Journal of Magnetism and Magnetic Materials 104-107 (1992) 1871-1872
North-Holland

Perpendicular anisotropy in Co/Ru epitaxial superlattices

A. Dinia [a], K. Ounadjela [a], A. Arbaoui [a], G. Suran [b], D. Muller [a] and P. Panissod [a]

[a] IPCMS-GEMME, Université Louis Pasteur, 4 rue Blaise Pascal, 67070 Strasbourg, France
[b] Laboratoire de Magnétisme, 92190 Meudon-Bellevue, France

We present recent results on the magnetic properties of Co/Ru hcp superlattices. From magnetization and FMR measurements, we determine the rather strong uniaxial anisotropy, which tends to align the moments along the normal to the layers for Co thicknesses < 15 Å. This anisotropy is analyzed in terms of interface anisotropy and magneto-elastic anisotropy of the strained Co lattice which adds to the bulk magnetocrystalline anisotropy of the hcp oriented cobalt layers.

A great deal of interest has recently been focused on the study of the magnetic properties of magnetic metallic multilayers. The magnetic anisotropy exhibited by some of these multilayers is particularly interesting, for fundamental studies as well as for applications to recording media in relation to high density magnetic recording. In order to understand the origin of the magnetic anisotropy, much work has been undertaken on sputtered films and magnetic superlattices. It has been reported [1] that for the Co/Au and Co/Cu superlattices grown by MBE technique [1], the surface anisotropy leads to an easy axis normal to the film plane below a crossover Co thickness of 19 Å in the Co/Au and 10 Å in the Co/Cu. In contrast Den Broeder et al. [2] have shown that as-grown Co/Au multilayers prepared by IBS technique have the magnetic easy axis in the film plane, mainly due to the form anisotropy. The annealing of the latter sample at 250-300 °C leads to a perpendicular anisotropy for Co thickness below 14 Å. It seems then clear that the magnetic anisotropy is strongly related to interfacial effects, and that the quality of growth is an important parameter to obtain pronounced magnetic anisotropies.

In this paper we present magnetization and FMR measurements performed on Co/Ru hcp (0001) superlattices prepared by UHV evaporation. We show the rather strong uniaxial anisotropy which tends to align the moments along the normal of the film plane below a crossover Co thickness of 15 Å, and analyze it in terms of interfacial anisotropy, magneto-elastic anisotropy induced by strains in the Co lattice and bulk magnetocrystalline anisotropy.

Co/Ru superlattices were grown by UHV evaporation onto mica in ultrahigh vacuum with a background pressure of better than 10^{-10} Torr. A single crystalline and flat Ru buffer layer (150 Å) was deposited onto mica at a temperature of about 500 °C. After cooling the substrate to 120 °C, Co and Ru layers were subsequently grown at a rate of 0.05 Å/s. For this study samples with Co thicknesses varied from 10 to 32 Å and fixed Ru thickness (32 Å) were prepared. The RHEED patterns observed during evaporation show that the growth is epitaxial consisting of hcp (0001) Co and Ru layers. Superlattices growth and structural characterization are reported elsewhere [3].

The magnetization measurements were performed using a vibrating sample magnetometer. Hysteresis loops were measured with applied field of up to 17 kOe both parallel and perpendicular to the film plane at 300 K. Two typical results are shown in fig. 1. One for the [Co(19 Å) Ru(32 Å)] superlattice which is more easily magnetized with the field parallel to the film plane, and a second for the [Co(10 Å) Ru(32 Å)] superlattice which is more easily magnetized with the field perpendicular to the film plane. For the two samples the saturation magnetization is only achieved in a rather strong field for any direction ($H_s \approx 2$ T). This is explained by the fact that over the perpendicular anisotropy, there exists an oscillating ferro-antiferromagnetic exchange coupling as a function of ruthenium thickness (see Ounadjela et al. [4]), and for a Ru thickness of 32 Å, this exchange coupling is still strong. The thinnest Co sample, 10 Å, presents a saturation

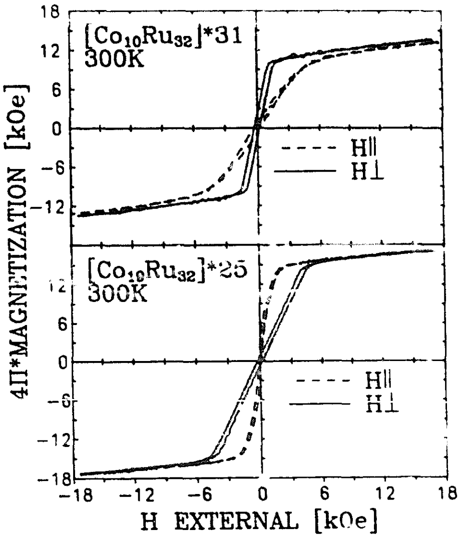

Fig. 1. Magnetization loops measured at 300 K of (a) [Co(10 Å) Ru(32 Å)]$_{31}$ and (b) [Co(19 Å) Ru(32 Å)]$_{25}$ superlattices with the applied field parallel (dashed curves) and perpendicular (solid curves) to the film plane.

value around 1090 emu/cm^3 which is reduced relative to the bulk Co value (1440 emu/cm^3), while the thickest Co sample exhibits a saturation value very close to the bulk one. The reduction of M_s when the Co thickness decreases is certainly explained by some intermixing at the interfaces lowering the magnetization. The analysis of our NMR data [5] suggest that about two monolayers are intermixed at the interfaces.

