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Investigation of Magneto-Impedance Effect of Bilayer Iron Films

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Abstract. Magnetoimpedance (MI) cell was fabricated using a non-magnetic layer among magnetic bilayer (Fe/Cu/Fe) on the glass substrate has been studied by using electron microscopy, X-ray diffraction, magnetic and magnetoimpedance measurements. In order to observe MI effect, frequency dependence of impedance measurements has performed under applying static low magnetic fields. The impedance value of the cells has been characterized by using constant 4 mA AC current source at frequencies 1 - 25 MHz and DC magnetic fields (-25 to 25 Oe). Double peak responses have been obtained, showing MI ratios up to % 35 and its sensitivity is around 23.7 %/Oe. For future sensing applications, this material is made a promising candidate for giant magnetoimpedance effect with the range of low price and relatively high sensitivity features.

Keywords: Fe multilayers films, Magnetoimpedance, Sensing element

Çift Katmanlı Demir Filmlerin Manyeto-Empedans Etkilerinin İncelenmesi

Özet. Cam zemin üzerinde manyetik çift katmanlı arasında manyetik olmayan bir tabaka kullanılarak (Fe/Cu/Fe) üretilen manyeto-empedans hücre (ME) elektron mikroskobu, X-ışını kırınımı, manyetik ve manyeto-empedans ölçümleri yapılarak incelenmiştir. ME etkisini gözlemlemek için frekansa bağlı empedans ölçümleri statik düşük manyetik alan altında yapılmıştır. Hücrelerin empedans değeri, 1 - 25 MHz frekans aralığında ve DC manyetik alanda (-25 - 25 Oe) sabit 4 mA AC akım kaynağı kullanılarak karakterize edilmiştir. Çift tepe tepkileri elde edilerek, ME etkisi % 35' e ve duyarlılığı 23.7 %/Oe' e kadar çıkartılmıştır. Gelecekteki sensör uygulamaları için bu malzeme, düşük fiyat aralığında ve kıyasla yüksek hassasiyet özelliklerine sahip dev manyeto-empedans etkisi gösterdiğinden dolayı umut verici bir aday haline getirilmiştir.

Anahtar Kelimeler: Demir çok katmanlı filmler, Manyetoempedans, Sensör element

1. INTRODUCTION

The giant magneto-impedance (GMI) effect is caused a huge change in the electrical impedance of materials with soft magnetic features through applying low direct current (dc) magnetic field. Since its discovery in 1994, the research involving GMI effect sensors has become one of the focus points for potential applications especially in the range of ultra low magnetic fields [1]. Due to its high coherent in which it is located, high stability and reversibility, magnetic sensors based on GMI are currently being used in many applications such as satellite communication technology, high density recording apparatus, high-tech target detections, tracking systems, non-destructive inspection and magnetic marking applications, bio-magnetic measurements [2-6]. A straightforward physical phenomenon which is called the magnetoimpedance is utilized under using of many of these areas. Magnetic sensors perform sensing

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by converting the magnetic field amplitude value directly into an electrical signal [2]. The high-performance magnetic sensors development has been made possible by using a huge impedance change.

By fundamentally, the magnetoimpedance effect is defined as the change of the impedance (Z) of material with magnetic properties under applied dc magnetic field amplitude. Total impedance variation based on the frequency of the alternating current in ferromagnetic materials. This is also the case, Z=Z(f), where f=ω/2π. An electric current flow through an indiscrete plain film the magnitude of magnetic field conceived by the electrical current will excite oscillations of magnetization. It means that the thin film impedance value depends not only on the conductivity (σ), but also its magnetic permeability (μ). Magneto-impedance, GMI ratio, percentage changes with applied DC magnetic field is expressed as follows:

$$\Delta Z(\%) = 100\,\% \frac{Z(H) - Z(H_{max})}{Z(H_{max})} \tag{1}$$

where Z(H) and $Z(H_{max})$ represent the impedance in a magnetic field, H, and maximum magnetic field, H_{max} respectively. And the DC magnetic field sensitivity of a cell of GMI defined as follows:

$$\eta = \frac{(\Delta Z/Z)_{max}}{\Delta(H)} \tag{2}$$

where ΔH is the full width at half maximum peak of GMI (%) versus magnetic field [7, 8]. The H_{max} value is the magnetic field value required to saturate the impedance value. This value is taken in practice as the greatest value of the system being measured [8].

