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Ni/Cu/Co TRILAYERS WITH OUT-OF-PLANE Ni MAGNETIZATION: *in-situ* MOKE INVESTIGATIONS

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Abstract: We have prepared $Cu/Ni/Cu_x/Co/Cu(001)$ films in ultrahigh-vacuum (base pressure of about 5×10^{-11} mbar) with variable spacer thickness (4 ML < x < 50 ML), where ML denotes a monolayer, and constant thickness of Ni (9 ML), Co (1.8 ML) and capping Cu (5 ML) layers. Usually trilayers characterized by either in-plane or perpendicular anisotropy for *both* ferromagnetic (FM) films are studied. The thickness of FM films we have used leads to the exceptional case of perpendicular Ni and in-plane Co magnetization orientation, which is a result of the different out-of-plane anisotropies. We have measured *in-situ* polar dc-MOKE (magneto-optical Kerr effect) hysteresis loops. The polar geometry is sensitive only to the perpendicular component of the magnetization, therefore only the Ni film contribution has been measured. Our investigations concern the influence of the interlayer exchange coupling on the measured polar MOKE loops with the coupling modified by changing the spacer Cu thickness. The question of the temperature dependence of the magnetization curves is also addressed. The experimental results are supported by model calculations of the hysteresis loops.

1. INTRODUCTION

The magnetic properties and interlayer exchange coupling of Co(Ni)/Cu/Co(Ni) trilayers for various combinations of the ferromagnetic (FM) elements and the thickness of the FM films have been in the focus of thorough investigations for many years [1, 2]. However, the studies have considered mainly the case of in-plane or out-of-plane orientation of both magnetic layers [1, 2]. The orientation of the easy axis of a ferromagnetic film can be easily manipulated by diverse parameters, e.g., the thickness, the interface topology, surfactants or by using a cap layer.

We have epitaxially deposited 1.8 monolayers (ML) of Co on a Cu(001) single crystal substrate. Subsequently a Cu spacer and 9 ML Ni layers have been evaporated. The whole system is covered with a 4 ML Cu capping layer. Such a composition leads to a special situation of an in-plane Co and out-of-plane Ni film in the equilibrium remanent state. Co is in-plane in the whole thickness range and Ni undergoes a transition towards the perpendicular direction above 7 ML [3]. In addition, this Co thickness enables room temperature studies because the T_C of 2 ML Co is about 340 K. Thinner Co films would exhibit a lower anisotropy (better for magnetic measurements), which already for 2 ML is M_{eff} = 37.6 kG ($M_{eff} = 4\pi M - 2K_2/M$). However, below 1.8 ML of Co T_C drops down to about 200 K [4]. For comparison the effective magnetization of 9 ML of Ni is equal to $M_{eff} = -2.18$ kG. Similar trilayer systems with an out-of-plane Ni film were also studied qualitatively by Kirschner *et al.* [5] employing domain imaging techniques. They could successfully study the tilted magnetizations in remanent state as a function of Cu spacer. An application of external magnetic field enabled the estimation of the coupling due to the domain wall stray fields [6].

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We have measured *in-situ* polar *dc* magneto-optical Kerr effect (MOKE) hysteresis loops for different Cu spacer thicknesses, i.e., different coupling values J_{inter}. The measurements have been also carried out at increased temperatures. The presence of the interlayer exchange coupling in these samples was previously verified using ferromagnetic resonance (FMR). A system with mutually perpendicular anisotropies is supposed to be a good candidate for devices having the possibility of controllable switching between more than two magnetic configurations [6].

2. EXPERIMENTAL

We have prepared Ni/Cu_x/Co films on a Cu(001) substrate in ultrahigh-vacuum (base pressure of about 5×10^{-11} mbar) with variable spacer thickness (4 ML < x < 50 ML) and constant thickness of Ni (9 ML), Co (1.8 ML) and capping Cu (5 ML) layers. The films were evaporated at RT, only after the Cu spacer deposition the sample was annealed at 440 K for 10 min to ensure a good growth of the Ni film. The average evaporation speed was about 1 ML/min. The film growth was monitored by medium energy electron diffraction (MEED) oscillations and Auger electron spectroscopy (AES).

