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Ultra-high ferromagnetic resonance frequency in exchange-biased system

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ABSTRACT

Static and dynamic magnetic properties of exchange-biased FeCo/MnIr multilayers were systematically investigated. A huge increased ferromagnetic resonance frequency up to 10 GHz was observed in the case of thin MnIr layers being possibly interpreted as the contribution of the rotatable anisotropy. The rotatable anisotropy as well as the resonance frequency and frequency linewidth can be tuned by changing the thickness of MnIr layer. The correlation between the variation of rotatable anisotropy and enhancement of coercivity and magnetic damping is discussed.

Soft magnetic thin films aimed for high-frequency applications such as magnetic recording heads, wireless inductor cores, microwave absorbers have recently received much attention and extensively studied due to their high permeability [1–7]. One of the most important issues for these studies is how to tune the ferromagnetic resonance (FMR) frequency to meet the demand for specific high-frequency applications. In many modern devices, the operating frequencies have reached gigahertz bands [4–7]. The FMR frequency of magnetic thin films used in such devices should be very high, ideally beyond 5 GHz or even 10 GHz. In magnetic thin films with in-plane uniaxial anisotropy, the FMR frequency can be expressed as [8]:

$$f_{\mathrm{FMR}} = \frac{\gamma}{2\pi}\sqrt{H_{\mathrm{K}}^{\mathrm{dyn}}(H_{\mathrm{K}}^{\mathrm{dyn}} + 4\pi M_{\mathrm{S}})} \qquad (1)$$

Here, γ is the gyromagnetic ratio, M_{S} being the saturation magnetization of the thin films, $H_{\mathrm{K}}^{\mathrm{dyn}}$ being the dynamic magnetic anisotropy field. In order to push the FMR frequency to higher range, one should increase the saturation magnetization and/or the uniaxial anisotropy field. There are several methods to increase the uniaxial anisotropy field such as patterning thin films [3], field annealing [4], oblique deposition [5,6], employing multilayer-structure films [7], and using exchange bias effect [9–14]. When using exchange bias to obtain high FMR frequency, most groups tried to decrease the ferromagnetic (FM) thickness while keeping the antiferromagnetic (AF) thick enough so as to get the largest exchange bias field (H_{E}) [9–14]. This method however has a drawback that the filling ratio ($t_{\mathrm{FM}}/t_{\mathrm{AF}}$) is small causing a reduction of effective permeability since the thick AF layer does not contribute to the total permeability of the film [11]. In this paper, we propose that one can use rotatable anisotropy in exchange bias system to enhance the FMR frequency. Rotatable anisotropy found to be associated with exchange bias long time ago [15] is an angle-independent effect and manifests itself as an isotropic shift of the system energy [16]. This phenomenon is believed to result mostly from the instabilities of AF grains or domains [16–18] causing rotational hysteresis in high field [19], isotropic ferromagnetic resonance field shift [16], rotation of exchange field direction [20] and also having an influence on magnetization reversal [21]. It was also found that the rotatable anisotropy is most pronounced when the AF thickness is near the critical thickness for the onset of exchange bias [17,18]. By taking advantage of the large rotatable anisotropy in a sample with a very thin AF layer and a rather thick FM layer, we can push the FMR frequency up to 10 GHz even though the exchange bias field is small.

Series of samples with the stacks of [$\mathrm{Fe_{70}Co_{30}}$ (40 nm)/$\mathrm{Mn_{75}Ir_{25}}$ (t_{AF} nm)]$_{10}$ where the MnIr thickness is changed from 0.8 nm to 30 nm were fabricated onto 50-μm thick polyethylene terephthalate (also known as Mylar) substrates at ambient temperature using the reactive RF magnetron sputter-deposition system with the base pressure better than 7×10^{-7} Torr. A magnetic field of about 200 Oe was applied in the plane of the films to induce a unidirectional anisotropy. The argon pressure was kept at 10^{-3} Torr during the deposition process.

