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Spin engineering with Fe–Au monolayers

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Abstract

FeAu superlattices were grown using MBE by alternative deposition of Fe(0 0 1) and Au(0 0 1) atomic layers. Polar MOKE loops taken at the room temperature showed that all superlattices with single Fe monolayers (MLs) were magnetized along the film normal but the character of the hysteresis loop depended strongly on the repetition number N in a $(\mathrm{Fe_1Au_1})_N$ stack, where $\mathrm{Fe_1Au_1}$ denotes a single sequence of the Fe(0 0 1) and Au(0 0 1) MLs. The loop character changed from a low remanence one for $N = 20$ to a narrow ($H_C = 50\,\mathrm{Oe}$) rectangular one for $N = 3$. $(\mathrm{Fe_1Au_1})_3$ stacks, denoted as $(\mathrm{FeAu})_3$, were used to construct multilayers, in which they were spaced by K Au(0 0 1) atomic layers (AL). In the *tri-layer*, $(\mathrm{Fe_1Au_1})_3/\mathrm{Au}(d_{\mathrm{Au}})/(\mathrm{Fe_1Au_1})_3$, antiferromagnetic exchange coupling was clearly observed around the Au(0 0 1) spacer thickness $d_{\mathrm{Au}} = 10\,\mathrm{AL}$ (about 2 nm). For $[(\mathrm{Fe_1Au_1})_3/\mathrm{Au}\ (d_{\mathrm{Au}})] \times M$ ($M = 4, 6$) the magnetization process becomes more complicated revealing a sharp multistage spin-flip transition including well-distinguished surface spin flip. © 2001 Published by Elsevier Science B.V.

Keywords: Perpendicular magnetic anisotropy; Oscillatory exchange coupling; CEMS; FeAu monoatomic superlattices

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Combination of perpendicular magnetic anisotropy (PMA) and giant magnetoresistance (GMR) can be very interesting from the application point of view, because such systems are sensitive to magnetic fields along the film normal. In most cases, oscillatory exchange coupling was observed in magnetic multilayers having preferential in-plane orientation of the magnetization. There are only a few experiments known [1,2] in which the oscillatory character of coupling between the ferromagnetic layers with perpendicular magnetic anisotropy was clearly demonstrated and studied in detail. In all these works, thin cobalt films with a thickness below the spin reorientation transition, were used. The presence of uniaxial anisotropy ensures a discrete switching behavior of the magnetization (instead of a rotation process) simplifying the shape of the hysteresis loops and the data interpretation [2]. Discrete changes of the magnetization are followed by similar behavior of the resistance [3], which makes such systems extremely attractive from the point of view of magnetic recording applications.

Epitaxial metallic multilayers allow fabrication of the artificial phases having new magnetic properties. Monoatomic FeAu superlattices are one of the best example. The layer-by-layer growth by molecular beam epitaxy (MBE) stabilizes $\mathrm{L1_0}$-type ordered phase that does not exist in Fe–Au phase diagram. The superlattices possess intriguing magnetic properties like perpendicular magnetic anisotropy, large magnetic moments combined with a high Curie temperature, and peculiar interlayer exchange coupling [4–8]. In the present paper we demonstrate the coupling behavior of the FeAu layers, which are used as building blocks of FeAu/Au/FeAu multilayers.

The samples were grown by MBE in the UHV conditions (pressure during preparation below $10^{-9}\,\mathrm{mbar}$), at room temperature, on a 30 nm Au(0 0 1) buffer layer with the so-called *hex*-type surface

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reconstruction, deposited on cleaved MgO(0 0 1) substrates in a multistage process [9]. The thickness of the layers was controlled by a quartz microbalance with the accuracy of about 5%. The sample growth was monitored in situ by low-energy electron diffraction (LEED). All samples were covered by a 3 nm thick Au protective layer. Magnetic measurements were performed ex situ using the magnetooptic Kerr effect (MOKE) and conversion electron Mössbauer spectroscopy (CEMS).

Monoatomic $(Fe_1Au_1) \times N$ superlattices, where N denotes the repetition number of the single sequence of the Fe(0 0 1) and Au(0 0 1) monolayers (MLs), were obtained on the Au(0 0 1)-hex surface by alternate deposition of Fe and Au. Sharp diffraction spots and low background characteristic for LEED patterns in all stages of the growth indicated the high degree of the structural order. The Au(0 0 1)-hex surface reconstruction of the buffer layer disappears at the early stage of the superlattice growth (at about 0.3 of the first Fe ML) and is recovered after deposition of a few (2–3) atomic layers (AL) of the Au capping layer.

