Thickness-dependent dynamic hysteresis scaling behavior in epitaxial Fe/GaAs(001) and Fe/InAs(001) ultrathin films

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The dynamic hysteresis scaling behavior in epitaxial Fe/GaAs(001) and Fe/InAs(001) thin films (thickness range 7.3–150 Å) has been investigated as a function of Fe film thickness in the field sweep rate range 0.005–1000 kOe/s using the magneto-optic Kerr effect. The hysteresis loop area A follows the scaling relation $A \propto (dH/dt)^{\alpha}$. We find two distinct dynamic regimes: the low dynamic regime in the sweep rate range 0.005–250 kOe/s, and the high dynamic regime beyond 250 kOe/s. There is a marked increase in α between the low and high dynamic regimes which we attribute to the dominant reversal mechanism changing from domain wall motion to nucleation. In the low dynamic regime α is a decreasing function of Fe film thickness, and this behavior is attributed to the effect of interface-induced pinning.
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An understanding of the magnetization reversal dynamics in magnetic thin films is of both fundamental and technological importance. Studies of dynamic hysteresis scaling behavior can reveal information about the roles of domain wall motion and domain nucleation in the dynamics of magnetization reversal. They are also highly relevant to future high frequency device applications, since the coercivity of various recording media is strongly dependent on time scale.[1–3]

A recent theoretical study of dynamic hysteresis scaling behavior[4] proposed that the hysteresis loop area A follows the scaling relation $A \propto (dH/dt)^{\alpha}$, where dH/dt is the sweep rate of the external applied field and α is a dynamic scaling exponent. Specific values of α are predicted by the various theoretical models,[4,5] and assumed to be universal. On the other hand, recent experimental studies of the magnetization reversal dynamics in ultrathin films show that the dynamic scaling exponents vary with the choice of system, i.e., they are not universal. A few experiments,[6,7] including those on epitaxial Fe/GaAs(001)[8,9] and Fe/InAs(001)[9] thin films, show a dependence of the dynamic hysteresis scaling behavior on the sweep rate of the applied field. These studies show that distinct ''low'' and ''high'' dynamic regimes arise in which the dominant reversal mechanism is considered to be domain wall motion, and domain nucleation, respectively. Furthermore, in the low dynamic regime, the dynamic scaling exponents are dependent on ferromagnetic layer thickness (Table I). These data suggest that scaling exponents in the low dynamic regime are generally an order of magnitude larger for the thin (~few Å) than for the thick (~15 Å and beyond) films,[6,7,10–12] although no systematic thickness-dependent studies have been performed to date. The available experimental results suggest that key factors that may have a significant influence on the dynamic hysteresis scaling behavior are film thickness, anisotropy strength, and interface-induced pinning.

We chose to study the dynamic hysteresis scaling behavior in the Fe/GaAs(001) system with Fe thickness ranging from 7.3 to 150 Å. This allows a test of whether the thickness dependence of scaling exponents in the low dynamic regime suggested by previous studies[6,7,10–12] actually holds for one specific system. In particular, we wish to search for a possible change in the scaling behavior for films thinner than the exchange length $d_{ex} = \sqrt{(2A/\mu_0 M_S^2)}$ (in Fe, the exchange length $d_{ex} \approx 50$ Å). In addition we chose to investigate a similar series of Fe/InAs(001) films, with a view to determining the effect of the contrasting anisotropy strengths and symmetries. While the interface-induced uniaxial anisotropy dominates up to ~50 Å of Fe in the Fe/GaAs(001) system,[13] above ~15–22 Å of Fe, Fe/InAs(001) films exhibit a cubic in-plane anisotropy with negligible uniaxial anisotropy.[14,15]

The continuous Fe/GaAs(001) and Fe/InAs(001) films were prepared by MBE at ambient temperature (35 °C) in

TABLE I. Experimental dynamic scaling exponents α in $A \propto (dH/dt)^{\alpha}$ for various continuous ferromagnetic (FM) thin film systems.

System	FM layer thickness (Å)	α (low dynamic regime)	Ref.	Description
Fe/Au(001)[a]	4.3	$\alpha \sim 0.59$	10	Thin
		$\beta \sim 0.31$		
Au/Fe/GaAs(001)	7.3	0.14	Present work	
Co/Cu(001)[a]	2.5–5.0	$\alpha \sim 0.15$	11	
		$\beta \sim 0.02$		
Co/Cu(100)[a]	2.5–7.5	$\alpha \sim 0.67$	12	
		$\beta \sim 0.66$		
Au/Fe/GaAs(001)	18	0.04	Present work	Thick
	55	0.01		
	150	0.001		
Au/Fe/InAs(001)	21	0.05	Present work	
	56	0.01		
	141	0.02		
Au/Co/Au/MoS_2	80	0.036	6	
Cu/Co/Cu/Si(001)	40	0.02	7	

[a] $A \propto H_0^{\alpha} \Omega^{\beta}$ assumed, where H_0 = applied field amplitude, Ω = applied field frequency.