An M–H loop tracer was employed to measure the hysteresis loops of the samples at room temperature. Typical magnetization loops measured along easy and hard axes of the thin films with various AF thicknesses are shown in Fig. 1. For samples with very

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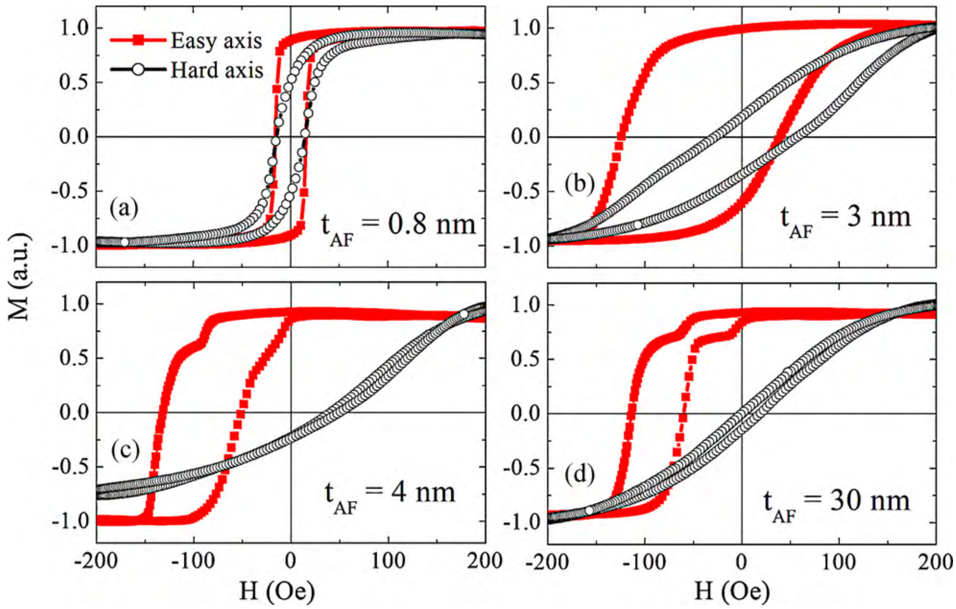

Fig. 1. Hysteresis loops of [FeCo (40 nm)/MnIr (t_{AF} nm)]$_{10}$ multilayers with several AF thicknesses.

thin AF layers, no loop shift, i.e. exchange bias, was observed and the loop shift is gradually increased with AF thickness and gets its saturation as the AF thickness is beyond 4 nm. This behavior is very typical in exchange bias system [17,18,22] and can be explained by arguing that the AF anisotropy is small when the AF layer is very thin thus causing AF magnetization thermally unstable and easy to follow the change of FM magnetization [17,18]. As the AF layer becomes thicker, the anisotropy energy of the AF results in stabilization of the AF magnetization and exchange bias occurs as a consequence [17,18].

The permeability spectra over the frequency range from 1 GHz to 10 GHz as shown in Fig. 2 were obtained by a shorted microstrip transmission-line perturbation method [23]. The frequency at which the imaginary permeability reaches its maximum corresponds to a FMR frequency. It is of great interest to compare the static magnetization curves in Fig. 1 with the dynamic magnetic properties in Fig. 2. For $t_{AF} = 0.8$ nm, no exchange bias is observed and the FMR frequency is about 3.5 GHz while $H_E = 43$ Oe and $f_{FMR} = 9$ GHz for the sample with $t_{AF} = 3$ nm. With further increasing t_{AF} exchange bias field is increased but FMR frequency slowly decreases. This behavior unambiguously indicates that exchange bias field is *not* the cause for the huge increase of FMR frequency in the case of $t_{AF} = 3$ nm. To quantify the contribution of rotatable anisotropy and exchange bias to the enhancement of FMR frequency, we employ an analysis based on the Landau–Lifshitz–Gilbert (LLG) equation [24–26]. As seen in Fig. 2, the calculated LLG curves fit well with the experimental permeability spectra. From the LLG fitting the dynamic magnetic anisotropy field H_K^{dyn} and the effective damping parameter α_{eff} can be derived.

