Magnetic Anisotropy Modulation in Ta/ CoFeB/ MgO Structure by Electric Fields

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Abstract. We investigate the magnetic anisotropy in as-deposited and annealed Ta/ CoFeB/ MgO samples prepared by sputtering and its CoFeB thickness dependence. The magnetic easy axis changes from in-plane to perpendicular with decreasing CoFeB thickness. The thickness, at which magnetic easy axis direction changes, is increased by annealing. It is also shown that the magnetic anisotropy can be modulated by electric field and its modulation ratio is larger for the annealed samples.

1. Introduction
Magnetic materials are utilized for information storage devices in which data are maintained by magnetization direction controlled conventionally by current generated magnetic fields. The requirement for the reduction of a writing current for high-density memories triggered the extensive studies on spin transfer torque magnetization switching [1,2]. In order to reduce drastically the power consumption for writing, one needs to find a different way of switching. The switching by the application of an electric field $E_G$ is one of the candidates, which is attractive because of not only extremely low power consumption for switching but also a high degree of compatibility with the present technology developed for integrated circuits. For ferromagnetic semiconductors, e.g. (In,Mn)As [3] and (Ga,Mn)As [4], it has been shown that $E_G$ can modulate their magnetic properties such as the Curie temperature [3], coercivity [5] and magnetocrystalline anisotropy which results in the change of a magnetization direction [6]. Stimulated by these demonstrations, more recently, studies on $E_G$ modulation of magnetic anisotropy is now progressing in material systems other than ferromagnetic semiconductors; these include ferromagnetic metals [7-10] and multiferroics [11]. Among them, ferromagnetic metals have attracted great attention from the application point of view, because relatively large $E_G$ control of anisotropy can be achieved at room temperature (RT) for the material system used for magnetic tunnel junctions with a high tunnel magnetoresistance ratio [12]. Most of the previous reports on ferromagnetic metals investigated electric-field effects in Fe or Fe alloys combined with a noble metal grown by molecular beam epitaxy [7-9]. In this work, we have prepared Ta/ CoFeB/ MgO stack by rf-sputtering, and investigate the CoFeB thickness dependence of perpendicular magnetic anisotropy and the electric-field effect on it for as-deposited and annealed samples [10].

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2. Method

2.1. Sample preparation
A wedged Co$_{40}$Fe$_{40}$B$_{20}$ with nominal thickness $t$ of 0-2 nm is deposited on underlying layers of Ta(5 nm)/Ru(10 nm)/Ta(5 nm) onto 3-inch thermally oxidized Si substrate by rf magnetron sputtering. The CoFeB layer is capped by a 2-nm thick sputtered MgO layer. The sample is cleaved into two parts; one is annealed at 400°C in vacuum under perpendicular magnetic field of 0.4 T. It is known that as-deposited CoFeB is amorphous, whereas annealed one has highly-oriented bcc (001) texture due to the presence of highly oriented MgO [13]. Both layers are processed into a number of Hall bar geometries with different $t$ by photolithography and ion milling. After forming Hall bars, the photoresist remaining on the MgO surface is removed by organic solvents and plasma ashing. Then, a 45 nm ZrO$_2$ insulator (dielectric constant $\kappa \sim 23$) is formed by using atomic layer deposition at 150°C. The deposition takes about 2 hours. Finally, 5 nm Cr/50 nm Au gate electrode is evaporated and lifted off (figure 1(a)).

2.2. Magneto-transport measurements
The magnetic properties of the resultant CoFeB films are measured by magneto-transport measurement using lock-in amplifier technique. Schematic of measurement configuration is shown in figure 1(b). We measure the Hall voltage using four terminal method by sweeping a perpendicular external magnetic field $H$. The Hall resistance $R_{\text{Hall}}$ of ferromagnetic materials is given by

$$ R_{\text{Hall}} = \frac{V_{\text{Hall}}}{I} = \frac{R_0}{t} \mu_0 H + \frac{R_S}{t} M_\perp, $$

where $V_{\text{Hall}}$ is a Hall voltage, $R_0$ the ordinary Hall coefficient, $R_S$ the anomalous Hall coefficient, $\mu_0$ permeability in free space and $M_\perp$ the perpendicular component of magnetization. The magnitude of an ac current $I$ is determined as applied ac voltage $V_i$ divided by reference resistance $R_r$ of 11 kΩ, which is much larger than sample resistance of ~500 Ω.