Amorphous thin films could be produced on a substrate by the varied techniques such as chemical or physical deposition, electro deposition, electro spinning, vapour deposition or magnetron sputtering method. The magnetron-sputtering method has become a frequently used technique due to the fast, adjustable and controllable to a high range of compositions, highly repeatable, low impurity level. The magneto-sputtering thin films present the amorphous structure if no annealing process applied. Also known by all of these, ferromagnetic amorphous films including high amounts of Co or Fe element generally indicates superior soft magnetic properties [4]. In many cases, the soft magnetic properties of these materials are higher than many other known materials [5]. The maximum η reached to date for GMI materials is approximately 600%/Oefor the use of GMI structures [9].

δ_m is the skin depth of the film as like ribbon, with transverse permeability (μ_T) for the case of the multilayer films,

$$\delta m = \sqrt{\frac{2}{\mu_T \omega \sigma}} \tag{3}$$

where ω is the frequency of the *ac* current and σ is the electrical conductivity of the layers in GMI cell. The main aim of endeavoring for non-homogeneous layers such as multilayered films have outer layer is ferromagnetic and inner layer is non-ferromagnetic. Recent studies on this subject have shown that this phoneme is come from the interaction among ferromagnetic layers yield the skin depth of ferro- and non-ferromagnetic layers [10]. Thus, it indicates that huge increase of sensor sensitivity in the range of low frequency [11].

The accomplishments of GMI have different aims. Many scientific groups have concentrated with understanding GMI mechanisms, the coupling the structural and magnetic features and connections between GMIs. The others have been focused on in the field of applications and to improve the magnetic properties of a system for practical purposes. The GMI study in thin films continues to attract interest because of its fundamental problems of magnetism and its prominence for possible applications. Within this research, we have investigated the influence of a non-magnetic layer among magnetic bilayer scheme (Fe/Cu/Fe) on a glass substrate for magnetic features and GMI response.

2. EXPERIMENTAL

Thin film structure - Fe/Cu/Fe (GMI cell) were deposited by using a magnetron sputtering system onto substrates (Glass) at room temperature (Fig. 1). The commercially sputtering target was comprised of high purity Fe (99.99%) and Cu (99.9999%) circular disk. Highly pure argon gas (99.999%) was introduced into the chamber as sputtering gas with the working pressure at 5 mTorr. For establishing a plane and smooth surface, 80 Watt power was applied to the sputtering gun. All performed measurements were made in the vicinity of room temperature. The error margin in the stated impedance value was within 1.5%. Magneto-impedance cells produced within the scope of this study have been developed using DC-RF sputtering system in Recep Tayyip Erdoğan (RTE) University Central Laboratory. The magnetoimpedance cell was fabricated by growing as 100 nm (Fe)/10 nm (Cu)/100 nm (Fe) on a glass substrate with 2 nm Si capping layer. Magneto-impedance measurements were performed for this produced cell.

The rate and thickness of film were controlled in-situ by a quartz microbalance and ex-situ by X-ray reflectometry (XRR). Glancing incidence X-ray diffraction (GIXRD) measurements and reflectometry measurements were done by Rigaku SmartLab X-ray Diffractometer with the CuK$_\alpha$ radiation at 1.54 Å and glancing incidence angle was selected as 2^o. Thickness, roughness, and density of the films were determined by fitting the XRR measurements simultaneously, using GlobalFit program. The homogeneity and surface morphology measurements were done by Jeol Scanning Electron Microscope Spectroscopy. Magnetic properties of the films were measured by a Vibrating Sample Magnetometer (VSM) which both out-of-plane (OOP) and in-plane geometry (IP) of the applied magnetic field for increasing and decreasing the magnetic field. The set-up of GMI effect measurement is shown in the inset of Fig. 1 (b). The 20 mA of AC current intensity was employed by AC function generator and it was in a linear excitation.

