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Effect of a transverse electric field on the resistance of Bi thin films on a mica and polyimide substrate

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Abstract. This work studies the effect of a transverse electric field on the resistance of bismuth thin films. The existence of an electric field effect in bismuth thin films on mica and polyimide has been experimentally confirmed. The study obtained experimental dependences of resistance on the transverse electric field strength for bismuth films of various thicknesses on mica and polyimide. It also revealed changes associated with a decrease in the thickness of the film and the material of the used substrate. A qualitative interpretation of the observed effect was given based on the analysis of changes in the mobility of free charge carriers in films depending on the direction of the electric field, as well as the thickness of the film and the substrate material.

Keywords*:* bismuth, thin films, resistance, transverse electric field effect

Introduction

The effect of the transverse electric field in semiconductors has been thoroughly studied. It is a powerful tool for changing the electronic properties of the near-surface layers of a semiconductor. This effect currently underlies the technology of the silicon microelectronics metal-dielectric semiconductor.

The use of the electric field effect (EFE) to change the electronic properties of semimetals, bismuth and its antimony alloys, is a matter of interest. EFE can lead to new effects given the peculiarities of the energy spectrum of charge carriers in semimetals.

EFE in semimetals has not been studied to date. There are several papers on the study of EFE in bismuth films (Butenko et al. 1997; 1999; 2000), but the information contained in them does not provide a holistic picture of how this effect manifests itself in semi-metals. All of the above factors prompted us to study EFE in films of semimetals. We have conducted a study of EFE in films of the bismuth-antimony system up to 12 at. % Sb on a mica substrate. The results were presented in (Grabov et al. 2023). A significant change in the field dependence of the resistance on the film composition was found. An increase in the antimony concentration leads to a change in the sign of the effect to the opposite. A significant dependence of the effect on the film thickness was found. We explained these changes by the changing mobility ratio of free charge carriers.

To confirm the proposed explanation of the EFE change, we conducted a study of the effect of crystallite sizes on EFE in films of semimetals.

Experiment

The research was carried out on films of pure bismuth. The films were obtained by vacuum thermal spraying in a vacuum of 10^{-5} Torr. Muscovite mica with a thickness of 20–40 microns and polyimide with a thickness of 30 microns were used as the substrate. The film was sprayed onto the substrate at a temperature of 120°C, followed by annealing at a temperature of 250°C. The annealing time was 30 min. (Grabov et al. 2023). Films with a thickness of 50–500 nm were studied. The film deposition modes used ensure the production of large-block films on a mica substrate (the block sizes are much larger than the film thickness). The crystallographic orientation of the film crystal is such that the plane (111) of the crystal is parallel to the plane of the film (Grabov et al. 2017). Bismuth films on polyimide have significantly smaller block sizes, and the (111) plane can have a misorientation of up to 10^{o} relative to the substrate plane. The effect of the transverse electric field on film resistance was studied on a capacitor structure in which the substrate was a dielectric. A bismuth film was applied to one side of the substrate, and a metal field electrode was applied to the other (Fig. 1). The bismuth film had contact pads for passing current and measuring the voltage drop. The field electrode covered only the active part of the bismuth film. The geometric dimensions of the active part of the film were 1 mm in width and 0.5 mm in length.

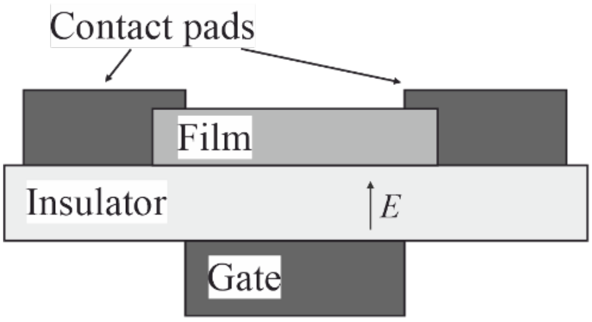

Fig. 1. Diagram of the samples under study

The measurements were carried out using direct current of the film and alternating voltage at the field electrode, which made it possible to directly measure the change in film resistance from the potential at the field electrode. This method improved the repeatability and accuracy of the results obtained. The measurements were carried out in the frequency range of 50–200 Hz. The polarity of the control field was determined by the polarity of the field electrode, i. e. a positive polarity meant that the film under study was negatively charged. The measurements were taken at temperatures of 77 K and 300 K.

