ARO

2022 YEAR IN REVIEW

DEVCOM ARMY RESEARCH LABORATORY

U.S. ARMY

SOLID STATE PHYSICS PROGRAM

Dr. James Harvey

Program Manager

Dr. Harvey graduated from the U.S. Military Academy with a B.S. in Engineering, from Dartmouth College with a Ph.D. in Physics, from Fairleigh Dickinson University with an MBA, and from the University of California, Davis, with a Ph.D. in Applied Science. He served in both tactical and technical assignments in the Army before joining ARO. He managed ARO's Electromagnetics program for over 28 years, served as technical director of the European Research Office, initiated the Minerva Program in social science, initiated ARO's Biotronics program, served overseas in the ARO International Program in Innovations in Materials Science, and is now responsible for ARO's Solid State Physics program.

Current Scientific Objectives

1 Discover and explain new electronic phenomena in the solid state that, if successful, will enable advances such as energy efficient electronics or some unforeseen technological opportunities.

2 Discover and understand strongly correlated phenomena in topological materials.

3 Discover how visible/IR/terahertz radiation may coherently couple to electronic phenomena in materials to alter properties.

SUCCESS STORY

High-Temperature and Tunable Quantum Magnetic Materials

New families of quantum topological magnetic and quantum magnetic materials have been discovered and synthesized by an ARO-sponsored team at Rutgers University, providing a wide range of applications for ultra-low power, ultra-low heating devices for information processing, computation, and highly sensitive magnetometers. These materials show the promise of spintronic and electronic operation at liquid nitrogen temperature (70 K), and even room temperature.

CHALLENGES

Further scaling up of computational capability for military applications is limited by the device size, power requirements, and heat dissipation in circuits depending on the manipulation of electronic charges. Topological devices offer a potential route to dissipation-less electron currents, spin currents for low-energy information processing, and/or quantum computing; however, materials for these devices generally require low-temperature or ultra-low-temperature operation. Material and magnetic defects are currently identified as sources of the problem.

ACTION

Shortly after the first experimental evidence of the 3D topological insulator (TI), the previous program manager (PM) for solid state and condensed matter, Dr. Marc Ulrich (ARO), recognized the potential scientific and application opportunities in this new form of solid state material—in particular, applications for low-power electronics. He structured this new thrust for his program on topological physics. At the same time, he helped develop an ARO collaboration of PMs with complementary programs in atomic and molecular physics, physical properties of materials, and solid state electronics to explore the new material. Out of this research the world's best TI (BiSeTe) was developed, and this platform permeates much of the TI research throughout the world today. The ARO program was one of the first DoD investments in topological materials, with the Air Force Office of Scientific Research, Office of Naval Research, and ARL's former Sensors and Electron Devices Directorate motivated to participate. From the resulting collaborative PM efforts, the Office of the Secretary of Defense's Topological Electronic Devices Applied Research for Advancement of S&T Priorities (ARAP) program was created. From many discussions and seminars in this environment, Drs. Ulrich and Joe Qiu (PM for ARO's Solid State Electronics program) realized that the research into TIs was becoming crowded, with so many U.S. and international funding agencies investing in exploiting the new material that the ARO Scientific Services Program (SSP) could have only a marginal impact. As a result, this topic was eliminated from

This success was made possible by:

Dr. Marc Ulrich; Emerging Electronics, ARL

Dr. Joe Qiu; Electromagnetic Spectrum Sciences, ARO

Dr. Chakrapani Varanasi; Sciences of Extreme Materials, ARO

Dr. Paul Baker; Photonics, Electronics, and Quantum Sciences, ARO

Citations:

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Liu, Y. et al. Thin Solid Films 751, 139197 (2022).

