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To cite this version:

M. Taborelli, O. Paul, O. Züger, M. Landolt. Fe/Au(100): MAGNETISM IN TWO DIMENSIONS AND COMPARISON TO Fe SURFACE-MAGNETISM. Journal de Physique Colloques, 1988, 49 (C8), pp.C8-1659-C8-1660. <10.1051/jphyscol:19888757>. <jpa-00229000>

HAL Id: jpa-00229000
https://hal.archives-ouvertes.fr/jpa-00229000
Submitted on 1 Jan 1988

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Fe/Au(100): MAGNETISM IN TWO DIMENSIONS AND COMPARISON TO Fe SURFACE-MAGNETISM

M. Taborelli, O. Paul, O. Züger and M. Landolt

ETH-Zürich, CH-8093 Zürich, Switzerland

Abstract. – The temperature dependence of the magnetization for ferromagnetic Fe/Au(100) epitaxial films, for the Fe(110) surface, and for the Fe single crystal are measured with spin polarized secondary electrons and Kerr ellipticity. From the low temperature region spin-wave parameters, and from the critical region critical exponents are reported and compared.

The influence of the dimensionality of the system on the magnetic behaviour is experimentally investigated in the present study. We measure the spin polarization of secondary and Auger electrons and the Kerr-ellipticity and we use as model systems an Fe(110) bulk single crystal, its surface, and thin films of bcc Fe epitaxially grown on Au(100).

The secondary electrons are excited by an unpolarized electron beam of primary energy $E_p$ and are then analyzed in energy and spin [1]. The spin polarization is defined as $P = (n \uparrow - n \downarrow) / (n \uparrow + n \downarrow)$, where $n \uparrow (\downarrow)$ is the number of electrons with magnetic moment parallel (antiparallel) to the magnetization. At constant energy the secondary electron spin polarization is proportional to the magnetization of the sample. For the single crystal surface study we use a primary energy of 100 eV and an energy of the secondary electrons of 50 eV to achieve a probing depth of only 2 Å corresponding to the topmost atomic layer. The effective polarization $P_{eff}$ of the Auger electrons, on the other hand, obtained from the secondary electron spectra after background subtraction in intensity and polarization, reflects the magnetic moment at an elemental site, independent of concentration [2].

The Fe(110) single crystal is prepared by heating and sputtering cycles: sharp LEED patterns confirm a good quality of the surface. The Fe thin films are evaporated on Au(100). The growth is epitaxial with bcc structure and the [011] direction of Fe is parallel to the [001] axis of Au. For the Fe/Au(100) films we confirm [3] a magnetic single-domain state at remanence with the easy axis of magnetization lying in-plane along a [001] direction. All the data presented below are obtained in this single-domain remanent state.

The temperature dependences of the remnant magnetization of Fe thin films, the Fe single-crystal surface, and bulk Fe, obtained from secondary electron spin polarization and Kerr effect, respectively, are presented in figures 1 and 2. First we consider the values of the ordering temperatures. The critical temperatures of the thin Fe/Au(100) films are lowered with respect to the Curie temperature of bulk Fe, and do strongly increase with increasing film thickness. This reflects the variation of the total exchange energy with the coordination number. The critical temperatures for bulk single crystal and surface, on the other hand, are found to be the same within the accuracy of the measurements: $T_C(\text{surf})/T_C(\text{bulk}) = 1 \pm 0.01$. The evident difference

\[ A_{\text{surf}} = \]
2.83 \times 10^{-5} \text{K}^{-3/2} \text{and } A_{\text{bulk}}=9.35 \times 10^{-6} \text{K}^{-3/2}, \text{respectively, with a ratio of } A_{\text{surf}}/A_{\text{bulk}}=3.0 \pm 0.3. \text{A recent calculation [5] of the spin-wave excitations predicts a Bloch law also for the surface magnetization, with a prefactor } A_{\text{surf}} \text{depending on the strength of the exchange interaction between surface and bulk. A value of } A_{\text{surf}}/A_{\text{bulk}} = 3 \text{ can easily be obtained [5] by a reduced exchange coupling and also was previously observed on amorphous Fe}_{40}Ni_{40}B_{20} [6].}

