Observation of Dynamic Scaling of Magnetic Hysteresis in Ultrathin Ferromagnetic Fe/Au(001) Films

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Dynamic scaling of magnetic hysteresis in a few monolayer thick Fe/Au(001) films was studied by using surface magneto-optic Kerr effect. For low values of the frequency (Ω) and amplitude (H_0) of an applied magnetic field, the hysteresis loss scales as $A \propto H_0^\alpha \Omega^\beta$ with $\alpha = 0.59 \pm 0.07$ and $\beta = 0.31 \pm 0.05$. Our results confirm a recently proposed scaling law. The exponents are consistent with recent numerical simulations of the hysteresis of 2D Ising spins and suggest that the hysteresis dynamics in ultrathin ferromagnetic films belong to a dynamic Ising universality class.

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The study of ultrathin film magnetism has gained intense interest due to practical applications and to fundamental discoveries in both theories and experiments [1]. Significant efforts have been focused on the studies of equilibrium phenomena. Hysteresis, the most commonly observed nonequilibrium phenomenon, has also gained attention recently. Examples are the studies of magnetic domain formation and magnetization relaxation [2]. If the dynamics of magnetization reversal remain the same in a dynamic region defined by the frequency and amplitude of an applied magnetic field, the magnetization curve, hence the hysteresis loss or the loop area, is expected to scale in those dynamic quantities. A deviation from the scaling behavior indicates a change of the mechanism in the magnetization reversal. For bulk materials, there have been studies of the dependence of the loop area on the field amplitude, some of them even dating back to the last century. For a variety of soft magnets the loop area, in a wide range of the field amplitude (500–15 000 Oe), satisfies the Steinmetz law [3] $A \propto H_0^{1.6}$.

Only recently have there been serious theoretical attempts to understand the dynamic response of magnetic hysteresis in a time-varying magnetic field. A study of both the amplitude and frequency dependence of hysteresis loops was made by Rao, Krishnamurthy, and Pandit (RKP) [4]. They studied a 3D continuous $(\Phi^2)^2$ field theory with $O(N)$ symmetry in the $N \to \infty$ limit, where the dynamics of the order parameter is governed by a Langevin equation. Their extensive studies have shown the following results. There is evidence for a dynamic transition. The shape of the hysteresis loops varies with the field frequency and amplitude. Most importantly, for low values of the frequency and amplitude, the loop area scales as

$$A \propto H_0^\alpha \Omega^\beta , \qquad (1)$$

where $\alpha = 0.66 \pm 0.05$ and $\beta = 0.33 \pm 0.03$. RKP also performed Monte Carlo simulations for a 2D Ising system, which corroborates those 3D results [4]. Other numerical simulations [5,6] also suggest that there is a dynamic universality class in the hysteresis of 2D Ising spins with a scaling law in the form of Eq. (1). Further, the shape of the hysteresis loop depends on the field frequency and amplitude.

To the best of our knowledge, there has not been any systematic experimental study of the frequency and amplitude dependence of the hysteresis loops for ultrathin ferromagnetic films. In this Letter, we present experimental results of the dynamic response of ultrathin ferromagnetic films, Fe/Au(001). We study how the shape and area of the hysteresis loops depend on the field frequency and amplitude. Our results confirm the recently proposed scaling law and are consistent with the predictions of theory and numerical simulations.

The Fe/Au(001) system has been actively pursued recently [7–9]. In our work, the Fe films were deposited by evaporation from an Fe foil in a UHV chamber with a base pressure of $\sim 1 \times 10^{-10}$ Torr. The deposition rate was ~ 1 ML/min (where ML denotes monolayer) with the substrate held at ~ 310 K. The growth was characterized as nearly a layer-by-layer growth by the angular profile measurement of high-resolution low-energy electron diffraction. The details will be published later [10]. We only note that a partial Au layer was found on the top of the films due to atomic place exchange during growth [8,10]. However, the Au cap should not have an appreciable effect on the scaling behavior of the ferromagnetic films. There was neither structural change nor contamination detected during the experimental period.

