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Magnetic anisotropy, magnetic moments and coupling of Cu/Co/Cu/Ni/Cu(001) trilayer

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Abstract. Polar magneto-optic Kerr effect (MOKE) measurements on an epitaxial Cu/Co (23 Å)/Cu (0–49 Å)/Ni (53 Å)/Cu/Si(001) structure reveal that the Ni magnetization 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 remanent magnetization for Co is always observed. Layer selective polarized neutron reflection (PNR) measurements yield almost bulk-like magnetic moments of 1.57 ± 0.08 μ_B for Co and 0.50 ± 0.04 μ_B for Ni for a Cu/Co (22 Å)/Cu (10 Å)/Ni (53 Å)/Cu/Si(001) structure at room temperature. A reduced remanence is observed for both the out-of plane magnetization by polar MOKE, and the in-plane magnetization for Co and Ni by PNR. This could suggest either a canted magnetization or multidomain state at remanence.

1. Introduction

It is well known that Ni/Cu(001) structures show perpendicular magnetic anisotropy (PMA) over a very large thickness range (∼10–100 Å) due to a tensile strain of the Ni film [1–6]. For thinner Ni films, an in-plane magnetization occurs due to a dominant negative Néel type surface anisotropy, whereas thicker Ni films show an in-plane magnetization due to the dominant shape anisotropy [1]. Co/Cu(001) structures on the other hand show an in-plane magnetization [7, 8]. For structures which combine Ni and Co films, novel magnetic behaviours can occur. Ni/Co bilayers are strongly ferromagnetically (FM) coupled, when the layers are in direct contact, and have a common Curie temperature [9–12]. For Co/Cu/Ni trilayers either FM or antiferromagnetic coupling and different Curie temperatures for the Co and Ni layers has been found for 2–6 monolayer thick Cu interlayers [12]. Here we have investigated epitaxial Cu/Co (23 Å)/Cu (0–50 Å)/Ni (53 Å)/Cu/Si(001) structures by MOKE and PNR measurements. We show that the Cu spacer layer thickness determines the magnetization orientation for the Co and Ni layers. PNR measurements enable us to layer selectively determine the magnetizations of the Ni and Co layers both at saturation and remanence, whereas by MOKE measurements the overall magnetic hysteresis behaviour is investigated.

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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 an overnight bake-out. The base pressure of the chamber was 3×10^{-10} mbar. Cu buffer layers were grown at ~20 Å min^{-1} at 4×10^{-9} mbar using an electron beam heated Mo crucible while Co and Ni films were grown at ~2 Å min^{-1} by thermal evaporation at a pressure of 2×10^{-9} mbar and 6×10^{-10} mbar. A Cu (42 ± 2 Å)/Co (23 ± 2 Å)/Cu (10 ± 2 Å)/Ni (53 ± 2 Å)/Cu (785 ± 2 Å)/Si(001) structure (sample A) was grown at room temperature. Also a wedged Cu/Co/0–49 Å Cu/Ni/Cu/Si(001) structure (sample B) with nominally the same Co, Ni and Cu buffer and capping layer thickness was prepared to study the magnetization behaviour by MOKE magnetometry for different Cu spacer layer thicknesses. The film thicknesses were monitored using a quartz crystal monitor placed close to the sample position during growth and more accurately determined from the fit to the PNR data for sample A. The cleanliness of the layers was checked by Auger electron spectroscopy (AES) after completion of each film growth. Reflection high energy electron diffraction (RHEED) images showed sharp streaks with low background and no qualitative change during the subsequent Ni, Cu and Co growth. This confirmed 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 axes as expected since both Co and Ni have an fcc (001) surface when grown on Cu(001) [13, 14]. The PNR experiments were carried out on the neutron reflectometer, CRISP, at the Rutherford Appleton Laboratory [15]. For the PNR measurements sample A was magnetized in the intraplanar Cu $\langle 110 \rangle$ direction along and normal to the scattering plane using an electromagnet ($H = 700$ mT). The $\langle 110 \rangle$ axis is the magnetocrystalline easy axis for fcc Co. It was separately confirmed by MOKE measurements that this field is sufficient to saturate the film in the plane [10, 16]. To fit the PNR data we assume bulk scattering densities and constant magnetic moments throughout the Co and Ni layers. Defects, steps, interdiffusion and local fluctuations can contribute to an effective roughness at each interface, which has the effect of reducing the specularly reflected intensity due to diffuse scattering. We have taken this into account by introducing a random Gaussian microscopic distribution at each interface as proposed by Nevot and Croce [17].

