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PERTURBED ANGULAR CORRELATION STUDY OF Fe/Cr (100) AND Fe/Co (1 −1 0) MULTILAYERS

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Recently we completed the very first and detailed perturbed angular correlation investigation on MBE-grown very thin film multilayers. The present paper aims to show that otherwise rather unaccessible but unique information on the (interface) magnetism could be obtained. For the Fe/Cr(100) multilayer system we observe, below a critical Cr thickness of 5.0 nm, a collapse of the spin-density-wave ordering in chromium. While the magnetization in the Fe-layer is in-plane, the Cr magnetization in thicker layers is out-of-plane. In the Fe/Co (1 −1 0) system, the observation of transferred magnetic hyperfine field satellites and their temperature dependence leads to the determination of an oscillating magnetic moment profile at the Fe/Co interface as well as a structure model for the superlattice.

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1. Introduction

The question on the stability of the bulk [1] spin-density-wave (SDW) magnetic ordering in chromium thin layers may be of crucial importance for the understanding of the interlayer coupling and the giant magnetoresistance effect in the Fe/Cr system. For this purpose one needs a direct determination of the net spin polarization *within* the Cr spacer. Here we will use perturbed angular correlation (PAC) spectroscopy to observe, at a radioactive (diamagnetic) trace impurity, the transferred magnetic hyperfine field originating from conduction electron spin polarization and derive the spatial distribution of magnetization. As a second application of the PAC technique in the study of multilayers, we discuss the observation of "Friedel" oscillations in the magnetic moments near the Fe/Co interface. By this report we hope to illustrate that the proposed "microscopic" technique can give complementary and unique information on the structure as well as on the magnetic behavior of low-dimensional systems.

The multilayers of high structural quality were grown by molecular beam epitaxy (MBE) techniques. The basics of PAC can be summarized as follows. In the intermediate nuclear state between the emission of two successive γ-rays, an oriented nuclear sub-ensemble is selected by detection of the first γ-ray (γ_1) in a particular direction. The subsequent emission of the second γ-ray (γ_2) reflects an

anisotropic correlation with respect to the γ_1 direction. When the decaying nucleus is a part of a lattice, its hyperfine interaction with the electromagnetic fields at the probes site perturbs this anisotropic correlation pattern. The anisotropy observed as a function of time thus depends on the properties of the lattice environment through the magnetic hyperfine field (hff) and electric field gradient (efg). Trace quantities of the nuclear probe ^{111}In(^{111}Cd) was incorporated into the multilayer sample by ion implantation. In the experiments each probe environment is characterized by a frequency ν (proportional to the local magnetic hyperfine field: $B_{\rm hf}(T) = 2\pi\nu$[MHz]/14.68) which may occur in the spectra together with its second harmonic. In addition but important, the relative amplitude of both harmonics is determined by the hyperfine field orientation (thus the magnetization) relative to the detector geometry.

2. SDW instability in Fe/Cr multilayers

For the experiments on the Fe/Cr multilayers we refer to Ref. [2] for a more detailed discussion, here the main observations only are collected. For Fe layers between 1.5 and 30 nm thick the hyperfine field is oriented along the in-plane (001) directions, while in the Cr layers, for thickness between 6 nm and 40 nm, along the out-of-plane (100) direction, i.e. the magnetization in the Cr layer is oriented *perpendicular* to the layers and to the Fe magnetization. Remarkably, Cr layers with thickness below 5 nm were probed as non-magnetic down to 4.2 K.

The existence of a rather abrupt threshold around 5 nm for the crossover from the magnetic to non-magnetic state in chromium layers is well documented by the present experiments [2] and confirmed by resistivity measurements [3]. We conclude that in thin layers, chromium orders as a longitudinally polarized spin-density-wave structure, with the spins along a single Q-vector oriented parallel to the growth direction of the multilayers. The suppression of the antiferromagnetic order below a critical layer thickness is apparently correlated with the wavelength of the SDW. The same single-Q type of ordering is sustained up to epitaxially grown thickness of the order of at least 40 nm. This observation correlates well with the experience [1] suggesting that compressive strain present in the multilayers is responsible for the Q-vector being normal to the layers.

3. Near interface magnetic moment oscillation in Fe/Co multilayers

The multilayers are of the form (1 −1 0)-GaAs/Fe 20.0 nm/$(\mathrm{Co/Fe})_{10}$ with a Co thickness of 2.0 nm and Fe thickness of 1.0, 2.5 and 4.0 nm. Figure 1 shows a room temperature $R(t)$ spectrum taken on one of the multilayers and a fit to the data. Similar spectra were taken on all samples at various temperatures. We need a model containing 8 probe sites to fit all 36 recorded spectra consistently. For the thinnest sample 75% of the probes (60% for the thickest one) is found in the broad field distributions $\Delta_{\rm Co}$ and $\Delta_{\rm Fe}$. They result from probes in many microscopically slightly different probe environments, contributing a fast decay of the anisotropy in the first 50 ns (see Fig. 1). Since the mean fields in these distributions are between the field values for bulk Fe and for bcc Co and because their fractions are roughly proportional to the interface density, we assign them to probe atoms in a mixed FeCo environment at a *diffuse interface*. The other

