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InSb semiconductor-metal hybrid structure (SMH) as a magnetic sensor prepared by flash evaporation

F. S. Terra[1], A. A. Higazy[2], G. M. Mahmoud[1], A. M. Mansour[1*]

[1]*Physics department, National Research Center, Dokki, Cairo, Egypt*
[2]*Physics department, Faculty of Science, Menofia University, Shebeen El-Kom, Egypt*

Abstract

n-type indium antimonide-Au van der Pauw (vdP) shape hybrid macro-structure were successfully fabricated on glass substrates by flash evaporation technique. The elemental composition of the prepared films was confirmed by energy dispersive X-ray spectroscopy microanalysis (EDX). The morphologies and crystal structures of the films were characterized by scanning electron microscopy (SEM) and X-ray diffraction (XRD) respectively. The magnetoresistance of the prepared hybrid structure was measured at room temperature and 100mA current and a variable magnetic field (0-8kG). The effect of sensor geometry on magnetoresistance was studied.

Keywords: Semiconductor metal hybrid structure, Magnetoresistance, Flash evaporation.
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1. Introduction

Magnetoresistance (MR) is the relative change of electrical resistance produced in a current-carrying conductor or semiconductor due to application of a magnetic field H. The magnetoresistance of a material consists of a physical component and a geometric component. The physical component involves the magnetic field dependence of material properties such as mobility or carrier density. The geometric component is due to a change in the current distribution in the device when subjected to a magnetic field. Geometric MR is influenced by electrode configuration, material composition, and the shape of the device [1].

Narrow-gap semiconductor/metal hybrid structures have recently been developed to exploit the geometric component of MR in order to exhibit much larger room-temperature MR than physical-MR-based sensor materials [2]. In 2000, Solin et al. [3] reported a large change in resistance of Au-InSb hybrid structures when subjected to a transverse magnetic field. The magnitudes of this magnetoresistance (MR) significantly surpass the traditional MR caused by Lorentz-force deflection of current. This effect was called extraordinary magnetoresistance (EMR). Magnetic field sensors based on EMR have exhibited room-

[*]) For correspondence; E-mail: amamansour@gmail.com.

temperature resistance increases (ΔR/Ro) up to 75000% for a transverse magnetic field of 4T.

The EMR effect has important implications for magnetic field sensing applications that include position/speed sensing and high-density magnetic data storage. In particular, prospective EMR read-head sensors would exhibit higher sensitivity and significantly faster response times than conventional multi-layer metallic (spin-valve) read heads [4]. This class of MR device has been characterized almost exclusively for sensor applications, most notably for the development of read-head sensors for ultrahigh-density magnetic recording applications [5-7].

A common feature of all III-V compounds is that they dissociate during vaporization and, as a result, fractional evaporation takes place. This makes it impossible to obtain stoichiometric thin films by direct vaporization of the compound [8]. A good candidate is the flash evaporation method. Flash evaporation is a powerful method for the deposition of films whose constituents have different vapor pressures [9].

In the present work, the MR of SMH structure prepared by flash evaporation was measured at different magnetic field values and different diameter of metallic inclusion. Also, the aim of this research is to establish a relationship between the radius of metallic cylindrical layer to the radius of semiconductor cylindrical layer (a/b) and the magnetoresistance at room temperature of a magnetic sensor prepared by flash evaporation.

2. Experimental Procedures

2.1. Fabrication of n-InSb-Au Hybrid Structure

The principle of flash evaporation is that the powdered material is continuously delivered to the evaporation source (usually a boat) and from there flash evaporated. Therefore, in this method the average vapour composition is exactly stoichiometric, but local composition fluctuations can be a problem.

A 18 mm diameter cylindrical n-InSb thin films layer was prepared by flash evaporation technique under 10^{-4} Pa onto pre-cleaned glass substrates held at a temperature ~ 340 K using a high vacuum coating unit (Edwards E 306 A, England). The flash evaporation attachment is nearly similar to that described in ref. [10]. The thickness of InSb films was monitored with the help of a digital quartz thickness monitor as 1.4 μm.

