Temperature Dependence of Domain-Wall Creep in Pt/CoFe/Pt Films

Junyeon Kim, Kab-Jin Kim, and Sug-Bong Choe

School of Physics, Seoul National University, Seoul 151-742, Korea

The temperature dependence of the magnetic domain-wall creep behavior is examined in Pt/CoFe/Pt films with perpendicular anisotropy. The domain-wall creep behavior is monitored by a magneto-optical Kerr effect microscope equipped with a cryostat, which enables us to control the temperature from the ambient temperature down to 85 K. It is found that the domain-wall speed under a fixed magnetic field is decreased exponentially proportional to the inverse of the temperature, which can be explained as a typical behavior of the thermally activated process. By measuring the field-dependent domain-wall speed, we confirm that the domain-wall creep theory is valid with the value of the creep exponent 1/4, over the temperature range we examine.

Index Terms—**Creep, cryostat, low temperature, magnetic domains, magnetization reversal, magnetooptic Kerr effect.**

I. Introduction

DOMAIN-WALL dynamics in ferromagnetic structures driven either by a magnetic field or by an electric current have drawn great attention due to their crucial role in achieving high performance of technological applications such as the nonvolatile memory and logic devices [1], [2]. Precise control of domain-wall motion in such devices is a key issue for applications, and thus, understanding domain-wall dynamics is essential. It has been found that the domain-wall motion driven by an external magnetic field H exhibits three distinct regimes—creep, depinning, and flow [3]–[5], mainly governed by the domain-wall depinning field $H_{\rm dp}$, where the depinning field is determined by the quenched structural disorders caused by crystallites or steps at the frontiers of flat atomic terraces [6], [7]. In the flow regime ($H > H_{\rm dp}$), the domain-wall speed is proportional to the strength of the external magnetic field. On the other hand, in the creep regime ($H < H_{\rm dp}$), another distinct behavior occurs. In this case, the domain-wall dynamics are governed by the competition between the elastic energy and the quenched disorder. Even though the domain-wall has to be pinned when $H < H_{\rm dp}$ at zero temperature, the thermally activated fluctuation, at a finite temperature, triggers the domain-wall depinning from the structural disorder. The domain-wall thus exhibits a slow motion, which is known as the domain-wall creep [7]–[9]. In the creep regime, the domain-wall speed is given by

$$V = V_0 \exp\left[-\frac{U_{\rm C}}{k_{\rm B}T}\left(\frac{H_{\rm dp}}{H}\right)^{\mu}\right] \quad (1)$$

where V_0 is the characteristic constant in the dimension of speed, $U_{\rm C}$ is a constant related to the pinning strength, and μ is the creep exponent [6], [7]. The creep exponent has been found to be equal to 1/4, in 2-D films with 1-D domain-wall [7]. Such creep motion has been reported in ferromagnetic single layers [7]–[9], multilayers [10], and patterned wires [11], [12] at room temperature. Here we examine the creep motion with changing temperature and confirm the validity of the creep theory over the range from 85 K to the ambient temperature.

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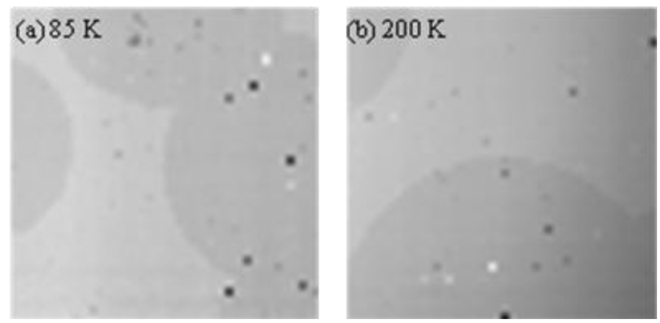

Fig. 1. Typical magneto-optical image of domain at (a) 85 K and (b) 200 K (0.5 mm × 0.5 mm), respectively. The dark regions correspond to the reversed domain.

