Giant Magnetoresistance by Exchange Springs in $DyFe_2/YFe_2$ Superlattices

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Magnetization and magnetoresistance measurements are reported for antiferromagnetically coupled $DyFe_2/YFe_2$ multilayers in fields up to 23 T. It is demonstrated that the formation of short exchange springs (~20 Å) in the magnetically soft YFe_2 layers results in a giant magnetoresistance as high as 32% in the spring region. It is shown that both the magnitude of the effect and its dependence on magnetic field are in good agreement with the theory of Levy and Zhang for domain wall induced giant magnetoresistance.

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Giant magnetoresistance (GMR) materials challenge our understanding of spin-polarized electron transport and have many important technical applications (sensors, magnetic read heads, etc. [1]). GMR is observed in a variety of magnetic systems including multilayers [2], spin valves [3], and granular materials [4]. A typical GMR multilayer consists of ferromagnetic layers, separated by *nonmagnetic* spacer layers. The effect occurs because of a large difference in the scattering rates of spin-up and spin-down electrons in the magnetic layers. The resistance of a given GMR structure is a maximum when magnetic moments in the consecutive magnetic layers are antiparallel and minimum when they are parallel. When a magnetic field is applied, the directions of magnetization in consecutive layers can be switched, resulting in a dramatic change in the resistance of the structure as a whole.

It has also been argued that a domain wall in a ferromagnet should give rise to a GMR-like magnetoresistance [5,6]. In particular, Viret *et al.* [5] suggested that the inability of an electron spin to track the reorientation of magnetization within a domain wall should give rise to GMR. Subsequently, a more complete, quantum mechanical, treatment of domain wall GMR was put forward by Levy and Zhang [7] describing both the case with currents in the plane (CIP) and with currents perpendicular to the plane. According to this model, electron spin mistracking causes a mixing of states with opposite spins resulting in GMR due to spin-dependent scattering by impurity centers within domain walls. In particular, the magnitude of the effect should increase rapidly with decreasing domain wall width (δ_w).

Experimentally, GMR has been witnessed in striped domain walls, in magnetically prepared thin films of Ni and Co [6] and FePd [8]. However, in practice, considerable difficulties were experienced. First, the GMR effect is small (<1.5%), because of the low density of domain walls and their comparatively large widths δ_w (>75 Å) [7–9]. Second, it is difficult to separate the normal anisotropic magnetoresistance (AMR) from that of GMR. These difficulties can be overcome using artificially tailored domain walls known as "magnetic exchange springs." In this Letter, it is argued that exchange spring multilayers are ideal systems for GMR studies. First, the "artificial domain walls" occupy a significant fraction of the sample volume (up to ~50%). Second, the domain wall width δ_w can be varied over a wide range, either by changing the thickness of the magnetically soft layers or the strength of the applied magnetic field, or both. Third, magnetization measurements can be used to obtain values for δ_w of the exchange springs. In this context, it should be noted that Mibu *et al.* [10] have studied the effect of exchange springs in the *ferromagnetically coupled* bilayer system SmCo/NiFe. However, the magnetoresistance (MR) is small (~1.5%) and dominated by AMR. The contribution from GMR, estimated at ~0.1%, is weak because the SmCo/NiFe system cannot exhibit magnetic exchange springs shorter than ~300 Å. In ferromagnetically coupled systems, exchange springs disappear when B_{app} exceeds the coercive field B_C. So it is difficult to exploit the fact [11] that δ_w decreases with increasing applied field B_{app}, especially in the SmCo/NiFe system, where B_C is only 0.25 T at 5 K.

In this Letter, we report the first observation of significant exchange spring driven GMR. We used a $DyFe_2/YFe_2$ multilayer system, which allows very short exchange springs to be set up, as a direct result of the *antiferromagnetic* coupling between the $DyFe_2$ and the YFe_2 layers. Our calculations show that exchange springs as short as 20 Å can be set up in the YFe_2 layers. In addition, it is shown that both AMR and GMR effects can be clearly separated. Experimentally, the GMR results are found to be in good agreement with the model of Levy and Zhang [7], both in magnitude and the functional dependence on the domain wall width δ_w.

