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Giant Magnetoimpedance in Electrodeposited Cobalt on Silver Wires

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ABSTRACT

Cobalt of thickness from 1 to 25 μm was coated onto 120 μm-diameter silver wires by electrodeposition. Giant magneto-impedance (GMI) of electrodeposited cobalt on silver wires was measured with ac current from 1 kHz to 1 MHz. Their impedance decreased with a longitudinal magnetic field and saturated under 1.5 kOe. With increasing cobalt thickness, the critical frequency decreased but the GMI ratio increased. A maximum GMI ratio of over 200 % and sensitivity of about 0.5 %/Oe were observed in a 25 μm-thick sample at the frequency of about 500 kHz. The results can be explained by the dependence of the circumferential permeability on the magnetic field and frequency of ac current.

Keywords: Giant magnetoimpedance, magnetic permeability, skin depth, electrodeposition

INTRODUCTION

Giant magnetoimpedance (GMI) is a large decrease of electrical impedance of soft ferromagnetic conductors in an applied dc magnetic field [1,2]. The effect has been observed in soft magnetic wires [3,4], microwires [5], strips [6], ribbons [7] and thin films [8]. GMI effects in soft magnetic wires and microwires has become a topic of interest because of their novel applications as small sensors [9-11]. Several techniques, such as in-rotating-water quenching, melt-extraction, and melt spinning, have been implemented to produce magnetic wires. Electrodeposition is also a very interesting method to coat a magnetic layer on metallic wires according to the suggestion by Gromov and Korenivski [12] that magnetically coated wires had higher GMI than those of homogeneous wires. In this paper, electrodeposited cobalt on silver wires were prepared and their GMI effects studied as a function of the magnetic field, frequency and thickness of the magnetic layer.

MATERIALS AND METHODS

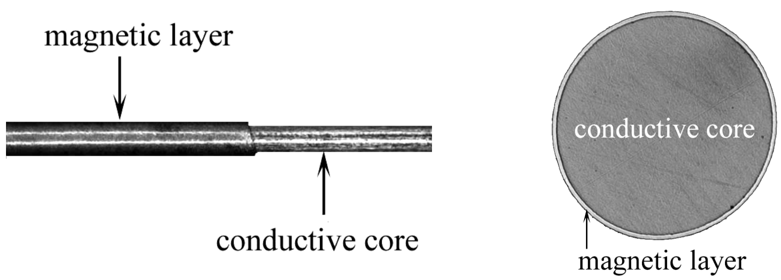
In the electrodeposition system, the electrolyte solution was prepared using distilled water with $CoSO_4{\cdot}7H_2O$ (Aldrich) as a reagent. The metallic ion concentration was maintained at 0.1 M and the pH of the solution was adjusted to 2.5 using H_2SO_4. Cobalt rods (Aldrich, 99.95 %) and rotating 120 μm-diameter silver wires (Aldrich, 99.99 %) were used as electrodes. Cobalt layers ranging from 1 to 25 μm in thickness were electrodeposited on silver wires at a dc current density of 150 mA/cm^2. Before every deposition, the electrodes were cleaned in an ultrasonic water bath for 2 min.

Magnetic properties of the wires are characterized by a hysteresis meter with the magnetic field parallel to the wire. In GMI measurements, the 3 cm-long samples were placed in the longitudinal dc magnetic field (H) supplied by an electromagnet. The impedance (Z) of the samples was measured by a precision LCR meter (HP4284A) with the four-terminal pair connection technique. Correction functions (OPEN and SHORT) of the LCR meter were performed to eliminate measurement errors due to parasitics of test fixtures and cables. The amplitude of the ac driving current was kept constant at 20 mA during the sweeps of the frequency (1 kHz to 1 MHz) and the applied magnetic field (0 to 1.5 kOe). For this paper, the GMI ratio is defined as $(Z_H - Z_{1.5kOe})/Z_{1.5kOe}\times 100$, where Z_H

and $Z_{1.5kOe}$ represent the impedance in the magnetic field H and in the 1.5 kOe magnetic field respectively. The field sensitivity of the GMI is defined as $[d(\Delta Z/Z)/dH]$.

