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Magnetic studies of bct Fe(100)p(1 × 1)/Pd(100) films

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Abstract

Electron capture (ECS) and spin-polarized electron emission spectroscopy (SPEES) studies are performed at surfaces of ultra-thin bct Fe(100)p(1 × 1) films deposited on atomically flat Pd(100) substrates. For well-annealed films, the electron spin polarization (ESP) is oriented in-plane, and ferromagnetic order sets in at a surface Curie temperature $T_{Cs} = 662.3$ K (4 ML). Near T_{Cs}, the ESP follows the power law $(T_{Cs} - T)^{\beta}$, with a critical exponent $\beta = 0.129 \pm 0.01$ evaluated near T_{Cs}. Varying the probing depth, it is found that the layer-dependent average (ESP) at the topmost surface layer (37%) is enhanced by 32% as compared to that of bulk layers (28%). Pd Auger electrons emitted from the Fe/Pd *interface* are spin polarized with their ESP oriented parallel to that of emitted Fe Auger electrons.

Magnetic phenomena at surfaces, interfaces, in thin films and multilayered materials receive great attention [1]. This stems not only from the fact that such magnetic systems serve as nearly ideal systems to study many basic concepts in theoretical physics, such as phase transitions in low dimensions, but also from the recent interest in the development of novel and sophisticated electronic and magnetic devices of dimensions in the nanometer range which requires a fundamental understanding of many new electronic and magnetic phenomena such as the interplay between oscillatory ferromagnetic exchange coupling between magnetic layers separated by nonmagnetic spacer layers and the modification in the electronic and magnetic structure of the spacer layers occurring at the interface between the magnetic and the spacer layers.

In this paper, we report on the layer-dependent and interface magnetic properties as well as on the surface critical behavior of ultra-thin bct Fe(100)p(1 × 1)/Pd(100) films. This system was already studied by electron capture spectroscopy (ECS) [2], surface magneto-optical Kerr effect (SMOKE) [3], LEED and angle-resolved photoemission spectroscopy (ARPES) [4]. The present experimental results are obtained using ECS and spin-polarized electron emission spectroscopy (SPEES) [2]. These techniques, which are based on ion-induced capture and emission of spin polarized electrons from magnetic surfaces, allow us to determine the existence of long-ranged ferromagnetic order in magnetic systems, which can be characterized by the electron spin polarization (ESP), P, of the detected electrons. Defining P along the direction of the magnetization yields $P = (n^+ - n^-)/(n^+ + n^-)$, with n^+ and n^- the numbers of up(majority) and down(minority) spin electrons.

For the deposition of ultra-thin iron films, atomically clean and flat Pd(100) substrate crystals are prepared in UHV. The surface orientation of the Pd(100) crystals is better than 0.01° as monitored by using a precision X-ray diffractometer. Applying standard cleaning and annealing procedures, residual C and O contaminations are measured to be less than 1% of a monolayer (ML). The single crystalline p(1 × 1) state of the Pd(100) surfaces is detected by using LEED. The Fe films are deposited by electron-beam evaporation at 8×10^{-10} mbar. For a substrate temperature of 293 K and an evaporation rate of 0.02 Å/s, homogeneous and island-free growth of the Fe films is obtained. LEED measurements show a p(1 × 1) structure for all films studied so far [4]. The thickness of the films is determined with a calibrated quartz oscillator and with calibrated Auger signals. The bct Fe(100)p(1 × 1)/Pd(100) samples are studied in situ at 2×10^{-10} mbar. Small applied magnetic fields have a negligible effect on P, which shows that, within experimental errors, the remanent magnetization is equal to the saturation magnetization.

Using ECS, we find that 4 ML thin Fe(100)/Pd(100) films order ferromagnetically at low temperatures. Fig. 1 shows the reduced ESP, P/P_0, as function of the reduced temperature $t = T/T_{Cs}$ with $T_{Cs} = 662.3$ K. The solid and dashed lines represent, respectively, the exact solution of the 2D Ising model and the power law approximation for $T \to T_{Cs}$ and $\beta = 0.125$. T_{Cs} and β are determined by a linear least-squares fit of the ESP under the assumption of a power law of the form $(T_{Cs} - T)^{\beta}$ for t between 0.98 and 1.0. The value of β is found to be $\beta = 0.129 \pm 0.01$

