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► **To cite this version:**

Lisa Michez, B J Hickey, Smadar Shatz, Nathan Wisser. Direct evidence for mean-free-path effects in the magnetoresistance of magnetic multilayers with the current perpendicular to the planes. *Physical Review B*, 2004, 70 (5), pp.052402. 10.1103/physrevb.70.052402 . hal-04063695

**HAL Id: hal-04063695**

**<https://hal.science/hal-04063695>**

Submitted on 9 Apr 2023

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# Direct evidence for mean-free-path effects in the magnetoresistance of magnetic multilayers with the current perpendicular to the planes

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(Received 10 September 2003; revised manuscript received 11 February 2004; published 13 August 2004)

Experimental evidence is presented showing that for magnetic multilayers measured in the CPP mode (current perpendicular to the planes), the magnetic-field dependence of the magnetoresistance  $MR(H)$  is dominated by scattering processes in which the electron is scattered by the potential due to *pairs* of neighboring magnetic layers. It is demonstrated experimentally that curtailing such scattering processes leads to a significant decrease in  $MR(H)$ . These results are confirmed by a calculation.

DOI: 10.1103/PhysRevB.70.052402

PACS number(s): 75.70.Cn, 73.40.-c, 75.47.De

## INTRODUCTION

The giant magnetoresistance exhibited by magnetic multilayers continues to be the subject of intense activity since the effect was discovered over a decade ago.<sup>1</sup> We shall here report the results of measurements of the magnetic-field dependence of the magnetoresistance  $MR(H)$  measured in the CPP mode (current perpendicular to the plane of the layers).<sup>2</sup>

Earlier measurements of  $MR(H)$  in the CPP mode had dealt with multilayers consisting of one type of magnetic layer (denoted 1M multilayers). For 1M multilayers, the  $MR(H)$  curve is a single symmetrical peak and the quantity of interest is the magnitude of this peak, which is well accounted for by the comprehensive Valet-Fert theory.<sup>3</sup>

More recently,  $MR(H)$  measurements have been carried out for multilayers consisting of two different types of magnetic layers (denoted 2M multilayers).<sup>4-8</sup> For 2M multilayers, the  $MR(H)$  curve exhibits considerable structure, consisting of one or more peaks, which may be symmetrical or asymmetrical. A satisfactory explanation of these data should account for the detailed *shape* of the  $MR(H)$  curve, including the number of observed peaks, their location as a function of magnetic field, and explaining why certain peaks are symmetrical whereas others are asymmetrical. Since the Valet-Fert theory has not yet been generalized to calculate  $MR(H)$  curves as a function of magnetic field, we use a phenomenological theory<sup>9</sup> to analyze our  $MR(H)$  data.

We had previously proposed that the electron mean free path  $\lambda$  is *central* to explaining  $MR(H)$  data for 2M multilayers.<sup>6</sup> In particular, for long  $\lambda$ ,  $MR(H)$  is dominated by scattering events in which the electron is scattered by the potential due to pairs of neighboring magnetic layers. Our proposal became the subject of controversy, having been challenged<sup>7</sup> and subsequently defended.<sup>8</sup> The matter is still unresolved, with both sides claiming that the  $MR(H)$  data can be explained according to their respective interpretations.

In the present paper, we shed additional light on this controversy by presenting  $MR(H)$  data obtained from 2M multilayers specially prepared to curtail electron scattering by

pairs of neighboring magnetic layers. For these specially prepared multilayers, we find that  $MR(H)$  is significantly reduced. The observed decrease in  $MR(H)$  is shown to agree with our prediction. This supports the proposal that electron scattering by pairs of neighboring magnetic layers must be taken into account to explain the  $MR(H)$  data.

## EXPERIMENTAL DETAILS AND SAMPLE PREPARATION

We are dealing with 2M multilayers in the separated configuration, consisting of the following structure:  $[M1/NM]_N[M2/NM]_N$ , where M1 and M2 denote the two types of magnetic layers, NM is the nonmagnetic spacer layer, and the subscript  $N$  gives the number of repeats ( $N=6$  for our samples). The nonmagnetic layer is sufficiently thick (250 Å for our multilayers) to ensure that there is no coupling between neighboring magnetic layers.