RESULTS AND DISCUSSION

Microscope images of the electrodeposited cobalt (Co) on silver (Ag) wire are shown in **Figure 1**. As seen in **Figure 1b**, the silver core is uniformly coated by a cobalt layer and the thickness of cobalt layer may be determined. **Figure 2** shows axial hysteresis loops obtained from samples with different cobalt thicknesses at room temperature. The remanent magnetization, saturation magnetization, coercivity and permeability increase with the cobalt thickness. With increasing ratio of cobalt mass to the total mass, the magnetic properties approach those of bulk cobalt.



(a) (b)

Figure 1 Microscope images of electrodeposited cobalt on silver wire, (a) side view and (b) cross-sectional view.

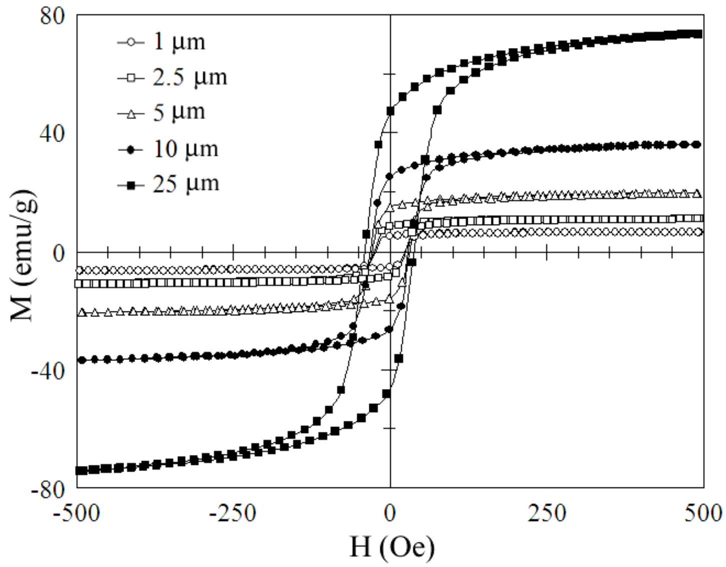


Figure 2 Room temperature hysteresis loops for samples with different cobalt thicknesses.

Figure 3 shows the impedance as a function of frequency for the 25 μm-thick sample. The zero field impedance (Z_0) is rather constant in the low frequency regime (< 50 kHz). However, above the critical frequency of 50 kHz, the zero field impedance increases rapidly with the frequency. In a 1.5 kOe field, the impedance ($Z_{1.5kOe}$) is also insensitive at low frequencies and the critical frequency shifts to 200 kHz. The behavior of the impedance can be analyzed as follows. In a low frequency regime, current flows mainly in the silver core because its conductivity is larger than that of cobalt. Therefore, the impedance of the coated wires is attributable to the inductive reactance of the outer magnetic layer and the resistance of the conductor core [13]. For a cylindrical conductor (of radius a, length l and conductivity σ_0) covered by a magnetic shell (of thickness d and circumferential permeability μ_ϕ), the total impedance Z is basically composed of the resistance (R) of the conductor core and the inductive reactance (ωL) of magnetic shell and can be estimated as in Eq. (1).

$$Z = R + j\omega L = \frac{l}{\sigma_0 \pi a^2} + j\omega \frac{\mu_\phi l}{2\pi} \ln \frac{(a+d)}{a} \tag{1}$$

This impedance can be modified via the concept of skin depth (δ), the depth at which the current density reduces to $1/e$ of the value at the surface. The skin depth is a function of the frequency of ac current (f), the conductivity (σ) and the circumferential permeability (μ) of materials as in Eq. (2).