The magnetic properties of the $(Fe_1Au_1) \times N$ superlattices were studied in detail for the high N values ($N > 20$) [4,5]. To our knowledge there is no experimental data concerning dependence of the magnetic properties on the repetition number N. Fig. 1 shows Polar-MOKE (PMOKE) hysteresis loops for $N = 3$, 5, 10, 20. The MOKE results as well as CEMS spectra (not shown, for details compare Ref. [10]) prove for all N the presence of a strong perpendicular magnetic anisotropy. The shape of the magnetization curves changes strongly with the repetition number N. For $N = 20$, the loop with a low remanent magnetization and a high saturation field was observed indicating the existence of stripe domains, in accordance with the previous studies [5]. With decreasing N, the domain structure simplifies gradually, leading to the one domain state for $N < 8$ manifested by a rectangular hysteresis loop with the coercivity reduced down to 0.002 T for $N = 3$. The primary reason for the observed change in the character of the magnetization curve is certainly the thickness effect on the domain size determined by an equilibrium between domain wall energy and magnetostatic energy, as discussed by Thiele et al. for FePt films [11].

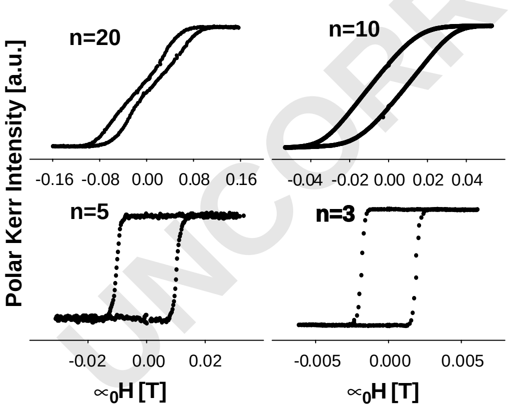

Fig. 1. Comparison of polar Kerr magnetization loops for $(Fe_1Au_1) \times N$, where N denotes the repetition number of the single Fe_1Au_1 sequence.

As evidenced by the LEED patterns, the Au(0 0 1)-hex structure restores after few Au AL deposited on the FeAu superlattices. It indicates the possibility of fabricating structures, in which two or more $(Fe_1Au_1)_3$ stacks grown at almost identical conditions are spaced with Au layers. $(Fe_1Au_1)_3/Au(d_{Au})/(Fe_1Au_1)_3$ tri-layers were grown at room temperature on the Au buffer for different number d_{Au} of atomic layers in the Au spacer. Example of PMOKE hysteresis loops is presented in Fig. 2 for $K = 4$, 10. The antiferromagnetic (AF) alignment indicated by zero remanent magnetization was clearly observed for 10 AL of the Au spacer. The hysteresis loop for $d_{Au} = 10$ in Fig. 2 corresponds to a spin-flip transition, similarly as it was observed by Willekens et al. for Co/Pd–Ru multilayers [3]. Such spin-flip transition is characteristic for systems with the magnetic anisotropy dominating over the exchange coupling. The use of the FeAu superlattices resulted here in the spin-flip field by two magnitudes lower than that reported previously [3].

Additional confirmation of the AF coupling was given by room temperature magnetoresistance measurements, which displayed for sample with the strongest AF coupling ($d_{Au} = 10$) a typical GMR behavior. Magnitude of the GMR effect (0.5%) is quite high taking into account the 30 nm thick Au shunting layer and T_c proximity.

