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Role of Pressure in Modulating Bulk and Surface Conductance in Topological Insulators

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ABSTRACT

The discovery of topological insulators (TIs) has initiated a new era in condensed matter physics and materials research, representing a groundbreaking phase of matter. Topological insulators differ from conventional insulators due to a distinctive characteristic: they are electrically insulating inside while potentially supporting robust conductive states outside, such as on their surfaces or edges. The transport properties of BTS and BSTS single crystals were examined under different temperature and pressure conditions after their synthesis by the vertical Bridgman method. The high-pressure resistance and X-ray diffraction (XRD) investigations were conducted in diamond anvil cells and Toroid-type high-pressure cells, respectively, using newly cut materials with exposed (001) surfaces. The pressure was assessed by either seeing the lead's superconducting transition or using ruby fluorescence. Upon examining the conductance of materials in both bulk and surface states, it is evident that the bulk conductance exhibits a distinct pressure-temperature relationship, indicating that it increases with rising temperature and pressure, but the surface conductance remains largely invariant to these factors.

Keywords: Topological, Conductance, Temperature, Insulators, Surface

INTRODUCTION

Discovered in the early 2000s, topological insulators are one-of-a-kind materials that exhibit an uncommon mix of bulk insulating characteristics and surface conducting states. Topology, a subfield of mathematics that studies characteristics that maintain their values during continuous deformations, provides the foundation for this exceptional behavior, which is not just the product of atomic composition. The unique electrical features of TIs are derived from their topological invariants, as opposed to the symmetry-breaking transitions used to classify ordinary materials. Potentially revolutionary in areas like as quantum computing and spintronics, these invariants shield TI surface states from disorder and contaminants.

In most cases, classical band theory can explain how electrons behave in conventional materials. For example, insulators are substances that do not allow electron transport at low energies because their electronic bands are completely filled and separated by an energy gap. While topological insulators do not conduct electricity throughout their bulk, electrons are able to travel over their surface due to certain quantum mechanical phenomena, resulting in strong conducting states. The electrical structure of the material, and more especially its nontrivial topology, is responsible for this effect. A two- or three-dimensional topological insulator's electrons can be best understood by thinking of them as being limited by some topological invariant, most often the Z2 invariant. No matter how little the structural disorder or how many impurities there are, the surface states will be intact and conductive because this invariant guarantees that the system's time-reversal symmetry (the symmetry retained when time flows backward) will be preserved. The essential and economically important attribute of TIs is their stability against disturbances. This sets them apart from traditional materials, whose properties can rapidly alter owing to flaws or contamination.

Particularly noteworthy about TIs is a quantum phenomena known as "spin-momentum locking," in which the direction of motion of an electron is closely tied to its spin, or intrinsic angular momentum. An electron's spin is trapped perpendicular to its travel in these materials as it goes over the surface. One of the two main benefits of this phenomena is that it greatly reduces the likelihood of backscattering, which occurs when electrons are scattered backward from impurities or defects. This is due to the fact that in these systems, the energetic prohibition of electron spin reversal makes backscattering very rare. Secondly, spin-momentum locking paves the way for TIs to be used in spintronics, an area of electronics that processes and stores data via the spin of electrons instead of their charge. The stable, spin-polarized surface states of TIs might be crucial in making the quicker and more energy-efficient devices promised by spintronics a reality.

The dimensionality of the topologically protected states is used to categorize topological insulators. In the first two-dimensional (2D) implementation of a TI, researchers saw the quantum spin Hall effect in HgTe/CdTe quantum wells. This effect is defined by the presence of edge currents with opposite spins that flow in opposite directions along the material's boundaries. The presence of two-dimensional conducting states on the material's surface causes spin-polarized surface currents in three-dimensional (3D) TIs. Bi2Se3, Bi2Te3, and Sb2Te3 are well-studied for their topological surface states and notable for their three-dimensional TI behavior. Experimental methods like angle-resolved photoemission spectroscopy (ARPES) which can map the electronic structure of the material and reveal its unique Dirac-like dispersion confirm topologically protected surface states of these materials, which have conducting surfaces and an insulating bulk. This feature indicates a linear energy-momentum relationship on the surface, similar to graphene.