The multilayers were grown using a sputtering system consisting of dc-magnetrons for the deposition of Cu, Co and Nb. Our CPP measurements use the superconducting Nb electrode technique, developed by Pratt *et al.*<sup>2</sup> The CPP multilayers are sandwiched between strips of Nb that are 0.5 mm wide. The superconducting equipotential ensures that the current is perpendicular to the layers.

The samples were prepared as follows. A Nb strip, of thickness 1500 Å, is first deposited on a silicon substrate, followed by 200 Å of Cu deposited as a buffer layer. The required multilayer is then deposited. Finally, a strip of Nb, of thickness 1500 Å, is grown on top of the multilayer.

We use a SQUID-based current comparator, which enables us to measure changes in the sample resistance of order 10 pΩ. To avoid driving the Nb normal, the resistivity measurements are performed at 4.2 K in magnetic fields below 3 kOe.

For our two magnetic layers, we chose Co of 70 Å thickness and Co of 20 Å thickness. This choice yields two magnetic layers whose magnetizations reverse direction at very different fields. The saturation fields are about 400 Oe for Co(70 Å) and about 700 Oe for Co(20 Å).

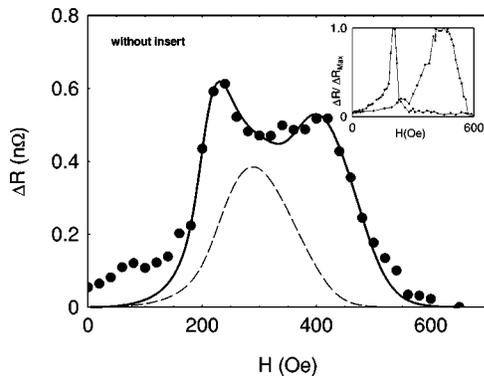


FIG. 1. Magnetic-field dependence of the magnetoresistance of the 2M multilayer described in the text, with  $N=6$  repeats. The symbols give the data, the solid curve gives the calculated values, and the dashed curve gives the contribution to  $MR(H)$  arising solely from the boundary layer. The inset gives the  $MR(H)$  curves for two 1M multilayers, as explained in the text.

#### DATA AND QUALITATIVE DISCUSSION

The measured  $MR(H)$  data are given in Fig. 1. (The calculated curves will be explained presently.) The difference in the saturation fields  $H_{sat}$  for Co(70 Å) and for Co(20 Å) is expected to lead two well-defined peaks in  $MR(H)$ , separated by a “valley,” one peak corresponding to each type of magnetic layer, centered at its coercive field (about half  $H_{sat}$ ).

The two peaks are indeed present in the  $MR(H)$  data, but the peaks are not separated by the expected deep “valley.” Rather, the “valley” between the two peaks has been washed out by an additional contribution to  $MR(H)$ .

To clarify this point, we also give (inset in Fig. 1) previously reported  $MR(H)$  data<sup>10</sup> for two similar 1M multilayers, each consisting of only one type of magnetic layer, either Co(70 Å) or Co(10 Å). These data show, as expected, that each 1M multilayer exhibits one peak in  $MR(H)$  centered at its coercive field. Moreover, the sum of the two 1M  $MR(H)$  curves in the inset exhibits the expected deep valley between the two peaks. Similar results for  $MR(H)$  for 1M multilayers had also been previously reported by others.<sup>11</sup>

The question raised by the  $MR(H)$  data in Fig. 1 is the following. What feature is present in the 2M multilayer but absent in 1M multilayers that accounts for the additional contribution to  $MR(H)$  between the two peaks?

Our answer is that the extra feature present in the 2M multilayer is the boundary layer M1/NM/M2 between the two types of magnetic layers. The contribution to  $MR(H)$  due to this boundary layer causes the 2M  $MR(H)$  data to differ from the sum of the two 1M  $MR(H)$  curves.

