

# Investigation of InSb:Mn thin films magnetoresistance by I-V characteristics method

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**Abstract.** We have investigated the effect of magnetoresistance in the thin films of InSb:Mn using the data of I-V curves. The thin films were produced by pulsed laser deposition (PLD) method from the InSb+MnSb composite alloy targets with the concentrations of MnSb to 20%. The temperature dependence of magnetoresistance of the films has been studied in the temperature range from 10K to 300K.

## 1. Introduction

The fabrication of In<sub>1-x</sub>Mn<sub>x</sub>Sb thin films with a uniform distribution of magneto-active component presents a challenge [1]. The investigation of thin films of ferromagnetic semiconductors (AIII-BV):Mn is of great interest in connection with a possibility of their use in the magnetoelectronic and spintronic devices [2]. A bulk sample of the InSb-MnSb composite eutectic represents the narrow band semiconductor of p-type that has the lattice parameters approaching those of InSb and is characterized by high mobility of carriers. The Curie temperature in In<sub>1-x</sub>Mn<sub>x</sub>Sb alloys reaches 600 K. Low solubility of manganese in InSb is responsible for formation of nanoclusters of MnSb in bulk sample with concentrations higher than 3,5% [3]. Though solubility of manganese in InSb is small, the pulsed laser deposition method (PLD) makes possible obtaining homogeneous thin films of InSb:Mn with concentration of manganese to 20% from the targets of InSb-MnSb alloys. The PLD method allows producing thin films of various materials on single-crystal, amorphous and flexible organic substrates [4]. The presence of drops is the main factor of reduction in the quality of the films obtained by traditional PLD. Application of the droplet-free mode of PLD provides the production of the high-quality smooth uniform films on the substrate of room temperature owing to removing of the drops which take off from the target and fall on the substrate in the process of film deposition. In the process of film growth the mechanical separator permits the passage of quickly flying atoms and ions to the substrate, but presents falling of large drops on the growing film. The droplet-free mode of film deposition provides smooth homogeneous high-quality films even at the ambient temperature of the substrate thanks to elimination of the drops which are emitted from the target onto the substrate in the deposition process [5]. The films of the

diluted magnetic semiconductors with high Curie temperature and high extent of spin polarization of carriers [6] were obtained by this method. The magnetoresistance in thin films of InSb:Mn can have influence on the characteristics of the magneto-operated p-(InSb+MnSb)/n-InSb diodes in which the effect of giant magnetoresistance is observed [7-9].

## 2. Experimental procedure

The thin InSb:Mn films were grown on sapphire (0001) substrates by ablation with an excimer KrF laser using the droplet-free pulsed laser deposition (PLD) method [4]. The size of substrates was 10x10 mm. The InSb+MnSb composite alloy target contained up to 20% of MnSb. The composition homogeneity and the morphology of the films were investigated by the X-ray spectroscopy, the SEM method with an attachment for energy-dispersive X-ray spectroscopy, by X-ray phase analysis (XPS), and by the AFM method with a magnetic cantilever. We used Hall method to measure the conductivity type of the charge carriers in the films. The films exhibited p-type conductivity. The thickness of the films was determined with the aid of the MII-4 interferometer.

## 3. Results and discussion

The investigation of the films with SEM showed the homogeneous distribution of the In, Sb and Mn elements in the surface layer of the film. According to the results of energy-dispersive X-ray spectroscopy, the concentration of these elements corresponded to the composition of the initial target. We deposited 10 films with concentration of manganese from 3,5% (eutectic) up to 20%. Thickness of the films was 50-80 nm. The results of the AFM analysis using a magnetic cantilever point to the presence of ferromagnetic clusters of the size of 4 nm of our thin films of InSb:Mn with concentration

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of manganese 20%. The InSb: Mn films with MnSb concentration of 3,5% (eutectic) were examined with the help of SEM and AFM, which showed the homogeneity of the distribution of elements on the surface of the InSb:Mn film. X-ray diffraction studies of the InSb:Mn film on a Bruker D8 Advance diffractometer showed the presence of very weak MnSb peak (Fig.1).