To obtain van der Pauw semiconductor-metal hybrid structure, by using of thermal evaporation technique under 10^{-4} Pa held at a temperature ~ 340 K using a high vacuum coating unit (Edwards E 306 A, England), another cylindrical layers of Au (with diameters 2, 4, 6, 8, 10, 12, 13, 14, 15 and 16mm) were evaporated through suitable masks on the earlier prepared 18 mm diameter cylindrical n-InSb thin films layer. The resulted samples shape were as shown in Fig. 1 where a is the radius of Au cylindrical layer (2, 4, 6, 8, 10, 12, 13, 14, 15 and 16mm) and b is the radius of InSb cylindrical layer (equal to 18mm).In order to measure the magnetoresistance of Au-InSb hybrid structure, electrical contacts were equipped with copper wires mechanically applied to the four metallic electrodes using thermosetting silver paint.

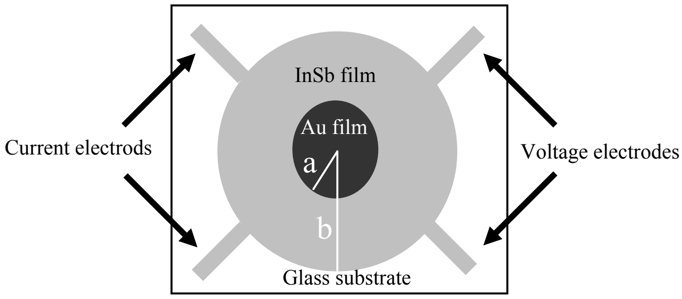

Fig.1: InSb-Au van der Pauw shape hybrid structure.

2.2 Characterization Techniques

The structural properties of the n-InSb films were investigated by X-ray diffraction (XRD), using filtered CuKa radiation with a Philips X'pert operated at 40kV and 30 mA. The film morphology was investigated by scanning electron microscopy (SEM) using model Philips XL 30 attached with EDX Unit, with accelerating voltage 30 K.V., magnification 10x up to 400.000x and resolution 3.5nm.

The magnetoresistance measuring experiment contains an electro-magnet (NEWPORT instruments-Type A) with a current source power supply (Ealing Beck Ltd. Germany). The power supply is controlled by a digital current controller (LakeShore, 321 Autotuning). The sample was placed in a copper holder of a metallic cryostat (Cryo. Industries, USA), which was suitable for the magnetic measurements.

The relative magnetoresistance MR was measured from the potential difference (V) between two points that were parallel to the sample current direction. It was calculated as follows:-

$$MR = \frac{\Delta\rho}{\rho_o} = \frac{\rho_B - \rho_o}{\rho_o} = \frac{R_B - R_o}{R_o} \tag{1}$$

Where ρ is the resistivity, R is the sample resistance. The subscripts B and 0 denote the measurement under magnetic field and at zero magnetic field respectively under constant sample current (100mA). The current across the sample was measured by a milliammeter, while the voltage was measured by a Kiethley 617 electrometer. All measurements were carried out at room temperature and constant applied current which equal to 100mA.

3. Results and Discussion
3.1 Morphology Characterization

The morphology and microstructure of the n-InSb prepared by flash evaporation technique were analyzed by SEM as shown in Fig. 2. It is shown that the grains of different size and shape are homogeneously distributed over the entire surface of the sample. The grain size of the InSb is in the range of 50-100 nm. The large sized grains are agglomeration of many small ones.

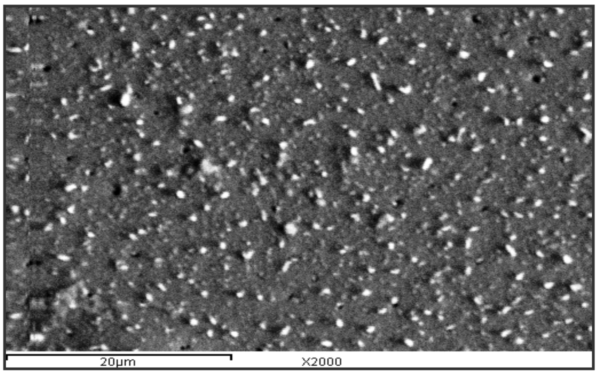

Fig.2: SEM of prepared n-InSb film.

3.2 Composition Characterization

Fig. 3 shows the EDX analysis for the InSb film prepared by flash evaporation technique. The In/Sb atomic ratio of the prepared films was computed as 1:1.13, which is near to the stoichiometric ratio. The obtained results give a support for the good quality of the prepared InSb films by flash evaporation technique.

