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Magnetisation Reversal Dynamics in Epitaxial Fe/GaAs(001) and Fe/InAs(001) Thin Films

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We present the magnetisation 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 (MOKE). 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 α=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 magnetisation reversal process with increasing sweep rate. Domain wall motion dominates the magnetisation 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.

1. Introduction

The magnetisation reversal dynamics of magnetic thin films are of fundamental importance and are 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 magnetisation reversal in ultrathin ferromagnetic films [4-9] and mesoscopic structures [10, 11].

The dynamic behavior varies for different ultrathin film structures, and fcc Fe/Au(001) [4] and bcc Fe/W(110) [7] ultrathin films, for instance, are found to have very different dynamic properties, suggesting that the magnetic anisotropy may be important. Although the influence of the magnetic anisotropy on the static magnetisation reversal process has been studied in continuous epitaxial Fe/GaAs [11-16] and Fe/InAs [17, 18] systems, no studies of the magnetisation reversal dynamics have yet been reported. From a technological viewpoint, Fe/GaAs and Fe/InAs systems are of particular importance due to their potential for use in spintronic devices, *e.g.* as spin injection electrodes [17, 18]. 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). As will be demonstrated in this article, the dynamic magnetic hysteresis can reveal new information on the effect of the field sweep rate $\dot{H}$ on the dynamic magnetisation reversal process. We have also investigated the magnetic relaxation process (magnetic after-effect) using time-resolved magneto-optical magnetometry and have used scanning Kerr microscopy to observe the microscopic reversal process.

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2. Experiment

The continuous Fe/GaAs(001) [15, 16] and Fe/InAs(001) [17, 18] films were prepared in ultrahigh vacuum (UHV) by electron beam evaporation. The base pressure during growth was kept at ~6×10^{-10} mbar and growth rate was ~1 Å/min. Each film was capped with 20 Å Au for *ex-situ* measurements in order to prevent oxidation of the Fe layer. 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* magneto-optic Kerr effect (MOKE) and *ex-situ* Brillouin light scattering (BLS) [14, 16]. Magnetisation 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 monolayers 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 MOKE magnetometry with a probing laser beam spot of diameter ~2 mm, for fields applied along the global easy magnetisation axis [13, 16] close to the [001] direction for Fe/GaAs(001) and along the [001] direction (cubic easy axis) for Fe/InAs(001). These field directions give rise to a single step switching for the magnetisation reversal in both systems. The applied magnetic field was driven by a time-varying current at a frequency between 0.01 Hz and 5 kHz. A Hall probe 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 magnetisation 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.

3. Results and Discussion

Recent work [1-5, 7-9, 11] on the dynamic scaling of hysteresis behavior has focused on the area of the hysteresis loop (A) as a function of applied field amplitude (H_0) and frequency (Ω). Theoretical predictions [1-3] and experimental results [4, 5, 7-9, 11] have demonstrated that the loop area A follows the scaling relation

$$A \propto H_0{}^{\alpha}\Omega^{\beta}T^{-\gamma} \quad (1)$$

where α, β and γ are exponents that depend on the dimensionality and symmetry of the system. Although there have been several recent efforts to describe the scaling behavior observed in ultrathin and thin ferromagnetic films, based on the continuous spin system and 2D Ising spin model, the values of universal dynamic exponents still are under debate [7-10].

On the other hand, Zhong *et al.* [3] 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) [3],

$$H_0 = \dot{H}\, t, \quad (2)$$
$$A \propto \dot{H}^{\alpha}. \quad (3)$$

While Jiang *et al.* [5] demonstrated that the exponent α is identical to β from Eq. (3), which is consistent with a mean-field Ising model, other experimental observations [5, 7] 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).