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \quad (2)$$

When the skin depth is larger than the radius of a coated wire, ac current flows through the entire cross section of the silver core accounting for constant impedance. An increase in either frequency or permeability decreases the skin depth. A skin effect occurs at the critical frequency when the reduced skin depth is comparable to the wire radius. Since the cross sectional area of current flow is decreased by the skin effect, a significant rise in the impedance is expected as a result. However, the calculated value for silver skin depth is comparable to the wire radius at the frequency of 500 kHz. This frequency is much larger than that observed from **Figure 3**. The shift of the critical frequency to lower frequency for an inhomogeneous wire can be explained using frequency dependence of real and imaginary impedance curve shown in **Figure 4**.

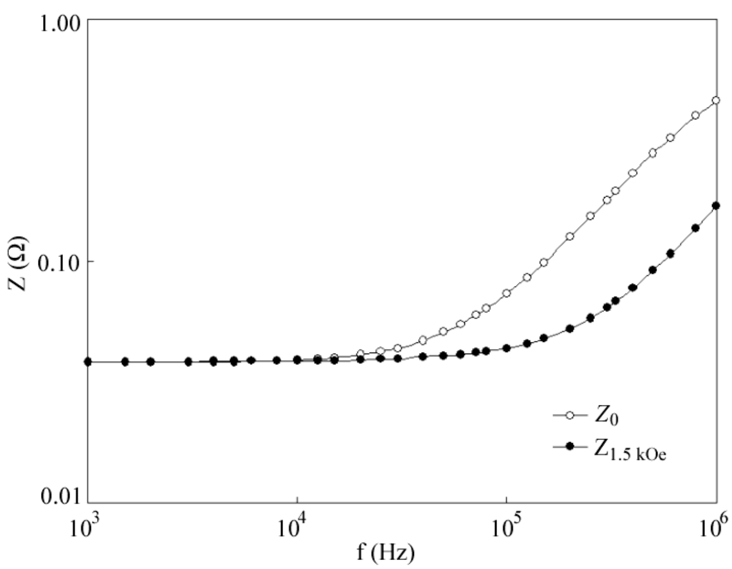


Figure 3 Frequency dependence of impedance in zero field and 1.5 kOe field for a 25 µm-thick sample.

Figure 4 shows the real and imaginary components of impedance as a function of frequency. The zero field reactance (X_0) exhibits a linear increase with frequency as expected from Eq. (1). In contrast, the zero field resistance (R_0) is rather constant at low frequency and gradually increases at higher frequencies when the current in the cobalt shell increases. A rapid increase in resistance starts at about 200 kHz when the skin depth becomes comparable to the radius of the sample and the current flows mainly in the cobalt shell. At low frequencies, the resistance dominates over the reactance. At higher frequency, the behavior of impedance depends on both resistance and reactance. It is noted from **Figure 4** that the impedance rapidly increases when the reactance dominates over the resistance. The application of 1.5 kOe field decreases the permeability, resulting in a decrease in the reactance and increase in the skin effect. Therefore, the critical frequency shifts to a higher frequency as seen in **Figure 3**.

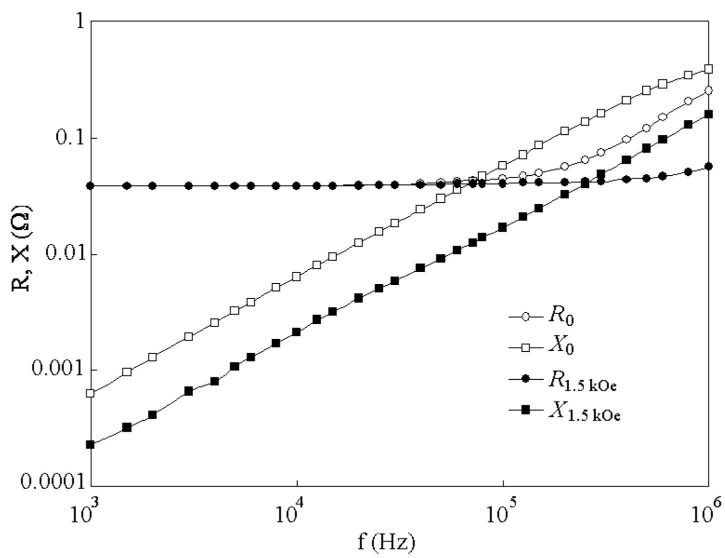


Figure 4 Frequency dependence of real (R) and imaginary (X) impedance in zero field and 1.5 kOe field for a 25 μm-thick sample.