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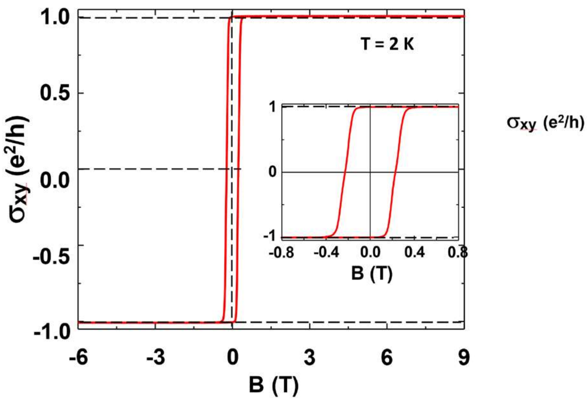

Figure 1. First achievement of QAHE at 2 K without electrical gating. The sharp hysteresis in the magneto-resistivity of the TI sample quantized to precisely e2/h is the signature of QAHE. The edge current flowing without dissipation is seen where the conductivity (σ) goes to zero with zero external magnetic field.

the SSP, but at the same time results from the ARAP convinced them that magnetic–topological interactions offered very promising opportunities for entirely new physical phenomena, as well as a basis for important applications in ultra-low-power electronics, quantum computing, and control of topologically nontrivial spin waves.

RESULTS

The Rutgers team has made three breakthroughs that open the door to significant applications of quantum topological magnetic materials in advanced electronic systems:

1. Chemical and electro-chemical treatments were first discovered, which induce the anomalous Hall effect (AHE) in PdCoO2 films and regulate the electrical and magnetic properties. The AHE in the material can be moderated, and even changed from plus to minus, and a strong perpendicular ferromagnetism in this normally nonmagnetic material can be induced by altering the treatment conditions. In addition, the first observation of plasmons in PdCoO2 was made, which will enable infrared generation. PdCoO2 is highly conductive at room temperature (equivalent to copper or gold), and the AHE provides extreme sensitivity and control of spintronic devices without an external magnet, enabling smaller low-power magnetic, spintronic, and optoelectronic devices.

2. By careful engineering of the interface defects, the world's highest-temperature quantum anomalous Hall effect (QAHE) was demonstrated in a topological material without an electric gate (no external E-field) and in a large-scale material. The temperature at 2 K was four times the temperature of previous reports and is projected to go as high as 70 K with further defect engineering. The QAHE material (Cr-doped (Bi,Sb)2Te3) supports topologically protected electrical currents on the edges but is totally insulating in the interior. The topologically protected edge currents propagate without dissipation and, unlike the quantum Hall effect, do not require an external magnetic field. Figure 1 shows the sharp hysteresis in the magneto-resistivity of the TI sample quantized to precisely e2/h, which is the signature of QAHE.

3. For the first time, a superconducting, macroscopically contiguous oxide film was grown epitaxially on a TI layer. Previously, TIs were grown on superconductors (SCs) by van der Waals epitaxy, but SCs could not be grown on TIs (except in limited cases of elemental metals or in the monolayer limit). Here the Rutgers team has discovered and exploited "hybrid symmetry epitaxy" to grow SC Fe(Te,Se) (FTS) film on the TI Bi2Te3 and the magnetic TI manganese telluride (MnTe) where the materials have a uniaxial lattice match. This breakthrough opens the way for the synthesis of superlattices composed of alternating TI and SC layers, with potentially new and unprecedented topological heterostructures such as topological superconductors or the elusive Weyl superconductor. These heterostructures provide a unique platform for investigating the basic interactions between topological superconductivity and magnetism, as well as the investigation of Majorana states for fault-tolerant quantum computing.

Figures 2a and 2b show the reflection high-energy electron diffraction (RHEED) patterns of the MnTe layer and the Fe(Se, Te) layer grown on top of the MnTe. The bright streaky features imply the high quality of the epitaxial growth. The in-plane lattice symmetries of these two layers can be confirmed by the spacing ratio of the RHEED streaks in two high-symmetry directions. For the MnTe layer, the lattice symmetry is sixfold, which is consistent with the spacing ratio of √3 marked in Figure 2a.

