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## ABSTRACT

The electric field (EF) modulation of magnetic domain wall (DW) creep velocity $v$ in the Pt/Co/Pd structure with perpendicular magnetic anisotropy (MA) has been studied. The structures with different Co thicknesses $t_{Co}$ up to ∼1 nm are investigated. In all samples, applying a gate voltage induces a clear change in $v$. Thicker samples provide a higher $v$ modulation efficiency, and the $v$ modulation magnitude of more than a factor of 100 times is observed in the thickest $t_{Co}$ of 0.98 nm. The parameter characterizing the creep motion is significantly affected by the EF, resulting in the modulation of $v$. Unlike the $v$ case, the MA modulation efficiency decreases with increasing $t_{Co}$. The present results are discussed based on the EF-induced change in the interfacial Dzyaloshinskii–Moriya interaction (iDMI), which has been recently demonstrated in the same structure, and $t_{Co}$ dependence of the DW energy. The $t_{Co}$ dependence of the $v$ modulation suggests that the EF effect on the iDMI is more important than the MA.



Magnetic properties of ferromagnetic thin films can be controlled by the application of a gate electric field (EF). The EF application is considered to modulate the electronic structure at the surface of the ferromagnet, resulting in the change in the Curie temperature $T_C$[1–3] and magnetic anisotropy (MA).[4–11] Moreover, the EF application is also a powerful tool for controlling the magnetism in nanoparticle based systems.[12] The EF control of the magnetic domain wall (DW) motion is expected to enable high-speed and low-power operation of the race track memory[13] and DW Magnetoresistive Random Access Memory (MRAM).[14] Modulation of the DW velocity by the EF has been reported in Co/Pt and CoFeB/MgO systems with a perpendicular MA.[15–19] The EF modulation of the velocity in the creep region was conventionally discussed based on the change in MA in previous studies. On the other hand, it has been pointed out that in ferromagnet/heavy metal systems, the interfacial Dzyaloshinskii–Moriya interaction (iDMI) affects the DW creep motion.[20,21] In Ref. 19, it has been shown that the DW velocity in the fast flow regime is controlled by the EF through the EF modulation of iDMI. However, it is not clear how the EF-induced iDMI change[19,22–24] affects the DW creep velocity.

In this study, we have investigated the EF effect on the creep velocity $v$ in the Pt/Co/Pd structure with different Co thicknesses $t_{Co}$ up to ∼1 nm, where the iDMI modulation by the EF has been experimentally confirmed.[19] The EF modulation efficiency of $v$ increases with $t_{Co}$. The $t_{Co}$ dependence of $v$ modulation suggests that the EF effect on the iDMI is more important than the MA.

Figure 1(a) shows the sample structure used in this study. The structure consisting of Ta(2.6 nm)/Pt(2.4)/Co($t_{Co}$)/Pd(0.4)/MgO(2.0) was deposited on a thermally oxidized Si substrate using rf sputtering. Three films with nominal $t_{Co}$ values of 0.78, 0.88, and 0.98 nm were prepared. The thickness of each layer was determined from the deposition rate. The magnetic easy axis of all films is perpendicular to the plane because of the interfacial MA at Pt/Co and Co/Pd interfaces. The ferromagnetic proximity effect is expected to make a whole Pd layer and a part of Pt layer (∼2 nm from the Pt/Co interface) magnetized.[25]

The films were fabricated into a wire structure with Hall probes by photolithography and ion milling. The wire width was 20 $\mu$m. The fabricated film was covered by a 50-nm $HfO_2$ insulator layer. The $HfO_2$ layer was deposited at 150 °C using atomic layer deposition. Finally, the Cr(1)/Au(10) electrode was formed on the wire to apply a gate voltage $V_G$. In this study, the positive $V_G$ corresponds to the

