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Sweep rate-dependent magnetization reversal in epitaxial Fe/GaAs(001) and Fe/InAs(001) thin films

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We present the magnetization reversal dynamics of epitaxial Fe thin films grown on GaAs(001) and InAs(001) studied as a function of field sweep rate in the range 0.01–160 kOe/s using magneto-optic Kerr effect. For 55 and 250 Å Fe/GaAs(001), we find that the hysteresis loop area A follows the scaling relation $A \propto \dot{H}^{\alpha}$ with $\alpha = 0.03–0.05$ at low sweep rates and 0.33–0.40 at high sweep rates. For the 150 Å Fe/InAs(001) film, α is found to be ~ 0.02 at low sweep rates and ~ 0.17 at high sweep rates. The differing values of α are attributed to a change of the magnetization reversal process with increasing sweep rate.
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The magnetization reversal dynamics of magnetic thin films is of fundamental importance and is also highly relevant to future high frequency device applications. Recent theoretical studies[1–3] of the dynamic scaling of hysteresis behavior have focused on the area of the hysteresis loop as a function of applied field amplitude and frequency. Experimental work[4–11] has been carried out to describe the dynamics of magnetization reversal in ultrathin ferromagnetic films[4–9] and mesoscopic structures.[10,11] Although the influence of the magnetic anisotropy on the static magnetization reversal process has been studied in continuous epitaxial Fe/GaAs[11–16] and Fe/InAs[17,18] systems, no studies of the magnetization reversal dynamics have yet been reported. In order to clarify the effect of magnetic anisotropy on the dynamic behavior we studied in the present work thin (55–250 Å) epitaxial Fe films grown on GaAs(001) and InAs(001).

The continuous Fe/GaAs(001)[15,16] and Fe/InAs(001)[17,18] films were prepared in UHV by electron beam evaporation. The base pressure during growth was kept at $\sim 10^{-9}$ mbar and growth rate was $\sim$ 1 Å/min. Each was capped with 20 Å Au for *ex situ* measurements in order to prevent oxidation of the Fe layer.[14,16] Magnetization curves during film growth revealed a continuous directional change of the anisotropy axes with increasing film thickness. This behavior arises from the combination of uniaxial and cubic in-plane magnetic anisotropies, which are both thickness dependent.[14] In contrast to the Fe/GaAs(001) films, above 10 ML of Fe, Fe/InAs(001) films exhibit a cubic in-plane anisotropy with negligible uniaxial anisotropy.[17]

Hysteresis loops were measured *ex situ* at room temperature using magneto-optic Kerr effect (MOKE) magnetometry with a probing laser beam spot of diameter ~ 2 mm, for fields applied along the global easy magnetization axis[13,16] close to the [001] direction for Fe/GaAs(001) and along the [001] direction (cubic easy axis) for Fe/InAs(001). The applied magnetic field was driven by a time-varying current at a frequency between 0.01 Hz and 1 kHz. A Hall probe in the frequency range studied was used to detect the effective magnetic field at each frequency. We have measured magnetic relaxation and observed domain structures using time-resolved scanning Kerr microscopy, in which the probing laser beam size is controllable. The magnetization as a function of time t, $M(t)$, was measured under a constant amplitude reverse field. Magnetic domain images were taken using a scanning Kerr microscope with a resolution of 1.5 μm.

In Fig. 1, we present the log–log plots of dynamic coercivity (H_c^*) against field sweep rate at various frequencies and field amplitudes for the 55 and 250 Å Fe/GaAs(001) films. The inset displays the log–log plots of H_c^* against field sweep rate for the 250 Å Fe/GaAs(001) and 150 Å Fe/InAs(001) films. The dynamic coercive fields were determined for frequencies and field amplitudes 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 exponents in the hysteresis scaling relation[1,2]

$$A \propto H_0^{\alpha} \Omega^{\beta}, \tag{1}$$

where H_0 is the amplitude of an oscillating magnetic field, Ω is the frequency, and α, β are exponents that depend on the dimensionality and symmetry of the system. We find that the dynamic coercivities superimpose well for the 55 and 250 Å Fe/GaAs(001) films, respectively. Since the amplitude- and frequency-dependent H_c^* superimpose, Fig. 1 demonstrates that the scaling behavior for the variation of the hysteresis loop area A for a sweep rate $\dot{H}(dH/dt)$ reduces to a power law function of the form[3]

