Neutron reflectometry on Co–Cr layers

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Polarized neutron reflection experiments were performed on a thin in-plane magnetized Co–Cr layer deposited on a quartz substrate. Data taken at a low magnetic field (≈ 0.1 T) clearly indicate the existence of an initial layer at the substrate side, whereas data at saturation (≈ 0.7 T) are consistent with a rather homogeneous magnetization.

1. Introduction

As thin films of Co–Cr (100–300 nm thick) are candidate materials for perpendicular magnetic recording media, it is important to obtain detailed knowledge of the magnetic properties of such layers. To investigate the microstructure [1] and the magnetic properties [2] of Co–Cr layers several techniques have been used in the past; electron microscopy [3], magnetization measurements and magneto-optics [4], bitter colloid-SEM [5], neutron depolarization [6] and SANS [7]. Neutron depolarization experiments provided evidence that a (thickness-dependent) ‘initial layer’, with magnetic properties different from those in the domains in the ‘bulk’ of the film, might exist on the substrate side of the film. The average magnetization of the lower 10–15 nm of the initial layer has been investigated using the magneto-optic Kerr effect.

2. Neutron reflectometry

Neutron reflectometry is a technique for studying the nuclear and magnetic structure perpendicular to a flat surface or interface [8,9]. An extremely well collimated neutron beam impinges on a flat sample at grazing incidence and the intensity of specularly reflected neutrons is measured as a function of q_0 , the component of the incoming wavevector perpendicular to the surface, which is determined by the grazing angle θ and the neutron wavelength λ :

$$q_0 = \frac{2\pi}{\lambda} \sin \theta. \quad (1)$$

In a time-of-flight reflectometer variation of q_0 is achieved through the wavelength of a neutron, deter-

mined from the velocity v which follows from the time it takes a neutron to travel the distance from a chopper, where it enters the instrument, to the detector

$$\lambda = h/mv, \quad (2)$$

where h is Planck’s constant and m is the mass of the neutron. The angle of incidence θ is of the order of 1° . Resolution requirements lead to allowed divergencies of the order of 0.1 mrad. This makes, together with the relatively low neutron fluxes available, a neutron reflectometer a large instrument. Also the size of the samples should be large, of the order of a few cm^2 . It is an essential requirement that the sample is very flat.

The (q_0 -dependent) specularly reflected neutron intensity is proportional to the square of the modulus of the reflection amplitude of the neutron wavefunction perpendicular to the surface, which satisfies the Schrödinger equation

$$\frac{\partial^2 \psi(z)}{\partial z^2} + (q_0^2 - \Gamma(z))\psi(z) = 0. \quad (3)$$

The scattering length density

$$\Gamma_{\pm}(z) = 4\pi \langle n(z)(b_n(z) \pm C\mu(z)) \rangle \quad (4)$$

depends on the (in-plane averaged) atomic number density $n(z)$, the nuclear scattering length $b_n(z)$ and the average in-plane magnetic moment $\mu(z)$ of the atoms as a function of the depth z , the value of C is $2.645 \text{ fm}/\mu_B$. The + or – sign in $\Gamma(z)$ represents the neutron spin parallel or anti-parallel to the in-plane magnetic moment. The nuclear scattering length of the elements and isotopes varies more or less ‘randomly’ over the periodic system, so that the contrast in $\Gamma(z)$ can be varied by isotopic substitution. Obviously the magnetic term in $\Gamma(z)$ can be exploited to investigate the magnetic structure as a function of depth in the film.

The relatively weak interaction of a thermal neutron and an atom results in a large ‘penetration depth’

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of the neutron in the surface. In contrast to X-rays, absorption (taken into account by a complex component in the scattering length b_n) is for most elements negligible. The sensitivity for the magnetic state makes neutron reflectometry a unique method for investigating non-homogeneous magnetic structures in (multi) layer systems and thin films.

3. Data analysis

The measured reflectivities cannot be inverted directly into a scattering length density profile $\Gamma(z)$. Instead, the reflectivity for a parametrized function $\Gamma(z)$ is calculated according to eq. (3) as a function of q_0 . The parameters that describe $\Gamma(z)$ are determined from a least-squares fitting procedure of the calculated reflectivity, convoluted with the experimental resolution function, to the data. Standard optical matrix methods [10] can be used, since eq. (3) is completely equivalent to a description of the neutron beam in terms of a depth-dependent neutron index of refraction

$$N(z) = \left(1 - \frac{\Gamma(z)}{k_0^2} \right)^{1/2}, \quad (5)$$

where k_0 represents the wavenumber of the neutron ($k_0 = 2\pi/\lambda$). The weak interaction of thermal neutrons and atoms yields values of $N(z)$ that deviate less than 10^{-4} from 1. For most elements the nuclear scattering length b_n is positive, thus for most materials external total reflection can be observed.

Simultaneous analysis of two reflectivities measured on the same sample, with the spin parallel and anti-parallel to the magnetization, yields separate information on the nuclear and the magnetic structure perpendicular to the surface.

4. Experiments on Co–Cr layers

The present experiment on an in-plane magnetized layer of $\text{Co}_{81}\text{Cr}_{19}$, rf sputtered onto a polished quartz substrate [2], was performed on the time-of-flight neutron reflectometer ‘CRISP’ of ISIS at the Rutherford–Appleton Laboratory. Magnetic fields between 0.01 and 0.7 T were applied.

The results of the analysis of the data taken at the higher applied field were: film thickness 145 nm, average nuclear scattering length density 0.0028 nm^{-2} , average magnetic scattering length density 0.0016 nm^{-2} or average magnetic moment per atom $0.6\mu_B$. These figures are in good agreement with the expected values, 0.0030 nm^{-2} for the nuclear and 0.0015 nm^{-2} for the magnetic scattering length densities, calculated ac-

cording to bulk density and the assumption of a magnetic moment of $0.5\mu_B$ per atom.

The analysis of the data at a lower applied field (0.1 T) indicates clearly an initial magnetic layer (i.e. an enhanced magnetic scattering length density) at the substrate side. Although it proved to be essential to take into account an ‘initial magnetic layer’ of the order of 15 nm thick to obtain a satisfactory fit to the neutron reflection data, the accuracy of the present data is not sufficient to quote definitively a thickness or precise shape for this layer. Note that the thickness of the initial layer observed by Bernards et al. [11] on 400–600 nm thick Co–Cr layers is of the order of the total thickness of the sample used in the present experiment.

Fig. 1. Observed specular reflectivities of Co–Cr film on glass together with model fits (a) at low magnetic field (0.1 T), and (b) at saturation magnetic field (0.7 T). The data for the neutron spin anti-parallel to the magnetization have been divided by a factor 10. In the fits nuclear and magnetic scattering length densities have been used, as shown in the inserts.

Unfortunately until now the data taken at 0.01 T could be fitted only using spurious scattering length density profiles.

In fig. 1 measured reflectivities, for parallel and anti-parallel spins, together with fitted curves are shown. The average magnetic scattering length density at the low field (0.1 T) is 0.8 of the value at saturation. This high value might indicate a low perpendicular anisotropy field of the order of 0.1 T. This assumption was confirmed qualitatively by VSM measurements on the same sample. Future neutron reflection experiments will be carried out to study the field dependence of the 'initial magnetic layer' at fields below 0.1 T.

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