Magnetic ordering and anisotropies of atomically layered Fe/Au(001) multilayers

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We investigate the temperature dependence of the magnetization reversal process and of spinwaves in epitaxially grown (001)-oriented $[Fe_m/Au_n]_{30}$ multilayers (m = 1, 2; n = 1–6). Both polar magneto-optic Kerr effect and Brillouin light scattering measurements reveal that all investigated multilayers, apart from the $[Fe_2/Au_1]_{30}$-sample, are magnetized perpendicular to the film plane. The out-of-plane anisotropy constants are obtained. At high temperature, the magnetization curves are well described by an alternating stripe domain structure with free mobile domain walls, and at low temperature by a thermal activation model for the domain wall motion.

Since a technological progress in preparation and characterization methods enables the possibility to grow artificial multilayered structures consisting of magnetic films with the thickness down to one monolayer, new types of ordered materials can be created and observed. One of the very interesting material systems is the Fe/Au multilayer system, for which the artificial fabrication of a metastable ordered alloy has been recently reported.[1,2] Electron band calculations predict enhanced magnetic moments in monolayered Fe/Au structures due to the reduction of the number of next neighboring atoms[3,4,5] and the creation of a large out-of-plane anisotropy.[6] In this paper we study the magnetic order and the magnetization reversal processes of Fe/Au(001) multilayers with Fe layer thicknesses of 1 and 2 monolayers (ML) and Au layer thicknesses between 1 and 6 ML by means of temperature dependent static and dynamic magnetization measurements.

The preparation of the samples was performed at the IFF, FZ Jülich, on MgO(001) single crystal substrates using MBE. A 10 Å Fe seed layer and a 500 Å Au buffer layer provide conditions for monocrystalline growth. The growth temperature was 60 °C. A 20 Å Au cap-layer was deposited onto the multilayer structure in order to establish equal boundary conditions on both sides of the multilayer stack. The growth process was monitored using SPA-LEED, RHEED and Auger spectroscopy confirming the layer-by-layer growth and the chemical cleanness of the samples.

To observe the magnetization behavior, temperature dependent polar magneto-optic Kerr effect (MOKE) investigations were performed. The Brillouin light scattering (BLS) technique was used for determination of the spinwave frequencies, which are directly connected with the anisotropy constants.[7] From BLS experiments a second power uniaxial out-of-plane anisotropy constant, $K_S^{(2)}$, is obtained. Details of the procedure to determine these values are described elsewhere.[8] The experimental findings are summarized in Table 1.

In Fig. 1 temperature dependent out of plane hysteresis loops for the $[Fe_1/Au_3]_{30}$ sample are shown. It is seen, that the coercive field, H_C, as well as the remanent magnetization, M_R, increases with decreasing temperature. Moreover, the high temperature magnetization curve (300 K) shows a vanishing M_R and a turning point in the slope at zero field.

For the modeling of the observed high temperature magnetization curves, we use a model proposed by Draaisma et al.[9] In this model an alternating stripe domain structure

Sample	d_{bi} [Å]	magnetization direction	$K_s^{(2)}$ [10^6erg/cm^3]	T_c [K]	σ_W [erg/cm^2]	$\sigma_W/2\pi M_s^2$ [Å]	λ [Å]	l_B [Å]$_{at\ 10\ K}$
$[Fe_1/Au_1]_{30}$	3.48	out-of-plane	1.54	>460	14.4	55	1450	--
$[Fe_1/Au_2]_{30}$	5.52	out-of-plane	1.54	458	13.5	55	2280	--
$[Fe_1/Au_3]_{30}$	7.56	out-of-plane	0.18	344	6.4	48	2360	--
$[Fe_1/Au_4]_{30}$	9.60	out-of-plane	0.09	325	7.1	51	3430	220±20
$[Fe_1/Au_5]_{30}$	11.64	out-of-plane	0.02	294	1.6	42	2950	190±5
$[Fe_1/Au_6]_{30}$	13.68	out-of-plane	0.01	220	--	--	--	--
$[Fe_2/Au_1]_{30}$	4.91	in-plane	0.25	>460	--	--	--	--
$[Fe_2/Au_3]_{30}$	8.99	out-of-plane	1.50	>460	3.5	21	54	--
$[Fe_2/Au_4]_{30}$	11.03	out-of-plane	0.39	>460	3.5	22	68	--

Table. 1: Obtained parameters for the studied samples. d_{bi} is the bilayer thicknesses calculated from the a standard solid sphere model. T_c is the Curie temperature determined from the onset of remanent magnetization. $K_s^{(2)}$ is the uniaxial out-of-plane anisotropy constant obtained by BLS. σ_W is the domain wall energy, λ is the domain size, and l_B is the Barkhausen length at 10 K as described in the text.

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with infinitely thin and free mobile domain walls is assumed. The magnetization is calculated as a function of the out-of-plane applied magnetic field by minimizing three competing energies, which are the magnetostatic energy, the domain wall energy, and the Zeeman energy. The domain wall energy per unit area, σ_W, and the period of the stripe domain structure, λ, are used as free variables. By adjusting the two fitting parameters the model reproduces well the observed shapes of the curves, except for zero H_C due to the free mobility of the domain walls.

