Magnetostatic coupling in soft/hard biphase magnetic systems based on amorphous alloys

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We report on magnetic bias in biphase systems arising from by dipolarlike interaction. Composites consist of amorphous ribbons and wires prepared by rapid solidification techniques, surrounded by an electroplated layer. Amorphous metallic core is $(\text{Co}_{0.94}\text{Fe}_{0.06})_{72.5}\text{Si}_{12.5}\text{B}_{15}$ with ultrasoft magnetic behavior (coercivity of $10\text{--}10^{-1}$ A/m), and the electroplated coating is crystalline $\text{Co}_{85}\text{Ni}_{15}$ alloy with harder magnetic character (coercivity of 10^4 A/m. After premagnetizing in a dc saturating field (10^6 A/m), the low-field ($\pm 10^3$ A/m) hysteresis loops are ascribed to the magnetization process of the soft core and exhibit a typical shift towards the direction of the premagnetizing field. This shift is ascribed to the magnetostatic field generated by uncompensated poles at the edges of the hard layer, which remains close to its remanence state. The influence of the geometry of both phases on magnetostatic energy term allows us to tailor the bias field and susceptibility of the core. These results open other possibilities to use these materials as sensing elements in magnetic sensor.

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Magnetic bias is a powerful tool for obtaining unique properties of multicomponent magnetic systems of technological interest in spin-valve reading heads, magnetic biosensors, random access memories,¹ security tags,² or giant-magnetoresistance valves.³

In multilayered and nanogranular systems, three main types of magnetic interactions can be distinguished: (a) the exchange coupling between touching (ferro-/antiferro- or ferro-/ferromagnetic) phases, (b) Indirect Ruderman-Kittel-Kasuya-Yosida (RKKY)-like coupling through an interfacial nonmagnetic metallic layer, and (c) long-range dipolarlike coupling. The main features of magnetic bias are its unidirectional anisotropy and the shift of hysteresis loop away from the zero field axis.⁴ The magnitude of this shift is labeled as bias field H_b , whose direction can be either parallel or antiparallel to the “frozen-in” spin direction of the pinning phase (antiferromagneticlike or hard ferromagneticlike, respectively).

In this work the magnetostatic bias phenomenon is investigated in biphase magnetic systems: bilayer ribbons and multilayer microwires. These multilayer systems are composed of an amorphous nucleus with ultrasoft magnetic character and of a crystalline harder magnetic outer shell. The amorphous nucleus is fabricated by rapid solidification techniques onto which the outer shell is electroplated. In the multilayer microwires, the two magnetic layers are separated

by nonmagnetic intermediate layers. In both materials, the magnetostatic coupling has been analyzed as a function of the dimensions of the two magnetic layers.

The composition of precursor polycrystalline mother alloy, $(\text{Co}_{0.94}\text{Fe}_{0.06})_{72.5}\text{Si}_{12.5}\text{B}_{15}$, has been selected because of its vanishing magnetostriction constant, 1×10^{-7} , which results in an ultrasoft magnetic character of the final amorphous component. Planar flow casting has been used to prepare amorphous ribbons of 0.12 cm wide and 20 μm thick. On the other hand, quenching and drawing method has been used to fabricate glass-coated microwires, with 17.4 μm diameter for the inner metallic nucleus and 12.1 μm thick Pyrex glass coating. The hard magnetic outer shell, CoNi, has been electroplated directly onto the amorphous ribbons using an aqueous solution and electrolytic cell as earlier reported.⁵ In the case of the glass-coated microwires, a 30 nm thick Au nanolayer was first sputtered onto the Pyrex, which played the role of electrode/substrate for the final electroplating of the magnetically harder CoNi outer microlayer. The thickness and composition of the CoNi layer depend on the current density and the time of electroplating.⁶ A current density of 12 mA/cm² was used in the present experiments for which the composition of plated alloy was $\text{Co}_{85}\text{Ni}_{15}$, exhibiting hcp crystalline structure as deduced from x-ray diffraction.

