Magnetoresistance of magnetic multilayers: a phenomenological approach

2006 J. Phys.: Condens. Matter 18 4641

(http://iopscience.iop.org/0953-8984/18/19/017)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS: CONDENSED MATTER

J. Phys.: Condens. Matter **18** (2006) 4641–4647 doi:10.1088/0953-8984/18/19/017

Magnetoresistance of magnetic multilayers: a phenomenological approach

L A Michez[1], B J Hickey[1], Smadar Shatz[2] and Nathan Wiser[2]

[1] School of Physics and Astronomy, E C Stoner Laboratory, University of Leeds, Leeds LS2 9JT, UK
[2] Department of Physics, Bar-Ilan University, Ramat-Gan, Israel

Received 6 January 2006, in final form 3 April 2006
Published 26 April 2006
Online at stacks.iop.org/JPhysCM/18/4641

Abstract

A phenomenological approach is presented for the giant magnetoresistance (GMR) of magnetic multilayers oriented in the CPP mode (current perpendicular to the plane of the layers). New results are found for the dependence of the GMR on the number of repeats of the multilayer.

1. Introduction

Since the effect was discovered nearly two decades ago, the giant magnetoresistance exhibited by magnetic multilayers has not ceased to be the subject of intense activity [1]. In recent years, interest has focused on the magnetoresistance (MR) measured in the CPP mode (current perpendicular to the plane of the layers) [2].

Earlier measurements of MR in the CPP mode had dealt with multilayers consisting of one type of magnetic layer (denoted 1M multilayers). However, it is now realized that there is much to be learned from MR measurements of multilayers consisting of two different types of magnetic layers (denoted 2M multilayers), and many such measurements have recently been carried out [3–8].

Here, we present a phenomenological approach to the calculation of the GMR for 2M multilayers. The advantage of this approach is the complete transparency of the underlying physics. Exploiting this advantage, we obtain new results for the dependence of the GMR on the number N of repeats of the 2M multilayer. Although we shall concentrate on the N-dependence of the GMR, the phenomenological approach can also be applied to the calculation of other properties of the GMR, including the dependence of the GMR on the thickness of the magnetic layers and the structure of the magnetoresistance curves as a function of the applied magnetic field.

2. N-dependence of the GMR for 2M multilayers

Interest has centred on comparing the values of the GMR for a pair of 2M multilayers with the following structures: $[\mathrm{M1/NM/M2/NM}]_N$ (interleaved configuration) and

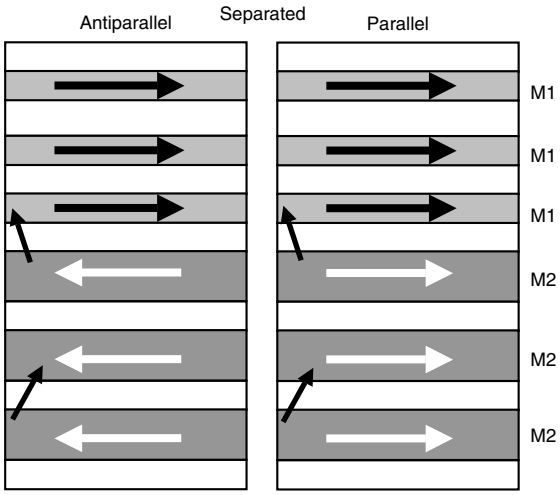

Figure 1. Schematic representation of the 2M multilayer for the separated configuration. The thick horizontal arrows give the directions of the moments in the magnetic layers (black arrows for M1 and white arrows for M2), whereas the thinner nearly vertical arrows depict the trajectories of representative electrons between spin flips. The left-hand side and the right-hand side of the figure represent the antiparallel and the parallel states, respectively.

$[\mathrm{M1/NM}]_N[\mathrm{M2/NM}]_N$ (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. The NM layer is sufficiently thick to ensure that there is no coupling between neighbouring magnetic layers. These two configurations differ only in the ordering of the magnetic layers.

