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LETTER TO THE EDITOR

Thermally activated and field sweep rate-dependent switching in epitaxial Fe/GaAs(001)

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Abstract

The dynamic coercive field H_c^* for a 15 nm epitaxial Fe/GaAs(001) film is measured by magneto-optic Kerr effect for sinusoidal applied fields in the frequency range 1–2300 Hz. A dip in H_c^* is found at the cross-over from low dynamic regime to high dynamic regime, which occurs at ∼400 Hz at room temperature. The same measurement at successively lower temperatures extending down to 80 K reveals that the dip shifts to lower applied field frequencies as the temperature is reduced. This indicates both that the dip is real and that thermal activation is important in the reversal dynamics. Further, the existence of the dip implies that there are two distinct time-scales associated with the reversal process. We speculate that these time-scales correspond to domain nucleation and wall motion, respectively. An existing model for magnetization reversal dynamics in ultra-thin magnetic layers is adapted to describe the measurements empirically.

Ferromagnet/semiconductor heterostructures such as Fe/GaAs(001) are currently being researched extensively due to their potential for use in magneto-electronic applications [1, 2]. Clearly an understanding of the reversal dynamics of such systems is vital to the successful development of ultra-fast magneto-electronic devices. Previous experiments to probe the reversal dynamics of Fe/GaAs(001) have measured sweep rate-dependent ('dynamic') coercivity under sinusoidally varying external fields, with field frequency typically in the range 0.01 Hz–5 kHz [3, 4]. On a double logarithmic plot of dynamic coercivity versus field frequency, there are two distinct regions in which approximately linear behaviour occurs. At low frequency the dynamic coercivity is an almost constant function of frequency (low dynamic regime) for films thicker than the exchange length. At a critical (cross-over) frequency, f_c, the coercivity starts to increase more quickly as a function of frequency (high dynamic regime). The aim of this work is to examine the effect of temperature on the two dynamic regimes.

A Kerr magnetometer (laser spot size ∼1 mm) was used to collect dynamic hysteresis (M–H) loops across an applied field frequency range of 1–2300 Hz at various sample

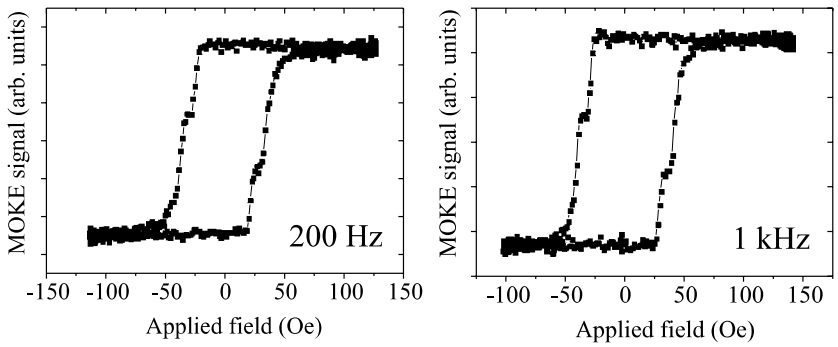

Figure 1. Easy-axis hysteresis loops for 15 nm Fe/GaAs(001) at 250 K and at two values of applied field frequency, measured by Kerr magnetometry. The two-jump switching, evident as a small plateau near $M = 0$, is a result of the inequivalence of the cubic hard axes.

temperatures of 80–300 K. The sample was 15 nm epitaxial Fe/GaAs(001) grown by molecular beam epitaxy in ultra-high vacuum ($<10^{-9}$ mbar) at 35 °C and oriented with the time-varying field $H(t) = H_0 \sin(\omega t)$ along one of the cubic in-plane easy axes $\langle 100 \rangle$. In epitaxial Fe/GaAs(001) there is a surface-induced uniaxial anisotropy along [110] which is thickness dependent and causes an inequivalence in the cubic hard axes for 15 nm Fe [5]. This inequivalence leads to two-jump switching of the magnetization when the field is applied along the in-plane $\langle 100 \rangle$ directions. Despite the two-jump switching, this particular field orientation was chosen in order to be able to properly saturate the Fe film across the entire frequency range. For this sample the cubic in-plane easy-axis loops saturate at a low applied field compared to those obtained with other field orientations. Hence $\langle 100 \rangle$ orientation enables best use to be made of the electromagnet, where the attainable field is increasingly limited at high frequency. The photodetector ($M(t)$) and Hall probe ($H(t)$) signals were captured on a 400 MHz-bandwidth oscilloscope. The bandwidth and response time of the photodetector were 30 MHz and ∼30 ns, respectively, representing a significant improvement over earlier experiments (e.g. [3]) and sufficient to ensure that the photodetector current was an accurate measure of the dynamic Kerr signal, $M(t)$, at the highest applied field frequencies used in the experiment. Hysteresis loops were recorded after averaging over typically a few hundred cycles of the applied field.

