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Perpendicular coupling and spin reorientation transition in FCC Fe/Cu/Fe trilayers

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Abstract

The ferromagnetic coupling of FCC Fe/Cu/Fe trilayers is investigated as a function of the top Fe thickness by magneto-optical Kerr effect and in situ Kerr microscopy. A perpendicular magnetic coupling between the Fe layers is found. The data show that the magnetism of the trilayer is governed by the surface anisotropy of the top layer. The perpendicular coupling is ascribed to a magnetostatic interaction between the Fe layers.

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Keywords: Trilayer; γ-Fe; Perpendicular anisotropy; Perpendicular coupling; Magnetostatic coupling

The origin of the magnetic coupling of ferromagnetic layers separated by a nonmagnetic Cu spacer layer has been investigated extensively in the past [1–3]. In the case of BCC and FCC Fe/Cu/Fe trilayers and multilayers the coupling can be explained by the Ruderman–Kittel–Kasuya–Yosida indirect exchange (RKKY). In this paper experimental results on FCC Fe/Cu/Fe trilayers with perpendicular magnetic anisotropy are described which can rather be explained by the magnetostatic interaction between the Fe films.

In this work, γ-Fe films stabilized on Cu(0 0 1) are used as a template for the fabrication of FCC Fe/Cu/Fe trilayers. The easy magnetization axis of the γ-Fe layer is found to be perpendicular to the plane below a thickness of ~4 ML. The films have been prepared by molecular beam epitaxy under ultrahigh vacuum conditions. The substrate was held at 300 K during Fe deposition, and cooled to 140 K for deposition of the Cu spacer layer. The magnetism of the films after every preparation step was investigated by magneto-optical Kerr effect (MOKE) and in situ Kerr microscopy [4]. The polar MOKE loop in Fig. 1a taken at 3 ML Fe/Cu(0 0 1) shows the known result of perpendicular magnetization. The deposition of 2 ML Cu on top causes a reorientation of the magnetization into the film plane, as concluded from the hysteresis loop taken in longitudinal symmetry (Fig. 1b). No polar Kerr effect could be observed here. After deposition of a 3 ML Fe top layer the magnetization of the film is again out of plane, with a remanent Kerr intensity corresponding to the sum of the Kerr intensities of each individual Fe layer (Fig. 1c). Obviously, the top Fe layer induces a perpendicular magnetization in the bottom layer and therefore governs the trilayer magnetization.

The magnetization of the trilayer was studied as a function of the thickness of the top Fe layer, t_2, with the thickness of the bottom Fe layer and the Cu spacer kept constant. For the experiment, a top Fe layer of varying thickness, $t_2 = 0-6$ ML, was deposited onto 2 ML Cu/3 ML Fe. Magnetic measurements could thus be done for different t_2 at the same sample. Fig. 2a shows the remanent (●) and the saturation (○) polar Kerr intensity of MOKE loops taken at 140 K on this trilayer. The saturation signal clearly reflects the presence of a ferromagnetic alignment of both Fe layers. It increases linearly with top Fe thickness until it vanishes at $t_{crit} = 5.7$ ML. Extrapolation of the saturation to $t_2 = 0$ ML yields the polar Kerr signal of the bottom Fe layer. The absence of perpendicular magnetization

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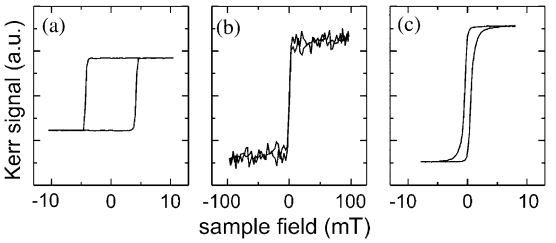

Fig. 1. Polar (a, c) and longitudinal (b) MOKE hysteresis loops of 3 ML Fe (a), 2 ML Cu/3 ML Fe (b) 3 ML Fe/2 ML Cu/3 ML Fe (c) films on Cu(0 0 1).