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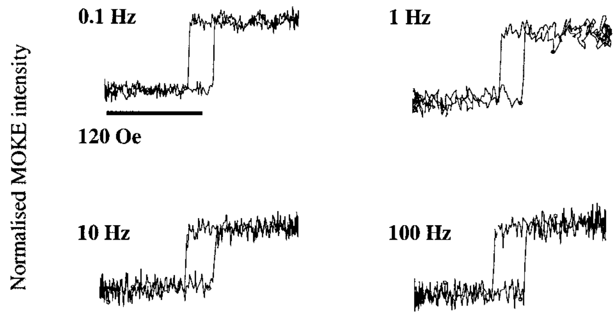

FIG. 1. Evolution of frequency-dependent hysteresis ($M-H$) loops for the 18 Å Fe/GaAs(001) film.

ultrahigh vacuum. The base pressure during growth was kept at $\sim 10^{-9}$ mbar and the growth rate was 1 Å/min. *Ex situ* magnetization measurements showed that the entire Fe film was ferromagnetic with a bulk-like moment: $1.6\pm 0.2 \times 10^3$ emu/cm^3 after the onset of the ferromagnetism at $\sim$5 ML Fe.[14] Each film was capped with 20 Å Au in order to prevent oxidation of the Fe layer during *ex situ* measurements.

Hysteresis loops were measured *ex situ* at room temperature using magneto-optic Kerr effect magnetometry with a probing laser beam spot of $\sim$0.5 mm. A magnetic field in the gap ($\sim$20 mm) of a C-shaped silicon–iron laminated core was produced by passing a sinusoidal time-varying current through the Cu coil around the core. The magnetic field was applied in the plane and along the easy-axis direction of the film ([001] for Fe/GaAs(001) and Fe/InAs(001) with dominant cubic anisotropy, $[0\bar{1}\bar{1}]$ ([011]) for Fe/GaAs(001) (Fe/InAs(001)) with dominant uniaxial anisotropy), and maintained at 120 Oe (sufficient to saturate the Fe layer for all samples and all frequencies) while the frequency was varied from 0.01 Hz to 2.3 kHz. A Hall probe suited to measurement across the chosen frequency range was used to detect the effective magnetic field. A Hamamatsu photodiode (response time$\sim$few ns) and Avtech amplifier were used to convert the reflected laser light into a current proportional to the magnetization along the easy axis direction of the film.

Figure 1 shows the evolution of frequency-dependent hysteresis ($M-H$) loops for the 18 Å Fe/GaAs(001) film. Similar sequences of $M-H$ loops are observed for the remaining Fe/GaAs(001) and Fe/InAs(001) films. The dynamic coercivity H_c^* is seen to be an increasing function of the frequency.

Figure 2 presents the dynamic coercivity as a function of the logarithm of the field sweep rate (proportional to frequency) for the Fe/GaAs(001) films. The dynamic coercivities H_c^* were determined for frequencies at which the hysteresis loops are saturated. We used the fact that H_c^* is proportional to the $M-H$ loop area A in this case for the determination of the exponent α in the scaling relation $A \propto (dH/dt)^{\alpha}$.[8] Hence, in fitting the data, we obtained the values of the exponent α from the log–log plot of the variation of H_c^* versus the field sweep rate in the low dynamic regime (Table I).

It is clear that the gradient and hence the exponent α varies with the field sweep rate. Two distinct regions are seen in which approximately linear behavior occurs but with different values of α, in accordance with the results of our previous studies of thin Fe films.[8,9] These regions are termed the low dynamic regime and the high dynamic regime, respectively. Here, a critical transition occurs at $\sim$250 kOe/s separating the two regions for all films.

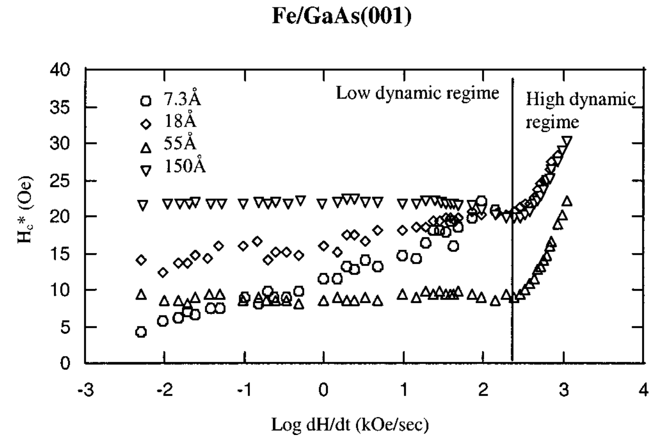

FIG. 2. Variation of dynamic coercivity H_c^* as a function of the logarithm of the field sweep rate for the Fe/GaAs(001) films.