Representative hysteresis loops for the 15 nm Fe/GaAs(001) sample measured at 250 K by Kerr magnetometry are shown in figure 1. The loop measured at a field frequency of 1 kHz is perceptibly broader than that measured at 200 Hz. The values of dynamic threshold field H_t^* (the point at which reversal begins, measured from either the top-left or bottom-right corner of a loop) were extracted from the loops and plotted as a function of frequency. This is shown in figure 2 for six temperatures in the range 80–300 K. For this sample, in the frequency range studied, the dynamic threshold field evolves with frequency in the same way as the dynamic coercive field of either the first (1) or the second (2) jump. Hence H_t^* rather than H_{c1}^* or H_{c2}^* is chosen to represent the reversal. Equally, in this experiment the dynamic threshold field and dynamic coercive field(s) are interchangeable.

The data shows two regions where there is an approximately linear relationship between H_t^* and $\log(f)$: these are the low dynamic regime (the flat section of data at low frequencies) and high dynamic regime (the upward-sloping section at high frequencies), respectively, which have been seen in previous work [3]. However, in this case, the improved bandwidth of the photodetector means that the Kerr signal is captured accurately even for fast field-driven

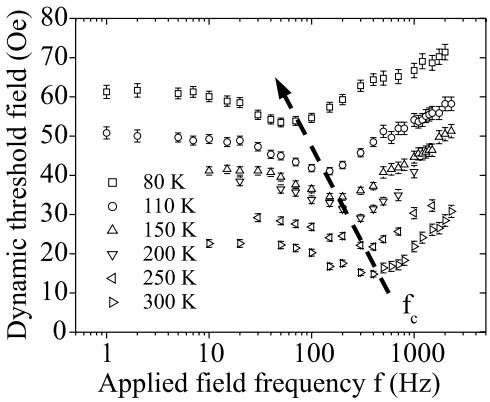

Figure 2. The dynamic threshold field H_t^* as a function of the logarithm of applied field frequency for 15 nm Fe/GaAs(001) at temperatures in the range 80–300 K. Although H_t^* does increase with falling temperature, as shown, for clarity the data-sets are spaced more widely in the vertical direction than is actually the case. The shift of f_c (the cross-over between low and high dynamic regimes) to lower frequencies with reduction in temperature is highlighted by a dashed line.

switching, and a 'dip' in threshold field is recorded at the cross-over, f_c, between the low and the high dynamic regime. The finding that the dip is present at all temperatures and at a range of frequencies suggests that it is a real effect and not an experimental artefact. That the dip occurs at lower frequencies as the temperature is reduced suggests that thermal activation is important in the reversal dynamics. If reversal proceeds by thermal activation of domain nucleation and wall depinning processes, one would expect to wait longer for such activation at reduced temperature. A model for reversal dynamics of ultra-thin ferromagnetic films by Ruiz-Feal *et al* [6] implies that the (quasi-static) sample switching time determines the frontier between the low and high dynamic regimes. The cross-over into the high dynamic regime occurs when the applied field changes on this timescale. If we assume that domain wall motion is very rapid relative to the thermal activation of domain nucleation and wall depinning, i.e. that the time for thermal activation is the greater part of the total switching time, then we can conclude that the high dynamic regime ensues when the applied field changes on the time-scale for thermal activation. Since this time-scale increases as the temperature falls, the shift of f_c to lower frequencies with a reduction in temperature can, at least qualitatively, be well understood.

A useful model for the analysis of a frequency-dependent coercive field is that of Raquet *et al* [7]. They developed an expression to describe the magnetization of MoS_2/Au/Co/Au sandwiches as a function of applied field that accounts for nucleation and wall motion processes and directly incorporates physical parameters such as Barkhausen volume and temperature. The main result in the context of the present work is that thermally activated domain wall motion is the main reversal process in the low dynamic regime, whereas domain nucleation dominates the reversal in the high dynamic regime. We infer similar behaviour for our 15 nm Fe/GaAs(001) film.