Fig. 3(a) presents the AF thickness dependences of coercivity along easy axis H_C^{EA}, uniaxial magnetic anisotropy field H_K and exchange bias field H_E extracted from hysteresis loops in Fig. 1. The coercivity curve shows a peak at the onset of exchange bias similar to previous observations of other systems [17,18]. The static magnetic anisotropy field defined as the sum of exchange bias field and uniaxial anisotropy field ($H_K^{sta} = H_K + H_E$) is plotted in Fig. 3(b) together with the dynamic magnetic anisotropy field H_K^{dyn} as a function of AF thickness. It was found that for the thick AF layer beyond 10 nm, H_K^{sta} is quite close to H_K^{dyn} while there is a huge

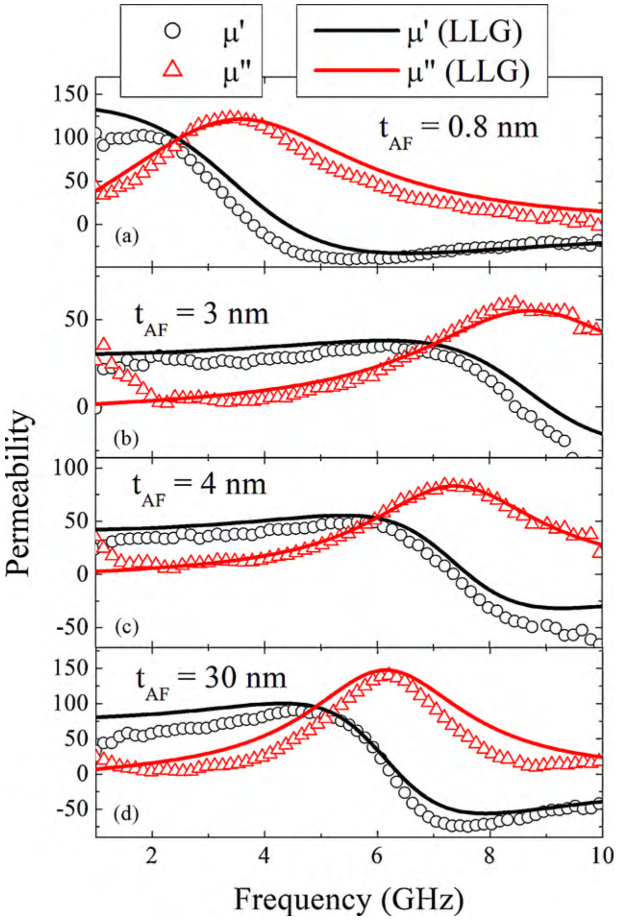

Fig. 2. Real (μ') and imaginary (μ'') permeability spectra of [FeCo (40 nm)/MnIr (t_{AF} nm)]$_{10}$ multilayers with different AF thicknesses. The lines are fitting curves based on LLG equation.

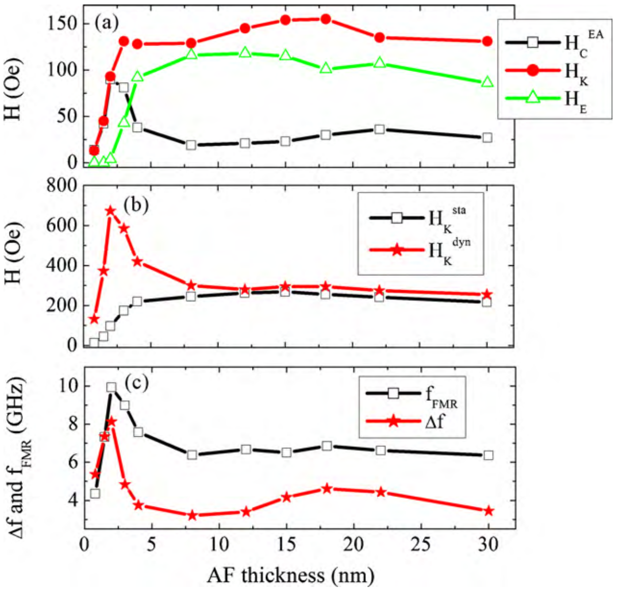

Fig. 3. (a) Variations of coercivity (along easy axis) H_C^{EA}, uniaxial magnetic anisotropy field H_K, exchange bias field H_E, on AF thickness. (b) Comparison of static (H_K^{sta}) and dynamic (H_K^{dyn}) magnetic anisotropy fields as a function of AF thickness. (c) AF thickness dependences of ferromagnetic resonance frequency f_{FMR} and frequency linewidth Δf.

