Methods of experimental studying the galvanomagnetic properties of thin semimetals films under conditions of plane stretch

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Abstract. In our work we present the method for studying the galvanomagnetic properties of thin semimetals films under plane stretch using a specially designed experimental installation. We discuss the design of this installation and the research methods on the example of the thin bismuth films on glass substrates.

1. Introduction

At present, the field using the methods of deformation engineering and physical phenomena in solids arising under the mechanical stresses and deformations is actively developing. This approach to research and control electronic properties of materials, to create new type of electronic devices with enhanced energy efficiency has gained so much attention that such researches have emerged into a new industry called stretchtronics [1]. Stretchtronics is especially important for semimetals and narrow-gap semiconductors. In these materials the electronic spectrum near the Fermi level is characterized by small energy gaps or zone overlaps, which leads to a significant change in the electronic properties during their deformation, especially in the region of cryogenic temperatures. In particular, the stretchtronics methods give the possibility for fine tuning of the Fermi level and topological states [2].

So, at the present time, the studies of the deformation effect on the electrical properties of thin films of semimetals and narrow-gap semiconductors in a wide range of temperatures and magnetic fields become very important. In most studies of the effect of deformation on thin films’ physical properties, deformation is created by using the mismatch of the film material lattice constants and the substrate. This method requires the use of very thin films. For example, for bismuth films, the mismatch effect between the film lattice constants and the substrate during the deposition process is already leveled by a 3–5 bilayer [3].

When studying the temperature dependences of the physical properties of films, there is also another mechanism for plane deformation – the discrepancy between the temperature expansion of the film and substrate materials [4–6]. This method of film deformation can be used for both thin films and films of large thickness. The substrate material effect on the structural perfection of the films and their crystallographic orientation can be neutralized using intermediate coatings, such as polyimide
varnish [6]. However, in this method it is extremely difficult to separate the contributions to the changes in the studied properties from the temperature and from the deformation.

In this paper we offer the method for creating a plane stretch of a thin film directly when measuring its galvanomagnetic properties in a continuous mode.

2. Experimental techniques

The main idea of this method is the dome-shaped deformation of an elastic substrate (for example, glass) by two concentric cylindrical surfaces (cylindrical knives), one of which is fixed (larger diameter), and the position of the other is set by a micrometer screw. As the result, the substrate takes the form close to the shape of a spherical segment. The inner surface of the substrate in this case is compressed, and the outer, together with the film deposited on it, is stretched (figure 1). If the film is sufficiently small and located in the center of the deformed region, in the first approximation the deformation can be considered uniform flat.

\[
\frac{\Delta S}{S} = \frac{R + \frac{3}{4}h}{\frac{R^2}{h} + R + \frac{1}{4}h} \cdot 100\%,
\]

where \( S \) – is the surface area; \( R \) – radius of curvature; \( h \) – substrate thickness; \( D \) and \( d \) – diameter of the knives; \( \Delta \) – its relative displacement.

The stretch value linearly depends on the relative displacement of the cylindrical knives. Also the stretch value depends on the substrate thickness – the greater the thickness, the greater film deformation can be achieved with the same displacement of the micrometer screw, but the harder should be the equipment as a whole.

To reach our goals, the experimental installation was created. The main structural elements are made from bronze. The accuracy of the micrometer screw movement is about 0.01 mm. The installation design gives the possibility to make experiments in vacuum in the temperature range of 77–300 K, for this purpose the evacuated volume is placed in a Dewar vessel with liquid nitrogen. The dimensions of the measuring cell are selected so that the FL-1 electromagnet can be used to create a magnetic field with induction up to 0.8 T. Borosilicate glass 0.1 mm thick was used as a substrate. For this substrate, the stretch of about 0.2% was achieved, which is confirmed by an independent measurement of the curvature radius of the substrate surface by optical methods. Galvanomagnetic properties are measured in a constant magnetic field at the constant current.

The bismuth films were created with the help of thermal evaporation in a vacuum up to \( 10^{-5} \) Torr. The substrate temperature during deposition was 390 K. Annealing was carried out at 520 K during 1 hour.
The surface structure was analyzed using an NT-MDT Solver Pro-47 atomic force microscope using selective chemical etching [7].

3. Results and discussion

The results of the structure analysis showed that the films were block with a block size of 2–3 μm. The orientation of the C3 axis of the crystallites is oriented along the normal to the film surface.

Figure 2 shows the dependences of the resistivity and magnetoresistance upon induction of a magnetic field of 0.6 T on the deformation of a 1 μm bismuth film on a glass substrate at a temperature of 77 K.

It can be seen from the figure that with increasing film stretching, the resistivity and magnetoresistance increase according to a law similar to a linear one. This is in qualitative agreement with the studies of the films on substrates with different coefficient of thermal expansion (CTE) [5, 8]. The plane stretch, similar to the stretch obtained by the proposed method, is realized on substrates with CTE less than the CTE of the substrate material. In the aggregate, the increasing of the resistivity and magnetoresistance qualitatively indicates on the decrease in the concentration of charge carriers.

The Hall coefficient in the film, taking into account its crystallographic orientation, corresponds to the weak component of the tensor of the Hall coefficient $R_{123}$. This component is very sensitive to the balance of the contributions of electrons and holes; therefore, its analysis is rather difficult. $R_{123}$ of the studied films has a positive sign over the entire range of deformations. The absolute value of the Hall coefficient decreases with the increasing of the film stretching.

In the case of block films, the quality of the crystal structure has a great influence on the value of the Hall coefficient [8]. In this case, it is very interesting to study and compare the dependences of the Hall coefficient on the plane deformation of monocrystal bismuth films and massive bismuth monocrystals under the action of hydrostatic pressure and uniaxial deformations, which is supposed to be carried out later.

4. Conclusions

Thus, the paper presents a technique for studying the galvanomagnetic properties of thin semimetals films under conditions of controlled plane deformation. It is shown that the plane deformation of thin pure bismuth films on the glass substrates causes the increase in the concentration of charge carriers, which qualitatively coincides with the studying results of the bismuth films under plane deformation caused by other methods. This method gives the possibility to clarify the deformation effect on the change in the band structure of thin semimetals and narrow-gap semiconductors films.

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