ARL Competencies:

Photonics, Electronics, and Quantum Sciences

Network, Cyber, and Computational Sciences

Electromagnetic Spectrum Sciences

Results

- Discovered chemical and electro-chemical treatments that induce and tune the anomalous Hall effect and a strong anisotropic ferromagnetic transition in an ultra-high conductivity oxide, opening the way for new magnetic devices not needing an external magnet.
- Demonstrated world's highest-temperature QAHE in large-scale TI without external electric field, promising high-temperature spintronic and quantum devices.
- Demonstrated the epitaxial growth of a superconducting film on a TI, with the potential for the first SC/TI superlattices, which would make possible the exploration of entirely new physics as well as new quantum devices.

Anticipated Impact

These results will lead to ultra-low-powered, low-heating electronic and photonic devices for extremely small low-power communications, sensing, electronic warfare, and computational systems supporting the Army's Network/C3I priority and the Intelligence and Mission Command Functional Concepts.

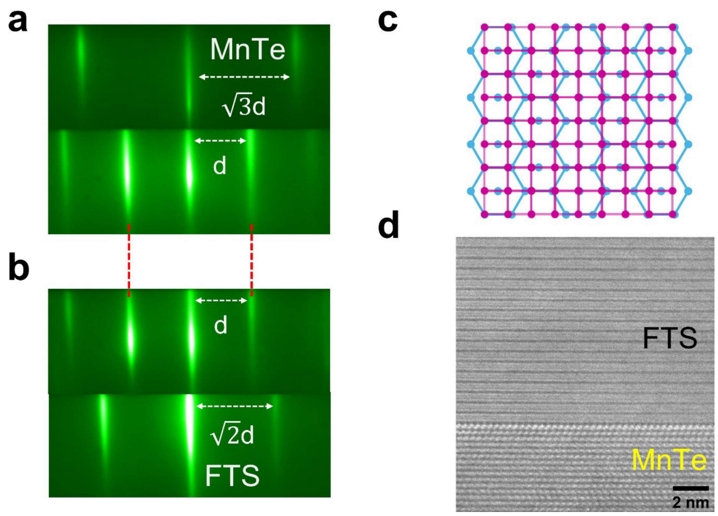

Figure 2. First epitaxial deposition of superconducting Fe(Te, Se) (with fourfold symmetry) on hexagonal TI MnTe via hybrid symmetry epitaxy. RHEED patterns for (a) 10-nm MnTe and (b) 22-nm Fe(Te, Se) grown on MnTe. The arrows indicate the RHEED streak spacings, while the red dashed guidelines indicate that the RHEED spacings are the same. (c) Schematic of the Fe(Te, Se) (purple) lattice overlaid on top of the MnTe (blue) lattice; the dots represent Te(Se) atoms. (d) High-angle annular dark-field scanning transmission electron microscopy image for the Fe(Se, Te)/MnTe sample.

Similarly, the fourfold Fe(Se, Te) layer shows a spacing ratio of √2 in Figure 2b. As indicated by the red dashed lines connecting Figures 2a and 2b, the RHEED spacings of the MnTe and Fe(Se, Te) layers are the same in one high-symmetry direction, despite their different in-plane lattice symmetries. The well-defined sharp interface between the layers shown in Figure 2d confirms the high quality of the heterostructure, enabled by the uniaxial lattice match.

WAY AHEAD

The Rutgers team will explore the limits of defect engineering of TI films to establish QAHE above 4 K (liquid helium), 10 K, then up to 70 K (liquid nitrogen). Further research will also focus on developing QAHE in a ferromagnetic TI and exploring the new physics observable in new QAHE superlattice structures. Dr. Ulrich is now the chief of ARL's Emerging Electronics Branch. Close collaboration with his branch will be maintained, as well as collaboration with the other branches in the ARL Photonics, Electronics, and Quantum Sciences competency for transitioning high-temperature ultra-low-power devices in support of the Army's Network/Command, Control, Communications and Intelligence (C3I) priority and the Intelligence and Mission Command Functional Concepts.