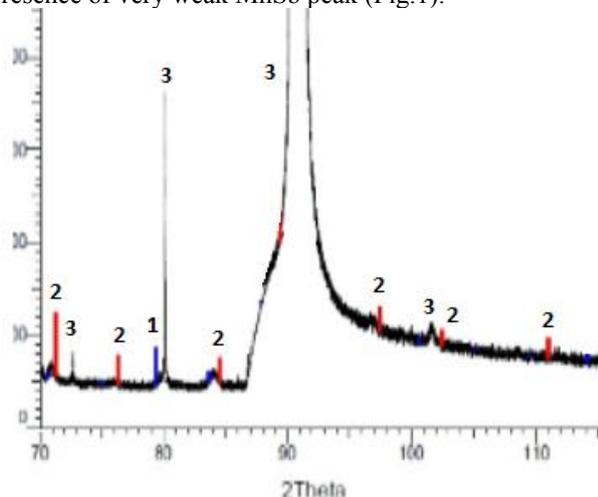


Fig.1. X-ray pattern of an InSb:Mn film with MnSb concentration of 3,5% (eutectic) on a sapphire substrate: 1 – MnSb phase, 2 – InSb phase, 3 – InMnSb phase (eutectic).

### 3.1. Magnetoresistance of thin InSb:Mn films

In this paper, we have for the first time investigated the magnetoresistive effect in the thin InSb:Mn films using the  $I$ - $V$  curve method. Thin films of InSb:Mn ferromagnetic semiconductors are widely investigated [1,7]. However, the papers does not show the dependence of the magnetoresistance of films on the voltage applied in the plane of the film. Such dependencies can be obtained from the  $I$ - $V$  characteristic. The magnetoresistance of the  $p$ -(InSbMn) films with MnSb concentration of 3,5% (eutectic) was measured under the constant magnetic field of two values, 0.15 T and 1 T. The measurements were made under room temperature. The field of 0.15 T was applied collinearly to the current flowing in the film (Fig.2), and the field of 0.15 T or the field of 1 T was applied perpendicular to the film plane and to the current flowing in the film (Fig.3). The indium ohmic contacts were formed on the film surface before measuring of the  $I$ - $V$  curve using the Keithley 2612 device. The  $I$ - $V$  curve was measured in the range of applied voltage from -10 V to +10 V in steps of 1 mV. Switching of the voltage polarity allowed reversing the polarity of the electric field. Figures 2, 3 illustrates the dependence of the magnetoresistance of the  $p$ -InSb:Mn thin films on the voltage for collinear and perpendicular electric and magnetic fields under room temperature. The magnetoresistance  $MR$  (%) was measured on the basis of  $I$ - $V$  curve in the temperature range from 10 K to 300 K using the formula  $(R(H) - R(0)) / R(0) * 100\%$ , where  $R(0)$  and  $R(H)$  are the resistances in the absence and presence of a magnetic field, respectively. It was observed that the magnetoresistance of the sample was negative and depended on the magnetic field orientation with respect to the current direction at room temperature.

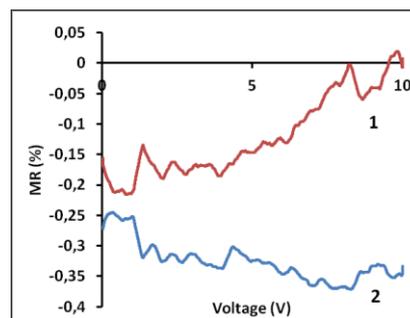


Fig.2. The magnetoresistance of the  $p$ -InSb:Mn thin films vs the voltage for collinear electric and magnetic fields located in the plane of the film under room temperature (1 -  $E\uparrow\downarrow B$ , 2 -  $E\uparrow\uparrow B$ ),  $B=0.15$ T.

The observed different behavior of the magnetoresistance of the films depending on mutual orientation of the collinear magnetic and electric fields can be caused by different mean free paths of the charge carriers for the parallel and antiparallel directions of the fields  $E$  and  $H$  in the thin InSb:Mn films caused by the presence of surface magnetic nanoclusters, which are registered by the AFM with a magnetic cantilever.

The measurements were made of the dependence of the film magnetoresistance on the voltage for the magnetic field perpendicular to the film surface for two magnetic field values  $B = 0.15$  T and  $B = 1$  T. The electric field is localized within the film plane (Fig.3).

