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Three dimensional simulation of giant magneto-impedance effect in thin film structures

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In this paper, a three dimensional model for the giant magneto-impedance (GMI) effect in thin film structures is developed using the finite element method (FEM) with a GMI permeability model embedded. One-layer, three-layer, and five-layer thin film structures are simulated. The GMI effect and the sensitivity are calculated as a function of the external magnetic field, driving frequency, and the thickness of the magnetic layers. The results show that the five-layer structure has the best performance, which is in accordance with experimental results. The GMI ratio and the sensitivity first improve with the increasing thickness of the magnetic layer but reach saturation at a certain value of the thickness. In a five-layer structure, saturation of the GMI effect becomes effective at about 3 μm thickness of the magnetic layers, where a GMI ratio of 1125% was obtained, with a corresponding sensitivity of 0.37%/A/m (29.6%/Oe). © 2011 American Institute of Physics. [doi:10.1063/1.3556947]

I. INTRODUCTION

As a potential technology for next generation, magnetic microsensors with a high sensitivity to low magnetic field changes, the giant magneto-impedance (GMI) effect has attracted increasing interest in the past decade. The GMI effect was originally found in ferromagnetic microwires, which, so far, proved to have the best performance compared to other GMI structures. However, the fabrication technology of the microwires adds complexity and costs to the production of an integrated sensor. Consequently, more and more effort has been put into the research of thin film GMI structures in order to improve the sensitivity.

A single layer thin film GMI structure consists of a soft magnetic thin film with magnetic domains transversal to the longitudinal axis.¹ An alternating current I_{ac} generates a transverse flux B_{tran} inside and around the film. After applying an external field H_{ext} , domain wall motion as well as magnetization rotation contribute to a permeability change in the transversal direction, leading to a change in impedance. Based on the single layer GMI structure, several other configurations such as three- and five-layer structures have been developed to improve the GMI performance.²⁻⁴ In these structures, improvement is achieved by reducing the base impedance using a highly conductive metallic inner layer and isolating the conductive layer from the magnetic ones.^{5,6}

In general, the dependence of the permeability on H_{ext} can be obtained by solving the Landau–Lifshitz equation. Much work has been done previously to develop permeability models and simulate the impedance change in different GMI structures.⁷⁻¹⁰ However, analytical solutions of the GMI effect for more complex structures are difficult to obtain. In this case, the finite element method (FEM) is a

suitable method to evaluate the impedance change of the GMI structure, providing flexibility with respect to the design of the structures. Previous work, using FEM, focused on the skin effect in a two dimensional (2D) model¹¹ without considering the dependence of the permeability on the external field.

In this paper, the FEM is applied in combination with previously developed permeability models⁹ for the GMI effect in order to study the performance of GMI thin film structures. The 3D models for one-, three-, and five-layer structures are developed, and the dependencies of the GMI effect and the sensitivity on the geometrical parameters as well as the frequency are calculated.

II. METHOD

The GMI ratio is the relative change of the impedance with respect to the external magnet field

$$\frac{\Delta Z}{Z}(\%) = 100\% \times \frac{Z(H_{ext}) - Z(H_0)}{Z(H_0)}, \quad (1)$$

where $Z(H_{ext})$ is the impedance under a certain external field H_{ext} and H_0 is the zero external magnetic field.

The sensitivity is defined by

$$\zeta = (100\% \times) \frac{Z(H_2) - Z(H_1)}{Z(H_1)} / (H_2 - H_1). \quad (2)$$

The impedance in the ferromagnetic thin film can be expressed as

$$Z = \frac{V_{ac}}{I_{ac}(H_{ext})}, \quad (3)$$

where V_{ac} is the voltage applied to the sensor and I_{ac} is a function of H_{ext} .

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FIG. 1. (Color online) A 3D plot of the circumferential magnetic flux of the (a) three-layer and (b) five-layer thin film GMI sensors.

The 3D finite element analysis was carried out using a commercial software (COMSOL-multiphysics).¹² A value of $V_{ac} = 5$ V was defined as a boundary condition on one end of the sensor, whereas the other end was set to the ground potential. In the case of five-layer structure, V_{ac} was applied only to the metal layer. In order to find I_{ac} , the permeability dependence of the ferromagnetic material on the external field is required. We applied the permeability model developed previously.⁹

$$\mu = \frac{\gamma \cdot M_s (\gamma \cdot H_{equ} + i\alpha\omega) \sin^2(\theta + \theta_0)}{(\gamma \cdot H_{equ} + i\alpha\omega)^2 - \omega^2}, \quad (4)$$

where ω is the angular frequency, θ is the angle between M_s and the easy axis, θ_0 is the small angle existing between the direction of the ideal anisotropy and the real easy axis, and H_{equ} is the magnetic field component that affects the saturation magnetization. Under the assumption of a magnetic anisotropy in transversal direction, the third order permeability tensor for the model reduces to

$$\begin{bmatrix} \mu & 0 & 0 \\ 0 & \mu & 0 \\ 0 & 0 & 1 \end{bmatrix}.$$

The three different thin film structures—one-, three-layer, and five-layer—that were investigated showed dimensions of width $w = 50 \mu\text{m}$ and length $l = 200 \mu\text{m}$ (Fig. 1). A thickness of $t_{mag} = 1 \mu\text{m}$ and $t_{met} = 4 \mu\text{m}$ was assigned to the magnetic layer and the conducting layer, respectively. However, the

FIG. 2. (Color online) Current density distribution along the cross section under the external field of 2200 A/m in a (a) 3-layer and (b) 5-layer GMI structure.

