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1997 J. Phys.: Condens. Matter 9 L145

(http://iopscience.iop.org/0953-8984/9/10/001)

J. Phys.: Condens. Matter **9** (1997) L145–L149. Printed in the UK PII: S0953-8984(97)79712-1

LETTER TO THE EDITOR

# The dependence of giant magnetoresistance in an Fe–Mo multilayer on the thickness of the Fe layers

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Received 13 November 1996

**Abstract.** The magnetoresistance in Fe–Mo multilayers increases with decreasing thickness of the Fe layers. By comparing magnetoresistance and magnetization results, evidence for interlayer coupling variation was found with decreasing Fe layer thickness. Moreover, the behaviour of discontinuous or granular layers was observed in a sample with ultrathin Fe layers. The specific field dependence of the magnetoresistance, which obeys a Langevin-like function, suggests that scattering from an assemblage of superparamagnetic spins could be responsible for the observed magnetoresistance behaviour.

Since the discovery of giant magnetoresistance (GMR) in Fe–Cr multilayers by Baibich *et al* [1], GMR has been observed in a variety of magnetic multilayers [2–5] and granular thin films [6, 7]. The materials with enhanced magnetoresistance (MR) offer new potential candidates for magnetoresistive read heads in magnetic recording storage devices. During the past few years, the GMR effect has been understood semi-quantitatively regarding the variation of nonmagnetic spacer layers, temperature, preparation parameters etc. Recently, of particular interest has been the dependence of GMR and interlayer coupling on the thickness of the ferromagnetic layers [8–13]. Bruno [8] and Barnas [9] predicted theoretically that magnetic coupling may vary with the ferromagnetic layer thickness. This behaviour was observed by Okuno and Inomata [10] and Bloemen *et al* [11] in Fe–Cr and Co–Cu, respectively. However, more recent results reported by Bian *et al* [12] and Kubinski and Holloway [13] show no clear evidence of an oscillatory dependence of coupling strength on the thickness of the ferromagnetic layer thickness in Fe–Cr or Co–Cu. By contrast, the saturation field, $H_s$, was found to decrease monotonically with increasing ferromagnetic layer thickness ($t_F$) simply as $1/t_F$. Thus the MR dependence on Fe layer thickness still remains an open question. In this letter we present a comparison of magnetic measurement and MR results in Fe–Mo multilayers, and especially focus on the dependence of magnetization and MR upon Fe layer thickness $t_{Fe}$.

Fe–Mo multilayers were prepared by magnetron sputtering with a base pressure better than $3 \times 10^{-5}$ Pa. The samples were deposited on water cooled glass substrates in an Ar pressure of 0.5 Pa. The multilayer structures were glass–Fe (60 Å)/[Fe ($t_{Fe}$)–Mo (13 Å)]$_{30}$, and were identical except for varying $t_{Fe}$. A 60 Å Fe layer was used as a buffer layer.

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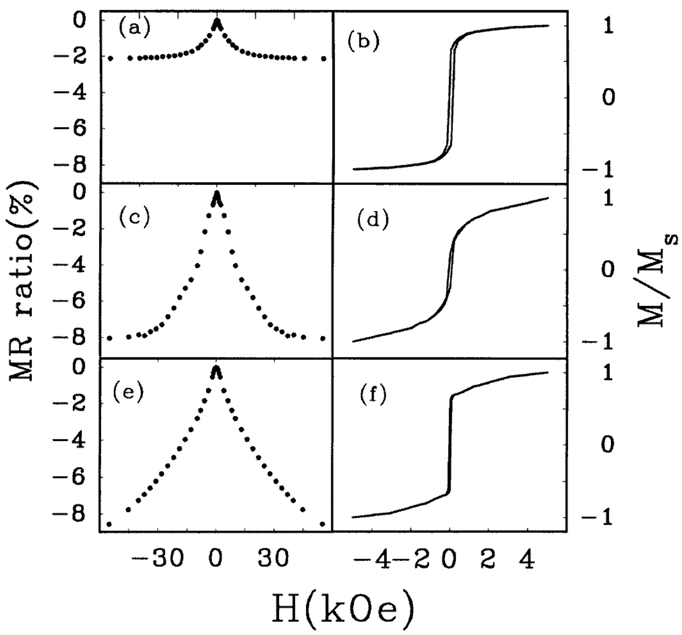


**Figure 1.** MR curves ($T = 4.2$ K) and magnetic hysteresis loops ($T = 300$ K) of three Fe–Mo multilayers with different Fe layer thicknesses. Here, each Mo layer thickness is fixed at 13 Å. (a), (b) 21 Å Fe; (c), (d) 10 Å Fe; (e), (f) 4 Å Fe.

