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Asymmetric magnetoimpedance effect in CoFeSiB amorphous ribbons by combination of field and current annealing for sensor applications

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ABSTRACT

The roles of applied magnetic field during the current annealing of $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ soft magnetic amorphous ribbons are studied. Samples heat treated by Joule heating effect in open air and simultaneously in the present of longitudinal external magnetic field showed asymmetric magnetoimpedance (AMI) behavior. The AMI profile can be related to the exchange bias interaction between the soft magnetic amorphous material and a harder magnetic crystalline phase formed on the surface of the ribbon. This effect stems from thermal effect, the transverse Oe field generated from the annealing current which is thickness dependent and the longitudinal external field. The single peak AMI with the field sensitivity of 101%/Oe for DC annealing current is achieved. Our results could address a simple way to achieve the AMI response toward developing high sensitive magnetic field sensors.

1. Introduction

The magnetoimpedance (MI) effect is a classical electrodynamic phenomenon in magnetic metals as the electrical impedance changes against external magnetic field. The MI is correlated with the skin depth (δ), $\delta = (\rho/\pi\mu f)^{1/2}$, of the high frequency f current and therefore the magnetic permeability μ (here ρ is electric resistivity) [1]. Change in the magnetic permeability against the external field results in a new current skin depth and thus vary the MI response. The MI response in addition to its fundamental understanding is ferromagnetic metals, is known to be promising for development of high sensitive magnetic field sensors [2]. To archive high sensitive MI magnetometers soft magnetic materials have shown to be the promising candidates. Toward this, the MI effect studied in different soft magnetic materials such as amorphous wires, ribbons, films, and their nanocrystalline counterparts [3–7]. The sensitivity and linearity against the external magnetic field are the most important parameters for practical application of MI elements, e.g. magnetic sensors [8].

The MI effect is known to be significantly affected by materials composition, samples shape, annealing conditions and quenched in internal stresses during fabrications and treatments. The annealing conditions can influence the direction of

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magnetization, i.e. can re-define the magnetic anisotropy, and change domain structures. Such treatment finally can vary the magnetic permeability which results in different MI effect. Among the known annealing techniques, current annealing proved to be easy and handy and can strongly affect the domain structure inside the samples and therefore the magnetic permeability and the MI response [9,10,31]. This treatment technique can be carried out in the vacuum [11,12] or in the present of air [13], with improving the magnetic softness [14], increasing the magnetic permeability [15], and stress reduction [14,16], etc.

One of the techniques to implement the MI effect for sensor application is to provide a linear MI response against the external field. Toward this purpose, the asymmetric MI (AMI) effect was suggested [17–20]. The AMI effect was seen based on two different scenarios as follows i) by temporary mixing the magnetic field landscape in the sample, e.g. adding AC/DC magnetic field/current during the measurements [18,19], and ii) by annealing techniques and inducing anisotropy [20,21]. The later needs the sample to be heat treated e.g. by common annealing techniques. Here, we will pay our attention to suggest a different annealing mechanism to achieve the AMI effect.

The AMI effect based on annealing mechanism was observed in the CoFeNiBSi amorphous ribbons after thermal annealing at 380 °C in open air in the present of a weak longitudinal magnetic field [20,22]. As the samples annealed in vacuum did not display AMI response, the phenomenon was connected to oxidation-assisted surface crystallization. It was attributed to the exchange interaction of bulk amorphous state with the magnetically harder crystallites devitrificated at the surface of the ribbon [20,22]. In their report, during the open air annealing, B and Si preferentially diffuse to the ribbon surface to form the oxides. The crystallization temperature of the B and Si depleted underlayer decreases and uniaxial magnetic anisotropies are induced in both the crystalline layer and the amorphous bulk. As the crystalline phase is magnetically harder, it remains magnetically ordered along the direction of the field applied during the annealing, in a relatively large range of magnetic fields [22].

In order to use the AMI sensor in sensing technology, MI with linear magnetic field dependent response is required. There are reports about using AMI, e.g. Refs. [20–22], where it asymmetric response been achieved by magnetic field annealing of amorphous ribbon in open air. For example, by rounding the ribbon around a current carrying cable, a current sensor was realized based on the AMI effect. The voltage over that AMI sensor increased with increasing cable current with a good linearity [23]. Together with other means of technical application of such sensing element, they are yet subject of open studies to improve sensor performance for required demands. Another means of heat treatment which has shown quiet handy and accessible is the current-Joule heating effect [24]. This heat treatment can provide internal magnetic field provided by the current, can heat up the sample and be carried out in different environments [25].

In this paper, the MI effect was investigated in current-field annealed $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ amorphous ribbons as functions of the annealing field, H_a. The application of external magnetic field during the current-Joule heating of Co-based amorphous ribbons was carried out in open air and vacuum toward studying of the AMI effects. The annealing was carried out by I = 600 mA (26.04 A/mm^2, DC or AC) in the presence of longitudinal external magnetic field. The optimum AMI response, which corresponds to the high field MI sensitivity, was observed in optimum DC and AC annealing currents and field. This technique can address an accessible way to be implemented to anneal sensors after they have been attached to the board or for re-calibration.

1.1. Experimental details

Amorphous ribbons of nominal composition $Co_{68.15}Fe_{4.35}Si_{12.5}B_{15}$ were prepared by a conventional melt spinning technique. Pieces of particular dimensions (0.8 mm width, 40 mm length and about 28.8 μm thickness) are subjected to DC and AC Joule heating in two different ambient: (i) in air and (ii) in the vacuum of 2×10^{-2} mbar. Samples are treated at selected DC and AC current 600 mA (26.04 A/mm^2, well below the crystallization temperature [26]) for 15 min and in the presence of longitudinal external magnetic field of 0.5–120 Oe. At the beginning of current annealing procedure, the external magnetic field is applied and after 15 min, when the annealing current is turned off, the external magnetic field is continued for about two more minutes. Fig. 1 shows the schematic diagram of magnetic field–current annealing for samples. The direction of the magnetization M in the two surfaces results from the combined effect of the external longitudinal field H_a and the transverse field h generated by the annealing current.

Longitudinal hysteresis loop was measured by alternating gradient force magnetometer (AGFM). To measure the MI response of samples, an external magnetic field was applied along the ribbon axes. This magnetic field was produced by a solenoid (40 cm long), which can generate a magnetic field up to 130 Oe. The longitudinal direction of samples was perpendicular to the Earth magnetic field to minimize its effect on the MI response of samples. The impedance was measured by means of four-point probe method. An AC current passed through the longitudinal direction of the ribbon with a frequency of 4 MHz supplied by (INSTEK-SFG 830) function generator, with constant amplitude of 10 mA. The frequency settled to be 4 MHz as MI has shown in earlier report for this material with the largest value than that in other frequencies [11]. The impedance was evaluated by measuring the voltage and current across the sample using a (Tektronix TDS 2014 C) digital oscilloscope. The MI ratio (MIR) can be defined as