FIG. 3. (Color online) Impedance change and GMI ratio as a function of the external magnetic field for one-, three-, and five-layer thin film structures.

influence of different values of t_{mag} was also investigated. The isolation layer was set as SiO_2 . The conductivities of the ferromagnetic and conducting layer were 7.69×10^5 S/m $[(\text{CoFe})_{80}\text{B}_{20}]$ and 4.56×10^7 S/m (Au), respectively. All the parameters including $M_s = 5.6 \times 10^5$ A/m, $\gamma = 2.2 \times 10^5$ m/As, $\alpha = 0.3$, and $\theta_0 = \pi/180$ were taken from literature.¹⁰

The simulations were carried out for values of H_{ext} from 0 to 4800 A/m and, if not stated otherwise, with a driving frequency of 80 MHz.

III. RESULTS

The circumferential magnetic flux of the three- and five-layer GMI thin film structures are presented in Fig. 1. The circumferential magnetic flux generated by the five-layer structure is stronger than the three-layer structure, which is a result of the higher current density obtained in the five-layer structure. Figure 2 shows the current density distribution along the cross sections of the three-layer and five-layer structures. As can be seen, the insulation layer in the five-layer structure prevents the current from leaking into the magnetic layer. This current leakage causes an increase of the impedance of the three-layer structure compared to the five-layer structure.

The impedance and the corresponding GMI ratios as a function of H_{ext} are presented in Fig. 3. The results show that the single layer GMI has the highest absolute impedance but the lowest GMI ratio. The GMI ratio of the single layer structure is in good agreement with the results found previously,¹⁰ which is less than 10% at 80 MHz for this specific material.

FIG. 4. (Color online) Dependence the GMI ratio of the five-layer structure with different values of the thickness of the magnetic layer as a function of the external field.

FIG. 5. (Color online) Sensitivity of the five-layer GMI structure with different values of the thickness of the magnetic layer and as a function of the external field.

The five-layer structure is superior to the other two structures and results in the highest GMI ratio of up to 625%.

Figure 4 shows the influence of t_{mag} on the GMI ratio for a five-layer structure. An increased thickness yields an increase of the GMI ratio, and the maximum GMI ratio found was 1321% at $H_{\text{ext}} = 2200$ A/m. As for the sensitivity (Fig. 5), an increased thickness also resulted in an increased value. The sensitivity reaches 0.55%/A/m (44%/Oe) at the thickness of 13 μm . Interestingly, a maximum sensitivity is obtained at lower values of the field as the thickness increases. It is also observed that the sensitivity shows negative values at weak magnetic fields. This behavior is a result of the permeability model, in which the real part of the permeability shows a decrease for small values of the magnetic field. Figure 6 shows the maximum values of the GMI ratio and the sensitivity as a function of t_{mag} . It is evident that the increase of both the GMI ratio and the sensitivity with t_{mag} approaches saturation. This is an important finding considering the challenges associated with the fabrication of thin films with a thickness of several micrometers. From this result, a thickness of $t_{\text{mag}} = 3$ μm seems to be most effective because a further increase in thickness causes only a small increase of the GMI ratio. The sensitivity shows a slower

FIG. 6. (Color online) Maximum GMI ratio and sensitivity of the five-layer GMI structure as a function of the thickness of the magnetic layer.

FIG. 7. (Color online) Dependence of peak GMI ratio of the five-layer GMI structure with different values of the thickness of the magnetic layer as a function of the driving frequency.

approach toward saturation, and a thickness beyond $t_{\text{mag}} = 3$ μm might still be beneficial. In Fig. 7, the GMI dependence on the driving frequency and t_{mag} is shown. The results show that the optimal frequency range of this five-layer structure is almost independent of the thickness of the magnetic layer and lies between 80 and 90 MHz.

IV. CONCLUSION

A 3D model has been developed using the finite element method to determine the GMI ratio and the sensitivity in different thin film GMI structures. The current density distribution and the skin effect were observed and discussed. The results confirmed that the five-layer structure has superior performance, which is in accordance with experimental results, and the optimum frequency with respect to the GMI ratio is between 80 and 90 MHz. A study on the influence of the thickness of the magnetic layer on the GMI ratio as well as the sensitivity was carried out. Both were found to first increase with the increasing thickness and then approach saturation. This finding provides valuable information for efficient fabrication of GMI sensors.

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