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## Reduced stochasticity in domain wall motion with increasing pinning density in thin Fe films

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**Abstract.** We report in this paper the decrease of the stochasticity of magnetization half-reversal time with increasing domain wall (DW) pinning in Fe films investigated by means of time-resolved magneto-optic Kerr microscopy. The domain images in the films reveal that the density of DW pinning sites increases with increasing Fe thickness. However, we found that the stochasticity of the magnetization half-reversal time significantly decreases with increasing DW pinning. The major reason for the reduced stochasticity is shown to be due to a thermally activated DW creep mechanism that becomes dominant during magnetization reversal due to increased DW pinning.

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## 1. Introduction

The dynamics of magnetic domain walls (DWs) is an important issue in magnetism not only due to its technical applications in spintronic devices, but also from a fundamental perspective [1–4]. It is often found that the field-induced dynamics of DWs in ferromagnetic materials shows stochastic behavior that reflects the underlying randomness in, for example, the magnetization reversal time and domain jump size [5–11]. Nowadays, interest in this subject is growing substantially because the stochastic nature of DW motion is a major challenge to the realization of spintronic memory and logic devices [12, 13].

One of the most interesting and unsolved questions is: How does the density of defects affect the stochasticity of DW motion? Defects, randomly distributed within the magnetic material, result in local variations of the DW energy, which gives rise to pinning and depinning of the DW during, for example, magnetization changes or reversal [3, 14–16]. In this situation, slight fluctuations in the initial state of DWs can lead to significant stochasticity, since the DWs are randomly pinned at defects. Thus, one can expect that DW pinning defects and their density have a great influence on the stochasticity of DW motion. In recent years, to elucidate the underlying mechanism of stochastic DW motion, many experimental studies have been carried out in disordered ferromagnetic materials, which show a random pinning of DWs during magnetization reversal [17–24]. The experiments have focused mainly on the role of pinning defects in a single sample or in materials that have similar defect densities. Systematic experimental studies to elucidate the influence of the density of defects (or the density of DW pinning sites) on the stochasticity of DW motion have not yet been reported. Thus, our understanding of this issue is far from complete.

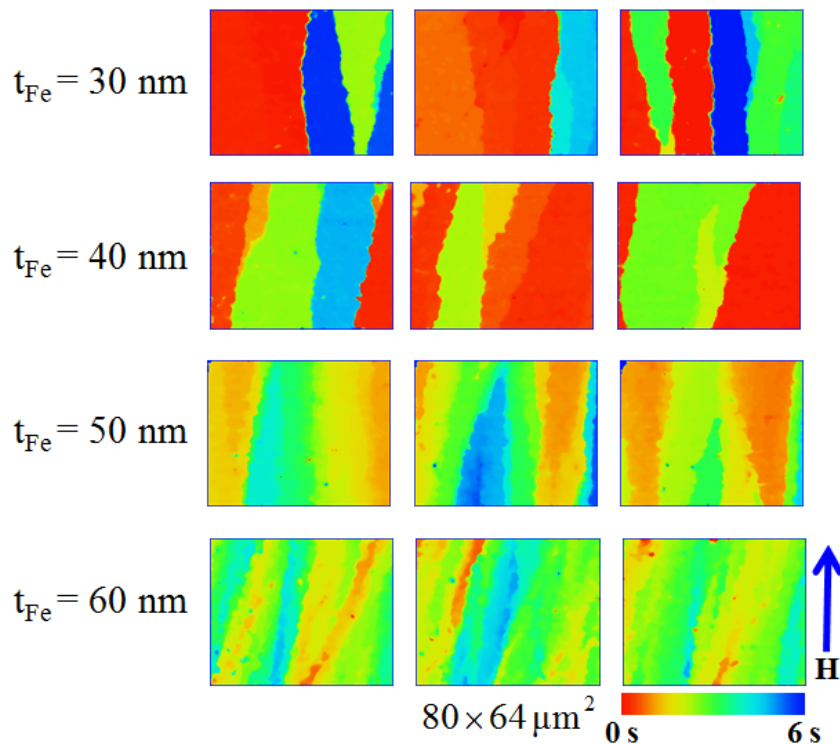
In this paper, we have investigated the stochasticity of DW motion in Fe films with varying thickness ( $t_{\text{Fe}}$ ). From time-resolved magnetic domain reversal patterns, we found that DW pinning gradually increases with increasing  $t_{\text{Fe}}$ . Interestingly, the stochasticity of the magnetization half-reversal time is significantly reduced as the pinning of DWs in the Fe film increases.

