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Research articles

Asymmetric giant magnetoimpedance effect created by micro magnets

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ABSTRACT

Asymmetric giant magnetoimpedance (AGMI) effect has been investigated in as-prepared and current annealed amorphous $(Co_{0.9}Fe_{0.05}Ni_{0.05})_{75}Si_{15}B_{10}$ ribbons. Asymmetry was created by micro magnets. Different numbers of magnets were used and it was found that increasing number of magnet, the shift in AGMI curves increases. When two micro magnets were placed 1 cm away from the ends of ribbon, a distortion in two peak shape of the GMI curve was observed. At high frequency range, a linear change in the AGMI was observed for the current annealed sample.

1. Introduction

When a magnetic conductor carrying a high-frequency alternating current is subjected to an external magnetic field, the impedance of the material changes. The phenomenon has been discovered many years ago for iron-nickel wires [1]. The effect has been attracted much attention when advanced technologies of the production of conducting soft magnetic materials with a high permeability have appeared [2–4]. Due to large change in the impedance in soft magnetic conductors this effect has been referred to as the giant magnetoimpedance (GMI) [3–5]. GMI sensors can be used in many applications such as magnetic field, stress, torque, biosensor, current, force [6–14]. GMI properties of samples with various compositions have been investigated in the ribbon, wire, film, magnetic tube and multilayer film forms (see, for example, [5,15] and references therein).

The GMI can be explained by the skin effect, which is related to the permeability of the magnetic material. The skin depth, δ, for a ferromagnetic conductor can be written as $\delta = (\rho/\pi f \mu \mu_0)^{1/2}$ [16], where ρ is the electric resistivity, f is current frequency, μ_0 is the permeability of free space and μ is the permeability. In magnetic materials, μ, so δ depend on the frequency and amplitude of ac current and the external magnetic field. The strong dependence of μ on the external magnetic field in soft magnetic materials leads to the GMI effect.

Different measurement and annealing methods have been applied to ferromagnetic materials with different composition and shapes to improve the magnitude of GMI effect. One of the main problems in the GMI effect is that magnetic materials show generally same dependence on positive and negative magnetic fields values and the impedance changes gradually around zero magnetic fields. In practise, a linear and sharp change in output as a function of magnetic field is desired. Asymmetric GMI effect could be one of the possible solutions to design the linear GMI sensors. Basically, the asymmetric giant magnetoimpedance effect (AGMI) can simply be defined as the distortions of symmetry in GMI curves.

There are several types of the AGMI [5]. The first one has been observed when Co-based amorphous wire was twisted and the DC bias and AC driving currents were applied to the wire together [17]. It has been shown that without bias current a symmetric double-peak GMI curve can be observed. When the DC bias current increases, one peak enhances and the other diminishes, depending on the DC bias current orientation [18]. The origin of this type of the asymmetry has been attributed to the combination of helical magnetic anisotropy with circumferential DC field produced by the bias current. Effects of bias current and torsional stresses on the AGMI have been reported in many other studies [19–24]. Another method of producing the AGMI consists in applying an axial AC bias field to a sample [25]. In this case, the asymmetry results from the mixing of the diagonal and off-diagonal components of the impedance tensor due to the AC cross-magnetization process. However, large power consumption is required in these methods [5]. In this connection, other methods to obtain the AGMI have been studied.

The third type of the AGMI has been observed in Co-based amorphous ribbons annealed in the presence of a weak magnetic field [26,27]. It has been observed that the GMI peak in the region where the applied field is antiparallel to the annealing field

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decreases with annealing field, showing an asymmetry in the GMI profile. Eventually, the GMI peak in the antiparallel-field region disappears, and a drastic step-like change in the GMI peak is revealed for an applied field which is parallel to the annealing field of 500 mOe. The appearance of the AGMI in field-annealed Co-based ribbons has been attributed to surface crystallization. The magnetostatic or exchange coupling between the surface crystalline layer and amorphous bulk produces an effective bias field resulting in the asymmetry in the DC magnetization and GMI response. Later, the AGMI effect due to the exchange bias has been observed in partially crystallized amorphous ribbons [28]. The asymmetry in the GMI response can be explained by the dipolar field created by the hard magnetic crystallites in amorphous phase.

The AGMI has been intensively studied in the thin-film and multilayer structures. In particular, it has been found that the AGMI in $Co_{73}Si_{12}B_{15}$ thin films occurs at some frequencies and film thicknesses [29]. The AGMI has been investigated also in ferromagnetic biphase films with distinct non-magnetic metallic spacer layers [30]. It was shown that the nature of the non-magnetic metallic spacer material does not have significant influence on the AGMI behaviour. The AGMI strictly depends on the structure of the biphase films and can be understood in terms of the orientation of the ferromagnetic layers and kind of magnetic interaction between the ferromagnetic layers [30]. The theoretical study of the AGMI in two-phase ferromagnetic film structures demonstrated that the occurrence of asymmetry in the field dependence on the impedance of the film structure is related to the magnetostatic interaction between the magnetic layers [31]. The AGMI has been observed also in [Ti/FeNi](5)/Ti/Cu/Ti/[FeNi/Ti](x) (x = 0–5) multilayers prepared by sputtering [32] and in exchange-coupling NiFe/IrMn multilayers [33].

So far AGMI has been worked on many materials and different heat treatments have been applied. In this study, we report a simple and easy method to form AGMI in amorphous ferromagnetic ribbon. Very small magnets were placed on the top of magnetic material to create non-uniform magnetic bias field, which leads to AGMI effect.