The GMR is defined by $\Delta R/R$, where ΔR is the difference in resistance for the parallel and antiparallel alignments of the magnetic moments of neighbouring magnetic layers. We have calculated the GMR for the two configurations as a function of the number of repeats N, to be denoted GMR(N).

We find that for the separated configuration, GMR(N) *first increases, but then sharply decreases* with increasing N. In complete contrast to this result, for the interleaved configuration, GMR(N) *always increases* with increasing N. Moreover, the increase in GMR(N) for the interleaved configuration is rather modest (tens of per cent), whereas the decrease in GMR(N) for the separated configuration is nearly an order of magnitude larger (factor of 2–4).

3. Separated configuration

Figure 1 illustrates the magnetic multilayer $N = 3$ in the separated configuration. The left-hand side of the figure represents the antiparallel state, meaning that the magnetic moments of the M1 layers (thick black arrows) are aligned antiparallel to the moments of the M2 layers (thick white arrows). One can obtain such an alignment if there is a large difference in the coercive fields for the two magnetic layers. (The thinner nearly vertical arrows will be discussed soon.) If a strong magnetic field is applied, the directions of the magnetic moments of the M1 and the M2 layers become parallel, as illustrated in the right-hand side of the figure.

Figure 1 shows that upon applying a strong saturating magnetic field, the only change that occurs in the multilayer is the alignment of the M1 moments relative to the M2 moments.

However, *within* the group of M1 layers and *within* the group of M2 layers, the moments of the layers were aligned parallel both *before* and *after* the application of the saturation field. Therefore, if an electron were to remain *within* the M1 layers or *within* the M2 layers, then that electron would experience *no* change in resistance upon applying a saturating magnetic field and would *not* contribute to the GMR. The importance of this result comes into play when one considers spin flipping.

Since the GMR effect requires the electron to traverse the magnetic layers *without* flipping its spin, the 'effective' trajectory of the electron is limited by its spin diffusion length, which is the distance diffused by the electron *before* flipping its spin. This is shown schematically by the two vertical arrows on each side of figure 1, which represent the spin diffusion length of the two representative electrons.

Let N_0 denote the number of M1 layers that lie within the spin diffusion length of the electron. Therefore, if the electron starts its trajectory in M1 within the N_0 layers that lie nearest to the M1–M2 boundary, then the electron will reach the M2 layers without flipping its spin and thus contribute to GMR $= \Delta R/R$. All other M1 layers that lie further from the M1–M2 boundary serve only to dilute the GMR, by increasing the resistance R but without contributing to ΔR.

One may express this idea numerically by introducing a dilution factor (df). Dilution occurs if the number of M1 layers exceeds N_0. Therefore, we write

$$\mathrm{df} = \frac{A}{A + (N - N_0)}, \qquad N > N_0 \tag{1}$$

where N–N_0 gives the number of repeats beyond where dilution begins, and A is a number of order unity. For $N = N_0$, the dilution factor is unity, as required.

The N-dependence of GMR(N) for $N > N_0$ is given by

$$\mathrm{GMR}(N) = \mathrm{GMR}(N_0) \times \mathrm{df}(N), \qquad N > N_0 \tag{2}$$

where GMR(N_0) is the value of the GMR for a multilayer of N_0 repeats. In order to obtain GMR(N_0), it is first necessary to discuss the interleaved configuration.

4. Interleaved configuration

The interleaved configuration for $N = 3$ is illustrated in figure 2, where the left-hand and right-hand sides of the figure display the orientation of the magnetic moments in the antiparallel and parallel states, respectively, in analogy with figure 1. For the interleaved configuration, every M1 layer is followed by an M2 layer. This implies the important result that *every layer is a boundary layer*. In other words, *every electron* passes from an M1 layer to an M2 layer (both upper *and* lower arrows) before flipping its spin, and therefore *every electron contributes to GMR(N)*.