A comparison of the earlier results of simulations and experimental observations of Au/8 ÅCo/Au/MoS_2 sandwiches with perpendicular magnetic anisotropy[6] indicated that H_c^* depends directly on the competition between nucleation and wall motion, the number of nuclei sites, and the Barkhausen volume. Below the critical transition, the main reversal mechanism is attributed to domain wall motion, but upon increasing the field sweep rate, the wall motion process becomes less and less efficient.[6] A similar behavior is inferred for the Fe/GaAs(001) and Fe/InAs(001) systems studied here.[8,9]

Fatuzzo's theory[16] for polarization reversal in ferroelectric systems is consistent with magnetization reversal in GdTbFe films[17] and Cu/Ni/Cu/Si(001) films.[18] This theory suggests that the reversal depends on the parameter $k = v/r_c R$ (r_c=critical radius of a nucleus, v=domain wall velocity, R=nucleation rate), the ratio between the reversal rates of the nucleation and wall motion processes, and the parameter that characterizes the competition between them. Raquet *et al.* found a value of $k=9$ in the low dynamic regime and $k=5\times 10^{-3}$ in the high dynamic regime.[6] We conclude that at the critical transition of 250 kOe/s observed here, $k\sim 1$ and the wall motion and nucleation processes contribute equally to the reversal process.

Figure 3 shows the dynamic scaling exponents α as a function of Fe film thickness, for the Fe/GaAs(001) system. It is clear from this figure, and from Fig. 2, that in the low dynamic regime α is a decreasing function of Fe film thickness. A similar behavior is observed for the Fe/InAs(001) system. It is seen that α varies on a length scale on the order of d_{ex}. For $d < d_{ex}$, the larger value of α indicates a markedly steeper increase of H_c^* with sweep rate compared with the corresponding variation seen for $d > d_{ex}$. The thickness-dependent scaling behavior we observe indicates that the interface controls the behavior, suggesting that interface-

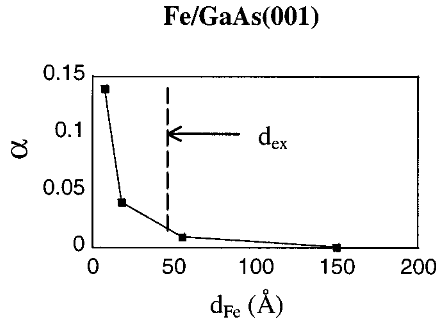

FIG. 3. Dynamic scaling exponents α as a function of Fe film thickness for the Fe/GaAs(001) system.

induced pinning has a strong influence. Pinning sites arising from interface roughness are expected to trap domain walls more effectively at lower Fe thickness.[19] Evidence for such pinning sites in 55 Å Fe/GaAs(001) spatially distributed on a few hundred μm has been previously inferred from Kerr microscopy studies.[8]

Our values of α above d_{ex} for the Fe/GaAs(001) system compare well with the value $\alpha=0.02$ found in Cu/40 ÅCo/Cu/Si(001)[7] at low sweep rates. Below d_{ex} they compare well with the value $\alpha\sim0.15$ found in 2.5–5.0 ÅCo/Cu(001).[11] These values, as well as conflicting with the proposed universality of dynamic scaling exponents, are a factor of 3 or more different from those predicted theoretically.[4,5] In the low dynamic regime for the Fe/InAs(001) films the values of α are found to be similar to those for Fe/GaAs(001) films of corresponding thickness ($\sim$20 Å Fe, $\alpha\sim0.05$; $\sim$55 Å Fe, $\alpha\sim0.01$), despite the fact that the two systems have contrasting anisotropy strengths and symmetries. Since the anisotropy strengths vary with thickness in both of these systems, such a dependence may be reflected in the scaling behavior via the strength of the effective energy barrier for pinning.

Variations in surface roughness and film morphology often have a significant effect on magnetic structure. Roughness is very important because surface steps break translational invariance and induce local, in-plane anisotropies that differ from the intrinsic in-plane anisotropy of the flat film.[20,21] This is significant because local anisotropies can nucleate and pin domain walls during the reversal process.[22] In a recent study[23] Hyman *et al.* used classical spin simulations to study magnetization reversal in ultrathin (1–6 ML) films with planar magnetization and surface roughness typical of epitaxially grown samples. The models demonstrate that local step anisotropies become more important and magnetostatic interactions become less important as the film thickness decreases. Ferré *et al.*[24] studied domain configurations and magnetization reversal dynamics in Au/Co/Au(111) ultrathin films with variation of the Co layer thickness. For the thinnest Co layers (<2 ML) the magnetization reversal dynamics were found to be very sensitive to tiny changes in sample roughness.

In summary, by studying systematically the dynamic hysteresis scaling behavior in one system, epitaxial Fe/GaAs(001), we have shown that in the low dynamic regime the scaling exponent α varies with the Fe thickness d. Importantly the characteristic length scale for this variation is the exchange length d_{ex}. We conclude that the thickness-dependent dynamic hysteresis scaling behavior in both Fe/GaAs(001) and Fe/InAs(001) ultrathin films derives from an increasing sensitivity of the magnetization reversal dynamics to interface-induced pinning sites with decreasing Fe thickness.

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