Multijump Magnetic Switching in In-Plane Magnetized Ultrathin Epitaxial Ag/Fe/Ag(001) Films

R. P. Cowburn,* S. J. Gray, and J. A. C. Bland

Cavendish Physics Laboratory, Madingley Road, Cambridge CB3 0HE, United Kingdom

(Received 10 April 1997)

We predict and verify experimentally using magneto-optics a new magnetic switching mechanism involving *three* irreversible transitions in in-plane magnetized ultrathin epitaxial films. These transitions are mediated by the sweeping of 90° and 180° domain walls at three distinct applied field strengths. The prediction and observation of this new phenomenon shows that the complex domain processes which determine magnetic switching in such films can be accurately modeled by a single parameter which corresponds physically to the maximum pinning pressure that defects can exert on a domain wall. [S0031-9007(97)04522-5]

PACS numbers: 75.60.–d

An important property of ultrathin epitaxial magnetic films is the unusual magnetic switching processes they display [1]. In such processes the in-plane spin configuration changes abruptly at well defined applied magnetic field strengths. Because the internal exchange forces in ultrathin films give rise to a giant moment which is confined to the plane of the film by dipolar forces in the absence of perpendicular magnetic anisotropy, the switching processes correspond to abrupt transitions between near single domain states mediated by domain processes [2]. Recent work [3] has shown that the existence of stable configurations can be predicted from simple energy minimization but that the energetics of domain formation and propagation are crucial in understanding the spin reversal process. This is a complex problem but the reduced symmetry and the well defined anisotropies of ultrathin epitaxial magnetic structures provide an opportunity to study the various roles of domains and to test model predictions.

For example, Moschel *et al.* [4] have shown that the atomic scale roughness, which is present in all real films, can greatly affect the spin reversal by creating at the edges of the atomic steps sites at which domains can be nucleated and pinned. Smith *et al.* [5] have shown that the energy of domain formation significantly affects the coercivity behavior of epitaxial structures with cubic anisotropy. In the spin reorientation transition, it has recently been shown that the role of domain formation is central in understanding the thickness and temperature dependent transition [6,7]. In general, all of these processes can be understood in terms of a competition of energies, but the energetics of the domain structures are crucial.

A simple model has been successfully developed by Cowburn *et al.* [8] in which a well defined domain wall pinning energy is considered along with the anisotropy energy surface in order to determine the energetics of the switching process. The model predictions are in agreement with the experimental observation [8–10] that spin reversal in the model magnetic system of epitaxial bcc Fe can proceed via an intermediate state in which the spins are oriented at 90° to the initial and final remanent directions. The hysteresis loop of such a switching process shows rather strikingly *two* irreversible transitions at two distinct applied field values.

In this Letter, we predict a new reversal process in materials with 4-fold symmetric anisotropy involving *three* abrupt jumps between four stable spin configurations, each aligned close to a magnetic easy axis, and present experimental results which confirm the prediction. This finding clarifies our understanding of the role of the domain energetics in the spin reversal process and provides a new phenomenon which offers possibilities for controlling the magnetic reversal behavior of thin and ultrathin films.

Figure 1 summarizes the anisotropy and applied field geometry which will be used in this Letter. A weak in-plane uniaxial anisotropy K_u is assumed to superimpose the strong cubic magnetocrystalline anisotropy. The sample is also assumed to be magnetically soft, such that it switches at applied fields considerably smaller than the cubic anisotropy field. Coherent rotation of the spins [11] is thus ignored in the model. It will also be assumed that domain wall (DW) propagation as opposed to domain

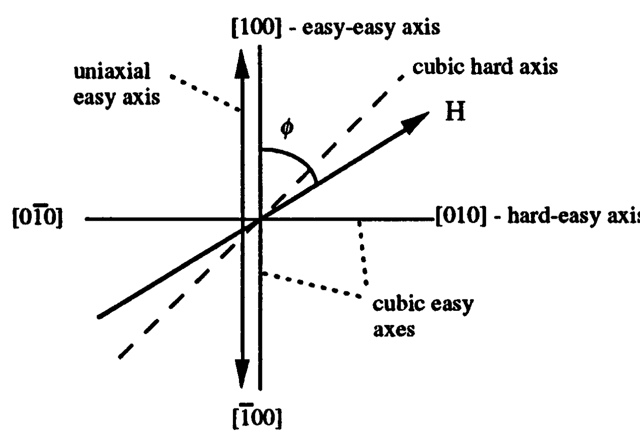

FIG. 1. The anisotropy and applied field geometry used in this Letter.