FMR measurements have been carried out at 300 K and $f = 9.8$ GHz. The resonance spectra for thick Co thicknesses ($t_{Co} \geq 15$ Å) show complex behaviour due to the existence of several peaks, in particular when the field is normal to the film plane. In order to localise the main mode, we have followed the resonance fields versus the angle ϕ between static applied field and film plane. The effective anisotropy was deduced by using the following expressions where the resonance H_{res} corresponds to the main mode:

$$(\omega/\gamma)^2 = H_{\parallel}(H_{\parallel} + 4\pi M - H_K), \quad (1)$$

$$(\omega/\gamma) = H_{\perp}(4\pi M - H_K). \quad (2)$$

One should observe that the in phase main mode is not affected by the antiferromagnetic coupling as shown by Krebs et al. [6]. The effective anisotropy K_{eff} was also deduced from VSM measurements as the area between the perpendicular and the parallel magnetization curves, in order to get rid of the exchange coupling. In fig. 2 we report the variation of $K_{eff}t_{Co}$ obtained from both FMR and VSM measurements as a function of Co thickness (t_{Co}). The effective anisotropy can phenomenologically be described as: $K_{eff} = 2K_s/t_{Co} + K_v$, where K_v is the contribution to the anisotropy per volume unit Co, t_{Co} is the Co layer thickness, K_s is the interface anisotropy (the factor of two arises from the two interfaces of each sublayer, which are assumed to contribute the same way). The anisotropy values obtained by both techniques agree very well. A positive value of K_{eff} means that the perpendicular magnetization may be stabilized, and in our case for $t_{Co} < 15$ Å, the direction of the spontaneous magnetization is perpendicular. The experimental data are well approximated by a linear relation for $t_{Co} > 13$ Å corresponding to $K_v = -6.78 \times 10^6$ erg/cm^3 (which is the sum of demagnetization energy $K_D = -2\pi M_s^2 = -12.3 \times 10^6$ erg/cm^3 and a magnetocrystalline energy $K_{MC} = +5.52 \times 10^6$ erg/cm^3 very close to the value of bulk Co) and $K_s = +0.5$ erg/cm^2. The deviation observed in $K_{eff}t_{Co}$ from the linear fit below $T_{Co} = 13$ Å is explained by the transition from an incoherent structure where dislocations release the misfit strains ($T_{Co} > 13$ Å) to a quasi-coherent structure where Co is expanded in plane as observed by RHEED [3]. In the coherent region, K_s is significantly reduced from what is expected from the extrapolation to $t_{Co} = 0$ in the incoherent region. Actually, in case of coherent growth the stress induced anisotropy of the strained layers is a volume contribution to the anisotropy of the films [2] and then the surface anisotropy arises only from the reduced symmetry at the surfaces usually named "Néel" surface anisotropy. Our measurements indicate that the magnetoelastic anisotropy in the strained coherent lattice corresponds to about $+6.5 \times 10^6$ erg/cm^3 added to the magnetocrystalline anisotropy of relaxed Co and the Néel term is very small. In case of incoherent growth, a model developed by Chappert et al. [7] for a single layer, and Van der Merwe et al. [8] for a symmetric multilayer suggests that residual misfit strains give rise to a magnetoelastic anisotropy which is proportional to $1/t_A$. The apparent surface anisotropy K_s is then enhanced in the incoherent growth region. However, the results obtained in this study indicate that the thickness dependence of K_{eff} can be accounted essentially by the demagnetization and bulk Co anisotropies. Then we do not expect a strong $1/t_A$ term arising from the mechanism described above. Consequently the K_s value is mostly related to a Néel term and is stronger than the value in the coherent regime. The difference between the two Néel terms arises obviously from the different nature of the interfaces in the two regimes and particularly to the expansion of the in plane Co–Co distance in the coherent regime and to the existence of dangling bond in the incoherent one.

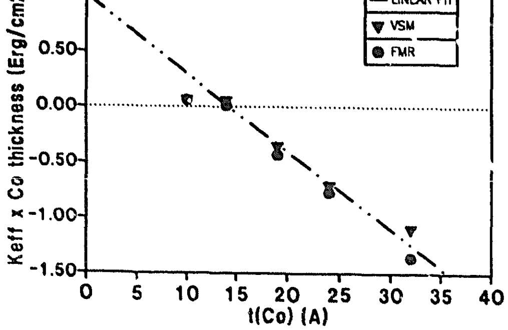

Fig. 2. Anisotropies for a series of [Co(x Å) Ru(32 Å)] superlattices from (a) VSM (▼) and (b) FMR (●) measurements.

References

[1] C.H. Lee, Hui He, F.J. Lamelas, W. Vavra, C. Uher and Roy Clarke, Phys. Rev. B 42 (1990) 1066.

[2] F.J.A. den Broeder, D. Kniper, A.P. Van der Mosselaer and W. Hoving, Phys. Rev. Lett. 60 (1988) 2769.

[3] D. Muller et al., J. Magn. Magn. Mater. 104–107 (1992) in sections 18 and 25.

[4] K. Ounadjela et al., ibid. in section 25.

[5] P. Panissod et al., private communication.

[6] J.J. Krebs, P. Lubits, A. Chaiken and G. Prinz, Phys. Rev. Lett. 63 (1989) 4828.

[7] C. Chappert and P. Bruno, J. Appl. Phys. 64 (1988) 5736.

[8] van der Merwe and W.A. Jesser, J. Appl. Phys. 63 (1988) 1509.