GIANT MAGNETO-IMPEDANCE IN THIN FILM STRUCTURES.

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Abstract - Giant magneto-impedance (GMI) properties of the thin film multilayer structure: $F/SiO_2/Ti/Cu/Ti/SiO_2/F$ where F stands for $Fe_{73.5}Cu_1Nb_3Si_{16.5}B_6$ have been studied within the frequency range of 0.5 - 1250 MHz . The GMI is shown to exist in the multilayer structure even when the minimum skin depth in the ferromagnetic layers is of the order of their thickness. A maximum GMI sensitivity of 10 %/Oe has been achieved at high frequencies. A model theory of the GMI has been developed explaining qualitatively the experimental results.

A. Introduction

The magneto-impedance phenomenon implying a change of the complex resistivity $Z(\omega) = R(\omega) - iX(\omega)$ of a ferromagnetic conductor (ω is a frequency of the current passing through the conductor) caused by an external magnetic field has been known for more than 50 years. However, a giant change of the impedance $\Delta Z/Z = [Z(\omega,H_{ex}) - Z(\omega,0)]/Z(\omega,0)$ (more than 100 %) which some soft magnetic materials exhibit in the presence of a weak external magnetic field (less than 1-10 Oe) has been found quite recently [1-5]. The phenomenon has attracted a great deal of interest among the designers of magnetic sensors and heads, stimulated a search for new materials possessing the giant magneto-impedance properties (GMI) and motivated theoretical works on the GMI at low and high frequencies. At present time the GMI has been studied in detail in amorphous Co-based wires [1-4], in amorphous stripes and films [2,3,5] over the frequency range of up to 200 MHz, investigations of sandwich structures have started[6,7], and a basic theory of the GMI has been developed [2,3]. Although the GMI is basically a "complex magneto-resistance at a high frequency" it occurs not due to a spin-dependent scattering of the conduction electrons responsible for the giant magneto-resistance (GMR) in ultra thin sandwiches, multilayers and granular alloys. The GMR occurs only in magnetically nonuniform media with a characteristic length (layer thickness or granular size) of the order of 10 nm whereas the GMI effect has been observed in uniform media. The GMI materials possess a fairly low magneto-resistance in DC mode. The GMI is a classical phenomenon which occurs due to a redistribution of the alternating current density over the cross-section of the sample under an external magnetic field. A typical sensitivity of the GMI materials with respect to the external magnetic field $\Delta Z/Z(\omega,0)/\Delta H_{ex}$ at room temperature is 50-100%/Oe which is at least one order higher than the highest sensitivity of the GMR structures. However, a sensitive element of the GMR magnetic sensor may have a thickness of a fraction of a micron which is very important for read-out heads for super high density magnetic storage whereas a submicron GMI sensor up to now has been considered as hardly probable due to the origin of the phenomenon.

According to the adopted conception of the GMI [2,3] it can be observed only under the condition of a strong skin-effect, namely at

$$\delta \ll a \qquad (1)$$

where a is a characteristic size of the cross-section of the ferromagnetic sample (the half-thickness of a stripe or a film, or the radius of a wire),

$$\delta = c\ [\ \rho/(2\pi\omega\mu_{eff}(\omega))]^{1/2} \qquad (2)$$

is the skin-depth, ρ is the specific resistivity, $\mu_{eff}(\omega)$ is the frequency dependent magnetic permeability. An external magnetic field can significantly change (by two or three orders) the value of the $\mu_{eff}(\omega)$ within a soft magnetic material thus causing the GMI. However, experimental and theoretical studies performed by our group and authors of Refs. [6,7] have shown that the condition (1) is not mandatory for multilayer structures based on amorphous or nanocrystalline magnetic layers sandwiching a highly conductive layer to exhibit the GMI effect. The basic structure is F/Cu/F where F are soft ferromagnetic layers sandwiching a layer of Cu. The resistance of the whole structure at low frequencies is determined by the resistance of the Cu layer since the minimum skin-depth (at maximum $\mu_{eff}(\omega)$) of the layers is much larger than half-thickness of the layers and the specific resistivity of Cu is much lower than that of the ferromagnetic layers. An external magnetic field effecting $\mu_{eff}(\omega)$ and therefore inductance of the whole structure does not change the cross-section distribution of the current essentially. Therefore the real part of the impedance remains almost constant, whereas the imaginary part (inductance) increases noticeably thus causing a significant change of the impedance (GMI). At higher frequencies when the minimum skin-depth of the ferromagnetic layers becomes comparable with the layer thickness a small variation of the δ under an external magnetic field causes essential change of the electric field and current distributions. Therefore at high frequencies the real part of the impedance can vary noticeably as well thus improving the GMI sensitivity. The authors of Refs. [6,7] who studied the GMI properties of the thin film sandwiches CoSiB/Cu/CoSiB [6] and NiFe/Cu/NiFe [7] came to similar conclusions. However those sandwiches exhibited a sensitivity of not more than 2 %/Oe at high frequencies.

