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Magnetotransport response in the 3D topological insulator Bi_2Te_3 with indium superconducting electrodes

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Abstract. This report studied the magneto-transport properties in the hybrid structure which combines thin flakes of 3D topological insulator (TI) Bi_2Te_3 with topside indium superconducting electrodes. The observed anomalous magnetoresistance suggests two critical transitions. The first transition, obtained approximately at $T = 3.4$ K, is attributed to superconductivity in the indium electrodes. While the second transition, observed at lower temperature, is attributed to the proximity effect generated from the interface between the TI and the superconductor.

1. Introduction

Over the past decade, a new class of quantum spin Hall insulators, called Topological Insulators (TI), have been examined both theoretically and experimentally.[1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11] Topological insulators (TIs) are electronic materials with a bulk insulating band gap including metallic states on their edges or surfaces in the 2- and 3- dimensional cases, respectively. These exotic gapless surface states of TI display a linear dispersion relation within a single "Dirac cone" and these surface states are topologically protected by the time-reversal symmetry from backscattering by impurities [1, 2, 3, 4, 5, 6, 7]. Among investigations of TI, transport studies of TI-superconductor hybrid structures are thought to be particularly interesting because electrical experimental approaches via the proximity effect have been suggested to find the theoretically predicted Majorance fermions at the TI-superconductor interface [8, 9, 10]. Beyond the conventional proximity effect, which leads to a leakage of Cooper pairs from the superconductor side to the normal metal side, the 3D topological insulators in the presence of an s-wave superconductor are expected to host an exotic p-wave superconductivity capable of hosting Majorana fermions. Thus, motivated by such possibilities, this study examines the magnetotransport response in flakes of 3D topological insulator Bi_2Te_3,[11] contacted with indium superconductor electrodes.[12, 13, 11] We have observed two anomalous transitions on the magnetoresistance below $T = 4.2$ K, which are attributed here to the superconductivity effect in the contacts and generalized proximity effect at the interface, respectively.[11]

2. Experiments and Results

Thin Bi_2Te_3 flakes ($\sim$25 μm) were mechanically exfoliated from high-quality single crystals and transferred onto Si/SiO_2 substrates. TI/superconductor junctions were realized by directly pressing indium on the surface of Bi_2Te_3 in a Hall bar configuration, see the schematic of measurement in Fig.1(a). The magnetic field was applied perpendicular to the Bi_2Te_3 surface in the range of $-0.3\text{T} \leq B \leq 0.3\text{T}$. The four-terminal lock-in technique was utilized to obtain the magnetoresistance response within a measured section with the length-to-width ratio, $L/W \approx 2$. Various temperatures in range of 1.7 K $\leq T \leq$ 3.8 K were obtained in a ^{4}He cryostat by controlling the vapor pressure of liquid helium. Here, indium is a s-wave superconductor with the critical temperature $T_c = 3.41$ K. Hall effect measurements indicated the carrier concentration is 10^{19} cm^{-3} in the measured samples.