We now consider the implications of this result for the N-dependence of GMR(N). The resistance R (appearing in the denominator of GMR $= \Delta R/R$) contains both a spin-dependent part, R_s, which contributes to GMR(N), as well as a spin-independent part, R_si, which does not contribute to GMR(N) (because $\Delta R_\mathrm{si} = 0$, by definition). The effect of R_si is thus to 'dilute' GMR(N) and to diminish it. It follows that the larger the value of R_s relative to R_si, the smaller the dilution will be and GMR(N) will be larger. Therefore, GMR(N) will increase for any change in the multilayer that increases the ratio $R_\mathrm{s}/R_\mathrm{si}$.

The spin-independent scattering resistance R_si has two contributions, one contribution arising from the layers, R_si(layer), and a second contribution arising from other sources of scattering unrelated to the layers themselves, R_si(other). Increasing the number of magnetic layers increases both R_s and R_si(layer), whereas R_si(other) remains unchanged. Hence,

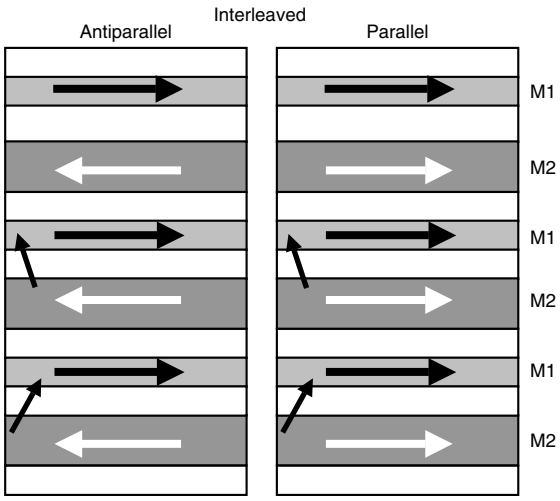

Figure 2. Schematic representation of the 2M multilayer for the interleaved configuration. The thick horizontal arrows give the directions of the moments in the magnetic layers (black arrows for M1 and white arrows for M2), whereas the thinner nearly vertical arrows depict the trajectories of representative electrons between spin flips. The left-hand side and the right-hand side of the figure represent the antiparallel and the parallel states, respectively.

increasing N enhances the ratio R_s/R_{si}, which *diminishes* the 'dilution' of GMR(N) and therefore *increases* GMR(N). However, this effect is relatively small. Since R_s and R_{si}(layer) are already larger than R_{si}(other), a further increase in their values by increasing N will yield only a *small increase* in GMR(N).

These ideas may be expressed numerically. One writes

$$\mathrm{GMR}(N) = \frac{\Delta R}{R_s + R_{si}(\mathrm{layer}) + R_{si}(\mathrm{other})} = \frac{N\Delta R(1)}{NR_s(1) + NR_{si}(\mathrm{layer},1) + R_{si}(\mathrm{other})} \tag{3}$$

where $\Delta R(1)$, $R_s(1)$, and R_{si}(layer, 1) are the values of ΔR, R_s, and R_{si}(layer), respectively, for $N = 1$. We may assume that R_s and R_{si}(layer) scale linearly with N. Rewriting equation (3) gives

$$\mathrm{GMR}(N) = \frac{\mathrm{GMR}(\infty)}{1 + B/N} \tag{4}$$

where $\mathrm{GMR}(\infty) = \Delta R(1)/[R_s(1) + R_{si}(\mathrm{layer},1)] = \Delta R/[R_s + R_{si}/(\mathrm{layer})]$ is the magnetoresistance in the absence of R_{si}(other) and $B = R_{si}(\mathrm{other})/[R_s(1) + R_{si}(\mathrm{layer},1)]$ is the ratio of the resistance due to sources other than the layers to the resistance due to the layers for a single repeat. Since most of the resistance in a magnetic multilayer arises from the layers, even for $N = 1$, the value of B is small.

The increase in GMR(N) with increasing N may be exhibited explicitly by rewriting equation (4) as

$$\frac{\mathrm{GMR}(N)}{\mathrm{GMR}(1)} = \frac{1+B}{1+B/N} \approx 1 + B\frac{N-1}{N} \tag{5}$$

where it is seen that the percentage increase in GMR(N) is always less than B and hence quite modest.