This can be demonstrated experimentally. To show that pushing up the valley in the  $MR(H)$  data in Fig. 1 is due to the boundary layer, we prepared 2M multilayers (to be described presently) whose boundary layer makes a much reduced contribution to  $MR(H)$ . Measuring  $MR(H)$  for these two such specially prepared 2M multilayers yields the data shown in Figs. 2 and 3. (The calculated curves will be explained presently.) It is seen that for each multilayer, the valley between the peaks is indeed deep, in contrast to the  $MR(H)$  data of Fig. 1. In fact, the  $MR(H)$  data of Figs. 2 and

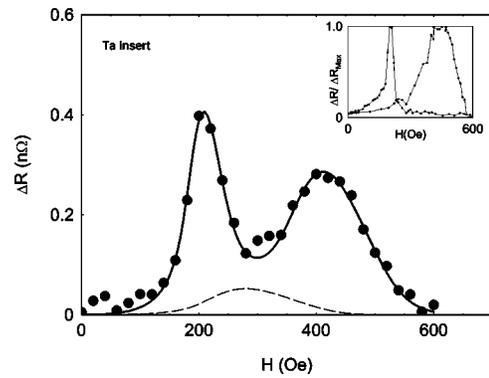


FIG. 2. Magnetic-field dependence of the magnetoresistance of the multilayer in Fig. 1, except that a 50 Å layer of Ta has been inserted in the nonmagnetic boundary layer. The symbols give the data, the solid curve gives the calculated values, and the dashed curve gives the contribution to  $MR(H)$  arising solely from the boundary layer. The inset gives the  $MR(H)$  curves for two 1M multilayers, as explained in the text.

3 resemble the sum of the two sets of  $MR(H)$  curves obtained for two similar 1M multilayers (see inset of each figure).

Consider a hypothetical 2M multilayer (denoted h2M), whose  $MR(H)$  consists of the sum of the values of  $MR(H)$  for two 1M multilayers having saturation fields of, say, 50 and 500 Oe. At the negative saturation field,  $MR(H)=0$  because all the magnetic moments are aligned. As the magnetic field passes through zero and reaches 50 Oe, the values of  $MR(H)$  will again be nearly zero because, once again, all the magnetic moments are aligned, or nearly aligned, in each of the two 1M multilayers. The first 1M multilayer has saturated (its  $H_{sat}=50$  Oe), whereas the moments of the other 1M multilayer are but little affected by such a small field (its  $H_{sat}=500$  Oe). Hence, the  $MR(H)$  curve for the h2M multilayer will exhibit a deep valley at a field of 50 Oe. However, such a deep valley in  $MR(H)$  is not observed in the data of Fig. 1.

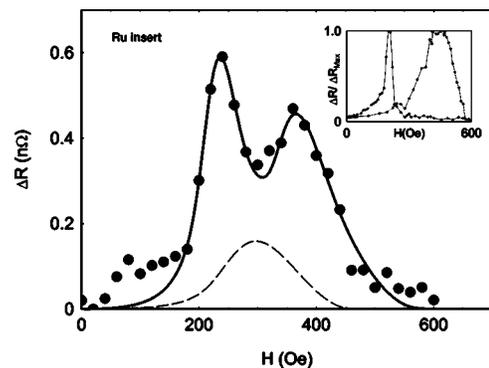


FIG. 3. Magnetic-field dependence of the magnetoresistance of the multilayer in Fig. 1, except that a 20 Å layer of Ru has been inserted in the nonmagnetic boundary layer. The symbols give the data, the solid curve gives the calculated values, and the dashed curve gives the contribution to  $MR(H)$  arising solely from the boundary layer. The inset gives the  $MR(H)$  curves for two 1M multilayers, as explained in the text.

The partial washing out of the valley in the MR(H) data of Fig. 1 must be due to the M1/NM/M2 boundary layer, which is the only difference between the actual, measured 2M multilayer and the hypothetical h2M multilayer. However, the boundary layer can play an important role in MR(H) only if the electron “feels” *both* the M1 and the M2 magnetic layers before scattering, and this can occur only if the mean free path  $\lambda$  is sufficiently long.