II. Samples and Experimental Techniques

For this study, 2.5-nm Pt/0.3-nm $Co_{90}Fe_{10}$/1.0-nm Pt ultrathin films with perpendicular anisotropy are deposited on a Si substrate by dc-magnetron sputtering. All the samples exhibit out-of-plane magnetization, and the domain-wall type is Bloch wall. It is confirmed that the films have rare nucleation cites and the magnetization reversal is dominated by domain-wall motion. Fig. 1 shows the circular domain-wall growth from a nucleation cite, captured at different temperatures (a) 85 K and (b) 200 K, respectively. Due to the clear circular expansion, it is easy to determine the domain-wall displacement. For this observation, we use a polar magneto-optic Kerr effect (PMOKE) ($\lambda = 780$ nm) microscope equipped with a cryostat, which controls the temperature from ambient temperature to 85 K when cooling with liquid nitrogen.

To measure the domain-wall speed, we first saturate the film by applying a large magnetic field and, then, generate a nucleated domain centered at a nucleation cite by applying a short reversed magnetic field pulse. We confirm that the nucleation is fairly reproducible. Once we generate the nucleated domain, the probing laser spot is moved by a distance l in the normal direction from the initial domain-wall position. Then, the domain-wall motion is triggered by applying an external magnetic field pulse and the domain-wall arrival time Δt is measured, which finally gives the domain-wall propagation speed

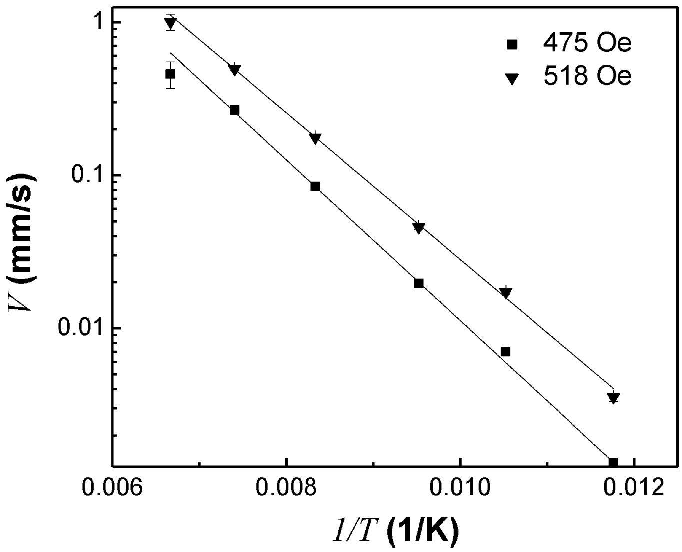

Fig. 2. Domain-wall speed with respect to the temperature for several magnetic fields. The solid squares and triangles are the domain-wall speed measured at 475 and 518 Oe, respectively. Solid lines are the best fits with (1).

$V = l/\Delta t$. While one generated field pulse during 1 ms–60 s, the domain-wall moved about 0.07–0.4 mm in our experiments. We use two electromagnets for magnetic field pulse generation. The larger one generates a larger magnetic field (< 840 Oe) with a longer rising time ($\sim 100\ \mu$s), whereas the smaller one generates a smaller magnetic field (< 330 Oe) with a faster rising time (~ 100 ns). The smaller electromagnet is placed close to the sample, and the magnetic field pulse is controlled by a computer via an operational amplifier circuit and a data acquisition board.

III. Results and Discussion

Fig. 2 shows the domain-wall speed with changing temperature, under several different external magnetic fields as denoted in the figure. The symbols show the averaged value of the domain-wall speed from five times repeated measurements, and the error bars are the standard deviation. It is interesting to see that the domain-wall speed is very drastically changed with changing temperature—more than 300 times between 85 and 150 K. The temperature-dependent domain-wall speed can be explained by the thermally activated process, whose rate is in general exponentially proportional to the inverse of the temperature, i.e., $\ln(V) \sim 1/T$, as seen in (1). The solid line in the figure is the best fit with this equation.

The scaled plot of the creep motion is shown in Fig. 3. In the plot the ordinate is scaled with $\ln(V)$, and the abscissa is scaled with $H^{-1/4}$. It is clearly seen from the plot that all the data show a clear linear dependence in the scaled axes over several orders of the domain-wall speed variation. One can thus conclude that the creep theory and the value of the creep exponent 1/4 are valid over the temperature range from the ambient temperature to 85 K.