Two series of hysteresis loops with the applied field parallel to the microwire/ribbon axis have been analyzed in detail: (i) high-field (± 40 kA/m maximum applied field) hys-

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FIG. 1. High-field hysteresis loop for multilayer magnetic microwires with different CoNi thicknesses.

teresis loops using a vibrating sample magnetometer (VSM) and (ii) low-field (± 500 A/m maximum applied field) hysteresis loops measured after premagnetizing under a nearly saturating field of ± 40 kA/m using a high sensitivity inductive ac hysteresis loop tracer with a 0.8 cm long pickup coil.⁷

The high-field hysteresis loops of the biphasic systems have been analyzed. The magnetization process takes place in two steps denoting its biphasic magnetic character: (i) a giant Barkhausen jump at low very field (few A/m) that must be ascribed to the magnetization reversal of the amorphous nucleus and (ii) an additional jump (spread in the range between 10 and 20 kA/m) corresponding to the harder CoNi outer shell. Figure 1 shows the high-field hysteresis loops of biphasic multilayer magnetic microwires with different CoNi thicknesses t_{CoNi} . The lengths of both phases, the soft nucleus, L_s , and the CoNi outer shell, l_{CoNi} , were 5 mm. As observed, coercivity, remanence, and saturation magnetization of the biphasic magnetic system increase with the CoNi thickness.

Figure 1 does not offer information about the possible magnetic interaction between the two magnetic phases. To investigate such interaction, the following two-step process has been considered: (a) The biphasic samples are premagnetized under a nearly saturating dc magnetic field (± 40 kA/m) and (b) the hysteresis loop is then analyzed at low field under a maximum applied field large enough to reverse the magnetization of the soft phase (± 500 A/m) but sufficiently small to keep the hard phase close to its remanence state far from its irreversible magnetization processes. In this case, only the internal nucleus contributes to the low-field hysteresis loops.

Figure 2 shows the low-field hysteresis loop of a multilayer microwire magnetic microwire with a CoNi thickness t_{CoNi} of 5 μm (its high-field loop is given in Fig. 1), measured after premagnetizing at ± 40 kA/m. One can observe that (a) the loops are shifted towards the orientation of the premagnetizing field by a bias field of ± 55 A/m and (b) both loops exhibit very modest hysteresis.

A similar effect is observed for bilayer ribbons. Figure 3 shows the low-field hysteresis loops of bilayer ribbons with different CoNi thicknesses, after premagnetizing at

FIG. 2. Low-field hysteresis loops for a multilayer magnetic microwire with CoNi thickness of 5 μm , after premagnetizing at ± 40 kA/m.

+40 kA/m. Now, the lengths of the nucleus, L_s , and the CoNi outer shell, l_{CoNi} , are 4 and 2 cm, respectively. As observed, the bias field increases with CoNi thickness, and for the larger values two slopes in the magnetization process of the nucleus can be identified. This indicates the presence of two regions within the soft magnetic phase with different susceptibility: (a) region 1 with higher susceptibility χ_1 and given fractional volume V_1 , which would give rise to a bias field H_{b1} , and (b) region 2 with smaller susceptibility χ_2 , bias field H_{b2} , and fractional volume V_2 . The evolution of susceptibilities and fractional volumes can be followed in Fig. 3: a monotonic decrease of V_1 and parallel increase of V_2 with the CoNi thickness are observed. Consequently, the thickness of the outer shell actually determines V_1 and V_2 . The inset in Fig. 3 shows the dependence of the bias field on the thickness of the hard layer, t_{CoNi} . As observed, the bias field increases nearly linearly until the thickness reaches a value of 18 μm . Along this linear region, $V_1 > V_2$, and H_b is mainly determined by region 1 with higher susceptibility. For larger thickness, the linear behavior is broken due to $V_1 < V_2$ and H_b is mainly controlled by the region 2.

The shift of the low-field hysteresis loops for biphasic ribbons and wires is in the same direction as that of the previously applied saturating field. It shows that H_b is opposite to the remanence of CoNi, which denotes the antiferromagnetic-like character of the bias coupling. This kind of interaction can be expected for a short-range antiferromagnetic contact exchange coupling at the hard/soft magnetic

FIG. 3. Low-field hysteresis loops of bilayer ribbons with different t_{CoNi} , after premagnetizing at +40 kA/m. Inset: the bias field dependence on the CoNi thickness.

