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Thickness dependence of conductivity in Bi₂Se₃ topological insulator

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Abstract. The electrical resistivity of thin films of a topological insulator of Bi₂Se₃ with a thickness of 10 nm to 75 nm, single crystal of Bi₂Se₃ with thickness of 0.65 mm in the temperature range from 4.2 to 300 K was measured. A size effect in the electrical conductivity of Bi₂Se₃ films was observed, i.e. linear dependence of the conductivity of the sample on its inverse thickness. It was suggested that similar effects should be observed in other TIs and systems with non-uniform distribution of direct current over the cross section of the sample.

1. Introduction

The study of new topological materials [1–3] is one of the main directions of modern condensed matter physics. Such materials have a rich potential for use in electronics and spintronics devices, since they have unique electronic properties arising from their unusual band structure. One of such promising materials are the topological insulators (TIs) [1], which have a nontrivial topological band structure, arising from strong spin-orbital interaction [2]. The TI has an energy gap in the bulk and “metallic” states on the surface, which are protected topologically. Electrons in topological insulators are Dirac fermions with a linear dispersion law, and their spins are rigidly connected with their momentum. Elastic backscattering in such a system is forbidden in the absence of magnetic impurities [3, 4]. This feature of TI leads to the emergence of spin polarization of charge carriers and the possibility of a spin-polarized current flowing near the TI surface with practically no loss [5]. This spin-polarized surface current can be used for spintronic devices.

It is known that Bi₂Se₃ compound is the TI with a metallic conductivity near surface and the gapless semiconductive one [6] in its bulk. Since the electroconductivity value in a bulk and near surface of such materials can differ substantially, it is of interest to “divide” them experimentally. In Ref. [7], we studied the size effect only in thin films of Bi₂Se₃. The aim of this paper is to study the size effect in the electronic transport of TI Bi₂Se₃ in a wide range of sample thicknesses, namely, in the case of a “thick” single crystal.

2. Samples and measurements

Thin films of Bi₂Se₃ were grown by the molecular beam epitaxy method on Al₂O₃ substrates [8, 9] with thickness from 10 to 75 nm. Single crystal (SC) of Bi₂Se₃ with thickness 0.65 mm was cleaved from a boule grown by melting stoichiometric mixtures of high-purity elemental Bi and Se. The XRD data and the atomic content of elements analysis showed the synthesized films have Bi₂Se₃



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composition (see Refs. [8, 9]). The atomic content of elements was measured by a scanning electron microscope equipped with an EDAX X-ray microanalysis attachment. Our examination showed that the deviations from a stoichiometric composition were insignificant in all samples. The measurements of the electroresistivity ρ_0 were carried out by the conventional 4-points method at dc-current in the temperature range from 4.2 to 300 K. The results are presented in units of conductivities $\sigma_0 \approx 1/\rho_0$.

3. Results and discussion

Schematic view of the sample of 3D TI is shown in figure 1a. The electric current I is passed through the sample of thickness d and width c (figure 1a), and the voltage U is measured between the potential leads located at a distance L . In the subsurface layer of thickness δ , a region with high surface conductivity σ_{surf} appears.

Since the conductivities of TIs in a bulk and near the surface differ significantly, TI can be represented as a system of two parallel-connected conductors: a "metal" surface and a "semiconductor" bulk (see [7, 10] and references therein). As was shown in [7], the conductivity σ of such a system can be represented as:

$$\sigma \approx \sigma_{surf} \cdot \frac{\delta}{d} + \sigma_{bulk} \quad (1)$$

where σ_{surf} is a surface conductivity of the subsurface layer with a thickness of δ , σ_{bulk} is a bulk conductivity. Thus, the dependence of conductivity σ on the inverse film thickness d^{-1} should be observed, i.e. $\sigma = f(d^{-1})$.

The first term in Eq.(1) is proportional to surface conductivity σ_{surf} and second one is the bulk conductivity σ_{bulk} , i.e. we can "separate" σ_{surf} and σ_{bulk} . Taking into account Refs [3], it was assumed that delta is not more than 1 nm*.

