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Field-driven creep motion of a composite domain wall in a Pt/Co/Pt/Co/Pt multilayer wire

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ABSTRACT

We have studied the field-driven motion of a pair of coupled Bloch domain walls in a perpendicular magnetic anisotropy Pt/Co/Pt/Co/Pt multilayer Hall bar. The nucleation of an isolated but coincident pair of walls in the two Co layers, observed by Kerr microscopy, took place at an artificial nucleation site created by Ga^+ ion irradiation. The average velocity v of the wall motion was calculated from time-resolved magnetotransport measurements at fixed driving field H, where the influence of the extraordinary Hall effect leads to the observation of voltages at the longitudinal resistance probes. We observed a good fit to the scaling relation $\ln v \propto H^{-1/4}$, consistent the motion of a single 1-dimensional wall moving in a 2-dimensional disordered medium in the creep regime: the two walls are coupled together into a 1-dimensional composite object.

1. Introduction

Domain walls (DWs) are topological structures where the magnetization in a ferromagnet rotates in direction. Decades ago, magnetic bubble memories based on DW motion were developed [1], although they did not meet with commercial success at that time. The development of more advanced materials and nanofabrication techniques has revived interest in DW-based technologies, for instance for performing binary logic operations [2]. Introducing the additional concept of driving DW motion with a spin-polarized current [3] offers the prospect of realising advanced memory [4] or logic [5] architectures.

Nevertheless, these prototype technologies are all based on Permalloy nanowires, in which domain walls are rather complex in structure [6] and lack rigidity when set in motion [7,8]. Perpendicularly magnetized multilayer materials offer the prospect of narrow, rigid DWs with a simple Bloch structure [9]. Kerr imaging has been used to study DW motion in extended Pt/Co/Pt trilayer films showing this property [10,11]. Perpendicularly magnetized materials often have a high sensitivity to pinning, as the sizes of pinning sites can often match the narrow DWs found within them, and the interaction of an elastic DW with suitably weak pinning leads to the DW motion in this material to have three theoretical regimes of velocity with respect to applied field at a finite temperature [12]. These are: the creep regime at low applied fields, where DW motion arises from thermal activation; the depinning transition regime; and for higher fields, dissipative viscous flow. The dimensionality of the system leads to typical values of the exponent relating wall velocity to the strength of the driving field [12,13]. Whilst all these effects are present in confined structures, further pinning can occur where the DW intersects the edge of the structure. This has previously been demonstrated in studies of the depinning of a DW from a Hall cross [14–16], as well as studying the effects of wire width [13,17], in trilayer films. In these cases the DW was nucleated at a natural defect of the material, or an artificial defect created using an atomic force microscope tip. In all these instances, the DW exists as a line defect in the single magnetic Co layer, and so can reasonably be considered as a 1-dimensional object, an idea borne out by the experimentally observed creep scaling relations [10,13,17]. Technologies based on these materials are starting to be developed, for instance, there has been a recent demonstration of a magnetic NOT-gate for DW logic based on a Pt/Co/Pt trilayer [18].

In this paper we report on the study of isolated magnetic Bloch-like DWs, nucleated at a defect that was produced artificially using focussed ion beam (FIB) irradiation, in a perpendicularly magnetized Hall bar wire [19]. The microstructure was fabricated from a sputtered Pt/Co/Pt/Co/Pt multilayer, where Ga^+ ion implantation can mix the layers locally reducing the anisotropy and magnetically softening the material [20,21]. After confirming the nucleation process produced an isolated pair of coincident DWs in the two Co layers in the nanostructure by Kerr microscopy, we studied the magnetization reversal process using ac-transport measurements at room temperature, provide

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information on the motion of the DWs along the wire between various voltage contacts. The scaling behavior of the dynamics of the motion showed that it occurred in the creep regime, with an exponent consistent with a 1-dimensional object. We have found qualitatively similar behavior in a number of samples, however, here we will concentrate in the results from one of them, where the most detailed measurements have been done.

2. Experimental details

The sample studied was a sputtered multilayer of structure Pt(28 Å)/[Co(5 Å)/Pt(10 Å)] × 2, which exhibits a perpendicular anisotropy $K_{eff} \approx 0.3 \times 10^6$ J/m^3 (as determined from a pair of longitudinal and polar magneto-optical Kerr effect hysteresis loops, combined with a vibrating sample magnetometer measurement of the total moment of the sample), a value similar to similar that reported for a trilayer [17]. This yields an approximate width of $\Delta \sim \sqrt{A/K_{eff}} \approx 10$ nm for the Bloch-like DWs in this material [16]. (Here A is the exchange constant for Co, $A=3 \times 10^{-11}$ J/m). This was patterned by electron beam lithography and liftoff into a Hall bar of width 5 μm, with the voltage contacts of the same size (see Fig. 1(a)). This patterning has been shown not to affect the magnetic properties of the multilayer material [19]. FIB was then used to create the artificially softened region in the nucleation pad: in this case a dose of 4.83×10^{12} Ga$^+$/cm^2 was used. A Kerr micrograph of the initial stage of a reverse domain spreading from this site is shown in Fig. 1(c). When the pad is fully reversed, an isolated DW spanning both Co layers propagates down the Hall bar, as shown in Fig. 1(a). A more detailed description of the device fabrication methods and the operation of the nucleation region are given in our previous publication [19]. Here we discuss wall velocity measurements subsequently made using these types of devices.