$$A \propto \dot{H}^{\alpha} \tag{2}$$

and that the exponent α is identical to β in Eq. (1). However, it is clear that the exponent α in Eq. (2) varies with the field sweep rate, but two distinct regions are seen in which approximately linear behavior occurs but with different values of α. By extrapolating the two distinct linear regions in the log–log plot of H_c^* against the field sweep rate, the critical transition is found to occur at ~ 16 kOe/s for the 55 and 250 Å Fe/GaAs(001) films. The exponent α is found to be identical to the corresponding exponent β in Eq. (1) in each of these linear regions. On the other hand, for the 150 Å

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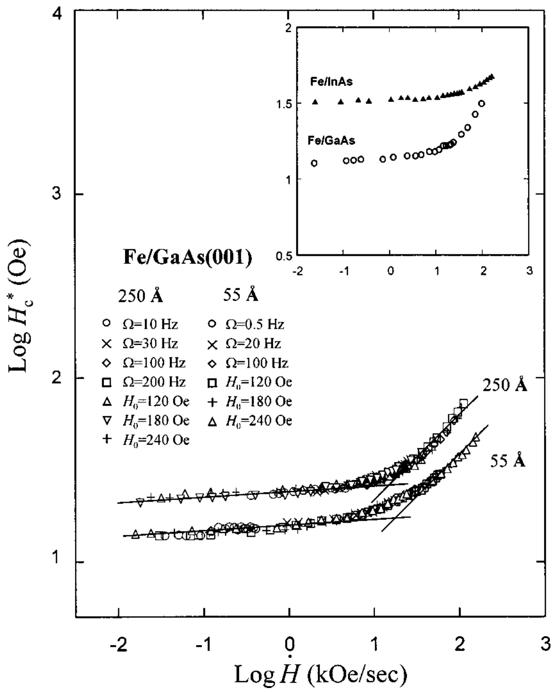

FIG. 1. Log–log plots of dynamic coercivity (H_c^*) against field sweeping rate $\dot{H}$ at various frequencies and field amplitudes for 55 and 250 Å Fe/GaAs(001) films. The lines are guides for the eye to distinguish two regions. The inset displays log–log plots of H_c^* against field sweep rate for the 250 Å Fe/GaAs(001) and 150 Å Fe/InAs(001) films.

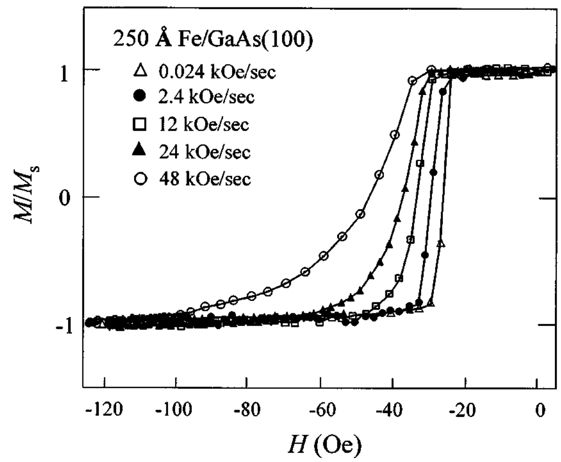

FIG. 2. Hysteresis loops of 250 Å Fe/GaAs(001) film in a negative magnetic field for several field sweep rates $\dot{H}$.

Fe/InAs(001) film, the corresponding transition from low to high values of α occurs at $\sim$35 kOe/s as seen in the inset of Fig. 1.

A similar variation of H_c^* against sweep rate was observed in Au/Co/Au/MoS_2 with perpendicular magnetic anisotropy by Raquet *et al.*[6] A sharp transition was observed in the variation of H_c^* versus the field sweep rate at 180 kOe/s. Below 180 kOe/s, 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] In the higher dynamic regime, the H_c^* variation was attributed to nucleation dominating processes.