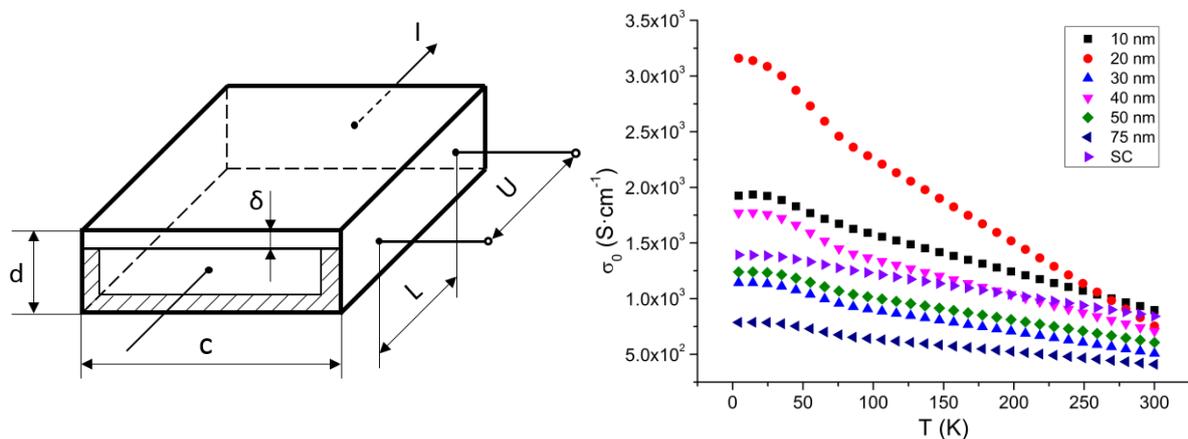


Figure 1(a, b). (a) The schematic view of experiment. Where c is the width of the sample; d is the thickness of the sample; δ is the thickness of the near-surface layer; L is the distance between potential contacts, I is dc current, U is measured voltage.; (b) Temperature dependence of conductivity of TI Bi_2Se_3 films and SC.

Figure 1b shows the temperature dependence of the electroconductivity for Bi_2Se_3 samples. One can see the conductivity value depends on a sample thickness. In [7], according to this method, the size effect was studied only in thin films and at the temperature range from 4.2 K to 80 K. In this paper, we studied the size effect in the case of a "thick" single crystal sample in the temperature range from 4.2 K to 300 K.

Figure 2a shows the dependence of the electrical conductivity on the inverse thickness of the samples at the temperature of liquid helium. The experimental points correspond to thin films with

thicknesses of 10, 20, 30, 40, 50, 75 nm and a single crystal with a thickness of 0.65 mm (this point is located almost on the y-axis.). It can be seen that there is a fairly good agreement between the calculation and the experiment. Figure 2b shows a similar dependence at the room temperature.

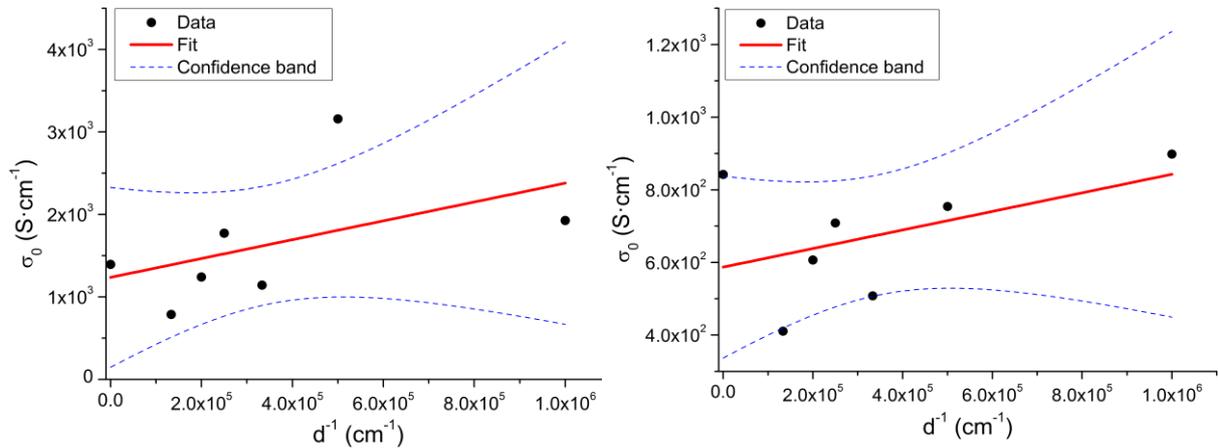


Figure 2(a, b). (a) Size effect in the conductivity of Bi_2Se_3 at 4.2 K; (b) Size effect in the conductivity of Bi_2Se_3 at 300 K.

It can be noted that with increasing temperature the linearity of the experimental dependence deteriorates, nevertheless, even at 300 K the experimental points are in the confidence band of the mathematical model used.

According to evaluations at $T = 4.2$ K, $\sigma_{\text{bulk}} \sim 1.2 \cdot 10^3 \text{ S} \cdot \text{cm}^{-1}$ and $\sigma_{\text{surf.}} \sim 1.1 \cdot 10^4 \text{ S} \cdot \text{cm}^{-1}$ and $\sigma_{\text{bulk}} \sim 0.5 \cdot 10^3 \text{ S} \cdot \text{cm}^{-1}$ and $\sigma_{\text{surf.}} \sim 2.5 \cdot 10^3 \text{ S} \cdot \text{cm}^{-1}$ at $T = 300$ K. That means the surface conductivity $\sigma_{\text{surf.}}$ is almost 9 times higher than σ_{bulk} at the temperature of liquid helium and is almost 5 times higher at the room temperature. The obtained results are in good qualitative agreement with the Ref. [6].

