Journal of Magnetism and Magnetic Materials 400 (2016) 321–326

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Thin-film magneto-impedance structures with very large sensitivity

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ARTICLE INFO

Article history:
Received 22 June 2015
Received in revised form
24 July 2015
Accepted 29 July 2015
Available online 30 July 2015

Keywords:
Magneto-Impedance (MI)
Magnetic sensors
Thin films
Finite Element Method (FEM)

ABSTRACT

Thin film-based Magneto-Impedance (MI) structures are well suited for developing highly sensitive magnetic microsensors, which can be directly integrated into microelectronic circuits. Permalloy (Py) based structures benefit from well-established preparation procedures and enhanced structural stability over amorphous based sensors. In this work we use Finite Element Method calculations to complement our previous studies on high permeability Py multilayers, in order to determine the combination of magnetic and non-magnetic layers that maximizes the MI performance in sandwiched structures. The results indicate that optimum behavior is expected when the thickness of the non-magnetic layer equals the magnetic ones. The study is performed with an open flux configuration (Py not enclosing the central non-magnetic conductor), which permits the fabrication of the complete stack of layers in a single deposition process. On the outcome of that analysis, samples with a sandwiched multilayer structure defined as $[Py(100\ nm)/Ti(6\ nm)]_4/Cu(400\ nm)/[Ti(6\ nm)/Py(100\ nm)]_4$ have been prepared by magnetron sputtering and photolithography, having different dimensions. They were magnetically characterized by magneto-optical Kerr effect, displaying a well-defined transversal anisotropy, and the MI was measured in a network analyzer using a microstrip test-fixture. The measured MI ratio, defined as (Z-Zmin)/Zmin $\times$ 100, reaches extraordinary values of 350%, while the sensitivity, calculated as the field derivative of the MI ratio, goes up to 300%/Oe (27 kΩ/T in absolute units). The MI ratio is lower than the best reported previously for amorphous CoSiB/Ag/CoSiB thin-film samples with closed-flux structure, but the sensitivity, which is the key parameter for the performance of sensors, is six times larger. These figures can be compared favorably with the ones obtained in wire-based samples, and definitely opens the way to incorporate thin-film structures in low-field MI magnetic sensors.

1. Introduction

The Giant Magneto-Impedance (GMI) effect has been considered as a promising candidate for high performance magnetic field sensing since its rediscovery in the 90s [1–3]. It is based on the large variation of the electrical impedance experienced by a magnetic conductor under the influence of an external magnetic field. This effect is completely classical (it can be traced back to the works of Lord Rayleigh in 1887 [4]) and is based on the dependence of the penetration depth of the electromagnetic field on the permeability of the material: the effective cross section available for the flowing of an alternating electric current (of a high enough frequency) is reduced when the permeability increases, producing a concomitant increase of both the resistance and the inductance of the conductor. The GMI effect is especially significant in soft magnetic materials that present large permeability changes at small fields. The best-suited materials are Co-based amorphous wires (up to 200 μm in diameter) and glass-coated microwires (of about 20 μm). The magneto-impedance ratio, defined as the relative variation between the maximum and minimum impedance values, can reach 800% [5], whereas the field sensitivity of the GMI can be as high as 500%/Oe [6]. Many other materials have been studied in the GMI context, including amorphous ribbons, and thin film-based systems. A comprehensive compilation of the GMI performance of different materials can be found in different reviews [7,8]. The excellent sensibility of the GMI has produced numerous attempts to develop sensing devices operating in a field range from 10^{-10} to 10^{-4} T, competing with Giant Magneto-Resistance (GMR), fluxgate and Anisotropic Magneto-Resistance (AMR) sensors [9]. Recently, the introduction of magnetic sensors

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http://dx.doi.org/10.1016/j.jmmm.2015.07.107
0304-8853/

to implement electronic compasses and related functionalities in personal handheld devices such as smart phones and playing gadgets has boosted the development of miniaturized sensors capable of detecting small magnetic fields, allowing to detect small variations in fields of the order of the Earth magnetic field ($\sim 5 \times 10^{-5}$ T). Although the only successful commercial GMI sensor for these applications, produced by Aichi Micro, uses wires as sensing elements, it is widely accepted that, for miniaturization and integration with microelectronic circuitry, thin film-based materials are highly desirable. They can be produced by vapor-deposition techniques (sputtering preferred) and patterned using photolithography methods, which are the standard fabrication processes of the microelectronic industry. Among the different soft magnetic materials that can be prepared in thin-film form, Permalloy (Py) based systems benefit from well-established preparation procedures, since they are used for AMR sensors. Besides, they provide an enhanced structural stability over amorphous materials, which may be important in some demanding applications.

During the last years, we have systematically analyzed the influence of the preparation conditions and the structure on the properties of thin film Py-based multilayers. In this work we use the acquired knowledge to develop an optimum combination of magnetic and non-magnetic layers to maximize the Magneto-Impedance (MI) performance, which allows us to develop a thin-film structure that displays a magneto-impedance ratio of 350% and a sensitivity of 300%/Oe. These values are still somewhat lower than those displayed by amorphous wires, but they are the largest reported for thin films and open the possibility of considering them as a real alternative for thin film-based MI sensors.

