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The giant-magneto-impedance effect in FM/Ag/FM (FM ≡ FeCuCrVSiB) sandwich films

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Abstract. Sandwich films with the structure FM/Ag/FM have been prepared by radio-frequency sputtering and then annealed at an optimized temperature (here FM represents the FeCuCrVSiB amorphous soft magnetic layer). The giant-magneto-impedance (GMI) effects for the samples have been studied as a function of alternating-current frequency (50 kHz to 13 MHz) and external magnetic field. When the frequency increases above a critical frequency f^* (about 150 kHz), the GMI ratio increases quickly with increasing frequency, and reaches a maximum value at a characteristic frequency f_m of about 4 MHz. GMI ratios at f_m as large as 109% and 135% were obtained for longitudinal and transverse applied magnetic fields, respectively. These results are much better than those obtained for single-layer films, and the frequencies used in producing the effect are very low.

1. Introduction

The giant-magneto-impedance (GMI) effect in soft ferromagnetic alloys has been studied extensively because of its potential applications in magnetic sensors and devices. Earlier works focused on Co-based amorphous wires with a slightly negative magnetostriction of the order of 10^{-7} [1–3]. Now investigations on the GMI effect have expanded to include Fe-based nanocrystalline ribbons [4–6] and many other soft magnetic materials with various geometries, and in particular to films [7–9]. The origin of the GMI effect lies in classical electromagnetism, i.e., the field dependence of the impedance Z as a result of the skin effect in conjunction with the transverse magnetization associated with an alternating current passing. In order to obtain a sensitive GMI effect in a film, a high-frequency current, up to 100 MHz, usually has to be applied [9]. The transverse permeability is associated with both domain wall movement and moment rotation. Normally, at low frequencies, the contribution to the GMI from domain wall motion is dominant over that from rotational processes. As the frequency increases, the domain wall motion will be damped and the rotational contribution to the GMI will grow and become important, so the anisotropy field will play a significant role in the GMI effect. The anisotropy may be of magneto-elastic origin or induced by annealing in an external field, and its importance has been studied extensively for wires as well as for ribbons and films [3, 6, 10].

Recent studies show that the GMI effect in a structure with two soft magnetic layers sandwiching a highly conductive metal can be very large, even at low frequencies [11–13]. In this structure, the inner conductor provides the main path for the alternating current, and the outer enveloping magnetic layers provide the paths for the magnetic flux induced by the alternating current, and there is a weak influence of the stray magnetic field. Theoretical

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analysis shows that the inductive component of the impedance in a sandwich film is proportional to the transverse permeability μ_T of the magnetic layers and can provide the main contribution to the impedance even in the case of a weak skin effect [11].

In this paper, results on the GMI effect in FM/Ag/FM sandwich films are presented (here FM represents the FeCuCrVSiB amorphous soft magnetic layer). Superior soft magnetic properties have been obtained for nanocrystalline FeCuCrVSiB ribbons [14]. The coercive force $H_c = 0.07$ Oe and initial permeability above 10^5 indicate comprehensive applicability in the field of magnetic sensors. Ag is a material with high conductivity. It is expected that samples made of such materials will show large GMI effects. Some investigations of GMI in sandwich films constructed from Co-based amorphous magnetic films [11] or from Fe–Ni-based crystalline [12] or amorphous magnetic films [13] have been performed. Few works deal with the GMI effect obtained in sandwich films consisting of Fe-based amorphous magnetic films. Our work showed that superior results were obtained by using these kinds of alloy. This extends the variety of the materials used in GMI investigations of the sandwich films.