Hysteresis loops were measured at room temperature *in situ* with the surface magneto-optic Kerr effect [11]. The magnetic field was driven by a time-varying current and is practically uniform in the central region of the gap between the poles [12]. The uniform region, ~ 6 mm in diameter, is larger than the laser beam size, which ensures the homogeneity of the field in measurements. A longitudinal field was applied as a triangular wave. The magnetization evolves periodically with the applied field. Typically, more than 20 loops were collected and averaged in all the loops presented here. The data shown here are collected from the Fe/Au(001) films with a coverage of ~ 3 ML. Consistent results have been obtained in both field configurations, longitudinal and perpendicular,

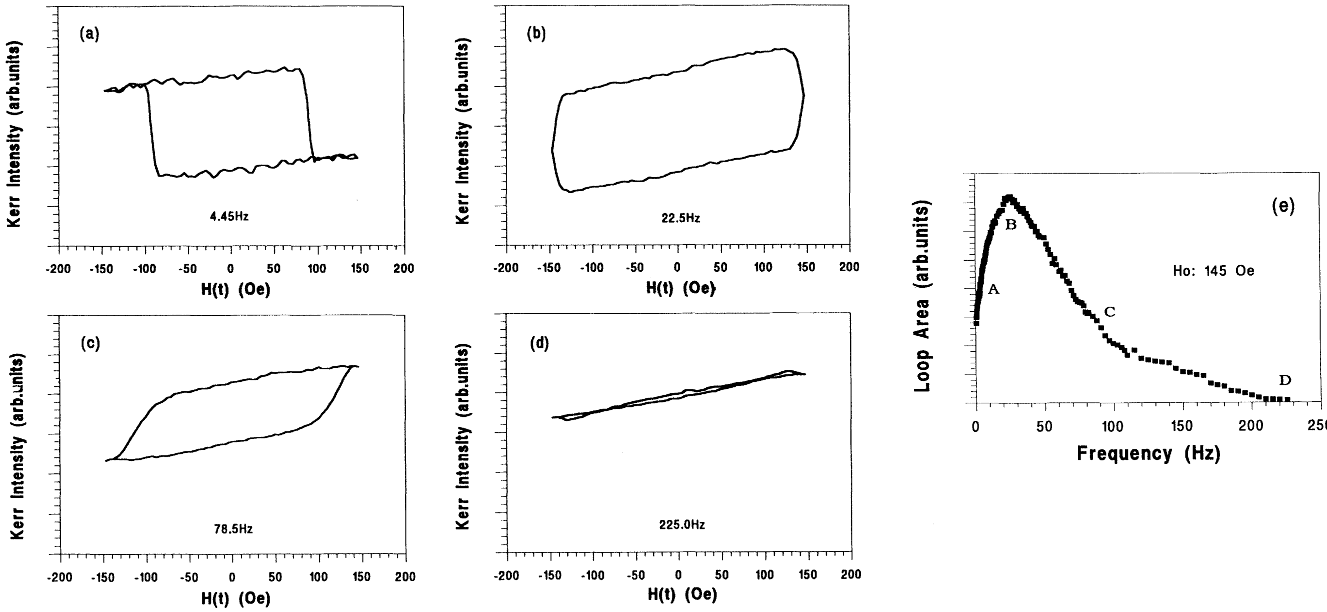

FIG. 1. The hysteresis loops measured at various frequencies: (a) 4.45 Hz; (b) 22.5 Hz; (c) 78.5 Hz; and (d) 225 Hz. The loops are classified as types A, B, C, and D, respectively. (e) The loop area as a function of frequency. The field amplitude was fixed at 145 Oe.

and for all films ranging from ~1.5 to ~3.3 ML. Thinner films are paramagnetic since their critical temperature is below the room temperature.

Figures 1(a)-1(d) show a family of hysteresis loops at various frequencies with the field amplitude fixed at 145 Oe. A similar sequence of the loop shapes can also be obtained at a constant frequency by varying the field amplitude. It is clear that the shape of the hysteresis loop varies with both the frequency and amplitude. The shape can be classified into four types, qualitatively consistent with RKP's predictions. For a given field amplitude, at low frequency the magnetization saturates. Therefore, the hysteresis loop is typically squarish (type A) as commonly observed in ferromagnetic films. At higher frequency the loop then rounds at the corners (type B). The loop further forms a "parallelogram" at even higher frequency (type C, the magnetization is no longer saturated, fluctuating around a nonzero time average instead). Eventually, the loop collapses to a straight line (type D) when the frequency is further increased. The tilt of the loops is mainly due to the diamagnetism of the substrate. Only the frequency dependence, however, is important. It is interesting to note that the change of the loops, especially the shift of their positions [upwards in Fig. 1(c)] showing a nonzero time average of magnetization, indicates a dynamic phase transition, since the type A and the type C regions belong to different dynamic phases in terms of the hysteresis symmetry [4-6,13]. We also note that the shape of the hysteresis loops at high frequency (type C) is different from the elliptic shape predicted by RKP. A shape similar to ours has been obtained for 2D Ising spins by Lo and Pelcovits [5] [Fig. 4(b) therein] and Sengupta, Marathe, and Puri [6] [Fig. 2(b) therein], although their calculated loops are rather noisy. Figure 1(e) shows the loop area as a function of frequency at an amplitude of 145 Oe. The area monotonically increases (type A) at low frequency and saturates (type B) in a small range of frequency. Then, it monotonically reduces to zero (types C and D) as the frequency is further increased.

