Magnetoresistance of as-prepared samples of magnetic multilayers: A unified picture

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We discuss the magnetic-field dependence of the magnetoresistance MR(H) of magnetic multilayers for samples in the as-prepared state (meaning the first time the magnetic field is swept), pointing out the importance of the electron-scattering mean-free path. We show that the value of MR(0) in the as-prepared state is related to MR(H) data for field-swept samples (meaning samples for which the magnetic field has been swept back and forth). We use this relationship to obtain the value of MR(0) for an as-prepared sample. Our prediction agrees with the data.

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I. INTRODUCTION. The giant magnetoresistance exhibited by magnetic multilayers has remained the subject of intense activity since the effect was first discovered two decades ago.[1] Of particular interest are measurements in the current perpendicular to the plane of the layer (CPP) mode of the magnetic-field dependence of the magnetoresistance MR(H) for multilayers containing two types of magnetic layers (denoted 2M multilayers).[2–12]

There are two distinct experimental situations. One may measure the MR(H) curve *after* the magnetic field has been swept back and forth, which is the usual case. Further cycling of the field does not change MR(H). Alternatively, one may measure the MR(H) curve for an as-prepared sample, meaning the *first time* that the magnetic field is swept. Very different results were obtained[9] for MR(H) for these two situations. We shall here discuss the value of MR(0) for the as-prepared sample, showing that this value can be obtained from the MR(H) data for field-swept samples. The analysis is based on the role played by the electron-scattering mean-free path in determining MR(H), both for as-prepared samples as well as for field-swept samples.

An important advance in our understanding of as-prepared samples came from the measurements of Borchers *et al.*[13] These workers measured a sample whose nonmagnetic spacer layer was thick enough to ensure the absence of exchange coupling between neighboring magnetic layers. Nevertheless, they found that, in the as-prepared state, about 60% of the domains in neighboring magnetic layers were oriented antiparallel, an effect that completely disappeared after the field was swept. They concluded correctly that the qualitative explanation for the unusual MR(H) curves observed for as-prepared samples resulted from the antiparallel orientation of the neighboring magnetic layers. However, no attempt was made at a *quantitative* explanation of the MR(H) curves.

We shall see that the measured magnetic properties of as-prepared samples permit one to determine the *magnitude* of MR(H). In particular, a single datum from the magnetic properties suffices in yielding the magnitude of MR(0) for the as-prepared samples. The single datum required is that 60% of the domains were observed[13] to be oriented antiparallel in the as-prepared state. It will be shown that this datum, together with the MR(H) data for the *field-swept* samples, is sufficient to yield MR(0) for the *as-prepared* samples. We also show that, in complete contrast to field-swept samples, MR(H) for as-prepared samples is predicted to be virtually the same for both the interleaved and the separated configurations. This prediction is in agreement with experiment.

We previously showed[14] that the electron-scattering mean-free path plays an important role in determining the MR(H) curves for field-swept samples, and we here extend the analysis to as-prepared samples. Thus, a unified picture emerges for MR(H) of 2M multilayers, both for as-prepared samples as well as for field-swept samples.

MR(H) *data.* A key feature of 2M multilayers is that the same set of magnetic layers can be arranged in different structures. The two structures most commonly studied are: $[\mathrm{M1/NM/M2/NM}]_N$ (interleaved configuration) and $[\mathrm{M1/NM}]_N[\mathrm{M2/NM}]_N$ (separated configuration), where M1 and M2 denote the two types of magnetic layers, NM denotes the nonmagnetic spacer layer, and the subscript N gives the number of repeats.

Figure 1 displays the MR(H) data[9] both for the as-prepared state (full symbols) and also after the field has been cycled (empty symbols). The lines are drawn to guide the eye. These data were obtained for 2M multilayers for which M1 is Co(60 Å), M2 is Co(10 Å), NM is Cu(200 Å), and the number N of repeats is eight.

The MR(H) data for as-prepared samples (full symbols) are very different from the MR(H) data obtained after sweeping the field (open symbols), and this is true for both the interleaved and the separated configurations. Moreover, for the as-prepared samples, the MR(H) curves are seen to be very similar for both configurations, with both configurations having MR(0)=27%.

