Real time dynamics in epitaxial Fe(100) disks

S. Gardiner,[a] J. Rothman, Y. B. Xu, M. Tselepi, and J. A. C. Bland
Cavendish Laboratory, University of Cambridge, CB3 0HE Great Britain

Y. Cheng and F. Rousseaux
CNRS, L2M, 196 Av. Henri Ravera, 92225 Bagneux, France

Real time resolved scanning Kerr microscopy has been used to study the switching dynamics of 50 μm diameter epitaxial Fe(100) disks. The measurements were performed using a sinusoidal sweeping field with a sweep rate of $dH/dt = 10$ kOe/s. By performing repetitive one-shot measurements, we have mapped the statistical fluctuations and the probability distribution of characteristic switching parameters as the switching instant t_0, and the switching speed, V. We observe a substantial difference in the parameters estimated from the average of several measurements compared to the parameters extracted from the probability distributions. This illustrates the potential risks of using averaging techniques in dynamic measurements, in addition to the loss of the statistical information. The disks were found to display an inhomogeneous switching, which is believed to be caused by defect damped motion of the domain walls and a inhomogeneous distribution of defects. [DOI: 10.1063/1.1357144]

Interest in dynamic magnetization reversal has been increasing in recent years, due to growing technological pressure as well as the development of experimental techniques permitting access to dynamic regimes of the switching. Industrial needs have focused the main activity in this field on achieving the highest sampling speed possible, using stroboscopic and averaging measurement techniques to achieve time resolution down to a few picoseconds.[1–3] Hence, these techniques allow the limit of conventional dissipative switching to be probed in the nanosecond range. However, it should be stressed that the understanding of the magnetodynamics in ''slower'' dynamic regimes, i.e., below the gigahertz range, is still far from complete. This is illustrated by recent studies of dynamic scaling of the coercive field in thin ferromagnetic films.[4] In addition, these techniques discard information on the stochastic nature of the switching, which is fundamental for both the understanding of the switching itself and for applications, where reproducibility is crucial. In this study, we show that the stochastic nature of the magnetic reversal process cannot be ignored. Using real time-resolved scanning Kerr microscopy (RTSKM) we have accessed the local distribution of switching parameters, which allows consideration of models based on stochastic material parameters (e.g., distribution of defects or domain-wall pinning sites).

We present a proof-of-concept study of 50 μm diameter epitaxial Fe dots that show complex reversal behavior. These results illustrate the utility of RTSKM and emphasize that many-average studies can be misleading.

The real time-resolved scanning Kerr microscope measurements were performed using a modified static-field scanning Kerr microscope, optimized for maximum Kerr signal (rather than maximum resolution) with a spatial resolution of 2 μm and a time-resolution of 1 ms. The magnetic switching was induced by an electromagnet driven by a sine-wave signal generator through a 1 kW audio amplifier. By using high speed photodiodes and a magnet that can produce a range of sweeping rates we observe the Kerr signal in real time, storing many of these ''single-shot'' measurements to analyze the statistics of reversal which occur at one spot on the sample.

A typical one-shot measurement can be characterized by the moment in time when the magnet switches, the switching instant, or the time it takes for the region probed by the focused laser to switch, the switching time. The interpretation of these parameters depends on the switching mechanism in the sample. The most simple hypothesis is that the system reverses by a domain nucleation-propagation mechanism and the signal results from a single domain wall passing through the laser spot. In that case the switching instant will depend on the history of propagation of the domain walls and the switching time will be a measure of the inverse of the domain-wall speed. In the case where the laser beam has a Gaussian profile, the function that describes the MOKE intensity signal will be the error function (erf)

