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LETTER TO THE EDITOR

Resistance of a domain wall in a thin ferromagnetic wire

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Abstract. The resistivity of a ferromagnetic wire depends on the magnetic domain configuration. We describe results for very narrow Ni wires which clearly reveal the effect of a domain wall on the resistance. Interestingly, the presence of a domain wall *lowers* the resistance, i.e., the resistance with a wall present is lower than that of the same wire without a wall. The magnitude of this effect is consistent with a recent theoretical prediction of Tatara and Fukuyama. Other possible explanations are also discussed.

The transport properties of magnetic materials have attracted a good deal of interest in recent years. Most of this interest has been connected with materials which exhibit giant magnetoresistance (GMR) effects [1], but the problem has been central to other areas as well, including quantum tunnelling of domain walls [2], and the transport properties of ferromagnetic thin films [3] and narrow wires [4, 5]. Of particular interest in these experiments is the contribution to the resistivity which is found when a conduction electron passes between regions with different magnetizations, $\boldsymbol{M}$. Work on GMR usually involves multilayer structures, so the process of interest typically occurs when an electron moves between layers of different composition (and hence also different $\boldsymbol{M}$, either in direction, or magnitude, or both). Similar physics is encountered when an electron passes through a domain wall in a 'chemically homogeneous' material, as can occur in a simple ferromagnetic wire [2] or film [3].

In this letter we report some experimental results which concern this problem. The specific geometry we consider is a narrow ferromagnetic strip (i.e. 'wire') composed of Ni. Our strategy is to simply compare the resistance of the strip when it contains no domain walls to the case when it contains one or a few walls. The difference then yields information on the nature of the electron motion between regions with different $\boldsymbol{M}$. Interestingly, we find that the contribution of a domain wall to the resistance is effectively *negative*; i.e. a sample containing domain walls has a *lower* resistance than a sample without walls. As far as we know, this is the first observation of a 'negative' domain wall resistance. This effect can be explained, at least qualitatively, in terms of a recent theory of Tatara and Fukuyama [6]. Other explanations will also be discussed.

Our experiments employed very narrow strips which were patterned from Ni films evaporated onto glass substrates. The patterning was accomplished using a step-edge method [7], with typical thicknesses and widths of 200–400 Å, and sample lengths of $\sim 10\ \mu$m. The low temperature resistivity was $\sim$ 10–20 $\mu\Omega$ cm, which implies that the elastic mean-free-path was comparable to, or slightly smaller than, the strip cross section. The resistance was measured using standard AC bridge techniques at temperatures in the range 1.4–20 K, with a magnetic field applied along the axis of the wire. Further experimental details are given elsewhere [2, 5]. All of the measurements presented in this paper were obtained at 4.2 K; the results of interest here were the same at other temperatures in the range given above. We should also note that the results for the domain wall resistance for this sample were completely reproducible, and that similar results were found for other samples.

While we have discussed the connection between the magnetoresistance and domain wall motion previously [2, 5], it is useful to repeat the main arguments here. Figure 1 shows some results for the resistance as a function of field, $R(H)$, as the field was swept up (toward positive values) at a constant rate. Prior to beginning the measurements in figure 1 a field of $\sim +2000$ Oe was applied along the axis of the strip. This was sufficiently large so as to saturate the magnetization in the positive direction, hence during the initial sweep, labelled 1, the magnetization throughout the sample was in the positive direction. When moving down along curve 1 and onto curve 2, the resistance was completely reversible until the sweep passed the resistance minimum, which in this case occurred at approximately -100 Oe. That is, starting from large positive fields the behaviour was completely reversible and reproducible until the field was swept below ~ -100 Oe. Once this field was passed, the behaviour was hysteretic. Since hysteresis is associated with the presence of domain walls, this indicates that domain walls first entered the sample at ~ -100 Oe.

