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Electrical Resistivity Measurements for Bismuth-Antimony Topological Insulators Containing Dislocations

Hiromu Hamasaki, Yuki Tokumoto and Keiichi Edagawa

Institute of Industrial Science, Univ. of Tokyo
4-6-1, Komaba, Meguro-ku
Tokyo 153-8505, Japan
Phone: +81-3-5452-6110 E-mail: hamasaki@iis.u-tokyo.ac.jp

Abstract

The formation of one-dimensional gapless states along dislocations in a three-dimensional topological insulator of Bi-Sb has been investigated experimentally. Well-aligned, high-density dislocations with the Burgers vector satisfying the conductivity condition derived previously are introduced successfully in Bi-Sb single crystals by plastic deformation. Micrometer-sized samples are cut out, and electrical resistivity measurements are carried out with the current direction parallel to the dislocation line direction. A dramatic resistivity drop with decreasing temperature has been observed, which is attributable to one-dimensional conduction along dislocations.

1. Introduction

Three dimensional (3D) topological insulators (TIs) are quantum materials that have a bulk bandgap and a gapless surface state. This gapless state behaves as a metal with the conduction of spin polarized electrons showing remarkably high mobility. In 2008, the first example of the 3D TI was identified in Bi-Sb alloys with the Sb concentration of the range 7-22% [1].

In 2009, it was theoretically predicted that the gapless metallic states also form along dislocations in 3D TIs when the following condition is satisfied [2]:

$$\mathbf{b}\cdot\mathbf{M} = \pi \ (\mathrm{mod}\ 2\pi)$$
$$\mathbf{M} = (\nu_1\mathbf{G}_1 + \nu_2\mathbf{G}_2 + \nu_3\mathbf{G}_3)/2 \ . \qquad (1)$$

Here, $\mathbf{b}$ is the Burgers vector of the dislocation, ($\mathbf{G_1}$, $\mathbf{G_2}$, $\mathbf{G_3}$) are the reciprocal lattice vectors, and (ν_1, ν_2, ν_3) are the Z_2 topological numbers that can be calculated from the bulk band structure. Though such metallic dislocations in TIs have a potential for novel applications as robust quantum nanowires, no experimental works had been reported until very recently; we reported in a previous paper [3] that conductivity measurements on plastically deformed Bi-Sb TIs showed excess conductivity owing to dislocation conduction. However, in the measurements, millimeter-sized specimens were used, in which dislocations did not penetrate the sample completely. As a result, the ratio of the dislocation conductance to the bulk one was fairly small, hampering further detailed studies of dislocation conduction. In the present study, we carried out the resistivity measurements for micrometer-sized specimens of deformed Bi-Sb alloys, in which dislocations should penetrate the sample.

2. Experimental procedures

Bi-Sb single crystals were grown under a controlled temperature. Electron probe microanalyses showed the compositions of the grown crystals to be $Bi_{1-x}Sb_x$ (x≈0.15), which were within the insulating regime of $0.07<x<0.22$. Rectangular samples of 1 x 1.5 x 2 mm^3 in size were cut out, and uniaxially compressed to introduce dislocations. Here, the compression axis was chosen to be $[2\bar{1}\bar{1}]$ to suppress the primary slip system of $(111)-<1\bar{1}0>$ and to activate a secondary one of $(011)-[100]$; the dislocations to be introduced in the latter system should have $\mathbf{b}$=[100], which satisfies Eq.(1). Here, we note (ν_1, ν_2, ν_3)=(1,1,1) for Bi-Sb TIs. Transmission electron microscopy (TEM) observations were performed to examine the density, Burgers vector, and configuration of the introduced dislocations.

For resistivity measurements, micrometer-sized samples with dimensions 4.3 x 4.4 x 13 μm^3 were cut out by focused ion beam. The resistivity measurements were carried out by a four-probe method in the temperature range $2-300$K.

2. Results and Discussion

Fig. 1 shows an optical micrograph of an undeformed (0%), and 3, 8, and 18% deformed samples. As the deformation proceeds, the slip line becomes prominent. This verifies that the slip deformation, which should be mediated by dislocation motions, is the dominant process in the deformation. The orientation of the observed slip traces was confirmed to be consistent with the slip system of $(011)-[100]$. TEM experiments for the deformed sample showed that the introduced dislocations are dominantly of the edge type with $\mathbf{b}$=[100], where the dislocation line is along $[0\bar{1}1]$. The dislocation density was estimated to be $10^{10}-10^{11}$ cm^{-2} for the 18% deformed sample. Thus, we have succeeded in introducing well-aligned dislocations with the Burgers vector satisfying the conductivity condition of Eq. (1).

