Journal of Magnetism and Magnetic Materials 165 (1997) 230–233

ELSEVIER

journal of magnetism and magnetic materials

Thermal effects on the surface magnetism of a 10 ML Fe/Ag(100) film studied by spin polarized metastable deexcitation spectroscopy (SPMDS)

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Abstract

The influence of annealing on the surface magnetism of a 10 ML film of Fe grown at 120 K on Ag(100) has been investigated with topmost layer sensitivity by spin polarized metastable deexcitation spectroscopy (SPMDS). Silver starts to diffuse to the surface at a temperature of 300 K. The surface magnetization goes through a maximum at $T = 300$ K and then decreases to zero at higher temperatures indicating that the improvement of the structural order dominates up to room temperature and then is overcome by the presence of silver on the surface that screens the electronic states of iron.

Keywords: Surface magnetism; Multilayers; Magnetization - temperature dependence; Spin polarized metastable deexcitation spectroscopy

1. Introduction

The magnetic properties of surfaces and thin films are currently an area of great interest. The low dimensionality of these systems gives rise to unique characteristics such as enhanced magnetic moments, thickness-dependent spin anisotropy, different Curie temperatures with respect to the bulk values, influence of the segregation of atoms from the substrate on the surface [1].

Fe/Ag(100) is one of the systems most widely studied both theoretically and experimentally [2–4]. Yet, there are some aspects that deserve further investigation. One of these is surely represented by the effect of the annealing on the magnetic properties of iron both for the possibility to obtain an improvement of the crystallographic order and for the segregation of silver on top of the surface.

Obviously, in order to study this kind of effects, the availability of a technique sensitive to the first layer of the sample is of primary importance.

A new technique has been developed recently which exploits the electron emission induced by deexcitation at surfaces of spin polarized metastable helium atoms (spin polarized metastable deexcitation spectroscopy) [5–7].

At the surface of 3d metals, the deexcitation process of metastable atoms takes place in two steps [8]. Due to the high values of the surface work function with respect to the He^* ionization potential, the 2s electron of He^* tunnels in an empty state of the solid leaving the incoming atom in a ionic state (resonance ionization: RI). The hole in the 1s level of the ion is then filled by an electron of the valence band of the metal while a second electron of the solid is emitted in vacuum (Auger neutralization: AN) provided that its energy is sufficient to overcome the surface barrier potential.

The surface specificity of this spectroscopy derives from the fact that the AN step is effective at a distance $z_{AN} \approx 2$–3 Å outside the surface plane, being then sensitive to the tail of the charge density which spills out into vacuum at that distance [8,9].

If the incoming metastable atoms are spin-polarized, the neutralization process is sensitive to the spin-selected density of states [9]. In particular, it is possible to introduce the asymmetry

$$A^{exp}(E) = \frac{1}{P}\frac{I_\downarrow(E) - I_\uparrow(E)}{I_\downarrow(E) + I_\uparrow(E)}, \qquad (1)$$

where P is the polarization degree of the He^* beam and $I_{\downarrow(\uparrow)}(E)$ are the experimental energy distributions of the ejected electrons following the interaction of spin-polarized He^* atoms with polarization parallel ($\uparrow$) or anti-parallel ($\downarrow$) to the magnetization direction of the sample.

A major limit of this spectroscopy, however, was given by the difficulty to extract, from the measured asymmetry, quantitative information on the minority and majority density of states effective in the deexcitation process, and therefore on the magnetic state of the surface. To over-

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PII S0304-8853(96)00517-3

come this problem, a simple model based on the theory of Penn and Apell [9] and described in detail in Ref. [10] has been introduced to calculate, from the experimental data, the spin-selected density of states of the electrons involved in the AN process.

In this paper, using the SPMDS technique, we have explored the magnetic properties of an iron film deposited on a Ag(100) substrate. In particular we report the results for a 10 ML Fe(100) film grown at $T = 120$ K and the annealing effects up to 550 K. Some details on the experimental procedures are given in Section 2. The data are presented and discussed in Section 3 and the results are summarized in Section 4.

2. Experimental

The experimental apparatus employed in this work will be described elsewhere [11].

The metastable He beam is produced in a discharge between a tantalum tip and a stainless steel skimmer through a nozzle in a quartz glass tube. The intensity of the He^* atoms on the sample is 10^{11} at/s on a spot of 1 mm diameter. 90% of He^* atoms are in the triplet state and 10% in the singlet state. The contamination of UV photons in the beam is about 5%.

The He^* atoms in triplet state are spin polarized along a quantization axis fixed by a weak magnetic field (500 mG) by optical pumping with 1.083 μm light supplied by a laser diode and circularly polarized by a quarter wave plate. The degree of effective polarization of the whole beam (including the atoms in singlet state) as obtained by a Stern–Gerlach analysis is ~ 84% [12].

The energy spectra of the emitted electrons are measured in normal emission by a spectrometer which was designed to work in presence of magnetic fields and it is characterized by an acceptance angle of ~ 0.4 sr and an energy resolution of 250 meV [13].

