Barkhausen Effect in a Garnet Film Studied by Ballistic Hall Micromagnetometry

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Abstract. The movement of a micrometer-size section of a single domain wall in a uniaxial garnet film was studied using a ballistic Hall micromagnetometer at 77 K and 4.2 K. The wall propagated in characteristic Barkhausen jumps, with the jump size distribution following the power-law relation, \( P(S) \propto S^{-\tau} \). The scaling exponent, \( \tau \), was measured as 1.14 ± 0.05 at both temperatures. This is the first measurement of this exponent using such a device, and the first for a single wall in a two-dimensional sample with a low concentration of pinning centres, in which the magnetization of the sample is perpendicular to the surface.

1. Introduction
The Barkhausen effect is the name given to the discrete, non-reproducible propagation of magnetic domain walls due to an applied field. The walls remain stationary for a varying period of time, before shifting to a new stable configuration in a single jump, or a series of jumps (commonly referred to as an “avalanche”). It was discovered in 1919 [1], and has been the focus of much recent work in connection with the general theory of critical phenomena, and the proposal that the Barkhausen effect exhibits self-organized criticality (SOC). This idea reflects the fact that the effect can be produced in a ferromagnetic material, without requiring specific tuning of conditions [2, 3, 4, 5, 6, 7], and that the size, \( S \), and duration, \( T \), of the avalanches display scaling behaviour, and thus follow power laws. The power law for jump size can be expressed by

\[
P(S) = S^{-\tau} f(S/S_0),
\]

where \( S_0 \) is the cutoff limit, and \( \tau \) is the scaling exponent, which is linearly dependent on the applied magnetic driving rate.

We chose to study the Barkhausen effect exhibited by a single domain wall in a thin ferromagnetic garnet film sample as this provides a system that is close to an ideal two-dimensional system. These garnet samples display strong uniaxial anisotropy, so the magnetization lies in only two opposite directions. This leads to a series of domains of alternating magnetization direction perpendicular to the sample surface, which are separated by a system of 180° domain walls. An example of such a domain structure can be seen in Fig. 1, which shows a section of the garnet film used, pictured using transmitted polarized light, and showing the tendency for the walls to form parallel to each other. The sample has a thickness of 10 \( \mu \)m, and a total surface area of \( \sim 1 \) mm². Another useful property of garnet films is that they can be
manufactured with a very low level of defects, and most of those present are point-like pinning centres (length scale on the order of nm).

In addition to producing the simple domain arrangement shown in Fig. 1, the strong anisotropy prevents deformation of the domain wall away from the axis perpendicular to the sample surface, and so only one-dimensional vaulting is possible. Due to the low level of defects present in the film, at sufficiently low temperatures the walls tend toward greater rigidity, restricting the vaulting further. Using the CZDS model [4], one would expect the Barkhausen statistics to be characteristic of a two-dimensional domain wall system, as long-range dipolar interactions and the demagnetizing field are present as a result of the perpendicular magnetization, whereas this is not the case for the two-dimensional samples used in most of the previous literature, e.g. [10, 11, 12], as a result of the in-plane magnetization. The combination of these properties produce a system that is ideally suited for investigating the scaling exponents.

As an alternative to the previous methods used to study these samples, we describe here our use of ballistic Hall micromagnetometry, a novel technique in the study of the Barkhausen effect. As a result of the convenient and sensitive detection of local magnetic flux that this technique offers, it has been used to study a wide range of other phenomena, including magnetization switching behaviour in mesoscopic superconductors [14, 15], and in single and arrayed nanostructures [16, 17], the annihilation of domains [18], and the coercivity of a single pinning centre [19]. Although Hall probes have been used to study the Barkhausen effect previously, this used much larger intersection areas, and so was not operating in the ballistic regime [20]. Our technique is closely related to that using a standard Hall cross layout, but with \( \mu \text{m}-\text{scale} \) conducting channels, and a conducting material with very high mobility and a low level of defects. The particular device we used, shown in Fig. 1, was a GaAs/InGaAs heterostructure formed into 5 adjacent crosses, three with a channel width of 1.5 \( \mu \text{m} \), and the remaining two with channels of 1.0 \( \mu \text{m} \), making them an order of magnitude smaller than the average domain width. This has a 2DEG, with an electron density of \( 3.4 \times 10^{-12} \text{ cm}^{-2} \), embedded 60 nm below the surface, which acts as the conducting region. The high mobility means that transport along the conducting channels of the device is ballistic. This form of Hall probe was found to be the most suitable for our work [21].

