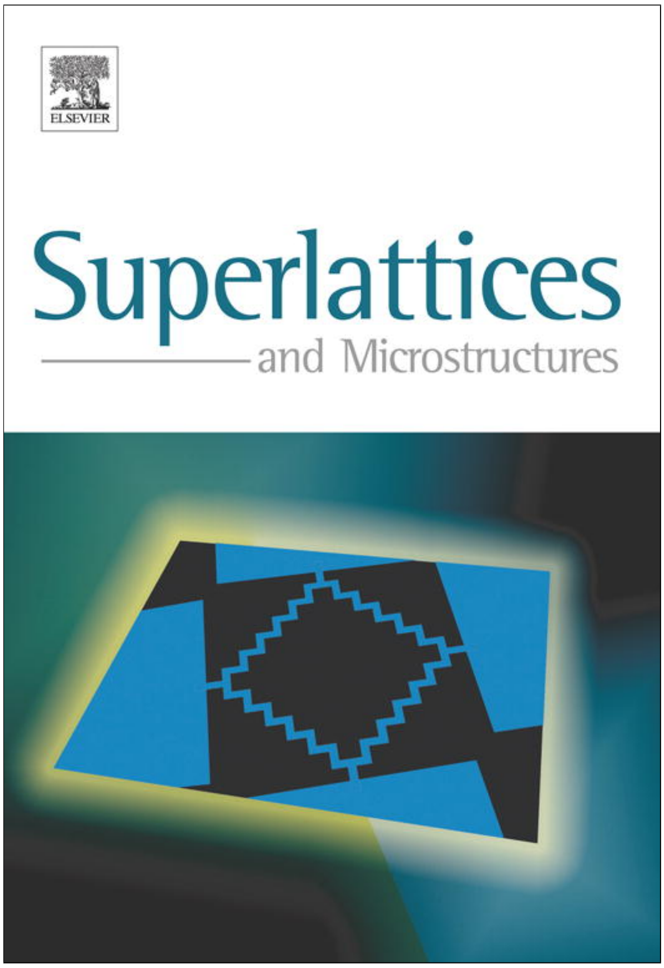
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Sensing domain wall pinning in the longitudinal magnetoresistance of a two-dimensional electron gas

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ABSTRACT

We investigate the sensing of domain wall pinning in thin Co wires positioned on top of a two-dimensional electron gas (2DEG) heterostructure by measuring the longitudinal resistance of the 2DEG as the magnetic field is swept, in an analogy to the Barkhausen effect. For comparison, we also measure the magnetoresistance of the ferromagnetic film in the same device in a subsequent sweep. Compared to the Hall measurements, the longitudinal measurement has the advantage of sensing magnetic activity over longer lengths, while compared to the measurement of the magnetoresistance in the ferromagnetic wire, it offers complementary information related to the pinning and unpinning of the domain wall, due to its sensitivity only to the out-of-plane magnetic field component.

1. Introduction

Control of domain walls is one of the possible routes towards applications such as fast high-density storage devices [1] or logic gates [2]. New advances in understanding and exploiting domain wall pinning [3] are made, while switching control by current pulses benefiting of the spin-momentum transfer [1,4–6] becomes increasingly relevant. Of course, one of the problems related to the domain wall motion is its detection. There are different ways of detecting the motion of a domain wall. One example is to take advantage of the anisotropic magnetoresistance (AMR) [7,8] where the decrease in the

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resistance of a ferromagnetic nanowire during a reversal process, combined with patterned constrictions, can serve in the understanding of the reversal processes, domain wall motion and pinning [9–11]. Another way of detecting the pinning of domain walls is by Hall magnetometry where a Hall cross created in a 2DEG and placed below the ferromagnetic wire can record Barkhausen jumps [12] in the Hall effect [13] due to the stray field coming from the nonuniformities of the domain walls.In this paper we detect the pinning of magnetic domain walls by measuring the longitudinal resistance of a 2DEG Hall bar, conveniently placed below a ferromagnetic Co wire, and, in a subsequent sweep of the magnetic field, we measure the AMR in the Co wire. We show that the longitudinal resistance measurement is more sensitive to domain wall pinning than the AMR, it brings complementary information and also detects multiple domain wall jumps by pinning at different locations.