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

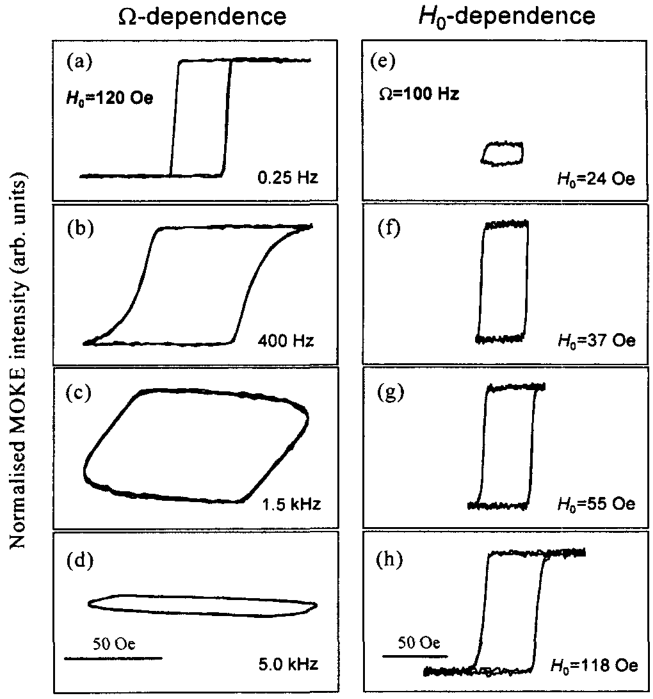

Fig. 1. Evolution of frequency (Ω)-dependent and magnetic field amplitude (H_0)-dependent hysteresis loops for 55 Å Fe/GaAs(001) film.

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 for the 250 Å Fe/GaAs(001) film. For the Ω-dependent hysteresis loops in Fig. 1(a)~(d), the loop shape can be classified into four types, in qualitatively good agreement with theoretical predictions [1-2] and experimental results on other epitaxial systems [7, 8]. In the frequency range 0.25~100 Hz, the magnetisation M exhibits an almost square loop. With increasing frequency (Ω) 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 [4, 5] [see Fig. 1(d)]. In contrast to the results of previous work on Fe/W(110) films [7] 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^*), below which minor loops are observed, *i.e.* $M < M_s$. Representative loops are shown for the fixed frequency of 100 Hz in Fig. 1(e)~(g). Once the applied field strength exceeds the threshold field, hysteresis loops which reach the saturation magnetisation (M_s) are obtained, as shown with the loop at 55 Oe [Fig. 1(f)]. An abrupt transition occurs at the threshold field, after which the area increases slowly with H_0. However, whereas the amplitude and frequency-

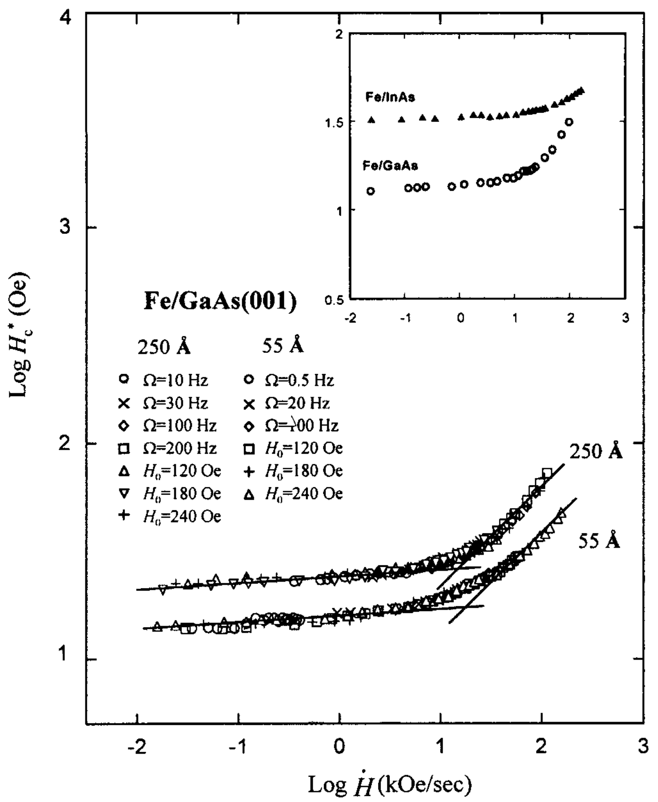

Fig. 2. Log-log plots of dynamic coercivity (H_c^*) against field sweeping rate $\dot{H}$ at various frequencies and field amplitudes for 55 Å and 250 Å Fe/GaAs(001) films. The lines are guides for the eye to distinguish two regions. The inset displays log-log plots of H_c^* against field sweep rate for the 250 Å Fe/GaAs(001) and 150 Å Fe/InAs(001) films.

dependent hysteresis behaviors in both Fe/GaAs films are qualitatively consistent with previous work [4, 5, 7-9, 11], 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 [1-3] and previous experimental results [4, 5, 7-9, 11].

In Fig. 2, we present the log-log plots of dynamic coercivity (H_c^*) against field sweep rate at various frequencies and field amplitudes for the 55 Å 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 Eq. (1). We find that the dynamic coercivities superimpose well for the 55 Å and 250 Å Fe/GaAs(001) films, respectively. Since the amplitude- and frequency-dependent H_c^* 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) [3]. 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/sec for the 55 Å 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 Fe/InAs(001) film, the corresponding transition from low to high values of α occurs at ~35 kOe/s as seen in the inset of Fig. 2.