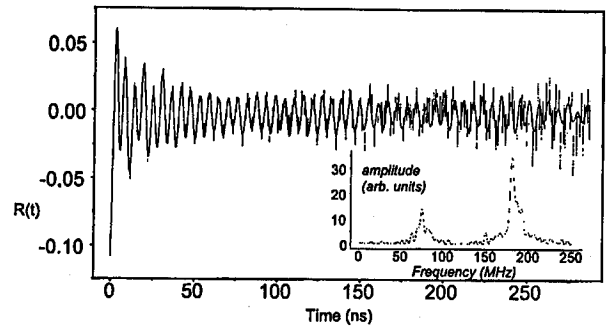

Fig. 1. PAC spectrum as taken on one of the multilayers. In the inset a Fourier transform of experimental data illustrates the existence of satellites on the main frequencies for Cd in bcc Co and in bcc Fe.

contributions, undoubtedly from their hff, originate from probes in pure bcc Fe and pure bcc Co [4] and for each of them we find two additional satellite fields. All these fields are sharply defined and the beating in part of the spectrum allows to resolve the satellite fields even though their fractions are of the order of 5 to 10% only. The satellites correspond to bcc Fe or bcc Co like configurations. Since no distribution or quadrupole interaction on these fields is observed, the satellite fields are assigned to probe atoms either in Fe or in Co layers in plateaus near a *sharp interface*. The PAC experiments thus evidence a structure model for the multilayer including both diffuse and sharp interfaces.

The magnitude of the fields for Cd in Fe and its two satellites decrease with temperature. For the Cd hyperfine field in Co and its satellites however we observe a small increase with temperature below 440 K while beyond this point the effect is much larger. Because the room temperature field values are fully restored after an annealing experiment up to 540 K, we may therefore exclude diffusion of the probes or interface alloying. Rather, it turns out that this anomaly in hff vs. T can be explained as a structural relaxation effect.

We use [4] the Stearns model for the hff to implement our experimental field values. Within this model the transferred hyperfine field ($B_{\rm hf}$) at a diamagnetic probe as ^{111}Cd, is the sum of a negative term due to the $4s$ conduction electron polarization at the probe site (B_Σ), induced by atomic magnetic moments of the surrounding lattice, and a term with opposite sign due to the shielding of the excess charge by the valence s-electrons near the probe atom ($B_{\rm v}$). The applicability of this model is first tested by reproducing the Cd hyperfine field in bcc Co [4]. By accounting for a monoclinic deformed bcc Co lattice due to the lattice mismatch, a magnetic moment of $1.64\mu_{\rm B}$ per Co atom is so observed. Next we use this model and the available data on the 5 near-neighbor shells to fit magnetic moment profiles in Fe and Co near the sharp interface. Starting from a moment configuration in which all Fe and Co layers have the bulk moment, $2.20\mu_{\rm B}$ for Fe and $1.64\mu_{\rm B}$ for Co, we calculate $B_{\rm hf}$ for 6 layers over both sides of the interface. We define χ^2 as the sum of the squared differences between the calculated fields and the closest experimental field. Consequently, χ^2 is minimized by varying one or more magnetic

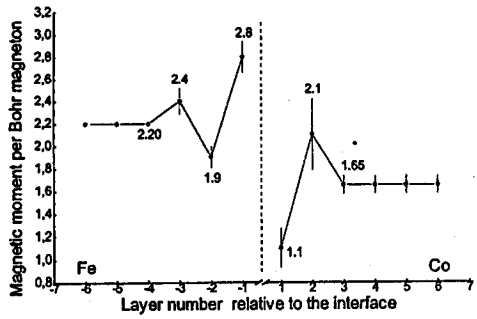

Fig. 2. Magnetic moment profile in Fe and Co near the (1,–1,0) Fe/Co interface.

moments near the interface. This procedure is followed for all configurations with less than 6 free moments near the interface. The resulting magnetic moment profile, shown in Fig. 2, oscillates with the layer number relative to the sharp interface. The damped oscillation has an amplitude of 30% of the bulk moment values. The same procedure is repeated for the other temperatures. Consistent results could be obtained for all measurements up to 570 K. The Co moments remain constant while the Fe moments decrease with temperature according to a $T^{3/2}$ dependence. We find that for all the interface Fe layers the temperature dependence of the magnetic moments normalized to their extrapolated $T = 0$ K value scales to the bcc Fe ones of the interior layers. Moreover, for Fe and Co the relative amplitude of the magnetic moment oscillation is temperature independent.

In conclusion, the cases selected here both essentially illustrate the potential value of the PAC technique as a competitive and complementary microscopic technique to probe the interface as well as the magnetism in reduced dimension.

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