We obtained the values of the exponent α in Eq. (2) from the log–log plot of the variation of H_c^* versus the field sweep rate in two distinct dynamic regimes for the 55 and 250 Å Fe/GaAs(001). In the low dynamic regime (below 6.3 kOe/s), the best fits give the values of $\alpha \approx 0.05$ and 0.03 for the 55 and 250 Å Fe/GaAs(001) films, respectively. In the high dynamic regime (above 16 kOe/s), the values of $\alpha \approx 0.33$ and 0.4 are obtained for the 55 and 250 Å Fe/GaAs(001) films, respectively. It is obvious that there is no significant difference in the dynamic response of the two films, which nevertheless have different uniaxial magnetic anisotropy strengths.[14] For the 150 Å Fe/InAs(001) film, the value of α is found to be $\sim$0.02 in the low dynamic regime and $\sim$0.17 in the high dynamic regime. Our values for the exponent α of both systems in Eq. (2) are quite similar to those found in Au/Co/Au/MoS_2:[6] $\alpha \approx 0.036$ in the low dynamic regime and $\alpha \approx 0.177$ in the high dynamic regime. Our values for the exponent α (in our case, $\alpha \approx \beta$) of both systems also agree with those of the exponent β in Eq. (1) found for Fe/W(110):[7] $\beta \approx 0.06$ up to 256 kOe/s. In the low dynamic regime (domain wall motion mechanism) our values for the exponents of both systems are a factor of 10 different from those of theoretical predictions,[1–3] whereas in the high dynamic regime (nucleation mechanism) our values are similar to those of the theoretical predictions.[1–3]

Our results support phenomenological models[6] that assume domain nucleation and wall motion process for the magnetization reversal, based on thermally activated relaxation. In Fig. 2, we present hysteresis loops of the 250 Å Fe/GaAs(001) film in a negative magnetic field for various field sweep rates. It was observed that the sharpness of the hysteresis loop diminishes with increasing sweep rate. This behavior becomes pronounced upon increasing the sweep rates between 24 and 48 kOe/s in Fig. 2. A similar behavior was also seen in the loops for the 55 ÅFe/GaAs(001) and 150 Å Fe/InAs(001) film. The shapes of the loops in both systems with varying field sweep rate are qualitatively compatible with those of Au/Co/Au/MoS_2 (Ref. 6).

Figure 3 shows magnetic relaxation curves for the 55 Å Fe/GaAs(001) film. For time $t<0$ and $t>45$ s the sample was saturated in the positive direction. The averaged magnetization within the area of the laser beam spot changes over time in a constant reverse field. It is clearly seen that relaxation proceeds by both discontinuous and single ''*jumps.*'' The relaxation curves differs from the results of previous work.[19–22] In Cu/Ni/Cu/Si(001) films[20] and Au/Co/Au films[21] with perpendicular magnetic anisotropy relaxation occurred by a smooth decay, whereas relaxation occurred by a series of discrete jumps in Fe/Ag(001) films,[22] where the laser beam spot was also $\sim$100 μm. On the other hand, very recently, González *et al.*[23] found that relaxation in Co/Ni multilayers occurs in a single step that corresponds to complete magnetization reversal, which is compatible with our present results.

As reported in previous studies[13,16] the magnetization reversal proceeds by the sweeping of a few 180° domain walls for fields along the easy direction of Fe/GaAs(001) films with strong uniaxial anisotropy. Our results demonstrate that relaxation jumps correspond to a domain wall moving further than 100 μm. We thus infer the existence of domain wall pinning sites, e.g., macropins by extrinsic defects,[22] that