The Laves phase $DyFe_2/YFe_2$ superlattices (110) were grown by a molecular beam epitaxy technique as described elsewhere [12,13]. The samples were grown on $(11\bar{2}0)$ sapphire substrates with a 500 Å (110) Nb buffer and a 30 Å seed layer of Fe. The magnetic measurements were made using a 12 T vibrating sample magnetometer. Transport studies were performed using 0.2 mA currents in plane, both parallel to and perpendicular to B_{app} using a standard four-point method. All resistivity results presented here were corrected for the measured contribution from the buffer layer ($\rho_{\mathrm{Nb}} = 5.1 \times 10^{-6}\ \Omega$ cm at 100 K). For all measurements the magnetic field was applied along a [001] axis, the direction of easy magnetization.

The magnetization of a 4000 Å $DyFe_2$ film, together with the MR curves, for both the current parallel ($\rho_{\parallel}$) and perpendicular ($\rho_{\perp}$) to B_{app} can be seen in Fig. 1. Both resistivity curves are hysteretic, with strong peaks (troughs) at the coercive field of $B_C = 1.2$ T. Note that the two MR curves show effects with opposite sign, implying that the MR is due to AMR. This reciprocity, in the vicinity of B_C, is typical of ferromagnetic materials [6].

The properties of the $DyFe_2/YFe_2$ superlattices are characterized by (i) dominant ferromagnetic Fe-Fe exchange (~600 T), (ii) a weaker antiferromagnetic Dy-Fe exchange (~100 T), and (iii) a Dy crystal field anisotropy (~10–100 T), which determines the direction of easy magnetization in the magnetically hard $DyFe_2$ layers. Our previous magnetization studies [14] of $DyFe_2/YFe_2$ superlattices have shown that exchange springs are set up within the soft YFe_2 layers, as illustrated schematically in Fig. 2. For fields less than a critical bending field, B_B, all the Fe magnetic moments in both YFe_2 and $DyFe_2$ layers (the magnetic moment of Y is small) are aligned parallel to each other, due to strong Fe-Fe magnetic exchange. But for $B_{\mathrm{app}} > B_B$ ($B_B = 7.5$ T), the magnetic moments within YFe_2 layers start to rotate, forming exchange springs which are pinned at the edges by the neighboring $DyFe_2$ layers. This results in a reversible increase of the magnetization above B_B. As demonstrated previously [15], the width of exchange springs can be evaluated from the reversible magnetization above B_B.

The MR for $DyFe_2/YFe_2$ multilayer samples is characterized by two distinct features associated with (i) irreversible switching of the magnetization in the $DyFe_2$ layers at ($B_{\mathrm{app}} \approx B_C$), and (ii) reversible winding/unwinding of exchange springs in the YFe_2 layers ($B_{\mathrm{app}} \geq B_B$). In the $DyFe_2/YFe_2$ multilayer system, both B_C and B_B can be varied by changing the relative thicknesses of the $DyFe_2$ and YFe_2 layers [13,14]. Here we present results for $B_B > B_C$ (Fig. 2), $B_B < B_C$ (Fig. 3), and $B_B \sim B_C$ (Fig. 4). In Fig. 2 ($B_B > B_C$), it will be observed that, when the field is swept up from a large negative value, there is a dip in the magnetoresistance ($\Delta R/R$), in the vicinity of the coercive field $B_C = 0.7$ T. This feature is associated with AMR, similar to that seen in the $DyFe_2$ film (Fig. 1). But in higher fields, there is a substantial increase in both ($\Delta R/R$) and magnetization, above the bending field B_B (= 7.5 T). This rise in MR is associated with the formation of exchange springs in the magnetically soft YFe_2 layers. We attribute the increase in ($\Delta R/R$) to exchange spring induced GMR.

