Journal of Magnetism and Magnetic Materials 339 (2013) 36–39

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Effects of sputtering Ar gas pressure in the exchange stiffness constant of $Co_{40}Fe_{40}B_{20}$ thin films

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ARTICLE INFO

Article history:
Received 22 October 2012
Received in revised form
25 February 2013
Available online 14 March 2013

Keywords:
Spin wave
Brillouin light scattering
Exchange stiffness constant

ABSTRACT

The exchange stiffness constants of 25-nm-thick $Co_{40}Fe_{40}B_{20}$ films are investigated by Brillouin light scattering. Series of $Co_{40}Fe_{40}B_{20}$ films is prepared with various Ar gas pressures, and we found that the exchange stiffness constant decreases from 1.41 to 0.98×10^{-11} 1rom 1.41 to 0.98ous Ar gas pressures, and we found that thin stiffness constants are much smaller than CoFe values due to the B atoms, and the dependence of Ar gas pressure is noticeable. Based on our previous theoretical work, the switching current density of spin transfer torque magnetic random access memory is very sensitive on the exchange stiffness constant; it implies that engineering the exchange stiffness constant by the fabrication process is important to reduce switching current density and the dispersion of switching current density.

1. Introduction

Recently, the magnetic properties of CoFeB are being actively studied because they are possible candidate materials for the spin transfer torque magnetic random access memory (STT-MRAM) application. Since CoFeB shows large tunneling magneto-resistance (TMR) and perpendicular magnetic anisotropy (PMA) with the MgO barrier layer, study of the magnetic properties of the CoFeB is important. However, only a few research studies have been found for the exchange stiffness constants of CoFeB [1,2]. The exchange stiffness constant is a basic physical quantity and related with the number of nearest neighbor magnetic atoms and Curie temperature of materials. In spite of the importance of the exchange stiffness constant, there is no systematic study about the exchange stiffness constant dependence on the fabrication processes such as Ar gas pressure. Furthermore, recently, we theoretically find that the dependence of the switching current density of the STT-MRAM on the exchange stiffness constant is much more serious than the crude approximation based on the macro-spin model [3]. During the switching procedure, spin configuration is far from the mono-domain [4], and the macro-spin model failed. The detail spin configuration or domain structure is determined by the competition between exchange and the shape anisotropy energies, by forming finite wave vector spin wave excitation. According to our previous micromagnetic study [3–5], the switching current density can be reduced by controlling the exchange stiffness constant. Therefore, the measurement and engineering of the exchange stiffness constants can be key technologies of the STT-MRAM.

In this work, we investigate the dependence of the exchange stiffness constants of $Co_{40}Fe_{40}B_{20}$ on the Ar gas pressure by employing Brillouin light scattering (BLS). The BLS has been widely used to study thermally excited surface and bulk spin wave modes in magnetic materials [6–8]. By the analysis of the surface and bulk spin wave mode, we determined the exchange stiffness constants for a series of $Co_{40}Fe_{40}B_{20}$ samples. We found that the exchange stiffness constants vary about 50% with the fabrication conditions such as Ar gas pressures.

2. Experimental

Series of 25-nm $Co_{40}Fe_{40}B_{20}$ was fabricated on Si(100) p-type substrate using a dc magnetron sputtering system. We used $Co_{40}Fe_{40}B_{20}$ alloy target with purity of 99.99%, and the deposition was carried out at 100 W under a base pressure of 2×10^{-8} Torr or lower. The deposition temperature of the substrate was room temperature. The pressure of Ar gas during the sputtering was varied as 1.5, 4.5, 7.5, and 10 mTorr. The thickness of $Co_{40}Fe_{40}B_{20}$ thin films was kept at 25 nm with 5-nm Ta capping layer. It must be noted that the compositions of our sample are of nominal values in this study.