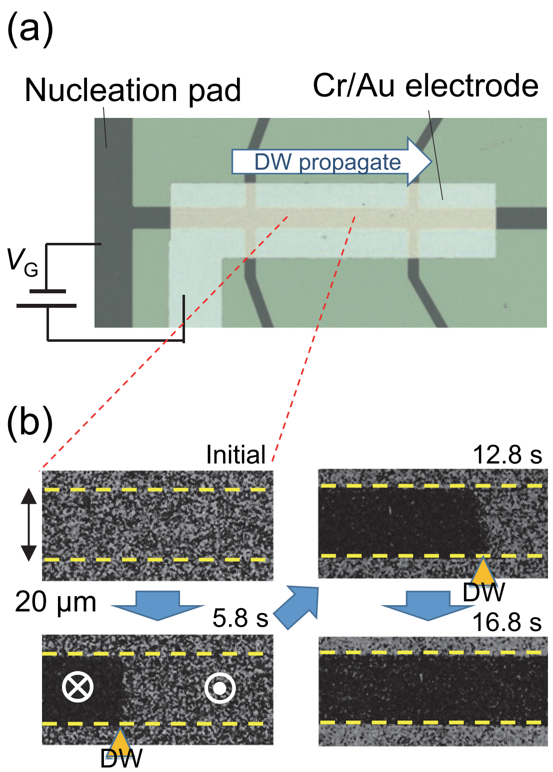


**FIG. 1.** (a) Optical microscopy image of the Hall structure with the Cr/Au gate electrode. (b) Magnetic domain images during the domain wall (DW) propagation obtained by the MOKE. Yellow dashed lines indicate the wire edge. The time shown in each image is the elapsed time from the observation start time.

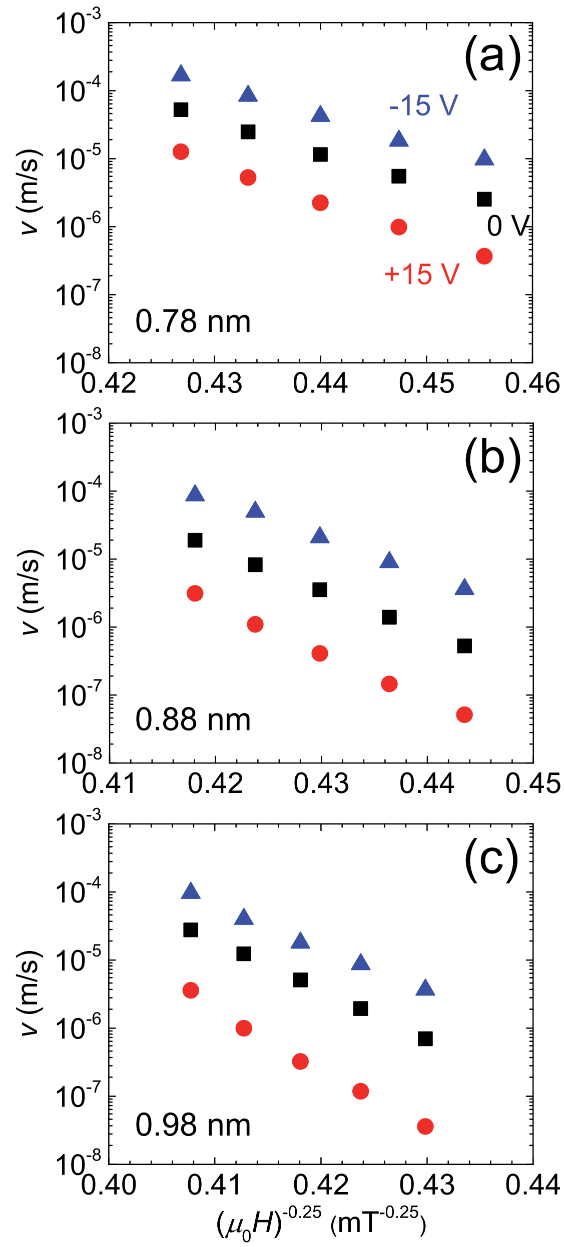


**FIG. 2.** $v$ as a function of $(\mu_0 H)^{-0.25}$ at a gate voltage $V_G = 0$ (black square), +15 (red circle), and –15 V (blue triangle) for the Co thickness $t_{Co}$ = (a) 0.78, (b) 0.88, and (c) 0.98 nm.

direction that electron density at the ferromagnet/insulator interface increases. The experiment was performed at 300 K.

