VOLUME 71, NUMBER 10 PHYSICAL REVIEW LETTERS 6 SEPTEMBER 1993

Origin of Enhanced Magnetoresistance of Magnetic Multilayers: Spin-Dependent Scattering from Magnetic Interface States

S. S. P. Parkin

IBM Research Division, Almaden Research Center, 650 Harry Road, San Jose, California 95120

(Received 16 June 1992)

The origin of giant magnetoresistance exhibited by ferromagnetic/nonmagnetic multilayered structures is examined by inserting thin layers of a second ferromagnetic material at the interfaces in ferromagnetic/nonmagnetic/ferromagnetic sandwiches. It is generally observed, for many different combinations of metals, that the magnetoresistance depends exponentially on the thickness of the interface layer, with a characteristic length, ξ. ξ is extremely short and is typically just $\simeq 1.5$ to 3 Å at room temperature. At lower temperatures ξ becomes even shorter. The giant magnetoresistance effect is thus clearly shown to be determined by the character of the ferromagnetic/nonmagnetic interfaces.

PACS numbers: 75.70.Cn, 73.50.Jt, 73.60.Aq

Very large, or "giant," saturation magnetoresistance (MR) has been reported for a variety of magnetic multilayers [1-5], with room temprature MR values exceedings 65% in Co/Cu [4,6]. The origin of this novel effect is of great interest and a number of theoretical models have been proposed to account for it [7-9]. An essential assumption of these models is that the majority-spin and minority-spin electrons in the magnetic layers are scattered differently within largely independent conduction channels, as described by spin-dependent mean free paths, $\lambda_\uparrow$ and $\lambda_\downarrow$, respectively [10]. It is then easy to show that the resistance of a multilayer comprised of alternating ferromagnetic (F) and nonmagnetic spacer (S) layers is higher when the magnetic moments of successive magnetic layers are aligned antiparallel compared to the case when these layers are aligned parallel [7]. When the relative orientation of neighboring magnetic layers is changed by application of a magnetic field this results in a magnetoresistance. The magnitude of the magnetoresistance is especially sensitive to the contrast in scattering within the two conduction channels. Some models assume scattering rates which are identical to those in the corresponding *bulk* magnetic materials and which are homogeneous throughout the magnetic layers [11]. Other models assume that the scattering rates are substantially different at the magnetic/nonmagnetic *interfaces* compared to the interior of the magnetic layers [7,8]. The relative importance of the contributions from bulk and from interface spin-dependent scattering varies considerably from model to model. In this Letter we demonstrate by the insertion of thin magnetic layers at the interfaces in sandwich structures that the magnitude of the giant magnetoresistance effect is determined largely by the character of the magnetic/nonmagnetic interfaces.

The samples were prepared by dc magnetron sputtering in a high vacuum system with a base pressure of $\simeq 2\times 10^{-9}$ Torr. The structures were deposited at $\simeq 2$ Å/sec in an argon pressure of 3.3 mTorr at $\simeq 40\,^\circ\mathrm{C}$. Series of up to 19 multilayers were prepared sequentially under computer control. The composition of alloy layers was checked with energy dispersive x-ray analysis. The resistance of the samples was measured using a low frequency ac lock-in technique with a four-in-line contact geometry and spring loaded gold plated contacts. The current and magnetic field were in the plane of the films with the magnetic field parallel or perpendicular to the current. The magnetoresistance, $\Delta R/R$, is defined as the maximum change in resistance observed over the field range of interest divided by the high field resistance.

