IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 11, Issue 6 Ser. II (Nov. – Dec. 2019), PP 20-25
www.iosrjournals.org

MnIr Thickness Dependence of Exchange Coupling Properties in CoFe/MnIr Bilayers

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We analyzed MnIr thickness dependence of exchange bias fields (H_{ex}) and rotatable anisotropy fields (H_{ra}) by the ferromagnetic resonance method in 300 °C annealed CoFe/MnIr(t_{AF}) bilayers. The critical thickness of MnIr was t_c = 3.0 nm, the H_{ex} as well as H_{ra} was appeared at $t_{AF} > t_c$. It was due to the grain size distribution of the MnIr. The Hex was induced by fixed AF spins of MnIr grains thicker than t_c, while H_{ra} was induced by rotatable AF spins of MnIr grains thinner than t_c. The exchange coupling field $H_{ec} = H_{ra} + H_{ex}$ did not depend on the MnIr thickness at $t_{AF} > t_c$, therefore, we concluded that the exchange coupling energy did not depend on the MnIr thickness at $t_{AF} > t_c$.

Date of Submission: 18-11-2019 Date of Acceptance: 04-12-2019

I. Introduction

F/AF materials composed of ferromagnetic (F) and antiferromagnetic (AF) double layers show exchange coupling properties that couple the two layers together. This characteristic causes the exchange bias phenomenon to move the magnetization curve to one side by the fixed AF spindle at the interface between the two films. H_{ex}, which causes this exchange bias, is expressed as $H_{ex} = J_{ex}t_FM_s$ in relation to the unidirectional energy J_{ex}, the thickness t_F of the ferromagnetic layer and the saturation magnetization M_s of the ferromagnetic layer [1]. This exchange bias magnetic field measurement using magnetization curve, unidirectional anisotropic energy measurement using torque signal, various methods such as unidirectional magnetic field measurement using ferromagnetic resonance signals have been used [2,3].

Since the exchange bias characteristic in surfaceoxidized Co/CoO particles was first discovered by Meiklejohn and Bean in 1956, researches to improve the exchange coupling characteristics have been actively conducted due to the application to commercially available hard disk head elements [7,8]. In the spin valve type large magnetoresistance or tunneling magnetoresistance material used as a head element, the exchange bias magnetic field stabilizes the output signal by fixing the magnetization of the ferromagnetic layer. As the antiferromagnetic material, MnIr is used in the head material because it shows the best exchange bias characteristics [9-12].

The exchange bias phenomenon is analyzed as a result of fixed non-complementary AF spins present at the F/AF interface above the critical thickness of the antiferromagnetic material [13]. On the other hand, below the critical thickness, the AF spin is not fixed and rotates together with the rotation of the ferromagnetic layer [14]. The coercivity of the magnetization curve increases, the rotational loss of the torque signal, and the rotatable anisotropy of the ferromagnetic resonance signal [15]. Whenthe magnetic anisotropy energy characteristics of the F/AF material were analyzed using the ferromagnetic resonance method, the rotational anisotropy characteristic, which is anisotropic energy as well as one-sided anisotropic energy, was observed according to the thickness of the AF. These characteristics are related to the size distribution of the AF grains [16].

In this study, CoFe(50 nm)/MnIr(tAF) heat-treated at 300 °C. The ferromagnetic resonance characteristics of MnIr were determined by the thickness t_{AF} of MnIr, and the exchange bias magnetic field H_{ex} and the rotational anisotropic magnetic field H_{ra} were derived.

