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Electric-field effect on the easy cone angle of the easy-cone state in CoFeB/MgO investigated by ferromagnetic resonance

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We investigate the effect of an electric field on the cone angle of the easy-cone state in a CoFeB/MgO stack by ferromagnetic resonance as a function of temperature. We find that the easy cone state appears in the CoFeB/MgO system below 200 K. The application of electric field E modulates the effective first-order magnetic anisotropy energy constant, whereas the second-order magnetic anisotropy energy constant is almost independent of E, resulting in the variation of the cone angle by E. The present observation reveals the importance of the modulation of the magnetic anisotropy by E in magnetic tunnel junctions exhibiting an easy-cone state under spin-transfer-torque-induced switching. *Published by AIP Publishing.* https://doi.org/10.1063/1.5026418

Magnetic tunnel junctions with a perpendicular easy axis (p-MTJs) are critical building blocks in spintronics-based integrated circuits where spin-transfer torque (STT) is utilized as a writing scheme.[1–4] It is necessary to achieve a reduction in the intrinsic critical current I_{C0} by spin-transfer torque (STT) and enhancement in thermal stability factor Δ at the same time in order to realize high-performance and low-power spintronics-based integrated circuits. For this purpose, MTJs with a free layer which exhibit an easy-cone state have recently attracted much attention.[5–7] The easy-cone state is obtained when the effective first-order perpendicular magnetic anisotropy constant K_1^{eff} and second-order perpendicular magnetic anisotropy energy constant K_2 satisfy a certain condition, where K_1^{eff} includes a shape anisotropy term. The easy-cone condition results in canting of the free layer magnetization from the film normal direction, and the cone angle in the easy-cone state is determined by the ratio of K_2 to K_1^{eff}. By adopting free layers exhibiting the easy-cone state, the reduction of both I_{C0} and switching time was predicted to occur.[6] To obtain the easy cone state, one needs to design the free layer such that negative K_1^{eff} is obtained, resulting in a reduction of Δ. However, by increasing K_2, this drawback of negative K_1^{eff} can be compensated and one can obtain both high Δ and low I_{C0}.[8]

To induce magnetization switching by STT, one needs to apply current to the MTJ, during which an electric field E is also applied. The electric field effect on magnetic properties, such as Curie temperature,[9] coercivity,[10] magnetic anisotropy,[11] and anomalous Hall coefficient,[12] was observed in magnetic semiconductors and then in metals.[13–16] The effect in metallic CoFeB/MgO has also been studied, which is an essential material system in p-MTJs for spintronics-based integrated circuit applications.[17] In the CoFeB/MgO system, we obtained experimental results, indicating the presence of K_2,[18–20] which is necessary to induce the easy-cone state. The presence of K_2 in the CoFeB/MgO system was also reported by other groups.[21,22] We have shown that K_1^{eff} is modulated by the electric-field, whereas K_2 shows almost a constant value.[19,20] Thus, one expects that the cone angle is modulated by the electric field, resulting in the modulation of intrinsic critical current in STT-induced switching. In this study, we investigate the electric-field dependence of the cone angle in the CoFeB/MgO system as a function of temperature by ferromagnetic resonance (FMR).

The stack used in this study, from the substrate side, Ta (5)/Ru (10)/Ta (5)/$Co_{0.2}Fe_{0.6}B_{0.2}$ (1.6)/MgO (2)/Al_2O_3 (5), is deposited by rf magnetron sputtering on the thermally oxidized Si substrate. Numbers in parentheses are nominal thicknesses in nm. The stack is annealed at 300 °C for 1 h in vacuum under a magnetic field of 0.4 T applied along the film normal direction. To fabricate a capacitor structure for the application of electric fields, the stack is processed into 1 mmϕ circular mesas by photolithography and Ar ion milling. Then, additional gate insulation 32 nm-thick Al_2O_3 is deposited by atomic layer deposition, and the top electrode Cr (3)/Au (50) is formed by evaporation and the lift-off technique. The capacitance of the device is determined to be 1.0 nF using a LCR meter. The positive sign of the electric field corresponds to the top electrode being biased positively with respect to the CoFeB layer. Assuming that the dielectric constant of MgO is 10, the applied electric field at the CoFeB/MgO interface E is calculated to be ~0.013 V/nm with an applied gate voltage of 1 V.[19] To evaluate K_1^{eff} and K_2, we conduct FMR measurements using a TE_{011} microwave cavity with a microwave frequency of 9 GHz in which the sample on a quartz rod is inserted. Derivative absorption FMR spectra with respect to dc magnetic field H are measured as a function of magnetic field angle θ_H from the film normal by

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the lock-in technique using a small ac magnetic field of 1 mT modulated at 100 kHz superimposed on the dc magnetic field. The lineshape of the FMR spectra is described by a derivative Lorentz function, and therefore, we define the resonance field H_R as the center field between the peak and dip fields. The FMR measurements are done at temperatures T varying from 4 K to 300 K.