The structures prepared for this study are comprised of exchange-biased sandwiches (EBS) of the form $F_\mathrm{I}/S/F_\mathrm{II}/$FeMn in which one of the magnetic layers, F_II, is exchange coupled to an antiferromagnetic layer of FeMn [12]. The latter imposes a unidirectional magnetic anisotropy on F_II. Thus the magnetic hysteresis loop of F_II is centered about a nonzero field H_B, whereas, providing the magnetic coupling of F_I and F_II via the spacer layer is weak, the magnetic hysteresis loop of F_I is centered close to zero field. The moments of F_I and F_II are thus aligned antiparallel for some field range intermediate between zero and H_B. A resistance versus field curve is shown in Fig. 1 for a typical exchange-biased sandwich structure where F_I and F_II are Py (permalloy$=\mathrm{Ni_{81}Fe_{19}}$) and S is Cu. The current and field are aligned along the unidirectional anisotropy direction. The structure displays a giant MR effect exactly analogous to that in multilayers with a higher resistance for fields where F_I and F_II are antiparallel. As is found for multilayered structures [4,5] replacing the Py layers with Co layers of the same thickness increases the magnetoresistance of the structure by approximately a factor of 2. Thus we can evaluate the importance of interface scattering by introducing thin layers of, for example, Co at the Py/Cu interfaces in Py/Cu/Py sandwiches. If spin-dependent interface scattering is the dominant mechanism giving rise to giant MR, thin layers of Co will produce a large increase in MR. In contrast, if bulk scattering lies at the origin of giant MR, much thicker layers of Co will be required to substantially alter the MR effect. Figure 1 shows that "dusting" of the Py/Cu interfaces with thin Co layers just 2.5 Å thick almost doubles the MR of the Py/Cu/Py

0031-9007/93/71(10)/1641(4)$06.00

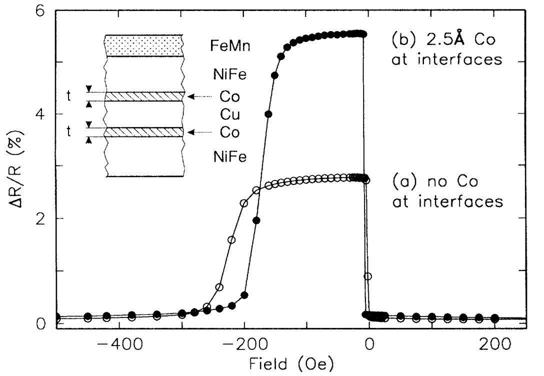

FIG. 1. Room temperature resistance versus field curves for (a) Si/Py(53 Å)/Cu(32 Å)/Py(22 Å)/FeMn(90 Å)/Cu(10 Å) and (b) the same structure with 2.5 Å thick Co layers added at each Py/Cu interface. (Note the thicknesses of the Py layers have correspondingly been reduced by 2.5 Å.)

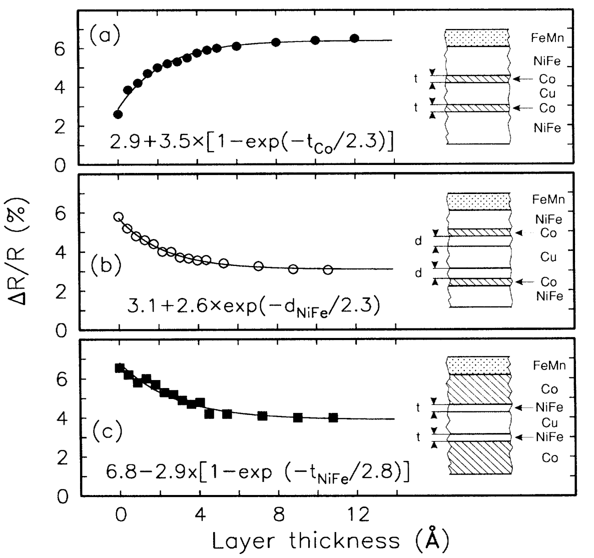

FIG. 2. Dependence of room temperature saturation magnetoresistance on (a) Co interface layer thickness, t_{Co}, in sandwiches of the form Si/Py($53-t_i$)/Co(t_i)/Cu(32)/Co(t_i)/Py($22-t_i$)/FeMn(90)/Cu(10), (b) distance of a 5 Å thick Co layer from the Py/Cu interfaces in sandwiches of the form Si/Py($49-d$)/Co(5)/Py(d)/Cu(30)/Py(d)/Co(5)/Py($18-d$)/FeMn(90)/Cu(10), and (c) Py interface layer thickness, t_i, in sandwiches of the form Si/Co($57-t_i$)/Py(t_{Py})/Cu(24)/Py(t_i)/Co($29-t_i$)/FeMn(100)/Cu(10). Note layer thicknesses are in angstroms.