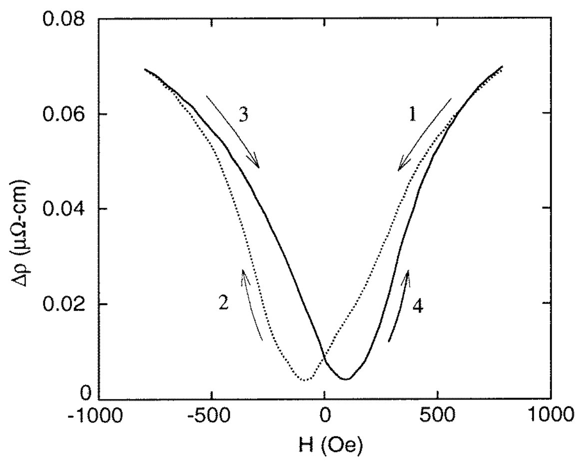

Figure 1. $R(H)$ for a Ni strip which was 400 Å wide, 400 Å thick, and 20 μm long. The temperature was 4.2 K, and the magnetic field was applied along the long axis of the strip. The field was swept at a constant rate of 0.5 Oe s^{-1}. The different curves are discussed in the text.

If the sweep was continued to more negative fields, the behaviour (now along curve 2 in figure 1) depended on the sweep speed, which again indicates that domain walls were present. However, at fields beyond ~ -600 Oe, which is the field at which curves 2 and 3 merge, the hysteresis vanished. Curve 3 was found when sweeping back up from large negative fields, so this result and also curve 2 at fields beyond -600 Oe correspond to the behaviour with all of the sample magnetized along the negative direction and with no domain walls present.

Along curve 3, the sweep up from large negative fields, the behaviour was completely reversible and reproducible until the minimum at $\sim +100$ Oe on curve 4 was passed. Thereafter we observed hysteresis indicating that domain walls had again entered the sample.

While these arguments based on the presence or absence of hysteresis tell us when domain walls were present, they do not give any information about the magnetization direction within the sample. For this we will now consider the magnetostatic energy for samples of this shape, together with measurements of the magnetoresistance for fields applied parallel and perpendicular to the long axis of the strip. For the samples considered here the length is greater, by a factor of $\sim$ 2000 or more, than either of the transverse dimensions. The magnetostatic energy will thus be much smaller when $\boldsymbol{M}$ is parallel to the long axis of the sample, as opposed to being perpendicular. Since the widths and thicknesses of our strips were comparable, a field of the order of $2\pi M$ will be required to tip $\boldsymbol{M}$ away from the axis. For Ni this field is $\sim$ 3000 Oe. Hence, we expect magnetization arrangements like those shown schematically in figure 2. The top and bottom configurations, A and C, are uniformly magnetized samples corresponding to sweeps 3 and 1 in figure 1, respectively. The middle configuration, B, shows a hypothetical domain wall separating regions with opposite $\boldsymbol{M}$, as would be found for sweeps 2 and 4 in figure 1.

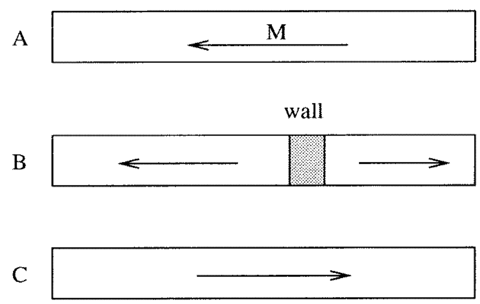

Figure 2. Schematic of the magnetization in several different cases. In A and C the sample is uniformly magnetized; i.e., $\boldsymbol{M}$ is the same throughout the entire sample. In B the sample contains a single domain wall, which separates regions of opposite $\boldsymbol{M}$.