 0031-9007/97/79(20)/4018(4)$10.00

nucleation is the limiting factor in the magnetic switching process; this has been found in other systems to be a characteristic of high quality films [12]. These three assumptions were found to be justified in a previous experimental study [8].

We consider the stable single domain spin states with the spins all aligned along one of the magnetic easy axes [100], [010], [$\bar{1}$00], and [0$\bar{1}$0]. It was shown in our previous paper [8] that the total energy density of these four states under the action of an applied field H can be written as

$$\begin{aligned} E_{[\bar{1}00]} &= MH\cos\phi\,, \\ E_{[100]} &= -MH\cos\phi\,, \\ E_{[0\bar{1}0]} &= K_u + MH\sin\phi\,, \\ E_{[010]} &= K_u - MH\sin\phi\,, \end{aligned} \tag{1}$$

where M is the saturation magnetization and ϕ is the applied field orientation. We also showed that for fields applied close to [100], magnetic switching is of the 1-jump variety, where the system makes a direct transition from [$\bar{1}$00] to [100] by the sweeping of 180° DW's. When, however, the field was applied close to [010], we showed that the more unusual 2-jump switching was energetically more favorable, where the system jumps from [0$\bar{1}$0] to [100] at a field called H_{c1} and then from [100] to [010] at a higher field called H_{c2}. Both of these transitions were mediated by the sweeping of 90° DW's. We now pose the question: Would it ever be possible to observe the sequence [0$\bar{1}$0] → [$\bar{1}$00] → [100] → [010] instead? Such a sequence would be mediated by the sweeping of 90° DW's at the first jump, then by 180° DW's at the second jump, and finally by 90° DW's again at the third jump. If it is to occur, then both of the first two jumps of the 3-jump route must be energetically preferred to the first two jumps of the corresponding 2-jump route.

Following the method which we described in Ref. [8], we say that each transition occurs when the energy density advantage ΔE in doing so is equal to the energy density cost in propagating a DW of the relevant type, ε_{90° or ε_{180°. ε is a phenomenological parameter of dimension energy density which describes the pinning of a DW. Physically, it corresponds to the maximum pinning pressure that defects can exert on a DW. No assumption has been made about the microscopic nature of the pinning. ΔE can be found from the difference of the two relevant equations (1). As an example, let us consider the energetics of a transition from the [$\bar{1}$00] oriented single domain state to the [100] state. From Eqs. (1), the energy density advantage in making the transition is $\Delta E = 2MH\cos\phi$, which will be mediated by the propagation of a 180° DW. Hence, at the jump field H_c, $2MH\cos\phi = \varepsilon_{180^\circ}$, and, therefore, $H_c = \varepsilon_{180^\circ}/(2M\cos\phi)$.

Turning now to compare a 3-jump switching route with a 2-jump route, the first 3-jump step is [0$\bar{1}$0] → [$\bar{1}$00] which competes with a 2-jump step [0$\bar{1}$0] → [100]. When two possible transitions compete, we assume that the one which can occur at the lower field will be the one which is observed. The relevant energy equations are

$$\begin{aligned} \Delta E &= K_u + MH(\sin\phi - \cos\phi), && \text{for the 3-jump route}, \\ \Delta E &= K_u + MH(\sin\phi + \cos\phi), && \text{for the 2-jump route}. \end{aligned} \tag{2}$$

Comparing the two resulting jump fields gives the first step of 3-jump switching to be feasible only if

$$\frac{\varepsilon_{90^\circ} - K_u}{\sin\phi - \cos\phi} \le \frac{\varepsilon_{90^\circ} - K_u}{\sin\phi + \cos\phi} \qquad 45^\circ < \phi < 90^\circ. \tag{3}$$

This condition is satisfied when $\varepsilon_{90^\circ} \le K_u$.

