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Hall Effect in “size” topological insulators Bi_2Se_3

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Abstract. The Hall resistance ρ_{xy} of thin films of the Bi_2Se_3 topological insulator with a thickness from 10 nm to 75 nm at a temperature of 4.2 K and in magnetic fields up to 10 T has been measured. The size effect was found, i.e. dependence of the Hall resistance and the Hall coefficient on the thickness of the studied films. Using a single-band model, the values of the current carrier concentration and their mobility are calculated, which also change with a change in the thickness of the samples.

Keywords: topological insulators, size effect, Hall Effect, thin films

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Эффект Холла в «размерных» топологических изоляторах Bi_2Se_3

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Аннотация. Измерено сопротивление Холла ρ_{xy} тонких пленок топологического изолятора Bi_2Se_3 толщиной от 10 нм до 75 нм при температуре 4.2 K и в магнитных полях до 10 Тл. Обнаружен размерный эффект, т.е. зависимость Холловского сопротивления и коэффициента Холла от толщины исследуемых пленок. Используя однозонную модель, рассчитаны значения концентрации носителей тока и их подвижности, которые также изменяются при изменении толщины образцов.

Ключевые слова: топологические изоляторы, размерный эффект, эффект Холла, тонкие пленки

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Introduction

In recent years, topological materials have attracted great interest both from the point of view of fundamental science and due to promising prospects for practical application for the development of new devices for ultrafast nanoelectronics and spintronics. There are topological insulators [1–3] and topological semimetals [4]. In topological insulators, their bulk is a dielectric or semiconductor, and the surface behaves like a topologically protected metal with a linear dispersion law. Current carriers in the “surface” layer of topological insulators are spin-polarized and practically do not scatter on defects, which can be used in spintronics and quantum computing.

Due to the large difference in the conductivity of the bulk and surface, the electron transport of topological insulators may experience a “size” effect, i.e., the dependence of the transport properties on the thickness of the sample. Thus, the dependence of the number of transport channels in thin Bi_2Se_3 films on their thickness was found in [5]. The authors of [6] found the dependence of the carrier relaxation time on the thickness of the Bi_2Se_3 film. The paper [7] describes the size effect in the parameters of quantum oscillations of films of the Bi_2Te_3 topological insulator. Considering the results of the work [8], the size effect in the conductivity of Bi_2Se_3 thin films was discovered in [9], i.e., a linear dependence of conductivity on their inverse thickness. Apparently, the size effect could be observed in other electronic transport properties, in particular, in the Hall resistivity.

In our previous paper [10] we registered the size effect in zero-magnetic field conductivity, $\sigma(T) = 1/\rho(T)$, i.e., the linear dependence of the conductivity on the reciprocal film thickness, d, in thin epitaxial films of Bi_2Se_3. While this effect was observed at zero applied magnetic field [10], the is an interest to extend experimental study of this effect in applied magnetic fields. In particular, the purpose of this work was to observe and study the size effect in the Hall Effect of Bi_2Se_3 films.

Materials and Methods

Thin films of Bi_2Se_3 were grown by the molecular beam epitaxy method on Al_2O_3 substrates with thickness from 10 to 75 nm. The Hall resistivity ρ_{xy} was measured by the conventional 4-, 5- and 6-points methods at dc-current at 4.2 K [11, 12] and in magnetic fields of up to 10 T in the Collaborative Access Center “Testing Center of Nanotechnology and Advanced Materials” of M.N. Mikheev Institute of Metal Physics of the Ural Branch of the Russian Academy of Sciences. The magnetic field was directed perpendicular to the film plane, and the signal at the Hall contacts was measured at two opposite directions of the field with respect to the sample with dc-electric current switching. Features of measuring the Hall Effect are described in detail in the works [11, 12].

Results and Discussion

Fig. 1 shows the field dependences of the Hall resistance at $T = 4.2$ K. It can be seen that the Hall resistance ρ_{xy} is positive for films 10 and 20 nm thick, and changes sign to negative with increasing thickness. In this case, the value of ρ_{xy} increases monotonically with increasing sample thickness. This is clearly seen from Fig. 2, *b*, which shows the dependences of the Hall coefficient RH on the film thickness d, as well as the “dimensional” dependences of its value modulo |RH| (see inset in Fig. 2, *b*).