By plotting the graphs presented at figure 2 for the temperature range, it is possible to calculate the temperature dependences for the bulk and surface contributions to the total conductivity. As shown in [7], the “surface” of Bi_2Se_3 thin films has a metallic conductivity, while the “bulk” is a semiconductor one. However, if we consider a situation where, in addition to thin films, we have a “thick sample,” the situation changes drastically. In this case, the “bulk” of sample also acquires a metallic conductivity type.

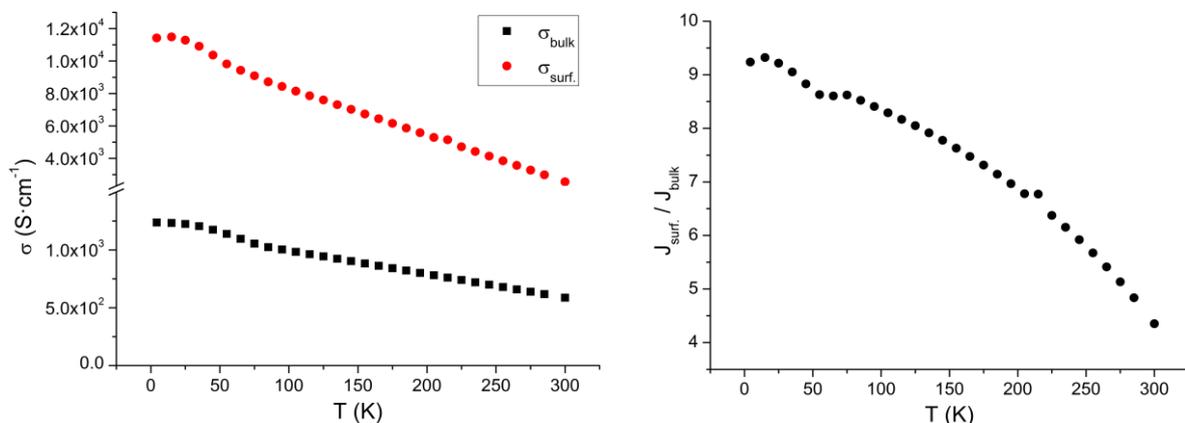


Figure 3(a, b). (a) Temperature dependences of bulk and surface contribute in total electroconductivity of TI Bi_2Se_3 ; (b) Temperature dependence of the ratio of current densities on the surface and in the bulk of Bi_2Se_3 samples.

Figure 3a show the temperature dependencies of surface conductivity σ_{surf} and bulk conductivity σ_{bulk} . Surface contributions to the conductivity decreases with temperature as it should be for protected conductive states on TI surface. Bulk contributions to the conductivity also decreases with temperature as it was observed for Bi_2Se_3 in Ref. [6] since Bi_2Se_3 has relatively small gap in its electron energy spectrum at Fermi level. It leads to that fact the scattering of charge carriers begin to play the main role in formation of its conductivity. As a result, bulk conductivity decreases with temperature due to the scattering processes.

It should be noted that a similar change in a type of temperature dependence for surface and bulk conductivities was observed in Refs. [11, 12], where dc-current was concentrated near a samples surface under the static skin effect [10, 13].

As mentioned above, the elastic backscattering of current carriers in the near-surface layer is prohibited if the magnetic impurities [3, 4] are absent. In our case, there are no magnetic impurities and the scattering mechanisms for such “near-surface” carriers should be similar to those in pure metals (see, e.g., [14-16] and references there), i.e. leading to a change in the mean free path of the conduction electrons and, hence, to a “metallic” type of conductivity with temperature. However, a more detailed study of the specific scattering mechanisms will be performed and presented in subsequent papers.

Figure 3b shows the temperature dependence of the ratio of current densities on the surface and in the bulk of Bi_2Se_3 samples. From this graph, it is seen that as the temperature rises, the influence of the particularity of the electron surface transport in the formation of total electrical conductivity decreases which leads to a decrease in the non-uniformity of distribution of the current density over the cross section of the sample.

4. Conclusions

The peculiarities of the electroconductivity in the TI Bi_2Se_3 were studied. It was found that the linear dependence of the electrical conductivity on the inverse thickness of the sample is maintained both in a wide range of sample thicknesses and for a wide temperature range. It was shown that it possible to experimentally “separate” the bulk and surface contributions into the conductivity of the TI Bi_2Se_3 . It was found that the value of the surface contribution to the conductivity by almost an order of magnitude exceeds the value of the bulk one. However, with increasing temperature, a significant decrease in the surface contribution to the total conductivity is observed. As a result, we can conclude that the electrical conductivity in Bi_2Se_3 is mainly determined by the processes of scattering of charge carriers.

The obtained results can be used for “separation” and evaluation of the values of surface and bulk conductivity also in other TIs and systems with non-uniform distribution of direct current over the cross section of the sample.

Acknowledgments

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