Physics of Semiconductors. Physics of thin films

UDC 538.935
EDN TFGFTE
https://www.doi.org/10.33910/2687-153X-2023-4-2-75-80

Effect of a transverse electric field on the resistance of thin films of the $Bi_{1-x}Sb_x$ (x = 0–0.12) system on mica

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For citation: Grabov, V. M., Komarov, V. A., Pozdnyakov, S. V., Gerega, V. A., Suslov, A. V. (2023) Effect of a transverse electric field on the resistance of thin films of the $Bi_{1-x}Sb_x$ (x = 0–0.12) system on mica. *Physics of Complex Systems*, 4 (2), 75–80. https://www.doi.org/10.33910/2687-153X-2023-4-2-75-80 EDN TFGFTE

Received 1 March 2023; reviewed 7 April 2023; accepted 7 April 2023.

Funding: This study was supported by the Ministry of Education of the Russian Federation as part of the state-commissioned assignment (project No. VRFY-2023-0005).

Abstract. The paper is devoted to the study of transverse electric field effect on transport properties of charge carriers in bismuth and bismuth-antimony thin films. Experimental results reveal the existence of electric field effect in thin films of composition up to 12 at.% Sb. The dependencies of resistance on magnitude of electric field are obtained in a wide range of film thicknesses. A qualitative interpretation of the observed effect is given based on the analysis of the mobility of electrons and holes in films depending on the sign of the electric field and the film thickness.

Keywords: bismuth, bismuth-antimony, thin films, electric field effect, mica substrate

Introduction

The electric field effect (EFE) in semiconductors has been well studied. The EFE is a powerful tool for changing the electronic properties of near-surface layers of a semiconductor. At present, this effect underlies the technology of metal-dielectric-semiconductor silicon microelectronics.

It is of interest to use the EFE to change the electronic properties of semimetals—bismuth and its alloys with antimony. Taking into account the features of the energy spectrum of charge carriers in bulk semimetals and its thin films (Chang et al. 2019; Ferreira 1968; Jezequel et al. 1997), EFE can lead to new effects.

EFE in semimetals has not been practically studied until now. There are several works on the study of EFE in bismuth films (Butenko et al. 1997; 1999; 2000; Hong et al. 2020). However, the information presented there does not allow one to obtain a complete picture of the manifestation of this effect in semimetals. The factors listed above led us to study EFE in semimetal films.

The paper presents the results of the study of EFE on the resistance of bismuth and bismuth-antimony (with antimony content 0, 3, 5, 8, and 12 at.%) films on thin mica substrate.

Experimental methods

The bismuth and bismuth-antimony thin films were produced by vacuum thermal deposition in a vacuum up to 10^{-5} Torr in the thickness range of 50–1000 nm. Bismuth-antimony films were produced using discrete thermal evaporation. The use of this method ensures a uniform distribution of antimony over the volume of the film. Muscovite mica 20–40 μm thick was used as a substrate.

The films were deposited on the substrate at a temperature of 120 °C and subsequently annealed at a temperature of 250 °C. The annealing duration was 30 min. The film deposition modes ensure the obtaining of large-block films on a mica substrate (the block sizes are much larger than the film thickness). Producing films with uniform block sizes is important, since it was shown that block size significantly affects the transport properties of charge carriers in semimetal films (Komarov et al. 2019).

The crystal structure was studied by atomic force microscopy (AFM) and Xray diffraction (XRD) using the equipment of Herzen University interdisciplinary core facilities. The study shows that the crystallographic orientation of the film crystal is such that the (111) plane of the crystal is parallel to the film plane, which is typical for bismuth films (Grabov et al. 2020; Krushelnitckii et al. 2017).

The study of the influence of the transverse electric field on the resistance of the film was carried out on a capacitor structure (Fig. 1). In this structure, the substrate was a dielectric, on one side of which a semi-metallic film was deposited and on the other side there was a metal field electrode. Contact pads were deposited on the edges of the film to carry out electrical measurements. The field electrode corresponds to cover only the active part of the bismuth film. The geometric dimensions of the active part of the film were as follows: the width was 1 mm and the length was 0.5 mm. The measurements were carried out at a direct current through the films and an alternating voltage at the field electrode. This made it possible to directly measure the change in the film resistance as a function of the potential at the field electrode and increase the accuracy and repeatability of the results obtained. The measurements were made in the frequency range 50–200 Hz. The polarity of the control field was determined from the polarity of the field electrode, i. e., positive polarity means that the film under study is negatively charged. The measurements were carried out at temperatures of 300 K and 77 K.