The monotonic rise of the area at a low frequency regime can be intuitively understood. At higher frequency the magnetization reversal lags the field more, so more work is done. Figure 2(a) shows a log-log plot of the area of type A loops versus frequency (typically ≤ 25 Hz at low field) for various amplitudes of the magnetic field. The data clearly exhibit the scaling behavior $A \propto \Omega^{\beta}$ where $\beta = 0.31 \pm 0.05$. Figure 2(b) shows a series of rescaled hysteresis loops at various frequencies with $H_0 = 145$ Oe. We rescaled the loops only in the horizontal axis according to the power law with $\beta = 0.31$. All the loops superimpose well.

The area of the type A hysteresis loops increases with the field amplitude in a manner similar to the frequency dependence. Figure 3(a) shows the area as a function of the field amplitude at various frequencies in a log-log plot. The areas follow straight lines, indicating a power law behavior $A \propto H_0^{\alpha}$ up to a field amplitude of ~400 Oe, where $\alpha = 0.59 \pm 0.07$. Figure 3(b) shows the rescaled hysteresis loops at various field amplitudes with $\Omega = 4.5$ Hz, where we rescaled the loops in the horizontal axis according to the power law with $\alpha = 0.59$. Again, the loops

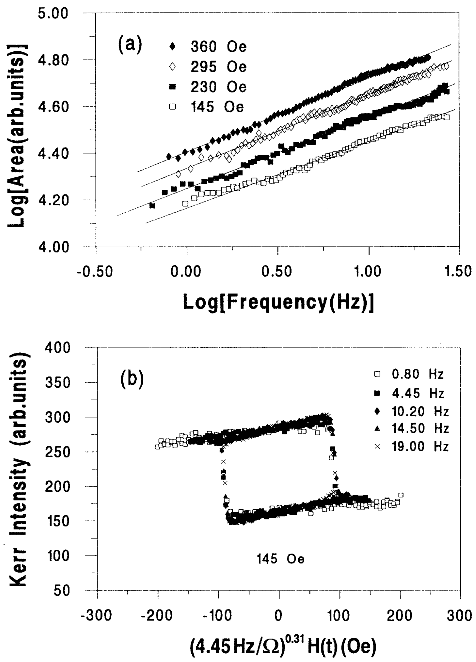

FIG. 2. (a) A log-log plot of the loop area vs frequency at various amplitudes. The slope yields $\beta=0.31\pm0.05$. (b) The rescaled loops for various frequencies with the amplitude fixed at 145 Oe. The loops are rescaled to the loop of 4.45 Hz according to the power law. The error bar is about the size of the symbol.

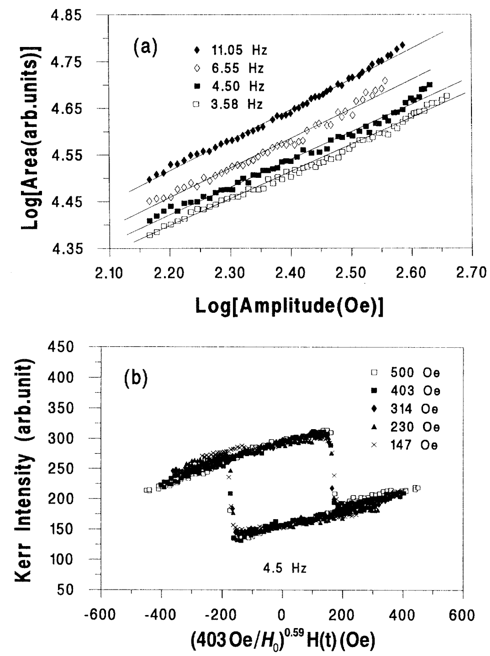

FIG. 3. (a) A log-log plot of the loop area vs amplitude at various frequencies. The slope yields $\alpha=0.59\pm0.07$. (b) The rescaled loops for various amplitudes with the frequency fixed at 4.5 Hz. The loops are rescaled to the loop of 403 Oe according to the power law. The error bar is about the size of the symbol.

superpose on each other well. The area scaling behavior of Eq. (1), therefore, can be equivalently explained as coercivity scaling.

To demonstrate the area scaling behavior of the hysteresis loops over both the field frequency and amplitudes, we replot part of the data in Figs. 2(a) and 3(a) as a function of $H_0^{0.59}\Omega^{0.31}$. As we see in Fig. 4, the areas of the hysteresis loops follow a straight line, which confirms the scaling law in the form of Eq. (1) for the ultrathin ferromagnetic films.