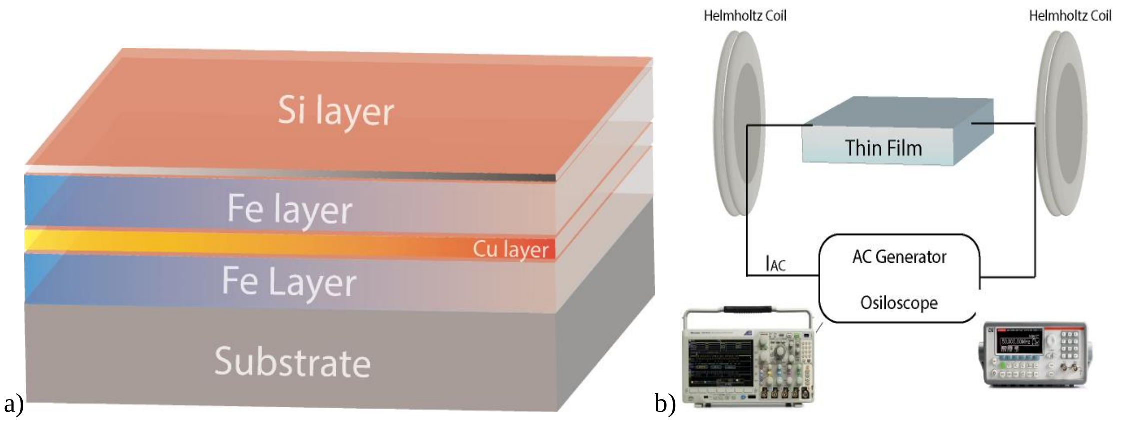

Figure 1. (a) Illustration structure of GMI cell is produced within the scope of this study and **(b)** set-up of GMI effect measurement

3. RESULTS and DISCUSSION

The XRD pattern (Fig. 2) of the GMI cell confirmed the absence of the short range ordering and crystalline phase in all cases under consideration. The diffraction patterns of the thin films obtained at different thicknesses have not been given in order to ensure complete integrity of the article. The GMI cell obtained in this work presented a clear amorphous structure. A broad diffraction peak ($2\theta = 44°$) is visible due to GMI cell incorporations which have a very small influence on the modification of the amorphous structure.

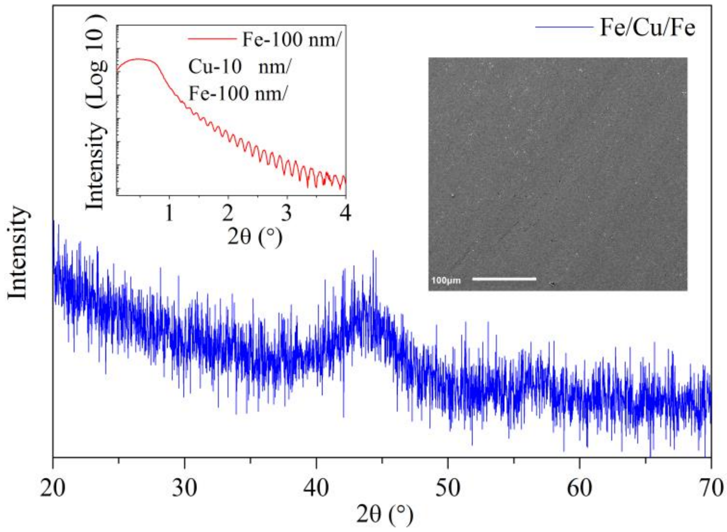

Figure 2. Glancing incidence X-ray diffraction (GIXRD) pattern of thin film at room temperature. Inset of X-ray reflectometry (XRR) pattern and SEM picture of thin film.