2. Experimental

Amorphous $(Co_{0.9}Fe_{0.05}Ni_{0.05})_{75}Si_{15}B_{10}$ ribbons were used in the experiments. Ribbons were cut to 5 cm in length and 2 mm in wide. Sample was current annealed at 600 mA for 10 min in air.

The impedance of ribbon was measured using an Agilent 4294A impedance analyser with a 42941A impedance probe which was connected to sample by silver conducting paint and amplitude of driving current was kept constant at 20 mA. A maximum ±3000 A/m magnetic field was applied along the ribbon length using a pair of Helmholtz coils and impedance was measured by software at each magnetic field value. Magnetic field was swept form $-H_{max}$ to $+H_{max}$ and then to $-H_{max}$ in all the MI measurements. The MI ratio as a function of the applied magnetic DC field, H, was defined as $\Delta Z/Z\ (\%) = 100\times[Z(H) - Z(H_{\max})]/Z(H_{\max})$, where the maximum applied field, $H_{\max}$ is 3000 A/m. The M–H loops of samples were obtained using a DC magnetic measurement.

NdFeB magnets, supplied from China, with 1 mm in length and 300 μm in diameter were used to induce irregular anisotropy in the sample. Structure of ribbons was investigated using Rigaku power diffractometer at room temperature using Cu Kα radiation.

3. Results and discussion

Both as-prepared and current annealed sample showed same X-ray spectrum (Fig. 1). A very large hallow peak shows that these samples have amorphous structure. So, no trace of crystallisation or oxidation was observed in annealed sample.

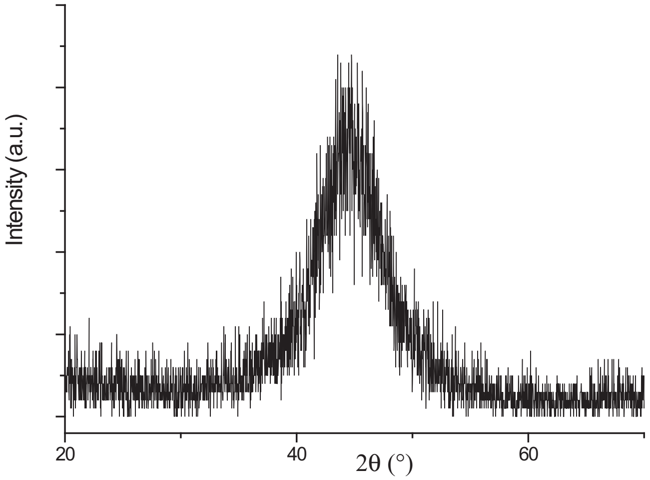

Fig. 1. XRD pattern of current annealed $(Co_{0.9}Fe_{0.05}Ni_{0.05})_{75}Si_{15}B_{10}$ ribbon.

Figs. 2–7 show the field dependence of GMI curves for as-prepared and the current annealed samples. The magnitude of GMI effect increases with increasing driving current frequency and reaches a maximum change around 1 MHz for both as-prepared and current annealed samples. Both as-prepared and current annealed samples, with no magnet, shows typical two peak GMI behaviour, at first, the impedance change increases after displaying a maximum near the anisotropy field then it starts to decrease with increasing applied field. $\Delta Z/Z$ of the current annealed samples reaches to nearly zero value around 0 A/m magnetic fields, showing existence of good transverse anisotropy. This feature has been observed previously in sample with transverse or circumferential anisotropy [5]. The details about GMI properties of as-prepared and current annealed amorphous $(Co_{0.9}Fe_{0.05}Ni_{0.05})_{75}Si_{15}B_{10}$ ribbons can be found in our previous study [34].

When the 2 micro magnets are placed 1 cm away from the one ends of the ribbon (see the drawing in Fig. 3), the GMI curve appears to be distorted (Fig. 3). Both of the peak values get smaller, the peak value at positive H region drops from 65% to 54% and the peak value at negative H region drops from 65% to 46% at 1 MHz driving current frequency, similar behaviours were also seen for other frequency values. So, the change in the GMI peak values in negative and positive magnetic field region are not the same. Additionally, the magnetic field values (H_a), where maximum change occurs are same for the sample with no magnet, but for sample with magnets the these magnetic field values shits from −95 A/m to −50 A/m and from +95 A/m to +225 A/m. So, simply placing a micro magnet on the top of the ribbon both peak values of MI and H_a values changes and AGMI curves can be formed. At higher frequency range the asymmetry becomes larger. As it is well known, at high frequency range mostly magnetic moment rotation is effective and domain wall motion contribution to MI effect is negligible. Therefore we assumed that sample with transverse anisotropy could give better AGMI response. Therefore ribbon was current annealed to create transverse anisotropy at 600 mA for 10 min.

MI results for current annealed sample are presented in Figs. 4–7. In this process, micro magnets were placed 1 cm away from one end of the ribbon. When only 1 magnet was placed 1 cm away from the ribbon end, a large change in the GMI curve was observed. Maximum in the GMI curves dropped nearly 20–30% and the minimum value shift to negative region. When we increased the number of the magnets it was found that the minimum of GMI curve shifts to more negative values and peak values decrease. The minimum values around zero field are 0, −36, −63, −65 A/m for samples no magnet, 1 magnet, 2 magnets,