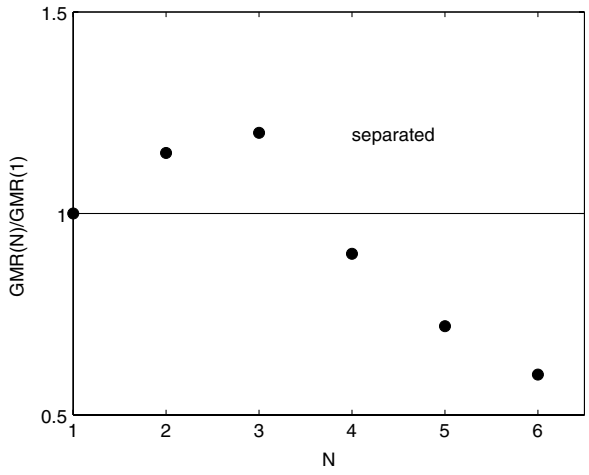

Figure 3. Dependence of the ratio GMR(N)/GMR(1) on the number of repeats N for the separated configuration. The curve has physical meaning only for integer values of N.

5. Separated configuration—GMR(N) for $N < N_0$

We now return to the separated configuration. For $N < N_0$, *every electron* that begins its trajectory in the M1 layers will reach the M2 layers before flipping its spin. Therefore, for $N < N_0$, increasing the number of M1 layers will increase the number of electrons that contribute to the GMR. Note that this situation corresponds exactly to the situation for the interleaved configuration. It follows, therefore, that the steps in the calculation of GMR(N) for the separated configuration for $N < N_0$ are the same as the steps in the calculation of GMR(N) for the interleaved configuration for all N. Therefore, we may immediately write, in analogy with (5),

$$\frac{\mathrm{GMR}(N)}{\mathrm{GMR}(1)} \approx 1 + C\frac{N-1}{N}, \qquad N < N_0 \tag{6}$$

where the parameter C in equation (6) for the separated configuration need not have the same value as the parameter B in equation (5) for the interleaved configuration.

6. Final result

Combining equations (1), (2) and (6) yields the expression for the ratio GMR(N)/GMR(1) for all N for the separated configuration. The most interesting feature of the N-dependence of GMR(N) is the initial *increase* (for $N < N_0$), given by equation (6), which is followed by a rapid *decrease* (for $N > N_0$), given by equation (2). This behaviour is exhibited schematically in figure 3.

7. Numerical example

It is instructive to consider a numerical example, which will also permit a comparison with the results of previous workers. Recently, Strelkov, Vedyaev, and Dieny (SVD) [9] applied the Valet–Fert theory [10] to calculate GMR(N) in the CPP mode. The particular 2M multilayer considered by SVD had M1 = NiFe (layer thickness of 80 Å) and M2 = CoFe (layer thickness

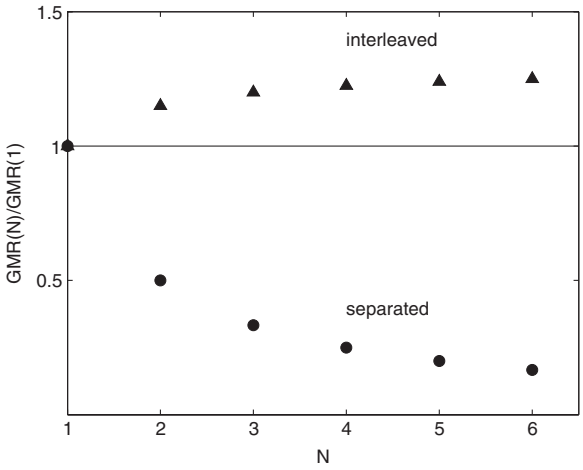

Figure 4. Dependence of the ratio GMR(N)/GMR(1) on the number of repeats N for both separated and interleaved configurations, for the case described in the text. The curve has physical meaning only for integer values of N.

of 30 Å). For the spin diffusion length l_{SF}, SVD propose the values l_{SF}(NiFe) = 50 Å and l_{SF}(CoFe) = 150 Å. With these values, the electron can hardly diffuse through a single layer of NiFe before flipping its spin. Therefore, $N_0 = 1$.