When the ballistic current is passed down a channel of the Hall crosses, variation in the external magnetic field passing through the central square intersection produces a corresponding measurable response in the Hall resistance, \( R_{xy} \), given by the equation

\[
R_{xy} = \alpha_H \langle B \rangle R_H
\]

where \( \alpha_H \) is a coefficient relating to the geometrical design of the Hall cross (1.2 for our device) [22], and \( \langle B \rangle \) is the magnetic field averaged over the Hall cross intersection; this simplifies
Figure 2. The main graph shows a typical section of a single sweep with three labelled Hall resistance values corresponding to the 3 domain wall positions shown on the inset. The inset is a representation of several positions of a domain wall moving past the intersection or sensitive zone of a Hall cross, with this zone shown shaded. The large arrow represents the direction of motion of the wall. The size of jump, $S$, as used in this paper, is defined as shown, for two arbitrary positions of the wall.

the treatment of data as the precise field configuration across the intersection need not be determined [23]. When a domain wall moves past this intersection or sensitive zone (SZ), the average magnetic field across it changes, thereby producing a corresponding change in the Hall resistance, allowing an accurate measurement of the wall movement. The extended parts of the wall that are outside the SZ have negligible effect on the Hall resistance.

It can be seen from Fig. 1 that on the scale of a typical cross ($\sim 1 \mu$m), it is only a small section of a single domain wall that is being studied, and at the temperatures used, this section will remain straight. This is supported by measurements taken at liquid helium temperature on two crosses simultaneously, when the crosses were aligned parallel to the domain wall [19]. In this instance identical movements were recorded by both crosses, meaning that walls move without bending over lengths of several $\mu$m. Therefore, the section of the domain wall under observation is a simple, rigid, one-dimensional structure, with no vaulting taking place within the SZ at all. Despite this, we would expect to measure statistical behaviour typical of a wall with one-dimensional vaulting, since this is the large scale nature of the domain walls across the whole of the sample, with long-range interactions connecting them.

Since the wall remains straight while traversing the Hall cross, the length of each jump, $S$, can be calculated. The maximum and minimum values of Hall resistance recorded over a full sweep correspond to the wall being at opposite sides of the cross, i.e. at positions 1 and 3 in Fig. 2. Thus, the average difference between these two limits is equivalent to a domain wall movement the size of the branch width of the Hall cross used.

2. Experimental Technique

The 5 Hall cross device is attached to the garnet sample, with a gap of under 200 nm between them. The sample and device were placed in a dewar of either liquid nitrogen or liquid helium, and at the centre of a solenoid, so as to ensure a uniform temperature and field. The field is perpendicular to the surface of the sample, and so parallel to the two possible magnetization directions. The ballistic current was directed down the long path of the Hall device (the horizontal path in Fig. 1), allowing the use of any of the five crosses. We employed a cross with channel width of 1.5 $\mu$m as it exhibited the lowest noise.

We used standard low-frequency lock-in techniques to measure the Hall resistance, producing sets of data similar to the example in Fig. 3. From the raw data, we calculated the size of each jump, yielding a set of data showing the relative probabilities of each jump size. This data was plotted to give a value for $\tau$.

The section of the highlighted loop within the box in Fig. 3 implies the motion of the domain wall reverses direction without such a change in the external magnetic field, but this is not the
Figure 3. An example of data taken at 4.2 K, showing a typical set of 20 sweeps. The total change in magnetic field is quite small (just over 100 G), and so doesn’t cause saturation. One loop has been highlighted to show more clearly the behaviour of the domain wall. It is apparent that, in the zoomed-in region in the inset, the change in Hall resistance reverses direction despite no such reversal occurring in the magnetic field. See the text for an explanation.

As the domain wall moves across the SZ of the Hall cross, the usual Barkhausen jumps are observed, following the shape of the hysteresis loop. However, once the wall has passed fully across and, continuing in the same direction as before, starts moving away from the Hall cross, the jumps in the opposite direction to the trend are observed. An example of a typical sweep displaying this external wall effect is depicted in Fig. 2. This behaviour is the result of the decay in the stray magnetic field as one moves away from a domain wall. These recorded jumps are not related to the critical behaviour of the Barkhausen effect and, if left mixed with the desired jump data, will distort the resultant jump size distribution. As a result, all changes in Hall resistance that occurred in the opposite direction to that expected were filtered out of the data.