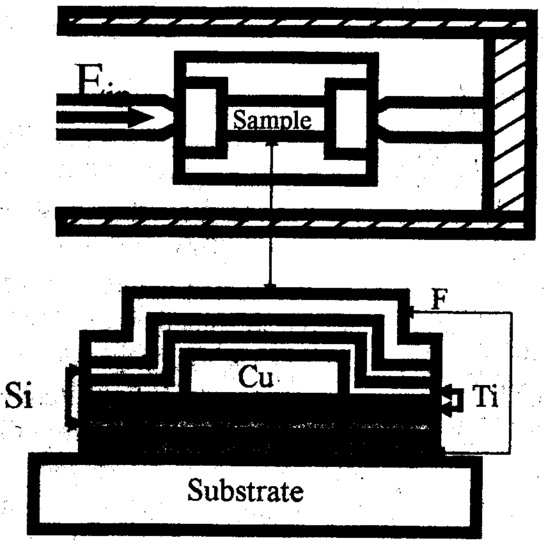

Fig. 1. Schematic diagram showing the GMI sandwich sample within a waveguide cell. On the inset is shown the multilayer structure of the sample.

B. Experimental method

The GMI samples were fabricated using a multilayer ion-beam sputtering technology. The multilayer structure was as follows: F(800nm) /SiO_2(80nm)/ Ti(10nm)/ Cu(800nm) /Ti(10nm) / SiO_2(80)/F(800nm) with the whole length of 9 mm and the width of 200 μm (see inset of Fig. 1). The ferromagnetic layers F were deposited using an ion-beam sputtering technique from an amorphous $Fe_{73.5}Cu_1Nb_3Si_{16.5}B_6$ (finemet) target. The SiO_2 and Ti layers were deposited in order to improve adhesion and to prevent exchange coupling between the two ferromagnetic layers. The dielectric spacer SiO_2

prevented also an interdiffusion between the layers and decreased losses within the ferromagnetic layers. The central Cu strip having a width of 100 μm was connected at the ends to 3x3 mm^2 contact squares. The multilayers were deposited onto sapphire, polycor or glass substrates under an external magnetic field H_p of 200 Oe applied in the sample plane perpendicular to the long side of the sample. The multilayer deposition was followed by a vacuum annealing at 280^0 C under H_p=420 Oe for 2 hours. The annealing was performed in order to transform an initial amorphous material to a nanocrystalline one possessing better soft magnetic properties [8], a higher permeability at high frequencies and a more stable induced transverse anisotropy. It should be mentioned that the as-deposited samples were partly nanocrystalline due to the substrate heating during deposition. Field-annealed samples were approximately pure nanocrystalline that was confirmed by structural investigations. However we did not achieve the law coercitive nanocrystalline state known from literature [8], probably due to rather high (500-600 °C) substrate temperature during sputtering.

The GMI characteristics were measured using a technique based upon high frequency measurements of complex coefficients of transmission or reflection of electromagnetic waves propagating through a coaxial waveguide. A sample under investigation was placed as a piece of central conductor (Fig. 1). The level of the high frequency current did not exceed 10 μA which allowed to maintain a linear mode of operation. An external magnetic field with a strength of up to 130 Oe was created using a coil driven by a DC power supply. The sample was oriented along a local magnetic field direction, so the coil also provided a compensation of the field.