Figure 5 shows the GMI ratio as a function of the frequency for thicknesses ranging from 1 to 25 μm. Each curve rises at its critical frequency and reaches its peak at a frequency called characteristic frequency. The critical frequency tends to decrease with increasing cobalt thickness. In the case of thick cobalt, the skin depth is comparable to the radius of sample at lower frequencies. Therefore, the strong skin effect in which the current mainly flows in the cobalt shell occurs at lower frequencies. Moreover, Eq. (1) shows that the reactance of the coated wires increases with increasing cobalt thickness resulting in a decrease in the critical frequency. The characteristic frequency corresponds to the critical frequency of the impedance under 1.5 kOe field because the rise of this impedance reduces the GMI ratio. The decrease in the characteristic frequency with increasing cobalt thickness is expected since the critical frequency of impedance under an applied field shifts to lower frequency for thicker cobalt layer samples. The GMI ratio also decreases with increasing cobalt thickness and the maximum GMI ratio is found in the 25 μm-thick sample at 500 kHz. The effect of the cobalt thickness on the GMI ratio can be explained by using the dependence of circumferential permeability on the magnetic field and frequency. With increasing cobalt layer thickness, the cross sectional area and reactance increase and the critical frequency consequently decreases. Since the GMI ratio depends on the relative variation of impedance, small impedance change in low impedance sample results in a large relative variation in impedance. Besides, the rise of impedance occurs at lower frequency for samples with thicker cobalt layer. Since the circumferential permeability strongly decreases with the application of a magnetic field in the low frequency regime, the larger GMI ratio is therefore observed in the case of thick cobalt.

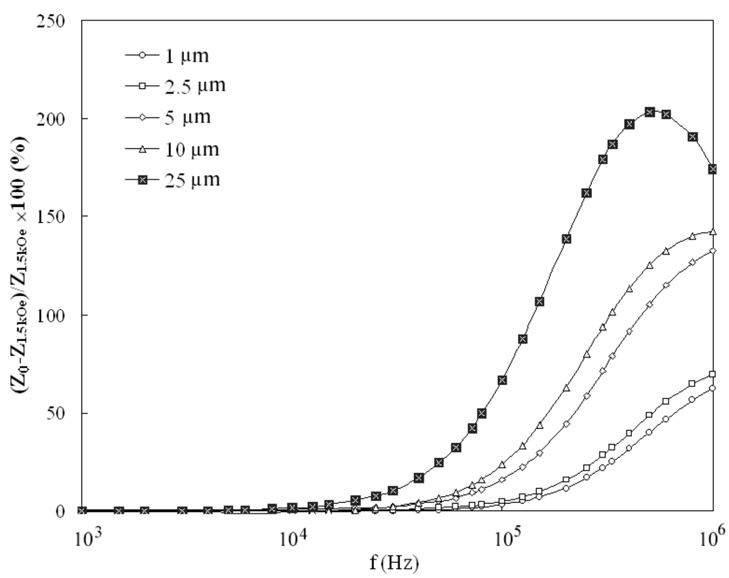


Figure 5 Frequency dependence of GMI ratio for samples of varying thickness.