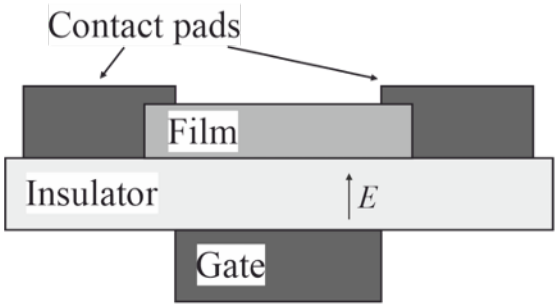

Fig. 1. Scheme of samples capacitor structure

Experimental results

Fig. 2 illustrates the results of the study regarding the EFE on the resistance of $Bi_{0.97}Sb_{0.03}$ films of various thicknesses. As can be seen from Fig. 2, the dependence of the resistance on the transverse field changes significantly with the film thickness. In films of large thickness, it has a non-linear character, both with positive and negative polarity at the field electrode. In $Bi_{0.97}Sb_{0.03}$ films, at a positive potential at the field electrode, an increase in the film resistance is observed with increasing field strength. The relative magnitude of the change increases with decreasing film thickness. With a negative polarity on the field electrode, the resistance of films with a thickness of 50 nm and 100 nm decreases. In thicker films, the dependence has a minimum. The position of the minimum shifts to the region of higher field strength with decreasing film thickness. Thus, for a 250 nm film, only the minimum is reached, but there is no increase in resistance within the limits of the achievable control field strength. A similar character of the dependences is also observed in films of pure bismuth.

https://www.doi.org/10.33910/2687-153X-2023-4-2-75-80

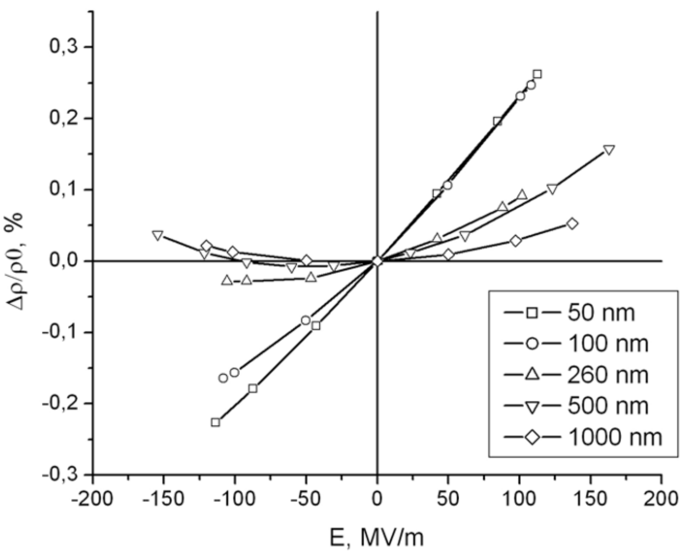

Fig. 2. Relative change in the resistance of $Bi_{0.97}Sb_{0.03}$ films of different thicknesses on the electric field strength at T =77 K

With an increase in antimony concentration, the observed dependences change in form. As an illustration, Fig. 3 shows similar dependences for $Bi_{0.92}Sb_{0.08}$ films. Comparison of the results shown in Fig. 2 and Fig. 3 reveals significant differences between them. For 500 nm thick films, the dependences qualitatively coincide in shape. For 250 nm films, the dependences change qualitatively: in $Bi_{0.97}Sb_{0.03}$ films, the resistance minimum is observed at negative polarity, while in the $Bi_{0.92}Sb_{0.08}$ film, it passes into the region of positive polarity at the field electrode. In 50 and 100 nm $Bi_{0.92}Sb_{0.08}$ films, the sign of the effect is opposite to that of the $Bi_{0.97}Sb_{0.03}$ films. A further increase in the concentration of antimony in the films leads to the fact that for films in the entire range of thicknesses, a decrease in resistance is observed at a positive potential at the field electrode.

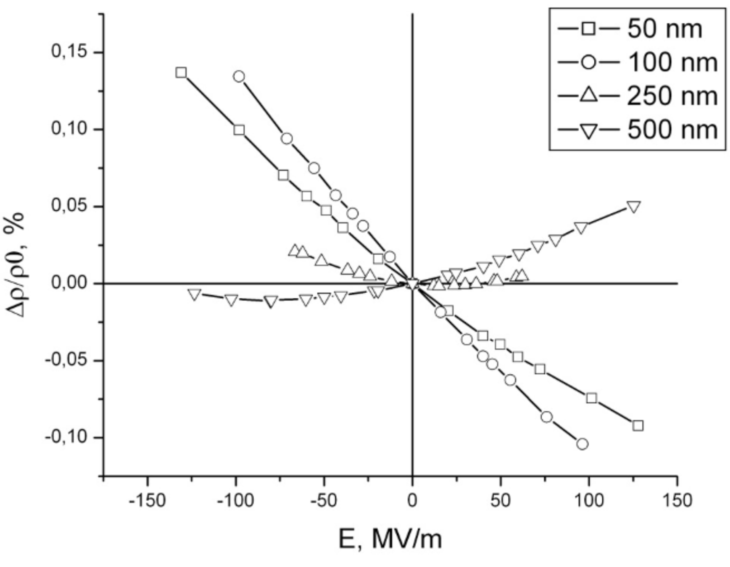

Fig. 3. Relative change in the resistance of $Bi_{0.92}Sb_{0.08}$ films of different thicknesses on the electric field strength at T =77 K