The silver crystal is cleaned by successive cycles of sputtering with Ne^+ at 2.5 keV followed by annealing at 700 K.

Iron is deposited by electron bombardment of a rod. After a thorough outgassing of the iron source, the pressure in the scattering chamber remains below 2×10^{-10} mbar during the whole operation of deposition.

It is well known that Fe grows epitaxially on Ag(100) forming, for a 10 ML film, a bcc structure with the surface plane of Fe(100) rotated of 45° with respect to the Ag lattice [14].

The magnetization of the film is provided by a current pulse in a coil surrounding the sample. A desired crystallographic direction of the sample can be set parallel to the axis of the coil and to the quantization axis of the He^* beam by using the azimuthal rotation axis of the manipulator. All the measurements reported in this paper were taken in remanence after in-plane magnetization of the iron film along the ⟨100⟩ direction, the easy magnetization axis of bcc iron.

Reversing of the polarization direction of the He^* beam is obtained by inverting the circular polarization of the laser beam after a 90° rotation of the quarter wave plate [12].

3. Results and discussion

The energy distribution curves (EDCs) from a 10 ML film of iron grown at $T = 120$ K on Ag(100) are reported in Fig. 1 for several annealing temperatures of the sample. The data shown in the figure were obtained with unpolarized He^*. For comparison, the spectrum from clean Ag(100) is also reported (curve g). All spectra were recorded for the same beam intensity and the same detection conditions so that the intensities of the EDCs are fully comparable.

The asymmetries (Eq. (1)) calculated from EDCs obtained in an $He^*_{\uparrow(\downarrow)}$ experiment are shown in Fig. 2.

The spectrum of Ag(100) (curve 1g) presents two step-like structures in the 6–10 eV and the 10–14 eV kinetic energy (K.E.) regions and is equivalent to the one measured on Ag(110) [15].

Deposition of iron determines a strong increase of the intensity in the 10–14 eV region (see Fig. 1a).

The deconvolution of the EDC measured from Ag(110) shows that the effective density of states is formed by two

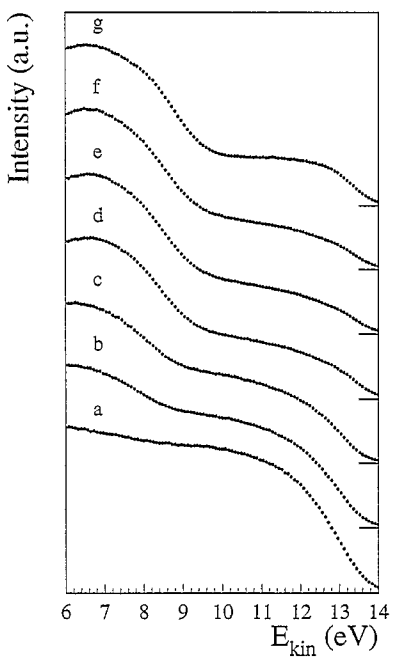

Fig. 1. Electron energy distribution curves as function of the annealing temperature after the deexcitation of He^* on a 10 ML iron film grown on Ag(100) at $T = 120$ K. (a) $T = 120$ K, (b) annealing to 300 K, (c) 360 K, (d) 420 K, (e) 500 K, (f) 550 K. For comparison the MDS spectrum from Ag(100) is also reported (curve g).

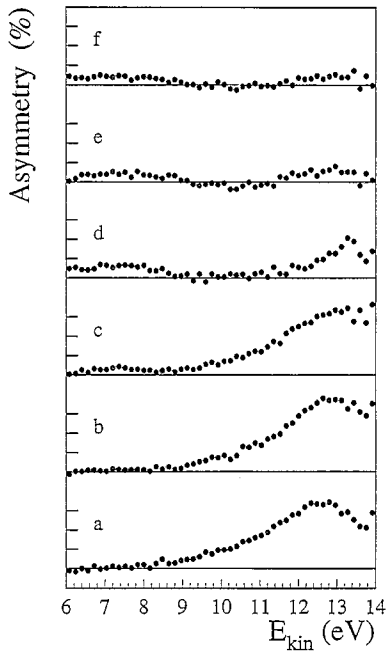

Fig. 2. Asymmetry parameter (Eq. (1)) from a $He^*_{\uparrow(\downarrow)}$ experiment. (a) $T = 120$ K, (b) 300 K, (c) 360 K, (d) 420 K, (e) 500 K, (f) 550 K.

peaks of equivalent intensity, the first centered at a binding energy (B.E.) of ~ 0.8 eV due to s–p states and the second centered at ~ 5.3 eV (B.E.) due to d states [15].

Returning to the EDC of Fig. 1g then, we can interpret the first step in the spectrum at 10–14 eV (K.E.) as due to the self-convolution of s–p electrons and the feature at 6–10 eV (K.E.) as due to the convolution of s–p and d electrons [15].

The equivalence of the weights of s–p and d states of silver is determined by the higher sensitivity of He^* to less localized states as the s–p ones. We have to remember that we are dealing with an effective density of states, where the matrix elements of the Auger transition play a substantial role.