3. THEORETICAL PREDICTIONS AND EXPERIMENTAL RESULTS

The demagnetization process in trilayers is usually calculated theoretically within two different approaches. The first model assumes that the system always finds a global energy minimum due to the domain nucleation and domain wall movements. It leads to a reversible magnetization process (dotted line in Fig. 1). In the second approach the system is assumed to follow a local energy minimum, the demagnetization process occurs *via* coherent rotation of the magnetizations. The second model provides an irreversible hysteresis loop, which is represented by the solid line in Fig. 1. The calculation in Fig. 1 is performed by either searching for the local or global minima of the free energy:

$$\begin{aligned} E = \sum_{i=1}^{2} \Big[& -d_i M_i H \cos\theta_i - d_i\left(2\pi M_i^2 - K_2^i\right)\sin^2\theta_i + \\ & -\frac{1}{2} d_i K_{4\perp}^i \cos\theta_i - \frac{1}{8} d_i K_{4\parallel}^i (3 + \cos 4\varphi_i)\sin^4\theta_i \Big] + \\ & -J_{\text{inter}}\left[\sin\theta_1 \sin\theta_2 \cos(\varphi_1 - \varphi_2) + \cos\theta_1 \cos\theta_2\right], \end{aligned} \tag{1}$$

where $i = 1; 2$, d_i is the thickness of the Co ($i = 1$) or Ni ($i = 2$) film. K_2^i represents the perpendicular anisotropy and $K_{4\parallel}^i$, $K_{4\perp}^i$ are the cubic in-plane and out-of-plane anisotropies, which are small, therefore neglected in these calculations.

The experimental loop shown in the inset of Fig. 1 is measured for an uncoupled film with a spacer thickness of 50 ML. It is visible that the coercive field is strongly reduced compared to the rotational model. The domain nucleation is favoured in polar measurements, however, the coercivity is not zero, which supports the prediction that intermediate behavior is observed [7, 8]. The expected effect of the interlayer exchange coupling is to deviate the Ni magnetization

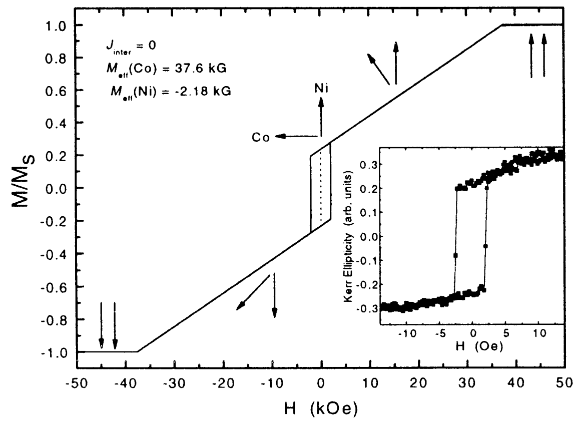

Fig. 1. Calculated magnetization curve of uncoupled $Cu_5/Ni_9/Cu_{50}/Co_{1.8}$/-Cu(001) trilayer (solid line – coherent rotation model, dotted line – domain wall movement model). Inset: Experimental polar MOKE hysteresis loop of the Ni component. One should note that the experimental coercive field is close to zero in the scale of the main figure