Based on the results presented above, $[(Fe_1Au_1)_3Au_{10}] \times M$ multilayers, consisting of $M = 4$ and 6$(Fe_1Au_1)_3$ stacks, spaced with the 10 AL thick Au spacer were prepared. Due to the uniaxial anisotropy with the easy axis along the film normal, the multilayer with AF coupling can be treated as a linear chain of AF-coupled spins. Every spin in the chain, represented by the magnetic moment of the $(Fe_1Au_1)_3$ entity, interacts

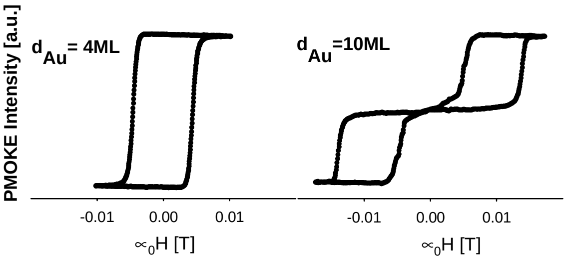

Fig. 2. Polar Kerr loops for the $(Fe_1Au_1)_3/Au(d_{Au})/(Fe_1Au_1)_3$ tri-layers for Au spacer thickness $d_{Au} = 4$ and 10 AL.

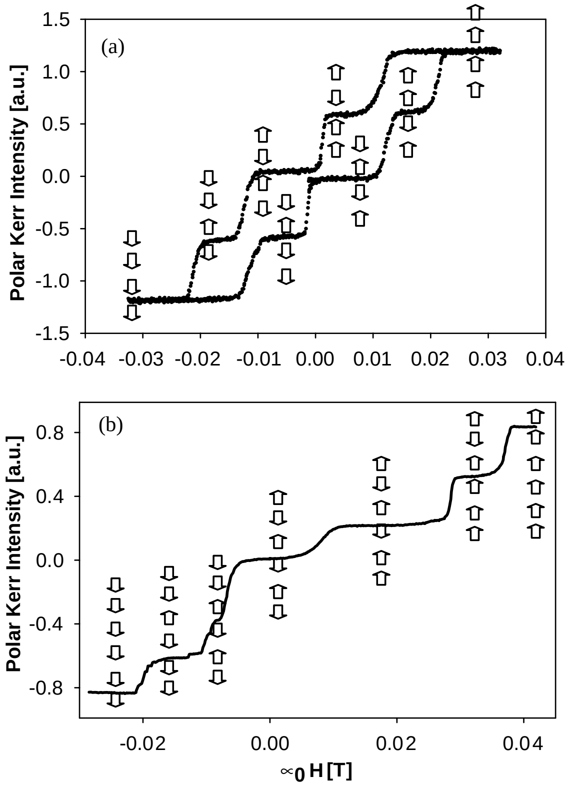

Fig. 3. Polar Kerr loop for $[(Fe_1Au_1)_3Au_{10}] \times M$ multilayers for (a) $M = 4$ and (b) $M = 6$. In (b) only one branch corresponding to the field change from H_{max} to $-H_{max}$ is shown for clarity. Arrows indicate configuration of the layer magnetization.

via the indirect exchange with the neighboring spins only. The PMOKE hysteresis loop measured at room temperature for $[(Fe_1Au_1)_3Au_{10}] \times 4$, as well as the configuration of the sub-layer magnetic moments (indicated by arrows) at the different stages of the magnetization reversal process are shown in Fig. 3a. Following the upper branch of the magnetization curve from the saturation (positive field) towards the remanent state and than towards the negative saturation, four well-distinguished transitions are visible. The first one is related to the reversal of the magnetic moment of an internal $(Fe_1Au_1)_3$ layer, closer to the surface, then the outer-bottom layer reverses. Identification of the individual transitions is possible by the height of the steps, because the Kerr signal is more sensitive to the layers closer to the surface. Applying the negative field, the third observed transition corresponds to the reversal of the outer-top layer and finally, the saturation is reached by the reversal of the inner-bottom layer. Clearly, the outer layers switch at lower fields than the inner ones, because they coupled only once, whereas the inner ones are coupled twice. This situation is analogous to the spin flip for finite antiferromagnets, theoretically predicted a long time ago [12] but only rarely observed [13].

For $N = 6$, the magnetization reversal process is even more complicated. Not only reversals of the outer layers but also all individual layer transitions are visible. In Fig. 3b, one branch of the magnetization loop related to the field changing from H_{max} to $-H_{max}$ and configurations of the layer magnetic moments for the plateaus are shown. Again, the transitions can be easily identified, and again, the sequence in which the layers reverse is very similar to that one for $N = 4$. Starting from the saturation, the first layer to reverse is the one with strongest AF coupling and the last ones to reverse are always the outer layers.

In conclusion, monolayer engineering gives wide possibilities of tailoring magnetization and coupling properties by different combinations of size and composition variation.

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