We ensured that the wall under observation moved past the entire SZ for every sweep of the applied external field, so as to produce consistent data, with a constant total variation in Hall resistance for each loop. This was achieved by ramping the field at a constant rate so that the domain walls passed back and forth over the Hall probe, between positions either at or just outside the edge of the SZ, e.g. at positions 1 or 2 in Fig. 2. The direction of field sweep switched once the maximum response of the device had occurred, which was recognizable by the cessation of significant change in Hall resistance.

The maximum allowed field was set at $\pm 200$ G, approximately the saturation magnetization of our garnet film, although the field rarely reached this level, staying within the $\pm 50$ G range. As the sample never reaches saturation, the simple wall propagation regime of magnetization is dominant, rather than those of domain nucleation or coalescence. These two processes, along with spontaneous spin rotation, are not governed by the same physical laws as the Barkhausen effect, and so all discussion in this paper is concerned with domain wall motion only.

3. Results and Analysis

Plotting the power spectra on double-log scales produces straight lines for each temperature, the gradients of which give the values for $\tau$, as would be expected from equation 1. Fig. 4 shows both plots on the same set of axes, and over the same range of jump sizes. Frequency, the label on the ordinate, refers to the number of occurrences of each value of $S$, and has been normalized to give the frequency per 1000 sweeps. The dotted line is a logarithmic fit to the data which has a gradient, $\tau_o$ of $1.14 \pm 0.05$ on the log scales used.

The data for 77 K was cut at 16.5 nm, and the data for 4.2 K was cut at 11.5 nm, as below these levels the uncertainty in the data for smaller jumps was significantly increased due to noise. This does not represent the maximum resolution achievable with this technique, as a resolution of 1 Å has already been reported [24]. However, this was achieved using Hall probes which, although
similar to the one described here, had a much lower electron concentration. The benefit of the higher concentration probes we have employed here is the ability to take measurements at room temperature, while the lower concentration probes must be used in liquid helium.

The higher cutoff, which appears at both temperatures at about 300 nm is present partly because of the size of the set of data used, but also due to the finite size effects caused by the physical size of the Hall cross employed. Several jumps were recorded above this size, but these were too scarce to be used to increase the accuracy of the gradient. The upper limit is ultimately controlled by the size of the Hall junction; as ours was 1.5 µm across, this is the absolute maximum value obtainable, though unlikely to be observed.

4. Discussion and Conclusions

The critical exponent appears to remain constant over the temperature range 4–77 K, with $\tau$ being $1.14 \pm 0.05$ for both tested temperatures. The lack of a strong response to temperature variation has been observed previously, though only in 3 dimensional samples [26], with thermally activated effects, such as domain wall creep, becoming apparent in thin films [27]. Other previous research on thin film samples found the value of $\tau$ to increase from 1.0 to 1.8 as the temperature was decreased from 300 K to 10 K in an iron thin film [25].

The reduction of temperature causes a decrease in internal energy within the sample, with several results. Firstly, this should cause the wall to display less vaulting, which would have the effect of reducing $\tau$. This effect will be small for our sample, as the vaulting is already constrained by the anisotropy, and so there is limited scope for constraining it further upon cooling below 77 K. In addition, the wall will be more susceptible to becoming trapped by a pinning centre during an avalanche, which will act to increase $\tau$. This will not be as noticeable an effect as for the film used in [25], as a result of the out-of-plane magnetization in our sample producing longer range interactions with the rest of the domain wall network.

Although the 77 K data is in reasonable agreement with the fitted line, there is a noticeable kink in the 77 K data around $S=50$ nm, with jumps at both extremes occurring less frequently than would be expected for the data to be straight. The data at 4.2 K shows the same cutoff at larger jump sizes, as detailed above.

The Hall cross used is so small that the domain wall is effectively a one-dimensional object, travelling through the SZ of the cross without bending in any significant fashion. This idea is supported by previous tests performed, whereby the same domain wall was observed passing the intersections of two different crosses on the same device at the same time [19]. However, since this small section of wall is still coupled to the whole wall, and undergoing dipole interactions
with other walls, we believe it produces the jump statistics of a two-dimensional object. The results obtained coincide with values published in previous work [10, 28], although these were produced using different methods.