Brillouin light scattering (BLS) measurements were performed with a (3+3) multipass tandem Fabry–Perot interferometer [9]. The excitation light source was a single longitudinal mode of the

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http://dx.doi.org/10.1016/j.jmmm.2013.03.005

$\lambda = 514.5$ nm line of an Argon ion laser with an output power of 160 mW. Backscattering geometry was used to observe the light scattered by thermal excitations with an in-plane wavenumber $q_{//} = 1.727 \times 10^5\ \mathrm{cm}^{-1}$ with the angle of incident as 45° in back scattered geometry. Magnetic fields of up to 8×10^6 A/m were applied parallel to the film plane and perpendicular to the scattering plane [10]. The accumulation time for each spectrum was about 50 min. All measurements were performed *ex*-situ at room temperature.

3. Result and discussion

Representative magnetic hysteresis loops measured by a vibrating sample magnetometer (VSM) with in-plane applied field are presented in Fig. 1 for several deposition Ar gas pressures. It is clearly shown that 1.5 and 4.5 mTorr samples have smaller coercivity (~7×10^3 A/m) and sharp switching, while 7.5 and 10 mTorr samples have larger coercivity (~18×10^3 A/m) and slow switching processes. Because all samples are nominally composed of the same materials, such different switching mechanisms indicate that there are noticeable changes in the microstructures because of the different Ar gas pressures.

Fig. 2 shows typical spin wave spectra obtained from 25-nm $Co_{40}Fe_{40}B_{20}$ film deposited at 1.5 mTorr Ar gas pressure. Two spectra, for the applied field 1.71 and 2.81×10^5 A/m, are plotted together in order to show the magnetic field dependence of the excited spin wave frequency. The stronger peak labeled DE observed on the anti-Stokes region (positive frequency shift) had its origin in scattering from the surface wave, localizing on the laser illuminated surface. For the ferromagnetic thin film, the surface wave is known as the Damon–Eshbach mode (DE mode) [11]. The peak labeled B_1 is the first-order bulk spin waves [12]. In order to determine the magnetic constants, the spin wave frequencies are measured as a function of the applied magnetic field, and the results are displayed in Fig. 3. The dependences of the DE mode and the first bulk mode both on the applied magnetic field have been used to obtain the exchange stiffness constant and the saturation magnetization with the excited spin wave frequencies as follows [13]:

$$f_{DE} = \frac{\gamma}{2\pi}[H(H+4\pi M_s)+(2\pi M_s)^2(1-e^{-2q_{//}d})]^{1/2}, \quad (1)$$

$$f_{Bulk} = \frac{\gamma}{2\pi}\left[\left(H+\frac{2A_{ex}}{M_s}\left(q_{//}^2+\left(\frac{n\pi}{d}\right)^2\right)\right) \times \left(H+\frac{2A_{ex}}{M_s}\left(q_{//}^2+\left(\frac{n\pi}{d}\right)^2\right)+4\pi M_s\right)\right]^{1/2} \quad (2)$$

where H is the applied magnetic field, γ is the gyromagnetic ratio ($\gamma = g|e|/2mc$, where g is the spectroscopic splitting factor, e is the charge of electron, m is the mass of electron and c is the velocity of light.), d is the ferromagnetic layer thickness, n is the order number for the bulk modes, M_s is the saturation magnetization, and A_{ex} is the exchange stiffness constant. The gyromagnetic ratio and saturation magnetization can be determined by fitting with Eq. (1) and the exchange stiffness constant from Eq. (2). The experimentally obtained spin wave spectra are represented by black circles for the DE mode and red circles for the bulk mode in Fig. 3. The black and red solid lines are the results of the fitting with the best-fit parameters. From these fitting procedures, we obtained g, M_s, and A_{ex}. The obtained g-values are 2.162 ± 0.003, 2.163 ± 0.009, 2.187 ± 0.003, and 2.172 ± 0.005 for 1.5, 4.5, 7.5

