ELECTRICAL AND TRANSPORT PROPERTIES OF FeBSi AMORPHOUS THIN FILMS

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ABSTRACT. The aim of this paper is to present some results concerning the electrical, galvanomagnetic and structural properties of Fe$_{60}$B$_{40-x}$Si$_x$ (x = 10, 20 and 30) thin films in view of their utilization for resistive components and magnetic sensors. As compared to the other materials, which are used for magnetic sensors, Fe$_{60}$B$_{40-x}$Si$_x$ thin films exhibit medium Hall sensitivity values, but they present a good linearity of the Hall voltage dependence of the magnetic field induction. The influence of the composition and post-deposition annealing on the electrical conductivity and Hall sensitivity of Fe$_{60}$B$_{40-x}$Si$_x$ thin films is also discussed.

1. INTRODUCTION

During the last years interest is raised to the study of amorphous alloys due to their combination of magnetic property applications in the field of high performance electro-magnetic devices. The transition metal – metalloid alloy thin films present interesting magnetic and electrical properties for different application and they attracted a considerable interest from point of view of material science and new engineering materials [1, 2]. FeBSi alloy with high metalloid content both in bulk form and thin films, are of great interest in the research field due to some special characteristics such as high corrosion resistance, high values of the electrical resistivity and low value temperature coefficient of resistivity (TCR). The transport properties of FeBSi alloys strongly depend on scattering of conduction electrons at disordered magnetic spins which in turns depend on the local environment of magnetic atoms [1].

The aim of this paper is to present some results concerning the electrical, galvanomagnetic and structural properties of Fe$_{60}$B$_{40-x}$Si$_x$ thin films in view of their utilization for manufacturing magnetic and/or resistive sensors. The dependence of conductivity, TCR and Hall sensitivity on the Si and B content and annealing temperature of these thin films was investigated.

2. EXPERIMENTAL DETAILS

FeBSi thin films were prepared by a conventional R.F. diode sputtering system (Z-400 Laboratory Sputtering Plant) using a composite target. The sputtering is made of Fe plate (7.5 cm in diameter) on whose surface small B and Si rectangular plates were disposed. Modifying the number of B and Si plates on the target surface B and Si content in films was changed. FeBSi thin films have a thickness of about 0.5 µm and they were deposited at room temperature, on glass and Mo substrates.

The structure of FeBSi thin films was investigated by X-ray diffraction (XRD) analysis. An X-ray diffractometer with a monochromatized Mo-K$_{a1}$ radiation was used in a Bragg - Brentano arrangement. The composition of the films deposited onto Mo substrates was determined by the electron microprobe technique.

The electrical conductivity and temperature coefficient of resistance (TCR) were measured using standard D.C. four - probe technique, with an experimental set - up described in a previous paper [4]. For TCR measurements the samples were disposed on a metallic plate, uniformly heated between 22°C and 122°C, in vacuum.

The Hall voltage measurements were made in air, at room temperature, for a sample biasing current of 2 mA and magnetic induction values up to 2T.
The structural analysis and the electrical and galvanomagnetic measurements were made as–deposited and thermally treated samples. \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) thin films were successively thermally treated in vacuum at temperatures between 130°C and 300°C, for 1 h at each temperature.

3. RESULTS AND DISCUSSION

The dependence of the Hall voltage \((U_H)\) on the magnetic induction \((B)\) for as-deposited \( \text{FeBSi} \) thin films is presented in Fig. 1. One can see that the Hall voltages increase with increasing metalloid content up to 40%. For this study we chose the compositions: \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) with \( x = 10, 20 \) and 30.

Table 1 presents the electrical conductivity of the as-deposited and annealed \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) thin films. The electrical conductivity for as-deposited \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) thin films decreases while Si content increasing and B content decreasing. After the thermal treatments at temperatures between 130°C and 300°C the electrical conductivity increases for all studied compositions.

The dependence of TCR on the annealing temperature for \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) thin films is presented in Fig. 2. It can be observed that the TCR values are lower than \( \pm 100 \text{ ppm/oC} \) for the entire investigated compositional range and are negative for \( x = 20 \) and 30 and positive for \( \text{Fe}_{60}\text{B}_{30}\text{Si}_{10} \). The thermal treatment up 200°C has not a significant influence on the TCR values. The presence of Si in films improves their thermal stability.

The dependence of the Hall voltage \((U_H)\) on the magnetic induction \((B)\) for \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) thin films in as–deposited state and after the thermal treatment at 300°C, is presented in Fig. 3a and 3b respectively. The negative value of Hall voltage for as-deposited \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) thin films and after thermal treatment at 300°C, indicates that electrons are dominant charge carriers in these materials. The Hall voltage dependence on the magnetic induction values for \( \text{Fe}_{60}\text{B}_{40-x}\text{Si}_x \) thin films is linear up 1.5 T. The thermal treatments improve the linearity for studied samples. The maximum values of the linearity errors are listed in Table 2, for both as–deposited and thermally treated at 300°C samples. We calculated the linearity error values by using the relation: 

\[
\varepsilon = \frac{(U_i - U_k)}{U_m},
\]

for the i point on the curve, \( U_i \) is the measured voltage in the i point, \( U_m \) is maximum Hall voltage.
value for the linear range, observed influence of the thermal treatment on the electrical conductivity (Table 1).

