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MAGNETIC PROPERTIES AND CRYSTALLOGRAPHIC STRUCTURE OF CO/W MULTILAYERED FILMS

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Abstract. — The magnetic properties and crystallographic structure of cobalt/tungsten multilayers have been investigated. Depending on the individual film thicknesses and the multilayer periodicity, the structures are found to be either crystalline or amorphous. This difference in structure has a considerable effect on the magnetisation, coercivity and magnetic anisotropy of the system.

Magnetic multilayers allow the exploration of magnetic interactions at interfaces and across spacings approaching atomic dimensions, and also the investigation of extrinsic properties related to composition, growth and microstructural factors. In this paper we extend our previous work [1] on cobalt-based multilayers.

The multilayers were prepared by alternately sputter depositing cobalt and tungsten onto rotating substrates (silicon and glass) as described previously [1]. The thicknesses of cobalt, $D_{Co}$, and tungsten, $D_{W}$, in the multilayers were related to the rotation rate of the substrates above the two targets and the sputtering powers. Individual layer thicknesses could be varied from nominal monolayer values to more than 50 nm.

The total multilayer thickness, measured from Rutherford back-scattering spectra (RBS), varied between 80 and 400 nm. RBS was also used to estimate the effective composition of the multilayers, and their wavelength was obtained from low angle X-ray diffraction patterns. The magnetic properties of the multilayers were measured by vibrating specimen and torque magnetometry and X-ray diffractometry gave their crystal structures.

As indicated schematically in figure 1, the multilayers are classified into four types or regions according to their layer thicknesses: I $D_{Co} > D_{W} > 1$ nm; II $D_{Co} > 1$ nm, $D_{W} < 1$ nm; III $D_{Co} > D_{W} > 1$ nm; IV $D_{Co} < 1$ nm, $D_{W} > 1$ nm. The dashed, irregular boundary line drawn between the regions separates systems which were found to be crystalline (above the line) or totally or partly amorphous (below the line).

In region I the layers of cobalt and tungsten are well separated structurally since X-ray reflections from h.c.p. cobalt and b.c.c. tungsten were observed simultaneously. Diffraction from the tungsten layers was characterised by a strong and broad (110) reflection indicating a textured polycrystalline growth with small crystallites. The lattice constant of tungsten was measured as 0.315 nm (the bulk value) and was independent of $D_{W}$ and $D_{Co}$. The cobalt layers are polycrystalline films with a random orientation and the bulk lattice constants ($a = 0.250$ nm, $c = 0.406$ nm).

The cobalt layers in region II are similar to those of region I, but the now thinner tungsten “spacing” layers are amorphous.

Region III is subdivided into two sub-regions. The dividing boundary here corresponds approximately to an effective concentration of tungsten, $C_{W}$, of 15 atomic percent (at %). In IIIa the multilayers as a whole are crystalline with a preferred hexagonal $[0001]$ $c$-axis texture. Figure 2a shows the dependence of the hexagonal (002) diffraction maximum intensity on $C_{W}$. The maximum intensity was observed round 10 at % of tungsten. Small wavelength values, $D_{Co+W}$, produce a more definite hexagonal $c$-axis orientation and can correspond to significant grain growth. Indeed, electron microscopy of such multilayers [1] has revealed the presence of pseudo-single crystal layers with $[0001]$ perpendicular to the layer plane and magnetic domain structures typical of films with significant perpendicular anisotropy.

The lattice constants of the hexagonal structure in

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Fig. 2. - (a) Intensity of the (0002) diffraction maximum, $I_{0002}$, (b) magnetisation of the cobalt content of the multilayers, $M_{Co}$, and (c) coercivity, $H_c$, all vs. tungsten content of the multilayers, $C_W$. Open symbols signify crystalline multilayers and closed symbols signify amorphous ones.

The intensity of the first order maximum depended strongly on $D_w$ and weakly on $D_C$. The signal was most intense with $D_W$ between 0.35 and 0.4 nm which corresponds to the formation of an apparent tungsten monolayer. These results suggest that the surface of the cobalt layers is less well defined than that of the tungsten.

The saturation magnetisation, $M_s$, of the multilayers in regions II, III and IV is apparently determined mainly by the effective concentration of tungsten. This is probably related to a significant amount of mixing at the layer interfaces. $M_s$ decreases linearly from 1400 emu cm$^{-3}$ (kA m$^{-1}$) with increasing $C_W$ until it is zero at about 25 at % of tungsten, in some agreement with published results for homogeneous thin film alloys [2]. $M_s$ was also found to decrease with decreasing cobalt layer thickness until a minimum constant value is reached at $D_C$ values of less than 0.6 nm. This is the case even though $C_W$ is kept constant with decreasing layer thicknesses.

The magnetisation of the cobalt component of the multilayers, $M_{Co}$, defined in terms of the volume of cobalt in the multilayers is given in figure 2b as a function of $C_W$. Here $M_{Co}$ decreases with increasing $C_W$ for $D_{Co}$ less than 1 nm. For greater thicknesses of cobalt $M_{Co}$ is independent of $D_{Co}$ and is equal to 500, 800 and 1100 emu cm$^{-3}$ for $D_{Co}$ values of 1, 1.5 and 3.0 nm respectively. An extrapolation to a magnetisation value equal to that of bulk cobalt suggests the existence of a non-magnetic region about 0.64 nm thick between the cobalt and tungsten layers of the multilayer. This region is a result of the mixing of cobalt and tungsten and its width agrees well with the observation of clear, low angle diffraction patterns down to $D_{Co}+w$ values of about 0.6 nm and also with computations of the multilayer profiles.

Well defined multilayers in region I show magnetic anisotropy characteristic of an in-plane easy direction. However, in region IIIa an intrinsic easy direction perpendicular to the multilayer plane is suggested. Multilayers showing significant positive intrinsic anisotropy, $K_u$, tend to have a period $D_{Co}+w$ which lies on the boundary between IIIa and IIIb. Some particular points are marked in figure 1. $K_u$ increases with decreasing $D_{Co}+w$, typically $4.1 \times 10^5$ ergs cm$^{-3}$ for $D_{Co} = 0.48$ nm and $D_W = 0.1$ nm and $2.9 \times 10^6$ ergs cm$^{-3}$ for $D_{Co} = 0.29$ nm and $D_W = 0.05$ nm. The perpendicular anisotropy also correlates well with the $I_{0002}$ intensity and the formation of a stripe-type magnetic domain structure, as discussed above.

Coercivity has a similar relationship to $I_{0002}$ as the intrinsic anisotropy. As shown in figure 2c, $H_c$ peaks at about 10 at % tungsten, particularly for small wavelength multilayers. When the multilayers become amorphous the coercivity drops sharply, as expected, to a value much less than 1 Oe ($\sim 80$ A m$^{-1}$).