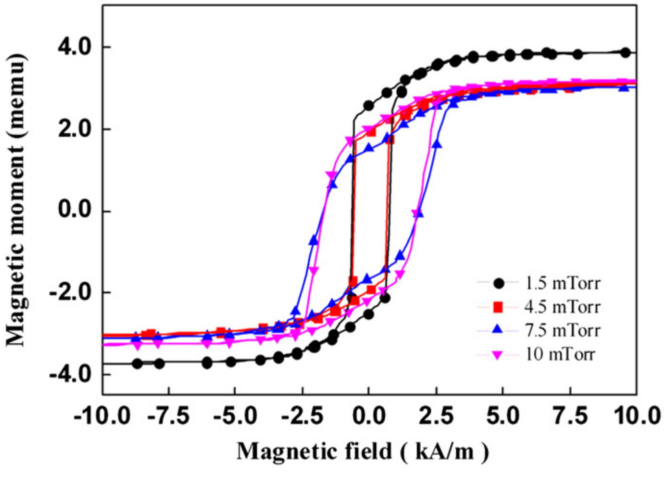

Fig. 1. Typical magnetic hysteresis loops for 25-nm $Co_{40}Fe_{40}B_{20}$ films with different Ar gas pressures.

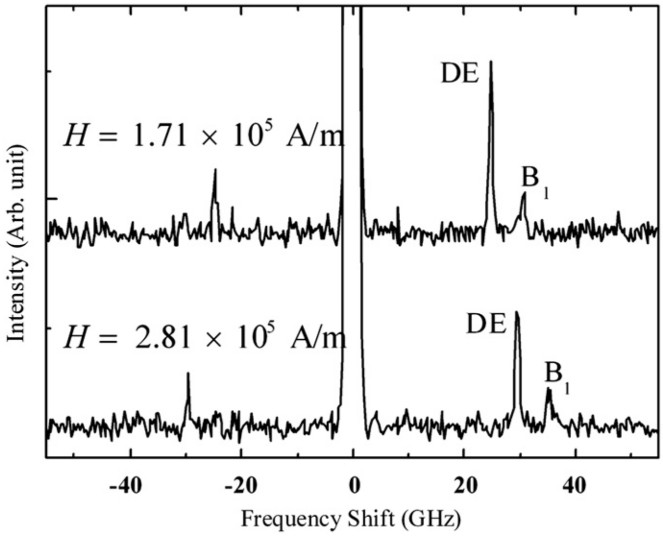

Fig. 2. Typical Brillouin light scattering spectra records from 25-nm $Co_{40}Fe_{40}B_{20}$ film deposited at 1.5t scattering spectra records from 25-nm Coss5, 103001 (201–Eshbach mode and "B_1" is the first order bulk mode.

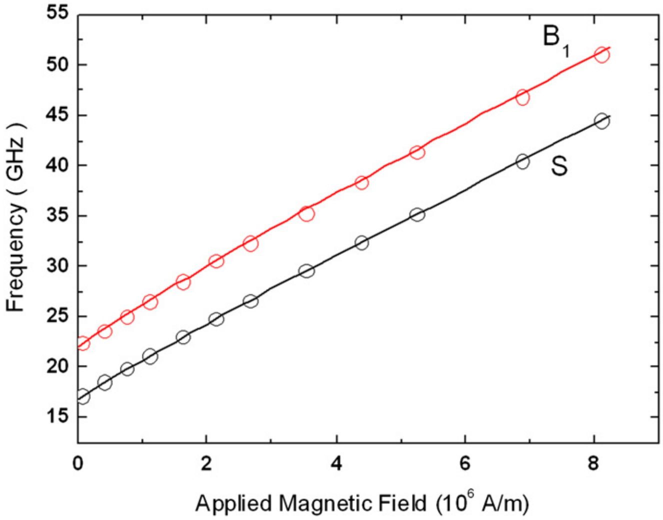

Fig. 3. Variation of spin wave frequencies with the applied in-plane magnetic field for the 1.5iation $Co_{40}Fe_{40}B_{20}$ film. The open black squares are Damon–Eshbach mode and the open red circles are the first order bulk mode. The lines are fitted curve with Eqs. (1) and (2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)