Magnetization reversal dynamics in epitaxial Fe/GaAs(001) thin films

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The magnetization reversal dynamics of epitaxial Fe films grown on GaAs(001) (thickness range 55–250 Å) has been investigated as a function of field sweep rate $\dot{H}$ in the range 0.01–160 kOe/sec using the magneto-optic Kerr effect. The hysteresis loop area A is found to follow the scaling relation $A \propto \dot{H}^{\alpha}$, with α in the range 0.032 ± 0.003–0.049 ± 0.003 at low sweep rates (below 6.3 kOe/sec) and 0.325 ± 0.006–0.399 ± 0.008 at high sweep rates (above 16 kOe/sec). The differing values of the exponent α are attributed to a change of the magnetization reversal process with increasing field sweep rate. Domain wall motion dominates the magnetization reversal at low sweep rates, but becomes less significant with increasing sweep rate. At high sweep rates, the variation of the dynamic coercivity H_c^* is attributed to domain nucleation dominating the reversal process. The results of magnetic relaxation studies for easy-axis reversal are consistent with the sweeping of one or more walls through the entire probed region (~100 μm). Domain images obtained by scanning Kerr microscopy during the easy cubic axis reversal process reveal large area domains separated by zigzag walls.
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I. INTRODUCTION

The magnetic reversal dynamics in thin film magnetism is of great interest to both theorists and experimentalists and is relevant to high-frequency device applications. The description of dynamic magnetic hysteresis has been a longstanding goal, ever since Steinmetz[1] found the empirical law that the hysteresis loop area A is given by $A \propto H_0^{1.6}$, where H_0 is the amplitude of an oscillating applied magnetic field. The increase in loop area with frequency reflects the fact that the system cannot respond instantaneously to the oscillating field.

Recent work[2–13,22] on the dynamic scaling of hysteresis behavior has focused on the area of the hysteresis loop, as a function of applied field amplitude and frequency. Theoretical predictions[2–6,13] and experimental results[7–11,22] have demonstrated that the loop area A follows the scaling relation

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

where α, β and γ are exponents that depend on the dimensionality and symmetry of the system. Specific values of the exponents are predicted for the various models, such as $\alpha = \beta = 1/2$ (Refs. 4, 5, 13) or $\alpha = 2/3$, $\beta = 1/3$, $\gamma = 1$ (Ref. 2) in a continuous spin system and $\alpha = \beta \approx 2/3$ (Ref. 6) or $\alpha = 0.7$, $\beta = 0.36$, $\gamma = 1.18$ (Ref. 3) in a mean-field Ising model. Even though there have been several recent efforts to describe the scaling behavior observed in ultrathin and thin ferromagnetic films (see Table I), e.g., Fe/Au(001),[7] Co/Cu(001),[8,10] Fe/W(110),[9] and polycrystalline $Ni_{80}Fe_{20}$ films,[11] based on the continuous spin system and two-dimensional (2D) Ising spin model, the values of universal dynamic exponents still remain controversial.[9–12]

Zhong and Zhang[5] proposed that, in the limit of low H_0 and Ω in Eq. (1), the field is a linear function of time t with a proportionality coefficient $H_0\Omega$ and thus $\alpha = \beta$. In this case, for a sweep rate $\dot{H}$ (dH/dt),[5,12]

$$H_0 = \dot{H}t, \tag{2}$$

TABLE I. Experimental dynamic scaling exponents in $A \propto H_0^{\alpha} \Omega^{\beta} T^{-\gamma}$ for various continuous thin films.

System	α	β	γ	Remarks	Reference
Fe/Au(001)	0.59 ± 0.07	0.31 ± 0.05		*In situ*	7
Co/Cu(100)	0.67 ± 0.01	0.66 ± 0.03		*In situ*	8
Fe/W(110)	~0.25	~0.06		*In situ*	9
Co/Cu(001)	~0.15	~0.02		*In situ*	10
$Cu/Ni_{80}Fe_{20}/Si(001)$	~0.9	~0.8	0.38 ± 0.01	*Ex situ*	11
$Au/Co/Au/MoS_2$	*~0.036 [a]			*Ex situ*	23
	*~0.177 [b]				
Cu/Co/Cu/Si(001)	*~0.02 [a]			*Ex situ*	27
	*~0.30 [b]				
Au/Fe/GaAs(001)	*~0.04 [a]			*Ex situ*	Present work
	*~0.4 [b]				