The amorphous structure has been traced to the occurrence of the long range ordering has been revealed through XRD analysis. Our result is consistent with the conjecture that the structure indicates major basis of low price MI cell. Inset of Fig. 1 infers XRR pattern of GMI cell. First iron and second iron layers are around 100 nm (±0.2). Also non-magnetic layer (Cu layer) is 10 nm (±0.3). The roughness of the GMI cell was calculated around 2.2 nm. Another inset of Fig. 2 depicts that SEM image of thin film. SEM measurements were imposed to figure out the surface morphology of the thin film, after deposition at room temperature. According to the SEM image with back scattering detector do not show any phase separation of iron, as deposited GMI cell exhibits no homogeneity and no precipitate difference with a flat surface.

In order to find out the maximum of magneto-impedance value, the applied frequency dependence of magneto-impedance measurement is measured under zero and applied magnetic field in Figure 3. After this measurement has been performed, the critical frequency value has been determined. The determination of this frequency is ascertained by the supreme difference value is obtained by subtracting the measurements taken at different magnetic fields from each other. Thus, it has been found that the magneto-impedance value is the highest for which frequency value.

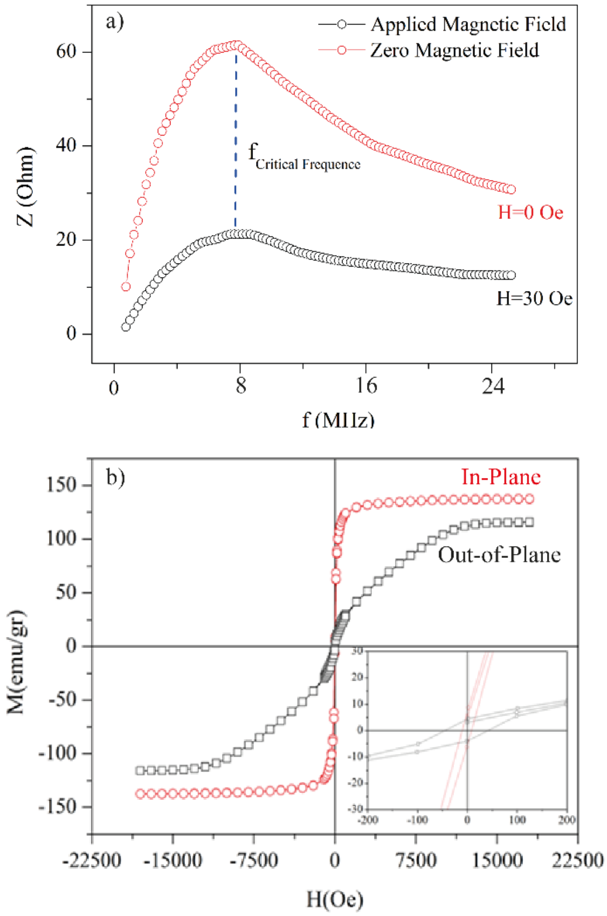

Figure 3.(a) Frequence dependence of magneto-impedance cell under zero and applied magnetic field and **(b)** in-plane (red one) and out-of-plane (black one) magnetization measurement of GMI cell. Inset of zoom in low magnetic field region.

In addition to all of these, magnetoimpedance magnitude varies depending on the frequency of the material which has the difference of the external magnetic field of 30 Oe. We were able to achieve magnetoimpedance value, based on the applied ac-signal of the frequency in the low regime. Also, from the straightforward specified of the frequency dependence of this kind of MI cell, we figure out not only an addiction of frequency effect but also a Critical Frequence ($f_{CriticalFrequence}$) effect. In all this, we thought that experimental results in this study are prodding to discover the non-magnetic layer among magnetic bilayer as well as spin ac-current transport in spintronic phenomena at low frequencies regime such as spin torque, spin accommodation devices. We performed the magnetic field dependence of magnetization both IP and OOP orientation for GMI cell and these measurements are shown in Figure 3 (b). IP orientation showed higher saturation magnetization value (M_s) for GMI cell. In addition, it was not high difference between IP and OOP measurements for high coercive field (H_c) in relatively low magnetic field region and made useful for soft magnetic applications (Inset of Figure 3 (b)). As expected, amorphous GMI cell reveals soft ferromagnetic features with low H_c and high M_s.