An ac-current lock-in technique was used to detect the DW motion. The excitation current of 10 μA, at a frequency of 1285 Hz, flows along the length of the wire between the current contacts (see Fig. 1(a)). The small current density ($\sim 10^3$ A/cm^2) does not affect the motion of the DW through spin-transfer effects [3], so that here the field is solely responsible for driving the DW motion.

Two lock-in amplifiers (LIAs) were connected between the contacts V_{A1} and V_{A2}, and V_{B1} and V_{B2} to measure longitudinal voltages between the first and second, and first and third Hall crosses, respectively.

Our measurement procedure was as follows. First a large negative field was applied, to bring the structure into a single domain saturated state, followed by a small positive field ($H \sim 150$ Oe) to nucleate a reverse domain in the irradiated area. Next the propagation field ($H \sim 200$ Oe) is set to propagate the DW along the wire, and simultaneous time-resolved measurements from both lock-in amplifiers are begun. The propagation field is kept constant during these measurements. All fields were applied along the sample normal. The effectiveness of this field protocol was checked using Kerr microscopy, where the motion of the wall can be observed in real time. The DW motion was seen to be jerky, with the wall front forming a rather ragged outline, typical of the creep regime. The DW motion was observed to always be coincident in the two layers, and so we can henceforth consider a single DW object spanning both layers moving along the wire, at least at times between jumps from one pinning site to the next.

The velocity of the DW along the bar was determined by the time-resolved resistance measurements, taken at a fixed field. We used the voltages V_R returned by the lock-in amplifiers calculate the resistivity using the expression $\rho = (wt/d)(V_R/I_{ac})$, where I_{ac} is the ac excitation current along the bar, t the film thickness, w the width of the Hall bar, and d the distance between the voltage contacts. In the single domain state the measured longitudinal resistivity was ~ 19.3 μΩcm, typical for thin film transition metal systems such as these [22].

3. Results and discussion

An example of one of our time-resolved data sets is shown in Fig. 2, in this case for a propagation field $H=200$ Oe. At the time we label $t=0$, the resistivities depart from their magnetically saturated values, which we can interpret as the DW traversing the first Hall cross and passing contacts V_{A1} and V_{B1}. Roughly 25 s later the resistivity measured by lock-in amplifier A returns to its saturated value, when the DW passes contact V_{A2}. After a further

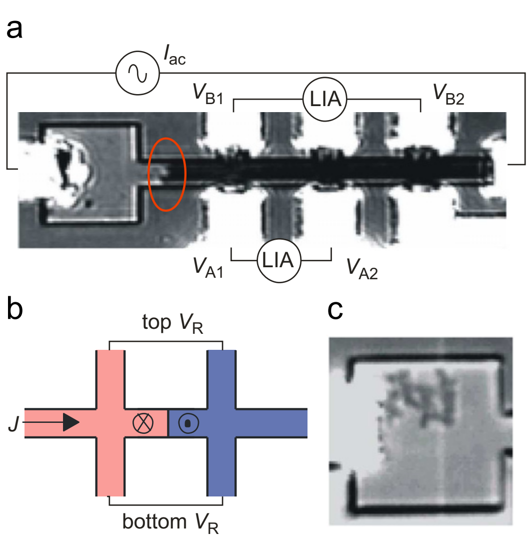

Fig. 1. (a) Kerr microscopy magnetic contrast of the Hall bar device, and where a single DW is positioned in the middle of the bar (circled) during propagation. The various current and voltage contacts are marked. (b) Schematic showing how a large AHE leads to a measurable voltage when a DW is between two voltage contacts on the same side of the Hall bar. (c) Kerr micrograph of a reverse domain spreading from the FIB irradiated site within the pad.

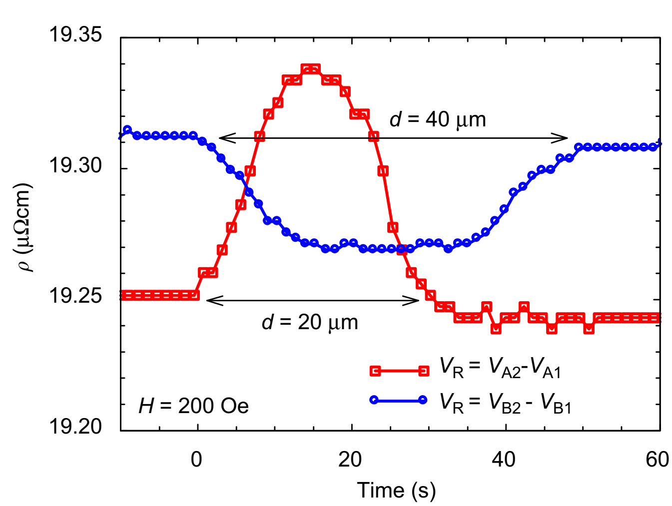

Fig. 2. Time-resolved resistivity measurements at constant field ($H=200$ Oe) of a DW moving along the bar. The square data points were measured using two bottom voltage contacts and lock-in amplifier A for two consecutive Hall crosses separated by 20 μm, according to the notation in Fig. 1(a). The circular data points were simultaneously measured by lock-in amplifier B using two top voltage contacts separated by 40 μm.