In complete contrast to these results, *after* sweeping the field, the MR(H) curves are very different for the two configurations. In particular, for the separated configuration [Fig. 1(a)], the peak value of MR(H) for the as-prepared sample is about twice as large as the peak value after sweeping the field. Moreover, for as-prepared samples, the peak in MR(H) occurs at $H=0$ for both configurations, whereas after sweeping the field, the peak occurs at a nonzero field. All these results find a natural explanation in our analysis.

II. DISCUSSION. For the thin multilayers under consid-

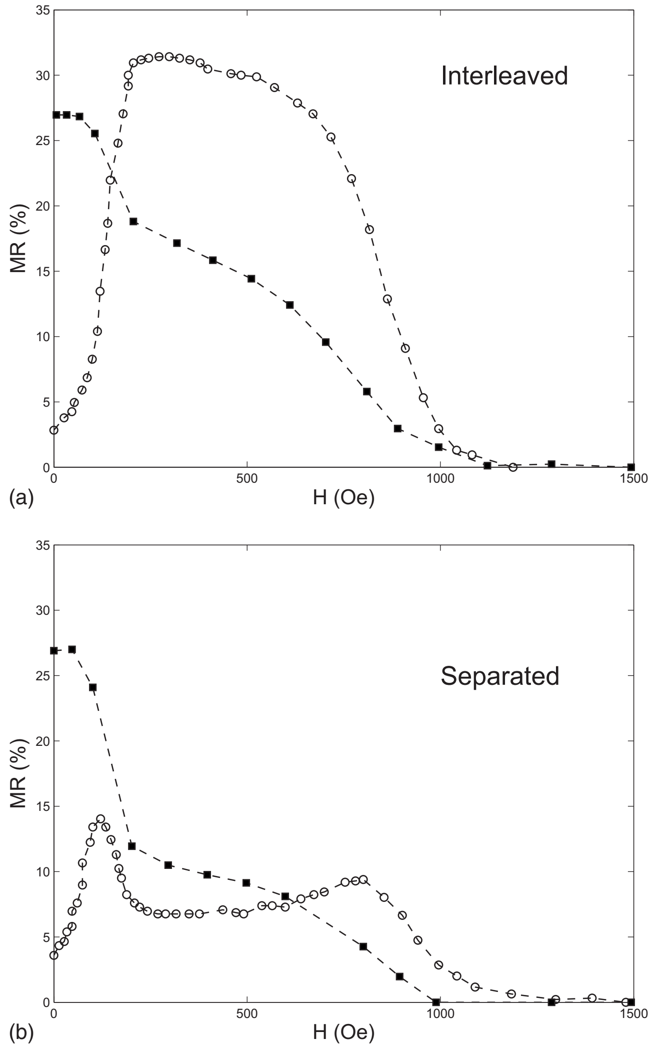

FIG. 1. Values of MR(H) as a function of the magnetic field for the 2M multilayer for which M1 is Co(60 Å), M2 is Co(10 Å), NM is Cu(200 Å), and the number of repeats is eight. The full and empty symbols correspond to MR(H) before and after the field was swept for the first time, respectively. The lines have been drawn to guide the eye. (a) and (b) present the data for the interleaved and the separated configurations, respectively.

eration, the electron mean-free path is longer than the thickness of the magnetic layers. If the electron mean-free path is long enough to include two magnetic layers, the electron will be scattered by the combined potential of both layers.[7,12] If the moments of the two neighboring magnetic layers are antiparallel at zero magnetic field, spin-dependent electron scattering makes a large contribution to MR(H), whereas if the moments are parallel, there will be only a minimal contribution. There is also a contribution to MR(H) due to interface scattering. However, since the probability for interface scattering also depends on whether the moments are aligned parallel or antiparallel, the same analysis covers both bulk and interface scatterings. Before discussing MR(H) for as-prepared samples, we review the calculation of MR(H) for field-swept samples.

A. Interleaved configuration after the field has been swept. In the interleaved configuration, neighboring magnetic layers (M1 and M2) are different in the sense that they have different saturation fields. Figures 2(a)–2(d) depict the orientation of the magnetic moments of neighboring magnetic layers for different strengths of the magnetic field. Applying a large negative field [Fig. 2(a)] aligns all the moments, and thus MR(H)=0. Increasing the field to H=0 does not significantly affect the orientation of the moments, which are still aligned in the negative direction [Fig. 2(a)]. This is not strictly true because of domain formation as the field approaches zero and, accordingly, one observes (Fig. 1) a small nonzero value for MR(0). However, for the present discussion, we may neglect this nuance.