This explains the importance of  $\lambda$  for determining MR(H).

### PREPARING THE “HYPOTHETICAL” 2M MULTILAYER

We used the following technique to prepare 2M multilayers whose boundary-layer contribution to MR(H) is curtailed. We inserted into the nonmagnetic spacer layer between the M1 layers and the M2 layers a thin layer of a transition metal having large spin-orbit coupling. In Figs. 2 and 3, we present the MR(H) data for such 2M multilayers, whose thin inserted layer was Ta (Fig. 2) or Ru (Fig. 3). It has been shown by experiments on spin valves that passing an electron through a thin layer of a transition metal tends to “erase the spin memory” of the electron.<sup>12</sup> Therefore, for our 2M multilayers with transition-metal inserts, the electron spin memory is partially erased as the electron traverses the boundary layer from the last M1 magnetic layer to the first M2 magnetic layer. This serves to isolate the M1 magnetic layers from the M2 magnetic layers. Since the electron does not simultaneously “feel” both the M1 layer and its neighboring M2 layer, the boundary layer will make a reduced contribution to MR(H). As a result, the MR(H) data from such a specially prepared 2M multilayer is expected to exhibit a deep valley between the two peaks. This prediction is confirmed in Figs. 2 and 3.

It should be noted that the resistance of the multilayer (8.8 n $\Omega$ ) is only changed by a few percent upon insertion of the thin layer of Ta or Ru. The transition-metal layer is inserted into only one spacer layer, whereas the multilayer contains  $2N=12$  magnetic layers. Hence, the change in total resistance is small.

We also measured the magnetization of our three samples and found virtually identical results. This confirms that the magnetization of the multilayer is not affected by the insertion of the single transition-metal layer.

### CALCULATIONS

These ideas can be confirmed quantitatively. The scattering probability of an electron is determined by the angle between the electron spin and the magnetic moment of the magnetic layer.<sup>13</sup> Since  $\lambda$  is larger than the thickness of the nonmagnetic layer, one must consider the electron as being scattered by the combined potential of a *pair* of neighboring magnetic layers. The contribution of this scattering event to MR(H) is given by the cosine of the angle  $\theta_{ij}$  between the moments of the neighboring (denoted  $i$  and  $j$ ) magnetic layers. According to the phenomenological theory of Wiser,<sup>9</sup> for the geometry under consideration here,

$$\text{MR}(H) = \sum_{ij} c_{ij} [1 - \cos \theta_{ij}(H)]^2, \quad (1)$$

where the sum is taken over all  $2N-1$  pairs  $i, j$  of neighboring magnetic layers, and the angles  $\theta_{ij}(H)$  depend on the magnetic field. For a 2M multilayer in the separated configuration, the sum in (1) can be written as three terms

$$\begin{aligned} \text{MR}(H) = & A_{11} [1 - \cos \theta_{11}(H)]^2 + A_{22} [1 - \cos \theta_{22}(H)]^2 \\ & + c_{12} [1 - \cos \theta_{12}(H)]^2, \end{aligned} \quad (2)$$

where the coefficients  $A_{11}$  and  $A_{22}$  represent, respectively, the contributions to MR(H) due to all  $N-1$  neighboring pairs of M1 magnetic layers and due to all  $N-1$  neighboring pairs of M2 magnetic layers. The last term represents the contribution of the single boundary layer, consisting of one M1-M2 pair of neighboring magnetic layers.

For a 1M multilayer, one obtains *either* the first term *or* the second term in (2). However, the MR(H) curve for the 2M multilayer is given by all three terms in (2). It is the third term in (2) that washes out the valley between the two peaks of MR(H) in Fig. 1.

### BOUNDARY LAYER

One might think that the boundary layer cannot make an important contribution to MR(H), because there is only one boundary pair of magnetic layers as compared to  $2N-2$  non-boundary pairs of magnetic layers. However, such an assessment would be in error. The boundary-layer contribution to MR(H) is important for two reasons: its large magnitude and the position of its peak.

