Research articles

Magneto-impedance Effects in Electrodeposited Multi-layer [NiFe/Cu]₃ on Cu Wire Substrates for kHz–order Frequency Measurements

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1. Introduction

The electrical impedance of some ferromagnetic materials greatly changes under an external magnetic field [1]. Such phenomena are known as magneto-impedance (MI). The MI effects play an important role in modern technology. In particular, they are exploited in variable magnetic sensors for ultra-low magnetic field applications such as cardiac magnetic activity detectors [2–5]. Atalay and Atalay investigated the effect of MI in a single-layered NiFe of different thicknesses on Cu wire substrate. They reported a significant effect of NiFe thickness on the MI ratio. The MI effect is also sensitive to the high frequency, such as much larger than megahertz order [6].

The complex impedance is expressed as $Z = R + iX$, where $R$ is the resistance (real part) and $X$ is the reactance (imaginary part). The magnitude of the MI ratio (ΔZ/Z) under an external field $H$ is expressed in Eq. 1:

$$\frac{\Delta Z}{Z} = \frac{Z(H) - Z(H_{\text{max}})}{Z(H_{\text{max}})} \times 100\%$$

where $Z(H)$ is the measured impedance (in the absence of the magnetic field) and $Z(H_{\text{max}})$ is the impedance at the maximum external magnetic field, and $\Delta Z$ is the threshold magnetic field required for saturated impedance.

The MI effect depends on the skin effect in the magnetic conductor [8]. In turn, the skin effect is related to the skin depth, which is a function of frequency and the electrical conductivity. The skin depth is given by Eq. 2:

$$\delta_m = \frac{c}{4\pi^2\rho f}$$

where $c$ is the speed of light, $\rho$ is the electrical conductivity, and $f = \omega/2\pi$ is the frequency of the alternating currents flowing through the sample.

The multi-layered structure consists of $N$ repeats of two magnetic layers separated by non-magnetic spacer layers. The impedance of multi-layer structure is given by Eq. 3:

$$Z = R_{\text{m}} \left(1 - 2i\mu_H \frac{d_1d_2}{\delta_H} \right)$$

where $R_{\text{m}} = \|2\omega c d_b\|$ is the resistance of the conductor layer, $\delta_H = \sqrt{2\mu_0\rho_H}$ is the skin depth inside the conductor layer, and $\mu_H$ is the permeability tensor, $d_1$ and $d_2$ are the thickness of the spacer and magnetic layers, respectively. As per Eq. 3, the MI ratio of multi-layer configuration enhanced at the low frequency when the skin depth effect is not subdued and is a linear function of $\mu_H$[9].

This study aimed to demonstrate the modulation of MI in a multi-layered structure. The magnetic layers are permalloy thin films of NiFe interdigitated with Cu film to form multi-layered structures [NiFe/Cu/N] where $N = 3$ is the repetition number and the Cu films are conducting spacer layers. Whole films were fabricated by electrodeposition on the wire substrate with modification by the thickness of the spacer layer.

2. Experimental Methods

The multi-layer structure of [NiFe(800 nm)/Cu(y nm)]₃ with $y = 0, 100,$ and 200 nm used in this experiment was fabricated by electrodeposition with a platinum wire electrode. The substrates were copper wires (diameter = 0.46 mm). Before electrodeposition, the substrate was cleaned with ultrasonic cleaners. The electrolyte baths used in the electrodeposition of the multi-layer structure [NiFe/Cu]₃ are listed in Table 1. The electrolyte bath solution was adjusted to a constant pH 2.7 by adding up to 0.05 ml of 1 M H₂SO₄.

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Table 1. Electrolyte bath used in the multi-layer [NiFe/Cu]$_x$ deposition

| Desired Layer | Electrolyte bath | Concentration |
|---------------|------------------|---------------|
| NiFe          | NiSO$_4$.6H$_2$O | 0.099 M       |
|               | FeSO$_4$.7H$_2$O | 0.012 M       |
|               | H$_2$BO$_4$      | 0.149 M       |
| Cu            | CuSO$_4$.5H$_2$O | 0.065 M       |
|               | C$_6$H$_5$COOH   | 0.002 M       |

The electrodeposition rates of NiFe and Cu spacer layers were 2 nm/s and 6 nm/s, respectively, achieved at current densities of 15.5 mA/cm$^2$ and 8 mA/cm$^2$, respectively. By repeating this electrolyte process, we fabricated multi-layered structures [NiFe(800 nm)/ Cu(y)]: with y = 0, 100 and 200 nm. The element compositions of the obtained multi-layer samples were characterized by X-ray fluorescence and their crystalline structures were determined by X-ray diffraction (data not shown). The magnetic characteristics were measured by a vibrating sample magnetometer (VSM). The magnetic dependence of the impedance (MI) was then measured by a conventional LCR meter as shown in Figure 1. The magnitude of the measured impedance was calculated as the square root of the sum of the squared real (resistance) and imaginary (reactance) component (\(Z = \sqrt{R^2 + X^2}\)).

The MI data were obtained by measuring the resistance value (\(R\)) and reactance (\(X\)) while varying the external field \(H\).

3. Results and Discussion

Figure 2 plot the MI ratio as a function of frequency \(f\). The characteristic MI curves in Figure 2(a) were obtained under an external magnetic field \(H\) with \(f = 20\) kHz and 100 kHz. Evidently, the shape of the MI versus \(H\) plot is identical at two frequencies, and the MI ratio maximized at \(H = 0\). The MI ratio rapidly decreased as \(H\) increased up to ±40 mT and became almost constant thereafter. The magnitude of \(H\) beyond which the MI ratio no longer changes was not significantly different between \(f = 20\) kHz and 100 kHz. However, the peak MI ratio significantly increased from 36.5% at \(f = 20\) kHz to 54.4% at \(f = 100\) kHz. The type of the MI ratio as a function of frequency is depicted in Fig 2(b), i.e., for \(f = 20\) kHz and 100 kHz. Other frequency also has a similar profile of the MI curve. It notes that the value of MI rapidly increased up to \(f = 40\) kHz and it thereafter tended to saturate. The MI realization at low frequency indicates that the MI support dominantly by the inductive component [2]. The obtained results are consistent with those of Mishra [5].

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**Fig. 1**. Experimental schematic of the measurement of MI effects

**Fig. 2**. (a) The typical MI versus \(H\) curves for multi-layered [NiFe$_{80}$Fe$_{20}$](800 nm)/Cu(300 nm)]$_x$ at applied frequencies of 20 kHz (triangles) and 100 kHz (circles) (b) MI ratio versus frequency.
4. Conclusions
This study investigated the MI effect in multi-layered systems of [NiFe/Cu]_{y} electrodeposited on Cu wires. The MI ratio was modified by varying the thickness of the Cu spacer layer. The multi-layered samples of [NiFe/Cu]_{y} were deposited by electrodeposition using a platinum electrode. The MI ratio rapidly increased to approximately 47% as the applied frequency increased to 40 kHz and it remained somewhat constant thereafter. In the multi-layered system of [NiFe(800 nm)/Cu(y nm)], the MI ratio decreased with increasing thickness of the Cu layer. The decreased MI ratio may be correlated to the lowering of the saturated magnetization in multi-layer systems with thicker Cu spacer.

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