Transport properties of defect-controlled Bi$_2$Te$_3$ single crystals: fingerprint of surface Dirac electrons

Heon-Jung Kim$^{1,*}$, Ki-Seok Kim$^{2}$, Mun Dae Kim$^{3}$, S. J. Lee$^{4}$, J. W. Han$^{1}$, A. Ohnishi$^{1}$, M. Kitaura$^{1}$, M. Sasaki$^{1}$, A. Kondo$^{5}$, and K. Kindo$^{5}$

$^{1}$ Department of Physics, College of Natural Science, Daegu University, Gyeongbuk 712-714, Republic of Korea
$^{2}$ Asia Pacific Centre for Theoretical Physics, POSTECH, Pohang, Gyeongbuk 790-784, Republic of Korea
$^{3}$ Institute of Physics and Applied Physics, Yonsei University, Seoul 120-749, Korea
$^{4}$ Department of Physics, Faculty of Science, Yamagata University, Kojirakawa, Yamagata 990-8560
$^{5}$ Institute for Solid State Physics, University of Tokyo, Kashiwanoha 5-1-5, Kashiwa, Chiba 277-8581

E-mail: hjkim76@daegu.ac.kr

Abstract. We show that in three-dimensional (3D) topological insulator Bi$_2$Te$_3$, the surface nature is revealed as a quantization of motion in Dirac fermions due to their confinement at the surface. The consequence of this z-quantization is the oscillation in magnetoresistance (MR) with periodicity proportional to the magnetic field. We demonstrate that based on single Dirac theory at the surface, where disorder is properly taken into account, the thickness of the surface state or a fundamental length scale of topologically nontrivial state is extracted from the oscillating part of MR data. The same theoretical framework also explains the nonoscillating part of MR and Hall resistance at the low field region, showing that topological contribution is important.

1. Introduction

Topology in physics has become an important topic since the discovery of quantum Hall effect in two-dimensional electron gas (2DEG) [1]. Topologically nontrivial nature of the 2DEG leads to conducting edge state in the quantum Hall regime while the charge carriers in the bulk are localized. This edge state is not described by Landau theory [2], which is a basic framework for the conventional phase transition. Landau theory can be only applicable in distinguishing symmetrically different phase by an order parameter. From the transition temperature, order parameter starts to appear with characteristic temperature dependence. This temperature dependence tells one the universal class to which a particular material belongs. In contrast, topologically nontrivial state collapses as the thickness of edge state, which is the fundamental length scale of topologically nontrivial state diverges and the edge states at opposite surface are mixed together [3,4].

* Corresponding author
Recently, topologically nontrivial state in 3 dimensional (3D) case has been newly discovered in semiconductors Bi$_2$Se$_3$ and Bi$_2$Te$_3$, which is now at the focus of extensive research [5]. This state has been predicted to have intriguing physical properties, some of which were really observed experimentally. For instance, as in quantum Hall systems, a metallic surface state protected from time-reversal invariant perturbations should exist while the charge carriers in the bulk are completely localized [5]. The angle-resolved photoemission (ARPES) measurements have identified this surface state with linear band dispersion and Dirac point in these compounds [6,7,8]. The surface band structure is similar to the band structure of graphene. However, the surface states in Bi$_2$Se$_3$ and Bi$_2$Te$_3$ are known to be profoundly different from the electronic state in graphene. The difference originates in the absence of sublattice degeneracy and this makes Bi$_2$Se$_3$ and Bi$_2$Te$_3$ have nontrivial topological nature.

Interestingly, in the Dirac fermions at the surface of topologically nontrivial 3D materials, the direction of spin is locked with that of momentum. As a consequence, the backscattering by time-reversal invariant impurity potential is completely suppressed and super-metallic state is predicted to exist. Despite its fundamental importance, the question how this topological and surface nature is realized in observable physical quantities such as MR and Hall resistance is still elusive.

Here we focus on MR and Hall measurements, which are of high importance for fundamental understanding and practical applications of topological insulators. We have observed new type of oscillation phenomena in MR with field-linear periodicity. We show that this oscillation is a result of the transport of confined Dirac fermions within the fundamental length scale at the surface. This naturally gives rise to a quantization of motion along the direction perpendicular to the surface. A single Dirac fermion theory with disorder properly accounted enables us to determine this fundamental length scale from experimental data, which turns out to be 5 atomic layers. Not only the oscillating part of MR but also topological properties implicit in MR and Hall resistance are also explained by this theory in a quantitative and a consistent way. In particular, among various topological terms identified as Berry curvature, side jump, and skew scattering, each portion is determined quantitatively from Hall resistance data.

2. Experiments

We have used defect-controlled Bi$_2$Te$_3$ single crystals in our experiments. Usually as-grown Bi$_2$Te$_3$ single crystals are known to be p-doped because of the anti-site defects in Bi sites. In order to tune the Fermi level, we have controlled the amount of the defects by adding extra Bi or Te: the doped Bi tends to increase the anti-site defects, while the doped Te tends to decrease them. Based on this principle, we have succeeded in growing Bi$_2$Te$_3$ single crystals, ranging from fully p-doped to fully n-doped regions. We have obtained fully insulating Bi$_2$Te$_3$ single crystals (TI-Bi$_2$Te$_3$ samples), too. The chance for obtaining these samples is around 3%. The carrier type has been determined by thermoelectric power at room temperature and by Hall sign measured at 4.2 K.