2. Experiments

Hall bars with a width of 1.5 μm are patterned with e-beam lithography and wet chemical etching on a GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure having a 2DEG located 85 nm below the surface, with an electron density of 1.8×10^{15} m^{-2} and a mobility of 84 $m^2/(Vs)$. Co wires with a length of 15 μm, thickness in the range of 25–70 nm, and widths of 500 nm are evaporated on top of the Hall bar. In Fig. 1a we show a room-temperature MFM image of a typical wire, obtained after application and subsequent removal of a magnetic field of 0.5 T. The shape of the wire is such that at one end it has a large pad which allows easy nucleation and can host domain walls at remanence [14,15], as visible in the MFM image in Fig. 1b, while the other end is sharp preventing domain wall nucleation [16]. Due to shape and polycrystallinity, the easy axis of magnetization lies in the plane of the layer, along the wire. Some of the Co wires have a constriction in the center of about 150 nm, Fig. 1c, which provides a strong pinning site for a domain wall. A complete picture of the sample showing the probe geometry is given in Fig. 1d.

In Fig. 2 we show the four-point magnetoresistance measurements at 4.2 K done on three Co wires, deposited on semi-insulating GaAs and covered in-situ with 5 nm of Au. Four Ti/Au contact electrodes are fabricated, similarly to the electrodes in Fig. 1d, enabling a four-point measurement. The wires have a width of 500 nm and three different constriction sizes. Our choice of wire range is similar to the one studied in Ref. [17], with AMR being the mechanism of the observed magnetoresistance. The MFM measurements at room temperature reveal that, at this width, the wires are divided by the constriction into two single-domain regions (see also Fig. 1a). This is also evidenced by the fact that the magnetoresistance at remanence is the same as that of saturation in an applied field. Due

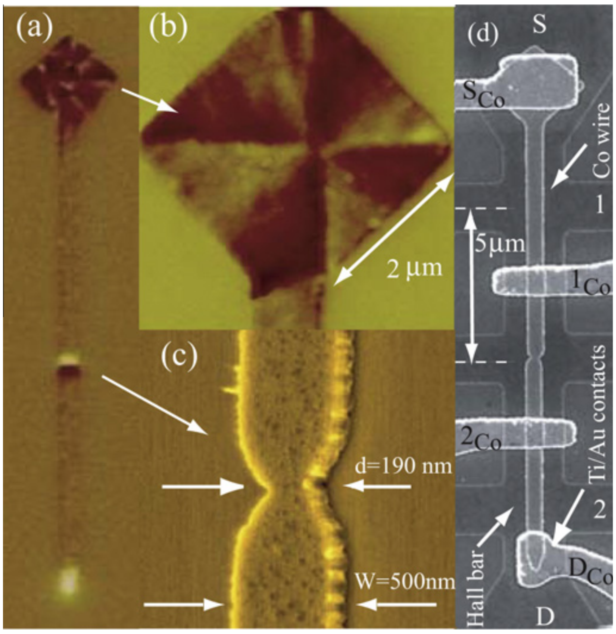

Fig. 1. (a) MFM picture of a typical Co wire with a large nucleation pad (b) and a constriction (c) of size d. (d) SEM figure of the Co wire on top of the Hall bar indicating the Co and the Hall bar contacts.