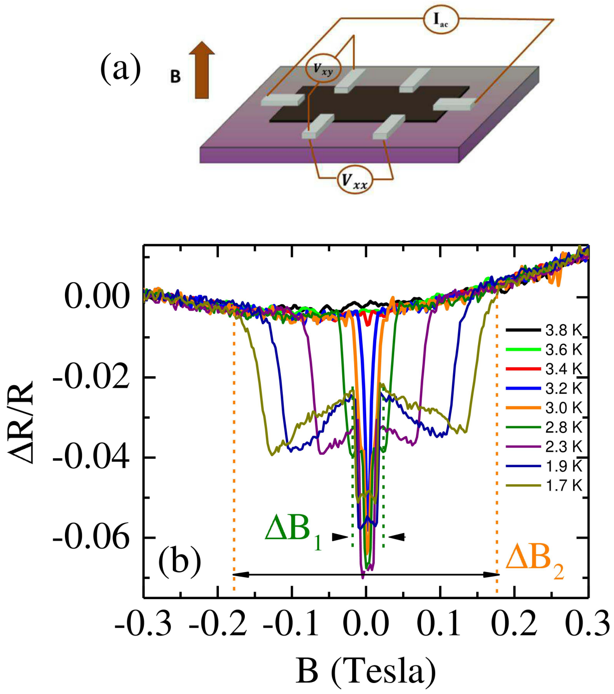

Figure 1. (*a*) The schematic of device measurement. Four-terminal measurement was carried out on the cleaved Bi_2Te_3 flake (black) through indium superconducting contacts (gray) in a Hall bar configuration.(*b*) Normalized magnetoresistance, $\Delta R/R$, vs. the magnetic field, B, at various temperatures in range of 1.7 K $\leq T \leq$ 3.8 K

The normalized magnetoresistance, $\Delta R/R$, which is defined as $\Delta R/R = [R(B) - R(B_N)]/R(B_N)$, where $B_N = -0.3$T is shown in Fig.1(b) for temperatures $1.7 \leq T \leq 3.8K$. Above $T = 3.4$ K, $\Delta R/R$ exhibits similar featureless weak positive magnetoresistance of $B = 0.3$T. Remarkably, at $T = 3.4$ K, which is slightly below the critical temperature of the indium superconductor, there appears a sudden and narrow drop in $\Delta R/R$ near zero magnetic field. This dip mainly grows in depth rapidly with the decreasing temperature until $T = 3.0$ K, while the width, denoted here as ΔB_1 increases. We found that down to $T = 1.7$ K, the critical field for this narrow dip, defined as $B_{c1} = \Delta B_1/2$, is smaller than the critical field of indium superconductor, i.e., $B_c^{In}(0K) = 0.0281$T. As temperature is reduced below $T = 3.0$K, there occurs a second, broad drop in the vicinity of $B = 0$. In contrast to the evolution of the first drop, this second dip becomes much broader in width, denoted as ΔB_2, but not depth, at lower temperatures. The critical field of this broad drop is defined as $B_{c2} = \Delta B_2/2$, exceeds the critical field of the indium superconductor at $T = 1.7$ K.

Fig. 2 (a) compares the magnitude of $\Delta R/R$ vs. T at selected constant magnetic field values, which are $B = 0$ mT, $B = 60$ mT, and $B = 120$ mT, respectively. The result demonstrates that the $\Delta R/R$ shows a sudden reduction with decreasing temperatures, and then plateaus. Moreover, the temperature at which the reduction appears is strongly dependent on B, with lower transition temperatures for higher magnetic fields. Next, we plot the critical field for the two terms, i.e., B_{c1} and B_{c2}, with temperature. Fig.2(b) and (c) exhibit the B_{c1} and B_{c2} which

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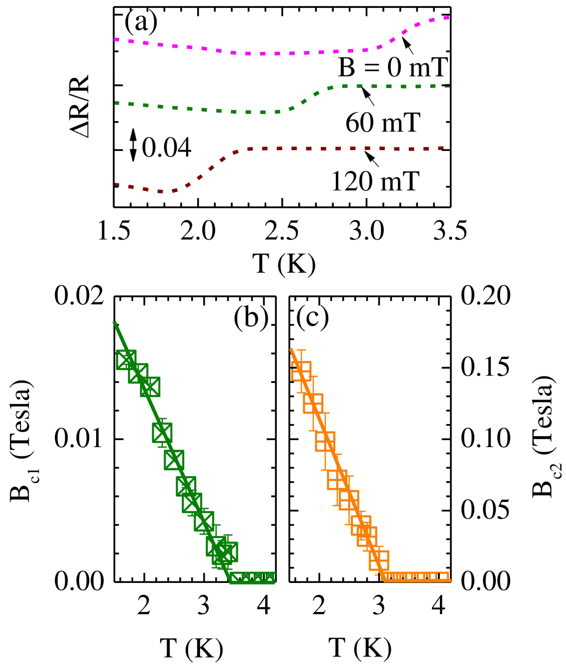

