Perpendicular magnetic anisotropy of exchange coupled Co/Cu/Ni/Cu/Si(001) structures

Cavendish Laboratory, University of Cambridge, CB3 0HE, UK
*Department of Physics, Atomic-scale Surface Science Research Center, Yonsei University, Seoul 120-749, Korea
†Rutherford Appleton Laboratory, Chilton OX11 OQX, UK
(Received: May 6, 1998 Accepted: August 26, 1998)

Polar magneto-optic Kerr effect (MOKE) measurements on epitaxial Cu/22ÅCo/0-49Å Cu/53Å Ni/Cu/Si(001) structures reveal that the Ni magnetisation is aligned in-plane for zero Cu spacer layer thickness and becomes increasingly aligned out-of-plane with increasing Cu spacer layer thickness, whereas an in-plane remanence for Co is always observed. Polarised neutron reflection (PNR) measurements at room temperature yield at room temperature a slightly reduced magnetisation of 1.57±0.08 µB for Co and 0.50±0.04µB for Ni for a Cu/22Å Co/10Å Cu/53Å Ni/Cu/Si(001) structure. PNR measurements yield also a reduced in-plane remanence for both Co and Ni. This could suggest either a canted magnetisation or multidomain state at remanence. The latter mechanism is supported by magnetic force microscopy images.

Key words: thin film, coupling, perpendicular magnetic anisotropy, magnetic moments

1. Introduction

It is well known that Ni/Cu(001) structures show perpendicular magnetic anisotropy (PMA) over a very large thickness range (10-100Å) due to a tensile strain of the Ni film [1,2]. Co/Cu(001) structures on the other hand show an in-plane magnetisation [3,4]. Ni/Co bilayers are strongly ferromagnetically (FM) coupled, when the layers are in direct contact [5,6], whereas for Co/Cu/Ni trilayers either FM or antiferromagnetic coupling have been reported [7]. Here we have investigated epitaxial 22Å Co/0-49ÅCu/53Å Ni trilayers on Cu/Si(001) structures by MOKE and PNR. We show how the Cu spacer layer thickness determines the magnetisation orientation for the Co and Ni layers. PNR measurements enable us to layer selectively determine the magnetisations of the Ni and Co layers both at saturation and remanence, whereas from MOKE measurements the overall magnetic hysteresis behaviour is investigated.

2. Experimental Conditions

The Si(001) substrates were etched in diluted HF solution for 12 minutes prior to loading into the growth chamber and annealed for 2 hours at ~200°C after overnight bake-out. The base pressure of the chamber was 3×10⁻⁶ mbar. Cu buffer layers were grown at ~20 Å/min at 4×10⁻⁶ mbar using an electron beam heated Mo crucible while Co and Ni films were grown at ~2 Å/min by electron beam evaporation at pressures of ~2×10⁻⁶ mbar and 6×10⁻⁶ mbar, respectively during deposition. A Cu/Co/10ÅCu/Ni/Cu/Si(001) structure (sample A) and a wedged Cu/Co/0-49Å Cu/Ni/Cu/Si(001) structure (sample B) with the nominally same Co, Ni and Cu buffer and capping layer thicknesses were prepared at room temperature. The film thicknesses were monitored using a quartz crystal monitor during growth and were more accurately determined from the fits to the PNR data for sample A as given in table 1. The cleanliness of the layers was checked by Auger electron spectroscopy after completion of each film growth. Reflection high energy electron diffraction images showed sharp streaks and no qualitative changes during the subsequent Ni, Cu and Co growth. This confirms the earlier finding [13] that three dimensional epitaxial growth with an fcc structure occurs along the [001] direction with the Cu, Ni and Co cubic axes rotated in-plane by 45° with respect to the Si(001) principal axis [13, 14]. The PNR experiments were carried out on the CRISP reflectometer at the Rutherford Appleton Laboratory [15]. For the PNR measurements sample A was magnetised (H=700 mT) in the plane Cu [110] direction, which is the Co easy axis, normal to the scattering plane. Earlier MOKE measurements showed that this field is sufficient to saturate the film in the plane. [10, 16]. For fitting the PNR data we use bulk scattering densities and constant magnetic moments throughout the Co and Ni layers.

3. Experimental results

Figure 1 shows the polar MOKE measurements up to (a) 2 and (b) 0.1 Tesla for the Co/Cu-wedge/Ni trilayer for selected Cu spacer layer thicknesses for sample B. For the Co/Ni bilayer (0 Å Cu), a typical hard-axis hysteresis loop with no out-of-plane remanence is observed. The Co and Ni films are FM coupled causing an in-plane magnetisation for the Co due to the dominant Co shape anisotropy [9-12, 17]. For the case of the Co/14ÅCu/Ni trilayer both an increased remanence and an increase in the saturation field is observed. The MOKE measurements of the Co/10Å Cu/Ni trilayer (sample A) were very similar to the MOKE measurements of the Co/14ÅCu/Ni trilayer (sample B). For the Co/49 Å Cu/Ni trilayer a square hysteresis loop at low field and a slightly larger saturation field is observed.

