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Study on ferromagnetic properties in FeCo-based amorphous thin films with different thickness

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ABSTRACT

Both static and dynamic magnetic properties of amorphous ferromagnetic thin-films were investigated to reveal the effect of thickness-dependent anisotropy and domain wall structure. Amorphous $Fe_{66}Co_{17}B_{16}Si_1$ and $Fe_{39}Co_{39}Nb_6Cu_1B_5$ alloy thin-films with different thicknesses are deposited on Si for comparison. The increase of thickness results in an indiscipline change of both ferromagnetic resonance and in-plane uniaxial anisotropy at a critical value of 80 nm. The phenomenon is ascribed to the evolution of magnetic domain wall from Néel type to Bloch type as a result of the competition between in-plane and out-of-plane anisotropy. OOMMF is used to simulate the magnetic reversal process, so that the domain wall change is proved.

1. Introduction

Microwave permeability spectrum, magnetic domain structures, and anisotropy field of ferromagnetic thin films are fundamentally affected by film's thickness. A lot of works have been done to reveal the corresponding relationships [1–3], but the thicknesses are usually controlled in the range of tens of nanometers [4,5]. In another aspect, magnetic thin film usually has a higher microwave permeability than its bulk and powder companies due to the two-dimensional feature. Demagnetizing field is responsible to this feature, especially for the amorphous films where the magnetocrystalline anisotropy diminishes. Since the demagnetizing factor along the thickness direction N_z is often considered as 1 [6], the amorphous films possess an in-plane anisotropy and the magnetic moments have a configuration in-plane. Generally speaking, the magnetic moments can also be twisted out of the thin film plane because of the thickness dependent evolution of domain wall energy. The effect produced by magnetic domain configuration can't be neglected [7–10] as it produces an out of plane anisotropy when domain wall energy is dominant. Moreover, magnetic amorphous thin films possessing a uniaxial magnetic anisotropy (UMA) find many important applications in fields such as information storage and magnetic field sensors [11]. UMA, either coincide with abovementioned anisotropies or not, should complex the magnetic moment configurations in the film. Therefore, the relationship among anisotropy, magnetic domain structure and thin film thickness must be carefully studied. In order to indicate the relationship is universal in amorphous films, FeCoSiB [12] and FeCuNbCuB [13], as two representative amorphous materials, are chose for comparison.

Actually, the change of static ferromagnetic properties with the growth of thin film thickness is complex. Dynamically, the microwave permeability of thin films is usually considered to be affect by saturation magnetization (M_s), anisotropic field (H_a) and damping factor (α) [14]. In our work, we find that there is an indiscipline change of microwave permeability in the prepared amorphous thin films when the thickness exceeds 80 nm. It is attributed to the appearing of Bloch wall. The configurations of magnetic moments in different excitation source conditions are observed through the means of OOMMF simulation. In this way, the presentation of Bloch wall is supported.

2. Experiment details

Amorphous $Fe_{66}Co_{17}B_{16}Si_1$ and $Fe_{39}Co_{39}Nb_6Cu_1B_5$ thin films (thickness $t = 20$, 40, 60, 80, 100, 120, 140 and 160 nm) were fabricated on the silicon substrate of 5 mm × 15 mm by DC magnetron sputtering. The ultimate pressure was $<5 \times 10^{-4}$ Pa, the sputtering voltage was 0.35 kV, and the sputtering current was 0.3 A. An external magnetic field of $1.2 \times 10^6\ A \cdot m^{-1}$ was applied along the width direction of the films during the sputtering process to induce an in-plane uniaxial anisotropy.

The morphology of the films was observed by scanning electron microscope (SEM), and the x-ray diffraction spectrum is measured by x-ray diffraction (XRD). Microwave permeability of these films in remanent state was obtained by vector network analyzer (VNA) using shorted microstrip-line method without bias field. To measure the

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hysteresis loops of in-plane easy and hard axis of these films by vibrating sample magnetometer (VSM), the samples were cut into 5 mm × 5 mm pieces.

3. Results and discussion

The data of 160 nm films measured by XRD are shown in Fig. 1 to make sure that the prepared films are amorphous. Both FeCoSiB and FeCoNbCuB films don't have obvious crystallization peaks. There is a relatively strong Si [111] peak refer to substrate. This peak value of Si is far less than the monocrystalline silicon should be, for the substrates are covered by films. A small pump is presented around 45° with the max intensity 20 which is treated as amorphous peak [15]. With the growth of film thickness, the energy of domain wall is changing. The energy of Néel wall and Bloch wall had been calculated by many researchers with different values [16], all the results show a transition point for the energy difference between these two types of domain wall. It is proposed that the energy of Bloch wall is less than Néel wall when the film's thickness is >80 nm to investigate the following change of magnetic properties.

In continuous amorphous thin film, the demagnetizing factor along thickness direction could be considered as 1, so the microwave permeability can be described by [17]

$$\mu_i = 1 + \frac{\gamma M_s(\gamma H_e + \gamma M_s + i\alpha\omega)}{(\gamma H_e + i\alpha\omega)(\gamma H_e + \gamma M_s + i\alpha\omega) - \omega^2}, \tag{1}$$

where γ is the gyromagnetic ratio, and ω is the angular frequency. This equation requires that the effective anisotropy field H_e is in-plane and the magnetic moments are laying in the same direction before processing. Actually, the magnetic moments laying in the same direction is impossible unless the applied field is large enough. The numerical value of microwave permeability is mainly determined by the numerical value of remanence M instead of M_s. To analyze this equation combining the measured microwave permeabilities shown in Fig. 2, we mainly focus on the imaginary part of the microwave permeabilities μ'' because it's easy to identify magnetic resonance by their peaks.