Fig. 2 shows a scanning electron micrograph of the sample for electrical resistivity measurements. This specimen was cut out from the 19% deformed sample. In particular, this was cut out from a part of the sample close to the surface, where the fluctuation of Sb concentration is minimum. Here, slip lines are clearly seen on the specimen surface, which are along $[0\bar{1}1]$. Current terminals are deposited on the right-hand and left-hand side-surfaces on the sample, and as a result, the current direction is along $[0\bar{1}1]$, i.e., the line direction of dominant dislocations. The distance between the current terminals is 13 μm: dislocations are expected to link the two terminals.

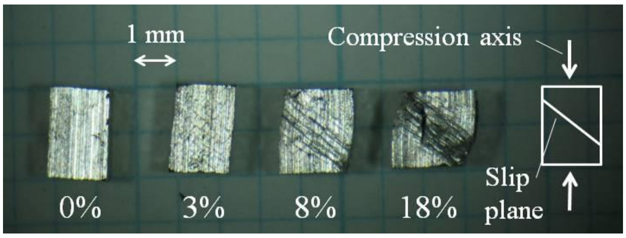

Fig. 1 Optical micrograph of an undeformed (0%), and 3, 8, and 18% deformed samples.

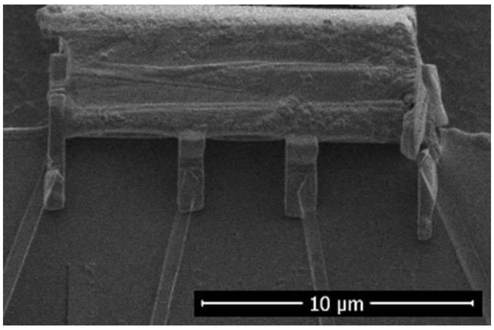

Fig. 2 Scanning electron micrograph of the sample for electrical resistivity measurements.

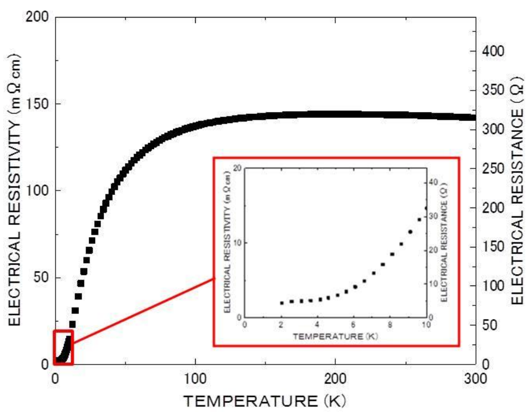

Fig. 3 The result of the resistivity measurement.

Fig. 3 presents the result of the resistivity measurement. The resistivity value at room temperature is about 140 mΩcm, which is much higher than those reported previously for Bi-Sb TIs (~1 mΩcm). This apparent discrepancy may be related to fluctuation of Sb concentration in the sample. Because Bi-Sb is a solid solution system, concentration fluctuation often occurs in bulk samples. Here, bandgap width, and therefore, the resistivity value varies with the Sb concentration. Then, the concentration fluctuation should suppress the resistivity value because low resistivity portion usually determines the measured value. In contrast, the concentration fluctuation must be severely suppressed for our micrometer-sized sample, which should result in a high resistivity value. Another possibility is that the resistivity has been raised by electron scattering by high-density dislocations.

The temperature dependence of resistivity in Fig. 3 is substantially different from those for conventional semiconductors and also from those previously reported for Bi-Sb TIs in previous works [1,3,4]. That is, the resistivity increase with decreasing temperature is not observed in Fig. 3. Instead, the resistivity decreases dramatically with decreasing temperature, going down to 2 mΩcm at 2K, which is only 1.4% of the room temperature value. Such a peculiar behavior can reasonably be attributed to dislocation conduction, as follows. For this sample, there should potentially be three different conduction paths: 3D bulk, 2D surface and 1D dislocation. Of them, the contribution from the 2D surface should be negligible because the sample is sufficiently thick [5]. According to the Landauer-Buttiker formalism, the electrical resistance of one 1D channel is approximately 26 kΩ when the conduction is ballistic. The number of dislocation in the sample can be estimated to be $10^2 - 10^3$ from the dislocation density and the cross section area. Then, the resistance value of the dislocation conduction is calculated to be 2.6 – 26 Ω, which is close to the measured value around 2K (~5 Ω). The plateau around 2K may be due to this quantized resistance.

3. Conclusions

To verify the formation of 1D gapless states along dislocations in 3D TIs, temperature dependence of electrical resistivity was measured for Bi-Sb TIs containing well-aligned, high-density dislocations. Here, the measurements were performed with the current direction parallel to the dislocation line direction. Micrometer-sized samples were used so that the dislocations penetrate them completely. A dramatic resistivity drop with decreasing temperature was observed, which could reasonably be attributed to one-dimensional conduction along dislocations.

Acknowledgements

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