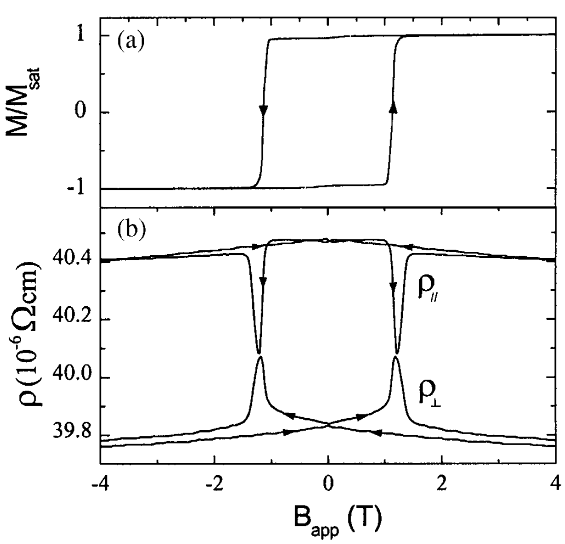

FIG. 1. The field dependent magnetization (a) and resistivity curves ($\rho_{\parallel}$ and $\rho_{\perp}$), for currents both parallel and perpendicular to the magnetic field B_{app} (b), in a 4000 Å thick $DyFe_2$ film at 100 K.

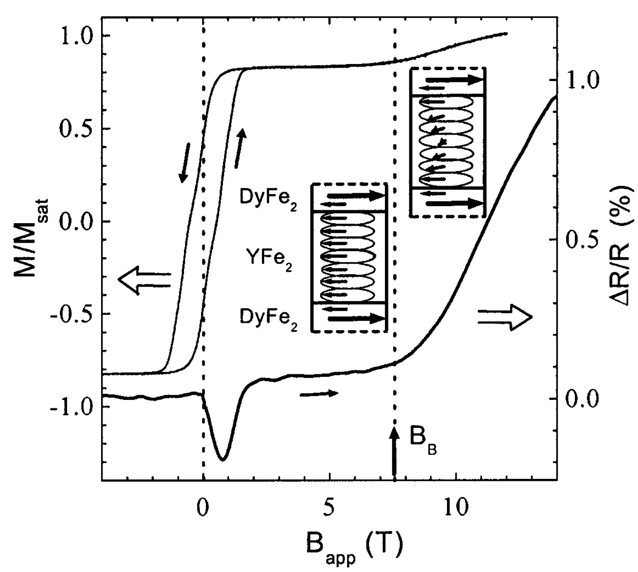

FIG. 2. Magnetization and magnetoresistance ratio $\Delta R/R$, for a current parallel to B_{app}, for the superlattice [60 Å $DyFe_2$/40 Å YFe_2] $\times$ 40 at a temperature of 200 K. Insets show the spin arrangement.

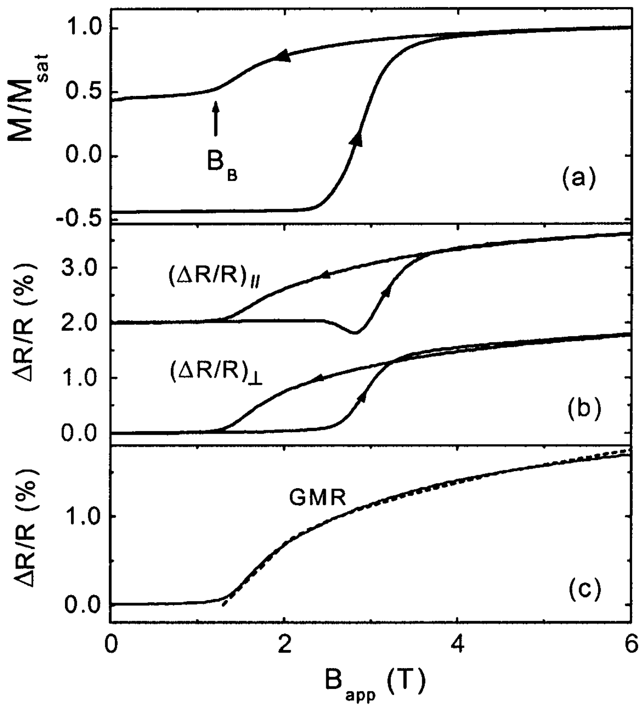

FIG. 3. Magnetization (a) and resistivity curves (b), for currents both parallel and perpendicular to B_{app}, for the superlattice film [150 Å $DyFe_2$/150 Å YFe_2] × 40 at a temperature of 100 K. The $(\Delta R/R)_{\parallel}$ curve has been shifted up by 2%. Also shown (c) is the GMR contribution (solid line) and the theoretical fit (dashed line).