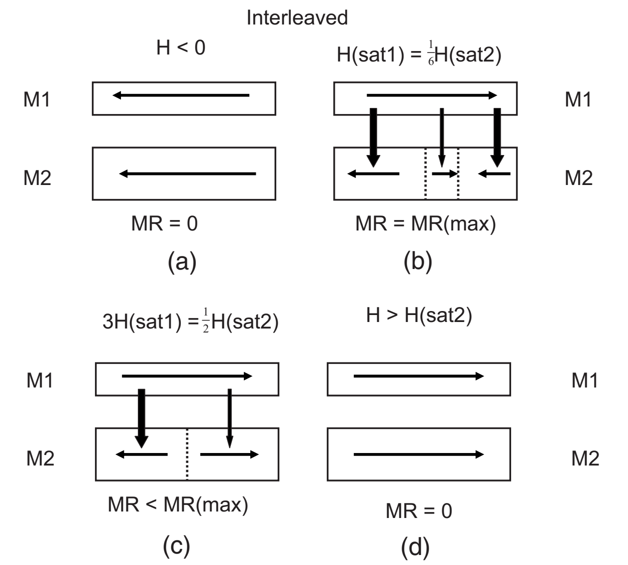

FIG. 2. The horizontal arrows represent the orientation of the magnetic moments in neighboring magnetic layers in the interleaved configuration for various values of the magnetic field. The thick and thin vertical arrows correspond to antiparallel and parallel relative orientations of the moments, respectively, in neighboring magnetic layers.

We denote the saturation fields for magnetic layers M1 and M2 by H(sat1) and H(sat2), respectively, where $H(\mathrm{sat2}) \cong 6(H\mathrm{sat1})$ for the layers under consideration, because the saturation field depends inversely on the thickness of the magnetic layer.

Figure 2(b) depicts the situation at the field H=H(sat1). The moments in layer M1 are all aligned in the positive direction, whereas in layer M2, only about one sixth of the moments are aligned in the positive direction since $H = H(\mathrm{sat2})/6$. The rest of the moments in layer M2 are still oriented in the negative direction.

In Fig. 2, we have depicted the orientation of all the moments being parallel to the plane of the layers. Although there also exist small domains orientated in different directions, our discussion concentrates on the large domains.

We now consider electron scattering. At H(sat1), most of the moments of the M2 layer into which the electron is scattered are oriented antiparallel to the moments in the M1 layer. If the electron is scattered from layer M1 into an M2 domain with antiparallel orientation of the moments [shown schematically by the thick vertical arrow in Fig. 2(b)], there will be a large contribution to MR(H). It is easy to see that scattering into an antiparallel domain occurs most frequently at $H(\text{sat1})$, implying that the peak value of $\text{MR}(H)$ occurs at $H(\text{sat1})$.

There are also domains of the M2 layer for which the moments are oriented parallel to the moments in the M1 layer. Electron scattering from M1 to those domains [shown schematically by the thin vertical arrow in Fig. 2(b)] makes only a minimal contribution to $\text{MR}(H)$. However, most of the electrons scatter into domains having antiparallel orientation of the moments.

The vertical arrows (thick and thin) are schematic. The trajectory of the electron can make an arbitrary angle to the plane of the magnetic layers. What is important for $\text{MR}(H)$ is whether the moments at the initial and final domains of the electron trajectory are parallel or antiparallel.

Figure 2(c) depicts the situation at $H=3H(\text{sat1})$. The moments in layer M1 are unchanged, having already saturated in the positive direction. However, in layer M2, half the moments are now oriented in the positive direction since $H=\frac{1}{2}H(\text{sat2})$. Therefore, half the moments of layer M2 are oriented antiparallel to the moments in layer M1 [thick arrow in Fig. 2(c)], whereas the other half are oriented parallel [thin arrow in Fig. 2(c)]. As a result, the value of $\text{MR}(H)$ is much reduced.

Finally, in Fig. 2(d), the magnetic field is further increased to $H=H(\text{sat2})$. Layer M2 now has all its moments oriented parallel to the moments in layer M1. Therefore, $\text{MR}(H)$ falls back to zero.