2. Selection of the multilayer structure

In a homogeneous sample, constituted by only one type of magnetic material, the MI is a direct consequence of the skin effect: the increase of permeability makes decrease the penetration depth and concomitantly, the impedance increases. For this basic mechanism to produce large impedance variations, the thickness of the material must match the penetration depth at the selected operation frequency. According to the classical expression for the penetration depth

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

at a frequency of $f = 100$ MHz, a 1.5 μm thick film of Permalloy ($Ni_{80}Fe_{20}$) would be necessary to display a perceptible effect (an electrical conductivity of $\sigma = 4.51 \times 10^6$ S/m, and a typical transverse permeability of $\mu_t = 10^3 \mu_0$ (being μ_0 the permeability of free space) have been used to perform the calculation, so δ equals half of the thickness). However, it is not possible to achieve such a large thickness in a sputtered Permalloy film without greatly degrading its magnetic properties. Usually, to obtain high values of the transverse permeability, Permalloy films are prepared with a transverse anisotropy that can be obtained by a post-deposition annealing, but preferentially by performing the deposition under a magnetic field. In this later case, a well-defined in-plane magnetic anisotropy can be established in thin films but, when the thickness is increased, an out of plane component of the anisotropy is developed as the film enters in the so-called "transcritical state", presumably caused by the columnar growth of the deposit, that dramatically reduces the transverse permeability. The critical thickness depends on the preparation conditions (sputtering power and chamber pressure, mainly) but an exhaustive investigation determined a thickness of about 170 nm as the limit for obtaining high permeability films [10].

To overcome that thickness limitation, several Py layers can be successively deposited, each one below the critical thickness, and separated by a very thin spacer [11–13]. During the deposition of the sample, after each Py layer, the deposition of the spacer interrupts the columnar growth, so a multilayer up to 1 μm thick can be obtained with a well defined transverse anisotropy and large permeability.

Of course, the magnetic properties of the Py layers, even below the critical value, depend on thickness. A study of the magnetic and magneto-impedance properties of Py/Ti multilayers with different thicknesses of the Py layers demonstrated that samples composed of 50 or 100 nm thick Py layers perform better than multilayers built with thinner (25 nm) Py films. Similar MI ratios of about 25% were obtained in multilayer samples composed by 4 layers of 100 nm thick Py and 8 layers of 50 nm thick Py [14]. From a technological point of view, the first combination (4×100 nm) is easier to fabricate.

The magneto-impedance is greatly enhanced in core-shell (in the case of wires) or sandwiched (in film-based systems) structures in which a non-magnetic conductor is surrounded by a high permeability material [15]. In this case, the current flows mainly through the inner conductor making that the real part of the impedance remains essentially constant with frequency and magnetic field. In contrast, the imaginary part of the impedance increases linearly with the frequency and is dominated by the permeability of the external magnetic material, which is highly sensitive to the magnetic field. This is often called the magneto-inductive effect. As a consequence, very large changes of the impedance can be obtained at moderate frequencies, since the impedance of the sample increases greatly once the magnitude of the imaginary part equals the magnitude of the real part [16].

The magneto-inductive effect is more effective when the magnetic material encloses completely the inner conductor, since the induced magnetic flux can then follow a closed path. Technologically, however, it is easier to fabricate sandwiched structures in which the central conductor and the external magnetic layers have the same width. In this case, the induced magnetic flux is closed either by the air or the conductor [17]. Large MI ratios and moderate sensitivities have been reported both in closed-flux [18] and open-flux [19] configurations.

Fig. 1a schematizes the structure of a multilayer sandwiched sample with open flux configuration that combines thick high-permeability magnetic layers with a central conductive non-magnetic layer to enhance the magneto-inductive effect. However, to optimize the MI response, it is necessary to determine the optimum thickness of both the inner non-magnetic layer and the external magnetic ones. The influence of the thickness of the central conductor has been studied experimentally for the case of copper layers [20], but a more systematic investigation is required.

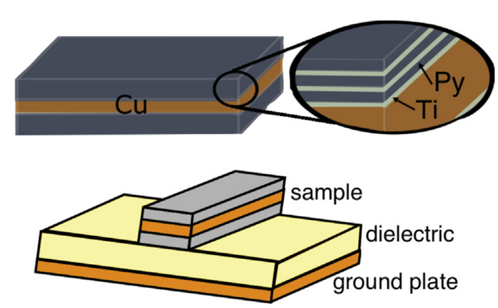

Fig. 1. (Top) Scheme of the structure of a multilayer sandwiched sample to optimize the MI response. (Bottom) Scheme of the system simulated in FEM calculations, including the dielectric and the ground plate of the microstrip line, to account for its contribution to the impedance. The drawing is not at scale.