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Journal of Magnetism and Magnetic Materials 148 (1995) 42–43

Journal of magnetism and magnetic materials

Magnetic order at stepped Fe/Cr interfaces

S. Miethaner, G. Bayreuther *

Institut für Angewandte Physik, Universität Regensburg, 93040 Regensburg, Germany

Abstract

The influence of surface atomic step density on the magnetic moment of Cr layers on Fe(001) has been studied in situ by Alternating Gradient Magnetometry (AGM). Contrary to previous results on flat surfaces where large Cr moments were observed coupled antiferromagnetically to their Fe nearest neighbours, the sample moment remains essentially unchanged if Cr is deposited on a strongly faceted Fe surface. During addition of a second Fe layer on a 6 ML Cr/Fe(001) film the sample moment stays constant up to an average Fe thickness of 5 ML and increases linearly with the nominal Fe thickness for thicker layers. This behaviour is interpreted as topological antiferromagnetism due to the specific step structure of the surface in agreement with recent tight binding calculations.

Magnetic order at Fe/Cr interfaces has recently attracted growing interest for several reasons: ab initio [1] and tight binding [2] band calculations have predicted strongly enhanced magnetic moments for a Cr overlayer on Fe (3.1 μ_B/atom [1] or 3.6 μ_B/atom [2] for 1 monolayer (ML) Cr on Fe(001) compared to the bulk atomic moment of $0.59\mu_B$) and an antiparallel alignment of the Cr moments relative to the Fe magnetization. The discoveries of an interlayer exchange and of a giant magneto-resistance, both oscillating with the thickness of intermediate Cr layers, have further stimulated this interest.

While many theoretical studies agree in predicting enhanced Cr moments at surfaces and interfaces, many experiments (e.g. by photoelectron spectroscopy [3] or X-ray circular dichroism [4]) did not succeed in verifying these predictions. Recently by using an in-situ alternating gradient magnetometer (AGM) it was possible to observe Cr moments up to $4\mu_B$ for submonolayer Cr on Fe(001) and an average moment of $3\mu_B$ for a 1 ML Cr film [5]. In addition, it was shown that the first Cr monolayer couples antiferromagnetically to the Fe magnetization and there is a significant deviation from layer-antiferromagnetic order in thicker Cr films. In this contribution these experiments are extended to strongly stepped surfaces in order to investigate the effect of the surface morphology on magnetic moments and magnetic order in a growing overlayer.

Films were grown in UHV ($p \approx 2 \times 10^{-10}$ mbar) on Au(001) films which in turn were grown on LiF(001) substrates. The film structure was verified by LEED and ex situ by transmission electron microscopy and diffraction. The magnetic moment of the samples was continuously measured during growth using an in-situ AGM in magnetic fields up to 9 kOe.

By using particular growth conditions (e.g. growth temperature 300 K) and after depositing several Au/Fe/Cr sandwich layers, strongly faceted surfaces resulted with a large step density. After the deposition of a gold layer of 30 Å a Fe film of 12.6 Å was deposited followed by 8.4 Å of Cr, 12.2 Å of Fe and a further Au layer (all grown at 300 K). The spontaneous magnetic moment (in relative units) as obtained from extrapolating the magnetization curves from fields between 1 and 2 kOe to $H = 0$ is shown in Fig. 1 for this deposition sequence.

We observe that a magnetic moment of the first Fe layer only starts to develop at an average thickness of ~ 1 ML. This is to be expected if we take into account that the Curie temperature of an Fe film grown on Au rises above 300 K between 1 and 2 ML.

Due to spin wave excitations the total moment is at 300 K reduced compared to the bulk value: extrapolation to zero Fe coverage yields a moment reduction by ~ 1 monolayer equivalent (1 'dead layer').

The slope of the sample moment versus thickness in the range above 5–6 ML is used for calibrating the magnetometer [5]: the deposition of an additional Fe monolayer according to ab initio band calculations [6] should yield an increase of the 'areal magnetic density', i.e. the moment per atom position after summation over all atomic layers, by $\sim 2.2\mu_B$. The temperature dependence of the average magnetic moment of a 6 ML Fe film leads to a moment reduction at 300 K of $\sim 5\%$ compared to the bulk ground

* Corresponding author. Fax: +49-941-943 4544; e-mail: guenther.bayreuther@physik.uni-regensburg.de.