When comparing the dependences of the film resistance on the field strength of films of various compositions of the same thickness of 50 nm, two types of dependences can be distinguished (Fig. 4). The first type includes films of pure Bi, and bismuth-antimony 3 at.% and 5 at.% Sb, in which the resistance increases at positive polarity. The second type includes films of bismuth-antimony 8 at.% Sb and 12 at.% Sb, in which the resistance decreases at positive polarity of the field electrode. A similar trend is also preserved in thicker films.

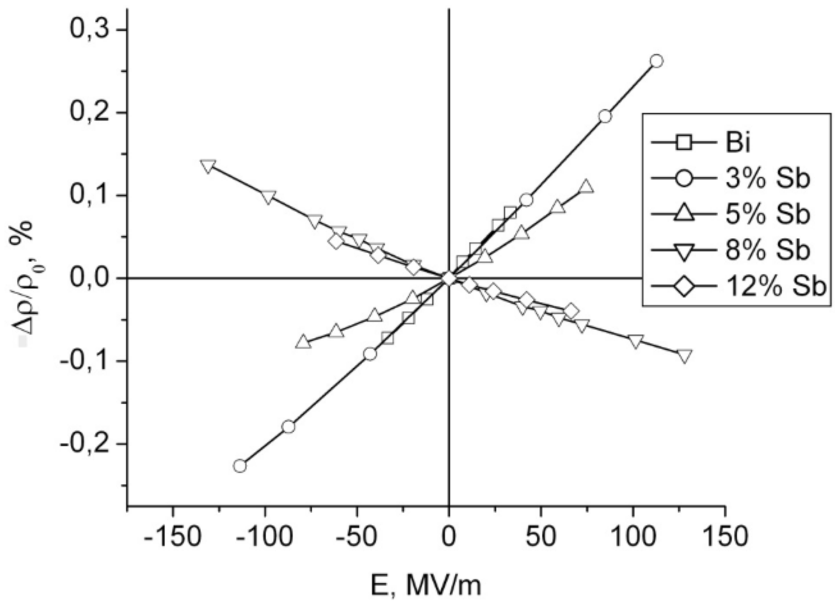

Fig. 4. Relative change in the resistance of 50 nm thick films with different antimony content on the electric field strength at T = 77K

To characterize the magnitude of the effect, we used the coefficient

$$B = \frac{(R - R_0)}{R_0 E}$$

Table 1 lists the values of the coefficient *B* for 50 nm films of various compositions. Films with a thickness of 50 nm were chosen to estimate the magnitude of the effect primarily because, for these films, the dependence of the resistance on the magnitude of the electric field strength is closest to linear, i. e., coefficient *B* is a constant value.

Table 1. The value of the coefficient *B* for 50 nm thick films of various compositions at 77 K

	Bi	**3 at.% Sb**	**5 at.% Sb**	**8 at.% Sb**	**12 at.% Sb**
B,10^{-3} %/MV/m	2.29	2.17	1.23 (1.48)	–0.878	–0.665

An increase in the film thickness leads to the fact that the dependence of the resistance on the field strength ceases to be linear, i.e., coefficient *B* ceases to be a constant value and its value decreases. In the studied films, the greatest deviation from the linear dependence is observed when the sign of the potential at the gate electrode corresponds to the resistance decreases: it is a negative potential for Bi films, 3 at.% and 5 at.% Sb, and a positive potential for films of 8 at.% and 12 at.% Sb.

 https://www.doi.org/10.33910/2687-153X-2023-4-2-75-80

Discussion

Before a discussion of the results obtained is started, it should be noted that the EFE in semimetals is fundamentally different from the effect in semiconductors. In semiconductors, the concentration of intrinsic charge carriers is very low, and free charge carriers are due to the ionization of dopant atoms. This leads to the fact that regions depleted of free-charge carriers can exist in the semiconductor. In semimetals, even at $T = 0$ K, the concentration of free charge carriers is nonzero. For example, in bismuth at $T = 4.2$ K, the concentration of free charge carriers is 3×10^{23} $1/m^3$. This fact makes it impossible to create regions with low electrical conductivity; one can only slightly increase or decrease it. Charging a semimetallic electrode leads to an increase in the concentration of one type of carriers and a decrease in the concentration of another type of charge carriers. The total concentration of charge carriers changes insignificantly. This suggests that the change in electrical conductivity is associated with the difference in the mobility of charge carriers of different signs and its change—with a change in the concentration of these charge carriers.