*$A \propto \dot{H}^{\alpha}$.
[a]At low sweep rates.
[b]At high sweep rates.

$$A \propto \dot{H}^{\alpha}. \tag{3}$$

While Jiang, Yang, and Wang[8] demonstrated that the exponent α is identical to β in Eq. (1), which is consistent with a mean-field Ising model, other experimental observations[7,9–11] are not compatible with this result. In real magnetic systems, the current key issues are the universality of hysteresis scaling behavior, the values of the exponents, and the possible correlation between α and β in Eq. (1).[9–12]

From a technological viewpoint, the Fe/GaAs system is of particular importance due to its potential for use in magnetoelectronic devices, e.g., as spin injection electrodes.[14,15] Although a number of studies of the static magnetization reversal process associated with the magnetic anisotropy in continuous epitaxial Fe/GaAs(001)[16–21] have been recently reported, to our knowledge, no dynamic studies of the magnetization reversal have yet been reported. As will be demonstrated in this paper, the dynamic magnetic hysteresis can reveal new information on the effect of the field sweep rate $\dot{H}$ on the dynamic magnetization reversal process.

We first present the results of an experimental investigation of the dynamic magnetization reversal in thin (55–250 Å) epitaxial Fe films grown on GaAs(001) with different magnetic anisotropy strengths. In order to clarify the microscopic magnetization reversal mechanism we have also investigated the magnetic relaxation process (magnetic aftereffect) using time-resolved magneto-optical magnetometry and used scanning Kerr microscopy to observe the microscopic reversal process.

II. EXPERIMENTS

The continuous Fe/GaAs(001) films were prepared in ultrahigh vacuum by electron-beam evaporation. The base pressure during growth was kept at 10^{-9} mbar and growth rate was 1 Å/min. Each was capped with 20-Å Au for *ex situ* measurements, which from electron energy-loss spectroscopy measurements was found to be sufficient to prevent oxidation of the Fe layer. *In situ* magneto-optic Kerr effect (MOKE) was used to study the evolution of the magnetic anisotropy, as the Fe films were grown so that films with different final anisotropy strength could be produced.[17,18]

We have previously studied the evolution of magnetic in-plane anisotropy in epitaxial Fe/GaAs(001) films as a function of the Fe layer thickness using *in situ* MOKE and *ex situ* Brillouin light scattering.[18,20,21] 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.[18]

Hysteresis loops were measured *ex situ* at room temperature using MOKE magnetometry with a probing laser beam spot of diameter ~2 mm. The applied magnetic field was driven by a time-varying current at a frequency between 0.01 Hz and 5 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.

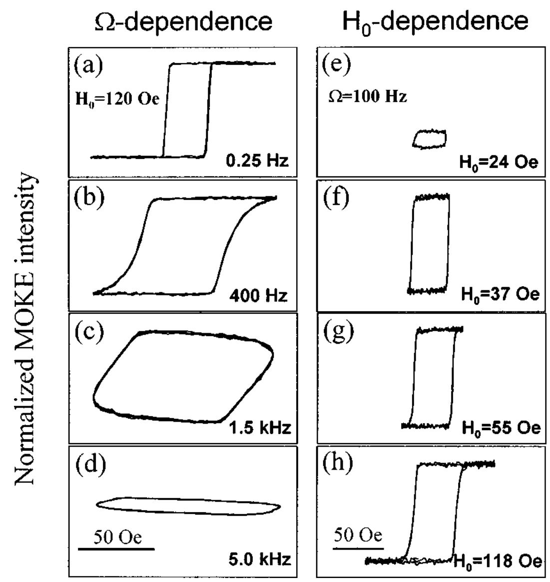

FIG. 1. Evolutions of frequency (Ω)-dependent and magnetic field amplitude (H_0)-dependent hysteresis loops for 55-Å Fe/GaAs(001) film.