The dependence of the Hall sensitivity ($|\Delta U_H| / \Delta B$) on the temperature of the thermally treated Fe$_{60}$B$_{40-x}$Si$_x$ thin films, for magnetic induction values up to 1 T is presented in Fig.4. An increase in Hall sensitivity values after the thermal treatments can be observed for all samples. This is a good agreement with the observed influence of the thermal treatment on the electrical conductivity (Table 1).

Table 2 The maximum linearity error for Fe$_{60}$B$_{40-x}$Si$_x$ thin films

<table>
<thead>
<tr>
<th>Sample</th>
<th>Maximum linearity error for as-deposited samples</th>
<th>Maximum linearity error for samples after annealing at 300°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$<em>{60}$B$</em>{30}$Si$_{10}$</td>
<td>1.5</td>
<td>-0.6</td>
</tr>
<tr>
<td>Fe$<em>{60}$B$</em>{20}$Si$_{20}$</td>
<td>1.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Fe$<em>{60}$B$</em>{10}$Si$_{30}$</td>
<td>-1.4</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Fig. 3. The dependence of the Hall voltage on the magnetic induction for Fe$_{60}$B$_{40-x}$Si$_x$ thin films in as–deposited state (a) and after the thermal treatment at 300°C (b).

Figure 5a shows XRD patterns at room temperature for as–deposited Fe$_{60}$B$_{40-x}$Si$_x$ thin films. It can be observed that the as-deposited Fe$_{60}$B$_{40-x}$Si$_x$ thin films are amorphous and partially amorphous for $x = 10$ and 20 respectively. The XRD pattern for Fe$_{60}$B$_{10}$Si$_{30}$ thin films reveals rather a nanocrystalline phase dispersed in an amorphous matrix. The dispersed nanocrystalline phase is shown by a peak at $2\theta = 19.5$ deg., specific to Fe–based compounds.

The XRD patterns for the samples thermally treated at 130°C and 230°C did not show structural changes as compared with the XRD patterns for as-deposited samples. The XRD patterns for Fe$_{60}$B$_{40-x}$Si$_x$ thin films thermally treated at 300°C for 1 h are presented in Fig 5b. It can be observed that the microstructure of the annealed Fe$_{60}$B$_{40-x}$Si$_x$ thin films consists in a mixture of amorphous and nanocrystalline phases, for all studied samples. The
structural analysis reveals that the addition of Si amounts over 20 at. % favors the formation of the nanocrystalline phase. The nanocrystalline phase could be a mixture of α- Fe and Fe₂B [5]. Although no structural changes are observed by XRD analysis after thermal treatment at 130°C and 230°C, the electrical and galvanomagnetic changes could be due to the structural relaxation phenomena and to the changes of the internal stresses at the atomic level [1].

![Graph showing X-ray diffraction patterns for as-deposited and annealed Fe₆₀B₄₀₋ₓSiₓ thin films](image)

Fig. 5 The X-ray diffraction patterns for as-deposited and annealing Fe₆₀B₄₀₋ₓSiₓ thin films

The experimental data analysis shows that higher Hall sensitivity values for Fe₆₀B₁₀Si₃₀ thin films as compared to Fe₆₀B₄₀₋ₓSiₓ thin films with x = 20 and 30 respectively, are probably due to the nanocrystalline phases, which determine an increase in the electrical conductivity and Hall sensitivity. It is also observed a good linearity of the Hall voltage for values of the magnetic induction up to 1.5 T, this may be interesting in application in the field of magnetic sensors.

4. CONCLUSIONS

The electrical and galvanomagnetic properties of Fe₆₀B₄₀₋ₓSiₓ thin films (with x = 10, 20 and 30) depend on Si content and annealing temperature.

The low electrical conductivity and TCR values of Fe₆₀B₄₀₋ₓSiₓ thin films made them suitable for applications in precision resistors with a good thermal stability (up to 100°C).

The Hall sensitivity of Fe₆₀B₄₀₋ₓSiₓ thin films takes values between 180 μV/T and 330 μV/T, for value of the magnetic induction up to 2 T. The linearity error of the Hall voltage, for magnetic induction values up to 1.5 T, is lower than ± 1.5 %. These characteristics made Fe₆₀B₄₀₋ₓSiₓ (x = 10, 20 and 30) thin films suitable for applications in the field of magnetic sensors, especially for high magnetic fields.

REFERENCES