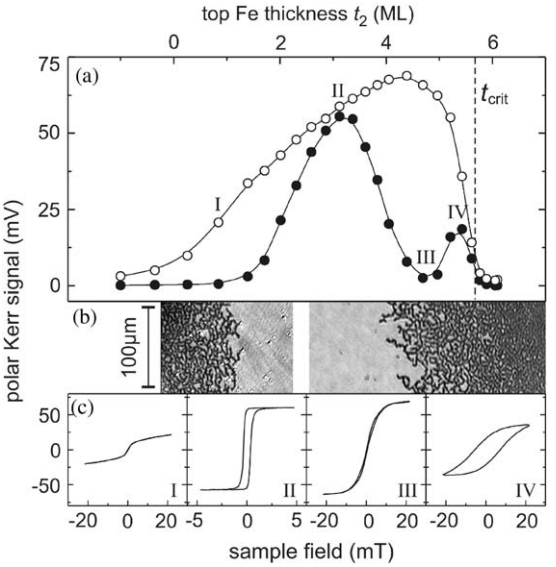

Fig. 2. (a) Magnetization of a trilayer, t_2 ML Fe/2 ML Cu/3 ML Fe/Cu(0 0 1), as a function of the top Fe thickness t_2, (b) Kerr images at $t_2 = 2.5$ ML (left) and 3.5 ML (right), (c) polar MOKE at $t_2 = 0.8$ ML (I), 3.1 ML (II), 4.7 ML (III), 5.4 ML (IV).

above the critical thickness $t_{crit} = 5.7$ ML in Fig. 2(a) is due to the spin reorientation into the film plane. Only in the thickness range 2.5 ML $< t_2 <$ 3.5 ML remanence and saturation have identical values. Here, square-shaped magnetization loops, as shown for $t_2 = 3.1$ ML in Fig. 2(cII), are found. Below 2.5 ML and above 3.5 ML, only s-shaped magnetization loops with no remanent magnetization at $H = 0$ are measured (Fig. 2(cI) and (cIII)).

The zero remanence for $t_2 < 2.5$ ML and $t_2 > 3.5$ ML was further investigated by in situ Kerr microscopy. The contrast in the Kerr images of Fig. 2b is due to the presence of magnetic domains with opposite magnetization perpendicular to the plane. Kerr images have been taken on the trilayer at positions of $t_2 = 2.5$ ML (Fig. (2b) left) and $t_2 = 3.5$ ML (right). Due to the wedge-shape of the top Fe layer, the thickness t_2 increases within the images from the left to the right by 0.1 ML per 100 μm. Both images clearly show a transition from single-domain to multi-domain magnetization state. The particular s-shape of the hysteresis loops can be understood by the break-up of the film magnetization into magnetic domains with opposite magnetization at zero field, thus canceling out the net magnetic moment accessible to MOKE. Such a transition into a multi-domain state is not uncommon for single films with perpendicular anisotropy at a thickness just below the spin reorientation transition into the plane [5]. It is the result of the competition between the energy needed to introduce domain walls, γ, and the gain of magnetostatic energy, f_{MS}, when the sample's stray field is reduced. On the other hand, the domain state transition below 2.5 ML is unusual. Additional experiments prove that a transition towards a multi-domain state only occurs if the t_2 is small compared to the bottom Fe layer thickness t_1, as is the case in Fig. 2. The ratio t_1/t_2 seems to be decisive for the domain state.

The results are in agreement with the picture of a coupled magnetization of the two Fe layers due to magnetostatic interaction. In this model, the magnetization of the bottom layer is aligned within the magnetic stray field of the top layer, which has a perpendicular easy axis due to the well-known anisotropy contribution at the γ-Fe-vacuum interface (Fig. 1(a)). Though, the total anisotropy, f_{tot}, of the trilayer is made up of the anisotropy contributions of *both* Fe layers. With increasing ratio t_1/t_2 the f_{tot} is reduced due to the in-plane anisotropy contribution of the bottom layer. As a result, for a large ratio t_1/t_2 the domain wall energy $\gamma \sim \sqrt{A f_{tot}}$ becomes small and the formation of domains energetically favorable since it decreases f_{MS}. Domains are thus created in two cases: if t_1 is large compared to t_2 due to the reduced perpendicular f_{tot}, and for large t_2 close to t_{crit} due to the large f_{MS}.

Further support for the dominating role of the top layer magnetization driving the magnetization of the whole trilayer comes from adsorption experiments: Adsorption of 1.8 L of oxygen leaves the magnetization of both Fe layers uncoupled within the plane. In equivalence to the oxygen adsorption on single γ-Fe layers [6] the anisotropy at the Fe-vacuum interface of the top layer is altered by the adsorbate, causing a spin reorientation into the plane. As a result, its magnetostatic field that aligns the bottom layer vanishes.

In conclusion, our experimental results allow interpretation of the ferromagnetic coupling of two FCC Fe layers separated by a Cu spacer layer as a magnetostatic interaction rather than the RKKY-type indirect exchange interaction often found for trilayer systems.

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