Experimental results

The results of the study into the effect of the transverse electric field on the resistance of Bi films of various thicknesses on mica at 77 K are shown in Fig. 2.

As can be seen from the figure above, the dependence of the resistance on the transverse field changes significantly with the thickness of the film. In films of large thickness (500 nm, 250 nm), it has a nonlinear character, both with positive and negative polarity at the field electrode. In films of this composition, with a positive potential at the field electrode, a monotonous rise in film resistance is observed with increasing field strength. The relative magnitude of the change increases with decreasing film thickness. With a negative polarity at the field electrode, the resistance of films with a thickness of 50 nm and 100 nm goes down.

In films of higher thickness, resistance decreases first and then increases. The position of the minimum resistance of the film shifts to a region of greater negative field strength as film thickness decreases. For the 250 nm film, the minimum is thus reached at 75 MV/m, and for the 50 nm film, the minimum is just beginning, and there is no increase in resistance within the achievable control field strength.

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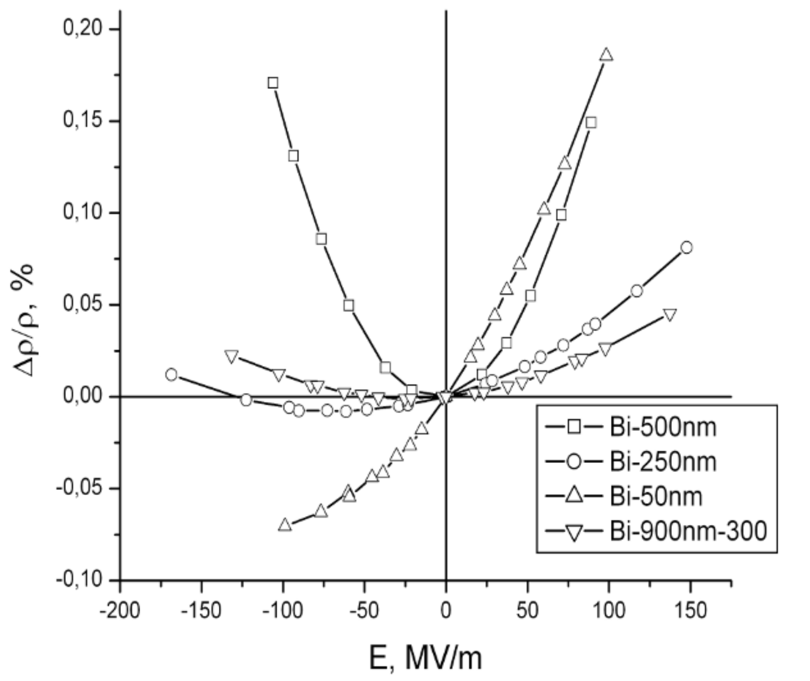

Fig. 2. Relative change in the resistance of Bi films of various thicknesses on mica depending on the electric field strength at T = 77 K

A rise in temperature leads to a decrease in the relative change in film resistance. For comparison, Fig. 2 also shows dependence for a 900 nm thick bismuth film at a temperature of 300 K. Although the magnitude of the change in resistance is less than at 77 K, the nature of dependence is similar to the dependence at 77 K.

Fig. 3 shows the study findings relating to the effect of EFE on the resistance of bismuth films on polyimide. The figure presents a significant change in the dependence of resistance on the strength of the transverse electric field. Films of all the studied thicknesses on polyimide have similar dependences with a minimum near the electric field strength equal to zero. However, it should be noted that the position of the minimum dependence varies with thickness. In the films with a thickness of 500 nm and 250 nm, it is located at negative values of the control field, and in the 50-nm film, in the region of a small positive field. For the film with a thickness of 100 nm, it practically coincides with a field strength of zero.