The measurement procedure is as follows. After making the sample single domain state by a large perpendicular magnetic field (~40 mT), a magnetic field ($H$) with an opposite sign was applied. When $H$ was sufficiently large, domain nucleation occurred in the nucleation pad connected with the left end of the wire. Then, the created DW was injected into the wire and propagated from left to right by $H$. The DW propagation in the wire covered by the gate electrode was captured using a magneto-optical Kerr effect (MOKE) microscope. Figure 1(b) shows the successive MOKE images taken during the DW motion under constant $\mu_0 H = 31$ mT for the 0.98 nm sample. The bright and dark regions correspond to the domains with up and down magnetizations, respectively. The boundary of the two regions, i.e., the DW, moves from left to right.

Figures 2(a)–2(c) plot $v$ as a function of $(\mu_0 H)^{-0.25}$ at $V_G = 0$ V for the samples with $t_{Co} = 0.78$, 0.88, and 0.98 nm, respectively. In all samples, $v$ ranges from $10^{-3}$ to $10^{-8}$ m/s and linearly depends on $(\mu_0 H)^{-0.25}$, which is consistent with the prediction from the creep theory in the ferromagnetic metal.[26] $v$ values for $V_G = \pm 15$ V are also shown in the same plots. While the linear dependence is still maintained, a clear increase (decrease) in $v$ is observed by applying –15 (+15) V in all samples, indicating that $v$ is modulated by the EF effect.

For the $t_{Co} = 0.98$ nm sample, a significant $v$ modulation of more than 100 times is observed [Fig. 2(c)].

In ferromagnetic metals, $v$ in the creep regime is described as

$$v = v_0 \exp\left[-\left(\frac{U_c}{k_B T}\right)\left(\frac{H_c}{H}\right)^{0.25}\right], \tag{1}$$

where $v_0$ is the numerical prefactor, $U_c$ is the pinning potential, $H_c$ is the depinning field, $k_B$ is the Boltzmann constant, and $T$ is the temperature.[27,28] By a linear fit to the plots in Fig. 2, $U_cH_c^{0.25}$ can be determined for each $V_G$. Figure 3 shows the $V_G$ dependences of $U_cH_c^{0.25}$ normalized by the value for $V_G = 0$ V, which is expressed as n_$U_cH_c^{0.25}$. $U_cH_c^{0.25}$ increases (decreases) with the positive (negative) $V_G$ in all $t_{Co}$ samples. This means that the EF-induced $v$ change is caused by the modulation of $U_cH_c^{0.25}$. The modulation by the positive $V_G$ is larger for the $t_{Co} = 0.98$ nm sample. The asymmetric EF response may reflect the shape of the d band structure around the Fermi level.[29] Here, we define Δn as n_$U_cH_c^{0.25}$ (+15 V) − n_$U_cH_c^{0.25}$ (−15 V). Figure 4(a) summarizes the $t_{Co}$ dependence of Δn. Δn is larger in thicker $t_{Co}$ samples. This result, that is, the EF effect is larger in the thicker Co sample, seems to be counterintuitive because the EF effect is expected to be purely the interfacial effect.

Below, we discuss the origin of the present EF effect. As shown in previous reports, the parameters of $U_c$ and $H_c$ increase with the DW energy density $\sigma$,[30] indicating that the EF effect on $\sigma$ contributes to the $U_cH_c^{0.25}$ change. Thus, the increase (decrease) in $v$ should occur when $\sigma$ is reduced (enhanced) by the EF application. In the present Pt/Co/Pd structure, $\sigma$ can be expressed as

$$\sigma = 4\sqrt{AK_u} + 2K_\perp\Delta - \pi D, \quad (2)$$

where $A$ is the exchange stiffness, $K_u$ is the anisotropy energy, $K_\perp$ is the hard axis anisotropy, $\Delta = (A/K_u)^{1/2}$ is the DW width, and $D$ is the iDMI energy.[20] The EF modulation of $A$ can be neglected because the experiment was conducted at a much lower temperature than $Tc$ of the samples.[31] Thus, the EF induced changes in $K_u$ and $D$ mainly contribute to the $\sigma$ modulation in this study. We have checked the EF effect on $K_ut$ in our Pt/Co/Pd samples. $t$ is the effective ferromagnetic thickness. $K_u$ is expressed as $K_u = M_sH_k/2$, where $M_s$ is the saturation magnetization and $H_k$ is the anisotropy field. To measure the EF effect on $H_k$, the in-plane saturation field of the sample was investigated using an anomalous Hall measurement under $V_G$. The details of the Hall measurement are explained in our previous publication.[32] The EF effect on the saturation magnetization (∼below 1%) was taken into