A similar variation of H_c^* against a 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/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 [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. (3) from the log-log plot of the variation of H_c^* versus the field sweep rate in two distinct dynamic regimes for the 55 Å and 250 Å Fe/GaAs(001). In the low dynamic regime (below 6.3 kOe/sec), the best fits give the values of $\alpha \approx 0.05$ and 0.03 for the 55 Å and 250 Å Fe/GaAs(001) films, respectively. In the high dynamic regime (above 16 kOe/sec), the values of α=0.33 and 0.4 are obtained for the 55 Å 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 ~0.02 in the low dynamic regime and ~0.17 in the high dynamic regime. Our values for the exponent α of both systems in Eq. (3) 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/sec. 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]. It is clear that this discrepancy arises from the fact that the theoretical predictions do not consider the actual domain wall motion and nucleation processes that govern the magnetisation reversal dynamics. On the other hand, the critical transition from low to high values of α is believed to result from the competition between domain wall motion and nucleation processes [6] but is not well understood.

Our results support phenomenological models [6] that assume domain nucleation and wall motion process for the

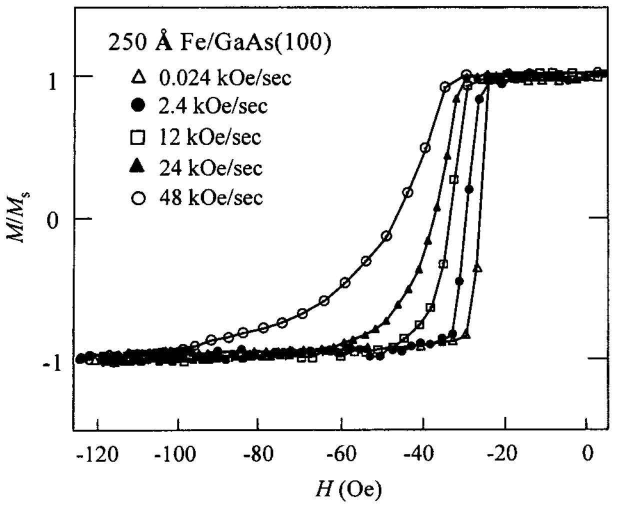

Fig. 3. Hysteresis loops of 250 Å Fe/GaAs(001) film in a negative magnetic field for several field sweep rates $\dot{H}$.

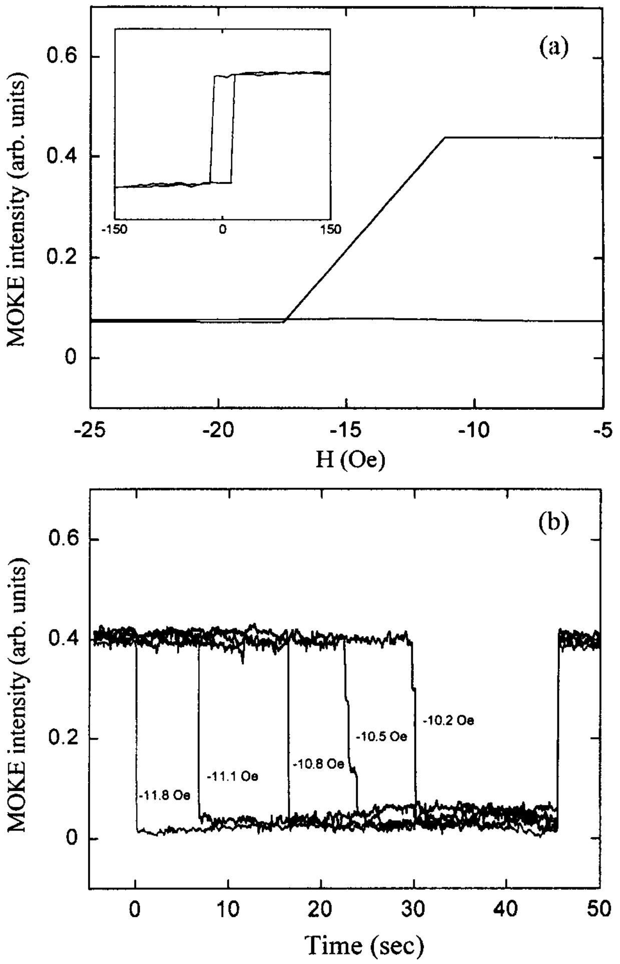

Fig. 4. (a) Part of a MOKE loop measured at a sweep rate of 0.01 kOe/sec and (b) magnetic relaxation curves of 55 Å Fe/GaAs(001) film under a constant reverse field. The inset of (a) shows the sharpness of the loop at low sweep rate. For time $t < 0$ and $t > 45$ seconds the sample was saturated in the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

magnetisation 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. 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/sec in Fig. 3. A similar behavior was also seen in the loops for the 55 Å Fe/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 sandwiches.