EBS, making it comparable to that of the EBS in which the Py layers are completely replaced by Co. This result demonstrates the predominant role of interfacial scattering. A similar increase in MR is found for Py/Cu multilayers when thin layers of Co are inserted at the Py/Cu interfaces [13]. However, in multilayer structures it is difficult to examine quantitatively the role of such interface layers since the degree of antiferromagnetic coupling of the magnetic layers and consequently the magnitude of the magnetoresistance is very sensitive to minor perturbations of the structure. In contrast, in EBS structures no reliance is placed on interlayer coupling. Consequently the dependence of the saturation magnetoresistance on the thickness of the Co interface layer t_i can be examined in detail as shown in Fig. 2(a). The thickness dependence is well described by a function of the form $\Delta R/R=a+b[1-\exp(-t_i/\xi)]$, where the length scale ξ is extremely short and is only $\simeq 2.3$ Å. Note that the thickness of the Py layers has been reduced by approximately the thickness of the Co layers inserted at the interfaces and that the sheet resistance of the structures shown in Fig. 2(a) varies by less than 5%. Note also that for these structures the magnetoresistance is relatively insensitive to the thickness of the Py layers, primarily as a result of significant current shunting through the relatively thick and highly conducting Cu layers. More importantly the dependence of MR on Co interface layer thickness does not depend on the thickness of F_{I} or F_{II}. This is demonstrated in Figs. 3(a) and 3(b) for two series of Py/Cu/Py EBS which show a similar dependence of MR on t_{Co} to that shown in Fig. 2(a) even though these series contain much thicker Py layers.

If bulk scattering were important, one would expect that insertion of Co layers anywhere in the interior of the Py layers in Py/Cu/Py EBS would substantially increase the MR. To test this possibility a companion set of structures to those shown in Fig. 2(a) was prepared in which 5 Å thick Co layers, initially positioned at the Py/Cu interfaces, were systematically displaced into the interior of the Py layers. As can be seen from Fig. 2(b) the MR rapidly decreases with increasing separation d of the thin Co layers from the Py/Cu interfaces. The dependence of MR on d is well described by $\Delta R/R=a+b\exp(-d/\xi)$, where ξ is $\simeq 2.3$ Å and the MR rapidly saturates at a value corresponding to that of the origin Py/Cu/Py EBS structure. Finally in Fig. 2(c) data are shown for a series of Co/Cu/Co/FeMn exchange-biased sandwiches in which thin Py layers are introduced at the Co/Cu interfaces. In this case the role of Py and Co have been interchanged, and the MR which is initially high is decreased by introduction of the Py layers, attaining a value comparable to that of a Py/Cu/Py sandwich. Again the length scale associated with the decay in MR is very short and in this case was determined to $\xi \simeq 2.8$ Å. A wide variety of structures comprising many different combinations of magnetic layers and magnetic interface layers were studied. In each case the saturation magnetoresistance found was determined by the character of the magnetic/nonmagnetic interface which was established within a characteristic length ξ of $\simeq 1.5$ to 3 Å.

The possibility of alloy formation between the interface

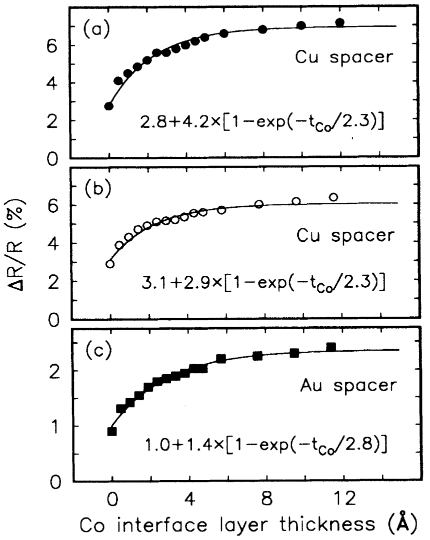

FIG. 3. Dependence of room temprature saturation magnetoresistance on Co interface layer thickness in structures of the form (a) Si/Py($75-t_i$)/Co(t_i)/Cu(25)/Co(t_i)/Py($50-t_i$)/FeMn(110)/Cu(10), (b) Si/Py($100-t_i$)/Co(t_i)/Cu(25)/Co(t_i)/Py($100-t_i$)/FeMn(100)/Cu(10), and (c) Si/Py($91-t_i$)/Co(t_i)/Au(24)/Co(t_i)/Py($38-t_i$)/FeMn(105)/Au(15). Note layer thicknesses are in angstroms.