For our experiments, we selected two p-type Bi$_2$Te$_3$ samples (fully p-type #1 and lightly p-type #2), two TI-Bi$_2$Te$_3$ samples (#3 and #4), and one n-type Bi$_2$Te$_3$ sample (#5). Magnetoresistance (MR) and Hall effect measurements have been carried out by a six-probe method at 4.2 K, using a superconducting magnet up to 4 T and a 60 T pulse magnet at ISSP in the university of Tokyo up to 55 T. Here, the direction of the magnetic field $H$ applied is perpendicular to the naturally cleaved plane, on which the current is applied. For MR and Hall measurements, we carefully contacted the lead wires to reduce induction noise for high-field pulse-magnet experiments. We have taken the anti-symmetrized and symmetrized parts in Hall and longitudinal resistances, respectively.
Results and Discussion

Figure 1 shows (a) temperature-dependent resistivity curves of Bi$_2$Te$_3$ as well as (b) MR and (c) Hall resistances measured up to 4 T. The resistivity curves of sample #1, #2, and #5 show metallic behaviour while those of sample #3 and #4 exhibit insulating characteristics. This indicates that the system evolves from p-doped to n-doped regions, between which insulating feature appears as the excess Te increases. This systematic tendency can be also seen in Hall resistivity: the samples #1−#4 are p-doped while #5 is n-doped. These results strongly imply that excess Te really produces negative charge carriers (electrons) as the anti-site defects in the Bi site decrease. Interestingly, both MR and Hall resistivity show nontrivial field dependence. In MR, saturation already starts at around 3−4T. According to the conventional theory of MR, this saturation appears when cyclotron radius becomes comparable to mean free path. Therefore, if this conventional picture were correct in Bi$_2$Te$_3$ samples, this saturation would indicate very long mean free path. Another interesting point is the Hall resistivity data in Fig. 1(c). Unlike what one can see in ordinary metals, Hall resistivity is not linear with field. If this nonlinearity were due to multi-channel character of electric transport, this would also indicate that one of channels has very long mean free path. Since our samples are not in such extremely clean limit, we believe that features found in MR and Hall resistivity occurs owing to surface Dirac fermions.

Another point which cannot be explained within conventional transport theory of metal is a new type of oscillation phenomenon in MR that has H-linear periodicity. Careful inspection of MR has revealed that this oscillation appears at low field region below 4 T. Figure 2 (a) shows second derivative curve of MR measured with a superconducting magnet system up to 4 T and this oscillation can be seen clearly. More interestingly, this oscillation with H-linear periodicity is observed together with SdH oscillation at higher fields. Figure 2 (b) and (c) indicates second derivative curve of MR measured with a pulse magnet system with respective to H and 1/H, respectively. In these plots, it is clear that the oscillation with H-linear periodicity appears at lower fields while SdH oscillation, which is periodic with 1/H occurs at higher fields.

We have thought that interesting results of MR and Hall resistivity, and new oscillation with H-linear periodicity originate from surface Dirac fermions. Especially, the oscillation with H-linear periodicity is what one has observed in metallic thin film due to confinement of charge carriers in a thin layer, called Sondheimer oscillation. In order to understand MR and Hall resistivity, and the oscillation with H-linear periodicity in a quantitative and consistent way, we have formulated a single Dirac theory with disorder properly taken into account. We found that insulating samples are well explained within this theory. The (red) solid line in Fig. 2(a) is a theoretical curve of Sondheimer oscillation [9]. We could estimate thickness of the surface Dirac layer to be 5 atomic layers [10]. It is believed that this thickness is an important length scale of Dirac fermions in 3D topological insulators.
4. Conclusions

We have reported transport properties of defect-controlled Bi$_2$Te$_3$ single crystals. We found that adding excess Te or Bi is an effective way to control doping state of Bi$_2$Te$_3$ single crystals. Owing to this method, we could change the doping state systematically. Transport properties of these single crystals such as MR and Hall resistivity shows features that cannot be explained within conventional transport theory of metals. Among them, new type of oscillation in MR with $H$-linear periodicity at low field region indicates that Dirac fermions are confined within a length scale. From the experimental periodicity, we could estimate this length scale or thickness of the surface layer.

5. References

[1] Klitzing K von, Dorda G and Pepper M 1980 Phys. Rev. Lett. 45, 494
[2] Ginzburg V L 2004 Rev. Mod. Phys. 76, 981.
[3] Nagaosa N, Sinova J, Onoda S, MacDonald A H, Ong N P 2010 Rev. Mod. Phys. 82, 153.
[4] Hasan M Z and Kane C L 2010 Rev. Mod. Phys. 82, 3045.
[5] Fu L, Kane C L, and Mele E J 2007 Phys. Rev. Lett. 98, 106803.
[6] Hsieh D et al. 2008 Nature 452, 970.
[7] Hsieh D et al. 2009 Science 323, 919.
[8] Chen Y L et al. 2009 Science 10, 178.
[9] Sondheimer E H 1950 Phys. Rev. 80, 401.
[10] Kim H-J et al. arXiv:1105.0731.

Acknowledgments
This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2010-0021438).