VARIATIONS OF COERCIVITY (H_c) AND REMANENCE MAGNETIZATION (M_r) AS A FUNCTION OF LAYER THICKNESS IN NiFe/Ag ULTRATHIN MULTILAYERS.

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Abstract
X-ray diffraction, magneto-transport and hysteresis loop measurements in as deposited ($Ni_{81}Fe_{19}$/Ag) multilayers provide information for the influence of interlayer stress on the observed GMR effect. A ferromagnetic coupling accompanied with oscillations of H_c and M_r at 5 K is observed as a function of Ag (t_{Ag}) but not with NiFe (t_f) layer thickness. The variation of hysteresis loop parameters can be related with the strees-induced reorientation of magnetization. A connection of the H_c and M_r oscillations to residual stresses in NiFe layers, which induce preferable magnetic easy-axes distributions along the strain direction, may reveal whether spin-dependent scattering from the magnetic layers occurs within the interior of NiFe or predominantly at the NiFe/Ag interfaces.

1. Introduction

In NiFe/Ag discontinuous (DML) films [1,2], consistent annealing is required to produce consistent grain size distributions for optimisation of the Giant magnetoresistive (GMR) effect (≈5% at RT). A systematic change in the saturation magnetostriction λ_s and GMR have been observed [3] as a function of annealing temperature (T_{an}). The increase of λ_s from negative to positive values as a function of T_{an} suggests that the films are under tensile stress in the as-deposited state. This stress is gradually reversed with annealing and for $\lambda_s \approx 0$ the GMR is maximum. It is believed that the relieved intralayer strain effects accompanied by grain boundary separation in NiFe layers, after annealing at 340° C, give rise to micromagnetic changes that favour an increased interlayer antiferromagnetic (AF) exchange coupling [4] J_{AF} ($\propto H_s M_s t_f/4$).
The observed oscillations in GMR of $Ni_{81}Fe_{19}$/Cu [5] and Co/Cu [6] multilayers as a function of Cu spacer thickness, measured at 4.2 and 300 K, provide evidence for the dependence of J_{AF} from M_s in magnetic layers. In both cases at 4.2 K well defined oscillations in GMR are found for increasing Cu thickness. For the Co/Cu system similar oscillations are found at all temperatures from below 4.2 K to above 400 K whereas in NiFe/Cu only a single oscillation is observed at RT for magnetron sputtered

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multilayers. This might be a consequence of the AF coupling since in the former system J_{AF} at the first oscillation peak weakens by only 25% between 4.2 K and 300 K, whereas in the latter J_{AF} changes by a factor of 2.5. Thus it seems reasonable to argue that in NiFe/Cu multilayers at low temperatures, where the AF coupling is considerably stronger, it is likely that more oscillations in coupling will be observed than at higher temperatures where the coupling may be weak compared to direct FM coupling via defects. As deposited NiFe/Au multilayers [7] exhibit oscillatory variations in saturation MR as a function of t_{Au} at RT and present the largest magnetic field sensitivities yet reported. However, the estimated J_{AF} is much weaker than in similarly prepared NiFe/Cu and NiFe/Ag multilayers. Consequently, for this category of NiFe/NM (NM=Cu, Ag, Au) multilayers the importance of J_{AF} in the GMR effect has to be reconsidered.

A systematic variation of MR related properties as a function of Ag (t_{Ag}) and NiFe (t_f) layer thickness in [NiFe/t_f/Ag/40 Å] and [NiFe/20 Å/Ag/t_{Ag}] as deposited thin films is presented here. The major concern is to investigate the mechanisms that primarily affect the GMR in this class of DML films [8]. The spin dependent scattering obviously derives from the magnetic layers, but of particular importance is whether this spin-dependent-scattering (SDS) occurs within the interior of the magnetic layers (bulk scattering) or predominantly at the interfaces between the magnetic and spacer layers (interfacial scattering).

2. X-ray diffraction results

The variation of the higher angle diffraction patterns in the vicinity of <111> and <222> Ag superlattice peaks is displayed in fig.1 for $t_{Ag}\approx 40$ Å versus t_f. The observed spectra display two important features: First, the intensity of the n=0 Bragg peak (I_o) tends to zero as t_f increases from 16 to 25 Å and I_2 becomes stronger at the same time. For t_{Ag}=40 Å and t_f=30 Å, I_o almost disappear while the I_{-1} and I_2 components become very intense. It is known that interface roughness effects can cause damping, broadening and shifting of the n≠0 satellite peaks but they can not reduce the n=0 peak to be less intense from the satellites. However the damping of I_o peak with t_f is a consequence of the interference conditions that depend on bilayer thickness. Second, in Ag <222> peak position there is a double Bragg peak for t_f=16 Å which merges to a single peak as the NiFe layer becomes thicker for constant $t_{Ag}\approx 40$ Å. Residual stresses and nucleation of Ag grains through NiFe grain boundary diffusion [2,3] might be related to the observed variations of the spectra.