The magnetic hysteresis loops were measured at room temperature using a vibrating-sample magnetometer and alternating-gradient force magnetometer. The in-plane MR measurements were made at 4.2 K by the four-point probe method with the field applied perpendicular to the current. MR was calculated in terms of $[(\rho_H - \rho_0)/\rho_0] \times 100\%$, where $\rho_0$ and $\rho_H$ represent the zero-field resistivity and the resistivity at external field $H$, respectively. Low-angle and high-angle x-ray diffraction measurements were made for the structure analysis. High-angle x-ray diffraction results shows that both the Fe layer and the Mo layer were of bcc(110) texture, and the multilayers were grown coherently in the surface normal direction [14]. Low-angle diffraction results showed that samples were layered, but the interfaces of Fe and Mo layers were intermixed over a number of atomic layers and rough [14].

For constant thickness of the magnetic layer in multilayers, the oscillation of the MR as a function of the nonmagnetic spacer thickness are often taken as a signature of antiferromagnetic interlayer coupling. In our previous studies of Fe–Mo multilayers [5], oscillatory MR was observed as a function of the Mo spacer thickness. In the thickness interval 6 Å $\leqslant t_{Mo} \leqslant$ 46 Å, three maxima of the MR were observed at $t_{Mo} = 11$, 23, and 35 Å. Also, the oscillations of saturation field $H_s$ and remanence/saturation magnetization ratio $M_r/M_s$ with the variation of the Mo spacer thickness $t_{Mo}$ were observed to coincide with that of MR. Clearly, GMR is associated with the existence of the antiferromagnetic interlayer coupling in Fe–Mo multilayers. Here, we describe the dependence of the MR on thickness of the Fe layer in Fe–Mo multilayers, where the thickness of the Fe layer ranged from 4 to 24 Å and the Mo layer was fixed at 13 Å.

Figure 1 shows typical MR curves of three Fe–Mo samples with Fe layer thicknesses of 21, 10, and 4 Å. Corresponding magnetic hysteresis loops of the three samples are also

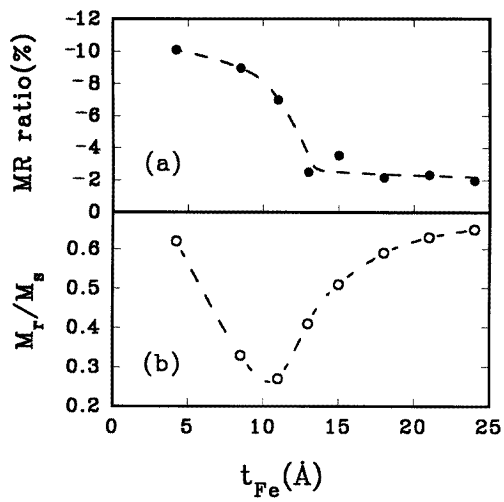


**Figure 2.** The variation of (a) the MR ($T = 4.2$ K) and (b) the ratio of remanence to saturation magnetization ($T = 300$ K) as functions of the Fe thickness $t_{Fe}$. Here, each Mo layer thickness is fixed at 13 Å. Dashed lines are a guide to the eye.

shown in figure 1. As can be seen, for the sample with $t_{Fe} = 21$ Å the MR is smaller, only about 2% (figure 1(a)), and the magnetic hysteresis exhibits a large remanence $M_r$ and small saturation field $H_s$ (figure 1(b)). For the sample with $t_{Fe} = 10$ Å, the MR is about 8% (figure 1(c)), and the loop shows small $M_r$ and larger $H_s$ (figure 1(d)). For the sample with $t_{Fe} = 4$ Å, the magnetoresistance is larger than 9% (figure 1(e)). The loop, which is different from that of the sample with $t_{Fe} = 10$ Å, shows larger $M_r$ and small $H_s$. Moreover, the magnetization saturation field $H_s$ is more than 80 times smaller than that of the MR curve. In fact, the MR is still changing significantly at a field of 65 kOe.

Figure 2 shows the variation of (a) $\Delta\rho/\rho_0$ and (b) $M_r/M_s$ as a function of Fe layer thickness. As seen from figure 2, MR increases steeply when the Fe thickness becomes smaller than 15 Å. $M_r/M_s$ decreases with decreasing Fe layer thickness, the value reaches a minimum at about a 10 Å Fe layer and then increases with further decrease of the Fe layer. In comparing figures 2(a) and (b) three types of behaviour are clearly observed, depending on the thickness of the Fe layer, as follows.

(i) For thicker $t_{Fe}$, $M_r/M_s$ is large and MR is small. Large $M_r/M_s$ with small MR indicates that the Fe layers in samples are coupled ferromagnetically or uncoupled.