III. RESULTS AND DISCUSSION

Figure 1 shows the evolution of frequency (Ω)-dependent and field-amplitude (H_0)-dependent hysteresis loops obtained from a 55-Å Fe/GaAs(001) film. The magnetic field was applied along the easy-axis direction of the film. It is obvious that the shape of the hysteresis loops varies with both the frequency (Ω) and field amplitude (H_0). A similar sequence of M-H loops is also observed from the 250-Å Fe/GaAs(001) film. For the Ω-dependent hysteresis loops in Figs. 1(a)–1(d), the shape of the loops is classified into four types, in qualitatively good agreement with theoretical predictions[2,3] and experimental results on other epitaxial systems.[7,8] In the frequency range 0.25–100 Hz the magnetization M exhibits an almost square loop. With increasing frequency the M-H loop develops rounded tips. As the frequency increases further, the M-H loops eventually can no longer be saturated with the available field, and then collapse gradually as predicted in theoretical work[2,3] [see Fig. 1(d)]. In contrast to the results of previous work on Fe/W(110) films,[9] no abrupt collapse of the M-H loop was observed at the critical frequency at which the dynamic coercivity (H_c^*) exceeds the applied field strength (H_0), $H_0 < H_c^*$.

On the other hand, for field-amplitude (H_0)-dependent hysteresis behavior, it is clearly seen that a critical threshold field (H_t) exists, corresponding to the dynamic coercive field (H_c^*), beneath which minor loops are observed, i.e., $M < M_s$. Representative loops are shown for the fixed frequency of 100 Hz in Figs. 1(e)–1(h). Once the applied field strength exceeds the threshold field, hysteresis loops which reach the saturation magnetization (M_s) are obtained, as shown with the loop at 55 Oe [Fig. 1(g)]. An abrupt transition occurs at the threshold field, after which the area increases slowly with H_0. However, whereas the amplitude-

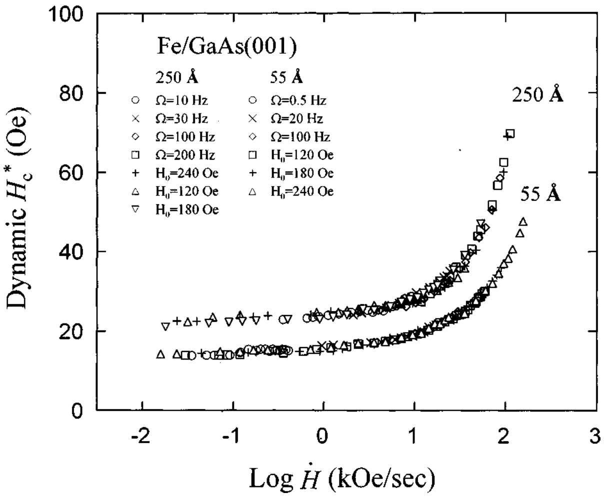

FIG. 2. Variation of dynamic coercivity (H_c^*) as a function of the logarithm of a field sweeping rate $\dot{H}(dH/dt)$ at various frequencies and field amplitudes for 55- and 250-Å Fe/GaAs(001) films.

and frequency-dependent hysteresis behaviors in both Fe/GaAs films are qualitatively consistent with previous work,[7–11,22] log-log plots of the loop area against Ω and H_0 (not shown) are found to be not linear for $H_0 > H_c^*$. This behavior is inconsistent with the theoretically predicted Ω- and H_0-dependent scaling behavior[2–6] and previous experimental results.[7–11,22]

In Fig. 2, we present the variation of dynamic coercivity (H_c^*) as a function of the logarithm of the field-sweeping rate at various frequencies and field amplitudes for the 55- and 250-Å Fe/GaAs(001) films. The dynamic coercivities (H_c^*) 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 Eq. (1).[2,7,11] We find that the dynamic coercivities (H_c^*) superimpose well for both films, respectively. Since the amplitude- and frequency-dependent H_c^* values superimpose, Fig. 2 demonstrates that the M-H loop area A is proportional to the sweep rate $\dot{H}$ in Eq. (3) and that the exponent α is identical to β in Eq. (1).[5,13] However, it is clear that the exponent α 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 a log-log plot of H_c^* against the field-sweep rate $\dot{H}$, the critical transition is found to occur at $\sim$16 kOe/sec 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.

A similar variation of H_c^* against a sweep rate $\dot{H}$ was observed in Au/Co(8Å)/Au/MoS_2 sandwiches with perpendicular magnetic anisotropy by Raquet, Mamy, and Ousset.[23] They have proposed an analytical expression for the magnetization, considering magnetic after-effects due to the competition between wall motion and nucleation processes. A sharp transition was observed in the variation of H_c^* versus the field sweep rate $\dot{H}$ at 180 kOe/sec. Below 180 kOe/sec, 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.[23] In the higher dynamic regime, the H_c^* variation was attributed to nucleation dominating processes.