Several theoretical models that include thermal fluctuations of the order parameter have yielded the scaling exponents consistent with our observations. The value of our exponent β (0.31 ± 0.05) agrees with 0.36 ± 0.06 predicted by Lo and Pelcovits for 2D Ising spins, but is slightly smaller than 0.40 ± 0.01 predicted by Sengupta, Marathe, and Puri. Our β value is also in good agreement with the prediction (0.33 ± 0.03) by RKP for a continuous spin system. This suggests that the scaling in the frequency may not be sensitive to the system dimension. When fluctuations are suppressed in a mean field approximation, the RKP theory is reduced to the dynamics of a particle with a driving force [4,14]: $dx/dt=ax-bx^3+H_0\sin(\Omega t)$, where x is the order parameter, and a and b are constants. The mean field description has been shown to yield $\alpha=\beta=\frac{2}{3}$ [14]. It is clear that the thermal fluctuations must be included to account for our observed exponent $\beta\approx0.31$. Our exponent α (0.59 ± 0.07) falls between the predictions for 2D Ising spins (0.46 ± 0.05 by Lo and Pelcovits and 0.47 ± 0.02 by Sengupta, Marathe, and Puri, respectively) and that of RKP (0.66 ± 0.05) for the continuous spin system. The deviation from RKP's prediction may be mainly due to the dimension dependence. In fact, a value of $\alpha\sim0.7$ has been obtained in thick films (discussed later). The slight difference between our α value and the 2D Ising predictions requires further study. However, based on our consistent α and β values obtained in the films ranging from

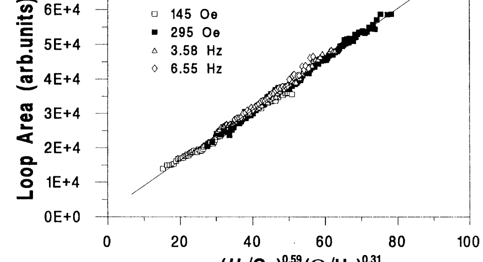

FIG. 4. An area plot which demonstrates the scaling of the hysteresis loops: $A\propto H_0^{0.59}\Omega^{0.31}$. The data are taken from Figs. 2(a) and 3(a). The straight line is a guide to the eye.

~ 3.3 down to ~ 1.5 ML and the consistency with 2D Ising predictions for the hysteresis loops, we believe the hysteresis dynamics of the ultrathin ferromagnetic films is consistent with the dynamics of the Ising universality class.

It has been pointed out that low values of the frequency and amplitude define the dynamic scaling region [4,15] where we observed the predicted scaling behavior. In a high frequency regime, however, the loop area decreases with frequency [see Fig. 1(e)], which is in qualitative agreement with a scaling law in this frequency regime proposed by RKP: $A \propto \Omega^{-1}$. In a high magnetic field (>450 Oe, but, still at low frequencies), the scaling behavior in amplitude collapses. The area measurements from ultrathin films are no longer reliable in high field, typically ~ 600 Oe depending on the frequency and film thickness, due to serious random distortions of the hysteresis loops. However, the loop areas can be reliably measured in the high field for thick films. For Fe films of ~ 100 ML, $\alpha \sim 0.7$ in regions below ~ 400 Oe and $\alpha \sim 1.3$ in regions of ~ 500–1800 Oe were obtained, respectively. Measurements above ~ 1800 Oe were limited by the electromagnet. RKP discussed the relevance of their prediction $\alpha \approx 0.66$ for a low field regime with the Steinmetz law $\alpha \approx 1.6$ in a field above 500 Oe. It is clear that a simple comparison is not quite proper, since the magnetic system belongs to different scaling regions across a critical field. The different scaling regions may result from different mechanisms of magnetization reversal in low and high fields, respectively. However, fundamental reasons behind this change are worthy of further study. Note that $\alpha \sim 1.3$ for pure Fe is less than $\alpha \approx 1.6$ in the Steinmetz law for soft iron in the same range of the field amplitude.

In conclusion, we have shown the evidence for the dynamic transition in ultrathin ferromagnetic films. The hysteresis strongly depends on the modulation frequency and amplitude of the applied magnetic field. Most importantly, for low values of the frequency and amplitude, the area of the hysteresis loops exhibits the scaling behavior in the form of $A \propto H_0^{0.59} \Omega^{0.31}$. The measured exponents are independent of the Fe coverage in a few monolayer regime. Our results suggest that the hysteresis dynamics of ultrathin ferromagnetic films are consistent with an Ising universality class. We expect that similar scaling behavior may be observed in a variety of ultrathin ferromagnetic films.

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