2. Experimental details

The samples were prepared by using radio-frequency (RF) sputtering equipment that has two targets. The FeCuCrVSiB target is a disc made of a sintered alloy with a nominal composition $Fe_{71.5}Cu_1Cr_{2.5}V_4Si_{12}B_9$ (at.%). Another target is a pure Ag disc. The targets and substrate holder were all water cooled. After the chamber system was evacuated to a high vacuum of about 4×10^{-6} Torr, 99.999% pure Ar was introduced and controlled at a pressure of 5×10^{-3} Torr during sputtering. The alloy target was cleaned by presputtering for four hours before deposition. The films were deposited onto Si substrates with the thickness of 0.5 mm. The deposition rates were 0.11 nm s^{-1} and 0.35 nm s^{-1} for FeCuCrVSiB and Ag, respectively. The sandwich films used in this investigation have a structure of FM(2.5 μm)/Ag(2 μm)/FM(2.5 μm). The inner Ag layer with two electrodes at both ends is 2 μm thick, 0.3 mm wide, and 15 mm long, while the outer magnetic layers are 2.5 μm thick, 3 mm wide, and 10 mm long. The shape of each layer was determined by a mask on the substrate.

The GMI effects for the samples were measured at room temperature using an HP4192A impedance analyser, the frequency of which ranges from 5 Hz to 13 MHz. The exposed parts of the Ag lead at both ends of the film were connected to the analyser by four coaxial cables. The measurements were carried out with the frequency ranging from 50 kHz to 13 MHz with a constant alternating current of 10 mA, and the probe current flowing along the long direction of the sample. A pair of Helmholtz coils (30 cm in diameter) was used to generate a dc magnetic field ranging from −70 Oe to 70 Oe. In order to minimize the influence of the Earth's magnetic field, the Helmholtz coils were so placed that the magnetic field generated was perpendicular to the Earth's magnetic field. We have studied GMI effects for the samples in the longitudinal (the magnetic field is along the alternating-current direction) and transverse (the magnetic field is perpendicular to the alternating-current direction in the film plane) cases.

3. Results and discussion

From our observations, the as-deposited samples are in the amorphous state and have no measurable MI effect. In order to eliminate the internal stress induced during the preparation and improve the soft magnetic properties of FM layers, the samples were annealed in a vacuum chamber (about 1×10^{-5} Torr) at selected temperatures in the range 200 °C to 400 °C for 1.5 h.

The results of the MI measurements for the annealed samples showed that 300 °C was an optimum annealing temperature, and a very sensitive GMI effect was observed. The annealing treatment eliminates most of the stress induced in the deposition process, and improves the soft magnetic properties of the magnetic layers. X-ray diffraction showed that the FeCuCrVSiB films annealed at 300 °C were still in the amorphous state. In this paper, we will focus our attention just on the samples annealed at this temperature.

Figure 1 shows the frequency dependence of the maximum GMI ratios for an annealed sandwich film in longitudinal (denoted by dots) and transverse (denoted by circles) magnetic fields. The GMI ratio is defined as $\Delta Z/Z_m = (Z_0 - Z_m)/Z_m$, where Z_0 and Z_m are the impedances of the sample at magnetic fields of 0 and 70 Oe, respectively. In order to observe the low-frequency behaviour of the GMI effect, we use logarithmic abscissae. We can see from figure 1 that there is a critical frequency f^* at about 150 kHz on the curve (as indicated by the arrow). When the frequency is lower than f^*, the GMI ratio is small. When the frequency increases above f^*, the GMI ratio increases quickly with increasing frequency. The critical frequency is so low that one can only obtain it in wires and ribbons whose thicknesses are in the range 20–30 μm [2–4]. So low a critical frequency has never been obtained in a single-layer film because its thickness cannot be large enough. In the cases of ribbons and single-layer films, the relation $t/\delta_c = 1$ applies at f^* [3, 15], where t is the thickness of the sample, $\delta_c = c/\sqrt{4\pi^2 f^* \sigma \mu_e}$ is the skin depth at f^*, σ is the conductivity, and μ_e is the permeability. When f is above f^*, the skin effect gradually appears and the GMI effect increases monotonically. We assume a FeCuCrVSiB single-layer film with a thickness of about 5 μm, which equals the total thickness of the magnetic layers in our sandwich films; the resistivity ρ of the film is 228 $\mu\Omega$ cm, and we use $\mu_e = 10^4$ (usually, μ_e is smaller than this value for soft magnetic films); then the critical frequency f^* is about 2.3 MHz, which is much higher than the critical frequency of 150 kHz for our sandwich films. This indicates that the GMI effect in the sandwich films can appear at relatively low frequencies where the skin effect is weak. This phenomenon is related to the special structure of sandwich films. In this structure, the inner conductor provides the main path for the alternating current, and the outer enveloping magnetic layers provide the paths of the magnetic flux induced by the alternating