A theoretical model proposed by Fatuzzo[24] for polarization reversal in ferroelectric systems, based on competing domain wall motion and nucleation processes, has been demonstrated to be consistent with the interpretation of the magnetization reversal in GdTbFe films[25] and Cu/Ni/Cu/Si(001) films.[26] The magnetization reversal process strongly depends upon a parameter k, given by

$$k = v/r_c R, \tag{4}$$

where r_c is the critical radius of a nucleus, v and R are the domain wall velocity and the nucleation rate, respectively, with

$$v = f_0 l_B \exp\left(-\frac{E_0^p - M_s V_B (H - H_c)}{k_B T}\right), \tag{5}$$

$$R = f_0 \exp\left(-\frac{E_0^n - M_s V_B (H - H_c)}{k_B T}\right), \tag{6}$$

where $f_0 = 10^9$ Hz is the attempt frequency, $E_0^{n,p}$ are the activation energies for domain nucleation and wall motion, respectively, M_s the saturation magnetization, V_B the Barkhausen volume, l_B Barkhausen length, and $k_B T$ the thermal energy. Domain wall motion and nucleation dominating reversals correspond to large and small k values, respectively. Raquet, Mamy, and Ousset[23] found $k = 9$ in the low dynamic regime and $k = 5 \times 10^{-3}$ in the high dynamic regime. Our results are in qualitatively good agreement with their experimental results and theoretical model.[23] In our case, a broad transition region occurs in the range 6.3–16 kOe/sec. We infer that this region corresponds to almost identical contributions due to wall motion and nucleation processes for the magnetization reversal, e.g., $k \approx 1$.

We obtained the values of the exponent α in Eq. (3) from the log-log plot of the variation of H_c^* versus the field-sweep rate $\dot{H}$ in two distinct dynamic regimes for the 55- and 250-Å Fe/GaAs(001) films. In the low dynamic regime (below 6.3 kOe/sec), the best fits give the values of $\alpha = 0.049 \pm 0.003$ and 0.032 ± 0.003 for the 55- and 250-Å Fe/GaAs(001) films, respectively. In the high dynamic regime (above 16 kOe/sec), the values of $\alpha = 0.325 \pm 0.006$ and 0.399 ± 0.008 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.[18,21] On the other hand, our values for the exponent α in Eq. (3) are quite similar to those found in Au/Co/Au/MoS_2 sandwiches:[23] $\alpha \approx 0.036$ in the low dynamic regime and $\alpha \approx 0.177$ in the high dynamic regime. Our values for the exponent α (in our case, $\alpha \approx \beta$) also agree with those of the exponent β found for Fe/W(110):[9] $\beta \approx 0.06$ up to 256 kOe/sec. In the low dynamic regime (domain wall motion mechanism) our values for the exponents are a factor of 10 different from those of theoretical predictions,[2–6] whereas in the high dynamic regime (nucleation mechanism) our values are similar to those of the theoretical predictions.[2–6] It is clear that this discrepancy arises from the fact that the theo-

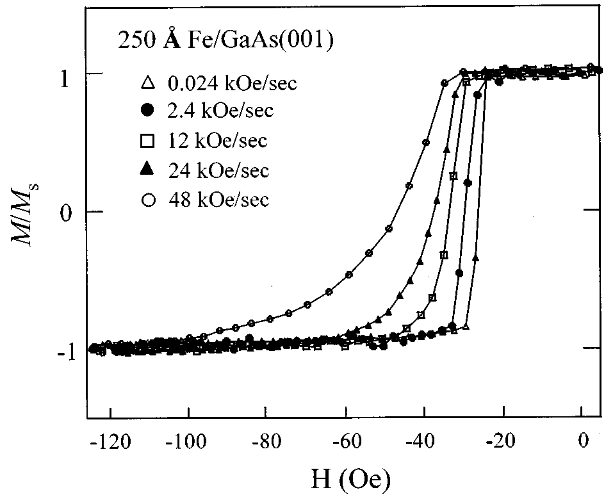

FIG. 3. Hysteresis loops of 250-Å Fe/GaAs(001) film in a negative magnetic field for several field-sweep rates $\dot{H}$.

retical predictions[2–6] do not consider the actual domain wall motion and nucleation processes which govern the magnetization reversal dynamics.