The hysteresis loops shown in Figure 1 can be understood as follows: since the Co/Ni bilayer is strongly
FM coupled, the magnetisations of the Ni and Co layers are aligned parallel. The Co/Ni bilayer has a smaller effective magnetisation compared to a Co film causing a smaller saturation field [9-11, 17]. If the FM coupling becomes weaker with increasing Cu spacer layer thickness, the Ni film shows PMA, whereas the Co film an in-plane magnetisation due to the dominant shape anisotropy. A square hysteresis loop at low field is attributed to the Ni layer and a typical hard axis loop at high field is attributed to the magnetisation reversal of the Co film as observed for the Co/49Å Cu/Ni trilayer.

![Graph](image)

**Fig. 1.** Polar MOKE measurements with the field applied perpendicular to the film of the Co/Cu/Ni trilayer for different Cu spacer layer thicknesses up to 0.1 Tesla (a) and up to 2 Tesla (b). The loops are normalised at the maximum applied field. A linear background has been subtracted.

Polarised neutron reflection (PNR) is a unique technique in that it can determine layer-selectively the magnetic moments and layer thicknesses of multilayered structures [18]. Figure 2 shows the measured and fitted spin-dependent reflectivity and spin asymmetry data for sample A as a function of the neutron scattering vector (2q) perpendicular to the film plane, where the magnetisation is saturated in the film plane. Several pronounced oscillations are seen in the reflectivity and spin asymmetry data. The results of the fits to the data are summarised in Table I. The fits yield atomic moments of $M_{Co} = 1.57\pm0.08\mu_B$ and $M_{Ni} = 0.50\pm0.04\mu_B$. These values are slightly reduced to the bulk values of $1.71\mu_B$ and $0.58\mu_B$ for Co and Ni at room temperature [19]. The Ni moment is in agreement with previous measurements on Ni films [20]. We have further performed PNR measurements for sample A at remanence under otherwise the same conditions. The fits yields remanent moments of $M_{Co} = 1.40\pm0.11\mu_B$ and $M_{Ni} = 0.16\pm0.05\mu_B$ along the Co and Ni [110] direction. The magnetic moment of Co along this direction is therefore slightly smaller than that of Co at saturation, and the remanence of Ni is strongly reduced along this direction.

**Table 1.** The layer thicknesses (t), atomic magnetic moments at saturation ($M_s$) and remanence ($M_r$) for sample A as determined from room temperature PNR measurements. Average interface roughness parameters [21] of 7 Å have been obtained from the fits.

<table>
<thead>
<tr>
<th>Material</th>
<th>t (Å)</th>
<th>$M_s$ (μB)</th>
<th>$M_r$ (μB)</th>
<th>$M_r$/$M_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>40±1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>22±2</td>
<td>1.57±0.08</td>
<td>1.40±0.11</td>
<td>89%</td>
</tr>
<tr>
<td>Cu</td>
<td>10±1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>53±1</td>
<td>0.50±0.04</td>
<td>0.16±0.05</td>
<td>32%</td>
</tr>
<tr>
<td>Cu</td>
<td>784±2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

![Graph](image)

**Fig. 2.** PNR reflectivity (a) and spin asymmetry (b) data (symbol) and their best fits (continuous line) for sample A at saturation. The spin asymmetry is given by $(R_{\text{spin-up}} - R_{\text{spin-down}})/(R_{\text{spin-up}} + R_{\text{spin-down}})$, where $R_{\text{spin-up}}$ and $R_{\text{spin-down}}$ indicate the reflectivities of the neutrons with spin parallel (spin-up) and antiparallel (spin-down) to the film magnetisation, respectively.

There are several possible causes for this behaviour:

1) The in-plane remanent magnetisation might not be aligned parallel to the neutron beam polarisation direction. Therefore the remanence along the direction parallel to
the beam polarisation is reduced. However we measured also the spin-asymmetry at remanence remanent after rotating the sample 90°, and found no significant spin asymmetry. Therefore a reduction in the in-plane remanence compared to saturation moment is not attributed to an in-plane rotation of the magnetisation.

2) If the Co/Cu/Ni trilayer were not significantly coupled, the Ni film would show an out-of-plane remanent magnetisation, whereas the Co film would show an in-plane remanent magnetisation, as evidenced from the polar MOKE measurements on the Co/49Å Cu/Ni trilayer (Fig.1). However the Ni and Co films of the Co/10Å Cu/Ni trilayer (sample B) are weakly coupled. This could therefore result in a twisted state as reported for Fe/Gd multilayers [22-25]. In the case of the Co/10Å Cu/Ni trilayer, the Ni film might be expected to show a small in-plane magnetisation component, whereas the Co film might show a small out-of-plane component due to the twisting of the magnetisation.

3) A final possibility is that a multidomain state might occur at remanence. The transition from out-of-plane to in-plane transition for Cu/Ni/Cu(001) structures is evidenced by magnetic force microscopy (MFM) images to occur by multiplication of domain walls, whose magnetisation lies in-plane rather than a coherent rotation [26]. Our MFM images on sample A show a similar multidomain pattern at remanence as for Cu/Ni/Cu(001) structures. Therefore the Ni in-plane remanent magnetisation of sample A is likely to be attributed to an in-plane magnetisation of the domain walls. Similar the small reduction in the Co in-plane remanent magnetisation observed in the PNR measurements might be attributed to a multidomain state of the Co film.

Acknowledgements We thank the EPSRC (UK) and the ESPRIT (EU) for financial support. W.Y. Lee thanks British Council Korea for financial support. J. Lee thanks ASSRC, Yonse University for financial support.

References