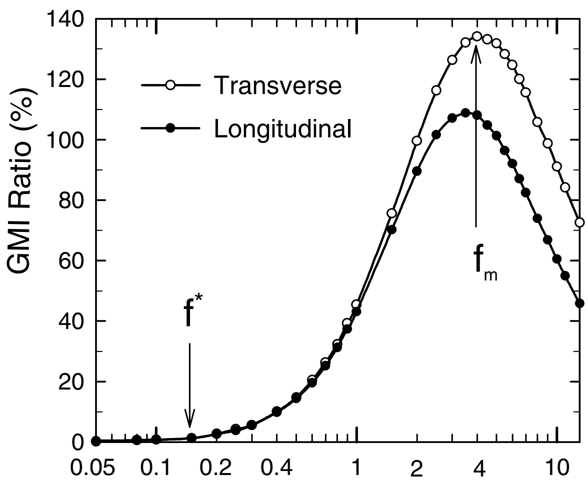

Figure 1. Frequency dependences of the maximum longitudinal and transverse GMI ratios.

current. Hika *et al* [11] showed theoretically that when $d_c\sigma_c/2 \gg d_m\sigma_m$, a low-frequency (with respect to the skin effect) expansion of Z_j leads to a simple form:

$$Z_j = R_c - \mathrm{i}\omega(d_m/2b)l\mu_{ef} \qquad R_c = (l/2)bd_c\sigma_c \tag{1}$$

where d_c and d_m are the thicknesses of the conductive layer (i.e. Ag in our case) and each magnetic layer, σ_c and σ_m are the conductivities of the Ag layer and of the magnetic layers, Z_j is the intrinsic surface component of the impedance Z, b is the width of the magnetic layer, l is the magnetic film length, μ_{ef} is the transverse complex permeability of the magnetic layers. Expression (1) shows that the GMI effect in the sandwich films can be very large even at relatively low frequencies when the skin effect is weak because of the linear GMI effect dependence on μ_{ef}.

Another obvious feature of figure 1 is that there is a characteristic frequency f_m (as indicated by the arrow) for the curves at which the GMI ratio reaches its maximum value, $(\Delta Z/Z_m)_{max}$. $(\Delta Z/Z_m)_{max}$ is about 135% in the transverse case, and is about 109% in the longitudinal case. The f_ms are almost the same for the longitudinal and transverse cases and are located at approximately 4 MHz. $(\Delta Z/Z_m)_{max}$ in the transverse case is obviously larger than that in the longitudinal one. We will discuss this phenomenon later. For soft magnetic wires and ribbons, the appearance of f_m can usually be analysed as follows: when the alternating current frequency increases from the critical frequency, the influence of the skin effect increases. This induces the increase of the GMI effect. On the other hand, when the frequency increases, the effective permeability of the sample will decrease because of the influence of eddy currents at high frequencies. This will decrease the skin effect, and weaken the GMI effect. As a result of the competition of these two factors, a maximum GMI value is bound to exist. When the frequency increases further from f_m, the GMI value decreases gradually as the decrease of the permeability overmatches the increase of the skin effect at high frequencies. For sandwich films, the high-frequency electromagnetic field coupling between the central conductor and outer magnetic layers changes the skin effect, and also changes the impedance characteristic of the sample. This results in the occurrence of a GMI effect at much lower frequencies. We believe that when the frequency is high enough, GMI effects will disappear because the permeability becomes very small and does not depend on the magnetic field any more. Due to the limitations of the drive alternating-current frequency in our measurements, we are unable to observe the disappearance of the GMI effect at high frequencies.