Our results support phenomenological models[23] that assume domain nucleation and wall motion process for the magnetization reversal, based on thermally activated relaxation. In Fig. 3, we present hysteresis loops of the 250-Å Fe/GaAs(001) film in a negative magnetic field for various field-sweep rates $\dot{H}$. It was observed that the sharpness of the hysteresis loop diminishes with increasing sweep rate $\dot{H}$. This behavior becomes pronounced upon increasing the sweep rates between 24 and 48 kOe/sec in Fig. 3. A similar behavior was also seen in the loops for the 55-Å Fe/GaAs(001) film. The shapes of the loops in the Fe/GaAs(001) films with varying field-sweep rate are qualitatively compatible with those of Au/Co/Au/MoS_2 sandwiches, which are in good accord with theoretical curves obtained from Ref. 23. Very recently, we also found similar dynamic behavior in an epitaxial Cu/Co/Cu/Si(001) structure,[27] which nevertheless differs from that of Co/Cu(001) (Refs. 8, 10) *in situ* (see Table I).

The phenomenological models[23–26,28] are based on demagnetizing time $t_{1/2}$ at which $M=0$, according to the following relation:

$$t_{1/2} \propto \exp\left(-\frac{M_s V_B (H-H_c)}{k_B T}\right). \quad (7)$$

The relaxation time $t_{1/2}$ is sensitive to the applied field H and increases with the applied field up to the saturation field H_s. We therefore extended our dynamic study to magnetic relaxation on the second time scale. The laser beam was focused to a spot of diameter approximately 100 μm and thus was sensitive to the magnetization vector aligned with an applied magnetic field averaged across this area. The samples were oriented such that the magnetic field was along the easy direction of the 55- and 250-Å Fe/GaAs(001) films.

Figure 4 shows (a) part of a MOKE loop measured at a sweep rate of 0.01 kOe/sec with the inset showing the sharpness of the loop ($H_c \approx 14$ Oe) and (b) magnetic relaxation curves for the 55-Å Fe/GaAs(001) film. For time $t<0$ and

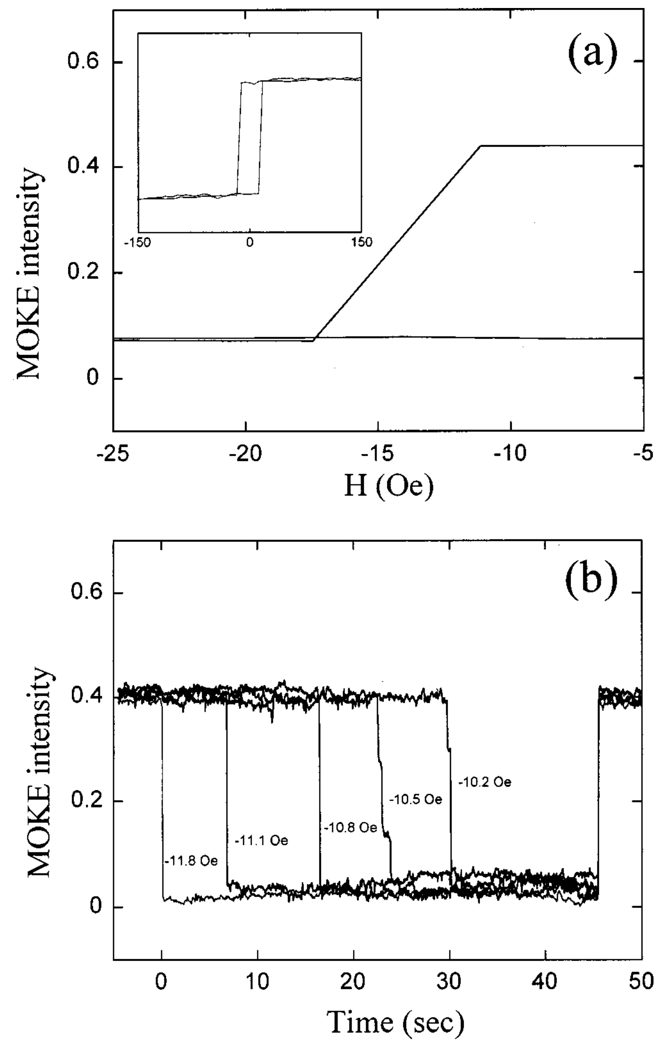

FIG. 4. (a) Part of a MOKE loop measured at a sweep rate of 0.01 kOe/sec and (b) magnetic relaxation curves of 55-Å Fe/GaAs(001) film under a constant reverse field. The inset of (a) shows the sharpness of the loop at low sweep rate. For time $t<0$ and $t>45$ sec the sample was saturated in the positive direction.