Figure 1 shows the magnetic field angle dependence of FMR spectra measured at 300 K and 20 K with no applied electric field. In both cases, H_R takes the maximum at $\theta_H = 0°$ and decreases with increasing θ_H, finding a minimum at a certain θ_H between 0 and 90°. The field angle at which H_R takes the minimum differs for the two cases, indicating that the ratio of K_2/K_1^{eff} is dependent on the temperature.

To investigate the effect of temperature T on K_2/K_1^{eff} in a systematic way, we perform FMR measurements at T varying from 300 K to 4 K. Figure 2(a) shows the magnetic field angle dependence of H_R as a function of T. As T decreases, the field angle giving the minimum H_R decreases from ∼64° at 300 K to 50° at 4 K. From the field angle dependence of H_R, we determine the magnetic anisotropy fields H_{K1}^{eff} and H_{K2} by the same method as used in a previous report.[19] H_{K1}^{eff} and H_{K2} are defined as $H_{K1}^{eff} = 2K_1^{eff}/M_S + 4K_2/M_S$ and $H_{K2} = 4K_2/M_S$, respectively, where M_S is the spontaneous magnetization. The temperature dependence of H_{K1}^{eff} and H_{K2} is shown in Fig. 2(b). Both H_{K1}^{eff} and H_{K2} increase monotonically with decreasing T. The increase in H_{K2} ($=4K_2/M_S$) indicates that K_2 also increases with decreasing T because M_S increases monotonically with decreasing T. From the temperature dependence of H_{K1}^{eff} and H_{K2}, we obtain the temperature dependence of $2K_1^{eff}/M_S$, which decreases gradually with decreasing T as shown in Fig. 2(b). The easy-cone state appears when the following conditions are simultaneously satisfied: $K_1^{eff} < 0$ and $K_2 > -0.5K_1^{eff}$, which can be converted into $K_1^{eff}/M_S < 0$ and $K_2/K_1^{eff} < -0.5$ as a more relevant form for the FMR results. In Fig. 2(c), we plot the relationship between K_1^{eff}/M_S and K_2/K_1^{eff} using the results shown in Fig. 2(b) as a function of T. The

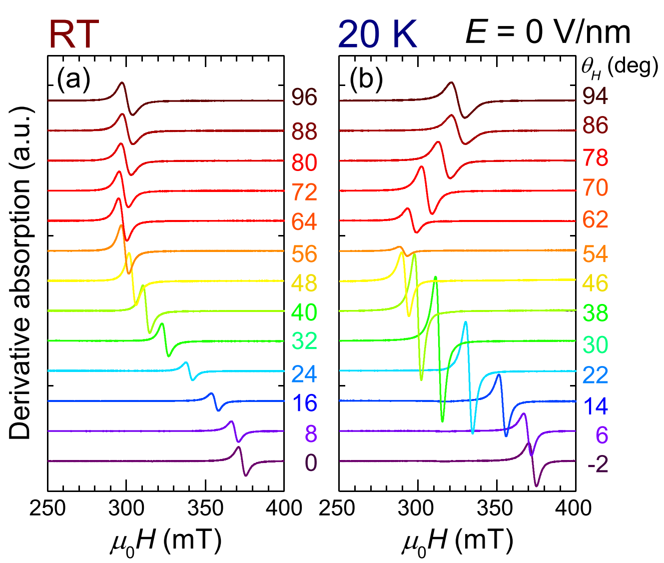

FIG. 1. Ferromagnetic resonance spectra measured at various magnetic field angles θ_H measured in the absence of the electric field at (a) 300 K and (b) 20 K.