The input impedance of the multilayer sample was determined using a sequence of the following steps. Using the data on the reflection coefficients we directly calculated the input impedance of the whole waveguide element. Then we determined the characteristic impedance of the magnetic sample itself followed by the final calculations of the input impedance of the magnetic sample. Throughout the paper we present data on the input impedance of the magnetic sample.

Magnetic measurements were performed using a vibrating sample magnetometer having a sensitivity of 10^{-6} emu. A Kerr loop tracer with a sensitivity of 10^{-3} degrees was used to measure surface loops on each magnetic layer separately. All measurements were carried out at room temperature.

C. Results and discussion

In the multilayer structures the thickness of the dielectric layers separating the ferromagnetic F layers exceeds the length of exchange interaction. In this case only magneto-static interaction between the layers can exist. The distribution of the magnetization in the layers F depends on the strength and direction of the induced anisotropy. If the easy axis of the induced anisotropy is perpendicular to the long axis (L_y) of the sandwich a transverse domain structure is energetically more favorable compared to a longitudinal one. The magnetization directions in the F layers are supposed to be opposite to each other in order to close the magnetic flux. Such structures has been observed in the sandwiches CoSiB/Cu/CoSiB [6] and NiFe/Cu/NiFe [7]. If the easy axis is parallel to L_y or the transverse anisotropy is small compared to the magneto-static energy a longitudinal domain structure becomes more favorable. Again the magnetic moments in the adjacent layers point in the opposite directions in order to minimize the magneto-static energy. At a certain intermediate value of the transverse anisotropy the magnetization can tilt with respect to the L_y axis.

Figure 2 shows magnetic hysteresis loops for the magnetic field direction along and perpendicular to L_y. The longitudinal loop in Fig. 2(a) indicates that the magnetic layers have different apparent coercivities. The layer with smaller coercivity begins to reverse at a negative field under the stray field from the second layer. Magneto-optic measurements revealed that the "harder" layer with a coercivity of 2.5 Oe is located directly on the substrate, whereas the top "soft" magnetic layer has a coercivity of 0.1 Oe. The transverse loop in Fig. 2(b) is wider than that in Fig. 2(a) (the coercivity is about 10 Oe). That may indicate that a transverse anisotropy has been induced in the sandwich.

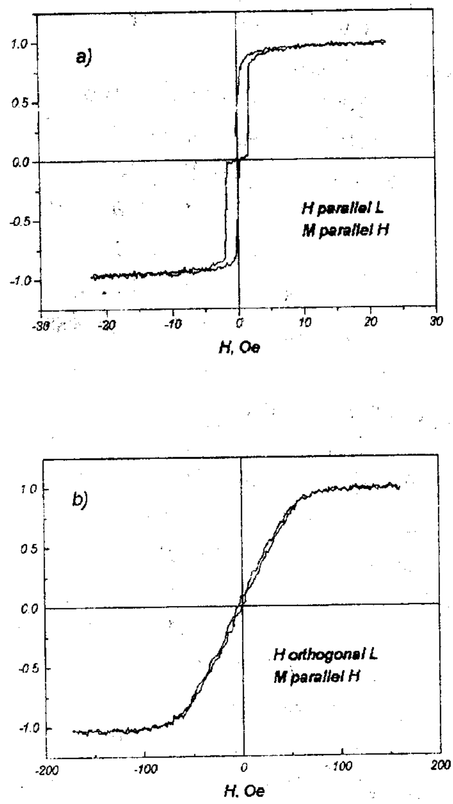

Fig. 2. Magnetic loops measured along and perpendicular to the long side (L_y) of the sample within the substrate's plane.

Sandwiched samples which were not subjected to a thermal annealing show much larger values of coercivity compared to annealed ones. The improvement seems to occur due to formation of a nanocrystalline phase which was confirmed by structural measurements.