II. Method

$Co_{70}Fe_{30}/Mn_{75}Ir_{25}$ structures were used as ferromagnetic/antiferromagnetic materials with exchange coupling properties. At this time, the thickness of the ferromagnetic CoFe thin film was fixed at 50 nm, and the thickness of the antiferromagnetic MnIr thin film was tAF=0, 1.5, 2, 2.5, 3, 3.5, 4, 5, 7, 10, 15, and 20 nm. These materials were deposited with Ta(5 nm)/Cu(20 nm) as a lower layer and Ta(5 nm) as a protective layer to prevent oxidation to enhance crystal growth of MnIr on Si substrates with oxide films. All materials were deposited using DC magnetron sputtering method, and vacuum magnetic field heat treatment was performed at 300 °C for 1 hour to improve exchange coupling properties. The vacuum degree was ~10^{-6} torr and the applied magnetic field was 3.0 kOe. The saturation magnetization M_s of CoFe, a ferromagnetic material, was determined from a magnetization curve measured on the easy axis of magnetization using a Vibrating Sample Magnetometer (VSM). The ferromagnetic resonance signal according to the magnetic field angle is 9.89 using a 3 mm×3 mm specimen. Bruker's Xepr device operates at GHz (X-band) frequency. To analyze the angle dependence, in-plane magnetic field direction (ΘH) is from 0 to 350 °C. After increasing by 10°C, the ferromagnetic resonance signal was measured according to the magnetic field. The uniaxial anisotropic magnetic field H_k, the unilateral anisotropic magnetic field H_{ex}, and the rotating anisotropic magnetic field H_{ra} of CoFe(50nm)/MnIr(t_{AF}) materials were derived from the Hres measurement results according to the angles.

III. Result and discussion

In F/AF, F is a ferromagnetic material with high saturation magnetization, while AF is an antiferromagnetic material without magnetization. Therefore, the magnetization curve or ferromagnetic resonance signal measured in F/AF with exchange coupling force reflects the magnetic properties of F changed under the influence of AF. Therefore, the magnetic properties of FM can be used to analyze the magnetic properties of F/AF with exchange coupling force.

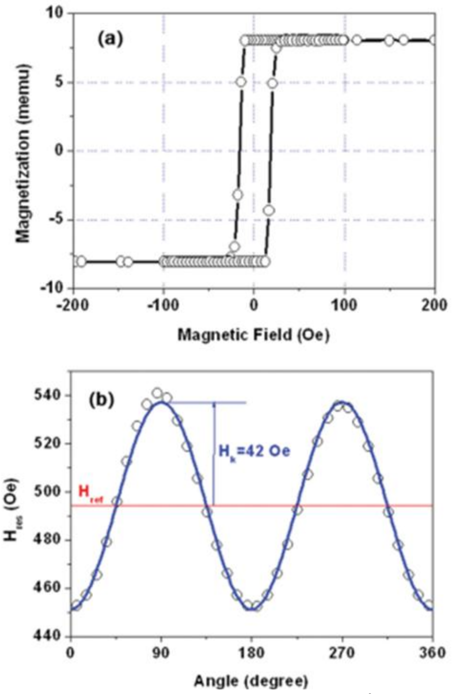

FIG. 1. (a) M-H loop and (b) angular dependence of H_{res} in 300°C annealed CoFe(50 nm) single layer, respectively. The red and blue lines are H_{ref} and H_{res} calculated by Eq. (1), respectively

In this study, the magnetic properties of CoFe (50 nm) materials were used to analyze the exchange coupling characteristics according to the thickness t_{AF} of MnIr of CoFe (50nm) / MnIr (t_{AF}) materials using ferromagnetic resonance signal measurement. Fig. 1 (a) and (b) show the characteristics of the ferromagnetic resonance magnetic field H_{res} according to the angle and the magnetization curve measured from the easy axis of magnetization of CoFe (50 nm) material. Fig. The magnetization curves of CoFe (50 nm) material from 1 (a) showed symmetrical hysteresis characteristics based on H = 0, and the coercive force H_c = 17.1 Oe of CoFe material. The saturation magnetization of the CoFe (50 nm) material obtained from the magnetization curve was M_s = 1680 emu/cm$^{3.}$ Fig. 1 (b) shows the characteristics of the ferromagnetic resonance magnetic field H res according to the angle of CoFe (50 nm) material. CoFe (50 nm) material is a material having uniaxial anisotropy, and the uniaxial anisotropic magnetic field was measured as Hk = 42 Oe. Ferromagnetic Resonance Magnetic Field Hres with Soft Magnetic Thin Films Hres of CoFe material with uniaxial anisotropy is expressed as follows when the condition of $4M_s<H_k$ is satisfied like CoFe thin film material. [15].