This picture is confirmed by the magnetoresistance measurements reported in [5]. There it was shown that for fields applied perpendicular to a long narrow strip, the resistance did not vary much until the field reached $\sim$ 500 Oe, at which point the resistance dropped. The resistance was approximately constant at fields above about 3000 Oe indicating that $\boldsymbol{M}$ was then perpendicular to the axis of the strip. The magnitude of this drop in the resistance is also in reasonable agreement with the expected anisotropic magnetoresistance (AMR) [8, 9, 10]. The AMR is a contribution to the resistivity which depends on the relative directions of the current and $\boldsymbol{M}$. This mechanism, which is due to differences in the scattering rates of spin polarized carriers in spin-split conduction bands, causes the resistivity to be smallest when the current and $\boldsymbol{M}$ are perpendicular.

The arguments given above concerning the direction of $\boldsymbol{M}$ and the domain configuration are admittedly indirect. It would clearly be desirable to obtain this information in a more direct manner, such as by Kerr microscopy, scanning electron microscopy with polarization analysis, or magnetic force microscopy (MFM). Unfortunately the small size of our samples makes most microscopy very difficult (or impossible), and our efforts to perform noninvasive measurements with MFM have so far been unsuccessful. However, we have obtained direct magnetization results for thin film samples [11], and they confirm our conclusions as to the fields required to move $\boldsymbol{M}$ about within the plane, and perpendicular to the plane.

It is interesting to consider the resistance as measured on curves 1 and 4 at $H \sim +90$ Oe. At this point, both of the curves correspond to a sample in a uniformly magnetized state; for curve C the sample was uniformly magnetized along the positive direction (figure 2(C)) while for curve 4 it was (at this value of the field) magnetized in the negative direction.

We see from figure 1 that there was a substantial difference in the resistance observed in these two cases. This difference is evidently due to a magnetoresistance which is a function of the relative directions of $\boldsymbol{M}$ and $\boldsymbol{H}$; i.e., it is a function of $\boldsymbol{M} \cdot \boldsymbol{H}$. This is *different* from the AMR mentioned above, since the AMR depends on the relative directions of the current and $\boldsymbol{M}$. In the cases considered here these two quantities are always parallel, so the AMR should be the same. So far as we know, the origin of this $\boldsymbol{M} \cdot \boldsymbol{H}$ magnetoresistance, which was discussed in [5], is unknown at present, although several possibilities have been considered [5]. It corresponds to a resistivity difference of $\sim 0.011\ \mu\Omega$ cm between the two phases ($\boldsymbol{M}$ positive and $\boldsymbol{M}$ negative) at a field of 100 Oe.

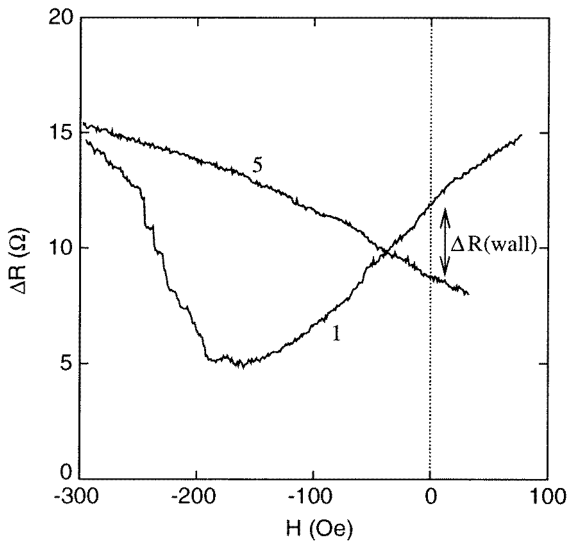

Figure 3. $R(H)$ for a Ni strip which was 300 Å wide, 300 Å thick, and 20 μm long. The total resistance of the sample was 5000 Ω, the temperature was 4.2 K, and the field was applied along the axis of the strip. The field was first swept down (at a rate of 0.5 Oe s^{-1}) from a large positive field yielding curve 1. After sweeping to $H \approx -300$ Oe, the field was then swept back up yielding curve 5. Similar results for the domain wall resistance were found using the opposite field polarity for the initial sweep.