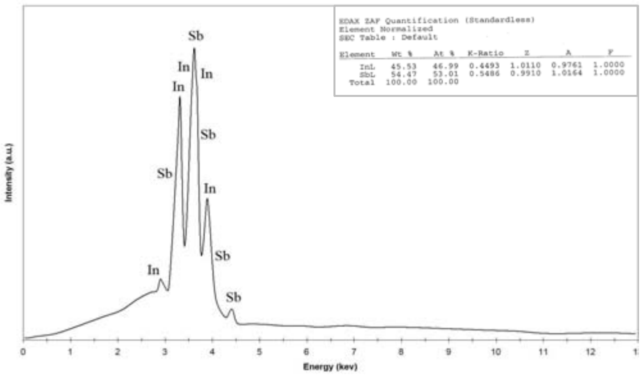

Fig.3: EDX analyses for the n-InSb film.

3.3 Crystal Characterization

X-ray diffraction patterns, XRD of the n-InSb prepared by flash evaporation technique is shown in Fig.4. The diffraction peaks present in the Fig.4 are consistent with the standard JCPDS card No. 73-1985 for InSb cubic system. The maximum intensity in the experimental pattern indicated by (111) plane corresponding to the maximum intensity line for the standard card which gives another support for the stability of the prepared InSb films.

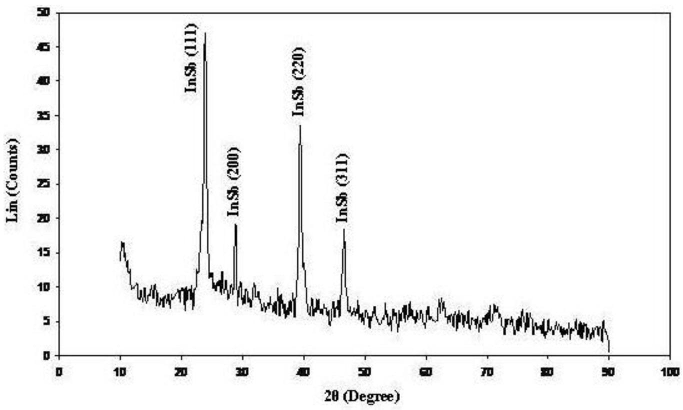

Fig.4: X-ray diffraction patterns, XRD of the n-InSb prepared by flash evaporation technique.

The crystallite size (D) of the InSb film was estimated from the broadening of few XRD peaks (spread in wide 2θ range) using the Scherrer's equation [11]

$$D = \frac{K_s \lambda}{\beta \cos\theta} \tag{2}$$

where λ is the X-ray wavelength of CuK_α (0.15418 nm), β is the width of the peak at half maximum intensity for the thin film , k_s is the Scherrer constant of the order of unity (0.95) and θ is the corresponding Bragg angle.

The dislocation density (δ), which is defined as the number of dislocation lines per unit area of the crystal was evaluated from the formula [11,12]:

$$\delta = \frac{1}{D^2} \tag{3}$$

It is found that the value of the crystallite size (D) is about 15-43 nm and the dislocation density (δ) is about $4.5\text{x}10^{-3} – 5.4\text{x}10^{-3}$ lines nm^{-2} for the InSb film.

3.4 Magnetoresistance results

The resistance and magnetoresistance was carried out as a function of magnetic field and a/b ratio, R(H, a/b). Fig. 5 shows the change of resistance with the change of magnetic field for samples with a/b equal to 2/18, 4/18, 6/18, 8/18, 10/18, 12/18, 13/18, 14/18, 15/18 and 16/18.

At H=0, it shows that R (0, a/b) drops monotonically with increasing a/b as a result of the increasing conductance of the inhomogeneity. However, because the conductivity of the Au shunt is finite, R (0, a/b) saturates at large a/b ≈ 12/18.

When saturation occurs, the resistance becomes field-independent up to a critical field above which it rises rapidly with increasing field. Thus, for sufficiently large a, the device acts like a magnetic diode or switch [2]. The resistance of the hybrid structure at high H is dominated by the resistivity of semiconductor and the metal film has a negligible contribution. This important observation supports the model of current redistribution [13]