$$H_{res} = \frac{\omega^2}{\Upsilon}\frac{1}{4\pi M_s} \quad (1)$$

where γ = 1.92 × 10^7 rad/sec·Oe is the gyro magnetic factor of the magnetic spin, and ΘH represents the magnetic field direction. The solid blue line in Fig.1(b) is the result calculated by the formula (1). It was confirmed that the CoFe material is a soft magnetic material having uniaxial anisotropy. The first term on the left side of Eq. (1) is H_{ref}. The reference magnetic field calculated by γ = 1.92×10^7 rad/sec·Oe of CoFe material, frequency f = 9.89 GHz and saturation magnetization M_s = 1680 emu/cm3 was H_{ref} = 494 Oe. In this study, Href was used as a reference magnetic field for the exchangecoupling characteristics analysis of CoFe/MnIr materials using ferromagnetic resonance. Hr_{ef} can be expessed as

$$H_{res} = H_{ref} - H_k cos2\phi_H \qquad (2)$$

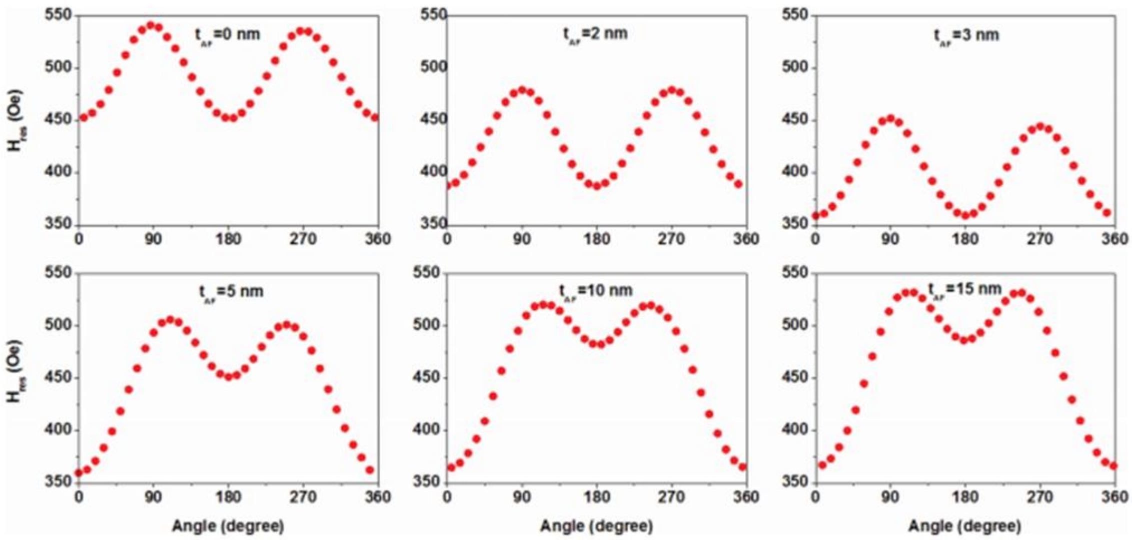

FIG. 2 Angular dependence of H_{res} in 300 ˚C annealed CoFe(50 nm)/MnIr(t_{AF}) with t_{AF} = 0, 2, 3, 5, 10 and 15 nm, respectively.