## 2. Experimental details

We have prepared Fe films with  $t_{\text{Fe}} = 30, 40, 50$  and  $60$  nm on glass substrates using magnetron sputtering in a deposition system with a base pressure of  $2 \times 10^{-6}$  torr and an Ar working pressure of 5 mtorr. The films were capped with 3 nm thick Pt layers to prevent oxidation. A magnetic field of  $\sim 500$  Oe was applied during film deposition using a permanent magnet to induce an in-plane uniaxial magnetic anisotropy within the Fe films.

The magnetization reversal process of each sample was directly measured in real time by means of a magneto-optical microscope magnetometer (MOMM) from which the magnetization reversal curve was found. The statistical distributions of the half-reversal times for each sample were determined from more than 50 measurements of the magnetization reversal curves. All measurements were carried out at room temperature ( $\sim 300$  K).

The MOMM system [6, 25] consists of a polarizing optical microscope, which images the in-plane magnetic domains in the film via the longitudinal magneto-optical Kerr effect. The spatial resolution is  $\sim 400$  nm at  $\times 500$  magnification, and the corresponding Kerr angle resolution is  $\sim 0.1^\circ$ . To store magnetic domain images captured by the CCD camera, the MOMM system is equipped with a frame grabber having an image grabbing rate of

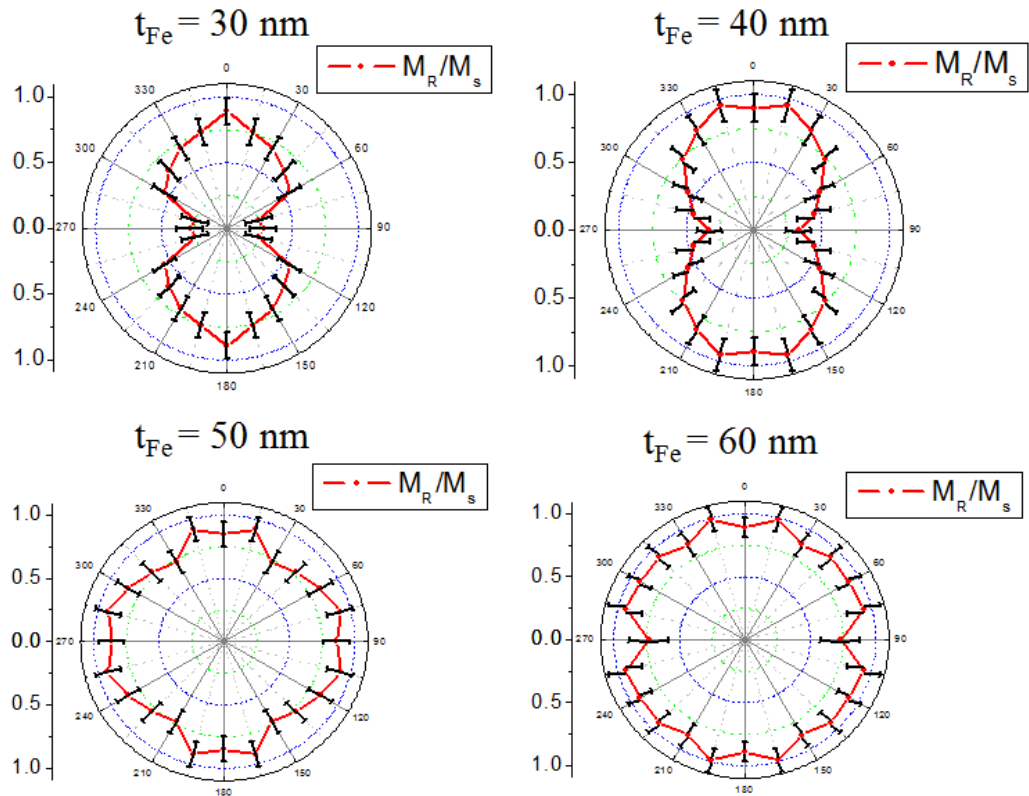


**Figure 1.** Representative magnetic domain reversal patterns of thin Fe films as a function of  $t_{\text{Fe}}$ . The color code from red to blue represents the elapsed time from 0 to 6 s after an external magnetic field with a strength of 97% of the corresponding films' coercive field was applied (in the direction indicated by the upward arrow). The film's magnetization was initially saturated in the opposite direction using a large magnetic field. The measurements were carried out at  $\times 500$  magnification, corresponding to an observation area of  $80 \times 64 \mu\text{m}^2$ .

$30 \text{ frames s}^{-1}$  in real time. The magnetization reversal curves of the sample were obtained by applying a constant magnetic field to an initially saturated film. Each domain image consists of  $200 \times 160$  pixels.