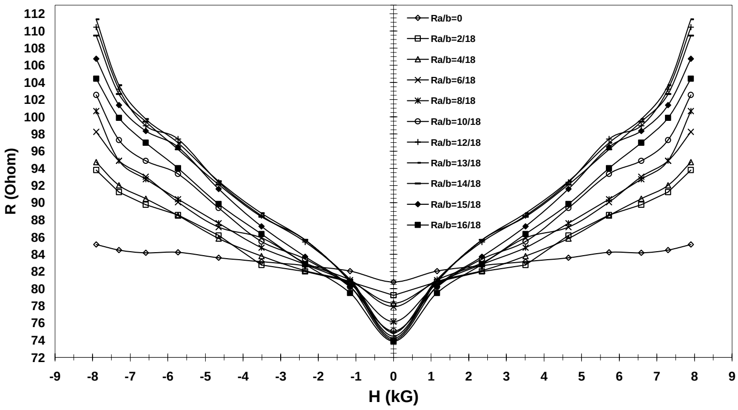

Fig.5: Resistance-magnetic field as a function of a/b ratio.

Fig. 6 shows the variation of MR with magnetic field for different a/b values. It shows an increase of MR with increase of H for all a/b values.

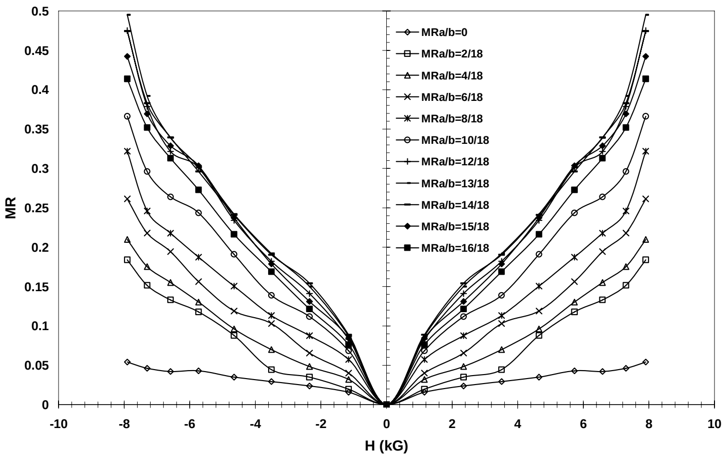

Fig.6: Magnetoresistance-magnetic field as a function of a/b ratio.

Fig. 7 shows the variation of Log(MR) with Log(H) for the investigated SMH structures. Straight line relationship which agrees the assumed relationship. The slope of the straight lines varies from ≈0.86 – 1.19.

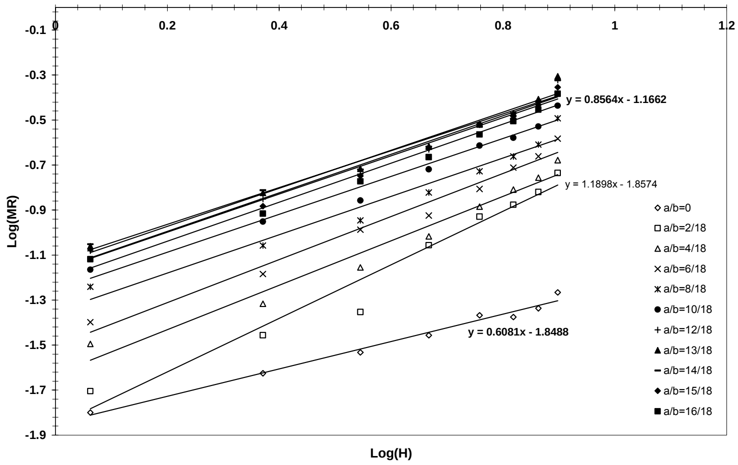

Fig.7: Log (MR) versus Log (H) at room temperature and different a/b ratio values.

When the values of MR in Fig. 6 are compared by that of the traditional sample (a/b=0), Fig. 8 is obtained, which gives the enhancement of MR of hybrid structure. This occurs due to the magnetic field dependant redistribution of the current between the semiconductor and the metal which exhibits a large difference in the conductivity [2]. At zero magnetic field, current flows preferentially through the metallic shunt since it is highly conductive and the current density vector is parallel to the electric field. In this case the shunt acts as a short circuit and the resistance of the hybrid structure is lower than that of a homogenous structure of the same size. At higher magnetic field, the current is deflected by the Lorentz force which becomes at an acute angle to the electric field. By virtue of the large mobility of the narrow-gap semiconductor matrix, this angle, i.e. the Hall angle, approaches 90°. Since the local electric field is perpendicular to the shunt-semiconductor interface, the current becomes tangent and is deflected around the shunt. At a sufficient magnetic field the current travels only in the semiconductor matrix; in this case the shunt acts as an open circuit. This transition of the shunt from short circuit to open circuit results in an enhanced geometric MR [14].