Figure 2 shows the dependences of the GMI ratio $\Delta Z/Z_m$ on the longitudinal applied magnetic field H_L at different frequencies, where $\Delta Z = Z_H - Z_m$ (Z_H and Z_m are the impedance values of the sample in magnetic fields of H and 70 Oe, respectively). We only give the results obtained with positive field. Similar results can be obtained when the magnetic field is negative, i.e., the GMI effect curves are symmetric with respect to the magnetic field. This is a usual feature of GMI effects obtained in amorphous ribbons and films [3, 8]. As one can see from figure 2, the GMI ratios decrease monotonically with increasing magnetic field at the frequencies 1 MHz and 3 MHz. When the frequency is high, a small peak appears at around the magnetic field of 3.5 Oe. This indicates that there is a small transverse anisotropy field H_k in the film, and the peak appears at $H = H_k = 3.5$ Oe. It is usually believed that in the lower-frequency range, the domain wall motion in the soft magnetic alloys gives the main contribution to the transverse magnetization process induced by the longitudinal alternating current. At high frequencies, the domain wall motion is damped, and the rotational magnetization process is responsible for the GMI effect, so the anisotropy field plays a significant role in this case [3]. As a result, there is no peak in the GMI curves at low frequencies, while a peak appears at high frequencies. We also notice that a field of 70 Oe is not sufficient for saturating the GMI effect of the sample.

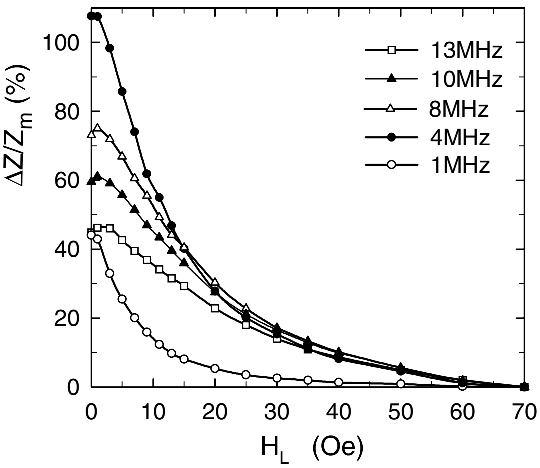

Figure 2. GMI ratios versus the longitudinal magnetic field H_L with frequency f as a parameter.

Figure 3 shows the dependences of the GMI ratio on the transverse applied magnetic field H_T at different frequencies. The GMI ratio decreases with increasing magnetic field monotonically, and no peak appears for any frequency. This indicates that there is no longitudinal anisotropy field in the film. Because the transverse magnetic flux loop for an ac magnetic field is closed, the influence of the shape anisotropy of the film is weak. The transverse GMI saturates at a field of about 40 Oe for all frequencies. This field is much lower than that in the longitudinal case, and the maximum value of the GMI ratio is larger than that in the longitudinal case.

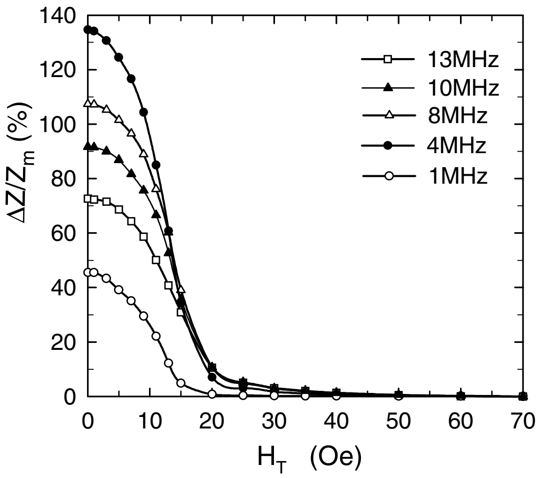

Figure 3. GMI ratios versus the transverse magnetic field H_T with frequency f as a parameter.