We note that the peak in $\text{MR}(H)$ is *asymmetrical* because $\text{MR}(H)$ attains its maximum value as the field increases from zero to $H(\text{sat1})$ but does not fall back to zero until the field reaches $H(\text{sat2})$, which is six times as large as $H(\text{sat1})$. The open symbols of Fig. 1(b) do indeed correspond to an asymmetrical peak.

B. Separated configuration after the field has been swept. In the separated configuration, we may treat separately each of the two groups of identical magnetic layers since each group contributes a separate peak to $\text{MR}(H)$. The boundary layer is not important for discussing the peaks because its contribution to $\text{MR}(H)$ occurs mainly in the valley between the two peaks.[7]

Consider the M1 layers. Figure 3(a) is identical to Fig. 2(a) and depicts the orientation of the moments after sweeping the field in the negative direction, which aligns all the moments. When the magnetic field is increased past zero to the coercive field, $H=H(\text{coer})=\frac{1}{2}H(\text{sat1})$, the magnetization vanishes because each M1 layer has a domain structure in which half the moments points in each direction [Fig. 3(b)].

The important question for $\text{MR}(H)$ is the relative orientations of the moments in the upper and lower M1 layers between which the electron traverses. The portions of the M1 layer with moments antiparallel to those in the neighboring-layer domain [thick arrow in Fig. 3(b)] will make a large contribution to $\text{MR}(H)$, whereas there will only be a minimal contribution from those portions for which the moments in the neighboring-layer domains are parallel [thin arrow in Fig. 3(b)]. At the coercive field [Fig. 3(b)], the two portions are equal. For the separated configuration, this is the maximum amount of electron scattering into a neighboring layer having antiparallel orientation of its moments.

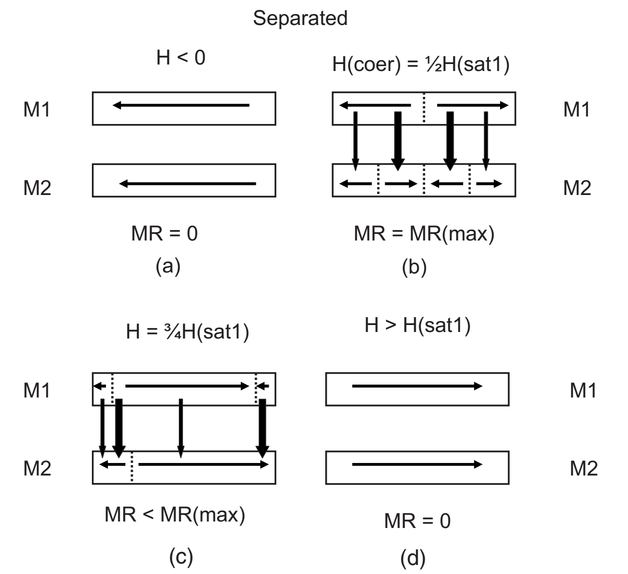

FIG. 3. The horizontal arrows represent the orientation of the magnetic moments in neighboring magnetic layers in the separated configuration for various values of the magnetic field. The thick and thin vertical arrows correspond to antiparallel and parallel relative orientations of the moments, respectively, in neighboring magnetic layers.

As one increases the field to $H=\frac{1}{2}H(\text{sat1})$, three quarters of the moments in both layers are oriented in the positive direction [Fig. 3(c)]. For this field, only a quarter of the upper M1 layer has moments oriented antiparallel to those that lie below [thick arrows in Fig. 3(c)]. For most of the M1 layers, the moments of neighboring-layer domains are oriented parallel [thin arrows in Fig. 3(c)]. Therefore, the value of $\text{MR}(H)$ is reduced. When the field is further increased to $H=H(\text{sat1})$, the moments are parallel throughout the M1 layers [Fig. 3(d)] and $\text{MR}(H)$ vanishes. The above discussion shows that the M1 layers produce a *symmetrical* peak in $\text{MR}(H)$ that is centered around the coercive field of the M1 layers.

The discussion for the M2 layers is identical and, therefore, the M2 layers also produce a symmetrical peak in $\text{MR}(H)$ centered around the M2 coercive field. The total $\text{MR}(H)$ curve will be the sum of these two peaks, plus the contribution due to the boundary layer that lies in the valley between the peaks,[7] as given by the open symbols of Fig. 1(a).

C. As-prepared samples. We now contrast these results to those obtained for an as-prepared sample. The important feature of as-prepared samples is the antiparallel correlation between the moments of the domains of neighboring magnetic layers.[13] This feature permit us to obtain an accurate estimate of $\text{MR}(0)$ for the as-prepared sample from the $\text{MR}(H)$ data from swept samples.