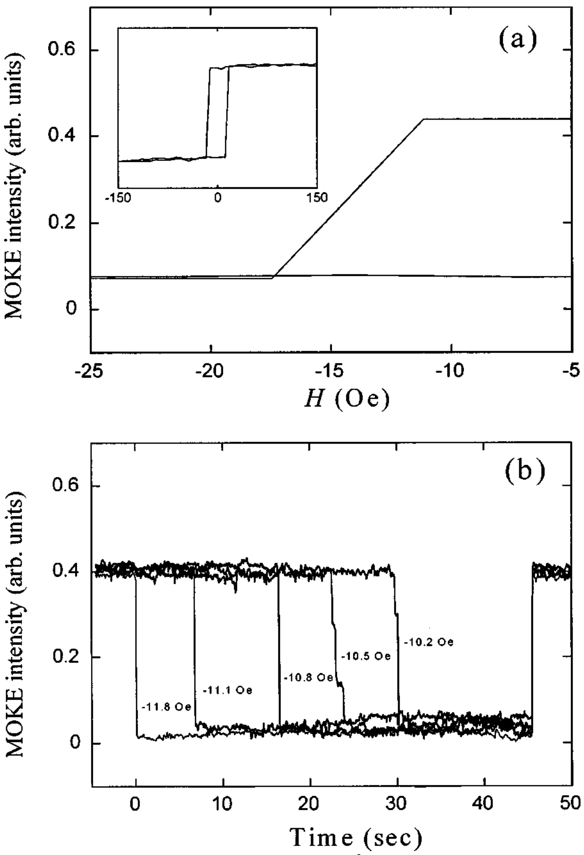

FIG. 3. Magnetic relaxation curves of 55 Å Fe/GaAs(001) film under a constant reverse field.

are spatially distributed on a few hundred microns. We also found that such a single jump was observed in relaxation curves for the 250 Å Fe/GaAs(001) and 150 Å Fe/InAs(001) films. Magnetic relaxation studies in both systems show that the magnetization develops through successive wall jumps of a few hundred microns at a constant field by thermal activation and the domain walls expand rapidly through the sample that thus gives rise to a square hysteresis loop which does not depend much upon the field sweep rate. The magnetic relaxation results thus support the view that rapid domain wall motion dominates the magnetization reversal process in the low dynamic regime (see Fig. 1), but the values of the exponent α are ten times smaller than those in the high dynamic regime where slower nucleation processes govern the magnetization reversal.

Further direct evidence demonstrating that the domain wall motion occurs in the low dynamic regime is presented in Fig. 4. We display the field-dependent evolution of domain structures in the 250 Å Fe/GaAs(001) film during the magnetization reversal process for a field applied along [010] axis, a combination of an easy cubic direction, and the hard uniaxial direction.[13,14] The area of each image is 1×1 mm^2, where black denotes the unswitched part and white the switched part. It is clearly seen that the nucleation is followed by the subsequent growth of domains separated by zigzag walls, and a small increase of the field promotes the domain growth via wall displacements over a few hundred microns. The magnetization develops through discontinuous wall jumps, illustrating that domain wall motion dominates

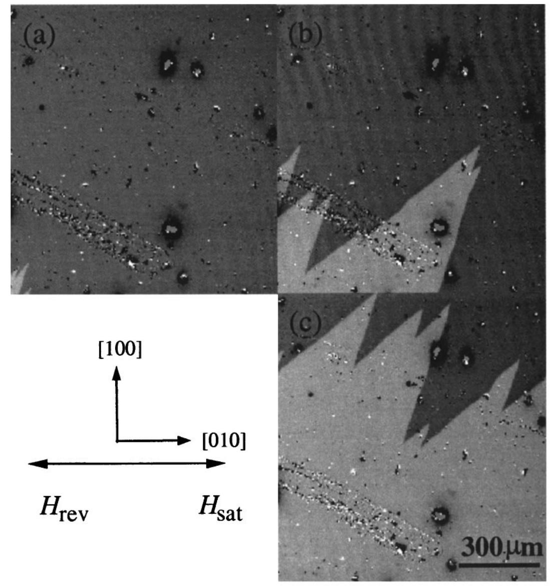

FIG. 4. Field-dependent evolution of domain structure at various fields in the 250 Å Fe/GaAs(001) film during the magnetization reversal process: (a) 24, (b) 29, and (c) 32 Oe.

the magnetization reversal. Such reversal behavior reveals a rapid dynamic response to a time varying external field in the low dynamic regime.

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