![Figure 1](image_url)

Figure 1. The schematics of (a) sample structure and (b) measurement configuration.

3. Results and discussions

3.1. Thickness dependence of magnetic anisotropy
We investigate $t$ dependence of perpendicular magnetic anisotropy. Figure 2 shows the $R_{\text{Hall}}-H$ curves for (a) as-deposited and (b) annealed sample as a function of $t$ at $E_G = 0$ and RT. At low magnetic fields, hysteresis and nonlinear slope are observed, which indicate that one can probe the magnetic properties by magneto-transport measurement through the anomalous Hall effect. In present samples, the sign of $R_S$ is found to be negative. At a high magnetic field region above 300 mT, $R_{\text{Hall}}$ increases almost in proportion to $H$ because of the dominant contribution of the ordinary Hall effect. Sheet carrier concentration calculated from the slope is of the order of $10^{17}$ cm$^{-2}$. The magnitude of $R_{\text{Hall}}$ decreases as $t$ decreases, which is due to the existence of parallel conduction in Ta/ Ru/ Ta underlying layer [10].

![Figure 2. $R_{\text{Hall}}-H$ curves under at $E_G = 0$ for (a) as-deposited and (b) annealed samples.](image)

We first focus on the results of as-deposited samples in figure 2(a). A rounded $R_{\text{Hall}}-H$ curve without hysteresis is observed at $t = 1.57$ nm, which indicates that the layer has in-plane magnetic easy axis. As $t$ decreases, the slope of $R_{\text{Hall}}$ in the vicinity of zero magnetic field increases rapidly. At $t = 1.44$ and 1.29 nm, hysteresis loops are observed; this indicates that the layers now have perpendicular magnetic easy axis. The perpendicular easy axis in the present system is considered to be originated from the superexchange coupling between 3d electrons of Co and/or Fe and 2p electrons of O at the interface of CoFeB and MgO [14,15]. Further reduction of $t$ below 1.2 nm results in almost linear curve without hysteresis; this is due to the superparamagnetic behaviour with blocking temperature below RT. The temperature dependence of magnetization shows the blocking temperature is about 100 K for the sample with $t = 1.18$ nm (not shown).

Next, we focus on the annealing effect on $R_{\text{Hall}}$ curves. As noticed from the comparison of figure 2(b) and (a), the annealed sample shows similar thickness dependence of magnetic anisotropy to that of as-deposited sample, but the change of magnetic easy direction occurs at a different thickness. The perpendicular easy axis starts to appear for the samples with $t$ between 1.5 and 1.7 nm. The result indicates that the enhancement of perpendicular magnetic anisotropy energy in the annealed samples compared with the as-deposited ones at the same $t$. This is probably related to the oxidation of Fe/ Co at the CoFeB/ MgO interface [15].

### 3.2. Magnetic anisotropy modulation by electric fields

We investigate the electric-field effect on magnetic anisotropy for both as-deposited and annealed samples. $E_G$ denotes the electric field in MgO determined by
\[ E_G = \frac{\kappa_{ZrO_2} V_G}{\kappa_{MgO} d_{ZrO_2} + \kappa_{ZrO_2} d_{MgO}}. \]  

Figure 3. Magnetic-field \( H \) dependences of Hall resistance \( R_{\text{Hall}} \) for as-deposited samples with (a) \( t = 1.57 \) nm and (b) 1.44 nm, and for annealed samples with (c) 1.78 nm and (d) 1.52 nm under three different electric fields; \( E_G = 4.6 \) MV/cm, 0 V/cm and -4.6 MV/cm.