Of those presented in Fig. 1 and 2, it can be concluded that holes are the main charge carriers for films 10 and 20 nm thick, while electrons are the main charge carriers for samples with thicknesses of 30, 50, and 75 nm. It can be seen in Fig. 2, *a*, that there is no linear dependence for the Hall coefficient RH vs reciprocal sample thickness, 1/*d*. However, surprisingly enough we reveal the RH linear dependence on film thickness, *d* (Fig. 2, *b*). It should be stressed that 95% confidence band (that is 2σ criterion) covers experimental data fit to linear function. Since there are “surface” and “bulk” current carriers in topological insulators [13], then it can be assumed that the main carriers in the “near-surface” layer are holes, and in the bulk, electrons. This can explain the change in the sign of the Hall resistance (Fig. 1) and the Hall coefficient during the “transition” from “thin” (10 and 20 nm) to “thicker” (d ≥ 30 nm) samples. The fact is that the number of “surface” carriers in all films is approximately the same, because it is mainly determined by the film surface and does not depend on the thickness *d*. On the contrary, the number of “bulk” carriers depends on *d*, and its specific fraction compared to “surface” holes increases with increasing sample thickness.

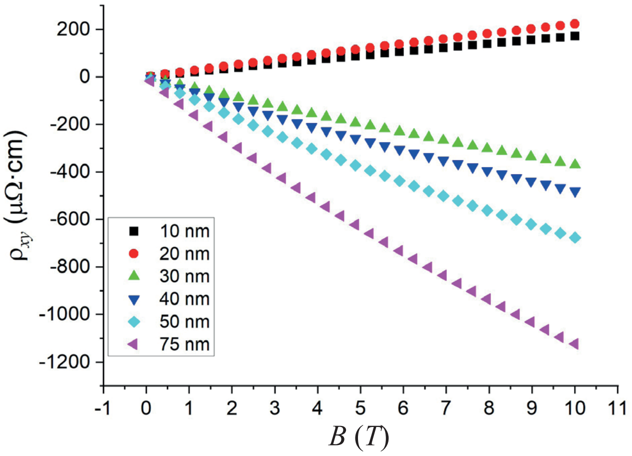

Fig. 1. Field dependences of Hall resistivity in Bi_2Se_3 films at $T = 4.2$ K

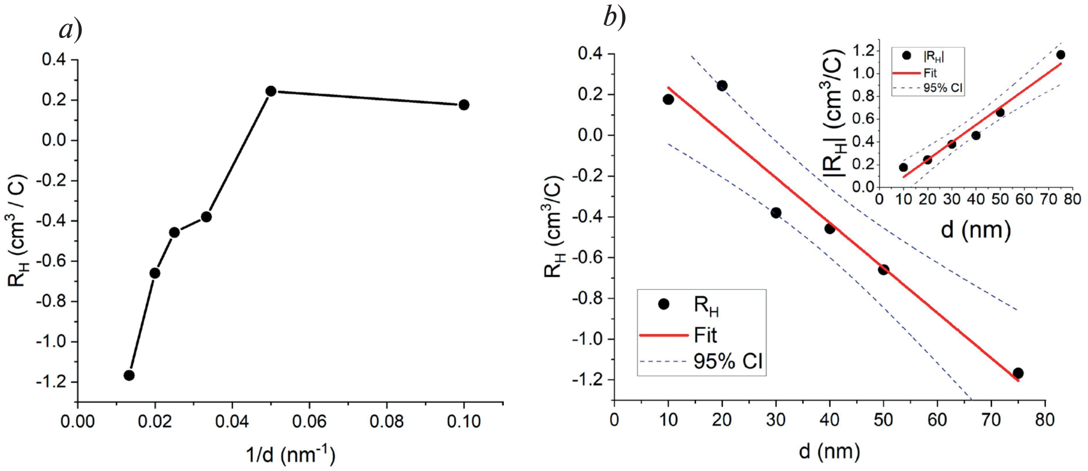

Fig. 2. Dependence of the Hall coefficient on the (*a*) reciprocal thickness and (*b*) thickness Bi_2Se_3 films at $T = 4.2$ K

If these considerations are correct, then it is logical to assume that a monotonic decrease in the concentration of charge carriers n with increasing d should be observed, and in the “size” dependences of their mobility μ, a singularity may appear in the region of the “transition” from 20 to 30 nm of the films, since it is in this region that the sign of the Hall resistance ρ_{xy} and the Hall coefficient RH change.