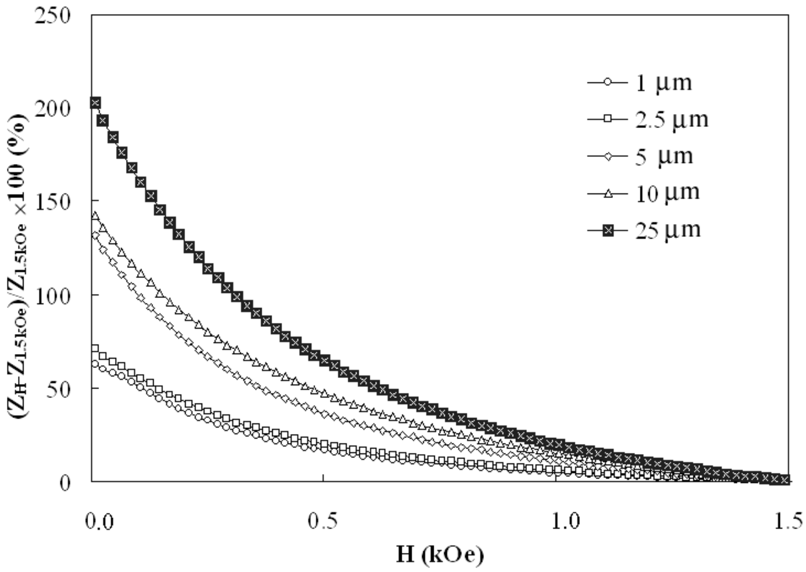


Figure 6 Magnetic field dependence of GMI ratio at frequency with the maximum GMI ratio for samples of varying thickness.

In **Figure 6**, the magnetic field dependence of the GMI ratio was measured at the frequency with the maximum GMI ratio for the samples of varying thickness. For every thickness, the impedance (Z_H) decreases with increasing magnetic field and saturates below 1.5 kOe. This can be explained in terms of the reduction of circumferential permeability by an applied magnetic field. Below 1.5 kOe, the circumferential permeability saturates and the field sensitivity reduces at high field as seen in **Figure 6**. The sensitivity is higher at low field and the maximum 0.50 %/Oe is observed in the 25 µm-thick sample. GMI increases with increasing cobalt thickness. With a thicker cobalt layer, the skin depth is comparable to the thickness of the cobalt layer at lower frequency. As the circumferential permeability is very sensitive to the magnetic field in a low frequency regime and because of the difference between $Z_{1.5kOe}$ and Z_0 the GMI ratio increases.

CONCLUSIONS

The GMI effect in electrodeposited cobalt on silver wires was studied. A maximum GMI ratio of over 200 % and a maximum sensitivity of about 0.5 %/Oe are observed in a 25 μm-thick sample at a frequency of 500 kHz. As the cobalt layer becomes thinner, the GMI ratio decreases but the critical frequency increases.

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บทคัดย่อ

พงศกร จันทรัตน์[1] และ ชิตณรงค์ ศิริสถิตย์กุล[2]

ไจแอนท์แมกนีโตอิมพีแดนซ์ ในลวดเงินชุบเคลือบไฟฟ้าด้วยโคบอลท์

เคลือบโคบอลท์ความหนาตั้งแต่ 1 ถึง 25 ไมโครเมตร บนลวดเงินเส้นผ่านศูนย์กลาง 120 ไมโครเมตร โดยใช้วิธีชุบเคลือบด้วยไฟฟ้า และทำการวัดไจแอนท์แมกนีโตอิมพีแดนซ์ (GMI) ของลวดเคลือบโดยใช้ไฟฟ้ากระแสสลับความถี่ 1 กิโลเฮิร์ตซ์ ถึง 1 เมกะเฮิร์ตซ์ จากการวัดพบว่าค่าอิมพีแดนซ์ของลวดเงินเคลือบโคบอลท์ ลดลงในสนามแม่เหล็กที่มีทิศเดียวกับความยาว และอิ่มตัวในสนามขนาด 1.5 กิโลเออร์สเต็ด ในกรณีที่โคบอลท์มีความหนามากขึ้น ค่าความถี่วิกฤตลดลง แต่ขนาดของ GMI เพิ่มขึ้น ค่า GMI สูงสุดมีค่ามากกว่า 200 % พบในตัวอย่างโคบอลท์หนา 25 ไมโครเมตรที่ความถี่ประมาณ 500 กิโลเฮิร์ตซ์ ผลการวิจัยสามารถอธิบายด้วยการที่สภาพซึมซาบได้ทางแม่เหล็กในแนวเส้นรอบวงของลวด ขึ้นอยู่กับสนามแม่เหล็กและความถี่ของกระแสไฟฟ้า

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