Typical field dependences of the impedance are shown in Figs. 3 and 4. The magnetic field was applied along the long axis of the sample. The impedance value was normalized to the DC resistance of the samples which equaled 4.8 Ohm before and 3.2 Ohm after annealing. General behavior of the ReZ(H_{ext}) is quite similar for annealed and unannealed samples, namely, the impedance increases with the magnetic field, gets its maximum value at a certain magnetic field H_{max} and then decreases approaching its saturation value at high magnetic fields. The H_{max} decreases with the frequency decrease and at the frequencies of the order of 1 MHz the minimum on the curve ReZ(H_{ext}) in the vicinity of H_{ext}=0 practically disappears. Up to the frequency of 500 MHz where the ferromagnetic resonance starts to effect the GMI behavior the dependences ImZ(Hext) shown in Fig. 3 are similar to those of ReZ(H_{ext}). The value of H_{max} for both annealed and as-deposited samples within the frequency range of 100-500 MHz approximately equals to the magnetic field required to close up the hysteresis loop shown in Fig. 2(a). The H_{max} in essence defines a working range for the GMI sensors in the high frequency region. The approaching of the ReZ and ImZ curves to a saturation value at strong magnetic fields also correlates with the magnetic curves shown in Fig. 2 (the magnetic curve exhibits a gradual increase in the field of up to 150 Oe).

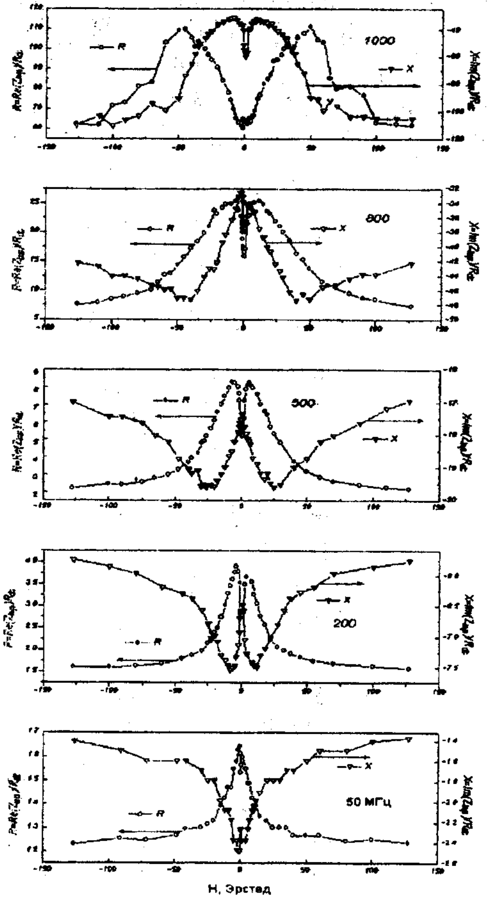

Fig. 3. Real (R) and imaginary (X) parts of the impedance versus external magnetic field measured at different frequencies. Δ represents the maximum GMI sensitivity at a specific frequency.

Figures 3 and 4 indicate that the amplitude of the variation of real and imaginary parts of the impedance in the presence of the external magnetic field remains fairly large for both low and high frequencies although the condition (1) is not valid almost for the whole frequency spectrum. For example, at a frequency of f=500 MHz the skin depth in Cu is $\delta_{Cu} \sim 1\ \mu m$, for the magnetic alloy with a resistivity of $\rho = 100\ \mu\Omega{*}cm$ and a transverse permeability of $\mu = 1000$ according to the expression (2) we obtain $\delta_F \sim 0.2\ \mu m$ whereas the half thicknesses of the Cu and the ferromagnetic layers are 0.4 μm.

For real sensor applications of the GMI elements an important characteristic is the maximum sensitivity $\Delta = (dZ/dH)/Z$. At different frequencies a maximum sensitivity is observed at different magnetic fields. The values of maximum sensitivity Δ at every frequency are shown in Figs. 3(a) through 3(e). The sensitivity Δ depends on the frequency however it remains fairly high up to 1200 MHz. Figure 4 indicates that the average sensitivity within the magnetic field range from 0 to H_{max} for the annealed samples is higher than that of the as-deposited samples and equals approximately 10% /Oe at the frequency of 500 MHz.

A high GMI sensitivity of the multilayer structures, a linearity and a lack of magnetic hysteresis at $H_{ext} < H_{max}$ as well as a higher stability of the nanocrystalline samples make them promising for the GMI applications.