Of primary interest in this letter is the contribution of a domain wall to the resistance. This cannot be unambiguously extracted from the results in figure 1, since the effect of the $\boldsymbol{M} \cdot \boldsymbol{H}$ magnetoresistance is generally also present. However, it was possible to devise a similar measurement in which the domain wall resistance could be observed directly, and the results of that measurement are shown in figure 3 [11, 12]. Here curve 1 was obtained by sweeping the field down from a large positive field; this is the same as with curve 1 in figure 1. The resistance minimum for the sample of figure 3 occurred at $H \sim -180$ Oe; this was the point at which domain walls first entered with this particular sample. (The results in figures 1 and 3 were obtained with different samples, and the field at which domain walls first entered varied from sample to sample.) For the measurements in figure 3 the field was swept to ≈ -300 Oe, and then it was swept back up yielding the result shown as curve 5. From the previous arguments we know that a field of -300 Oe was not large enough to sweep the walls out of the sample, hence all along curve 5 the sample contained domain walls (the resistance here was also found to exhibit hysteresis). The precise number of walls present is not known. Based on previous measurements [2, 11] we suspect that the domain walls entered from the ends of the sample, so that at most two walls were present. In order to obtain the contribution of the domain wall(s) to the resistance, without any interference from the $\boldsymbol{M} \cdot \boldsymbol{H}$ magnetoresistance, we simply compare the resistances at $H = 0$ along the two curves in figure 3. At this field the $\boldsymbol{M} \cdot \boldsymbol{H}$ magnetoresistance must vanish (by symmetry); the difference in R in the two cases is then solely due to the domain wall contribution. Note that in figure 1, curves 1 and 3 crossed at $H = 0$, since in those cases no walls were present.

A striking feature of the resistance difference at $H = 0$ in figure 3 is that the wall makes a *negative* contribution to the resistance. For this sample the difference, indicated by ΔR(wall) in figure 3, was 3.1 Ω. That is, the resistance was *lower* by this amount when a wall was present. This could seem contrary to ones intuition, but we will show below how it might be explained.

It is interesting to first consider how the effectively negative domain wall resistance observed in figure 3 relates to work on giant magnetoresistance materials. Discussions of GMR generally concern the contribution to the resistance which is encountered when an electron passes between layers which are magnetized in different directions, or between a magnetized and an unmagnetized layer. So far as we know, this contribution has always been found, or at least assumed, to be positive; i.e., this process increases the resistance [1, 13, 14]. Intuitively a positive contribution seems reasonable; one might expect that when an electron moves between regions with different $\boldsymbol{M}$ the effective 'transmission coefficients' for each spin polarization will in general be less than unity. This then leads to extra scattering at the interface, and an increase in the resistance when compared to the case of no interface. However, there are several possible ways to account for a 'negative' domain wall resistance.

One way has been proposed recently by Tatara and Fukuyama [6], who considered the weal localization (WL) contribution to the conductance. It is well known that in a material in which the spin-orbit scattering is relatively weak, such as Ni, the electron interference effects connected with WL make a negative contribution to the conductance [15]. However, the effective internal field associated with a domain wall will cause a suppression of WL, leading to an increase in the conductance relative to what would have been found if WL were at full strength [6]. When evaluated for the sample in figure 3, the theory of [6] predicts a wall resistance of -11 Ω. In obtaining this estimate we have assumed a wall thickness of 1000 Å (which, given measurements on other films [3], seems at least qualitatively reasonable), an elastic mean-free-path of 100 Å (as obtained from the measured resistivity at low temperatures), and the (measured) sample length of 20 μm. The other parameters involved in the theory concern quantities such as the band structure and Fermi surface; for these we took the values proposed in [6].

From figure 3 we find $\Delta R(\text{wall}) \sim 3.1$ Ω, which is about a factor of four smaller than the theoretical estimate. However, the uncertainties in all of the parameters which are involved (and in the band structure assumptions themselves), could, in our opinion, easily account for a factor of four or more. Hence, we believe that the theory is in very reasonable agreement with our experimental value.