Many studies in condensed matter physics and related fields have been sparked by the discovery of TIs and their possible uses. The field of quantum computing is one that shows great promise. At least in theory, qubit stability in quantum computers is hindered by specific forms of decoherence, although this is not the case for topologically protected surface states of TIs. One of the biggest challenges in developing trustworthy quantum computers is decoherence, which is brought on by interactions with the outside environment. In particular, when coupled with superconductors to generate topological superconductors, TIs might provide a stable substrate for qubits due to their atomic-scale disruption resistance. At the interfaces of transition metals and superconductors, exotic quasiparticles such as Majorana fermions, which are antiparticles in themselves, are expected to form. Such materials might facilitate their formation. Majorana fermions may find application in error-tolerant quantum computing due to their intrinsic error-proofing capabilities.

The area of low-power electronics is another potential use for TIs, alongside quantum computing. Because of the resistance that arises while moving charges, conventional electronics waste a lot of energy as heat. Electronic devices that are both efficient and environmentally friendly are now within reach, thanks to TIs' spin-polarized surface states, which enable spin-based information transfer with little energy dissipation. On top of that, TIs have the potential to be instrumental in the development of "topological transistors," which enable extremely efficient electrical switching by regulating the transistor's state through modulation of the material's topological phase. In comparison to traditional semiconductor-based devices, this application has the potential to produce devices with much lower power consumption and quicker processing rates.

As a tool to probe novel quantum events and deepen our knowledge of topological phases of matter, TIs have found a home in the field of basic physics as well. Exotic materials with topologically protected characteristics, such as Weyl semimetals and topological superconductors, have attracted interest because to TIs. The electrical characteristics and distinct quasiparticles of these materials force the current solid-state physics paradigms to be rethought and extended. Discoveries of basic particles and interactions may be made possible by the interaction of topology and quantum mechanics in these systems; these discoveries may have far-reaching consequences, going beyond the realm of condensed matter physics.

MATERIAL AND METHODS

The vertical Bridgman method produced high-quality BTS and BSTS single crystals. The crystals were newly sliced to reveal basal plane (001) surfaces before the trials. The two TIs' resistance was measured at high pressure using a toroidal cell. These studies employed a liquid pressure-transmitting medium of glycerin and water. Pure lead superconducting transition temperature changes were used to measure pressure.

High-pressure XRD investigations at ambient temperature were performed at beamlines 4W2 and 15U of the Beijing and Shanghai Synchrotron Radiation Facilities using a diamond anvil cell. These XRD studies employed low-birefringence diamonds. A monochromatic X-ray beam with a wavelength of 0.6199 Å was used, using silicon oil as the pressure-transmitting medium. All diamond anvil cell pressures were measured with ruby fluorescence.

RESULTS AND DISCUSSION

Figures 1, 2, and 3 demonstrate that the two-channel model accurately reflects our experimental findings. Figures 3, 4, and 5 demonstrate that the two materials analyzed exhibited measurable surface and bulk conductivities. The Gbul for both TIs significantly increases above 100 K, especially under pressure, while Gsur seems to be independent of temperature and pressure. To further explore this overall behavioral pattern, examine the temperature-pressure conditions in which surface and bulk states dominate the sample resistances, specifically for samples with a surface area to thickness ratio of about 4680 μm^2:12 μm (78 × 60:12 = 390:1). Note that the formula for conductance G is expressed as $G = (e^2/h)k_F l$, where e represents the charge, h denotes Planck's constant, kF signifies the wave vector of the Fermi surface, and l indicates the mean free path.