(ii) With decreasing $t_{Fe}$, $M_r/M_s$ decreases and MR increases. For $t_{Fe} \simeq 10$ Å, $M_r/M_s$ decreases, reaching the minimum. The smallest $M_r/M_s$ corresponds to the Fe layers in the sample being coupled antiferromagnetically.

(iii) The most striking result is that for $t_{Fe} = 4$ Å both $M_r/M_s$ and MR are larger. Generally speaking, multilayers with ferromagnetic coupling correspond to large $M_r/M_s$ and small MR. However, in our sample with an ultrathin Fe layer, the large $M_r/M_s$ indicates that Fe layers in this samples seem to be coupled ferromagnetically, by MR is still high.

Usually, the GMR of multilayers originates from the spin-dependent scattering mechanism based on antiferromagnetic coupling between the adjacent magnetic layers, but when the magnetic layer thickness decreases or a structural defect appears at the interface

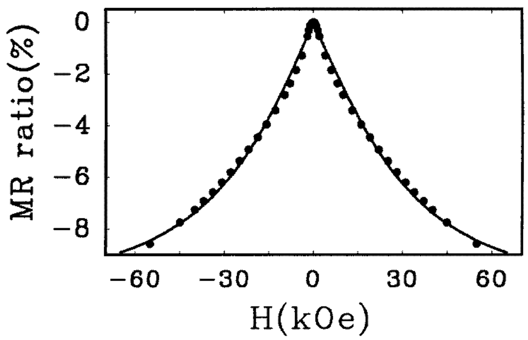


**Figure 3.** Langevin function fitting (line) and the experimental MR data for the Fe (60 Å)/[Fe (4 Å)–Mo (13 Å)]$_{30}$ sample.

an assemblage of paramagnetic spins may be present at the interface. The local magnetic moments are weakly correlated and aligned with the bulk layer, so an additional spin-dependent scattering, which arises from paramagnetic-like spins at the interface, will exist as well [15, 16]. Therefore, the GMR, which arises from spin-dependent scattering, is mainly controlled by the scattering competition between the antiferromagnetic coupling between the adjacent magnetic layers and paramagnetic-like spins at the interface. If the thickness of the ferromagnetic layer in the multilayers becomes small, the interface/volume ratio is increased. When the thickness of the ferromagnetic layer is very small, the ferromagnetic layer can be thought of as clustered or discontinuous layers. Thus, discontinuous ferromagnetic layers may contain isolated islands and be nearly superparamagnetic. We fitted the MR with a Langevin-like function:

$$\Delta\rho/\rho = \beta[\coth(\alpha) - 1/\alpha]$$

where $\alpha = N\mu_B h/k_B T$, $\mu_B$ ($= 9.27 \times 10^{-21}$ erg Oe$^{-1}$) is the Born magnetron, $k_B$ ($= 1.38 \times 10^{-16}$ erg K$^{-1}$) is the Boltzmann constant, $T$ ($= 4.2$ K) is temperature, and $H$ is the applied field, while $\beta$ and $N$ are fitting parameters. The fitting parameters $\beta$ and $N$ are 0.115 and roughly four, respectively. Figure 3 gives the field dependence of the MR for the sample with $t_{Fe} = 4$ Å. The curve is a fit to the experimental data using the Langevin function. It can be seen from figure 3 that the MR curve of this sample obeys a Langevin-like function well at high field. This specific field dependence indicates that scattering from an assemblage of magnetic excitations, mostly likely paramagnetic spins, may be responsible for this behaviour. The observed larger MR, therefore, seems to be a result of enhanced scattering by paramagnetic spins rather than ferromagnetic spins in the Fe layer, since the magnetic layers are already fully saturated at low fields in this sample. A similar behaviour of Co–Ag multilayers has been observed by Loloee *et al* [17], who attributed their results for Co layer thicknesses less than 4 Å to discontinuous or disclike clusters which act as small superparamagnetic clusters.

In conclusion, we have shown the dependence of the MR and interlayer coupling on the thickness of the Fe layer $t_{Fe}$ in Fe–Mo multilayers. For the samples with larger $t_{Fe}$, the interlayer coupling between adjacent Fe layers is ferromagnetic or uncoupled, which gives rise to a small MR. On decreasing $t_{Fe}$, the interlayer coupling between adjacent Fe layers changes from ferromagnetic to antiferromagnetic. Samples corresponding to the antiferromagnetic state (about 10 Å $t_{Fe}$) show a relatively large MR. Moreover, in a sample with ultrathin Fe layers we observed the behaviour of a discontinuous multilayer, in which the MR possesses a high value but is operative up to high magnetic field.

This work is supported by NSF/DMR-9623992 and CMRA in the US, and NNSF in China. The authors are very grateful to Professor Z Shan for support and encouragement.

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