The second step in the 3-jump switching route is [$\bar{1}$00] → [100] which competes with the 2-jump step [$\bar{1}$00] → [010]. The relevant energy equations are

$$\begin{aligned} \Delta E &= 2MH\cos\phi, && \text{for the 3-jump route}, \\ \Delta E &= MH(\cos\phi + \sin\phi) - K_u\,, && \text{for the 2-jump route}. \end{aligned} \tag{4}$$

3-jump switching is thus only feasible for this step if

$$\frac{\varepsilon_{180^\circ}}{2\cos\phi} \le \frac{\varepsilon_{90^\circ} + K_u}{\cos\phi + \sin\phi} \qquad 45^\circ < \phi < 90^\circ \tag{5}$$

$$\Rightarrow 45^\circ < \phi \le \tan^{-1}\left(\frac{K_u}{\varepsilon_{90^\circ}}\right). \tag{6}$$

In Ref. [8] we showed experimentally that $\varepsilon_{180^\circ} \approx 2\varepsilon_{90^\circ}$. Physically this comes about because in a cubic system a 180° DW is equivalent to two 90° DW's very weakly coupled together. The weak coupling comes from the fact that the spins are crossing a cubic easy axis at the coupling point, and so vary very slowly in space. Each 90° segment of the 180° DW thus acts essentially independently. The depinning condition for each segment is $MH = \varepsilon_{90^\circ}$, which must coincide with the depinning condition for the entire 180° wall, which happens when $2MH = \varepsilon_{180^\circ}$. Eliminating MH from these two equations gives $\varepsilon_{180^\circ} = 2\varepsilon_{90^\circ}$. This equality has been used in Eq. (6).

Equation (6) describes the conditions which are required in order to observe 3-jump switching. The condition derived from Eq. (3) for the first step to be feasible is already ensured by Eq. (6). Equation (6) has been used along with the conditions described in Ref. [8] for 1- and 2-jump switching to describe a complete phase diagram (Fig. 2), where the number of jumps expected during switching is given as a function of the applied field orientation ϕ and the ratio $K_u/\varepsilon_{90^\circ}$. One sees immediately that 3-jump switching is only possible for the case $K_u > \varepsilon_{90^\circ}$ and for fields applied moderately close to the cubic hard axis ($\phi = 45°$).

In order to test the prediction of a new 3-jump switching mechanism, we have grown by molecular beam epitaxy an ultrathin epitaxial Fe layer. The sample consisted of a GaAs(001) substrate plus a 10 monolayer (ML) seed layer of Fe on which were grown ~200 ML of Ag(001). The Fe layer of interest to this study was grown next with a wedge shaped thickness profile allowing Fe thicknesses in the range 0–13 ML to be studied. A further 10 ML of Ag were then deposited, followed by a 5 ML antioxidation Cr cap. Full details of the growth and structural and magnetic characterization have already been published [7,8]. We were able to deduce K_u and ε_{90° from a hysteresis loop measured along a [010] axis. Details of this technique have also already been published [8]. K_u and ε_{90° were found to be thickness dependent, and that the condition $K_u > \varepsilon_{90^\circ}$ was satisfied for Fe thicknesses in the range 7.5 to 9.5 ML. Hysteresis loops were, therefore, measured transverse to the applied field direction by the longitudinal magneto-optical Kerr effect [13] for different field orientations at an Fe thickness of approximately 9 ML. Figure 3 shows two of the resulting loops. The upper loop was taken with the field applied at $\phi = 74° \pm 3°$, and 2-jump switching resulted. Similar loops have been observed by other workers [10]. The lower loop was taken with the field applied at $\phi = 51° \pm 3°$ and shows as predicted 3-jump switching. This is the first observation of such a switching mechanism.

$K_u/\varepsilon_{90^\circ}$ was measured as 1.3 ± 0.1 from a hysteresis loop measured at the [010] axis. Figure 2, therefore, predicts 3-jump switching for fields applied within the range $45° < \phi < 52°$. Experimentally, 3-jump switching was observed in the range $45° < \phi < 52.5°$ ($\pm 3°$ systematic uncertainty in all measurements) from the hard axis, which is in good agreement.