$$\mathrm{MOKE} \propto \int_{-\infty}^{\infty} dy \int_{-\infty}^{x_{\mathrm{wall}}} dx \exp\left[-\frac{(x-x_0)^2+(y-y_0)^2}{2\sigma_{\mathrm{beam}}^2} \right]$$
$$= \mathrm{erf}\left(\frac{x_{\mathrm{wall}}-x_0}{\sigma_{\mathrm{beam}}\sqrt{2}} \right) = \mathrm{erf}\left(\frac{v_{\mathrm{wall}}t-x_0}{\sigma_{\mathrm{beam}}\sqrt{2}} \right) = \mathrm{erf}\left(\frac{t-t_0}{T\sqrt{2}} \right),$$

where $t_0 = x_0/v_{\mathrm{wall}}$ which we refer to as the switching instant, $T = \sigma_{\mathrm{beam}}/v_{\mathrm{wall}}$ which is the switching time, and σ_{beam} is the standard deviation of the Gaussian beam. For convenience, we also define the speed parameter to be $V = 1/T$,

[a]Electronic mail: smg34@hermes.cam.ac.uk

which, in the case of single domain wall propagation, is proportional to the domain wall speed. By using the earlier function to describe each one-shot measurement, it is possible to estimate the local distribution of the switching parameters. We note that even if the actual switching might be more complex, involving multiple domain walls or nucleation processes, the estimated parameters will still characterize the switching, even though they will not have a straightforward correspondence to, for example, the domain wall speed.

This function was therefore used for fitting the averaged MOKE signal and the single-shot measurements and it gave a reliably close fit. However, for the analysis of large datasets we substituted the hyperbolic tangent function (tanh), which behaves similarly to the error function and allows identical parameters to be extracted,[5] but the time taken to fit was significantly less.

RTSKM measurements were performed on 50 μm epitaxial Fe(100) disks, patterned from a continuous epitaxial magnetic film of 100 ML of bcc Fe(100) grown on GaAs(100).[6] The film was capped with 30 Å of Au to prevent oxidation. The sample was patterned using x-ray lithography and ion milling into 50 μm circular dots in a square array. The spacing between each dot and its nearest neighbor was twice its diameter to avoid interdot dipole interactions.[7] Scanning electron microscopy images were taken to ensure sample quality. It is expected that such an Fe/GaAs film would show bulk-like cubic anisotropy with a small uniaxial component.[8] In this case, a postpatterning study using a static field SKM showed that the cubic and uniaxial anisotropies were nearly equal. The uniaxial axis is aligned with the cubic hard axis, meaning the cubic hard axes were unequal. The easy axis switching field close to the perimeter of the dots ($H_c = 50$ Oe) is observed to be substantially less than in the center ($H_c = 83$ Oe) even though a study showed that there was little difference in the anisotropy strength between the two regions.

For the dynamic studies, the field was applied along the uniaxial easy axis, parallel to the (010) direction. The field frequency was 10 Hz and by altering the amplitude of the field we were able to vary the sweep rate at the switching instant in a range $dH/dt = 10-50\,\mathrm{kOe\,s^{-1}}$. In this article we will restrict the discussion to the results for a sweep rate of 10 kOe/s which is, compared to other dynamic studies of Fe/GaAs systems,[4] a relatively low field-sweeping rate. We performed a total of 50 samples per location and the sample was scanned with a step size of 2 μm.

In Fig. 1 we present the result of a one-shot measurement (a) which we compare with the mean MOKE signal formed from the 50 single-shot samples (b), both which were obtained in the center of the Fe disk. Also shown in the figures are fits to the data. We conclude first that the fit using the simple model is good for both plots; second, we observe that there is a significant difference in both the ''speed'' parameter ($V = 1/T$) and the switching instant (t_0). This illustrates that there are indeed fluctuations in these parameters, implying that there is a need to characterize their specific distribution in order to gain a complete understanding of the dynamics.