The dependence of σ_W both on temperature and on the Au-thickness shows a proportionality to M_S^2, which is predicted by the model (see Tab. 1). The variation of the ratio of $\sigma_W/2\pi M_S$ is less than 8% for each sample series. Therefore it can be regarded as a material parameter, which is (52±4) Å for the $[Fe_1/Au_n]_{30}$ samples and (21±2) Å for the $[Fe_2/Au_n]_{30}$ samples. The dependence of σ_W and λ on the Fe-layer thickness is due to the fact that the energy necessary for establishing domain walls in thin magnetic layers with an out-of-plane anisotropy strongly depends on the anisotropy value. Thus, larger values of the anisotropy in the $[Fe_1/Au_n]_{30}$ system lead to larger domain sizes than those in the $[Fe_2/Au_n]_{30}$ system.

The low temperature behavior (T<200 K) of the $[Fe_1/Au_n]_{30}$ samples (n = 1–6) cannot be explained within the frame of this model. Thermal effects become important for the description of the magnetization behavior in these systems. Magnetic viscosity (or magnetic aftereffect) means a time dependent magnetization behavior under constant external-fields.[10] For the investigation of this effect the magnetization, after saturation in a maximum field, was switched by a fixed field H_G to the opposite direction. In Fig. 2 the time dependent decay of the magnetization at 10 K with various H_G is shown for the $[Fe_1/Au_5]_{30}$ sample. The time dependent decay of the magnetization follows an Arrhénius Néel-type law based on superposition of the natural exponential decay of the magnetization with a fixed or distributed dispersion of the relaxation time, τ.[10] For the thermal activation of the domain wall movements, we assume a single τ given as: $\tau = \tau_0 \exp\left(\frac{E_A}{k_B T}\right)$ where E_A is the activation energy neces-sary for a single jump in the domain motion. E_A can be written as: $E_A = (-H_G M_S)V_B$, where V_B is a typical activation volume (Barkhausen volume), $V_B = t \cdot l_B^2$, where l_B is Barkhausen length and t is the thickness of the magnetic layer. The experiment confirms the expected behavior, $\ln\tau \propto -H_G$. The measured values of l_B, determined for each temperature are listed in Table 1. Due to the fact that the Barkhausen length is mainly determined by defects, l_B, is nearly independent on the temperature. Within this model we can understand the temperature dependence of H_C and M_R in the $[Fe_1/Au_{4,5}]_{30}$ samples quantitatively.

In conclusion we have shown that the magnetization process is well described at high and at low temperatures within the frame of an alternating stripe domain model taking into account the influence of thermal activation.

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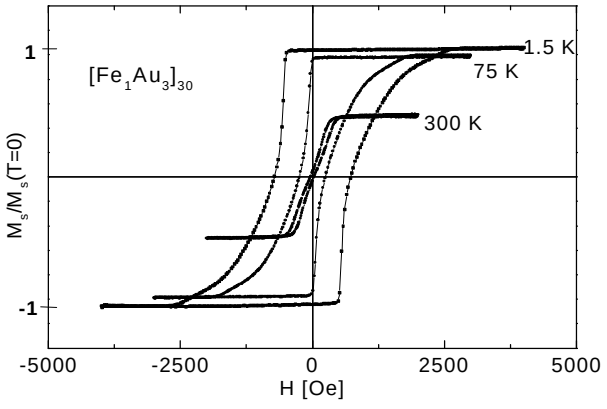

Fig. 1: Out-of-plane hysteresis loops for the $[Fe_1/Au_5]_{30}$ measured at various temperatures. Note the turning point in the slope at zero field on the 300 K curve.

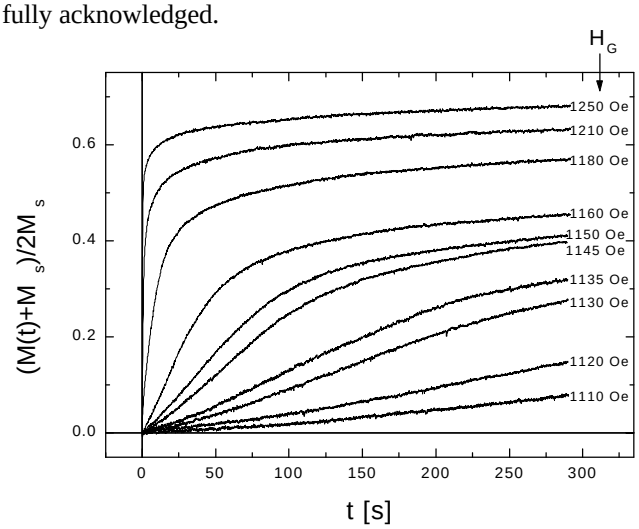

Fig. 2: Time dependence of the magnetization decay for the $[Fe_1/Au_5]_{30}$ sample measured by polar MOKE. Note that $M(t=0) = -M_S$.

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