FIG. 4. Low-field loops of bilayers ribbons, measured after premagnetizing under +40 kA/m for a range of different lengths of the (a) soft layer ($l_{\text{CoNi}}=1.8$ cm, $t_{\text{CoNi}}=12$ μm) and of (b) the hard layer ($L_s=7$ cm, $t_{\text{CoNi}}=12$ μm).

interface or for a long-range magnetostatic coupling of the soft magnetic phase with the stray fields of magnetic charges on the hard magnetic layers. The real origin can be determined from an analysis of the dependence of the bias field on the CoNi thickness. It is known that the exchange bias in FM/AFM bilayers does not depend on the AFM layer thickness for thickness above a few nanometers.⁸ Figure 3 shows, however, that the bias field is proportional to the micrometric thickness of the hard magnetic layer, which indicates that magnetostatic coupling is responsible for the magnetic bias. Moreover, in the case of the multilayer magnetic microwires, exchange bias coupling must be straightforwardly discarded because of the presence of nonmagnetic intermediate micro-

layers. The origin of the magnetostatic coupling can be understood as follows: the nearly saturating premagnetizing field creates net magnetic charges at the ends of the external CoNi layer, which remain unbalanced and create an antiparallel magnetostatic field H_b in the soft amorphous layer. When the CoNi thickness of the hard phase is large enough, the magnetization reversal of the soft nucleus is characterized by two regions with different susceptibilities and bias fields, due to the fact that internal magnetic field generated by the hard phase is not homogeneous.

On the other hand, as a consequence of the magnetostatic character of the coupling, the length of the different magnetic layers should play an important role. So, further experiments with different lengths of the layers (with constant CoNi thickness) have been performed to obtain detailed information on the magnetic interaction between soft and hard layers. Figure 4(a) shows the biased low-field loops of the soft layer ribbons with length L_s ranging between 7 and 3.5 cm, after premagnetizing at +40 kA/m. The length l_{CoNi} , and thickness t_{CoNi} , of hard layers remain constant at 1.8 cm and 12 μm , respectively. Again, the loops for all the samples are characterized by two regions with different susceptibilities. Note that the susceptibility in the lower-field region χ_1 decreases when the length of the soft layer decreases, which seemingly derives from the increase of the demagnetizing field of the nucleus that also gives rise to an effective increase of the bias field. The susceptibility of the higher-field region χ_2 remains practically unchanged with the modification of L_s .

In turn, Fig. 4(b) shows the low-field loops as a function of the length l_{CoNi} , for constant values $L_s=7$ cm and t_{CoNi}

TABLE I. Values of V_1 (%), V_2 (%), H_{b1} (A/m), H_{b2} (A/m), χ_1 , and χ_2 for bilayer ribbons with different dimensions: t_{CoNi} (μm), L_s (cm), and l_{CoNi} (cm).

t_{CoNi}	L_s	l_{CoNi}	V_1	V_2	H_{b1}	H_{b2}	χ_1	χ_2
6	4	2	100	0	15	0	9 680	0
12	4	2	71	29	18	63	9 680	4120
18	4	2	64	36	18.5	68	9 680	5630
24	4	2	35	65	23	89	7 930	4440
12	3.5	1.8	80	20	22.5	70	8 570	3330
12	5	1.8	73	27	13.5	55	17 460	3170
12	7	1.8	70	30	7.5	45	22.000	3250
12	7	2.7	72	28	8.4	38	22.000	9840
12	7	4.5	100	0	10.7	0	22.000	0

= 12 μm . It can be observed that the two-step behavior appears only for the shortest hard layers. Now, the susceptibility of the higher-field region χ_2 , decreases when the length of hard phase is reduced, as a consequence of the increase of demagnetizing field of the hard magnetic outer shell, while χ_1 remains constant. Thus, it can be concluded that L_s determines the susceptibility of region 1, while l_{CoNi} does so with the susceptibility of region 2. The reason why H_b only changes with L_s is ascribed to the fact that all samples in Figs. 4(a) and 4(b) exhibit $V_1 > V_2$, and H_b is mainly determined by region 1. Finally, the values of fractional volume, bias field, and susceptibility of each region (V_1 , V_2 , H_{b1} , H_{b2} , χ_1 , and χ_2) for bilayer ribbons of Figs. 3 and 4 are collected in Table I.

The magnetostatic coupling has been analyzed for biphasic systems (ribbons and microwires) with soft/hard magnetic behavior: a soft nucleus and a hard outer shell. The magnetostatic interaction of antiferromagneticlike character is ascribed to uncompensated poles at the ends of the hard layer. Moreover, two magnetic regions with different susceptibilities and fractional volumes have been identified within the soft nucleus. Finally, the relative geometry dimensions of the layers determine the described characteristics of the loops, which offer an additional interest of these materials to be used as sensing elements in sensor field devices.

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