Figure 2. (a) Temperature dependence of $\Delta R/R$ at fixed magnetic fields of $B = 0$ mT, $B = 60$ mT, and $B = 120$ mT, respectively. (b) The critical field associated with the narrow drop, B_{c1}, vs. T. (c) The critical field associated with the broad term, B_{c2}, vs. T.

are extracted from the first derivative of the measured magnetoresistance data by identifying the point of substantial change in the slope. The plot suggests that both critical fields exhibit an approximately linear increase with the decreasing temperatures. Apparently, the rate of increase of B_{c2} with decreasing T is nearly 10 times than that of B_{c1}.

3. Discussion and Summary

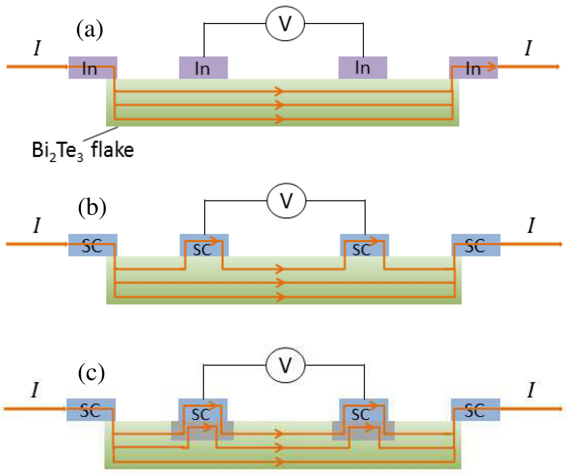

Figure 3. The schematic illustration for explaining the observed magnetoresistance behavior. (a) The image shows the current I flowing through Bi_2Te_3 flake when the temperature is above indium critical temperature, T_{c1}. (b) This illustration for temperature below T_{c1} shows that a fraction of the current I is shunted via indium contacts due to contact superconductivity. (c) The scenario as the temperature further decreases below T_{c2}. The Cooper pairs injected into the Bi_2Te_3 flake induce an additional shunted current in the vicinity of indium/TI interface due to the proximity effect.

The sketch in Fig.4 provides one possible scenario for the observed anomalous magnetoresistance behavior in TI/superconductor hybrid structure, based on previous studies of current flow anomalies.[12, 13, 14, 15] In these experiments, the current was applied through source and drain indium contacts, and voltage was measured through a pair of indium contacts on one side as in the typical four-terminal transport measurement. When $T \geq T_{c1}$, see Fig.4(a), the applied current is carried via both the bulk and the surface states of Bi_2Te_3. Note that in such a high temperature condition, the indium probes act as a normal metal. As the temperature is further reduced below T_{c1}, the indium probes become superconductors, which induces an additional fraction of current I to be shunted through the superconducting probes, as sketched in Fig.4(b). This scenario serves to explain the narrow drop in $\Delta R/R$ observed at $T \approx 3.4$K as mentioned above. Fig.4(c) depicts the situation that occurs with a further decrease in temperature below T_{c2}, where the broad drop in $\Delta R/R$ shows up. In this low temperature condition, proximity effect is induced at the interface in the vicinity of indium superconducting probes, as Cooper pairs are injected into Bi_2Te_3 side. The proximity effect regime, (see the gray areas in Fig.4(c)), results in another shunted current, which gives rise to the second correction in the magnetoresistance occurred at lower temperatures. The only unresolved issue in the experiments is the observed $B_{c2} > 0.028$T in experiment.

In summary, we examined the magnetoresistance in a 3D topological insulator Bi_2Te_3 flake with indium superconducting electrodes. The results indicate two critical transitions, which are associated with two anomalous drops observed in the magnetoresistane. The first transition, with the critical field smaller than the indium critical field, is attributed to the superconductivity effect. The second transition, with the critical field much exceeding the indium critical field is considered as a generalized proximity effect in the TI-superconductor system.

4. Acknowledgments

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