To further distinguish between the AMR and GMR contributions, MR measurements for transport currents parallel and perpendicular to B_{app} were compared. The MR ratios $(\Delta R/R)_{\parallel}$ and $(\Delta R/R)_{\perp}$, together with the magnetization curve, for the superlattice [150 Å $DyFe_2$/150 Å YFe_2] × 40 ($B_B < B_C$), are shown in Figs. 3(a) and 3(b). As the magnetic field is increased, a sudden upturn occurs in both $(\Delta R/R)_{\parallel}$ and $(\Delta R/R)_{\perp}$, at $B_C = 2.8$ T. This is associated with the irreversible switching of the $DyFe_2$ layers, accompanied by the simultaneous creation of magnetic exchange springs in the magnetically soft YFe_2 layers. Note that, in addition to the strong upturn, there is a small trough ~0.2% in $(\Delta R/R)_{\parallel}$, associated with AMR. However, the complimentary AMR peak in $(\Delta R/R)_{\perp}$ is masked by the strong upturn in resistivity due to the exchange springs. On reducing the applied field back to zero, the MR follows the upper curve in Fig. 3(b), in both cases, eventually reaching a flat minimum at the bending field of $B_B = 1.2$ T. This part of the MR curve is fully reversible. The average of $\frac{1}{2}[(\Delta R/R)_{\perp} + (\Delta R/R)_{\parallel}]$ for both the return curves can be seen in Fig. 3(c). This procedure removes any AMR contributions [6], leaving the GMR due to the exchange springs. In practice, the AMR contributions, calculated using $\frac{1}{2}[(\Delta R/R)_{\perp} - (\Delta R/R)_{\parallel}]$, were found to be an order of magnitude smaller than that of the GMR. Finally, the MR curve of a [45 Å $DyFe_2$/55 Å YFe_2] × 40 superlattice ($B_B \sim B_C$) can be seen in Fig. 4. A measured GMR ratio of 12% is reached in a field of 23 T. The return curve (lower one this time) is fully reversible. Note also saturation has not been reached even at the highest field.

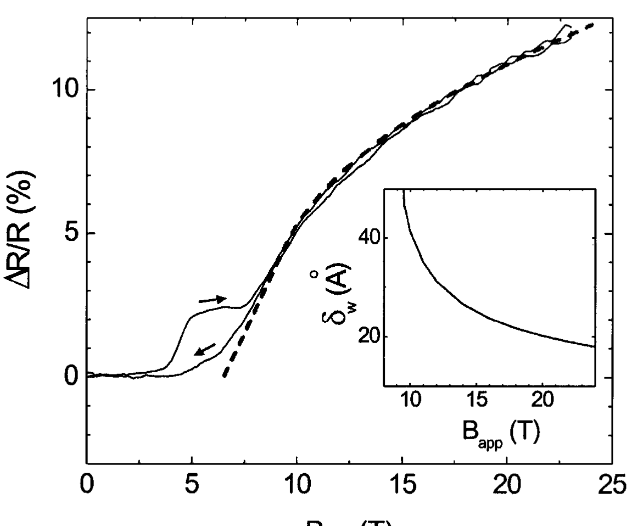

FIG. 4. Magnetoresistance ratio $\Delta R/R$ for a current perpendicular to the magnetic field B_{app}, for the superlattice film [45 Å $DyFe_2$/55 Å YFe_2] × 40 at a temperature of 100 K. The dashed line is a theoretical fit (see text). The inset shows the effective width of the exchange spring as a function of field.