The change in intensities of the superstructure pattern clearly shows the difference. A possible interpretation of changes in elastic strain with increasing thickness is the approach [9] to critical thickness t_c, that d_f and d_{Ag} relax to their bulk crystal spacings. In accordance the obtained d_f and d_{Ag} relaxed values, away from the interface of the layer, are close to bulk values 2.048 and 2.359 Å respectively only for the [NiFe/20 Å/Ag/40 Å] sample. An alternative explanation may fit better with the study of microstructure and magnetoelastic (ME) coupling coefficients in ultrathin $Ni_{80}Fe_{20}$/Ag films by Song et al [10]. It is observed that the effective ME coefficients B^{eff} of polycrystalline films have a surface dependent component which varies inversely with film thickness t_f. This component can change the sign of B^{eff} and dramatically increase its magnitude for $t_f \leq 26$ Å, while it is close to zero for $t_f \approx 30$ Å.

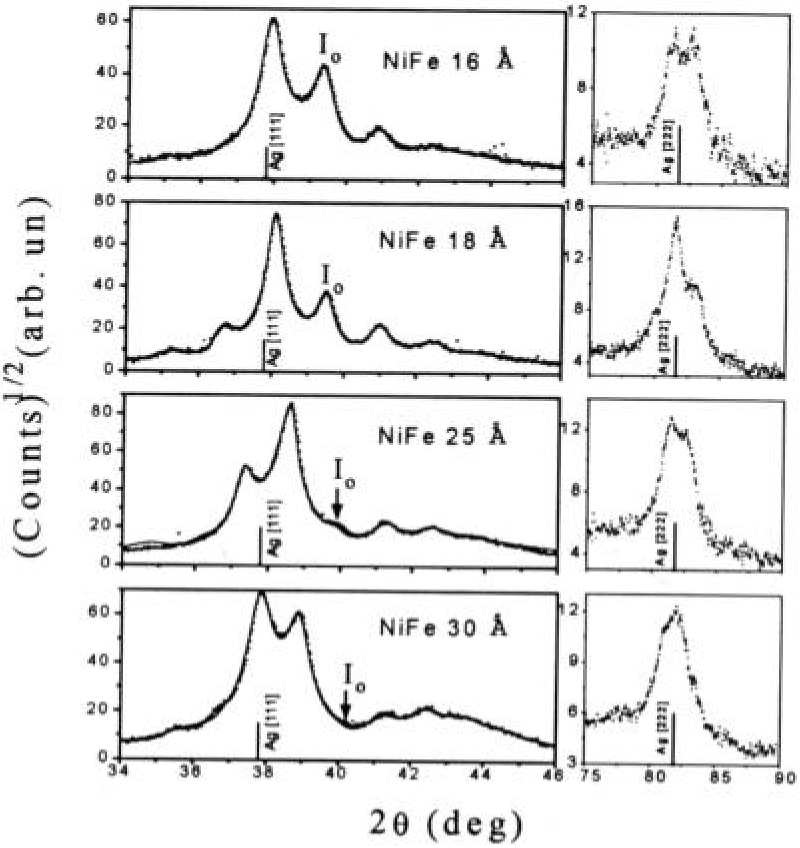

Fig1. XRD profiles (CuKα) for different t_f with $t_{Ag} \approx 40$ Å. The solid line is a fit from the Superlattice Refinement (SUPREX) program [11]. The peak positions are indexed about the average lattice constant d: $(2\sin\theta/\lambda)=(1/d)\pm(n/\Lambda)$, where n labels the order of the satellite around the main (n=0) Bragg peak.