### 3. Results and discussion

Figure 1 shows representative time-resolved domain evolution patterns for each of the Fe films. The color (from red to blue) indicates the elapsed time (from 0 to 6 s) from the initial application of the reversal field to the saturated sample. A reversal field equal to 97% of the coercive field of the particular film was applied. The observation area of each image is  $80 \times 64 \mu\text{m}^2$ . As seen in the domain images, the magnetization reversal in all the films proceeds via a sequence of domain jumps. Even though the measurements were carried out on exactly the same region of a film and under the same experimental conditions, successive domain reversal patterns were found to be very different from each other, clearly showing the stochastic nature of the DW motion. Note that the domain jump size generally decreases with increasing  $t_{\text{Fe}}$ , revealing an increase in DW pinning. Since all the films were deposited under the same deposition conditions, it can naturally

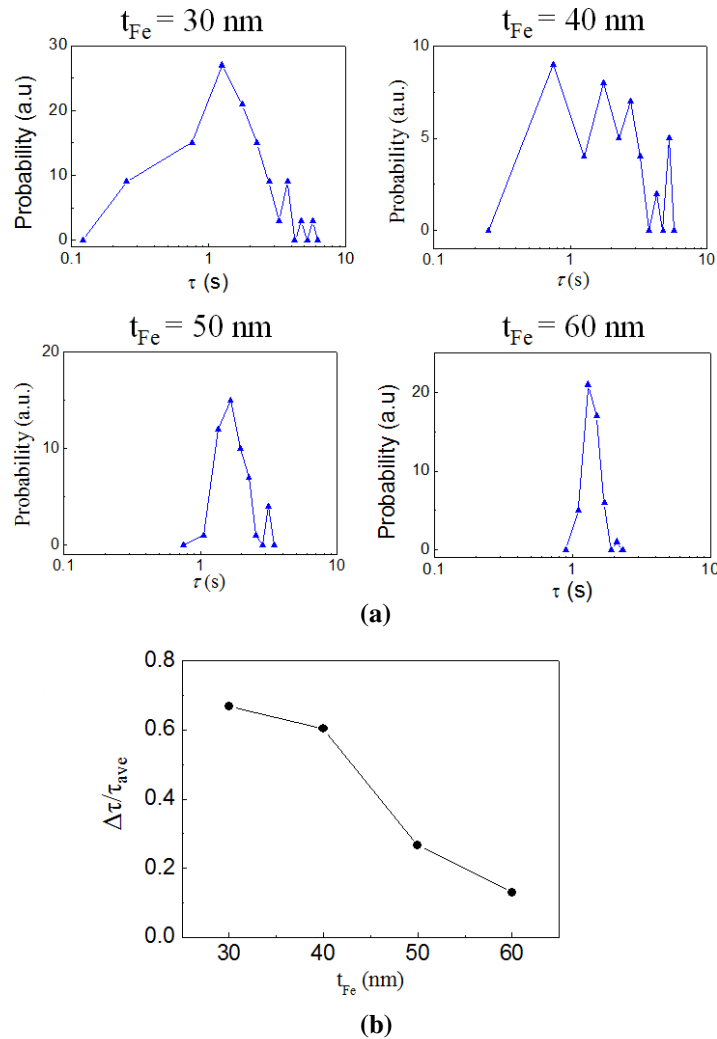


**Figure 2.** Angular dependence of the Kerr hysteresis loop squareness  $M_r/M_s$ , where  $M_r$  and  $M_s$  are the remanent and saturation magnetizations, respectively. The magnetic field is applied at an angle from the direction of the in-plane magnetic easy axis, which corresponds to  $0^\circ$ .

be expected that the number of defects in the films increases with increasing  $t_{\text{Fe}}$ . These defects then might act as the DW pinning sites.

Another possible reason for the increased DW pinning is due to changes in the magnetic anisotropy of the films. Figure 2 shows the angular dependence of the Kerr hysteresis loop squareness  $M_r/M_s$ , where  $M_r$  and  $M_s$  are the remanent and saturation magnetizations, respectively. As is evident from figure 2, the uniaxial anisotropy induced during the sample preparation gradually disappears with increasing  $t_{\text{Fe}}$ . For thin  $t_{\text{Fe}}$  films, the induced uniaxial anisotropy prevails and thus the anisotropy energy in the whole sample area is nearly the same, resulting in the low degree of disorder. However, for thicker Fe films (50 and 60 nm), one can expect that the crystalline anisotropy in each grain is rather randomly distributed, since the crystal structure of the film is not epitaxial. Thus, the orientations and magnitudes of isotropies in each grain are very different, resulting in the high degree of disorder [14, 26]. Therefore, we believe that crystalline anisotropy energy change is also a major cause of the increased DW pinning.