The solid red line at Fig.1(b) shows H_{ref} = 494 Oe as a straight line. Saturation magnetization M_s, H_k and H_{ref} of CoFe materials were used as reference magnetic properties for the exchange coupling characteristics of CoFe/MnIr materials. Fig.2 is t_{AF} = 0, 2, 3, 5, 10 in CoFe(50 nm)/MnIr(t_{AF}). The results of measuring the ferromagnetic resonance magnetic field H_{res} according to the angle for each material having a thickness of 15 nm. t_{AF} = 0 nm is the result of measuring the H_{res} of the CoFe (50 nm) material shown in Fig.1(b). H_{res} of t_{AF} = 2 and 3 nm materials show uniaxial anisotropic magnetic field characteristics of the same size as CoFe (50 nm), but are shifted toward lower magnetic fields than CoFe (50 nm). H_{res} of t_{AF} = 5, 10 and 15 nm materials exhibited anisotropic magnetic field mixtures of uniaxial magnetic field as well as uniaxial magnetic field. The isotropic properties seen by moving towards a lower magnetic field than CoFe(50 nm) are due to the rotation of the AF spin. The low rotational anisotropic magnetic field is H_{ra}, and the unidirectional anisotropic characteristic is the exchange bias magnetic field Hex due to the fixing of the AF spin. H_{res} of CoFe/MnIr material with exchange coupling force is expressed as

$$H_{res} = H_{ref} - H_{ex} H_k cos\Theta_H - H_k cos2\Theta_H \qquad (3)$$

H_{ra} and H_{ex} are magnetic properties due to exchange coupling, which are changed from H_{ref}-$H_k cos\theta_H$, the ferromagnetic resonance magnetic field of CoFe. Fig.3 shows the results of analyzing H_{res} measured in CoFe (50 nm)/MnIr(15 nm) material using equation (3).

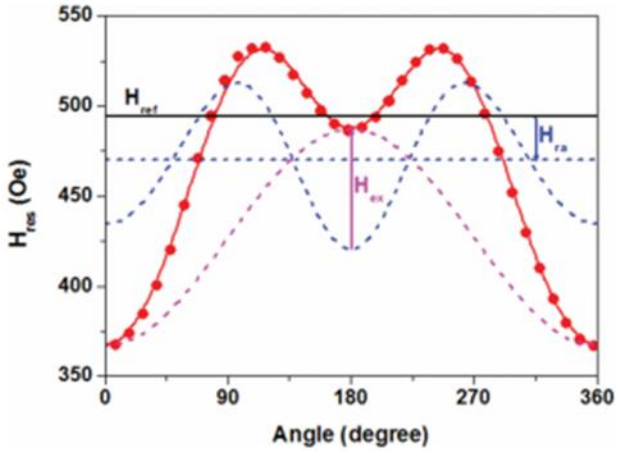

FIG. 3. Angular dependence of H_{res} in 300 ˚C annealed CoFe(50 nm)/MnIr(15 nm). The red line is calculated by

Eq. (3). The blue and magenta doted lines are corresponding to the exchange bias field effect and rotatable anisotropy field effect, respectively.

In Fig.3, the red marker is the measurement result, and the solid red line is the result calculated using Equation (3). Blue and purple dotted lines are calculated. The obtained H_{ra} and Hex characteristics are shown. In addition to the uniaxial anisotropic magnetic field H_k of CoFe, the material showed anisotropy in the form of a mixture of H_{ex}, a unidirectional anisotropy, and H_{ra}, a rotational anisotropy. In the same manner as shown in Fig.3, H_{ra} and Hex were extracted according to the thickness t_{AF} of MnIr from CoFe(50 nm)/MnIr(tAF) material.