After iron deposition at $T = 120$ K, the spectrum of curve 1a does not show significant contributions from the electronic states of silver, in substantial agreement with ion backscattering data [16].

Coming to the temperature behaviour (curves b–f of Fig. 1), it is possible to observe the variations induced in the measured spectra by successive annealings of the sample. In particular, an increase of the structure in the 6–10 eV K.E. region and a reduction of the intensity of the structure at 10–14 eV K.E. are clearly evident. At the highest temperature (550 K, see curve 1f), the measured spectrum presents a shape similar to the spectrum of clean Ag(100) but already at 300 K it is possible to observe some resemblance.

This behaviour as function of temperature has been discussed previously in terms of segregation of silver from the substrate to the surface of the iron film [2]. The present data, however, show that this process is active already at a temperature of 300 K, in close similarity with what found on iron films grown at room temperature on Au(100) [17] and previous measurements on the same system at a deposition temperature of 300 K [18].

We focus now on the magnetic properties of the film and we observe that the asymmetry reported in Fig. 2a, for a temperature of the sample of 120 K, presents a positive structure with a maximum at ~ 12.7 eV K.E.

The annealing of the film determines first a small increase of the intensity of this structure of $A^{exp}(E)$ from 3.3% to 3.7% (Fig. 2b) and then its strong reduction both in intensity and width.

At 360 K (Fig. 2c), a second positive peak appears centered at ~ 7.5 eV K.E., which increases its intensity and width at $T = 420$ K (Fig. 2d). After further annealing (Fig. 2e–f) it remains essentially constant in intensity and it broadens.

The results on the film at low temperature have been thoroughly discussed elsewhere [10]. Here we recall that the shape of the effective magnetization density $m(E)$, calculated by using the model mentioned in the introduction, is consistent with experimental [19] and theoretical [20] data on the iron surface. In particular, $m(E)$ presents a large, negative feature at $\simeq 0.8$ eV (B.E). This feature is consistent with the calculations of Wu and Freeman [21] on Fe(110) which shows how, near the Fermi edge, a dominance of minority spin states has to be expected. Consistently with previous SPMDS data on several systems [6,22,23], we have observed a negative magnetization as the negative component of $m(E)$ is larger than the positive ones. As discussed previously, we should remember that we are dealing with effective density of states, where s–p states could play a major role with respects to more localized d states. To obtain the true spin-selected density of states, an accurate calculation of the matrix elements entering the Auger transition should be performed.

Concerning the thermal behaviour of the magnetic properties, we observe a strong reduction in the intensity of $A^{exp}(E)$ at high kinetic energies as temperature increases (see curves c–f in Fig. 2), which can be related to the segregation of silver on the surface layer (see previous discussion on the EDCs). Silver atoms, segregated from the substrate, act as a screen which reduces the magnetic moment at surface as sampled by SPMDS.

However, we observe that the annealing of the sample at 300 K produces an increase of the asymmetry (Fig. 2b) and therefore of the electron spin polarization of these states even though the segregation of silver is already active. This can be explained by assuming that, at this temperature, from a magnetic point of view, the improvement of crystallographic order is more effective then silver contamination and underlines the strong interplay between

structural order, surface morphology and magnetic properties.

We turn now to the positive peak at 7.5 eV (K.E.) which appears in the asymmetry starting from 360 K (curve c in Fig. 2). This feature occurs at an energy where segregation of silver induces an increase of the EDC. This observation would suggest a spin polarization of the d states of silver and, on the other hand, evidence of spin polarization of noble metal atoms on ferromagnetic metals was observed on a silver monolayer grown on Fe(100) [24] and on copper spacers in Co/Cu multilayers [25].

However a similar feature has been detected, in the same energy region, following the dissociative absorption of oxygen on a low temperature film and it has been interpreted as the spin polarization of the O 2p states [26].

Up to now it is not possible to disentangle between the spin polarization of d electrons of segregated silver and the effects due to impurity traces of oxygen in consequence, for example, of CO emitted by heaters during the growth of the film and the annealing process.

At present, work is in progress to obtain the effective density of states and the magnetization density as function of temperature by applying the model of Ref. [10]. This analysis should be able to distinguish between the two contributions.

4. Summary

We have studied by SPMDS the thermal behaviour in the range between 120 and 550 K of a 10 ML iron film grown on Ag(100) at $T = 120$ K.

The extreme surface sensitivity of this technique has showed that the segregation of silver atoms from the substrate to the surface is active already at 300 K.

At the lowest temperature, iron states are spin-polarized and we observe, in agreement with previous SPMDS data, a negative magnetization.

A mild annealing of the sample at 300 K determines an increase of the magnetization due to a better structural order even though the segregation of silver is already active.

The improved structural order is more effective, on surface magnetization, than silver *contamination*.

The annealing to higher temperatures segregates more and more silver to the surface which screens the spin polarization of iron states. Starting from $T = 360$ K, a new feature appears in the asymmetry at 7.5 eV (K.E.), in a energy region which is common to electronic states of silver and 2p states of oxygen.

Calculations are in progress to obtain, from the experimental data, the effective density of states and the effective magnetization and their results should help to understand this point.

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