To the best of our knowledge, no model currently exists that predicts the dip we observe for this sample at the cross-over from low to high dynamic regime, but according to Raquet *et al* we can expect a competition here between domain wall motion and domain nucleation processes. That the dynamic coercive field decreases with frequency before increasing with further increasing frequency implies that there are two time-scales associated with the reversal process, and we speculate that these correspond to the wall motion and domain nucleation

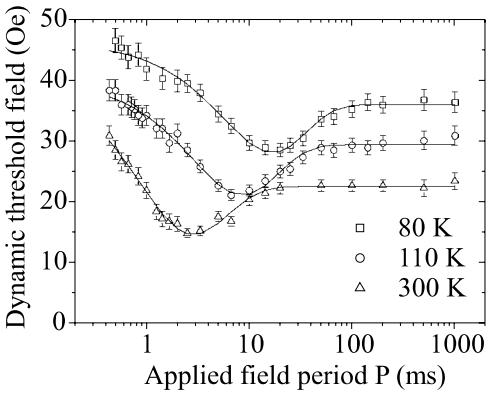

Figure 3. The fit to dynamic threshold field (H_t^*) data for 15 nm Fe/GaAs(001) at temperatures in the range 80–300 K.

processes. The sum of the two time-scales is the total switching time, i.e.

$$\text{nucleation time } (\tau_n) + \text{propagation time } (\tau_p) = \text{total switching time } (\tau). \tag{1}$$

The 'propagation time', τ_p, includes both wall depinning and motion between pinning sites. Using the idea of competing domain processes, we find that the following empirical expression is a good fit to the experimental dynamic threshold field data:

$$H_t^* = H_{t,P\to 0}^* \exp\left(\frac{-P}{P_n}\right) + H_t\left(1 - \exp\left(\frac{-P}{P_p}\right)\right). \tag{2}$$

In this expression, P is the drive field period, H_t is the value to which H_t^* tends at high P (the low-frequency threshold field), and $H_{t,\ P\to 0}^*$ is the value to which H_t^* tends as P tends to zero. P_n and P_p are the critical field periods for nucleation and propagation, respectively. The critical periods correspond to those frequencies where the field begins to be swept fast enough through the threshold field H_t that it changes by a measurable amount on the appropriate 'intrinsic' time-scale τ_n or τ_p. The first exponential becomes important as P approaches the same order of magnitude as P_n, and controls the onset of the high dynamic regime. The second exponential becomes important as P approaches the same order of magnitude as P_p, and controls the onset of the dip in H_t^*. The relation between critical periods $P_{n(p)}$ and intrinsic time-scales $\tau_{n(p)}$ is not straightforward because it depends on sweep rate which, for a sinusoidal applied field, varies with time.

As the field begins to be driven at high enough frequency to change on the propagation time-scale τ_p, we infer from the Raquet model that the domain walls start to be dynamically driven through the film. We suggest that forced depinning from nucleation sites at these frequencies gives the dip in threshold or coercive field. At still higher frequencies, the field changes on the nucleation time-scale τ_n. This change occurs before the magnetization changes significantly, so beyond the dip the threshold field increases steadily as a function of frequency.

The expression (2) fitted well to all temperature-dependent dynamic threshold field data. Figure 3 shows the fit to the data at 80, 110 and 300 K. Values of H_t, P_n and P_p can be obtained from the fitting procedure.

We need to relate P_n and P_p to the intrinsic time-scales τ_n and τ_p, respectively. We start by assuming that the threshold field H_t is the same for both nucleation and propagation processes. Then we note that there will be a time at which H_t is reached that is dependent on

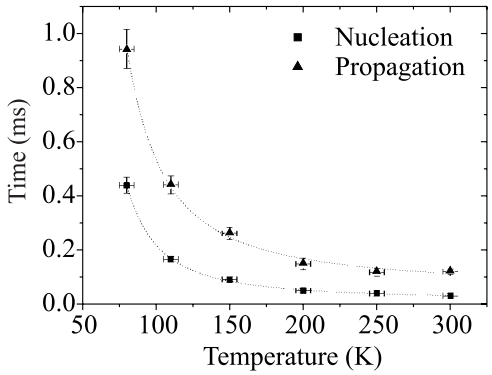

Figure 4. Time-scales τ_n (nucleation) and τ_p (propagation) for 15 nm Fe/GaAs(001) as a function of temperature T, obtained from fits to dynamic threshold field data using expression (2). The dotted curves are guides to the eye.

Table 1. Time-scales τ_n and τ_p and corresponding values of absolute temperature T for 15 nm Fe/GaAs(001).