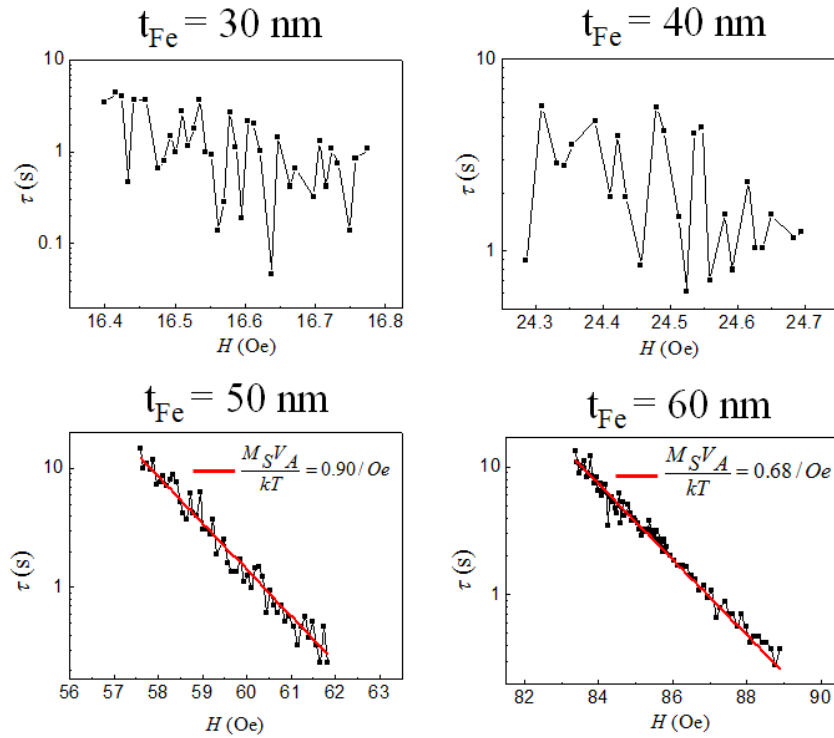
To investigate the dependence of the stochasticity of DW motion on the number of pinning sites, we found the distributions of half-reversal time, which is defined as the elapsed time  $\tau$  at which half the magnetization in the observation area has switched. The magnetization reversal curve is measured more than 50 times under an applied magnetic field  $H = 0.97H_C$ ,



**Figure 3.** (a) Distributions of the magnetization half-reversal time  $\tau$  obtained from repeated measurements of the magnetization reversal curve. (b) The normalized standard deviation  $\frac{\Delta\tau}{\tau_{\text{ave}}}$  dependent on  $t_{\text{Fe}}$ . The  $\frac{\Delta\tau}{\tau_{\text{ave}}}$  were obtained from the distributions of  $\tau$ .

where  $H_C$  is the coercive field. Figure 3(a) shows the distribution of  $\tau$  measured in Fe films. It is interesting to note that the stochasticity of  $\tau$  depends strongly on  $t_{\text{Fe}}$ . For thin Fe films ( $t_{\text{Fe}} = 30$  and 40 nm), the width of the distribution in  $\tau$  is very broad. However, for thick Fe films ( $t_{\text{Fe}} = 50$  and 60 nm), the width of the distribution in  $\tau$  is much narrower than that for thin Fe films, revealing the reduced stochasticity in the DW motion. Note, from figure 3(b), that  $\frac{\Delta\tau}{\tau_{\text{ave}}}$  decreases with increasing  $t_{\text{Fe}}$ , where  $\Delta\tau$  and  $\tau_{\text{ave}}$  are the standard deviation and the average value obtained from the distribution in  $\tau$ , respectively. This result clearly demonstrates that the stochasticity of  $\tau$  is significantly decreased with increasing DW pinning.

To elucidate the origin of the DW pinning-dependent stochasticity, we have measured the value of  $\tau$  for varying  $H$ . As seen in figure 4,  $\tau$  exponentially decreases with increasing  $H$ , for thick films with  $t_{\text{Fe}} = 50$  and 60 nm. Such a phenomenon can be explained by a thermally activated DW creep mechanism [27–31]. When the DW creep mechanism is dominant,  $\tau$  is



**Figure 4.** The half-reversal time  $\tau$  as a function of applied magnetic field  $H$ . Curves fitted with  $M_S V_A / kT = 0.90 \text{ Oe}^{-1}$  and  $M_S V_A / kT = 0.68 \text{ Oe}^{-1}$  are shown as solid lines in the graphs corresponding to  $t_{\text{Fe}} = 50$  and  $60 \text{ nm}$ , respectively.