While the weak localization mechanism of Tatara and Fukuyama seems quite plausible, one must keep in mind that the experiment actually measures the difference between a ferromagnet with a domain wall and a ferromagnet without walls. One must therefore also consider the WL behaviour in a ferromagnet. According to the theory [6, 16] the WL contribution for a ferromagnet should be substantial, but to the best of our knowledge it has not yet been measured experimentally [17].

Even though the agreement between the theory in [6] and the experiment is satisfactory, we should note that it is possible to account for a negative domain wall resistance in other ways. One alternative explanation involves the anisotropic magnetoresistance. The walls in a narrow strip separate regions of positive and negative $\boldsymbol{M}$, where positive and negative refer to the long axis of the strip which is also the direction of the current (figure 2). The transverse dimensions of our strips are comparable to each other, and are also comparable to, or smaller than, the domain wall thickness typically found in a thin film. This affects the interplay between the exchange and magnetostatic energy which, in more conventional sample geometries, leads to the usual Bloch and Néel domain walls. The precise spin configuration within a domain wall in our strips is not clear, although it is certain that the spins within the wall must rotate (continuously) through at least 180°, and hence that there will be a region where the current and the local $\boldsymbol{M}$ are perpendicular. In this region we would expect to find a resistivity of order $\rho_{\perp}$, which is lower than when the current and $\boldsymbol{M}$ are parallel $\rho_{\parallel}$. This difference is just the anisotropic magnetoresistance. We know from other measurements on similar Ni strips [5] that $\rho_{\parallel} - \rho_{\perp} \sim 0.1\ \mu\Omega$ cm. Using this value one can account for the experimental value of ΔR(wall) if one assumes a wall thickness of $\sim 2.5\ \mu$m. This seems a bit large, but given the nature of the approximations we have made, this explanation cannot be ruled out.

Another explanation which has been proposed [18] involves quantum interference effects associated with the Berry phase, which is accumulated when an electron moves in a spatially inhomogeneous magnetic field, here produced by the domain wall. The magnitude of this effect depends strongly on the spatial variation of the magnetic field, but estimates are that under the right conditions this effect can easily be large enough to explain our results. A better understanding of the role of this mechanism in our experiments will be possible when the spin configuration in our domain walls is known.

Our observation of a negative domain wall resistance should also be compared with previous experiments on both GMR systems and on domain wall type systems. In all of those cases the resistance associated with a boundary or wall has been found to be positive, in contrast to our negative value. This difference can be reconciled as follows. For the GMR systems there are other microscopic mechanisms (spin dependent interface scattering, etc) which are present, and these could easily overwhelm the negative contribution we have found. In addition, the interface widths in the GMR materials are typically a few Å, and the domain wall widths observed in previous work with thin ferromagnetic films are also quite small (widths of a few hundred Å or less [3]). The spin structure of the walls in our narrow strips is likely to be quite different from that found in films, so a much thicker wall would not be surprising in our case. If the walls in our strips are indeed much thicker than those in films, the interface effects mentioned above could be much smaller, and hence not mask the negative contribution we have observed. In conclusion, we have observed an effectively negative domain wall resistance in narrow Ni strips. This result has been obtained by comparing the resistance found at zero field, after exposing the sample to different field preparations. We should emphasize that although we do not know the precise spin configurations in our samples, there seem little doubt that our measurement compares the resistance of a sample with and without domain walls. Hence, the *sign* found for the domain wall resistance is unmistakable, and does *not* depend in any way on our subsequent analysis.

A quantitative comparison with the theory of Tatara and Fukuyama requires some assumptions about parameters such as the domain wall width. Choosing what we believe are reasonable values for these parameters produces an order of magnitude agreement with the theory, but further work is needed to determine if this is indeed the correct explanation of our experiment.

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