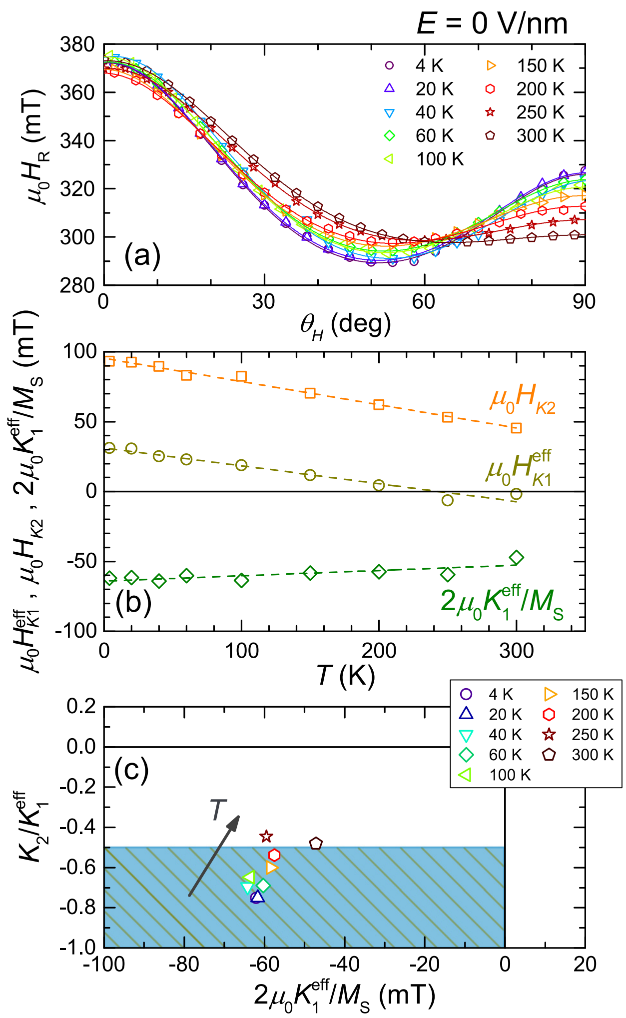

FIG. 2. (a) Magnetic field angle θ_H dependence of resonance field H_R as a function of temperature T in the absence of electric field E. The temperature dependence of (b) magnetic anisotropy fields H_{K1}^{eff} and H_{K2}. (c) The relationship between K_2/K_1^{eff} and $2K_1^{eff}/M_S$ at various temperatures where K_1^{eff} (K_2) is the effective first-order anisotropy energy constant (the second-order magnetic anisotropy energy constant) and M_S is the spontaneous magnetization. In the shaded area, the easy-cone state appears.

shaded area in Fig. 2(c) indicates the region where the easy-cone state appears. K_1^{eff}/M_S shows a negative value at all measured temperatures, and K_2/K_1^{eff} decreases with decreasing T, resulting in the appearance of the easy-cone state below 200 K.

Next, we conduct cavity FMR experiments under applied electric field E in order to elucidate the effect of E on the cone angle in the easy-cone state. The field-angle dependence of H_R under various E values at 4 K is shown in Fig. 3(a). Square, circular, and triangular symbols correspond to the results obtained under 0.10, 0, and −0.11 V/nm, respectively. The value of θ_H at which H_R takes the minimum varies with the electric field. We determine the anisotropy fields H_{K1}^{eff} and H_{K2} from the field-angle dependence of H_R. Figures 3(b) and 3(c) show the electric-field dependence of H_{K1}^{eff} and H_{K2} as a function of T, respectively. H_{K1}^{eff} linearly decreases by applying positive E and H_{K2} is virtually constant, consistent with previous studies.[19,20] While there are reports that suggest K_2 has its origin in interfacial anisotropy,[23,24] the experimental finding that K_2 is insensitive to the CoFeB thickness suggests that K_2 has its