discrepancy between these two parameters for the small AF thickness. The difference between H_K^{sta} and H_K^{dyn} is ascribed to rotatable anisotropy field H_{rot} ($H_{rot} = H_K^{dyn} - H_K^{sta}$) as shown in Fig. 4. Rotatable anisotropy field reported in previous publications [15–21] is usually small, which is less than a hundred Oe but in our case it can reach up to 600 Oe. Due to the contribution of this huge rotatable anisotropy field, the resultant dynamic magnetic anisotropy is large even though exchange bias field is small and as a consequence [see Eq. (1)] the FMR frequency is very high up to 10 GHz for the case of $t_{AF} = 2$ nm. Compared with other previously reported systems [11] using exchange bias field to push the resonance frequency beyond 5 GHz with the filling factor (t_{FM}/t_{AF}) of around 2, our samples taking advantage of rotatable anisotropy field are certainly much more advantageous with the filling factor of 20 and $f_{FMR} \approx 10$ GHz. Although rotatable anisotropy is a very possible reason for the huge resonance frequency in our case, further work on verification of this rotatable anisotropy should be carried. The changes of FMR frequency (f_{FMR}) and frequency linewidth (Δf) with AF thickness are shown in Fig. 3(c). The frequency linewidth Δf is determined from the following formula [26]:

$$\Delta f = \frac{\gamma \alpha_{eff}(4\pi M_S + 2H_K^{dyn})}{2\pi} \tag{2}$$

It is of great interest to see in Fig. 3(c) that Δf has a maximum coincident with the maximum of f_{FMR} implying that rotatable anisotropy not only causes the increase of resonance frequency but also broadens the frequency linewidth. This is another advantage of our system from the application point of view as it is known that the requirement for broadband microwave absorbers is indispensable [13]. The broadening of frequency linewidth can be understood by considering Eq. (2) showing that Δf is dependent on the effective damping coefficient α_{eff} as well as the dynamic magnetic anisotropy H_K^{dyn} where H_{rot} has a strong contribution. Moreover, as found in Fig. 4(a), the effective damping parameter α_{eff} derived from LLG curve-fitting follows almost the same dependence of the rotatable anisotropy H_{rot} with t_{AF}. This observation is consistent with the models explaining the damping by a two-magnon scattering contribution to the extrinsic damping due to an unstable AF magnetization which does not contribute to exchange bias [18]. The increased damping of spin waves is presumably due to the dragging of a fraction of AF spins correlating with the unstable anisotropy field [10,18]. Also, similar variations of H_{rot} and H_C^{EA} with t_{AF} are observed in Fig. 4(b). This behavior was previously observed in other systems [17] implying that the change of the rotatable part of AF magnetization is the main source for the enhancement of coercivity in exchange bias.

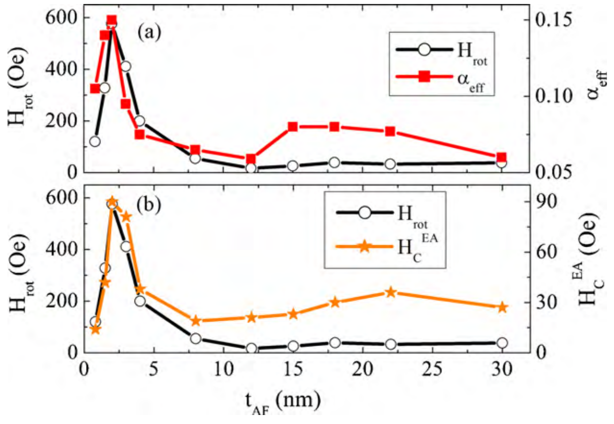

Fig. 4. Change of rotatable anisotropy H_{rot} together with the changes of (a) effective damping parameter α_{eff} and (b) coercivity (along easy axis) H_C^{EA} as a function AF thickness.

In short, we report our experimental observation that the resonance frequency can be driven up to 10 GHz in exchange-biased FM/AF system with very thin AF thickness and the reason for this behavior is possibly due to the contribution of rotatable anisotropy. The feasibility of tuning the FMR frequency from 3 GHz up to 10 GHz with very high filling factor of around 20 in FeCo/MnIr multilayers indicates that this system is quite promising for microwave applications. In addition, the frequency linewidth can be much broadened due to the enhancement of magnetic damping resulting from the dragging of the rotatable part of AF magnetizations.

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