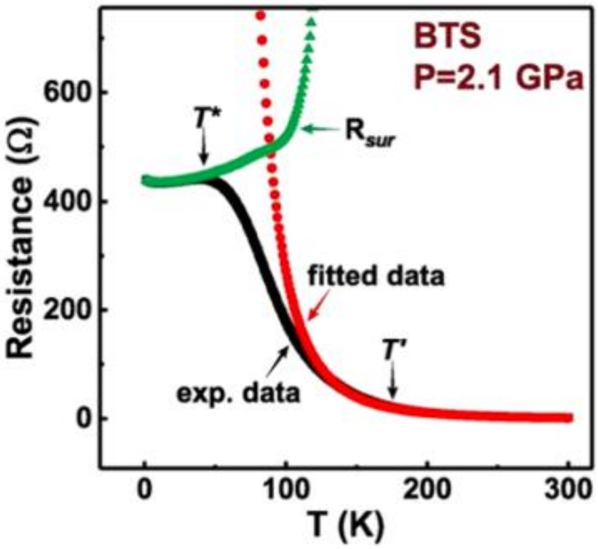

Figure 1: Temperature-dependent resistance at fixed pressure for the two BTS materials

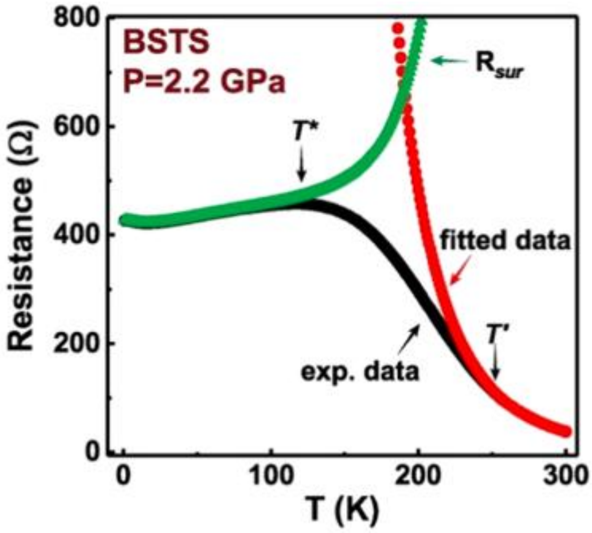

Figure 2: Temperature-dependent resistance at fixed pressure for the two BSTS materials

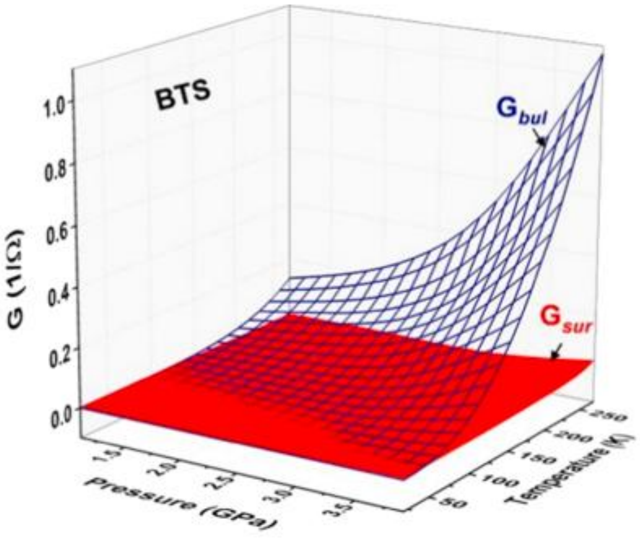

Figure 3: Temperature and pressure relationship of TSS conductance and BTS insulating bulk