In thin semimetal films, the mobility of charge carriers is largely determined by the action of the classical size effect. As shown in (Komarov et al. 2019), the thickness of the film reduces the electron mobility to a greater extent than the mobility of the holes, and the block sizes reduce the mobility of the holes more strongly. This leads to a change in the ratio of the mobility of electrons and holes in films of different thicknesses and with different block sizes.

A change in the antimony content in the alloy leads to a change in the band structure of the alloy. The ongoing changes in the band structure lead to a decrease in the contribution of holes to galvanomagnetic effects: the Hall coefficient of the films is 8 at. % and 12 at.% Sb has a negative sign over the entire temperature range and for all film thicknesses (Grabov et al. 2017). For example, Fig. 5 shows the dependences of the Hall coefficient on temperature for films of various compositions with a thickness of 1 μm.

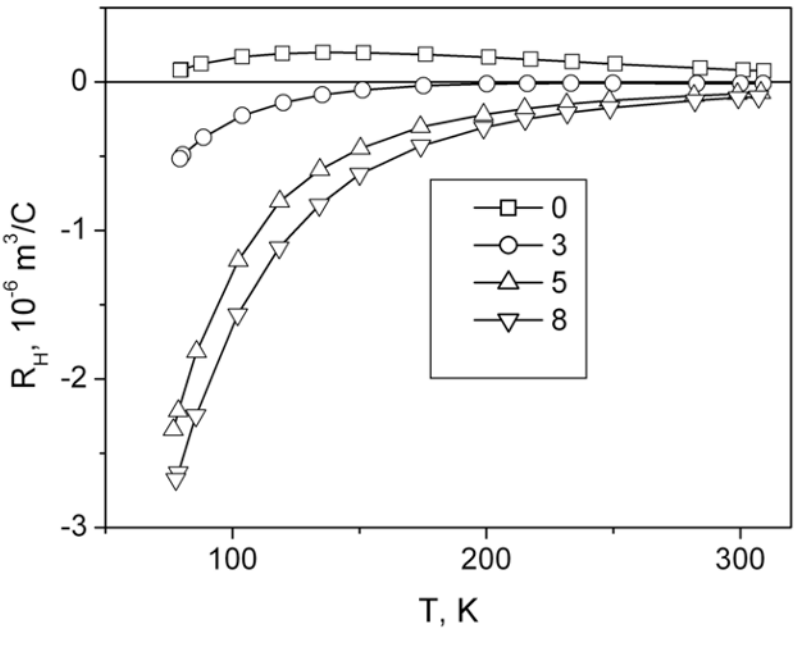

Fig. 5. Temperature dependence of the Hall coefficient of films of various compositions (0–8 at.% Sb) with a thickness of 1 μm (Grabov et al. 2017)

Accounting for the above facts, we can explain the observed experimental dependences as follows. Consider, for example, films of pure bismuth. When a positive potential is applied to the field electrode, the film becomes negatively charged; it increases the concentration of electrons and decreases the concentration of holes. Considering that in a bismuth film with a large block size, the mobility of holes is higher than that of electrons, such an increase in the electron concentration leads to an increase in the resistance of the film. The change of polarity at the field electrode leads to the enrichment of the film with holes and the depletion of electrons. At the initial stage, this leads to a decrease in the resistance of the film. With an increase in the excess concentration of holes, the resistance increases.

The position of the minimum resistance of the film depends on the initial ratio of the mobility of electrons and holes in the film. This ratio strongly depends on the action of the size effect, and hence on the film thickness.

Conclusions

The study experimentally confirmed the existence of an EFE in thin films of bismuth and bismuth-antimony alloys up to 12 at.% Sb. The dependence of the magnitude of the EFE on the thickness of the films was obtained: with a decrease in the thickness of the film, the magnitude of the effect increases. The dependence of the magnitude and sign of the effect on the concentration of antimony in the alloy is obtained. A qualitative interpretation of the observed effect and its change is given.

Conflict of Interest

The authors declare that there is no conflict of interest, either existing or potential.

Author Contributions

Vladimir Grabov—data analysis, editing, supervision; Vladimir Komarov—development of the setup for measuring the EFE in thin films, data analysis, editing, supervision; Stepan Pozdnyakov—measurements of the EFE in thin films; Vasilisa Gerega—sample production, preparation of the manuscript and figures; Anton Suslov—XRD and AFM measurements. All authors have read and agreed to the published version of the manuscript.

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