The resonance frequency in Eq. (1) can be written as $\omega_r = \gamma\sqrt{H_e(H_e + M_s)}$. The resonance frequencies measured by VNA are shown in Fig. 3. For the amorphous films with identical composition, the saturation magnetization almost keeps unchanged. So, the change of ω_r is mainly caused by the change of H_e. When $t \le 80$ nm, the magnetic domain wall is mainly Néel wall and ω_r is affected by the declining in-plane uniaxial anisotropy. Therefore, we can find that the μ'' peak position and the value of the peaks are almost linear varied with thickness. With the thicknesses l exceeds 80 nm, the change of ω_r becomes irregular.

To make a better understanding of domain structure evolution with thin film thickness, OOMMF is employed to analyze the magnetic moments configuration as shown in Fig. 4. In order to mimic our cases (infinite-size in two dimension) in OOMMF, the periodic boundary condition 2D_pbc module was introduced. The films are magnetized to saturation along y-axis as the initial state and then demagnetized to remanence, with the applied field varying from 1000 mT to 0 mT. The exchange constant is 1×10^{-11} J·m^{-1} [18]. The saturation magnetization is 1.4×10^{6} A·m^{-1}. The x-y cell size is 10 nm × 10 nm and z cell size is 5 nm as shown in Fig. 4. The uniaxial anisotropy energy is 2300 J·m^{-3} [19] along y-axis. In Fig. 4, we can find there is no Néel wall when the thickness is >80 nm.

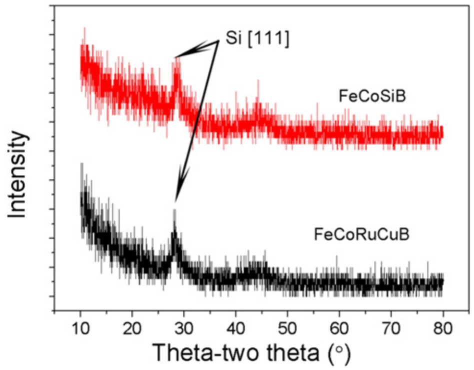

Fig. 1. The XRD data of FeCoSiB and FeCoNbCuB films with 160 nm thickness.

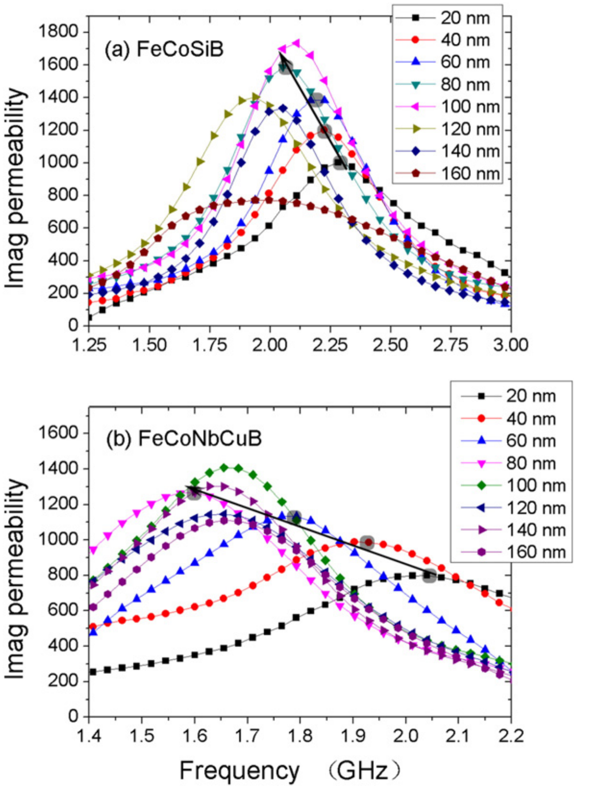

Fig. 2. The imaginary part of the microwave permeability of (a) FeCoBSi and (b) FeCoNbCuB with different thicknesses from 20 nm to 160 nm. The peaks under 80 nm are marked by translucent circle.

With the appearance of Bloch wall, the out of plane anisotropy is evidenced. For $t > 80$ nm, the in-plane change of magnetic moments is too weak to dominant the hysteresis loop and permeability spectrum. And the effective anisotropy field along z-axis changes irregularly with the film thickness so does the microwave resonance frequency.

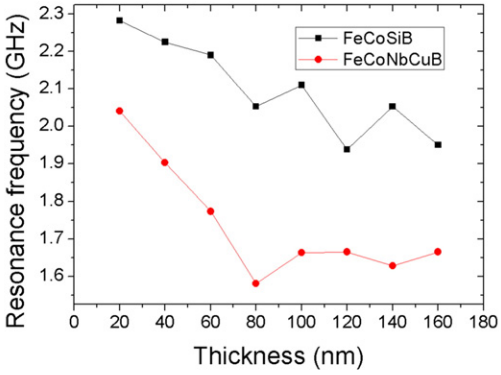

Fig. 3. The change of resonance frequency with the growing thickness. The resonance frequencies of FeCoBSi and FeCoNbCuB films tend to declining linearly when the thicknesses of films are <80 nm.