3. Experimental results

Figure 1 shows the polar MOKE curves for the Co/Cu wedge/Ni trilayer (sample B) for selected Cu spacer layer thicknesses. Figure 1(a), (b) shows the polar MOKE curves for applied fields up to 2 T and 75 mT, respectively. For the Co/Ni bilayer (0 Å Cu), a typical hard-axis hysteresis loop with no out-of plane remanence magnetization is observed. The Co and Ni films are FM coupled causing an in-plane magnetization for the Co due to the dominant Co uniaxial shape anisotropy as reported earlier [9–12, 18]. For the case of the Co/14 Å Cu/Ni trilayer both an increased remanence magnetization and an increase in the saturation field is observed. The MOKE measurements of the Co/10 Å Cu/Ni trilayer (sample A) were very similar to the MOKE measurements of the Co/14 Å Cu/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 can be understood as follows: since the Co/Ni bilayer is strongly FM coupled, the magnetizations of the Ni and Co layers are aligned parallel. The Co/Ni bilayer has a smaller effective magnetization per total magnetic layer thickness compared to a Co film. Therefore a lower out-of plane saturation field is expected for the Co/Ni bilayer compared

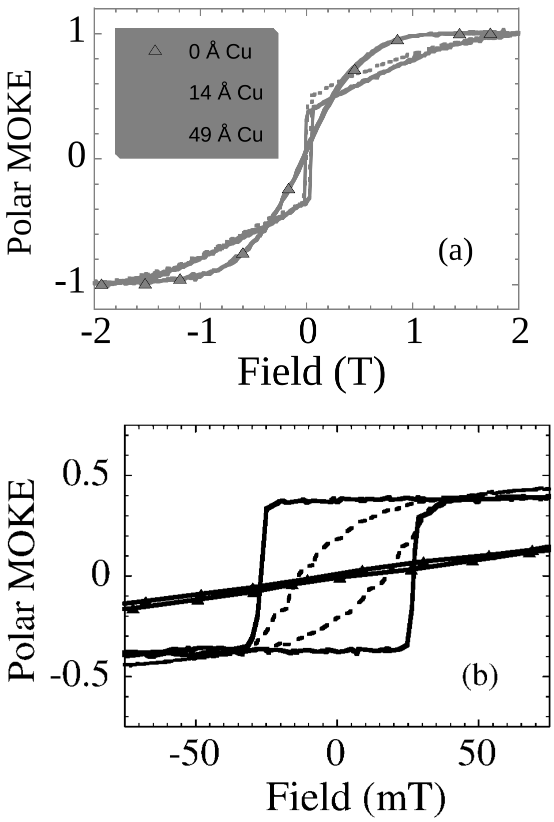

Figure 1. Normalized polar MOKE measurements with the field applied perpendicular to the film of the Co/Cu/Ni trilayer for different Cu spacer layer thicknesses up to (a) 2 T and (b) up to 75 mT. The loops are normalized by the intensity at the maximum applied field of 2 T.

to a Co film, since interface anisotropies do not cause PMA, as previously verified for this system [9–11, 18]. If the FM coupling becomes weaker with increasing Cu spacer layer thickness, the Ni can be expected to show a strain induced PMA, whereas the Co film can be expected to show an in-plane magnetization due to the dominant shape anisotropy. The square hysteresis loop as observed at low field is attributed to the Ni magnetization and the typical hard axis loop observed at high field is attributed to the magnetization reversal of the Co film.