The 50 single-shot field sweeps made at each point allowed an analysis of the distribution of switching parameters. In Fig. 2, we present maps of the average single-shot switching speed $\langle V \rangle$ [Fig. 2(b)], switching instant $\langle t_0 \rangle$ [Fig. 2(e)] and their estimated standard deviations, [Fig. 2(c)] and [Fig. 2(f)], respectively. For comparison, we also present maps of fits to averaged the MOKE signals $\langle M(t) \rangle$, $V_{\langle M \rangle}$ [Fig. 2(a)] and $t_{0\langle M \rangle}$ [Fig. 2(d)]; we note that the t_0 maps are

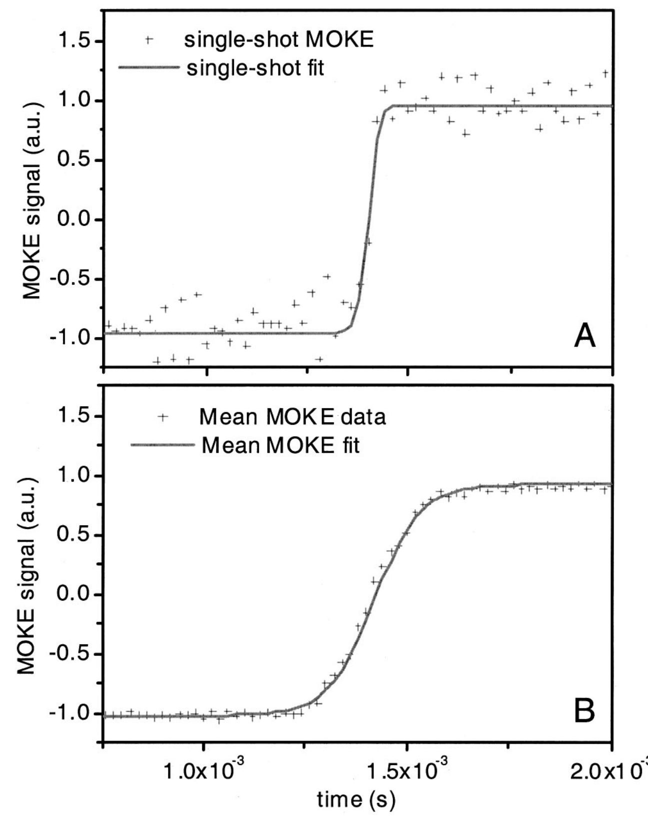

FIG. 1. Example MOKE data from the Fe dot sample showing differences between single-shot and averaged MOKE measurements; Fig. 1(a) shows a single-shot measurement (points) and a fit to the data (line), Fig. 1(b) shows an 50-sweep average MOKE signal (points) and a fit to the data (line).

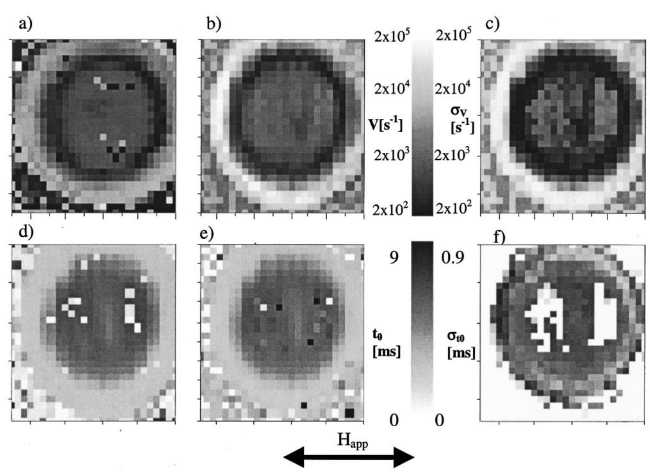

FIG. 2. Maps of fitted switching parameters from the 50 μm Fe dots: (a) and (d) are switching speed (V) and switching time (t_0), respectively, calculated using the averaged-MOKE signal, (b) and (e) are V and t_0, respectively, from the single-shot measurements, (c) and (f) are the standard deviations on V and t_0, respectively, from the population of single-shot fits.