where \( \kappa_{ZrO_2} = 23 \) and \( d_{ZrO_2} = 45 \) nm are the dielectric constant and thickness of ZrO\(_2\) and \( \kappa_{MgO} = 10 \) and \( d_{MgO} = 2 \) nm are those of MgO. The application of \( E_G = \pm 4.6 \) MV/cm used in this study is expected to result in the change of sheet carrier concentration of about \( \pm 2.6 \times 10^{13} \) cm\(^{-2}\). Figure 3 shows the typical result of \( R_{\text{Hall}}-H \) curves under \( E_G \) for the as-deposited sample with (a) \( t = 1.57 \) nm (in-plane easy axis) and (b) \( t = 1.44 \) nm (perpendicular easy axis) as well as the annealed sample with (c) \( t = 1.78 \) nm (in-plane easy axis) and (d) \( t = 1.52 \) nm (perpendicular easy axis). The samples with in-plane easy axis shows steeper slope under negative \( E_G \). This tendency is the same as the previous report in Au/Fe(FeCo)/MgO [8, 9] and CoFeB/MgO [10] system. We evaluate the magnitude of magnetic anisotropy modulation per sheet area \( \Delta Kt \) by \( E_G \) using equation (2) in [10]. Figure 4 shows the obtained \( \Delta Kt-E_G \) curves, which show almost linear dependence. From the slopes, we obtain the values of \( \Delta Kt/E_G = 12 \) and 32 \( \mu J/m^2 \) per 1 V/nm for the as-deposited sample with \( t = 1.55 \) nm and the annealed sample with \( t = 1.78 \) nm, respectively. These values are comparable with a theoretical value of 100 \( \mu J/m^2 \) calculated for Fe/MgO system [16]. The increase of \( \Delta Kt \) by annealing may be related to the degree of crystallization of CoFeB, because the occupation of \( d \) states of the CoFeB at the interface is expected to depend on the crystal orientation. For the samples with perpendicular magnetic easy axis, a coercivity is increased (decreased) by applying negative (positive) \( E_G \), which also reflects the change of \( \Delta Kt \) by \( E_G \). The larger modulation ratio of coercivity for annealed sample than that for as-deposited samples shows that one can expect larger modulation of anisotropy in annealed samples.
Summary
We investigate the CoFeB thickness dependence of perpendicular magnetic anisotropy and annealing effect on it in Ta/CoFeB/MgO structure deposited by rf magnetron sputtering. Magnetization easy axis is changed from in-plane to perpendicular as CoFeB thickness decreases due to the interfacial magnetic anisotropy. The interfacial magnetic anisotropy is found to be enhanced by annealing. We observed the modulation of the interfacial anisotropy by the application of electric fields and the larger modulation ratio for the annealed sample than as-deposited sample.

References
[1] Hosomi M et al. 2005 IEEE International Electron Devices Meeting USA, Dec. 5-7, pp 473-476
[2] Kawahara T et al. 2007 IEEE International Solid-State Circuits Conference USA, Feb. 12-14, pp 480-481
[3] Ohno H, Chiba D, Matsukura F, Omiya T, Abe E, Dietl T, Ohno Y and Ohtani K 2000 Nature (London) 408 944
[4] Chiba D, Yu K M, Walukiewicz W, Nishitani Y, Matsukura F and Ohno H 2008 J. Appl. Phys., 103 07D136
[5] Chiba D, Yamanouchi M, Matsukura F and Ohno H 2003 Science 301 943
[6] Chiba D, Matsukura F and Ohno H 2008 Nature (London) 455 515
[7] Weisheit M, Fähler S, Marty A, Souche Y, Poinsignon C and Givord D 2007 Science 315 349
[8] Maruyama T et al. 2009 Nature Nanotech. 4 158
[9] Shioya T, Maruyama T, Nozaki T, Shinjo T, Shiraishi M and Suzuki Y 2009 Appl. Phys. Express 2 063001
[10] Endo M, Kanai S, Ikeda S, Matsukura F and Ohno H 2010 Appl. Phys. Lett. 96 212503
[11] Cheong S W and Mostovoy M 2007 Nature Materials 6 13
[12] Ikeda S, Hayakawa J, Ashizawa Y, Lee Y M, Miura K, Hasegawa K, Tsunoda M, Matsukura F and Ohno H 2008 Appl. Phys. Lett. 93 082508
[13] Hayakawa J, Ikeda S, Matsukura F, Takahashi H and Ohno H 2005 Jpn. J. Appl. Phys. 44 L587
[14] Manchon A et al. 2008 J. Appl. Phys. 104 043914
[15] Nistor L E, Rodmacq B, Auffret S, Dieny B 2009 Appl. Phys. Lett. 94 012512
[16] Niranjan M K, Duan C G, Jaswal S S and Tsymbal E Y 2010 Appl. Phys. Lett. 96 222504

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