PNR is an ideal and unique technique in that it can determine layer-selectively the absolute value of the intraplanar magnetic moments and layer thicknesses [19]. More commonly used magnetometry techniques, such as alternating gradient field or superconducting quantum interference device magnetometry, have the disadvantage of measuring the total magnetization and are not able to distinguish the contributions from the separate layers, which is crucial in the present study. Figure 2(a) 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. The spin asymmetry is given by $(R_{spin\text{-}up} - R_{spin\text{-}down})/(R_{spin\text{-}up} + R_{spin\text{-}down})$, where $R_{spin\text{-}up}$ and $R_{spin\text{-}down}$ indicate the reflectivities of the neutrons with spin parallel (spin-up) and antiparallel (spin-down) to the film magnetization, respectively. A 700 mT in-plane field is applied to magnetically saturate the sample for this measurement. Several pronounced

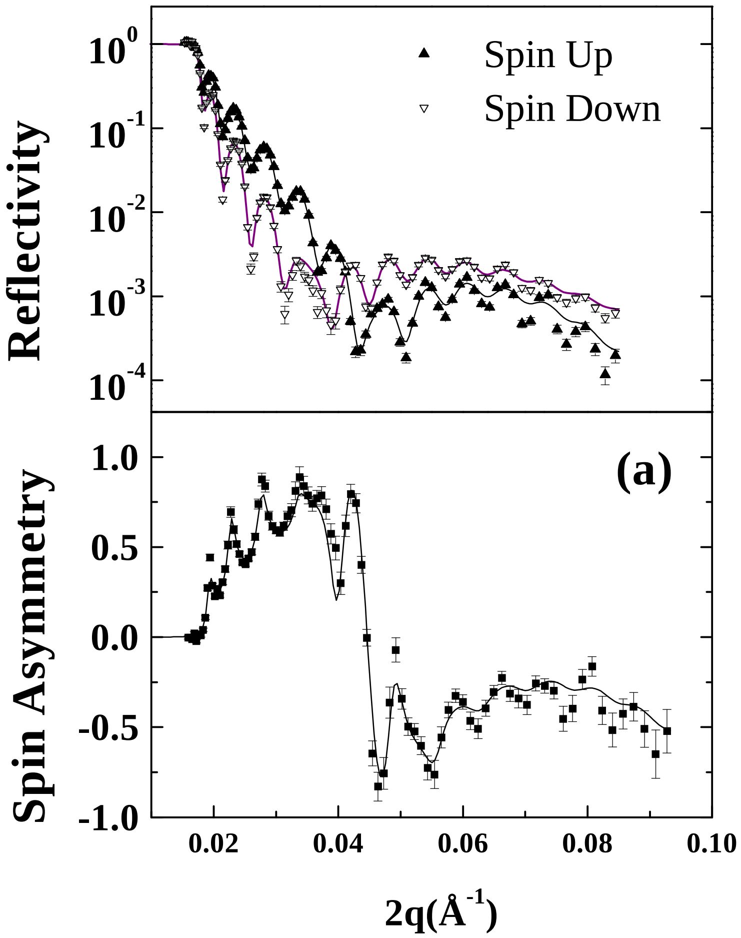

Figure 2. PNR reflectivity and spin asymmetry data (symbol) and their best fits (continuous line) for sample A (a) at saturation and (b) at remanence.

oscillations are seen in both the reflectivity and spin asymmetry data and excellent fits are obtained to the data up to large wavevectors. The magnetic moments, layer thicknesses and interface roughnesses obtained from the fits to the PNR data of sample A are shown in table 1. For sample A atomic moments of $M_{Co} = 1.57 \pm 0.08\ \mu_B$ and $M_{Ni} = 0.50 \pm 0.04\ \mu_B$ at room temperature are obtained. These values are only slightly lower than the bulk values of 1.74 μ_B and 0.58 μ_B for fcc Co and Ni at room temperature [20]. The atomic magnetic moment for the Ni film is in good agreement with the determined moment for an epitaxial Cu/50 Å Ni/770 Å Cu/Si(001) structure [21]. We have further measured the spin-dependent reflectivities for sample A in the same orientation at remanence as shown in figure 2(b). Excellent fits to the data can be obtained, using the same layer thicknesses. From the fits we obtain an atomic moment of $M_{Co} = 1.40 \pm 0.11\ \mu_B$ and $M_{Ni} = 0.16 \pm 0.05\ \mu_B$ 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, whereas the magnetic moment of Ni is greatly reduced at remanence along this direction. There are several possible causes for this behaviour one might consider:

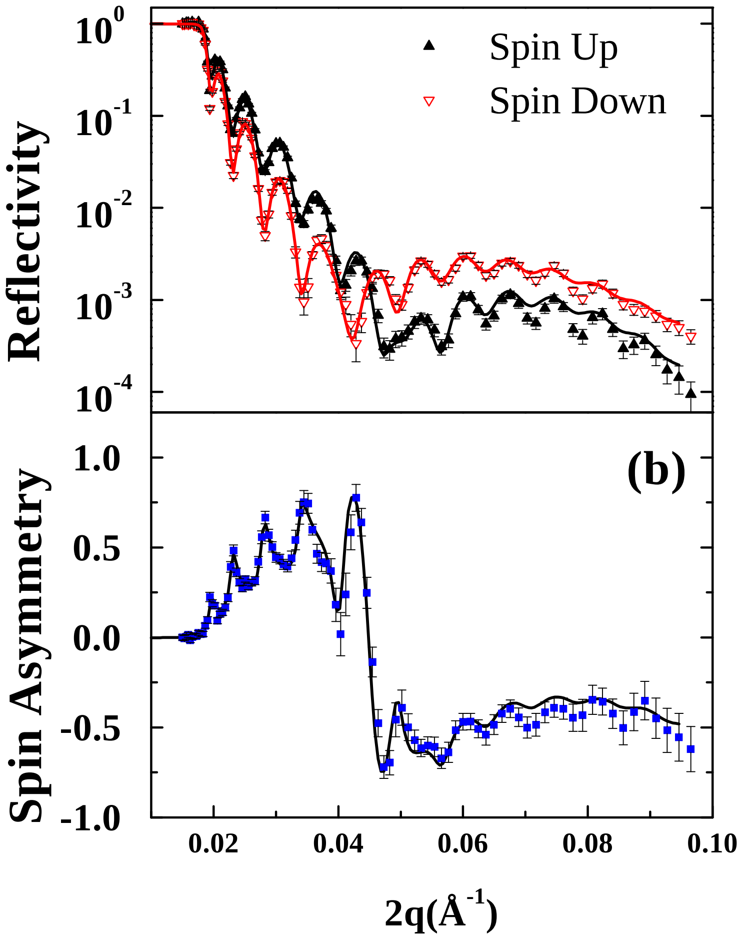

Figure 2. (Continued)

Table 1. The layer thicknesses (t), atomic magnetic moments at saturation (M_S) and remanence (M_R) at room temperature for sample A. Also average interface roughness parameters [17] of 7 Å have been obtained from the fits to the PNR data.

	t (Å)	M_S (μ_B)	M_R (μ_B)	M_R/M_S	Canting angle α (°)
Cu	40 ± 1				
Co	23 ± 2	1.57 ± 0.08	1.40 ± 0.11	89	63
Cu	10 ± 1				
Ni	53 ± 1	0.50 ± 0.04	0.16 ± 0.05	32	19
Cu	784 ± 3				

(1) The in-plane remanent magnetization is not aligned parallel to the neutron beam polarization direction. PNR is sensitive to the in-plane magnetization parallel to the polarization axis of the incident neutrons. If the in-plane magnetic moment were rotated away from this direction due to misalignment, a reduced spin asymmetry would be measured. If we assumed that the reduced remanent in-plane magnetic moment for Co of $M_R/M_S = 89\%$ as shown in table 1 were entirely due to misalignment, the angle