The reason for the large magnitude of the third term in Eq. (2) is that the angle  $\theta_{12}$  is much larger than the angles  $\theta_{11}$  and  $\theta_{22}$ . It is clear from (2) that the larger the angle, the larger the value of the term.

However, there is also a second reason for the importance of the boundary-layer term, which relates to the *position* of its peak. We shall see that the peak of the third term in (2) is located precisely in the valley between the two MR(H) peaks due to the first two terms. Therefore, the effect of the boundary-layer contribution is to raise the valley floor, which tends to wash out the valley in MR(H).

These points can be clarified by discussing the magnetic-field dependence of the angles  $\theta_{ij}(H)$ . If the magnetic layers were ideal single-domain structures, then the magnetic moments of each magnetic layer would react identically to the magnetic field and the angles  $\theta_{11}$  and  $\theta_{22}$  would both be zero at all fields. However, because of domains and structural imperfections, each magnetic layer reverses its magnetization at a somewhat different rate. As a result, the angles  $\theta_{11}$  and  $\theta_{22}$  become nonzero as the field increases, pass through a maximum at the coercive field, and then decrease to zero at the saturation field. Numerical calculations show that the maximum value of these angles lies within the range  $30^\circ$ – $60^\circ$ .

Now consider the boundary-layer angle  $\theta_{12}$ . It is readily seen from the following example that the maximum value of  $\theta_{12}$  can be quite large. Suppose that the saturation magnetic field for the second type of magnetic layer,  $H_{sat,2}$ , is three

times larger than that for the first type of magnetic layer,  $H_{sat,1}$ . Then, as the field increases up to  $H_{sat,1}$ , the angle  $\theta_1$  increases to  $180^\circ$ , while the angle  $\theta_2$  increases only to  $60^\circ$ . Therefore, at  $H=H_{sat,1}$ , the angle  $\theta_{12}=120^\circ$ , much larger than the maximum values of  $\theta_{11}$  and  $\theta_{22}$ .

The maximum boundary-layer contribution to MR(H) occurs at the magnetic field at which  $\theta_{12}(H)$  takes its maximum value. This field is  $H_{sat,1}$  which is precisely the field at which  $\theta_{11}(H)$  drops to zero, which is the position of the valley between the two peaks in MR(H). Since the maximum boundary-layer contribution to MR(H) occurs at the field between the two peaks, the boundary-layer contribution tends to wash out the valley in the MR(H) curve.

### COMPARISON WITH EXPERIMENT

To evaluate Eq. (2) for MR(H), we took the three coefficients ( $A_{11}, A_{22}, c_{12}$ ) to be adjustable parameters, determined by fitting to the MR(H) data. The resulting values for MR(H) are given by the solid curves in Figs. 1–3. For each multilayer, we found agreement between the calculated values and the experimental data.

To discuss the important role of the boundary layer, we display (dashed curve in each figure) the contribution to

MR(H) due *solely* to the boundary layer. As expected, the peak of the boundary-layer contribution lies in the valley between the peaks due to the two sets of magnetic layers.

For the 2M multilayer without an insert (Fig. 1), the boundary-layer peak was found to be very large, thus confirming our qualitative discussion. In fact, the boundary-layer peak is not much smaller than the other two peaks, being 73% of the smaller peak. By contrast, for the multilayers having an insert (Figs. 2 and 3), the boundary-layer peak is much reduced. For these multilayers, the ratios of the boundary-layer peak to the smaller peak are only 18% and 34%, respectively, which are two to four times smaller than for the multilayer without an insert. Thus, one sees that the transition-metal insert does indeed cause a substantial reduction in MR(H) in the region between the peaks.

### CONCLUSION

For 2M multilayers, we have shown the importance to MR(H) of electron scattering events involving the potential due to pairs of neighboring magnetic layers. The MR(H) data are found to be significantly reduced for specially prepared 2M multilayers for which such scattering events are curtailed.

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<sup>10</sup>See Ref. 8, Fig. 2.

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