given by the following:

$$\tau \sim \exp \left[ -\frac{M_S V_A H}{kT} \right], \quad (1)$$

where  $M_S$ ,  $V_A$  and  $kT$  are the saturation magnetization, the activation volume and the thermal energy, respectively. On the other hand, for the thin films with  $t_{\text{Fe}} = 30$  and  $40 \text{ nm}$ ,  $\tau$  has no correlation with  $H$ , consistent with random Barkhausen avalanches. When switching via random Barkhausen avalanches is dominant during the magnetization reversal,  $\tau$  cannot be determined from the function of  $H$ , resulting in the enhanced stochasticity of  $\tau$ .

From equation (1), we have deduced the activation length  $L_A$  ( $= \sqrt{\frac{V_A}{t_{\text{Fe}}}}$ ), which is generally interpreted as the average distance between DW pinning sites [32, 33]. For the films with  $t_{\text{Fe}} = 50$  and  $60 \text{ nm}$ ,  $L_A$  is about  $(21 \pm 2)$  and  $(16 \pm 1) \text{ nm}$ , respectively, using the measured value of  $M_S \sim 1750 \text{ emu cc}^{-1}$  for these films. These values show that the density of DW pinning sites for  $t_{\text{Fe}} = 60 \text{ nm}$  is higher than that corresponding to the film with  $t_{\text{Fe}} = 50 \text{ nm}$ . This indicates that the enhanced degree of disorder results in an increase of DW pinning density in the films as mentioned above. For the films with  $t_{\text{Fe}} = 30$  and  $40 \text{ nm}$  the characteristic domain jump size cannot be quantified and thus we could not obtain  $L_A$ . However, one can qualitatively expect that the domain jump size in these films is much larger compared with those in films with  $t_{\text{Fe}} = 50$  and  $60 \text{ nm}$ , as clearly confirmed by the domain images in figure 1.

Note, from figure 4, that the range of  $H$  for  $t_{\text{Fe}} = 30$  and  $40 \text{ nm}$  is much narrower than those for the thicker samples [11]. This is due to the fact that the magnetization could not be reversed



when  $H$  is slightly smaller than the value presented in figure 4. This is good evidence for the fact that the DW creep mechanism is not significant in these films. When the thermal fluctuation of the DWs is negligible during magnetization reversal, the DW cannot move when  $H$  is smaller than a characteristic critical field, which is generally the coercive field. On the other hand, in the thicker films for  $t_{\text{Fe}} = 50$  and 60 nm, the magnetization can be reversed even though  $H$  is smaller than the coercive field, which is good evidence for a DW creep.

The DW creep mechanism observed in thick Fe films ( $t_{\text{Fe}} = 50$  and 60 nm) can be accounted for by the increased DW pinning site density [11]. When the DW motion is induced by a thermally activated creep mechanism, the DW velocity ( $v_{\text{creep}}$ ) can be approximately determined by the following equation [27, 28]:

$$v_{\text{creep}} \sim \frac{1}{\tau} \sim \exp \left[ \frac{M_S V_A (H - H_C)}{kT} \right]. \quad (2)$$

When the density of the DW pinning sites is very low, one can expect that the characteristic domain jump size ( $V_A$ ) is very large and thus  $v_{\text{creep}}$  is nearly zero when  $H$  is slightly smaller than  $H_C$ . Therefore, the motion of DWs via thermal fluctuations can be nearly neglected during the magnetization reversal, revealing the dominance of a random Barkhausen avalanche reversal mode. In this condition,  $\tau$  cannot be determined from the dependence on  $H$  as mentioned before, resulting in the enhanced stochasticity of DW motion. On the other hand, when the density of the DW pinning sites is very high (small  $V_A$ ),  $v_{\text{creep}}$  has a finite value when  $H$  is slightly smaller than  $H_C$  and thus the DW creep mechanism becomes dominant during the magnetization reversal, which induces a reduced stochasticity of DW motion since  $\tau$  can be determined from the function of  $H$ .

#### 4. Conclusion

In conclusion, we have investigated the dependence of the stochastic nature of the magnetization reversal dynamics on DW pinning density in thin Fe films. Time-resolved magnetic domain images reveal that DW pinning systematically increases with increasing Fe thickness. Interestingly, the stochasticity of DW motion is significantly decreased with increasing DW pinning. We believe that the reduced stochasticity can be ascribed to a change in the magnetization reversal mechanism from a random Barkhausen avalanche dominant mode to a DW creep dominant mode with increasing DW pinning.

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