The slope of the linear dependence is given by $U_{\rm C} H_{\rm dp}^{\mu} / k_{\rm B} T$, which is proportional to the inverse of the temperature. Fig. 4 summarizes the slopes of the linear dependence in Fig. 3 with respect to the temperature. The solid line is the best fit with the inverse proportionality. From the best fit, the scaling constant $U_{\rm C} H_{\rm dp}^{\mu}$ is estimated to be 3.3×10^{-19} J $\cdot$ (A/m)$^{1/4}$.

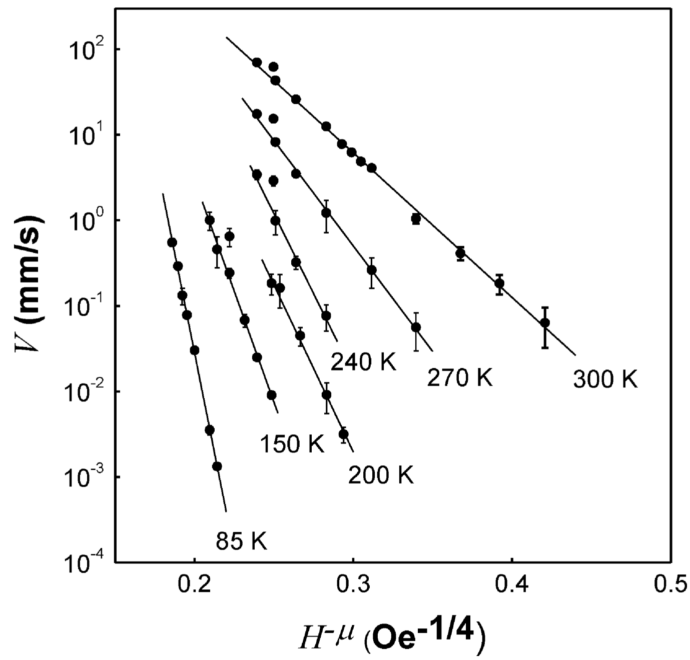

Fig. 3. Scaled plot of the domain-wall speed with respect to the field strength H for several different temperatures. The abscissa is scaled with $H^{-\mu}$, for the critical exponent μ, 1/4.

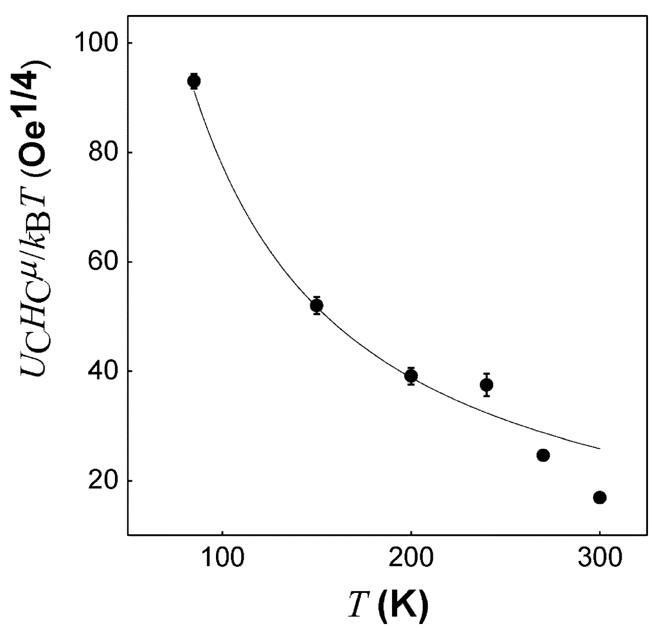

Fig. 4. Slope of the creep criticality with respect to the temperature. The solid line is the best fit with the inverse proportionality.

IV. Conclusion

We report the temperature dependence of the domain-wall dynamics in Pt/CoFe/Pt films with perpendicular magnetic anisotropy. The domain-wall speed is found to be drastically changed with changing temperature, which evidences the thermally activated process. The validity of the creep theory with the creep exponent 1/4 is verified over the temperature range from the ambient temperature to 85 K.

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