Fig. 3 shows the dependences of the concentration of charge carriers n and their mobility μ on the thickness of the Bi_2Se_3 films. It can be seen (Fig. 3, *a*) that the concentration n decreases monotonically with increasing film thickness *d*, tending to “saturation” at *d* = 75 nm. At the same time, there is an “anomaly” in the dependence μ = *f* (*d*) in the “transition” region of 20–30 nm in the form of a sharp jump in the mobility value with a decrease in the value by almost a factor of two.

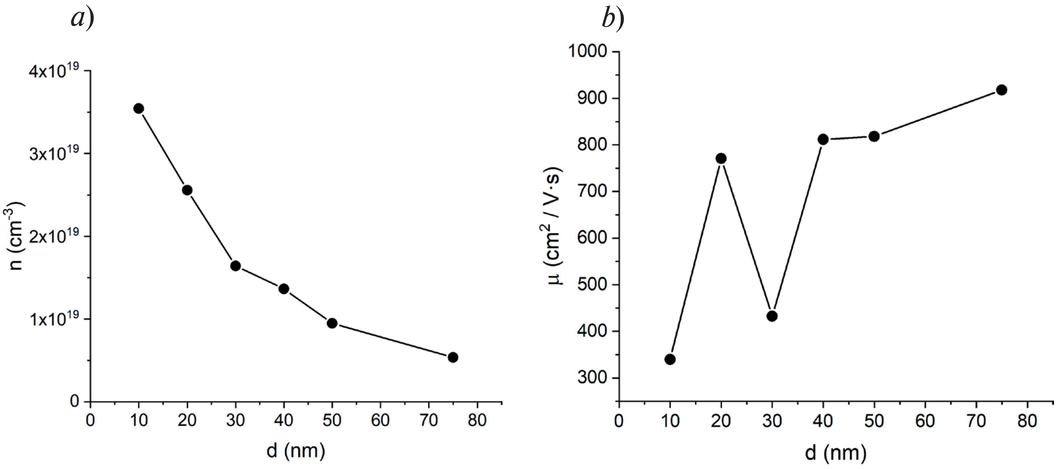

Fig. 3. Dependences of concentration (a) and mobility (b) of charge carriers on the thickness Bi_2Se_3 films at $T = 4.2$ K

We should note that in our previous paper we studied the size effect in zero-magnetic field conductivity in thin epitaxial films of Bi_2Se_3. In this paper we extended that study by measurements of Hall effect in the same films and observed the size effect. In contrast with our expectations, that the effect will be linear, the experiments shows that the effect is non-linear on reciprocal film thickness, $1/d$. However, we observed the linear dependence the RH on film thickness, *d* (Fig. 2, *b*). This linear dependence has confirmed within 95% confidence band of the experimental data fit to the linear function. This is primary experimental results of this study.

Conclusion

In conclusion, in this paper we performed the analysis of Hall Effect measurements and by utilizing the single-band model estimated the concentration and the mobility of charge carriers in thin epitaxial films of Bi_2Se_3. It should be stressed, that the single-band model is based on an assumption that material exhibits the only one type of charge carriers. However, it should be noted, that, as a rule, topological insulators (in particular Bi_2Se_3) have both electron and hole type, due to complex electronic structure [14] and their Fermi surface contains many sheets. It would be useful to perform data analysis by utilization two-band model (see, for example, [15]). In addition, there is another complication which is a necessity to separate the “surface” and “bulk” charge carriers. These studies are on-going.

Considering, that in this paper we also observed the size effect, i.e., the dependence of the Hall resistance and the Hall coefficient on the sample thickness, the developing complete model is challenging task.

Primary experimental result of this study is linear dependence the RH on Bi_2Se_3 film thickness, *d* (Fig. 2, *b*).

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