3. Magnetoresistance results (MR)

MR measurements at RT were performed with the external magnetic field direction parallel (right) and perpendicular (left) to film plane. The maximum MR (≈0.2%) is achieved for [NiFe/20 Å/Ag/40 Å], which shows a characteristic sharpening of the curve around zero field in the parallel direction. There is only one maximum of ΔR/R at zero

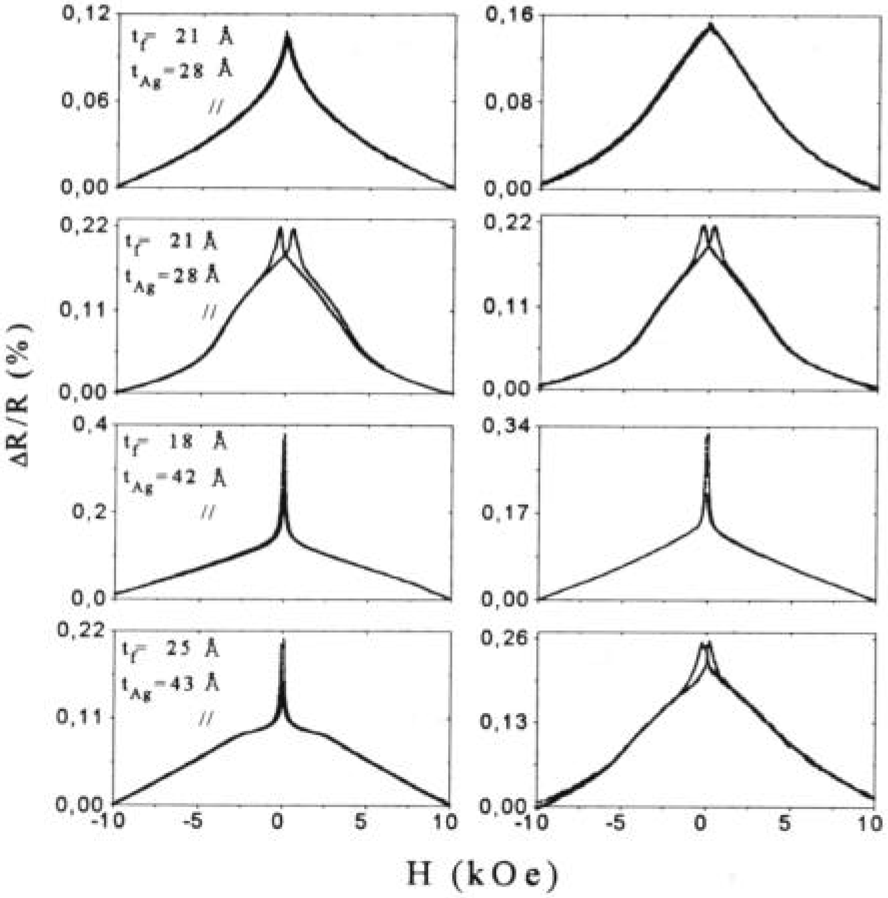

fig.2. MR measurements at 5 K for selected NiFe/Ag as deposited films, with the external magnetic field direction parallel (right) and perpendicular (left) to film plane.

field. The MR measurements at 5 K are shown in fig.2 for some selected samples. A considerable change in the response of transport properties to magnetic field variation occurs relative to RT measurements. For [NiFe/20 Å/Ag/40 Å] the effect is almost isotropic. Two common features appear in these measurements: (i) Saturation of the MR effect is not achieved and there is a linear decrease with increasing field above 0.5 T. The linear variation might be attributed to superparamagnetic NiFe particles [6]. (ii) Two maximum values of ΔR/R exist for non-zero negative and positive fields. Note that the maximum MR effect, of 1.5% at RT for H_s=100 Oe, has been observed for [NiFe/20 Å/Ag/40 Å] after 3 hrs annealing at 400° C in a vacuum sealed pyrex tube. In all annealed samples a coercive field H_c was apparent in the maxima of ΔR/R loops.