In the following, we deal with the high temperature region and adopt the picture of an exponential law for the order parameter near \( T_C \), \( P(0)/P(0) = M(T)/M(0) = (1-T/T_C)^0 \) with a critical exponent \( \beta \). For the bulk, the surface, and the thin films we find \( \beta_{\text{bulk}}=0.33 \pm 0.05, \beta_{\text{surf}} = 0.83 \pm 0.08, \beta_{\text{film}} = 0.22 (+0.1 - 0.05) \), respectively. For the thin ferromagnetic Fe/Au(100) films we expect a 2-dimensional behaviour, since the correlation length perpendicular to the film plane reaches the film thickness at a temperature \( T^* \) far below \( T_C \). Clearly \( T^* \) comes closer to \( T_C \) with increasing film thickness. \( \beta \) was determined from high-precision \( P \)-measurements for films of various thicknesses between 0.9 ML and 2.5 ML. The principal error of \( \beta \) arises from the uncertainty in the value of \( T_C \) since finite-size effects in the film plane provoke a considerable “rounding” in the vicinity of \( T_C \). The value of \( T_C \) is determined so that the largest part of the \( P(T) \) curve displays a linear behaviour on a logarithmic plot of \( \log (P) \) versus \( \log (1-T/T_C) \), and the given error bars of \( \beta \) reflect the ambiguity of \( T_C \). We find a constant critical exponent in the thickness range of 1.2 to 2.5 ML indicating that \( T^* \) is sufficiently far below \( T_C \) for 2.5 ML. \( \beta \) thus is the exponent of the 2-dimensional phase transition of bcc Fe. We note that the finite-size effects in the film plane become dramatic below 1 ML, as visible in figure 1, because it is not possible to avoid islanding below 1 ML. This breakdown of the behaviour in the critical region just below 1 ML indicates that our thickness calibration on an absolute scale is correct.

Various theoretical results are available for \( \beta \) in a 2-dimensional magnetic system with fully localized moments. In general the values for \( \beta \) are \( \beta = 1/8 \) (e.g. Ising) and thus much lower than the experimental value reported here, or, as in the case of the Heisenberg model with 4-fold symmetric anisotropy field, exhibit a continuous distribution [7]. Only molecular field approximations (MFA) yield high values for \( \beta \) [8]. This is caused by the infinite range of the interaction assumed in the MFA approach, in contrast to the nearest-neighbour-only interactions considered otherwise. The experimental value obtained for the Fe films could be higher than 1/8 because of an exchange interaction beyond the nearest neighbours and the critical exponents could reflect the range of the exchange interaction.

The critical behaviour of the Fe(100) surface, on the other hand, can be compared with various experimental results: Ni(100) with \( \beta = 0.825 \) [9] and EuS with \( \beta = 0.72 \) [10]. The first value agrees very well with our finding for the Fe(110) surface and is quite different from the EuS value. The main difference between these materials is the localization of the magnetic moments in EuS and the itinerant character of Fe and Ni. In contrast, the available theories predict the same \( \beta \) for itinerant and localized models. The itinerant model of Hasegawa [11] gives \( \beta_\text{surf} \approx 0.8 \) for the Fe(100) surface, and for the localized models values of \( \beta \) from 2/3 to 1 for Ising and \( \beta = 0.84 \) for Heisenberg, respectively, are calculated [12]. At present it is obviously not possible to determine the universality class. Moreover, a further itinerant spin-fluctuation theory by Dorantes-Davila et al. [13] predicts an almost identical general behaviour for bulk and surface, in pronounced contrast to figure 2.

We conclude that the temperature dependence of the magnetization for thin Fe films and Fe surfaces below \( T_C/2 \) can be well understood within the spin-wave model. The critical behaviour of 2-dimensional Fe films on Au(100) points towards a more-than-nearest-neighbour interaction. The comparison of the critical behaviour of the surface of Fe(110) with previous measurements indicates that the itinerant character of the ferromagnet leads to a fundamental difference in the critical exponent \( \beta_{\text{surf}} \).

Acknowledgments

It is a pleasure to acknowledge stimulating discussions with H.-C. Siegmann, expert technical assistance by K. Brunner, and financial support by the Schweizerischer Nationalfonds.