For $N_0 = 1$, equations (1) and (2) apply for all N for the separated configuration. Hence, we may write

$$\frac{\mathrm{GMR}(N)}{\mathrm{GMR}(1)} = \frac{A}{A + (N-1)}, \qquad \text{all } N. \tag{7}$$

In figure 4, the circles give GMR(N)/GMR(1) as a function of N for the separated configuration, based on equation (7), where the parameter A (of order unity) has been set equal to unity. The triangles give GMR(N)/GMR(1) for the interleaved configuration, based on equation (5), where the small parameter B has been set equal to 0.2.

There are two comments to be made. First, there is a striking difference between the upper and lower curves. Consider $N = 4$. For the interleaved configuration, GMR(N)/GMR(1) increases by only about 20%, whereas for the separated configuration, GMR(N)/GMR(1) decreases by a factor of three. Second, the values we obtained in figure 4 are in excellent agreement with the calculated results of SVD. This indicates that the phenomenological approach does not leave out any important physics contained in the Valet–Fert theory.

8. Final comment

The phenomenological approach presented here dealt with multilayers having a relatively short spin-diffusion length. For samples with a longer spin-diffusion length, one must also include the effects of the electron mean free path [5]. Indeed, there exist magnetoresistance data that cannot be explained without invoking mean free path effects. We refer to the magnetic-field dependence of the magnetoresistance MR(H) measured for 2M multilayers [11], and subsequently, also for 3M multilayers [8]. This wealth of MR(H) data have recently been explained in quantitative detail.

Acknowledgment

Support from the UK funding council (EPSRC) is gratefully acknowledged.

References

[1] Baibich M N, Broto J M, Fert A, Vandau F N, Petroff F and Etienne P 1988 *Phys. Rev. Lett.* **61** 2472
[2] Pratt W P Jr, Lee S F, Slaughter J M, Loloee R, Schroeder P A and Bass J 1991 *Phys. Rev. Lett.* **66** 3060
Lee S F, Yang Q, Holody P, Loloee R, Schroeder P A and Bass J 1993 *J. Magn. Magn. Mater.* **118** L1
Lee S F, Yang Q, Holody P, Loloee R, Hetherington J H, Mahmood S, Ikegami B, Vigen K, Henry L L, Schroeder P A, Pratt W P Jr and Bass J 1995 *Phys. Rev.* B **52** 15426
[3] Chiang W-C, Yang Q, Pratt W P Jr, Loloee R and Bass J 1997 *J. Appl. Phys.* **81** 4570
[4] Bozec D, Walker M J, Hickey B J, Howson M A and Wiser N 1999 *Phys. Rev.* B **60** 3037
[5] Bozec D, Howson M A, Hickey B J, Shatz S, Wiser N, Tsymbal E Y and Pettifor D G 2000 *Phys. Rev. Lett.* **85** 1314
[6] Eid K, Portner D, Loloee R, Pratt W P Jr and Bass J 2001 *J. Magn. Magn. Mater.* **224** L205
[7] Eid K, Portner D, Borchers J A, Loloee R, Darwish M A, Tsoi M, Slater R D, O'Donovan K V, Kurt W, Pratt W P Jr and Bass J 2002 *Phys. Rev.* B **65** 054424
[8] Michez L, Hickey B J, Shatz S and Wiser N 2003 *Phys. Rev.* B **67** 092402
Michez L, Hickey B J, Shatz S and Wiser N 2004 *Phys. Rev.* B **70** 052402
[9] Strelkov N, Vedyaev A and Dieny B 2003 *J. Appl. Phys.* **94** 3278
[10] Valet T and Fert A 1993 *Phys. Rev.* B **48** 7099
[11] Bozec D, Howson M A, Hickey B J, Shatz S and Wiser N 2000 *J. Phys.: Condens. Matter* **12** 4263