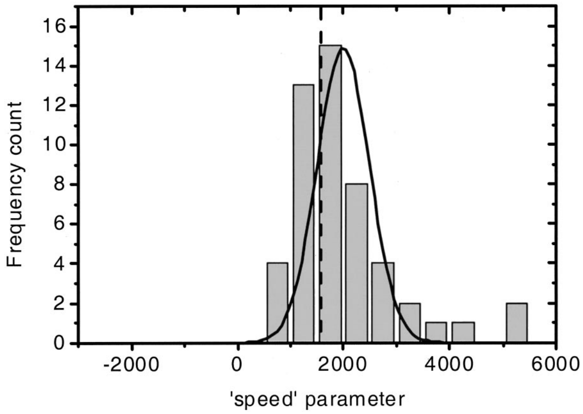

FIG. 3. Histogram showing the distribution of fitted switching speeds taken from the central region of the maps in Fig. 2. Solid curve is a Gaussian representing the arithmetic mean and standard deviation and dashed line shows the speed parameter extracted from the averaged-MOKE signal.

virtually identical, whereas the maps of V show large differences in magnitude if not in spatial distribution. This can be expected because a fluctuation in speed will not influence the average value of the switching instant t_0, whereas a fluctuation in t_0 will add to the average switching time, T in the mean MOKE signal, and hence, influence $V_{\langle M\rangle}$. This gives evidence of the errors that are introduced from an analysis based on the mean magnetization $[\langle M(t)\rangle]$ only. By comparing the different maps in Fig. 2, it is possible to evaluate how the different values and fluctuations are correlated. In particular, for an increasing value in the average switching instant $\langle t_0\rangle$ and of the switching speed $\langle V\rangle$, we observe an increase in their fluctuations. In some regions the value $\langle t_0\rangle$ also appears to be correlated to the average value of the switching speed $\langle V\rangle$, which indicates that the speed is increasing with time and therefore with the value of the applied field.

A more quantitative understanding of the switching is provided from the local distributions of the parameters. In Fig. 3, we show the histogram obtained from the fitting to 50 single-shot measurements taken from the central region of the maps given in Fig 2. We note that the distribution is poorly represented by a Gaussian distribution with the arithmetic mean and standard deviation (solid curve). Also, we can see the difference between the mean of the fits $\langle V\rangle$ and the fit to the averaged MOKE signal, $V_{\langle M\rangle}$ (dashed line), as mentioned earlier. The estimation of the local distribution functions of the switching parameters as a function of sweep rate provides a complete set of observations which will help to refine theoretical models of dynamic switching. In particular, they are very suitable for a direct comparison with functional integration approaches, which have been proposed for soft magnetic materials and allows the computation of the probability distribution and its time evolution of, for example, the domain wall speed.[9]

Finally, the analysis of the different maps in Fig. 2 also provides information which helps us to understand the inhomogeneous switching observed in the Fe disks. The nucleation of domains begins on the left side of the dot; they sweep around the edge and then after a waiting time of approximately 3 ms, the inner region switches as well. This appears to be due to a pinning of the reversed domains, approximately 5–10 μm from the edge of the disk. Considering the maps of V we see from the single-shot measurements that the sample is divided into three regions: the outer ring where switching speeds are very high ($V\sim 10^4\,\mathrm{s}^{-1}$), the central region where speeds are intermediate ($V\sim 10^3\,\mathrm{s}^{-1}$) and the pinning zone between them where V is very low ($\sim 10^2\,\mathrm{s}^{-1}$). Supposing single domain wall propagation and a spot size of about 2 μm, the domain wall speed can be estimated to be ranging between 0.1 and 100 mm/s. These speeds are significantly lower than those predicted for freely propagating walls, i.e., ~ 100 m/s/Oe,[10] which indicates that the walls are slowed down by defects. From the variation of the switching speeds Fig. 2(b), we conclude that the behavior is due to inhomogeneously distributed defects in the film, possibly originating from to the patterning, which results in the observed switching.

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