One can readily understand why the maximum value of $\text{MR}(H)$ occurs at zero field. Applying a magnetic field reduces the degree of antiparallel orientation of the moments of neighboring-layer domains. Therefore, in contrast to the field-swept samples, for the as-prepared samples, MR(max) occurs at zero field.

D. Estimate of MR(0) for as-prepared samples. We now turn to the central result of the analysis, namely, determining the value of MR(0). In an as-prepared sample, neighboring-layer domains have antiparallel orientation. This sample corresponds roughly to the interleaved configuration at H(sat1), as shown in Fig. 2(b).

If *all* the neighboring-layer domains were oriented antiparallel throughout the as-prepared multilayer stack, then MR(0) would be 31%, which is the measured value of MR-(max) for the interleaved configuration [Fig. 1(b)]. However, the experiments show[13] that, in the as-prepared state, only about 60% of the neighboring-layer domains are oriented antiparallel. Therefore, these 60% antiparallel domains contribute to MR(0) about 60% of the peak value for the interleaved configuration, which is 19%. The value of 60% of the domains having antiparallel orientation is the *only datum* from the as-prepared sample that we use to obtain our estimate of MR(0).

The remaining 40% of the domains are uncorrelated in the as-prepared sample. (Although the division into antiparallel domains and uncorrelated domains is, of course, artificial, it is adequate for our purposes.) One may obtain the contribution to MR(0) arising from these 40% uncorrelated domains as follows. Random orientation of the moments implies the same probability for the electron to be scattered into a neighboring-layer domain having parallel or antiparallel orientation of the moments. This situation at *zero field* for the as-prepared sample corresponds precisely to the situation at the *coercive field* for the separated configuration for the field-swept sample [see Fig. 3(b)], where the peak in MR(H) occurs.

According to Fig. 1(a), for the separated configuration, the measured MR(max) is 16% for the M1 layers and 11% for the M2 layers. However, since only 40% of the neighboring layers are uncorrelated, the contribution to MR(0) for the as-prepared sample is only 40% of these peak values, that is, about 6% from the M1 uncorrelated layers and about 4% from the M2 uncorrelated layers. Therefore, for the as-prepared sample, the total contribution to MR(0) from the uncorrelated domains is the sum of these two partial contributions, or about 10%.

Adding these two contributions to MR(0), namely, 19% (from antiparallel neighboring-layer domains) and 10% (from uncorrelated neighboring-layer domains), yields a predicted value of 29% for MR(0) for the as-prepared sample, in reasonable agreement with the measured value of 27% (Fig. 1).

E. Interleaved and separated configurations in the as-prepared state. A very important point is that the above discussion of MR(0) for the as-prepared samples does not distinguish between the interleaved and separated configurations. For both configurations, before the field is swept, the moments in neighboring-layer domains are partially antiparallel and partially uncorrelated. Therefore, the present analysis predicts that the value of MR(0) should be the *same* for both configurations. In accordance with this prediction, the measured value of MR(0) for the as-prepared samples is found to be 27% for *both* configurations.

F. Speculative note. We end on a speculative note. For the as-prepared samples, MR(0) is the same for the two configurations. However, a slight difference is observed between the shapes of the MR(H) curves, with MR(H) decreasing faster with increasing field for the separated configuration. A possible reason for this slight difference might be the following. Borchers *et al.*[13] have proposed that the measured antiparallel orientation of neighboring-layer domains is induced by the dipolar interactions arising from the magnetic fields at the edges of the micron-sized domains. The dipolar interactions might be different depending on whether or not neighboring-layer domains have the same thickness. Borchers *et al.*[13] measured Co/Cu multilayers for which all the magnetic layers had the same thickness. Therefore, their experimental results for as-prepared samples would correspond to the *separated* configuration for 2M multilayers. However, for the *interleaved* configuration, for which neighboring magnetic layers have different thicknesses, the dipolar interaction might have a different magnetic-field dependence. This would cause the shape of the MR(H) curves to be somewhat different for the two configurations.

III. SUMMARY. We have presented a unified picture of the magnetoresistance for 2M magnetic multilayers that enables one to obtain MR(0) for as-prepared samples from the measured MR(H) data for field-swept samples.

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