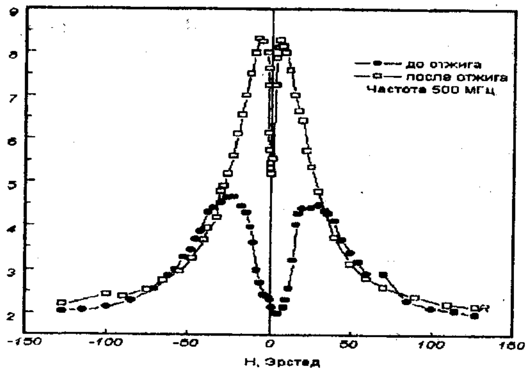

Fig. 4. Real parts of the impedance of the as-deposited and subsequently annealed sample versus external magnetic field measured at a frequency of 500 MHz.

For interpretation of the experimental data obtained let us consider a simple model of the sandwich consisting of two ferromagnetic layers having a thickness of L_z and a layer of a metal (Cu) having a high conductivity and a thickness of d and sandwiched between the two ferromagnetic layers. Denote the width and the length of the layers as L_x and L_y respectively. The layers are assumed to possess a domain structure and are described in terms of an averaged over the domains effective transverse magnetic permeability $\mu_{eff}(\omega,H_{ext})$. We use here an approach similar to one proposed in [2,7]. Taking into account in agreement with the experiment that $L_y \gg L_x \gg L_z$, d one can neglect the boundary conditions which results in the electric field $E_y(z,\omega)$ and the magnetic field $H_x(z,\omega)$ components to be dependent only on the perpendicular coordinate z. Thus solving the Maxwell equations for the field distributions $E_y(z,\omega)$ and $H_x(z,\omega)$ within every layer, one can obtain the following expression for the sandwich impedance which is the ratio of the electric field on the sample surface to the current passing through it:

$$Z=\frac{e_y\left(L_z+d/2\right)}{I_y}=R_{dc}\frac{\lambda_2\left(L_z+\frac{d\sigma_1}{2\sigma_2}\right)\left(\cos\lambda_2L_z\cos\frac{\lambda_1d}{2}-\frac{\lambda_2\sigma_1}{\lambda_1\sigma_2}\sin\lambda_2L_z\sin\frac{\lambda_1d}{2}\right)}{\sin\lambda_2L_z\cos\frac{\lambda_1d}{2}+\frac{\lambda_2\sigma_1}{\lambda_1\sigma_2}\cos\lambda_2L_z\sin\frac{\lambda_1d}{2}}, \tag{3}$$

where R_{dc} is the resistance of the sandwich's unit length at DC current, σ_1 is the conductivity of the nonmagnetic layer, σ_2 is the conductivity of the magnetic layers (we assume $\sigma_1 \gg \sigma_2$) and

$$\lambda_1=\frac{1+i}{\delta_{Cu}};\ \lambda_2=\frac{1+i}{\delta_f};\ \delta_{Cu}=\frac{c}{\sqrt{2\pi\omega\sigma_1}};\ \delta_f=\frac{c}{\sqrt{2\pi\omega\sigma_2\mu_\perp(\omega)}}. \tag{4}$$

So, both real and imaginary parts of the impedance depend in a complex way on $\mu_{eff}(\omega, H_{ext})$, thickness of the layers and their conductivities.

In the presence of an induced transverse anisotropy a transverse domain structure with the following components of magnetization:

$$M_y^{(0)}=M_s\frac{H_{ext}}{H_K};\ M_x^{(0)}=\pm\sqrt{1-\left(M_y^{(0)}\right)^2} \tag{5}$$

exists within the field range $0<H_{ext}<H_k$, where $H_k=2K/M_s$ is the anisotropy field, K is the anisotropy constant, M_s is the saturation magnetization. In the field $H>H_k$ the transverse domain structure disappears. A standard analysis using the Landau-Lifshitz-Gilbert equations leads to the following expressions for μ_{eff} in the two cases:

$$\mu_\perp=\frac{(\omega_H+\omega_m-\omega_K-i\kappa\omega)(\omega_H+\omega_m-i\kappa\omega)-\omega^2}{(\omega_H-\omega_K-i\kappa\omega)(\omega_H+\omega_m-i\kappa\omega)-\omega^2} \quad \text{at } H_{ext}>H_k, \tag{6}$$