In single-layer films, the transverse GMI effect is usually less good than the corresponding longitudinal one owing to the influence of the transverse demagnetization field. However, a better transverse GMI effect response is obtained in sandwich films, as one can see from figures 1, 2, and 3. This may be attributed to two factors. First, in sandwich films, the magnetic flux induced by the alternating current is closed in the transverse direction of the film, and the flux leakage through the conductive layer can be neglected, as can the field distribution near the edges [11]. So the influence of the demagnetization field in the transverse direction is less important in this case. Second, the differences between the longitudinal and transverse

GMI spectra can be understood in terms of the transverse and longitudinal permeability. In the longitudinal GMI measurements, the ac magnetic field $\boldsymbol{H}_{ac}$ produced by the alternating current is perpendicular to the dc magnetic field $\boldsymbol{H}$. Hence, it is the transverse permeability that gives rise to the longitudinal GMI effect. Likewise, in the transverse case, $\boldsymbol{H}$ is parallel to $\boldsymbol{H}_{ac}$; the longitudinal permeability gives rise to the transverse GMI effect [9]. In the longitudinal case, $\boldsymbol{H}$ tilts the circumferential flux lines generated by the alternating current towards the longitudinal direction. Therefore, the permeability of the film goes to the saturated state more slowly than in the transverse case. As a result, the GMI goes to saturation more slowly than in the transverse case.

In order to investigate the impedance effects in detail, we separate the GMI ratio of the film into two components, i.e., the magneto-inductance ratio, $\Delta X/X_m$, and the magneto-resistance ratio, $\Delta R/R_m$, where $\Delta X = X_H - X_m$, $\Delta R = R_H - R_m$, X_H and R_H are the inductive and resistive components of the impedance at the applied magnetic field H, X_m and R_m are the inductive and resistive components of the impedance for the 70 Oe field. Figures 4(a) and

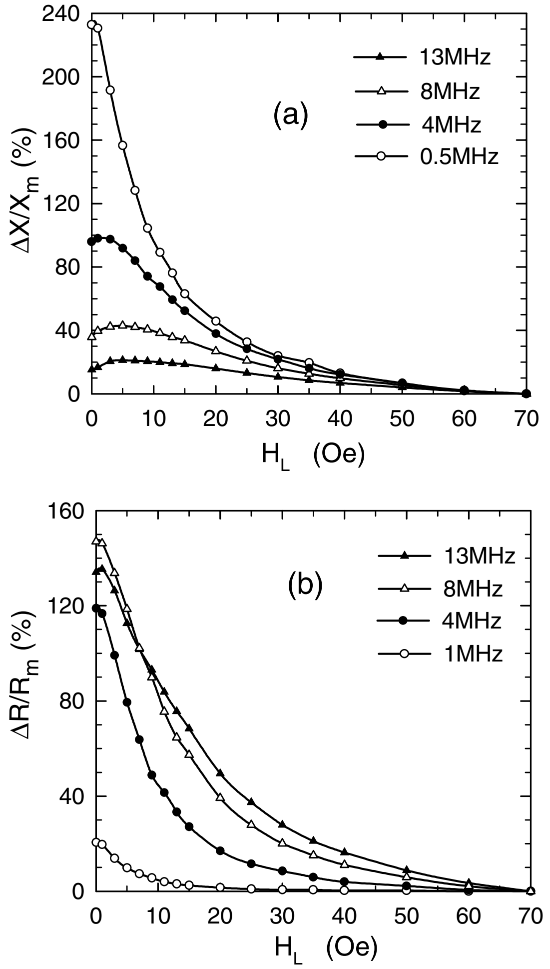

Figure 4. Magneto-inductance ratios (a) and magneto-resistance ratios (b) versus the longitudinal magnetic field H_L with frequency f as a parameter.