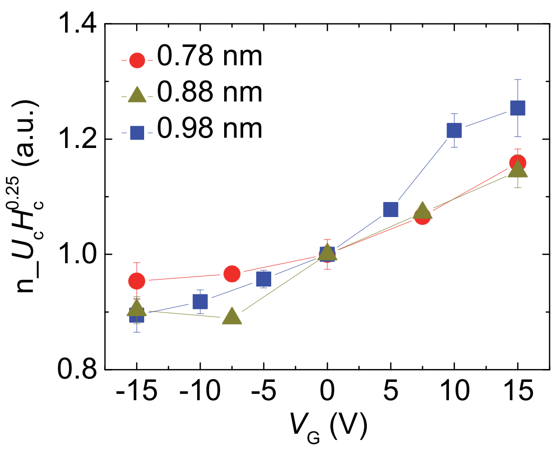


**FIG. 3.** $V_G$ dependences of $U_cH_c^{0.25}$ normalized by the value at $V_G = 0$ V. Data for the sample with $t_{Co} = 0.78$ (red circle), 0.88 (green triangle), and 0.98 nm (blue square) are plotted. The error bar stands for the fitting error of the linear fit to the plots shown in Fig. 2.

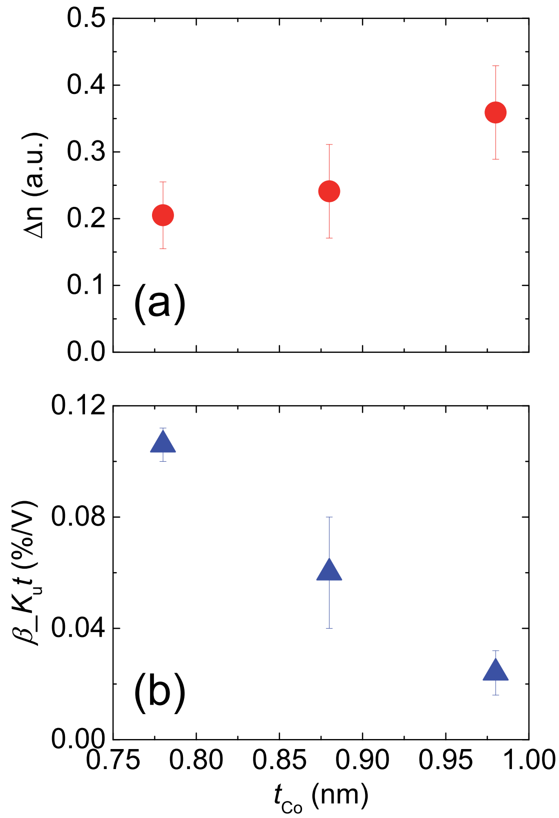


**FIG. 4.** (a) Δn, which is defined as n_$U_cH_c^{0.25}$ (+15 V) − n_$U_cH_c^{0.25}$ (−15 V) and (b) the modulation of areal magnetic anisotropy $K_ut$, for three samples.

account. We have confirmed that in all $t_{Co}$ samples, the positive (negative) $V_G$ increases (decreases) $K_ut$. Since the $K_ut$ increases $\sigma$ [see Eq. (2)], the sign of $K_ut$ modulation observed here is consistent with the present EF modulation of $v$. However, the magnitude of the $K_ut$ modulation efficiency $\beta$_$K_ut$ clearly becomes smaller with increasing $t_{Co}$ [Fig. 4(b)]. $\beta$_$K_ut$ for the $t_{Co} = 0.98$ nm sample is five times smaller than that for 0.78 nm sample. This is the opposite tendency as the Δn case, suggesting that the change in $K_ut$ is not the main factor for $v$ modulation in the present study.