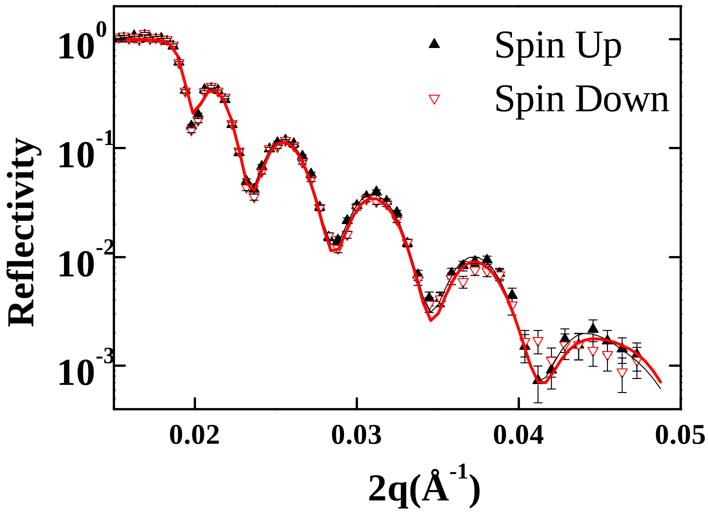

Figure 3. PNR reflectivity data (symbol) and their best fits (continuous line) for sample A at remanence after rotating the sample 90 degrees.

between the magnetization and beam polarization would need to be 27 degrees. To exclude such a misalignment we measured also the remanent magnetization by PNR after physically rotating the sample by 90 degrees with no field applied. If we assume that the magnetization were initially misaligned by 27°, we would expect to measure after such rotation for Co a magnetic moment of 0.7 μ_B [22]. Figure 3 shows the measured and fitted spin-dependent neutron reflectivity data for sample A after 90 degrees rotation. Basically no spin asymmetry is observed. For the fits to the data the same layer thicknesses and roughnesses as shown in table 1 are used. An in-plane magnetic moment of only $M_{Co} = 0.14 \pm 0.14\ \mu_B$ and $M_{Ni} = 0.02 \pm 0.05\ \mu_B$ is determined. This directly shows that the reduction in the in-plane magnetic moment (figure 2(b)) compared to the saturated case (figure 2(a)) for Co cannot be attributed to misalignment of the magnetization to the polarization direction of the neutrons.

(2) If the Co/Cu/Ni trilayer were not significantly exchange coupled, the Ni film would show an out-of-plane remnant magnetization, and the Co film an in-plane remanent magnetization, as evidenced from the polar MOKE measurements on the Co/49 Å Cu/Ni trilayer shown in figure 1. However the Ni and Co films of the Co/10 Å Cu/Ni trilayer (sample B) are weakly coupled as evidenced by the polar MOKE measurements. This could therefore result in a twisted state as reported for example for Fe/Gd multilayers [23–26]. In the case of the Co/10 Å Cu/Ni trilayer, the PNR measurements yield that the Ni film shows a small in-plane magnetization at remanence, whereas the Co film shows a small out-of-plane component at remanence. If we assume that the reduced in-plane remanence originates from canting of the magnetization, a canting angle (α) between the film normal and the direction of magnetization of $\alpha = 19^\circ$ for Ni and $\alpha = 63^\circ$ for Co is determined from the PNR measurements.

(3) A final possibility is that a multidomain state might occur at remanence. Domain image observations are needed to distinguish between this and a twisted state occurring at remanence.