The previous experimental work on 2D systems has produced different values, ranging from \( \tau \) being \( \sim 1.1 \) [10], to \( \sim 1.5 \) [12]. Our results are close to the lower of the two, though no explanation has been suggested as yet for the physical meaning of this value.

Using the basic ideas present in the CZDS model [4], one might expect a value of \( \tau = 1.33 \) for a domain wall in a two-dimensional system (from the equation \( \tau = 2 - \frac{2}{d+1} \), where \( d \) is the number of dimensions), and this has been used to support such values of \( \tau \) [11]. However, it is likely that the equation cannot be applied in such a simplistic way, as there are other factors to consider with two-dimensional samples. Among these, is the high level of anisotropy, which leads to a much reduced level of roughness of the wall (this certainly applies to the walls in our samples, which are flat). In such a case, renormalization group analysis has yielded a value of \( \tau = 1.25 \) [29], though this value is still larger than that observed in our experiment.

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References

[1] Barkhausen H 1919 Phys. Z. 20, 401
[2] Urbach J S, Madison R C and Markert J T 1995 Phys. Rev. Lett. 75, 276
[3] Cizeau P, Zapperi S, Durin G and Stanley H E 1997 Phys. Rev. Lett. 79, 4669
[4] Zapperi S, Cizeau P, Durin G and Stanley H E 1998 Phys. Rev. B 58, 6353
[5] Durin G and Zapperi S 1999 J. Appl. Phys. 85, 5196
[6] Babcock K L and Westervelt R M 1999 Phys. Rev. Lett. 64, 2168
[7] Cote P J and Meisel L J 1991 Phys. Rev. Lett. 67, 1334
[8] Alessandro B, Beatrice C, Bertotti G and Montorsi A 1990 J. Appl. Phys. 68, 2908
[9] O’brien K P and Weissman M B 1994 Phys. Rev. E 50, 3446
[10] Puppin E and Ricci S 2000 IEEE Trans. Magn. 36, 3090
[11] Kim D-H, Choe S-B and Shin S-C 2003 Phys. Rev. Lett. 90, 087203
[12] Wiegman N J 1977 Appl. Phys. 12, 157
[13] Schwartz A, Liebmann M, Kaiser U, Wiesendanger R, Noh T W and Kim D W 2004 Phys. Rev. Lett. 92, 077206
[14] Geim A K, Dubonos S V, Lok J G S, Grigorieva I V, Maan J C, Theil Hansen L and Lindelof P E 1997 Appl. Phys. Lett. 71, 2379
[15] Pedersen S, Kofod G R, Hollingbery J C, Sørensen C B, and Lindelof P E 2001 Phys. Rev. B 64, 104522
[16] Schuh D, Biberger J, Bauer A, Breuer W and Weiss D 2001 IEEE Trans. Magn. 37, 2001
[17] Rahm M, Bentner J, Biberger J, Schneider M, Zweck J, Schuh D and Weiss D 2001 IEEE Trans. Magn. 37, 2085
[18] Lok J G S, Geim A K, Wyder U, Maan J C and Dubonos S V 1999 J. Magn. Magn. Mater. 204, 159
[19] Novoselov K S, Geim A K, van der Bergen D, Dubonos S V and Maan J C 2002 IEEE Trans. Magn. 38, 2583
[20] Damento M A and Deemer L J 1987 IEEE Trans. Magn. 23, 1877
[21] Novoselov K S, Morozov S V, Dubonos S V, Misiss M, Volkov A O, Christian D A and Geim A K 2003 J. Appl. Phys. 93, 10053
[22] Li X Q and Peeters F M 1997 Superlattices Microstruct. 22, 243
[23] Peeters F M and Li X Q 1998 Appl. Phys. Lett. 72, 572
[24] Novoselov K S, Geim A K, Dubonos S V, Hill E W and Grigorieva I V 2003 Nature 426, 812
[25] Puppin E and Zani M 2004 J. Phys.: Condens. Matter 16, 1183
[26] Urbach J S, Madison R C and Markert J T 1995 Phys. Rev. Lett. 75, 4694
[27] Lemerle S, Ferré J, Chappert C, Mathet V, Giamarchi T and Le Doussal P 1998 Phys. Rev. Lett. 80, 849
[28] Paczuski M, Maslov S and Bak P 1996 Phys. Rev. E 53, 414
[29] Ertas D and Kardar M 1994 Phys. Rev. E 49, R2532
[30] de Queiroz S L A 2004 Phys. Rev. E 69, 026126