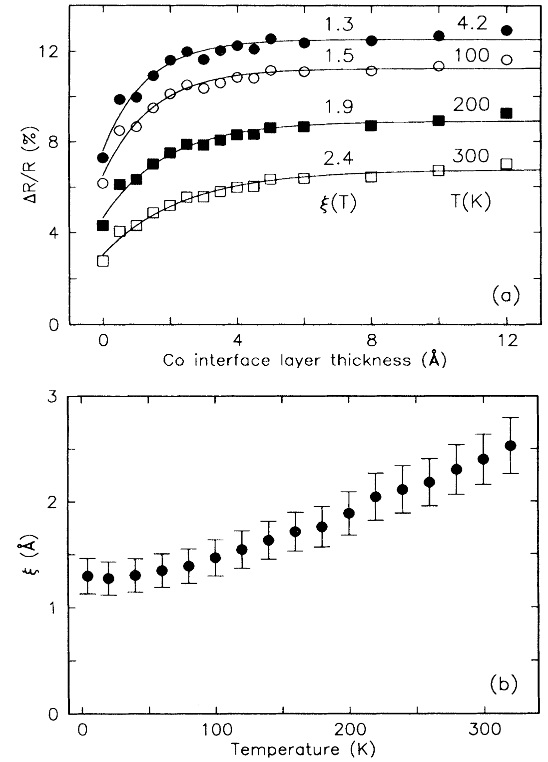

FIG. 4. (a) Dependence of saturation magnetoresistance on Co interface layer thickness for structures of the form Si/Py($53-t_i$)/Co(t_i)/Cu(32)/Co(t_i)/Py($22-t_i$)/FeMn(90)/Cu(10), at temperatures of 4.2, 100, 200, and 300 K. (Note layer thicknesses are in angstroms.) The curves through the data are fits of the form $\Delta R/R = a + b[1 - \exp(-t_i/\xi)]$. The values of ξ given by such fits are plotted in (b) as a function of temperature. Error bars (± 1 standard error) for ξ are also shown in the figure.

layers inserted in the sandwiches and the magnetic layers, F_I and F_{II}, was examined by introducing interface layers comprised of $Co_{1-x}Fe_x$ and $Co_{1-x}Ni_x$ alloys of various compositions (x ranging from 0.1 to 0.9). In these cases ξ were similarly short but the increased or decreased magnetoresistance values obtained were those corresponding to the respective alloy material. All of the alloy compositions studied gave lower MR values than the Co/Cu interface. An important conclusion is that alloy formation between the interface layers and F_I or F_{II} will not substantially alter the value of ξ and cannot account for the strong dependence of MR on interface layer thickness. A variety of spacer layers distinct from Cu were also studied. Figure 3(c) shows an example of a Py/Au/Py/FeMn sandwich in which Co interface layers are introduced. The dependence of MR on the Co interface layer thickness, shown in Fig. 3(c), is similar to that for analogous structures with Cu spacer layers, except that the MR values are smaller. The resistance versus field curves for these samples are similar to those shown in Fig. 1.

If the magnetoresistance arises from bulk scattering within the magnetic layers one would expect such scattering to be reduced as the temperature is decreased, giving rise to increased values of ξ. The temperature dependence of ξ was determined by measuring the dependence of saturation magnetoresistance on Co interface layer thickness for the same structures shown in Fig. 2(a) for a number of temperatures. Data are shown in Fig. 4(a) at 4.2, 100, 200, and 300 K. As can be seen from the figure the data at each temperature can be fitted with the same functional form, $\Delta R/R = a + b\{1 - \exp[-t_i/\xi(T)]\}$. The temperature dependence of ξ determined in this way is plotted in Fig. 4(b). As the temperature is reduced the magnitude of $\xi(T)$ decreases monotonically with, at 4.2 K, a value of just $\simeq 1.3$ Å, about half the room temperature value. This behavior is inconsistent with bulk scattering models since in such models scattering lengths will become larger at low temperatures, for example, as phonon and magnon scattering is reduced.

The origin of giant magnetoresistance (GMR) was originally speculated [1], by analogy with bulk alloys [14,15], to arise from spin-dependent scattering from atoms of the spacer material dissolved in the magnetic layers. A consequence of such a model is that increased interface disorder is expected to increase the magnitude of the MR. For the structures of interest here, annealing at elevated temperatures, which causes increased dissolution of the F/S layers, results in decreased MR. Similarly, the deliberate simulation of interface disorder by introducing thin ($\simeq$0.5 to 12 Å) nonmagnetic $Cu_{1-x}Ni_x$ (x varying from 0.11 to 0.32) alloy layers at the Py/Cu interfaces in Py/Cu/Py EBS, results in decreased MR. Such results suggest that increased interface disorder actually decreases the MR.