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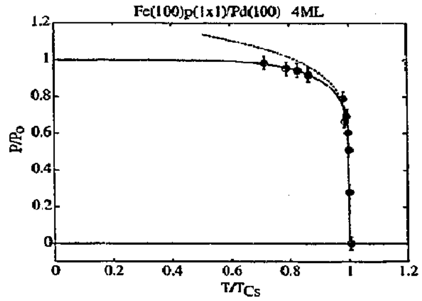

Fig. 1. Electron spin polarization P/P_0 as function of T/T_{Cs} for the surface of a 4 ML thin bct Fe(100)p(1×1)/Pd(100) film. The solid and dashed lines represent, respectively, the exact solution of the 2D Ising model and the power law approximation for $T \to T_{Cs}$.

giving the slope of a straight line in a log–log representation of the ESP data. The dashed curve in the figure, which corresponds to $\beta = 0.125$, fits the experimental data quite well for t between 0.98 and 1.0. Our experimental value (0.129) agrees well with the exact value ($\frac{1}{8}$) of the 2D Ising model for $T \to T_{Cs}$. Comparing our experimental data points for $0.7 \leq t \leq 1$, we find excellent agreement with the temperature dependence of the spontaneous magnetization as predicted by Yang for a 2D Ising magnet [5].

Using SPEES, we have studied, by varying the angle of incidence α of the 150 keV ions, the layer-dependent magnetic properties of 2 and 4 ML thin Fe(100)/Pd(100) films. At present, there is no comprehensive theory to correlate the data of the measured ESP of the emitted electrons to the magnetization of a material. Our recent magnetic data obtained at surfaces of bulk Fe [6] and data obtained with other spin-polarized electron spectroscopies on magnetic materials [7], such as Fe, suggest that the average ESP of electrons of energies of about 10–12 eV scales roughly to the net magnetization of the magnetic material.

Fig. 2 shows the dependence of the magnetization, or the average ESP (electron energy 10–12 eV) as function of the angle of incidence, α, for 4 ML thin Fe(100)/Pd(100) films. The highest ESP value (~37%) is obtained for $\alpha < 0.6°$ at which the incident ions cannot penetrate the topmost surface layer and, therefore, induce only electrons from the topmost surface layer. This value of the ESP should represent a measure of the surface magnetization. A drop in the average ESP from 37% to 28% is observed when the incidence angle is increased above 1–2° at which the incident ions penetrate the surface and induce electron emission from deeper layers. This change in the ESP corresponds to an enhancement of the ESP of 32% compared to that of the bulk value (28%) and is in excellent agreement (to within 1%) with theoretical predictions [8].

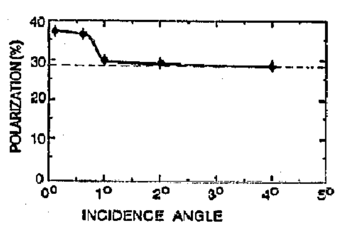

Fig. 2. Average ESP for 4 ML thin Fe(100)p(1×1)/Pd(100) films as function of the angle of incidence α of surface reflected ions.

For the electron energy range of 20 to 50 eV and $\alpha = 1^0$, where the ions can induce emission of Auger electrons from the Fe/Pd interface, we have measured the ESP and the energy distribution of Fe(MVV) Auger electrons emitted from 2 ML thin Fe(100)/Pd(100) films. The ESP of Fe(MVV) Auger electrons (at about 44 eV) amounts to approximately 36%. In addition, we clearly observe a peak in the ESP which is energetically located at the Pd (MVV) Auger electron peak energy (about 40 eV) and which is not observed for 4 ML Fe/Pd films. This is obvious because the mean free path of Pd(MVV) Auger electrons amounts only to a few Å. It is tempting to qualitatively correlate this ESP to the polarization of Pd(MVV) Auger electrons emitted from the Fe/Pd interface. The exact value of the ESP for Pd(MVV) Auger electrons cannot be extracted from these data because of the uncertainty in the contribution of Fe(MVV) Auger electrons to this peak at 40 eV. However, we can conclude that the ESP of Pd(MVV) Auger electrons emitted from Fe/Pd interface is oriented parallel to that of Fe(MVV) Auger electrons.

In conclusion, we state that the experiments presented here, give clear evidence that ECS and SPEES are powerful techniques to study *layer-dependent, interface* and *critical* magnetic properties of ultra-thin films.

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