry, and the Josephson behaviors support presence of Majorana bound states. Thus, in collaboration with a transport group, we have demonstrated that SnTe nanowires are a good model system to study 1D topological superconductivity.

In addition to SnTe nanowires, we have investigated other topological materials at the nanoscale. For example, our topological semimetal MoP nanowires show very low resistivity at the nanoscale, comparable to those of Cu interconnect wires, which suggests MoP might be an alternative metal for energy efficient interconnects. The DOE funds also enabled us to synthesize and study transport properties of two-dimensional layered topological materials, such as $MoTe_2$ and WTe_2.

Syntheses of these topological nanomaterials were achieved via vapor-liquid-solid and chemical vapor deposition growth methods. Transport measurements were carried out by fabricating nanoscale devices using electron-beam lithography and measuring the magnetotransport in the presence of magnetic fields down to 0.4 K in temperature. Before the transport measurements, these topological nanomaterials were characterized using a suite of material characterization

techniques, such as transmission electron microscopy, X-ray diffraction, energy dispersive X-ray spectroscopy, X-ray photoelectron spectroscopy, Raman spectroscopy, and scanning electron microscopy.

3. Scientific and Technical Reporting Products

During the period of performance between 2015 and 2021, we published 18 peer-reviewed papers and the PI and group members presented their results at department seminars, workshops, and conferences.

3a. Journal Article-Accepted Manuscript

Below is the complete list of the published papers that acknowledge the support of the DOE grant.

1. Structural phase transition and carrier density tuning in $SnSe_xTe_{1-x}$ nanoplates
   J. Shen, J. M. Woods, Y. Xie, M. D. Morales-Acosta, J. J. Cha, *Adv. Elec. Mater.* 2016, **2**, 1600144
   https://onlinelibrary.wiley.com/doi/full/10.1002/aelm.201600144

2. Suppression of magnetoresistance in WTe_2 flakes by surface oxidation.
   J. M. Woods, J. Shen, P. Kumaravadivel, Y. Pang, Y. Xie, G. A. Pan, M. Li, E. I. Altman, L. Lu, J. J. Cha, *ACS Appl. Mater. Interfaces* 2017, **9**, 23175-23180
   https://pubs.acs.org/doi/full/10.1021/acsami.7b04934

3. Synthesis and superconductivity of In-doped SnTe nanostructures
   P. Kumaravadivel, G. Pan, Y. Zhou, Y. Xie, P. Liu, J. J. Cha, *APL Mater.* 2017, **5**, 076110
   https://aip.scitation.org/doi/full/10.1063/1.4994293

4. Revealing the contribution of individual factors to hydrogen evolution reaction catalytic activity
   Y. Zhou, J. L. Silva, J. M. Woods, J. V. Pondick, Q. Feng, Z. Liang, W. Liu, L. Lin, B. Deng, B. Brena, F. Xia, H. Peng, Z. Liu, H. Wang, C. M. Araujo, J. J. Cha, *Adv. Mater.* 2018, **30**, 1706076
   https://onlinelibrary.wiley.com/doi/full/10.1002/adma.201706076

5. Dislocation-driven SnTe surface defects during chemical vapor deposition growth
   P. Liu, Y. Xie, E. Miller, Y. Ebine, P. Kumaravadivel, S. Sohn, J. J. Cha, *J. Phys. Chem. Solids* 2019, **128**, 351-359
   https://www.sciencedirect.com/science/article/pii/S0022369717314336

6. Recent progress on in situ characterizations of electrochemically intercalated transition metal dichalcogenides
   S. Yazdani, M. Yarali, J. J. Cha, *Nano Research* 2019, **12**:2126 – 2139
   https://doi.org/10.1007/s12274-019-2408-6

7. Unveiling the interfacial effects for enhanced hydrogen evolution reaction on the MoS_2/WTe_2 hybrid structures

Y. Zhou, J. V. Pondick, J. L. Silva, J. M. Woods, D. J. Hynek, G. Matthews, X. Shen, Z. Feng, W. Liu, Z. Lu, Z. Liang, B. Brena, Z. Cai, M. Wu, L. Jiao, S. Hu, H. Wang, C. M. Araujo, J. J. Cha, *Small* 2019, **15**, 1900078
https://onlinelibrary.wiley.com/doi/10.1002/smll.201900078

8. Topological nanomaterials
P. Liu, J. R. Williams, J. J. Cha, *Nat. Rev. Mater.* 2019, **4**, 479-496
https://www.nature.com/articles/s41578-019-0113-4