To estimate the GMR in exchange springs, we have used a simple model based on parallel resistances. Specifically,

$$\frac{\Delta R}{R} = \left[\left(\frac{t_{\mathrm{Y}}}{\rho_{\mathrm{Y}}} + \frac{t_{\mathrm{D}}}{\rho_{\mathrm{D}}}\right)\left(\frac{2\delta_w}{\rho_{\mathrm{Y}}} - \frac{2\delta_w}{\rho_w}\right)^{-1} - 1\right]^{-1}, \quad (1)$$

where ρ_w and δ_w are the resistivity and effective thickness of the exchange spring, respectively; ρ_{Y}, ρ_{D}, and t_{Y}, t_{D}, are the resistivities and thicknesses of the YFe_2, $DyFe_2$ layers, respectively, in the absence of exchange springs. The values of $\rho_Y = 3.4 \times 10^{-5}\ \Omega$ cm and $\rho_{\mathrm{D}} = 4.0 \times 10^{-5}\ \Omega$ cm at 100 K were obtained from measurements on thin films of $DyFe_2$ and YFe_2. To calculate the resistivity in exchange springs (ρ_w), we used the model of Levy and Zhang [7]. This model was originally formulated for magnetic scattering within domain walls but can be applied also to other magnetic structures where the direction of magnetization rotates in space. According to Levy and Zhang [7], the resistivity in the domain wall region for the CIP geometry can be written in the form

$$\rho_w = \rho_0\left[1 + \frac{\alpha}{\delta_w^2}\right], \quad (2)$$

where $\alpha = \frac{1}{5}(\pi\hbar^2 k_F/4\ \mathrm{m}J)^2(\rho_0^{\uparrow} - \rho_0^{\downarrow})^2/(\rho_0^{\uparrow}\rho_0^{\downarrow})$, $\rho_0^{\uparrow}$ and $\rho_0^{\downarrow}$ are the resistivities of the spin-up and spin-down current channels, respectively; $\rho_0 = [1/\rho_0^{\uparrow} + 1/\rho_0^{\downarrow}]^{-1}$ is the resistivity without domain walls; J is the magnetic exchange constant; k_F is the Fermi wave vector; and m is the effective mass of the electron. In the model of Levy and Zhang, the parameter δ_w is that distance which corresponds to a linear rotation of the direction of local magnetization through 180°. In the essence, it characterizes how rapidly the direction of magnetization changes in space. Following Refs. [14,15], the magnetic structure of the exchange springs can be extracted, using computer simulations of the measured magnetization associated solely with the exchange springs. Our estimates of δ_w were obtained by determining that thickness required for the Fe moments to rotate through 90°, and then doubling this value. The results for $\delta_w(B_{\mathrm{app}})$ for the [45 Å $DyFe_2$/55 Å YFe_2] × 40 superlattice are shown in the inset of Fig. 4.

For [45 Å $DyFe_2$/55 Å YFe_2] × 40 the measured value of $\Delta R/R$ is 12% at $B = 23$ T. Using Eq. (1), this requires the MR due to exchange springs to be $\Delta\rho_w/\rho_0 = (\rho_w - \rho_0)/\rho_0 = 32\%$. Levy and Zhang [7] estimate that, for Fe, Ni, and Co, $\Delta\rho_w/\rho_0$ lies in the range 0.3% to 1.8%, for $\delta_w = 150$ Å. Similar figures are expected for YFe_2 because the k_F, m, and J values are roughly similar for all these materials. According to Eq. (2), the $\Delta\rho_w/\rho_0$ increases as $1/\delta_w^2$ with decreasing the domain wall width. So it is expected to reach values in the range 17%–100% for $\delta_w = 20$ Å. This estimate is in agreement with our result of $\Delta\rho_w/\rho_0 = 32\%$. Computer fits to the GMR data (dashed lines) can be seen in Figs. 3(c) and 4. This shows that the calculations fit both the magnitude and the functional dependence of the MR. In addition, the parameter α, for measurements at the same temperature, was found to be the same to within 17%, for different samples.

In summary, we have demonstrated that significant GMR can be observed in multilayer samples that do not contain nonmagnetic spacers. In particular, it has been shown that the GMR in the $DyFe_2$/YFe_2 system is due to magnetic exchange springs formed in the YFe_2 layers. Both the magnetic and the functional dependence of the effect are found to be in good agreement with the domain wall scattering model of Levy and Zhang [7]. We have obtained values of $\Delta\rho_w/\rho_0$ of up to 32%, in the exchange springs when their width δ_w is reduced to ~20 Å. Finally, we stress that multilayers with antiferromagnetically coupled hard and soft layers present an ideal platform for the study of GMR, induced by noncollinear spin structures.

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