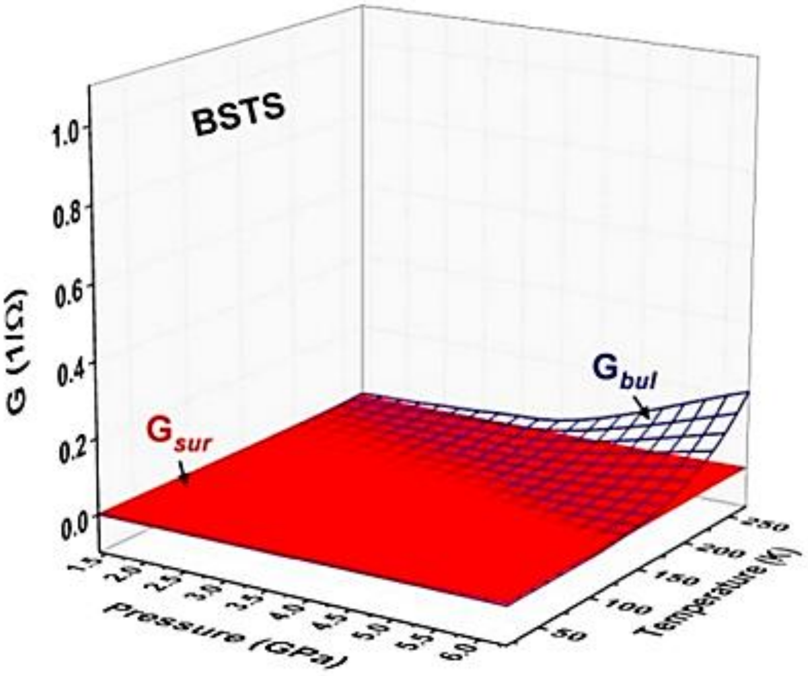

Figure 4: Pressure and temperature relationship of TSS and BSTS insulating bulk conductance

The bulk and surface state conductances are independent at low temperatures and pressures, as seen in Figures 5–9. A figure below shows the conductances in the bulk and surface states as a function of temperature and pressure, and we have also included a schematic of the materials' electronic structure to better explain the results. Figure 5 shows that pressure is crucial for both the surface-dominated behavior of BTS and BSTS at low temperatures and the bulk-dominated behavior of these systems at high temperatures. According to the logarithmic scales, the conductances at 270 K show a linear increase with increasing pressure, suggesting that the bulk exhibits thermal excitation behavior. However, the conductances tested at 10 K show no change when the pressure is low. Low temperature conductance for both TIs is mostly unaffected by pressure, as can be seen from the data shown as a relative change in conductance in Figure 6. Figure 6 shows that at low pressures and temperatures, the surface state conductance dominates, therefore the total sample conductance in BTS and BSTS is roughly constant.

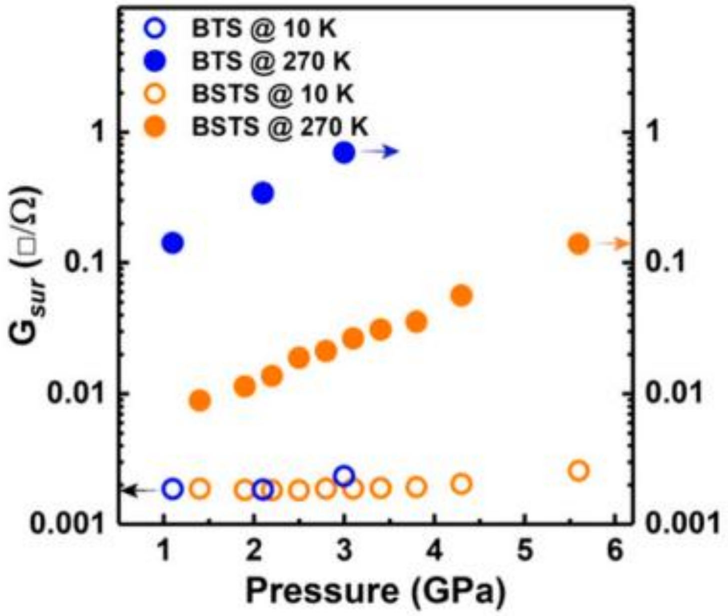

Figure 5: Temperature conductance from BTS and BSTS resistance data.