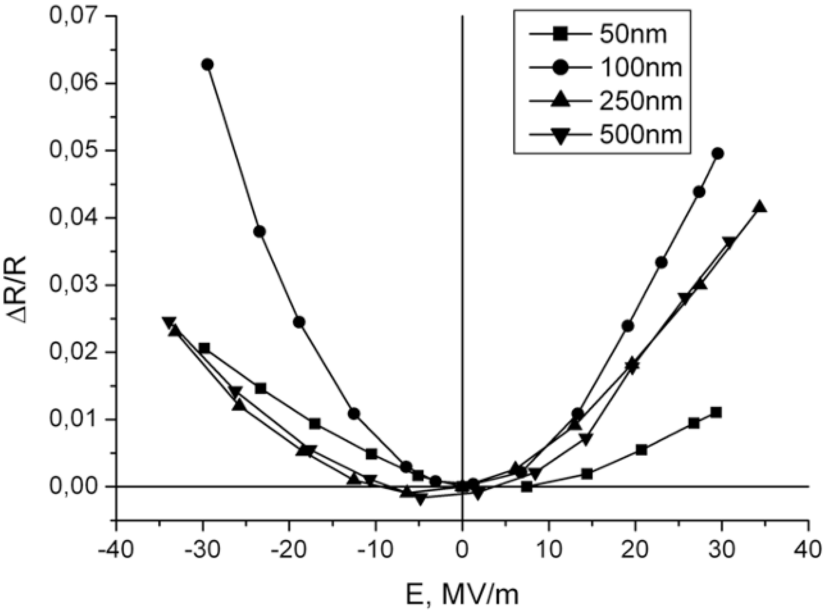

Fig. 3. Relative change in the resistance of Bi films of various thicknesses on polyimide depending on the electric field strength at T = 77 K

Our studies have shown that reducing the size of blocks in bismuth films significantly changes the effect of the transverse electric field on the resistance of the films.

Discussion

As we have already noted, the effect of the transverse electric field in semiconductors and semimetals is significantly different. In semiconductors, the concentration of intrinsic charge carriers is several orders of magnitude lower than in semimetals, and the conductivity is determined mainly by impurity charge carriers, while the mobility of charge carriers is weakly dependent on or independent of their concentration.

In semimetals, the concentration of intrinsic charge carriers is high, so in bismuth, even at 4.2 K, the concentration of free charge carriers is $3 \cdot 10^{23} 1/m^3$. The introduction of donor or acceptor impurities up to a certain point only changes the ratio between the concentrations of electrons and holes in the semimetal. In addition, an increase in the concentration of charge carriers is accompanied by a decrease in their mobility. This is clearly seen in the dependence of the resistivity of bismuth single crystals on the degree of doping with donor and acceptor impurities. Fig. 4, for example, shows the dependence of the resistivity of a single crystal of bismuth doped with tin on the degree of alloying.

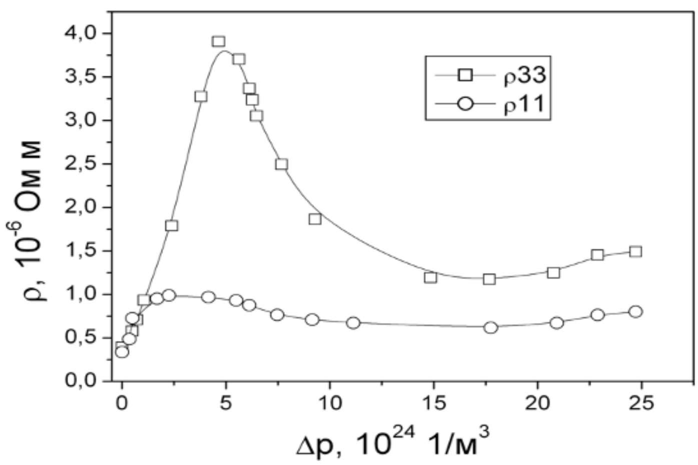

Fig. 4. Dependence of the resistivity of a single crystal of bismuth doped with tin on the difference in the concentrations of holes and electrons. T = 80 K

An increase in hole concentration during tin alloying leads to a rise in the resistivity of the bismuth single crystal. The effect of a transverse electric field on bismuth films is similar to the effect of doping these films with donor and acceptor impurities.