The detailed interpretation of ξ depends on the model used to account for the MR. In *bulk* scattering models ξ will be determined by the shorter of $\lambda_\uparrow$ and $\lambda_\downarrow$. However, ξ is much smaller than $\lambda_\uparrow$ or $\lambda_\downarrow$ inferred from the transport properties of bulk Co or Py or their alloys [10], indicating such models are inappropriate. The very short values of ξ strongly suggest that ξ is instead related to the special electronic or structural nature of the interfaces. Note that a lower limit on ξ is simply the thickness of material required to form the new I/S interface (where I represents the layer inserted between the F and S layers). This will be determined, in part, by the growth mode of the F/I/S layers but will be of the order of 1 to several monolayers. Detailed analysis of film growth [16] shows that, under plausible growth conditions, the proportion of F covered by S will decrease exponentially with the quantity of I deposited on F, consistent with the functional dependence of MR on thickness of I shown in Figs. 2, 3, and 4(a).

In summary we have demonstrated that the enhanced magnetoresistance of ferromagnetic/nonmagnetic/ferromagnetic sandwiches can be substantially altered by inserting thin magnetic layers, comprised of a different magnetic material, at the nonmagnetic layer interfaces. The magnetoresistance depends exponentially on the interface layer thickness, with an associated length, ξ, of $\simeq$2 to 3 Å at room temperature and even shorter values at lower temperatures. The magnitude of the magnetoresistance depends on the nature of the magnetic and nonmagnetic material at the interface, and is insensitive to the magnetic material within the interior of the magnetic layers. These data suggest that the origin of giant mangetoresistance arises from spin-dependent scattering from magnetic states predominantly localized at the magnetic/nonmagnetic interfaces.

I am especially grateful to K. P. Roche for technical support. I thank Professor R. Schrieffer and many colleagues at IBM Almaden for useful discussions, particularly, D. D. Chambliss, B. A. Jones, and R. F. Marks.

---

[1] M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Friederich, and J. Chazelas, Phys. Rev. Lett. **61**, 2472 (1988).

[2] G. Binasch, P. Grünberg, F. Saurenbach, and W. Zinn, Phys. Rev. B **39**, 4828 (1989).

[3] S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. **64**, 2304 (1990).

[4] S. S. P. Parkin, R. Bhadra, and K. P. Roche, Phys. Rev. Lett. **66**, 2152 (1991).

[5] S. S. P. Parkin, Appl. Phys. Lett. **60**, 512 (1992).

[6] S. S. P. Parkin, Z. G. Li, and D. J. Smith, Appl. Phys. Lett. **58**, 2710 (1991).

[7] R. E. Camley and J. Barnas, Phys. Rev. Lett. **63**, 664 (1989).

[8] P. M. Levy, K. Ounadjela, S. Zhang, Y. Wang, C. B. Sommers, and A. Fert, J. Appl. Phys. **67**, 5914 (1990).

[9] D. M. Edwards, J. Mathon, R. B. Muniz, and M. S. Phan, Phys. Rev. Lett. **67**, 493 (1991).

[10] P. L. Rossiter, *The Electrical Resistivity of Metals and Alloys* (Cambridge Univ. Press, Cambridge, 1987).

[11] D. M. Edwards, R. B. Muniz, and J. Mathon, IEEE Trans. Mag. **27**, 3548 (1991).

[12] B. Dieny, V. S. Speriousu, S. S. P. Parkin, B. A. Gurney, D. R. Wilhoit, and D. Mauri, Phys. Rev. B **43**, 1297 (1991).

[13] S. S. P. Parkin, Appl. Phys. Lett. **61**, 1358 (1992).

[14] J. W. F. Dorleijn, Philips Res. Rep. **31**, 287 (1976).

[15] I. A. Campbell and A. Fert, in *Ferromagnetic Materials,* edited by E. P. Wohlfarth (North-Holland, Amsterdam, 1982) Vol. 3, p. 747.

[16] See, for example, D. D. Chambliss, K. E. Johnson, R. J. Wilson, and S. Chiang, J. Magn. Magn. Mater. **121**, 1 (1993). This functional form holds true when impinging atoms remain within the atomic terrace on which they are initially deposited.