T (K)	τ_n (μs)	τ_p (μs)
80	440 ± 30	942 ± 72
110	168 ± 11	443 ± 33
150	94 ± 7	264 ± 22
200	53 ± 8	151 ± 21
250	43 ± 5	121 ± 14
300	34 ± 2	123 ± 9

field frequency and amplitude:

$$t_{n(p)} = \frac{P_{n(p)}}{2\pi} \sin^{-1}\left(\frac{H_t}{H_0}\right). \tag{3}$$

The sweep rate at this moment in time is

$$\dot{H}_{n(p)} = \frac{2\pi H_0}{P_{n(p)}} \cos\left(\frac{2\pi t_{n(p)}}{P_{n(p)}}\right). \tag{4}$$

Finally we can find τ_n and τ_p from the following:

$$\tau_{n(p)} = \frac{H_t}{\dot{H}_{n(p)}}. \tag{5}$$

Table 1 and figure 4 show the time-scales as a function of temperature. Both τ_p and τ_n increase as the temperature is reduced: this is the signature of thermal activation.

The values of τ_n and τ_p correspond well with the total switching time, τ, measured from Kerr signal traces for 15 nm Fe/GaAs(001) at room temperature. This data is presented in figure 5 and shows that τ is an increasing function of field period. Faster sweep rates speed up the nucleation and propagation processes and reduce the overall switching time, as predicted by the Fatuzzo–Labrune equations for nucleation rate and wall velocity [8]. Hence τ, τ_n and τ_p are dynamic quantities, and it is important to note that the values of τ_n and τ_p only apply at specific values of applied field period, namely P_n and P_p, respectively.

The fit to the experimental data in figure 5 is the following:

$$\tau = aP^b, \tag{6}$$

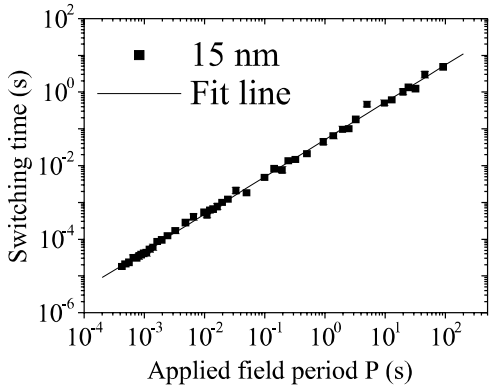

Figure 5. Switching time, τ, as a function of applied field period P for 15 nm Fe/GaAs(001) at room temperature, obtained from measurements of averaged Kerr signal step widths in the time domain. Error bars are approximately the same size as the data points.

where $a = 0.054 \pm 0.007$ and $b = 1.00 \pm 0.03$. Substituting the critical nucleation period $P_n = 1.11$ ms into this expression, a value of $\tau = 60$ μs is obtained. This is 57% larger than τ_n at this temperature (34 μs). However, under our assumptions the total switching time is the sum of the nucleation time and the propagation time ($\tau = \tau_n + \tau_p$). τ_p at this field period P_n is unknown, but it is certainly much less than that at the critical propagation period $P_p = 4.04$ ms (123 μs), since τ_p is an increasing function of period. Hence the total switching time measured directly from the Kerr signal traces (τ) and that obtained from the fitting procedure ($\tau_n + \tau_p$) are comparable. The same procedure with P_p yields a total switching time $\tau = 218$ μs. τ_p at this temperature is 123 μs and, adding τ_n (>34 μs at this frequency), this value of τ is approached.

In summary, the expression (2) assumes the existence of two time-scales for reversal corresponding to each of the domain processes of nucleation and wall propagation. When the field changes on the time-scale of the domain propagation, τ_p, the domain walls are assumed to depin faster from nucleation sites and to be driven continuously through the film by the field. Consequently, around the critical field period for propagation, P_p, the dynamic coercive field decreases as a function of frequency (the dip at the transition between low and high dynamic regime). When the field changes on the time-scale of domain nucleation, τ_n, or faster, the dynamic coercive field increases with frequency (high dynamic regime). It should be noted that the expression will equally well fit data where there is no dip in the transition region. In this case τ_p and τ_n are sufficiently close in value that the second term in the expression does not take effect.

Measurements of the dynamic coercive field in thin epitaxial Fe/GaAs(001) at a range of temperatures have shown that the cross-over from low to high dynamic regime is temperature-dependent and is characterized by a dip in the experimental data. The temperature dependence indicates that the dip is real and that thermal activation is important in the reversal dynamics. Two time-scales connected to the reversal process are implied, and are linked to domain nucleation and wall motion, respectively. Using an empirical adaptation of the Raquet model, the dynamic coercive field data has been fitted. The fitting expression accounts for the competing dynamics of the domain nucleation and wall motion at the cross-over from low to high dynamic regime.

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