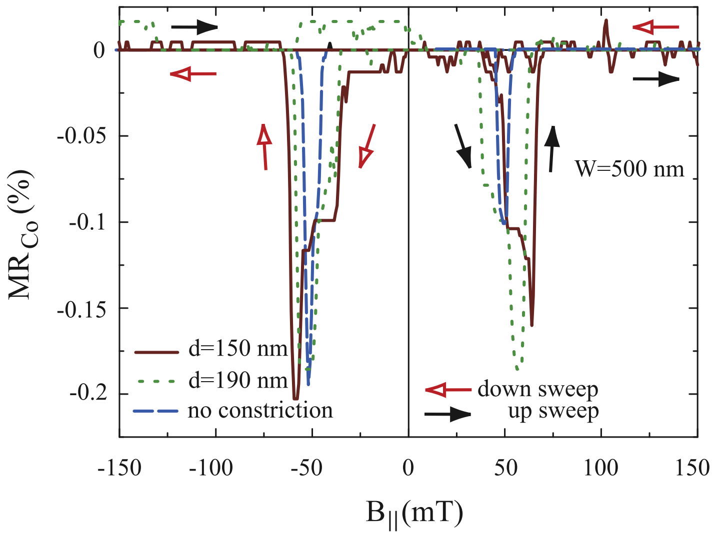

Fig. 2. The AMR as a function of the magnetic field applied in a direction parallel to the wire axis, for three wires with different constriction widths (d) and the same wire width (W).

to the polycrystalline nature of the wire we expect that there is no preferential magnetocrystalline anisotropy, and that a multidomain structure can form in the wire during the reversal of the magnetization, creating a level of magnetic disorder that is maximum for the coercive field where the total magnetization is zero. At the same time, in the wire without a constriction, the AMR goes through a minimum at the coercive field, when the micro-magnetic moments have the maximum component in the direction perpendicular to the current in the wire.

Compared to the wire without a constriction, which shows narrow dips at the coercive field, the wires having a constriction show higher coercivity and tend to become broader. One may also notice that higher coercivity is obtained for the wire with deeper constriction, due to a higher pinning energy. At the coercive field, the magnetization reverses, which is seen as an abrupt increase in the resistance of the wire.

To observe how the reversal process manifests itself in the magnetoresistance of the 2DEG nearby (MR_{2DEG}), we turn to the Co wires positioned on top of the Hall bar. We pass a current I_{Co} of 1 μA at 17 Hz from source (S_{Co}) to drain (D_{Co}) of the ferromagnetic film, while a current of 0.1 μA also at 17 Hz is passed from source (S) to drain (D) of the 2DEG in a subsequent magnetic field sweep in the same device. This ensures that measurements of the two magnetoresistances are independent, and do not influence each other for instance by changing the density in the 2DEG due to the application of voltages to the Co wire which acts as a gate (although the effect would be small compared to the measured features). The magnetoresistance of the ferromagnet is measured between contacts 1_{Co} and 2_{Co} while the resistance of the 2DEG is measured between contacts 1 and 2 such that possible pinning of domain walls at the contact 1_{Co} and 2_{Co} sites will also be observed (see Fig. 1d). The measurements are performed at a temperature of 1.5 K, with the applied magnetic field oriented along the wire axis. It must be noted that, during the 2DEG magnetoresistance measurements, all four contacts of the Co wire were kept at the ground potential, to avoid any interference with the 2DEG in the underlying Hall bar. We have measured a wire which was exposed to air such that a few nm thin Co oxide self-passivating layer [18] is formed on top, which results in additional lower coercivity pinning sites [10]. However, we can expect that the most important pinning sites are the central constriction and, to a lesser impact, the contacts 1_{Co} and 2_{Co} due to the stress and non-uniformity they introduce. The results are shown in Fig. 3.

3. Discussion

We notice that the magnetoresistance of the uncovered Co wire, MR_{Co}, varies when sweeping the field from saturation values towards remanence as opposed to the magnetoresistance of the covered

