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

C. CHRISTIDES, S. STAVROYIANNIS and D. NIARCHOS.
Institute of Materials Science, NCSR "DEMOKRITOS",
153 20 Agia Paraskevi, Attiki, Greece.

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 ($t$) layer thickness. The variation of hysteresis loop parameters can be related with the stress-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 optimization of the Giant magnetoresistive (GMR) effect (=5% at RT). A systematic change in the saturation magnetostriiction $\lambda_s$ and GMR have been observed [3] as a function of annealing temperature ($T_m$). The increase of $\lambda_s$ from negative to positive values as a function of $T_m$ suggests that the films are under tensile stress in the as-deposited state. This stress is gradually reversed with annealing and for $\lambda_s>0$ 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] $J_{AF} = \pi H_{AF} M_r / 4$.

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 $M_r$ 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
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 ($d_{Ag}$) and NiFe ($t$) layer thickness in [NiFe/$t$/Ag/40 Å] and [NiFe/20 Å/$t$/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 $t_{Ag}=40$ Å versus $t$. The observed spectra display two important features: First, the intensity of the $n=0$ Bragg peak ($I_{0}$) tends to zero as $t$ increases from 16 to 25 Å and $I_{0}$ becomes stronger at the same time. For $t_{Ag}=40$ Å and $t=30$ Å, $I_{0}$ 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 $n\neq0$ satellite peaks but they can not reduce the $n=0$ peak to be less intense from the satellites. However the damping of $I_{0}$ peak with $t_{Ag}$ 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 $t=16$ Å which merges to a single peak as the NiFe layer becomes thicker for constant $t_{Ag}=40$ 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 $d_{0}$ and $d_{Ag}$ relax to their bulk crystal spacings. In accordance the obtained $d_{0}$ 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$_{84}$Fe$_{16}$/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 \( t \). This component can change the sign of \( B_{\text{eff}} \) and dramatically increase its magnitude for \( t \leq 26 \, \text{Å} \), while it is close to zero for \( t \approx 30 \, \text{Å} \).

Fig 1. XRD profiles (CuK\( \alpha \)) for different \( t \) with \( t_{\text{Fe}}=40 \, \text{Å} \). The solid line is a fit from the Superlattice Refinement (SUPREX) program [11]. The peak positions are indexed about the average lattice constant \( d \) (2sin\( \theta \)/\( \lambda \))=(1/\( d \))=(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 \([\text{NiFe}/20 \, \text{Å}/\text{Ag}/40 \, \text{Å}]\), which shows a characteristic sharpening of the curve around zero field in the parallel direction. There is only one maximum of \( \Delta R/R \) at zero
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 $\Delta R/R$ exist for non-zero negative and positive fields. Note that the maximum MR effect, of 1.5% at RT for $H_0=100$ 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 $\Delta R/R$ loops.
Fig. 3. Variation of the estimated $d_f$ (top), observed $M_f/M_s$ (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 $H_f$ and circles for $H_{1f}$ directions.

4. Magnetic hysteresis

Isothermal SQUID magnetic measurements were performed with the field applied parallel ($H_0$) and perpendicular ($H_{1f}$) 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 $M_f/M_s$ 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 $\lambda$, in NiFe which induces a preferable EA in every layer. By this
action, for a material having a homogeneously positive magnetostriction, as in Ni$_8$Fe$_{12}$, 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$_{Ag}$$>$25 Å is attributed to Ag inter-diffusion between NiFe grain boundaries. The MR and hysteresis loop data show that for t$_{Ag}$=18 to 25 Å and t$_{Ag}$=38 to 43 Å the film is magnetically isotropic and presents easy magnetization reversal for low applied fields. The oscillatory variation of H$_c$ and M/M$_0$, 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 AR/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.

Acknowledgement
This work has been supported from the EKBRAN-280 project of the General Secretariat for Research and Technology of the Development Ministry in Greece.

References