The experimental confirmation of the predicted 3-jump switching, which we have reported in this Letter, shows that magnetic switching in high quality thin and ultrathin films can be described by DW mediated transitions between stable single domain states: The magnetic system

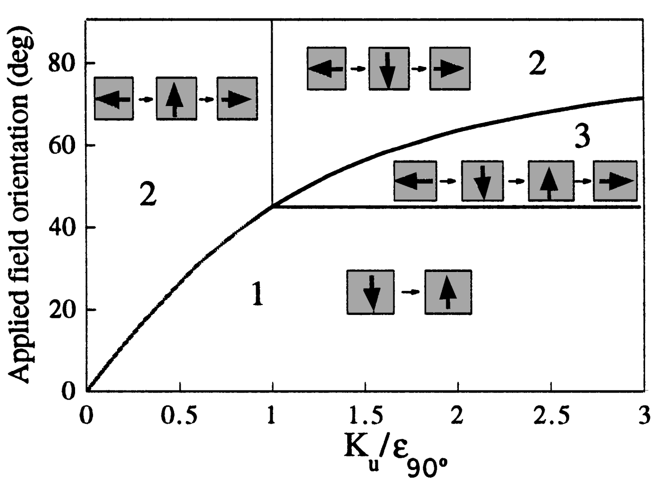

FIG. 2. A predicted magnetic phase diagram showing the number of irreversible jumps expected during spin reversal as a function of the applied field orientation ϕ and the ratio of the in-plane uniaxial anisotropy K_u to the pinning energy of a 90° DW ε_{90°. The spin states are shown schematically in shaded boxes.

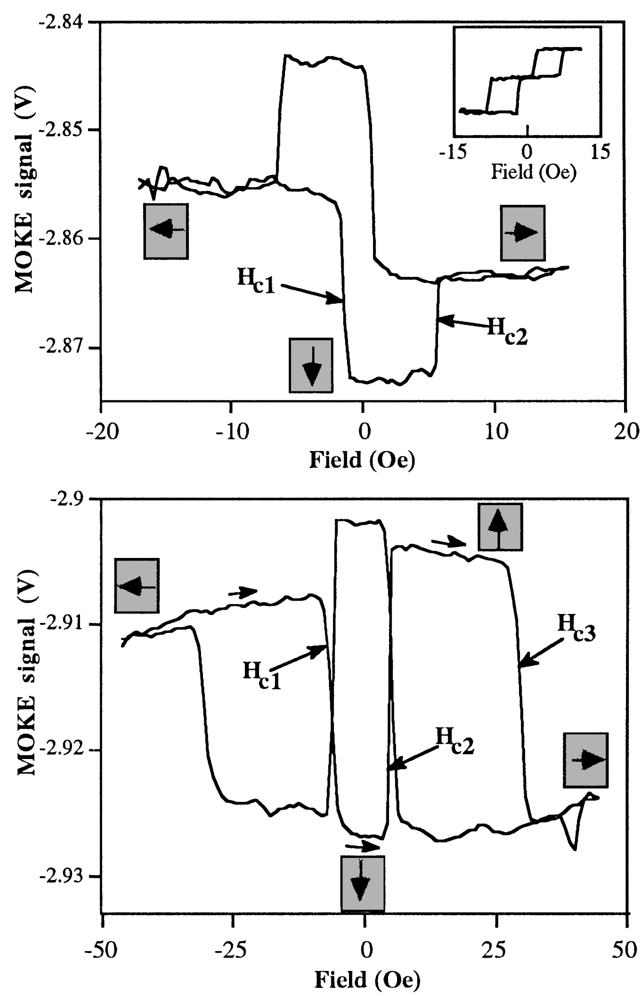

FIG. 3. Hysteresis loops measured transversely to the applied field direction for the field applied at $\phi = 74° \pm 3°$ (upper panel) and $\phi = 51° \pm 3°$ (lower panel). The spin states are marked at different points on the loops in shaded boxes. These two loops show, respectively, 2-jump switching and 3-jump switching at field directions, which are in good agreement with the theoretical phase diagram of Fig. 2 for $K_u/\varepsilon_{90^\circ} = 1.3$. Inset of the top panel is for comparison, a 2-jump loop measured *parallel* to the applied field direction.

will remain in one of these states until the energy advantage in making a transition to a lower energy state outweighs the losses in doing so. Most importantly, this result shows that it is possible to model the domain processes involved in this transition accurately by a well defined parameter ε which corresponds physically to the maximum pinning pressure which sample defects can exert on a DW. The question of the precise microscopic origin of pinning in such films still remains open, although our ability to describe the pinning pressure experienced by the DW is an important step towards a full microscopic understanding. This work also opens up the possibility of controlling magnetic switching by artificially modifying the energy level of these states by anisotropy and applied fields. We stress that only very small perturbations to the energy levels are required for dramatic results; the uniaxial anisotropy in our samples which produced the new 3-jump switching route was only $\sim 1\%$ of the bulk cubic anisotropy strength. Very sensitive magnetic field sensors could be produced by allowing the external field to modify the energy levels of certain states. Alternatively, the ability to control the transitions between discrete states could be used to implement magnetic logic for a new generation of nonvolatile digital signal devices. Equally, supposedly "pure" cubic systems may exhibit unexpected magnetic switching if tiny additional anisotropies are spuriously present.