4(b) show the dependences of $\Delta X/X_m$ and $\Delta R/R_m$ on the longitudinal field H_L at different frequencies. Figures 5(a) and 5(b) show the dependences of $\Delta X/X_m$ and $\Delta R/R_m$ on the transverse field H_T at different frequencies. We can see from figure 4 that the magneto-inductance ratio decreases with increasing frequency. In contrast, the magneto-resistance ratio increases with increasing frequency. These phenomena are similar to those observed in ribbons and single-layer films. The inductance is related to the transverse permeability, but the resistance is related to the skin effect. When the frequency increases, the permeability of the film decreases because of the increase in eddy current, and the skin effect increases. These changes cause the magneto-inductance effect to decrease and the magneto-resistance effect to increase. An inductance ratio as high as 311% is obtained in the transverse field at the frequency of 300 kHz, and a resistance ratio as high as 200% is obtained in the transverse field at the frequency of 13 MHz. In both cases there is a low saturation magnetic field.

In summary, the GMI effects in sputtered FeCuCrVSiB/Ag/FeCuCrVSiB sandwich films have been studied. Compared with single-layer films, the sandwich films have much higher

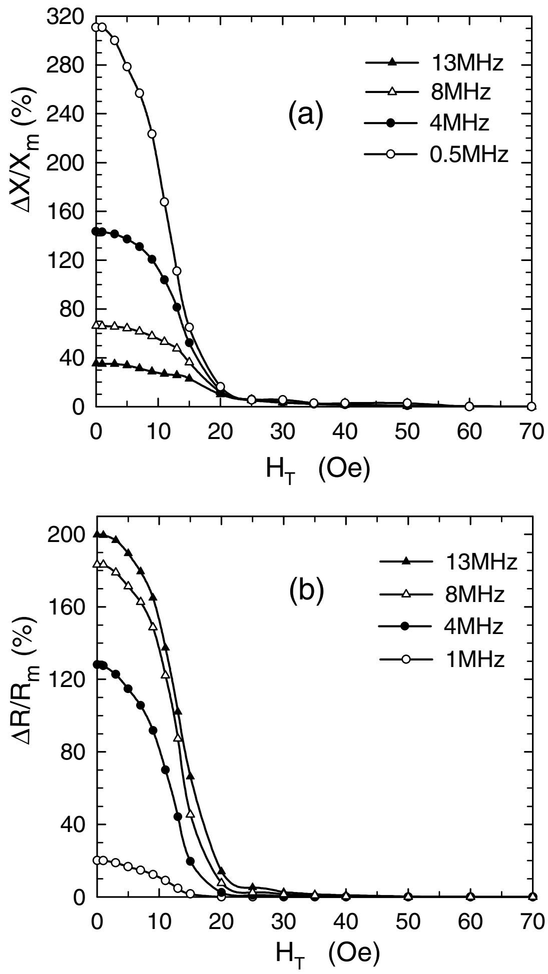

Figure 5. Magneto-inductance ratios (a) and magneto-resistance ratios (b) versus the transverse magnetic field H_T with frequency f as a parameter.

GMI ratios at relatively low frequencies. This is due to the separation of the alternating-current path from the magnetic flux loop. The inserted highly conductive metal reduces the alternating-current dissipation of the sandwich film, and the outer magnetic layers form a closed-loop structure. GMI ratios of 135% and 109% were obtained at 4 MHz in the transverse and longitudinal cases, respectively. The transverse GMI effect is better than the longitudinal one. This is associated with the closed ac magnetic flux loop in the transverse direction, and the influence of demagnetization for the ac magnetic field is also very weak. The magneto-inductance ratio of the samples decreases with increasing frequency, while the magneto-resistance ratio increases with frequency. An inductance ratio as large as 311% is obtained in a transverse field at the frequency of 300 kHz, and a resistance ratio as large as 200% is obtained in the transverse field at the frequency of 13 MHz. The results reported in this paper are much batter than those reported in our earlier work [13], in which the sandwich films had the structure FeNiCrSiB/Cu/FeNiCrSiB. With that structure, a maximum GMI ratio of 77% was obtained, and the characteristic frequency was as high as 13 MHz. This indicates that FeCuCrVSiB alloy is a good choice for incorporation in a sandwich film with a view to producing GMI effects.

Acknowledgments

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