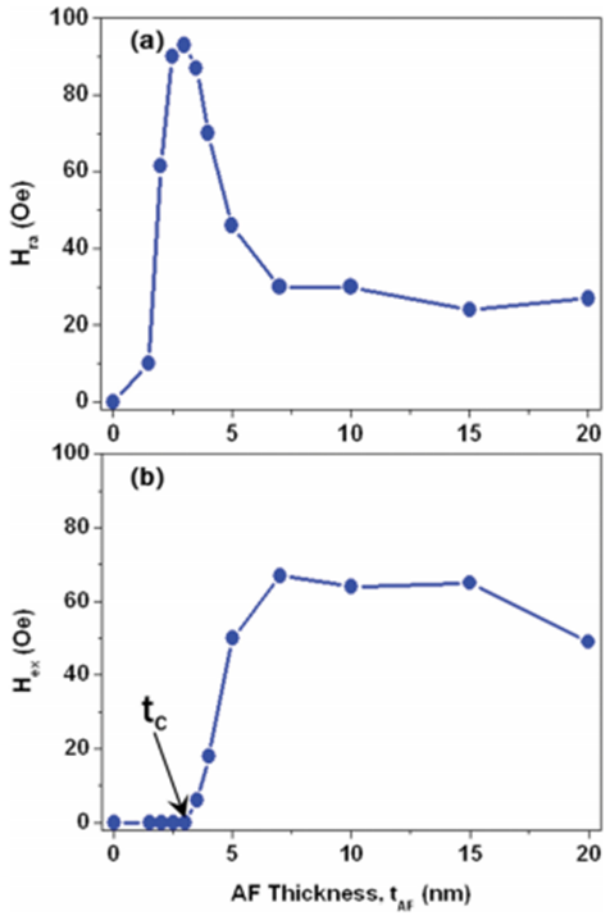

FIG. 4 MnIr thickness dependence of (a) H_{ra} and (b) H_{ex} in 300 ^oC annealed CoFe(50 nm)/MnIr(t_{AF}), respectively.

Fig. 4 (a) and (b) are MnIr in CoFe(50 nm)/MnIr(t_{AF}) materials. The characteristics of H_{ra} and H_{ex} according to the thickness t_{AF} are respectively shown. It began to appear at t_{AF} = 1.5 nm and peaked at t_{AF} = 3.0 nm. It decreases after reaching with almost constant above t_{AF} = 7.0 nm.. On the other hand, Hex began to appear at tAF = 3.5 nm, and showed an increasing characteristic in the region where H_{ra} decreased, and showed almost constant value above t_{AF} = 7.0 nm. These results indicate that the thickness of MnIr must be thicker than the critical thickness t_c in order to have H_{ex}, which is an exchange bias characteristic, so that the critical thickness of CoFe/MnIr material is t_c = 3.0 nm. H_{ra} is critical Maximums were obtained for materials with a thickness of t_{AF} = 3.0 nm. Exchange It can be seen that H_{ra}, the rotational characteristic of the AF spin by the sum, is the largest at the critical thickness. At $t_{AF} > t_c$, H_{ex} increased with decreasing H_{ra}. At this time, the appearance of H_{ra} and H_{ex} means that the fixed AF spin and the rotating AF spin coexist at the interface of the CoFe/MnIr thin film. The reason why H_{ra} as well as Hex was observed in $t_{AF} > t_c$ was analyzed due to the size distribution of MnIr grains. The grains thicker than tc were fixed to the AF spin to express H_{ex}, and the grains thinner than tc were rotated to express the H_{ra}. Therefore, the H_{ex} increase with the decrease of H_{ra} in $t_c < t_{AF} < 7.0$ nm proved that the distribution of grains thicker than t_c increased with increasing t_{AF}. As a result, it can be seen that the change of H_{ex} increased due to the change in the size distribution of the grains corresponding to the decrease of H_{ra}. Soboth H_{ra} and H_{ex} have exchange coupling forces It could be interpreted as a phenomenon exhibited by the size distribution characteristics of MnIr grains in CoFe/MnIr having. Therefore, the exchange binding energy of these materials can be analyzed by the effects of both H_{ra} and H_{ex}. Therefore, in this study, the combination of H_{ra} and H_{ex} was defined as the exchange coupling magnetic field H_{ec}. The exchange coupling magnetic field H_{ec} of the CoFe/MnIr material is expressed as follows.

$$H_{ec} = H_{ec} + H_{ex} \quad (4)$$

Fig. 5 shows the characteristics of the exchange coupling magnetic field Hec according to the thickness tAF of MnIr in CoFe(50 nm)/MnIr(tAF) material. Hec showed constant values regardless of thickness in tAF > tc materials. This suggests that the exchange coupling force, which is the interfacial effect of CoFe/MnIr materials, works consistently without depending on the MnIr thickness tAF. In tAF > t materials, Hec appears constant along MnIr thickness tAF. From the results, it can be seen that the exchange binding energy of CoFe/MnIr material works the same according to MnIr thickness tAF. Therefore, the exchange coupling energy Jec due to the fixed AF spin and the rotating AF spin shown in the CoFe/MnIr material is expressed as follows.