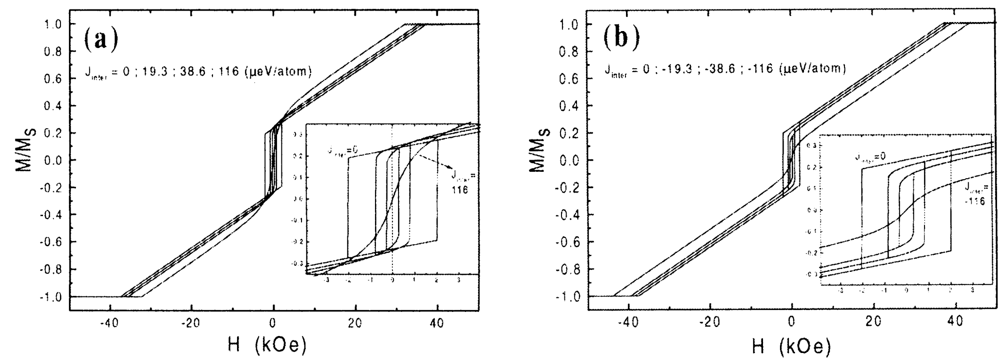

Fig. 2. Calculated magnetization curve of AFM and FM coupled $Cu_5/Ni_9/Cu_{50}/Co_{1.8}$/Cu(001) trilayer. Insets: enlargement of the low field parts

from the out-of-plane direction in the remanent state. The Co film is not so sensitive to the coupling value due to the large negative anisotropy. The decrease of the perpendicular component of the Ni magnetization should be visible both for the strong antiferromagnetic and ferromagnetic interlayer coupling. Figures 2a i b display the calculated hysteresis loops in the coherent rotation model for increasing negative and positive coupling, respectively. It is clearly visible that in both cases the coercive field decreases and the minor loop changes from rectangular to hard axis-like. The magnetization in remanence is zero for large values of FM or AFM coupling. The main difference lies in the saturation field, which is decreasing for FM and increasing for AFM coupling. The experimental measurements support the phenomenological calculations. Figure 3a shows the example of strong FM coupling for a Cu spacer thickness of x = 4 ML (the exact coupling value was not determined from FMR due to the usual lack of the optical mode in the limit of strong couplings [9]). No MOKE signal is detectable, which means that there is no perpendicular component of magnetization in remanence, due to the strong coupling aligning the magnetizations in the film plane, antiparallel to each other.

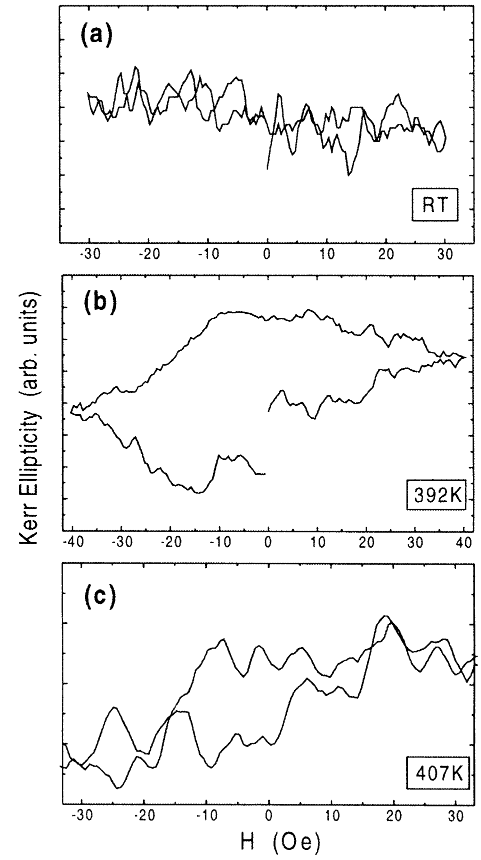

Fig. 3. Hysteresis loops measured at RT (a), 392 K (b) and 407 K (c) for a strongly FM coupled trilayer (4 ML Cu)

The Curie temperature of 1.8 ML Co is $T_C = 340$ K, therefore it can be expected that above this temperature the interlayer coupling will disappear and the Ni magnetization will switch back to the perpendicular orientation. It is indeed observed and presented in Fig. 3 b-c, which shows hysteresis loops measured at 392 and 407 K. The signal is decreasing with temperature because the T_C of the Ni film is approached. The decreasing signal and the incomplete saturation due to the limit of the applied field lead to the visible noise as well as the not full closing of the loops, respectively.