4. Summary

Polar MOKE measurements on an epitaxial Cu/23 Å Co/0–49 Å Cu/53 Å Ni/Cu(001) structure suggest that the Ni magnetization 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 remanent magnetization for Co is always observed. PNR measurements yield almost bulk-like magnetic moments of $1.57 \pm 0.08\ \mu_B$ for Co and $0.50 \pm 0.04\ \mu_B$ for Ni for a Cu/23 Å Co/10 Å Cu/53 Å Ni/Cu/Si(001) structure at room temperature. A reduced remanence is observed for both the out-of-plane magnetization by polar MOKE, and the in-plane magnetization for Co and Ni by PNR, which could suggest either the formation of a canted magnetization or multidomain state at remanence. We demonstrated that we can determine from PNR layer selectively the intraplanar atomic moments to a high accuracy in ultrathin Co/Cu/Ni/Cu(001) structures. The possibility of determining from PNR the magnetizations both at saturation and at remanence allows one to furthermore determine the magnetization directions of each layer in the Cu/Co/Cu/Ni/Cu(001) trilayers.

Acknowledgments

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References

[1] Jungblut R, Johnson M T, aan de Stegge J, Reinders A and den Broeder F J A 1994 *J. Appl. Phys.* **75** 6424
[2] Schulz B and Baberschke K 1994 *Phys. Rev.* B **50** 13 467
[3] Bochi G, Balalentine C A, Inglefield H E, Thompson C V and O'Handley R C 1996 *Phys. Rev.* B **53** R1729
[4] Lee J, Lauhoff G and Bland J A C 1996 *Europhys. Lett.* **35** 463
[5] Lee J *et al* 1997 *Phys. Rev.* B **55** 15 103
[6] Gradmann U 1986 *J. Magn. Magn. Mater.* **54–57** 733
[7] Krams P, Lauks F, Stamps R L, Hillebrands B and Güntherodt G 1992 *Phys. Rev. Lett.* **69** 3674
[8] Kowaleski M, Schneider C M and Heinrich B 1993 *Phys. Rev.* B **47** 8748
[9] Johnson M T, de Vries J J, McGee N W E, aan de Stegge J and den Broeder J A 1992 *Phys. Rev. Lett.* **69** 3575
[10] Lee J, Lauhoff G and Bland J A C 1997 *Phys. Rev.* B **56** R5728
[11] Lauhoff G, Lee J, Bland J A C, Schille J P and van der Laan G 1998 *J. Magn. Magn. Mater.* **177** 1253
[12] May F, Tischer M, Arvanitis D, Dunn J H, Henneken H, Chauvistre R and Baberschke K 1997 *J. Physique* IV **7** 389
[13] Naik R, Kota C, Payson J S and Dunifer G L 1993 *Phys. Rev.* B **48** 1008
[14] Heckmann O, Magnan H, le Fevre P, Chandesris D and Rehr J J 1994 *Surf. Sci.* **312** 62
[15] Penfold J 1991 *Physica* B **173** 1
[16] Hope S *et al* 1997 *Phys. Rev.* B **55** 11 422
[17] Nevot L and Croce P 1980 *Rev. Phys. Appl.* **15** 761
[18] Dürr H A, Guo G Y, van der Laan G, Lee J, Lauhoff G and Bland J A C 1997 *Science* **277** 213
[19] Bland J A C 1994 *Magnetism of Ultrathin Magnetic Structures* vol 1, ed J A C Bland and B Heinrich (Berlin: Springer) p 305
[20] Chikazumi S 1997 *Physics of Ferromagnetism* (Oxford: Clarendon) p 635
[21] Lee J, Lauhoff G, Fermon G, Hope S, Bland J A C, Schille J P, van der Laan G, Chappert C and Beauvillain P 1997 *J. Phys.: Condens. Matter* **9** L137
[22] The magnetic moment for Co is given by the saturation moment for Co times $\sin(27^\circ)$.
[23] Camley R E and Stamps R L 1993 *J. Phys.: Condens. Matter* **5** 3727
[24] Tsunashima S, Ichikawa T, Nawate M and Uchiyama S 1988 *J. Physique* **49** 1803
[25] Löwenhaupt M, Hahn W, Huang Y Y, Felcher G P and Parkin S S P 1993 *J. Magn. Magn. Mater.* **121** 173
[26] Dufour C, Cherifi K, Marchal G, Mangin P and Hennion M 1993 *Phys. Rev.* B **47** 14 572