$$J_{ec} = J_{ec} t_F M_s \quad (5)$$

In Fig.5, Hec was constant with MnIr thickness tAF in tAF > t material of 5, and the exchange coupling energy in this range was calculated using Eq. (5), and Jec = 0.8 erg/cm2. Therefore, the exchange coupling energy of the CoFe/MnIr material subjected to vacuum magnetic field heat treatment at 300 ◦C for 1 hour was Jec = 0.8 erg/cm2.

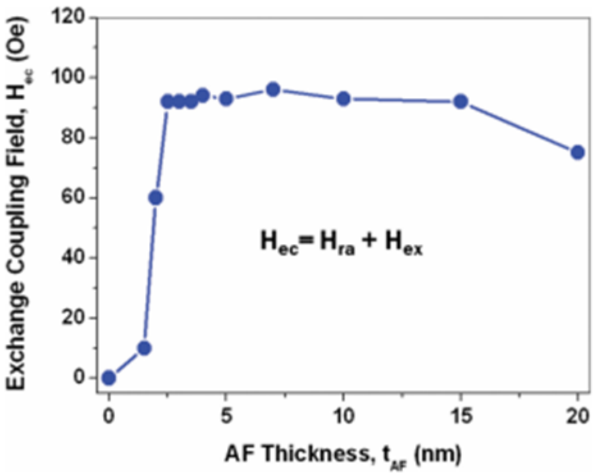

FIG. 5 MnIr thickness dependence of H_{ec} in 300 °C annealed CoFe(50 nm)/MnIr(t_{AF}).

IV. Conclusion

In CoFe (50nm)/MnIr (tAF) thin films Heat treated at 300 ˚C, the ferromagnetic resonance characteristics of the MnIr thickness t_{AF} were measured to derive the exchange bias magnetic field H_{ex} and the rotational anisotropic magnetic field H_{ra} due to the exchange coupling force. In this study, the saturation magnetization of CoFe of M_s = 1680 emu/cm^3 in order to analyze the exchange coupling characteristics of CoFe/MnIr materials. And uniaxial anisotropic magnetic field H_k = 42 Oe were used as reference magnetic properties. From the result of Hex, measurement according to t_{AF} in CoFe (50 nm)/MnIr (t_{AF}) material, the critical thickness of t_{AF} was t_c = 3.0 nm with H_{ra} measured to the maximum. At t_{AF}> t_c, H_{ex} increased with decreasing H_{ra}. At this time, not only H_{ex} but also H_{ra} were observed due to the influence of the size distribution of MnIr grains. That is, grains thicker than tc were expressed in H_{ex} by fixing the AFspin, and grains thinner than t_c were expressed in H_{ra} by rotating the AF spin. Therefore, the reason that Hex increases with the decrease of H_{ra} in the material of tc >t_{AF}>7.0 nm is because the distribution of grains thicker than tc increases with increasing t_{AF}.

On the other hand, in the t_{AF}> tc material, the exchange coupling magnetic field H_{ec} = H_{ra} + H_{ex} did not depend on t_{AF} and showed a constant value. This is because the exchange coupling force, which is an interfacial effect of CoFe/MnIr materials, is constant without depending on t_{AF}. Therefore, the exchange coupling energy of CoFe/MnIr material subjected to vacuum magnetic field heat treatment at 300 ˚C for 1 hour was J_{ec}=0.8 erg/cm^2.

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Eunsung Jekal. "MnIr Thickness Dependence of Exchange Coupling Properties in CoFe/MnIr Bilayers.″ IOSR Journal of Applied Physics (IOSR-JAP) , vol. 11, no. 6, 2019, pp 20-25.