$t>45$ sec 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 differ from the results of previous work on GdTbFe films,[25] Cu/Ni/Cu/Si(001) films,[26] Au/Co/Au films,[28] and Fe/Ag(001) films.[29] In Cu/Ni/Cu/Si(001) films[26] and Au/Co/Au films[28] with perpendicular magnetic anisotropy, relaxation occurred by a smooth decay, whereas relaxation occurred by a series of discrete jumps in Fe/Ag(001) films,[29] where the laser beam spot was also ~100 μm. As reported in previous studies[17,20] 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,[29] that are spatially distributed on a few hundred μm. On the other hand, micron-scale Barkhausen jumps by micron-pinning sites are also visible in Fig. 4(b).

We also found that such a single jump was observed in relaxation curves for the 250-Å Fe/GaAs(001) film. The relaxation study shows that the magnetization develops through successive wall jumps of a few hundred μm at a constant field by thermal activation and that 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 $\dot{H}$. 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. 2), 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. A detailed discussion of magnetic relaxation in epitaxial Fe/GaAs(001) continuous films and patterned structures will be presented separately.[30]

Further direct evidence demonstrating that domain wall motion occurs in the low dynamic regime is presented in Fig. 5. 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 the [010] axis, a combination of an easy cubic direction and the hard uniaxial direction.[17,18] The area of each image is 1×2 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 μm, as observed in previous work.[31] The magnetization develops through discontinuous wall jumps, illustrating that domain wall motion dominates the magnetization reversal. Such reversal behavior reveals a rapid dynamic response to a time-varying external field in the low dynamic regime.

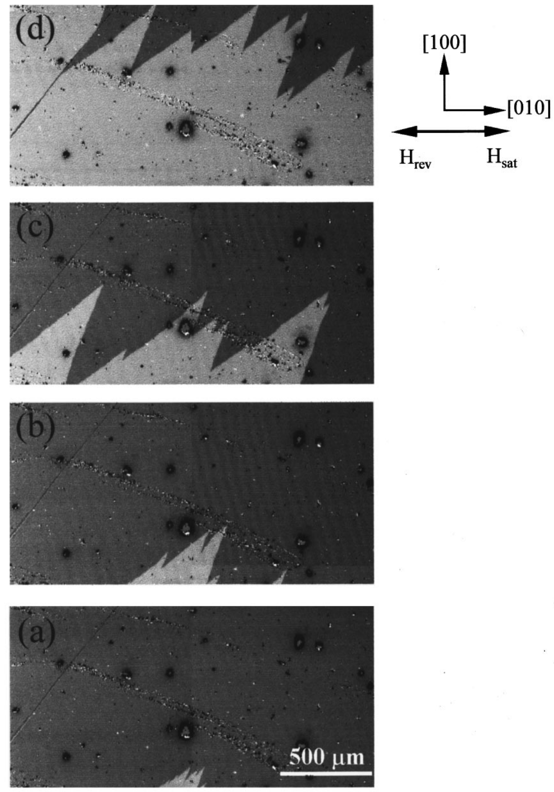

FIG. 5. Field-dependent evolution of domain structure at various fields in the 250-Å Fe/GaAs(001) film during the magnetization reversal for a field applied along the [010] axis, a combination of an easy cubic direction and the hard uniaxial direction: (a) 24 Oe, (b) 27 Oe, (c) 29 Oe, and (d) 32 Oe.

IV. CONCLUSION

We have studied the magnetization reversal dynamics of epitaxial Fe films grown on GaAs(001) (thickness 55 and 250 Å) in the field-sweep range 0.01–160 kOe/sec as a function of frequency and field amplitude using magneto-optic Kerr effect. Direct experimental evidence has been found for the variation of the magnetization reversal process with increasing field-sweep rate $\dot{H}(dH/dt)$ associated with the competition between domain wall motion and nucleation processes. Domain wall motion dominates the magnetization reversal in the low dynamic regime, but becomes less significant upon increasing the field sweep rate. In the high dynamic regime, the observed variation of dynamic coercivity H_c^* is attributed to predominant domain nucleation. Magnetic relaxation studies and domain observations reveal that large and abrupt wall displacements occur for the magnetization reversal. We conclude that the dynamic reversal process is dependent on the field-sweep rate and that domain wall motion is responsible for the dynamic response to a time-varying external field in the low dynamic regime. The small values of α in the low dynamic regime indicate that the dynamic response is rapid, in qualitative accord with the results of the relaxation studies.

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