SSDI 0304-8853(95)00142-5

state moment [7], which is not significant within the total experimental error. This calibration was verified ex situ after sample preparation with a SQUID magnetometer.

During the deposition of Cr no moment change is observed within the experimental uncertainty. This is in strong contrast with the result observed on films grown on flat surfaces [5] where a pronounced decrease of the sample moment accompanied the growth of the Cr overlayer. This can be explained by the surface morphology of this sample: topological antiferromagnetism has been shown by tight binding calculations [8,9] to exist on Cr vicinal surfaces; the same mechanism leads to a strong moment reduction of Cr atoms on a vicinal Fe surface (e.g. average moment of $\sim 1.4\mu_B$/atom for Cr on Fe(105) [8]). However, in order to understand the nearly zero average Cr moment deduced from Fig. 1 details of the surface structure would have to be known. This information is expected from in situ STM studies which are under preparation.

Another unexpected behaviour is observed when the second Fe layer starts to grow: the total sample moment stays constant until an average thickness of nearly 5 ML. The moment of the first Fe layer shows that this result cannot be explained by surface contamination. Instead, we assume that this again is a consequence of the large step density of the present surface leading to a topological antiferromagnetism of the Fe overlayer.

Fig. 2 shows a possible moment distribution of an Fe monolayer grown on a Cr(105) surface as calculated from a tight binding Hamiltonian [8]. It is obvious that the integral moment of this Fe layer vanishes due to the topological antiferromagnetism of the Cr surface and the antiferromagnetic coupling between the Fe and the Cr spins. We can imagine that depending on the local roughness of the surface the antiferromagnetic order in the Fe film can persist up to a certain thickness. A recent tight binding calculation of local ground state moments at vicinal Fe/Cr(107) surfaces indeed indicates a possible transition from antiferromagnetic order within the Fe overlayer to a single domain ferromagnetic state for Fe thicknesses of 2–4 monolayers as one of several numerically stable solutions [10]. No discontinuity in the Fe magnetization due to the transition from antiferromagnetic to ferromagnetic order of the Fe overlayer can be observed in our measurements. In contrast, the first 5 Fe layers seem to stay antiferromagnetically coupled, whereas the following layers order ferromagnetically. In order to understand this behaviour more calculations have to be carried out including thicker Fe layers. In addition, detailed structural investigations of the surface topology with STM are required for a quantitative comparison of experimental data with theoretical predictions.

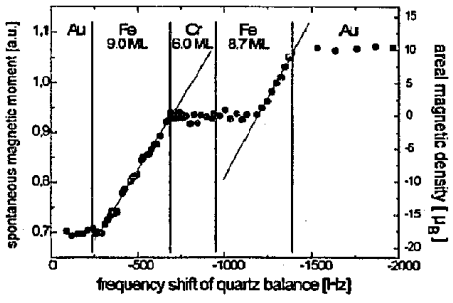

Fig. 1. Spontaneous magnetic moment versus frequency shift of the quartz balance for the deposition sequence Au, Fe, Cr, Fe, Au. Fe and Cr film thicknesses are indicated at the top. The slope of the sample moment during the first Fe deposition is used for calibrating the magnetometer and achieving the 'areal magnetic density' (right axis) in absolute units.

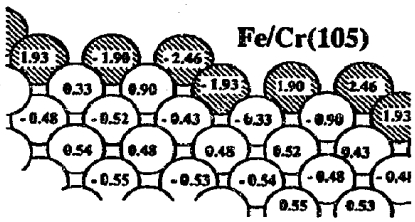

Fig. 2. Local ground state magnetic moment distribution of an Fe monolayer on Cr(105) obtained as one possible solution in tight binding calculations by Dreyssé et al. (white circles represent Cr atoms, dashed ones are Fe atoms; numbers denote the local moment).

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