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 $t > 45$ seconds the sample was saturated in the positive direction. The averaged magnetisation 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 [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 ~100 μm. On the other hand, very recently, González *et al.* [23] found that relaxation in Co/Ni multilayers occurs a single step that corresponds to complete magnetisation reversal, which is compatible with our present results.

As reported in previous studies [13, 16] the magnetisation 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 are spatially distributed on a scale of few hundred mm. 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 magnetisation develops through successive wall jumps of a few hundred μm at a constant field by thermal activation and the domain walls expand rapidly through the sample, giving 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 magnetisation 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 magnetisation reversal.

Further direct evidence demonstrating that the domain wall motion occurs in the low dynamic regime is presented

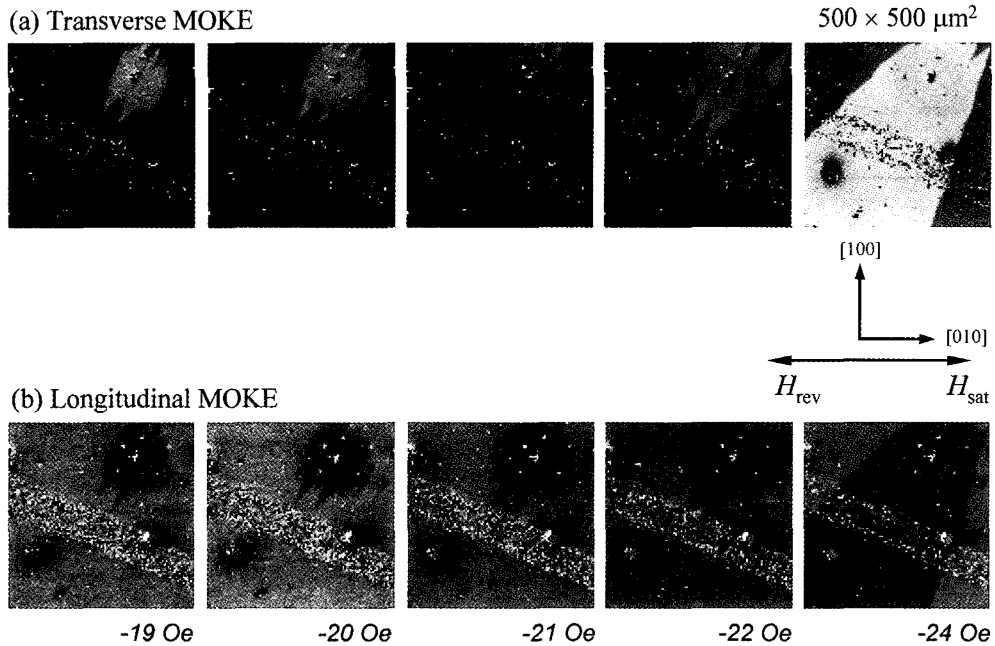

Fig. 5. A sequence of domain images showing nucleation and subsequent domain growth in the 250 Å Fe/GaAs(001) film during the magnetisation reversal.

in Fig. 5. We display the evolution of domain structure nucleation and subsequent domain growth in the 250 Å Fe/GaAs(001) film during the magnetisation reversal process for a field applied along [010] axis, a combination of an easy cubic direction and the hard uniaxial direction [13, 14]. Two MOKE signals, *i.e.* transverse and longitudinal MOKE, were obtained simultaneously by scanning Kerr microscopy [24]. In Fig. 5, it is clearly seen that a reversed domain nucleates at a defect when the magnetic field of ~17 Oe, which corresponds to the nucleation field (H_n), is applied. The reversed domain evolves with increasing field. It is evident that domain wall motion dominates the magnetisation reversal in Fe/GaAs(001) film, *i.e.* below the coercive field, nucleation is a rare event and is followed by subsequent domain growth [21]. A small increase of the field promotes domain growth *via* wall displacements over a few hundred μm, supporting the relaxation data. The magnetisation develops through discontinuous wall jumps, illustrating that domain wall motion dominates the magnetisation reversal. Such reversal behavior reveals a rapid dynamic response to a time varying external field in the low dynamic regime.

4. Conclusion

The magnetisation reversal dynamics of epitaxial Fe films grown on GaAs(001) and InAs(001) has been studied in the field sweep range of 0.01~160 kOe/sec as a function of frequency and field amplitude using magneto-optic Kerr effect (MOKE). Direct experimental evidence has been found for the variation of the magnetisation 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 magnetisation 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 magnetisation reversal.

We conclude that the dynamic reversal process in both systems 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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