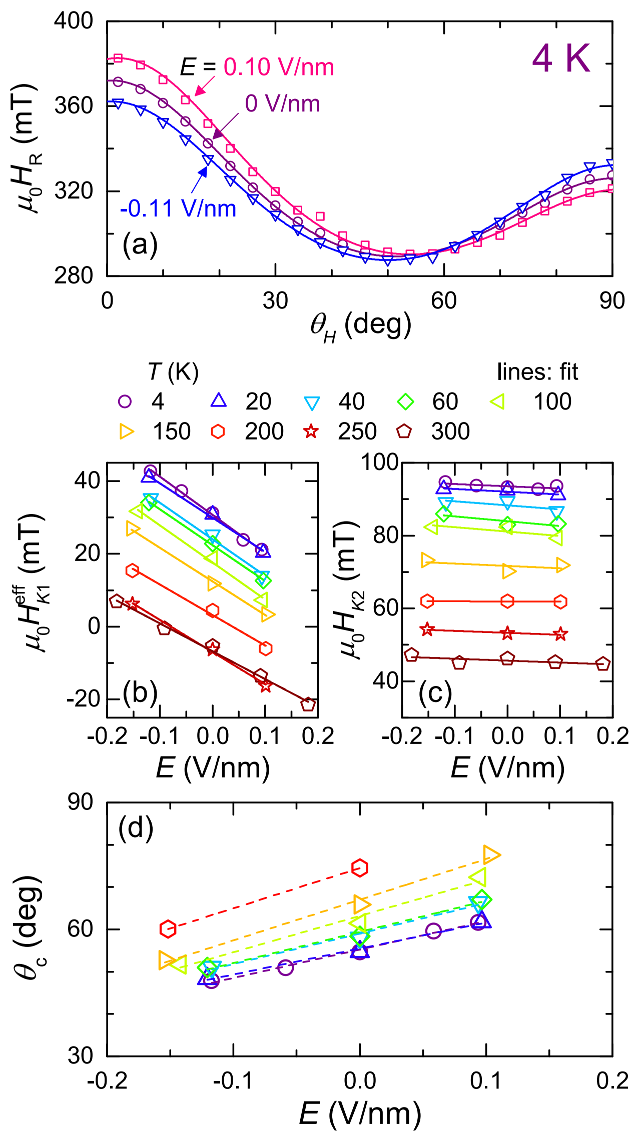

FIG. 3. (a) Magnetic field angle θ_H dependence of resonance field H_R as a function of electric field E measured at 4 K. Solid lines are fitting results. The electric-field dependence of (b) magnetic anisotropy fields $H_{K1}{}^{\mathrm{eff}}$ and H_{K2} as functions of temperature T. Lines in (b) and (c) are linear fits. (d) The electric-field dependence of cone angle θ_c as a function of T.

origin in bulk magnetic anisotropies.[19] Further studies including first-principles calculations are necessary to clarify the origin of K_2. The results indicate that $K_1{}^{\mathrm{eff}}$ can be modulated by E, whereas K_2 cannot be modulated, and as a consequence, $K_2/|K_1{}^{\mathrm{eff}}|$ decreases linearly with increasing E. Therefore, the cone angle θ_c can also be modulated by E, as seen from the following equation: $\theta_c = \sin^{-1}[(-K_1{}^{\mathrm{eff}}/2K_2)^{0.5}]$, where θ_c is measured from the film normal direction. By using this equation and the results shown in Figs. 3(b) and 3(c), we obtain the electric-field dependence of θ_c as a function of T as shown in Fig. 3(d). As can be seen, θ_c increases with increasing E, resulting from the decrease in $K_2/|K_1{}^{\mathrm{eff}}|$.

Finally, we discuss the impact of the cone angle modulation with the electric field on the intrinsic critical current in the MTJ using STT-induced switching. In the present study, we find that the cone angle varies about 10° by the application of $E = \pm 0.1$ V/nm. By using the analytical formula for intrinsic critical current density J_{C0} in the free layer exhibiting the easy-cone state,[6] a variation of J_{C0} by the electric field can be expressed as follows: $|J_{C0}(E)|/|J_{C0}(0)| = [\mu_0 H_{K1}{}^{\mathrm{eff}}(E)/\mu_0 H_{K1}{}^{\mathrm{eff}}(0)]^{3/2}$, from which the variation of J_{C0} is determined to be $\sim$0.5 for $E = 0.1$ V/nm using the value of $H_{K1}{}^{\mathrm{eff}}$ at 4 K shown in Fig. 3(b).[6] This calculation indicates that the modulation of magnetic anisotropy by the electric field needs to be taken into account for the MTJ using the free layer with the easy cone state.

In summary, we have studied the electric-field dependence of the cone angle in CoFeB/MgO as a function of temperature using ferromagnetic resonance. As temperature decreases, the second-order perpendicular magnetic anisotropy energy constant divided by the spontaneous magnetization K_2/M_S increases and effective first-order perpendicular magnetic anisotropy constant divided by spontaneous magnetization $K_1{}^{\mathrm{eff}}/M_S$ gradually decreases, resulting in the appearance of the easy-cone state below 200 K. By applying an electric field, $K_1{}^{\mathrm{eff}}/M_S$ is modulated, whereas K_2/M_S is virtually constant at all measured temperatures. From the electric-field dependence of $2K_1{}^{\mathrm{eff}}/M_S$ and K_2/M_S, we find that the cone angle is modulated by the electric field. The present study reveals that the modulation of anisotropy by the electric field needs to be taken into account for the magnetic tunnel junction using the free layer with the easy-cone state.

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