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

Eunsung Jekal
Department of material science, ETH Zurich, Zurich, Switzerland

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 $t_c = 3.0 \text{ nm}$, 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 $H_{ex}$ 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 $H_{ec} = H_{ia} + H_{ex}$ 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 $t_{AF} > t_c$.

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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 $H_{ex} = J_{sp} M_s$, in relation to the unidirectional energy $J_{sp}$, 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($t_{AF}$) 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

$Co_{30}Fe_{69}/Mn_{25}Ir_{25}$ 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 $t_{AF}=0, 1.5, 2, 2.5, 3, 3.5, 4, 5, 7, 10, 15, \text{ and } 20 \text{ nm}$. 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 $\sim 10^{-6} \text{ torr}$ 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 ($\Theta H$) 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(tAF) 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 (tAF) 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 $H_k = 42$ Oe. Ferromagnetic Resonance Magnetic Field $H_{res}$ with Soft Magnetic Thin Films $H_{res}$ 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].

$$H_{res} = \frac{\omega^2}{\gamma} \frac{1}{4\pi M_s} \Theta H$$

where $\gamma = 1.92 \times 10^7$ rad/sec·Oe is the gyro magnetic factor of the magnetic spin, and $\Theta H$ 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 $\gamma = 1.92 \times 10^7$ rad/sec·Oe of CoFe material,
frequency $f = 9.89$ GHz and saturation magnetization $M_s = 1680$ emu/cm$^3$ was $H_{\text{ref}} = 494$ Oe. In this study, $H_{\text{ref}}$ was used as a reference magnetic field for the exchange-coupling characteristics analysis of CoFe/MnIr materials using ferromagnetic resonance. $H_{\text{ref}}$ can be expressed as

$$H_{\text{res}} = H_{\text{ref}} - H_k \cos 2\phi_H$$  \hspace{1cm} (2)

The solid red line at Fig.1(b) shows $H_{\text{ref}} = 494$ Oe as a straight line. Saturation magnetization $M_s$, $H_k$ and $H_{\text{ref}}$ of CoFe materials were used as reference magnetic properties for the exchange coupling characteristics of CoFe/MnIr materials. Fig.2 is $t_{\text{AF}} = 0, 2, 3, 5, 10$ in CoFe(50 nm)/MnIr($t_{\text{AF}}$). The results of measuring the ferromagnetic resonance magnetic field $H_{\text{res}}$ according to the angle for each material having a thickness of 15 nm. $t_{\text{AF}} = 0$ nm is the result of measuring the $H_{\text{res}}$ of the CoFe (50 nm) material shown in Fig.1(b). $H_{\text{res}}$ of $t_{\text{AF}} = 2$ 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). $H_{\text{res}}$ of $t_{\text{AF}} = 5, 10$ 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 $H_{\text{ra}}$ and the unidirectional anisotropic characteristic is the exchange bias magnetic field $H_{\text{ex}}$ due to the fixing of the AF spin. $H_{\text{res}}$ of CoFe/MnIr material with exchange coupling force is expressed as

$$H_{\text{res}} = H_{\text{ref}} - H_{\text{ex}} - H_k \cos \theta_H - H_k \cos 2\phi_H$$ \hspace{1cm} (3)

$H_k$ and $H_{\text{ex}}$ are magnetic properties due to exchange coupling, which are changed from $H_{\text{ref}} - H_k \cos \theta_H$, the ferromagnetic resonance magnetic field of CoFe. Fig.3 shows the results of analyzing $H_{\text{res}}$ measured in CoFe (50 nm)/MnIr(15 nm) material using equation (3).
Eq. (3). The blue and magenta dotted 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 \( H_{ex} \) 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 \( H_{ex} \) were extracted according to the thickness \( t_{AF} \) of MnIr from CoFe(50 nm)/MnIr(\( t_{AF} \)) material.

\[
\begin{align*}
\text{FIG. 4} & \quad \text{MnIr thickness dependence of (a) } H_{ra} \text{ and (b) } H_{ex} \text{ in 300 °C annealed CoFe(50 nm)/MnIr(} t_{AF} \text{),} \\
\text{respectively.}
\end{align*}
\]

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 \( t_{AF} = 3.5 \) 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. \( H_{ex} \) critical Maximums were obtained for materials with a thickness of \( t_{AF} = 3.0 \) nm. Exchange It can be seen that \( H_{ex} \), 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 \( t_c \) were fixed to the AF spin to express \( H_{ex} \), and the grains thinner than \( t_c \) 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 \( H_{ra} \) increased due to the change in the size distribution of the grains corresponding to the decrease of \( H_{ra} \). So both \( H_{ra} \) 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
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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 \( H_{ec} \) according to the thickness \( t_{AF} \) of MnIr in CoFe(50 nm)/MnIr(\( t_{AF} \)) material. \( H_{ec} \) showed constant values regardless of thickness in \( t_{AF} > t_c \) 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 \( t_{AF} \). In \( t_{AF} > t \) materials, \( H_{ec} \) appears constant along MnIr thickness \( t_{AF} \). From the results, it can be seen that the exchange binding energy of CoFe/MnIr material works the same according to MnIr thickness \( t_{AF} \). Therefore, the exchange coupling energy \( J_{ec} \) 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, \( H_{ec} \) was constant with MnIr thickness \( t_{AF} \) in \( t_{AF} > t \) material of 5, and the exchange coupling energy in this range was calculated using Eq. (5), and \( J_{ec} = 0.8 \) 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 \( J_{ec} = 0.8 \) erg/cm2.

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

IV. Conclusion

In CoFe (50nm)/MnIr (\( t_{AF} \)) thin films, with the ferromagnetic resonance characteristics of the MnIr thickness \( t_{AF} \) 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 \( H_{ex} \) 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 \( t_c \) were expressed in \( H_{ex} \) by fixing the AF spin, 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 \( t_{AF} > t_{AF} > 7.0 \) nm because the distribution of grains thicker than \( t_c \) increases with increasing \( t_{AF} \).

On the other hand, in the \( t_{AF} > t_c \) 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\(^2\).

References

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