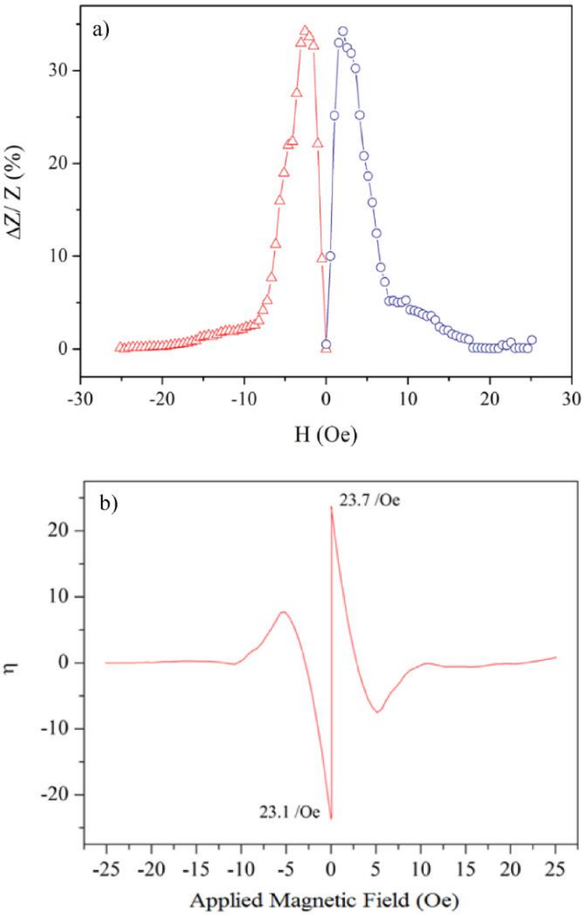

Figure 4. a) External applied magnetic field dependence (H) of magnetoimpedance value, b) Frequence dependence of magneto-impedance cell in zero and applied magnetic field.

Figures 4 (a) shows magnetoimpedance effect (ΔZ/Z, %) of Fe/Cu/Fe cell under ± 25 Oe applied magnetic field. Measurements were taken at a fixed frequency of 8 Mhz. Accordingly, the change value per magnetic field obtained from the magneto-impedance cell produced by using the copper interface between the iron surfaces is 4 times the change value per magnetic field obtained from the Fe magneto-impedance cell produced as a single layer. These values can be compared with the iron multilayer thin films (ΔZ/Z (%) = 40) in the literature [2]. Examination of materials exhibiting magneto-impedance effects constitutes a new field of study that can be used in technological applications. Figures 4 (b) calculates sensitivity of magnetoimpedance (η) of Fe/Cu/Fe cell in applied magnetic field using Equation 2. As clearly understood from Figures 4 (b), double peak responses have been obtained in both magnetic directions. η values are 23.7 %/Oe and 23.1 %/Oe in both under positive and negative magnetic field directions, respectively. The difference between these two values shows that the obtained alloy has a very good response to the magnetic field. Our η values for the magnetic field change of 25 Oe is comparable with the results of other magnetoimpedance materials that show GMI in the vicinity of room temperatures, such as multilayer NiFe/Cu/NiFe (16 %/Oe) [12] and $Fe_{25}Ni_{75}$ film (45%/Oe) [13].

4. CONCLUSION

100 nm Fe/ 10 nm Cu/ 100 nm Fe film was fabricated by using a non-magnetic layer among magnetic bilayer (Fe/Cu/Fe) on a glass substrate has been studied to achieve the soft magnetic properties for their potential applications in GMI sensors. The Fe/Cu/Fe films were deposited in a high vacuum chamber, using separate Fe and Cu targets. As expected, amorphous GMI cell reveals soft ferromagnetic features with low H_c and high M_s. The experimentally achieved values for GMI and η ratio were 35% and 23.7 %/Oe at 8 MHz for 3 Oe. By investigating of this kind of magnetoimpedance cells, the emerged of high impact materials problems can be solved. These cells can be operated at very low cost than squids and the problems experienced in detecting very low magnetic field will be overcome by newly developed systems.

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