The second feature of the transverse electric field in semimetals is the small thickness of the shielding in these substances, which is a consequence of the high concentration of free charge carriers compared with semiconductors. In bismuth at 4.2 K, for example, calculation gives a screening thickness of about 9 nm. In semiconductors with weak doping, this value can reach tens of micrometers. However, given that the dependence is exponential, it can be assumed that the changing concentration in the 'tails' of the exponent changes film resistance.

The third factor contributing to the effect of the transverse electric field on the resistance of thin films of semimetals is the classical dimensional effect. The peculiarity of the anisotropy of the properties of charge carriers in bismuth and bismuth-antimony alloys leads to the fact that the dimensional effect on the film thickness and block sizes can change the ratio of the contributions of electrons and holes to kinetic effects. This can lead to a change in the manifestation of the effect in films of different thicknesses. This mechanism is reviewed in detail using the example of the Hall and Seebeck effects in (Komarov et al. 2019).

One should also take into account that the bismuth film on the substrate is strongly deformed. This deformation leads to a change in the concentration of free charge carriers. At 77 K, the concentration of free charge carriers in a bismuth film on mica is about 0.75 concentrations in a single crystal and 2.9 concentrations in a single crystal in a polyimide film. This also leads to an additional change in carrier mobility. This is most evident in differential kinetic effects, such as the Hall effect. For example, Fig. 5 shows the temperature dependences of the Hall coefficient of bismuth films with a thickness of 800 nm with a different ratio of film thickness (L) and crystallite size (D).

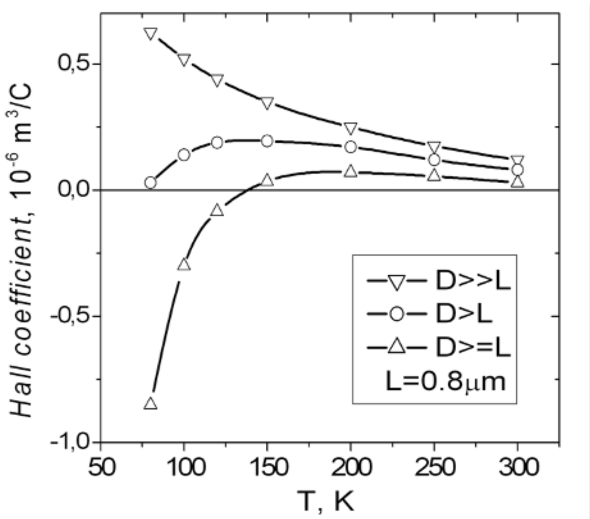

Fig. 5. Temperature dependence of the Hall coefficient of bismuth films with a thickness of 800 nm on mica with a different ratio of block size and film thickness

The above facts can elucidate the observed experimental dependencies. When a positive potential is applied to the field electrode, the film becomes negatively charged, which increases the concentration of electrons and reduces 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 elevated concentration of electrons leads to a higher resistance of the film. A change in the polarity on the control electrode induces the enrichment of the film with holes and a decrease in the number of electrons. At the initial stage, this leads to a reduced film resistance. With a rise in the excess concentration of the holes, the film resistance goes up due to a decrease in their mobility (Grabov et al. 2023)

Conclusion

Our study experimentally confirmed the existence of EFE in bismuth thin films. The dependence of the EFE value on the film thickness was obtained: as the film thickness decreases, the effect increases. A significant influence of the substrate material on the magnitude and nature of the EFE dependence was found, and a qualitative interpretation of the observed effect and its changes was given.

Due to the small magnitude of the effect, it can serve as an additional tool for the study of electronic and hole subsystems in bismuth thin films.

Conflict of Interest

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

Author Contributions

Vladimir Grabov — editing, supervision; Vladimir Komarov — research concept development, data analysis, editing, supervision; Veronika Prostova —producing samples, measurements of electrical properties. All the authors have read and agreed to the published version of the manuscript.

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