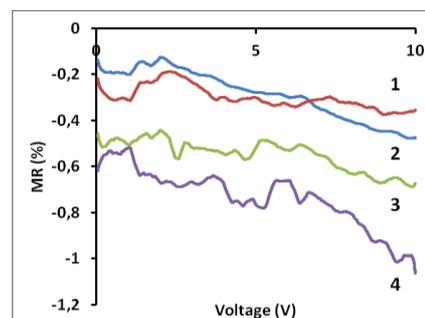


Fig.3. The magnetoresistance of the film vs the voltage for the magnetic field perpendicular to the film under room temperature (1 -  $B = 0,15$  T  $\uparrow$ , 2 -  $B = 0,15$  T  $\downarrow$ , 3 -  $B = 1$  T  $\uparrow$ , 4 -  $B = 1$  T  $\downarrow$ ).

For the magnetic field normal to the film a similar dependence on the magnitude of the field is disclosed [7].

The temperature dependence of the magnetoresistance of  $p$ -InSb:Mn films with the MnSb concentration of 20% was studied in the temperature range from 10 K to 300 K. The investigations were carried out by measuring and analyzing their  $I$ - $V$  curves in the temperature range from 10 K to 300 K. The measurement wires were connected to the indium ohmic contacts which were formed on the surface of each film. The films were placed in a cryostat. The measurements of the  $I$ - $V$  curves were performed in the field with permanent magnet and without it. The dependences of the magnetoresistance for a fixed temperature and magnetic field were calculated on the

basis of the I-V curve. The results of measurements R and calculations MR are shown in Fig. 4, 5.

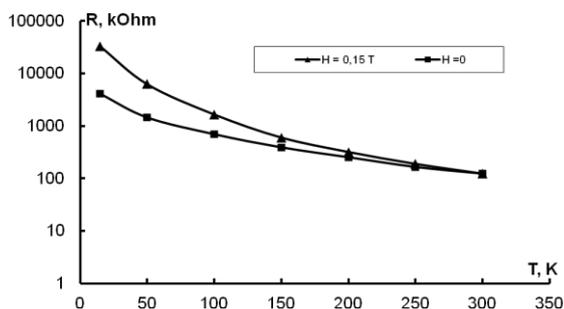


Fig.4. The dependence of the film InSb:Mn resistance on the temperature in the absence (squares) and in the presence of a magnetic field of 0.15 T (triangles). The voltage applied to the sample is 10V.

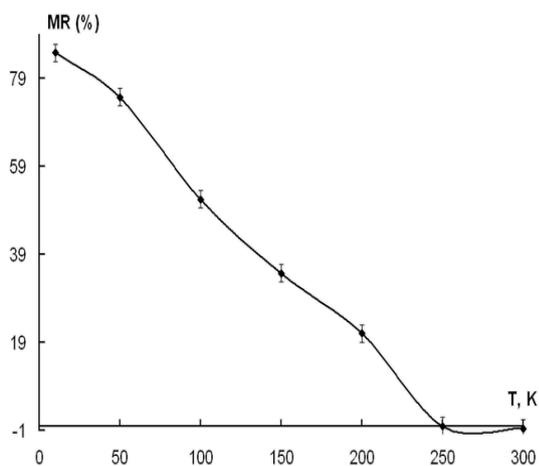


Fig. 5. The dependence of the thin InSb:Mn film magnetoresistance on the temperature at an applied voltage of 10V and under magnetic field of 0.15 T in the plane of the film.

Figure 5 shows that the crossover from positive to negative giant magnetoresistance (GMR) is observed at the temperature of 250 K during cooling. As the sample cooled down, the value of GMR increased and reached 80% at 15 K in the magnetic field of 0.15 T directed perpendicular to the plane of the film. Thus, it has been shown that the magnetoresistance of the InSb:Mn thin films is registered even at room temperature under small magnetic fields, which opens up considerable prospects for using this material to create various spintronic devices.

### Conclusion

The temperature dependence of the magnetoresistance of InSb: Mn films is studied. In the temperature range of the film from room temperature to 250 K, a negative magnetoresistance was observed. At 250 K, a transition from a negative giant magnetoresistance (GMR) to a positive one was observed. As the sample cooled down, the GMR increased and reached 80% at 15 K in a magnetic field of 0.15 T directed perpendicular to the plane of the film. The magnetoresistance of InSb: Mn thin films is recorded even at room temperature in small

magnetic fields, which opens the prospect of using this material to create various spintronic devices.

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