The behavior of the coercive field is not straightforward for the studied system and cannot be directly related to the coupling. A weak coupling means that the Ni film is close to the perpendicular direction, which implies tendency to domain nucleation leading to the decrease of coercivity (Fig. 1, dotted line). However, for intermediate values of coupling the equilibrium position of Ni in a region of small magnetic field will be tilted between perpendicular and in-plane orientation. Therefore, the perpendicular component of Ni will be decreased but still present, however the domain nucleation will not be so strongly preferred yielding a smaller reduction of coercivity. Indeed, it is observed for the example of a $Ni_9/Cu_x/Co_{1.8}$ trilayer with $x = 6.5$ ML and 9 ML, presented in Fig. 4. The coupling values obtained from FMR studies are J_{inter}(FMR) = – 1.4 μeV/atom for $x = 9$ ML and 6.65 μeV/atom for $x = 6.5$ ML. The hysteresis

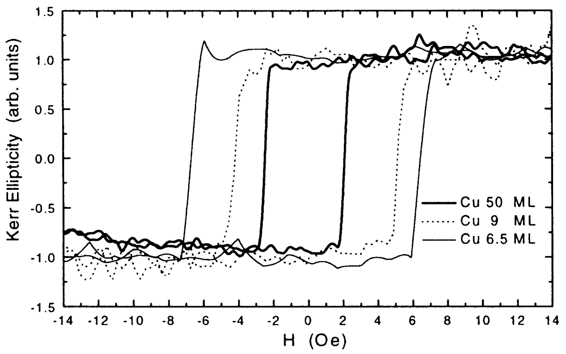

Fig. 4. Hysteresis loops measured at RT: $Cu_5/Ni_9/Cu_{50}/Co_{1.8}/Cu(001)$ trilayer with zero coupling and two trilayers with intermediate values of coupling (J_{inter}(FMR) = – 1.4 μeV/atom for 9 ML Cu and 6.65 μeV/atom for 6.5 ML Cu)

loops show an increased coercive field compared to the uncoupled case of $x = 50$ ML. The uncoupled film with fully out of plane Ni is characterized by $H_C = 2$ Oe, whereas the coupled trilayers are characterized by $H_C = 5$ Oe ($x = 9$ ML) and $H_C = 7$ Oe ($x = 6.5$ ML).

4. CONCLUSIONS

It has been shown that the hysteresis loop measured by a polar MOKE for a Ni/Cu/Co trilayer system with a perpendicular Ni and in-plane Co orientation is very sensitive to the value of the interlayer exchange coupling. Large couplings lead to an in-plane antiparallel alignment of both FM films in remanence with no coercivity. $J_{inter} = 0$ (perpendicular magnetization of Ni) gives a small coercive field and intermediate coupling values cause increased H_C due to the reduced nucleation of domains.

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References

[1] J. Lindner, E. Kosubek, P. Poulopoulos, K. Baberschke, B. Heinrich, J. Magn. Magn. Mater. **240** 220 (2002).
[2] J. Lindner and K. Baberschke, J. Phys.: Condensed Matter **15**, S465 (2003).
[3] K. Baberschke and M. Farle, J. Appl. Phys. **81**, 5038 (1997).
[4] P. Poulopoulos, P. J. Jensen, A. Ney, J. Lindner, K. Baberschke, Phys. Rev. **B65**, 064431 (2002).
[5] W. Kuch, Xingyu Gao, J. Kirschner, Phys. Rev. **B65**, 064406 (2002).
[6] W. Kuch, L. I. Chelaru, K. Fukumoto, F. Porrati, F. Offi, M. Kotsugi, J. Kirschner, Phys. Rev. **B67** 214403 (2003).
[7] B. Dieny and J. P. Gavigan, J. Phys.: Condensed Matter **2**, 187 (1990).
[8] T. Toliński and J. Baszyński, phys. stat. sol. (a) **169**, 139 (1998).
[9] A. Layadi, J. O. Artman, J. Magn. Magn. Mater. **92**, 143 (1990).