9. Synthesis of WTe_2 nanowires with increased electron scattering
J. M. Woods, D. Hynek, P. Liu, M. Li, J. J. Cha, *ACS Nano* 2019, **13**, 6455-6460
https://pubs.acs.org/doi/10.1021/acsnano.8b09342?ai=7286

10. Synthesis and resistivity of topological metal MoP nanostructures
H. J. Han, D. Hynek, Z. Wu, L. Wang, P. Liu, J. V. Pondick, S. Yazdani, J. M. Woods, M. Yarali, Y. Xie, H. Wang, J. J. Cha, *APL Mater.* 2020, **8**, 011103
https://aip.scitation.org/doi/10.1063/1.5130159

11. Synthesis of narrow SnTe nanowires using alloy nanoparticles
P. Liu, H. J. Han, J. Wei, D. Hynek, J. L. Hart, M. G. Han, C. J. Trimble, J. Williams, Y. Zhu, J. J. Cha, *ACS Appl. Electron. Mater.* 2021, **3**, 184-191
https://pubs.acs.org/doi/10.1021/acsaelm.0c00740

12. Crossover between weak antilocalization and weak localization in few-layer WTe_2: role of electron-electron interactions
X. Zhang, J. M. Woods, J. J. Cha, X. Shi, *Phys. Rev. B* 2020, **102**, 115161
https://journals.aps.org/prb/abstract/10.1103/PhysRevB.102.115161

13. Josephson detection of time-reversal symmetry broken superconductivity in SnTe nanowires
C. J. Trimble, M. T. Wei, N. F. Q. Yuan, S. S. Kalantre, P. Liu, H. J. Han, M. G. Han, Y. Zhu, J. J. Cha, L. Fu, J. R. Williams, *Npj Quantum Materials* 2021, **6**, 61
https://www.nature.com/articles/s41535-021-00359-w.pdf?origin=ppub

14. Cm^2-scale synthesis of $MoTe_2$ thin films with large grains and layer control
D. J. Hynek, R. M. Singhania, S. Xu, B. Davis, L. Wang, M. Yarali, J. V. Pondick, J. M. Woods, N. C. Strandwitz, J. J. Cha, *ACS Nano* 2021, **15**, 410-418
https://pubs.acs.org/doi/abs/10.1021/acsnano.0c08069

15. Effects of growth substrate on the nucleation of monolayer $MoTe_2$
D. J. Hynek, R. V. Sinhania, J. L. Hart, B. Davis, M. Wang, N. C. Strandwitz, J. J. Cha *CrystEngComm* 2021, **23**, 7963-7969
https://doi.org/10.1039/D1CE00275A

16. 1D topological systems for next-generation electronics
J. L. Han, P. Liu, J. J. Cha, *Matter* 2021, **4**, 2596-2598
https://doi.org/10.1016/j.matt.2021.05.020

17. Thickness-dependence of magnetotransport properties of tungsten ditelluride
X. Zhang, V. Kakani, J. M. Woods, J. J. Cha, X. Shi, *Phys. Rev. B* 2021, **104**, 165126
https://journals.aps.org/prb/abstract/10.1103/PhysRevB.104.165126

18. Seeing quantum materials with cryogenic transmission electron microscopy
J. L. Hart, J. J. Cha, *Nano Lett.* 2021, **21**, 5449-5452
https://pubs.acs.org/doi/full/10.1021/acs.nanolett.1c02146

3b. Scientific Conference Paper / Presentation

PI Cha presented the results funded by the DOE grant at 26 departmental seminars, 27 invited talks at conferences, and 8 lectures at workshops and summer / winter schools. Graduate students and postdoc scholars also presented their results annually at the Materials Research Society (MRS) fall meeting.

4. Broad Impact

Scientifically, the funded projects demonstrated that nanoscale topological materials can be a great platform to enhance and reveal the topological surface state properties in transport measurements. Collaborating with James Williams and his group at the University of Maryland, College Park, we have demonstrated time reversal symmetry breaking in induced superconductivity of SnTe nanowires via Josephson junction measurements, delivering on the original hypothesis of the proposal.

The project supported several postdocs, graduate students, and undergraduate researchers during the period of performance. Dr. Sazad Yazdani was supported by the grant, and went onto to join ASML. Dr. John Woods defended his PhD in 2020 and is currently a postdoc in CUNY. Dr. Pengzi Liu, who was primarily supported by the grant, successfully defended her Ph.D. on the SnTe nanowires and will start her consulting position in the spring of 2022. David Hynek is a senior graduate student who is involved in the DOE-funded research and will likely defend his PhD in the fall of 2022. Grace Pan and Julia Wei were Yale undergraduate students who participated in this research; Grace Pan is currently doing her Ph.D. at Harvard University and Julia Wei at UC Berkeley, both in condensed matter physics.