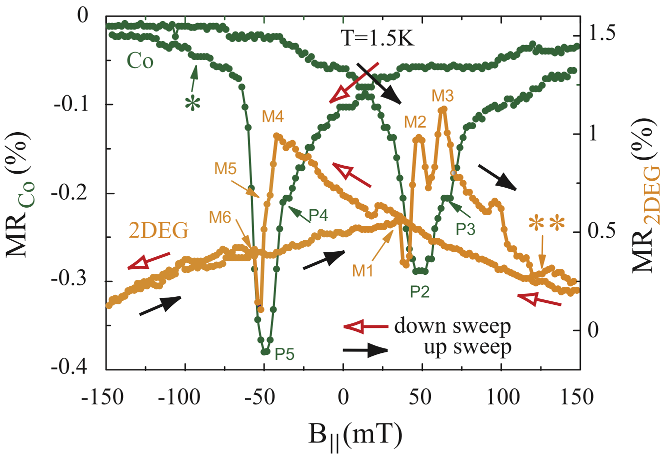

Fig. 3. The AMR of the Co wire MR_{Co} and the longitudinal magnetoresistance, MR_{2DEG} of the underlying 2DEG as a function of the applied parallel magnetic field. The maxima in MR_{2DEG} are indicated by M_i, also indicated by arrows where they are not strongly visible. The corresponding plateaus in MR_{Co} are indicated by P_i.

wires which present no variation in this range. This indicates that the naturally formed Co oxide on the surface has the effect of introducing nucleation centers, and a polydomain structure is thus already present at remanence.

The longitudinal resistance of the 2DEG, measured between contacts 1 and 2, is very sensitive to the perpendicular magnetic field features present between the contacts [19,20]. Such features are expected at the constriction and at pinning sites where the change of the magnetic moments inside the wall from one direction to another is not completely in the plane of the film. It is also expected that, if the distance between the magnetic domains is larger than the mean free path, the corresponding magnetoresistances will add up, and so individual changes of the domain wall configurations will leave a fingerprint on the magnetoresistance.

As we move from negative saturation towards positive field values, MR_{2DEG} shows a variation rich in reproducible maxima and minima. The maxima in MR_{2DEG} are associated with plateaus in MR_{Co} which are most visible in the cases of plateaus P_2 and P_3, with associated maxima M_2 and M_3. This suggests that the observed maxima in MR_{2DEG} are also related to a pinned domain wall. The plateau P_2 in MR_{Co} indicates that, locally, the magnetic field configuration in a plane perpendicular to the direction of the current stays constant. However, the variation in the MR_{2DEG}, which is only sensitive to the out of plane-component of the magnetic field, indicates that as the domain wall is pinned at a certain site, the out of plain component has a maximum and, when increasing the magnetic field to pass M_2 the micro-magnetic moments start to orient themselves in the x–y plane, resulting in a decrease of the out-of-plane component when the domain wall is unpinned. The domain wall then experiences a Barkhausen jump to another pinned position associated with another plateau, M_3 and a peak P_3, in the corresponding magnetoresistance traces, after which MR_{2DEG} starts dropping monotonously as domains and domain walls disappear, by orienting all magnetic moments in the direction of the applied field.

Turning our attention to the first maximum, we notice that up to M_1, at the same time with the monotonous decrease of the Co wire resistance, the polydomain structure which forms produces a certain magnetic field component outside the wire plane, which determines an increase in the magnetoresistance of the 2DEG. We also notice that there is no visible plateau in the MR_{Co}, which may be, to some extent, due to the resolution of the measurements, but is also masked by the general variation of the MR_{Co} at that point. However, the sudden decrease in MR_{2DEG} indicates that a domain wall got unpinned and the magnetic moments have reoriented in the plane of the film, giving a contribution only to MR_{Co}. In both magnetoresistance traces, one may also notice other smaller features that are not correlated on both traces and not reproducible which we believe to be due to noise and charging effects, for instance the plateau marked with $*$, which comes from digitizing, or the one fluctuation marked with $**$, which we believe it to be a charging effect.

4. Conclusion

In conclusion, we have used the 2DEG as a sensor of the changes in the local out of plane component of the magnetic field coming mostly from the domain walls. The magnetoresistance of the 2DEG is extremely sensitive to pinning of domain walls, showing abrupt variations when domain walls move. An overall 1% change is obtained in MR_{2DEG} while in MR_{Co} slightly less than 0.4% is observed. Further improvement is possible choosing a more shallow heterostructure and tuning the ratio between the wire and the Hall bar widths.

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