$$\mu_\perp=\frac{\left(\omega_m\left[\alpha_y^{(0)}\right]^2+\omega_K-\omega_H\alpha_y^{(0)}-i\kappa\omega\right)(\omega_K+\omega_m-i\kappa\omega)-\omega^2}{\left(\omega_K-\omega_H\alpha_y^{(0)}-i\kappa\omega\right)(\omega_K+\omega_m-i\kappa\omega)-\omega^2} \quad \text{at } H_{ext}<H_k, \tag{7}$$

where

$$\omega_H=\gamma H_{ext};\qquad \omega_m=4\pi\gamma M_s;\qquad \omega_K=\gamma H_K,\qquad \alpha_y=M_y/M_s. \tag{8}$$

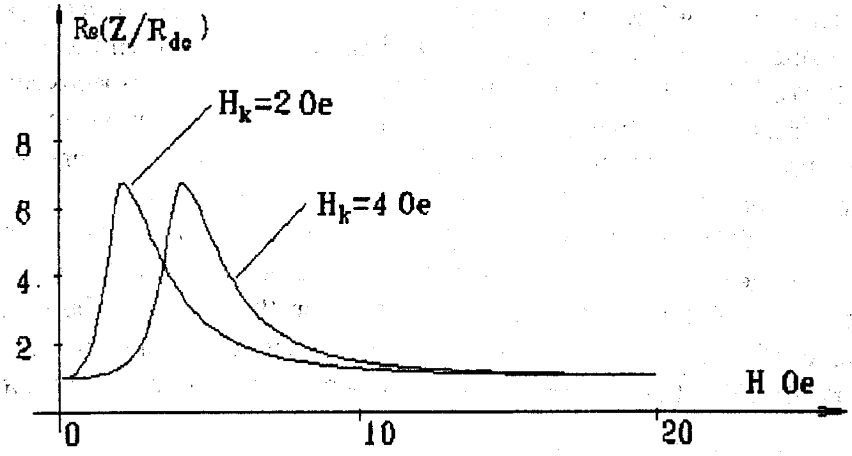

Fig. 5. Real part of the sandwich's impedance versus external magnetic field calculated at two different values of the transverse anisotropy field. Frequency - w = 200 MHz, damping parameter k - 0.1.

Figure 5 shows the dependence of the real part of the sandwich's impedance on the external magnetic field at ω=50 MHz plotted in accordance with the expressions (3-8). The figure indicates that in spite of a violation of the condition (1) for the strong skin-effect at such a low frequency the real part of the impedance strongly depends on H_{ext}. Within the limits of the considered model it occurs due to a redistribution of electric fields and currents under an external magnetic field.

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Preface.

The Russian-Japanese joint seminar “The Physics and Modelling of Intelligent Materials and their Applications” (PMIMA) was held from 19 through 21 September 1996 at the Faculty of Physics of Moscow State University in Moscow, Russia.

The seminar aimed to discuss various subjects on fundamental and applied problems on intelligent materials and connected topics.

The seminar gathered 61 participants (13 of them were from Japan). Russian participants were from Moscow University (faculties of physics and chemistry and institute of mechanics), Chelyabinsk and Vladikaukaz Universities, Baikov Institute of Metallurgy, Moscow institute for Radioengineering Electronics and Automation, Troitsk Institute for Innovation and Fusion research and other divisions of Russian Academy of Science. 43 papers were presented that were contributed by 122 authors.

The scientific program included 6 oral sessions and a poster session. Besides there were carried out an excursion over the scientific laboratories of the faculty of physics of the Moscow University.

The seminar has demonstrated the difference between Russia and Japan in that which can be called as “fundamental” and “applied” approaches. The seminar allowed to get the best from both approaches in our countries. The following list shows possible joint research projects that can be initiated soon:

a) ferromagnetic shape memory alloy;

b) non—destructive testing;

c) biomedical applications;

d) high-T_c superconductors.

I would like to thank all of the people who contributed to the success of the seminar. Especially I appreciate the essential contribution of professors Tani J. and Takagi T. from Tohoku University (Japan).

N.S.Perov
Program Committee Chairman

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