The EF effect on $D$ has been previously studied.[19] In the present film structure, $D$ of the whole system primarily originates from the iDMIs at the Pt/Co and Co/Pd interfaces. Since the ultrathin Pd (1–2 atomic layer) is inserted between the insulator and Co, the EF application can alter iDMI at the Co/Pd interface, which results in the modulation of $D$. According to the model by Fert and Levy, the spin–orbit coupling of the outermost d electron state of the heavy-metal layer plays an important role in the emergence of iDMI.[33] Therefore, one of the possible origins of the EF-induced iDMI change in the present sample is the modulation of the 4d electron state of the Pd layer. Note that the EF does not reach the bottom Pt/Co interface because of the screening effect. The calculated $D$ modulation efficiencies by the EF $\beta$_$D$ for the $t_{Co} = 0.78$ and 0.98 nm samples are 0.26(±0.10) % and 0.20(±0.13) %, respectively. Here, we define $\Delta\beta$ as $\beta$_$D$ (+15 V) − $\beta$_$D$ (−15 V). $\Delta\beta$ is much smaller than that for the $\beta$_$K_ut$ case.

**TABLE I.** Parameters used to determine $\sigma$ for $t_{Co} = 0.78$ and 0.98 samples. $K_u t$ is determined from anomalous Hall measurement. $A = 1.6 \times 10^{-11}$ J/m is used (Ref. 34). $K_\perp$ is calculated based on the spheroid approximation of DW. $Dt$ is referenced from Ref. 19.

| $t_{Co}$ (nm) | $K_u t$ (mJ/m$^2$) | $K_\perp$ (MJ/m$^3$) | $Dt$ (pJ/m) |
|---|---|---|---|
| 0.78 | 2.19 | 0.34 | 0.51 |
| 0.98 | 1.56 | 0.32 | 0.49 |

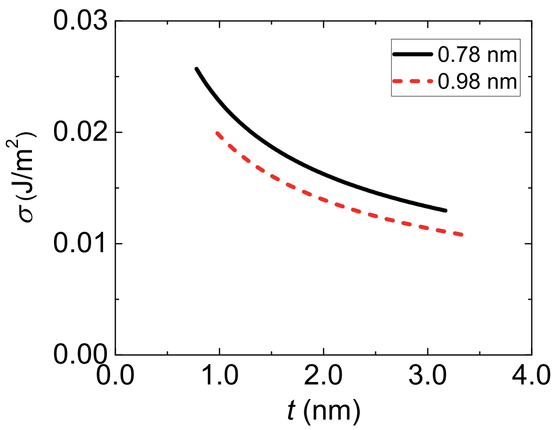


**FIG. 5.** Calculated $\sigma$s as a function of $t$ for the $t_{Co} = 0.78$ (solid line) and 0.98 (dotted line) nm samples.

Nevertheless, the mechanism of larger modulation efficiency in thicker $t_{Co}$ is not clarified solely by this fact.

The $t_{Co}$ dependence might be explained as follows. The *efficiency* of DW energy modulation is considered to determine Δn. This suggests that the EF effect becomes larger if the original value of $\sigma$ ($V_G = 0$ V) is smaller, even when $\beta\_D$ is almost constant with respect to $t_{Co}$. To check this, the original $\sigma$s for the $t_{Co} = 0.78$ and 0.98 nm samples were calculated using Eq. (2). Table I summarizes the parameters used in this calculation. Since the precise determination of $t$ is difficult due to the proximity effect, we calculated $\sigma$ in the $t$ range from $t_{Co}$ to the sum of $t_{Co}$ and the thicknesses of the magnetized Pd (0.4 nm) and Pt (2.0 nm) layers. Figure 5 shows the results. Regardless of the $t$ value, $\sigma$ for $t_{Co} = 0.98$ nm is smaller than that for 0.78 nm. Thus, the constant $\beta\_D$ and smaller $\sigma$ might result in the large EF modulation in thicker $t_{Co}$ samples.

In summary, the EF effect on $v$ is investigated in Pt/Co/Pd systems with different $t_{Co}$ values. Applying an EF clearly changes $v$. The EF modulation efficiency increases with $t_{Co}$. This thickness dependence cannot be explained by the EF effect on the MA. The modulation of the iDMI and the magnitude of $\sigma$ may determine the $t_{Co}$ dependence. Our result should provide important information to design the film structure of future DW and skyrmion devices based on the electrical iDMI manipulation.

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