In conclusion, we have sought in this Letter to understand more fully the domain processes which determine the magnetic switching behavior of thin and ultrathin epitaxial films. We have predicted and observed experimentally in an ultrathin bcc Fe film a new switching mechanism involving *three* irreversible transitions. These are mediated first by 90° DW's, then by 180° DW's, and finally by 90° DW's, each at a distinct applied field value. While, on the one hand, this shows that even supposedly simple magnetic materials like iron can exhibit complex switching routes, the prediction and subsequent verification of this new phenomenon confirms that magnetic switching in in-plane magnetized thin and ultrathin epitaxial ferromagnets can be accurately described by DW mediated transitions between stable single domain states. On a microscopic level, we have shown that DW's experience a well defined maximum pinning pressure. These findings, on the one hand, are an important step towards a complete microscopic understanding of DW pinning, and, on the other hand, open up the possibility of artificially controlling the switching by modifying the energy of these states by anisotropy or external magnetic fields.

This work was supported by the U.K. EPSRC and DRA (U.K.).

*Current address: Nanoscale Science Group, Department of Engineering, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, United Kingdom.

[1] W. Weber, C. H. Bach, A. Bischof, D. Pescia, and R. Allenspach, Nature (London) **374**, 6525 (1995); R. Kergoat, J. Miltat, T. Valet, and R. Jerome, J. Appl. Phys. **76**, 7087 (1994); G. J. Sinclair, G. A. Jones, P. J. Grundy, and K. O'Grady, J. Phys. D **28**, 1785 (1995); M. F. Gillies, J. N. Chapman, and J. C. S. Kools, J. Appl. Phys. **78**, 5554 (1995).

[2] J. L. Robins, R. J. Celotta, J. Unguris, D. T. Pierce, B. T. Jonker, and G. A. Prinz, Appl. Phys. Lett. **52**, 1918 (1988); E. Gu, J. A. C. Bland, C. Daboo, M. Gester, L. M. Brown, R. Ploessl, and J. N. Chapman, Phys. Rev. B **51**, 3596 (1995).

[3] C. Daboo, R. J. Hicken, E. Gu, M. Gester, S. J. Gray, D. E. P. Eley, E. Ahmad, J. A. C. Bland, R. Ploessl, and J. N. Chapman, Phys. Rev. B **51**, 15 964 (1995).

[4] A. Moschel, R. A. Hyman, A. Zangwill, and M. D. Stiles, Phys. Rev. Lett. **77**, 3653 (1996).

[5] E. R. Smith *et al.* (unpublished).

[6] A. Berger and H. Hopster, Phys. Rev. Lett. **76**, 519 (1996).

[7] R. P. Cowburn, J. Ferré, J.-P. Jamet, S. J. Gray, and J. A. C. Bland, Phys. Rev. B **55**, 11 593 (1997).

[8] R. P. Cowburn, S. J. Gray, J. Ferré, J. A. C. Bland, and J. Miltat, J. Appl. Phys. **78**, 7210 (1995).

[9] J. M. Florczak and E. Dan Dahlberg, Phys. Rev. B **44**, 9338 (1991); C. Daboo, R. J. Hicken, D. E. P. Eley, M. Gester, S. J. Gray, A. J. R. Ives, and J. A. C. Bland, J. Appl. Phys. **75**, 5586 (1994); J. R. Childress, R. Kergoat, O. Durand, J.-M. George, P. Galtier, J. Miltat, and A. Schuhl, J. Magn. Magn. Mater. **130**, 13 (1994).

[10] J. Chen and J. L. Erskine, Phys. Rev. Lett. **68**, 1212 (1992).

[11] E. C. Stoner and E. P. Wohlfarth, Philos. Trans. R. Soc. London A **240**, 74 (1948).

[12] J. Pommier, P. Meyer, G. Pénissard, J. Ferré, P. Bruno, and D. Renard, Phys. Rev. Lett. **65**, 2054 (1990).

[13] J. Ferré and G. A. Gehring, Rep. Prog. Phys. **47**, 513 (1984).