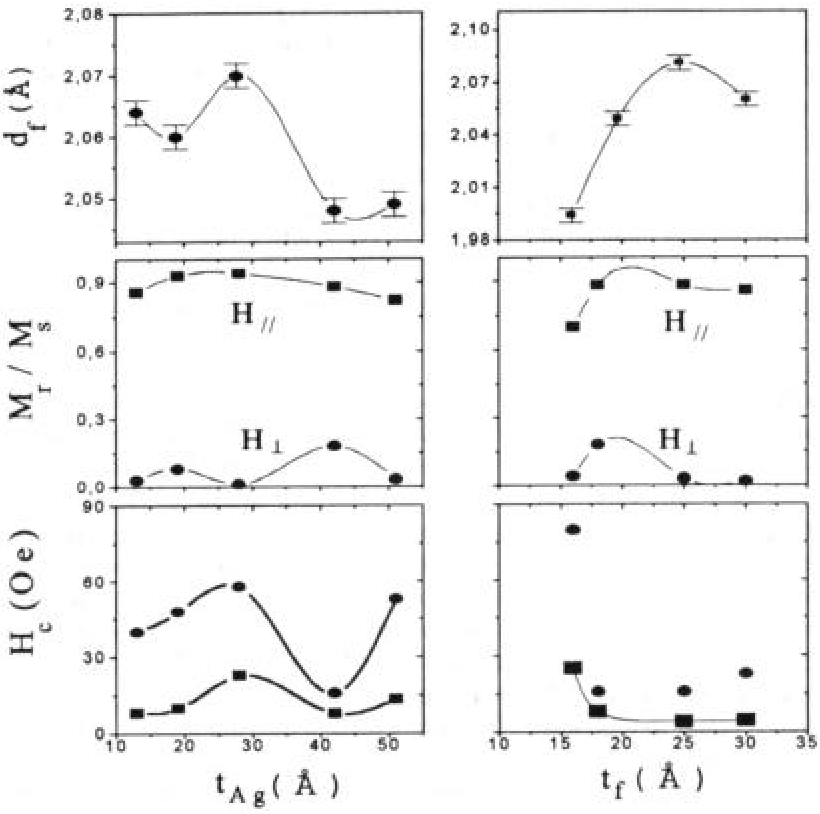

fig.3. Variation of the estimated d_f (top), observed M_r/M_s (middle) and H_c (bottom) values as a function of t_{Ag} (left) and t_f (right) at 5 K. Solid lines are guides to the eye. Squares are for $H_{//}$ and circles for $H_{\perp}$ directions.

4. Magnetic hysteresis

Isothermal SQUID magnetic measurements were performed with the field applied parallel ($H_{//}$) and perpendicular ($H_{\perp}$) to film plane at 300, 100 and 5 K. The loop shape was characteristic of ferromagnetically (FM) coupled material without any detectable coercive field (H_c) above 100 K. The variation of d_f, H_c and M_r/M_s as a function of t_{Ag} and t_f at 5 K is presented in fig.3. It is seen the resemblance of d_f and H_c oscillations as a function of t_{Ag} but not for variable t_f. The dependence of d_f and H_c with t_f in Fig.3 indicates that there is not a direct relationship between them caused from variable strain. Since our XRD analysis exclude the possibility of "bridging" among NiFe layers through Ag, that might vary H_c as well, variations in H_c and d_f with t_{Ag} can be understood in terms of stress induced anisotropy in ultrathin magnetic films.

In our samples, we have shown that the variation of Ag or NiFe layer thickness create different residual stresses. The residual stress causes additional negative or positive magnetostriction λ_s in NiFe which induces a preferable EA in every layer. By this action, for a material having a homogeneously positive magnetostriction, as in $Ni_{81}Fe_{19}$, the originally isotropic distribution of domain orientations will be squeezed into a narrower distribution along an EA parallel or vertical to film plane if the induced strain is tensile or compressive respectively. The observed loops are indicative that the EA lies in the film plane but for [NiFe/18 Å/Ag/42 Å] and [NiFe/25 Å/Ag/43 Å], where H_c is lowest for both directions, it may imply that the residual stress is minimal and the isotropic distribution of domain orientations is maintained. From Fig.2 is seen that only for these two samples is there an abrupt low field GMR effect, obviously related to easy magnetization reversal. Therefore our results are in support of a stress induced modification of NiFe EA intra-layer distributions that drive the magnetization reversal of the domains.

5. Conclusions

The XRD data are evidence that there is significant interface strain which is modified as a function of layer thickness. The observed splitting of <222> Ag superlattice peak for t_f<25 Å is attributed to Ag inter-diffusion between NiFe grain boundaries. The MR and hysteresis loop data show that for $t_f \approx 18$ to 25 Å and $t_{Ag} \approx 38$ to 43 Å the film is magnetically isotropic and presents easy magnetization reversal for low applied fields. The oscillatory variation of H_c and M_r/M_s as a function of t_{Ag} can be explained in terms of preferable EA directions in every NiFe layer induced from residual magnetostriction. The hysteresis loop shapes are typical of FM coupled layers and exhibit a non-zero coercive field below 100 K. The increase of GMR effect and $\Delta R/R$ field sensitivity at 5 K show that an enhancement of the average magnetic moment and hardening of magnetization reversal in individual NiFe layers (bulk scattering model) have a major contribution. In conclusion, an isotropic EA distribution of magnetic domains, due to small residual intralayer strain effects, dominates the low field GMR in sputtered NiFe/Ag multilayers.

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