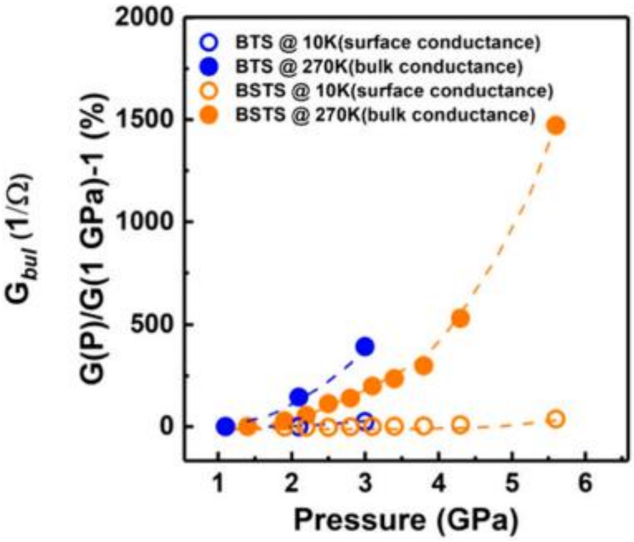

Figure 6: Relative pressure-dependent conductance alterations for BTS and BSTS

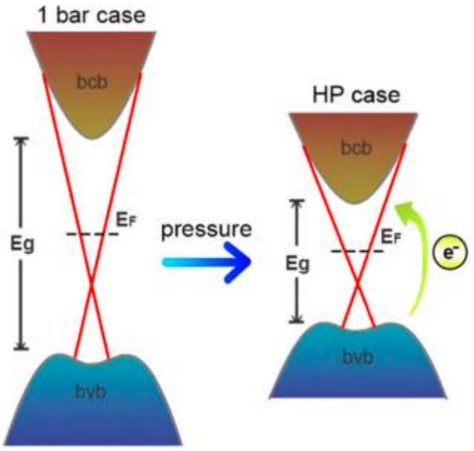

Figure 7: Electronic architectures for optimally doped BTS and BSTS around the gamma point.

The total conductance below T′ at ambient or low pressure is the sum of the bulk and surface contributions, which is a substantial quantity. Transport properties of surface states are practically independent of both pressure and temperature, while bulk characteristics change with decreasing temperature and may be changed by pressure. As the pressure increases, the activation energy gap decreases, which means that bulk carriers, who undergo thermal excitation to transition from the valence band, contribute more and more to total conductance (Fig. 7). By applying a crossover pressure (P*) of 3.0 GPa to BTS and 4.3 GPa to BSTS, the bulk carrier's effect on the transport property becomes more pronounced. Figures 5, 6 show that the surface state conductance increases with pressure beyond the crossover pressure. Because BTS has a lower bulk gap than properly doped BSTS, the crossover pressures of these two TIs are different. Due to the reduced ability to excite charge carriers into the conducting band, the surface state conductance of BSTS becomes less sensitive to changes in temperature and pressure.

CONCLUSION

This research demonstrates that the topological insulators BTS and BSTS exhibit different bulk and surface state properties in relation to their conductance behaviors as a function of temperature and pressure. We found that the bulk conductance grows exponentially with temperature and pressure due to thermal excitation processes, as measured by high-pressure resistance and X-ray diffraction, whereas the surface state conductance is almost unaffected by these parameters. The bulk contributions start to dominate at the crossover pressures of 3.0 GPa for BTS and 4.3 GPa for BSTS, highlighting how bulk carriers are sensitive to pressure. Surface state conductance, on the other hand, is very robust against environmental influences, remaining constant throughout a wide range of circumstances. The durability of the topological surface states is confirmed by their conductance independence from the bulk state. This highlights their potential in applications that need stable electrical characteristics under varying environmental circumstances. These results highlight the potential use of topological insulators in cutting-edge electrical and quantum devices and provide important new understandings of their basic characteristics.

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