Fig. 9 shows the variation of MR with the increase of a/b ratio at different H values. It is shown that there is an increase of MR with the increase of a/b ratio which takes its maximum value at a/b ≈ 12/18. The MR dependence upon a/b for a family of fixed magnetic fields (Fig. 9) shows that it grows monotonically up to a /b ≈ 12/18 or 13/18, above which it decreases.

The transition of the inhomogeneity from short circuit at low H to open circuit at high H results in a geometric enhancement of the MR of the semiconductor even if its physical MR is zero. The geometric MR increases with a/b increase because $R_0^{\ a/b}$ decreases.

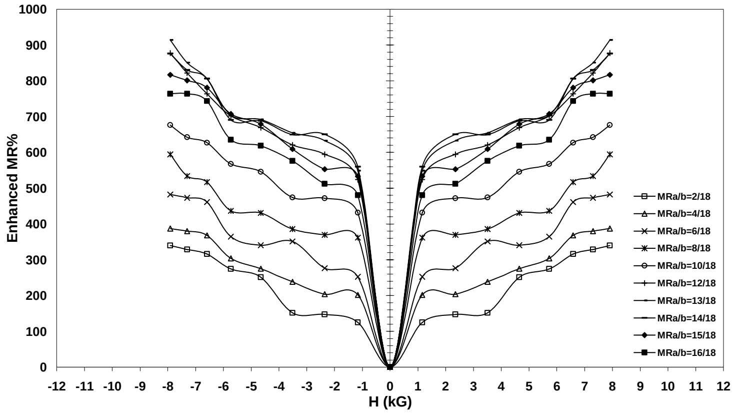

Fig.8: Optimizations of MR%-magnetic field as a function of a/b ratio.

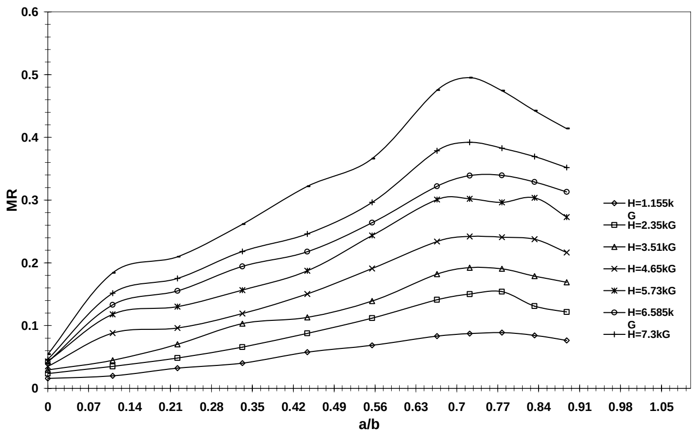

Fig.9: Relationship between magnetoresistance and a/b ratios as a function of magnetic field.

However, when a/b becomes sufficiently large so that the low-field current flows mostly through the inhomogeneity, the MR will be that of the inhomogeneity itself, which is negligibly small for Au. Then an appreciable MR is only observed when H is sufficient to deflect the current from the inhomogeneity such that the conductance through the metallic inhomogeneity is smaller than the conductance through the semiconductor cylindrical layer of thickness b-a.

4. Conclusion

n-type indium antimonide-Au van der Pauw (vdP) shape hybrid structure were successfully fabricated on glass substrates by flash evaporation technique. The XRD and EDX results give us a support for the quality and stability of the prepared InSb films by flash evaporation technique which indicates that the flash evaporation is a powerful method for the deposition of films whose constituents have different vapor pressures**.**

n-type indium antimonide-Au van der Pauw (vdP) shape hybrid structure shows an enhancement of room temperature magnetoresistance reaching about 900% greater than the traditional shape at the ratio a/b≈12/18 or 13/18 and at magnetic field 7.905 kG. Despite the InSb films were deposited on glass substrates with macrodimention, the obtained MR results are considered promising from our point of view.

In addition, the simple vdP geometry may not be optimal. Whatever the ultimate magnitude of MR, it is clear that careful design of simple metal-semiconductor structures can result in sensors with substantially enhanced room temperature geometric MR.

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