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Comparison of magnetism and morphology of ultrathin Fe films on Cu(100) and Cu_3Au(100)

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Abstract

In order to obtain a deeper insight into the inter-relation of magnetism and morphology we compare the properties of Fe films on Cu(100) and Cu_3Au(100) grown at different temperatures, using the magneto-optical Kerr effect and scanning tunnelling microscopy. In Fe films on Cu_3Au(100) for both room- and low-temperature growth (RT and LT growth) neither an antiferromagnetic phase nor a good layer-by-layer growth, as found for RT growth in Fe/Cu(100), was observed. The critical thickness at which the spin reorientation transition from perpendicular to in-plane easy axis starts, is found to be 3.5 ML for RT-grown Fe/Cu_3Au(100) as compared with 5.5 ML for the LT-grown films on both substrates.

Keywords: Growth mechanism; Surface morphology; Magnetic properties and measurements

The magnetic properties of a system with reduced dimensions are in a complicated way inter-related to its morphology and structure, which in turn depend sensitively on the substrate and the deposition conditions. Fe films on Cu(100), for example, exhibit various magnetic phases at different coverage regimes, which in turn vary with the growth temperature. One of the most convenient approaches to influence the deposition conditions is a variation of the growth temperature. Both the antiferromagnetic and ferromagnetic phase of fcc-Fe, for example, have been found in iron films on Cu(100) this way [1–3]. This behaviour can be attributed to the dependence of the magnetic phase of fcc-Fe on the lattice parameter. The fact that the lattice constant $a_0 = 3.61$ Å of Cu(100) lies midway between the values for the antiferromagnetic phase (3.59 Å from bulk experiment) [4] and the ferromagnetic phase (3.64 Å from theory) [5] of fcc-Fe suggests an extreme sensitivity of the magnetic phase of Fe/Cu(100) on the structure. Cu_3Au(100), on the other hand, has a lattice constant of 3.75 Å, thus lying in the range of the predicted ferromagnetic phase. Epitaxial Fe films on Cu_3Au(100) with an expanded lattice are therefore expected to be ferromagnetic only. Besides this particular case it is of more general interest to obtain a deeper insight into how the surface and volume anisotropies are affected by morphology and structure in a magnetic thin film system. To this aim we performed a comparative study of Fe films grown at different temperatures on both Cu(100) and Cu_3Au(100) substrates with respect to magnetic and morphological aspects, using magneto-optical Kerr effect (MOKE) and scanning tunnelling microscopy (STM), respectively. To ensure that a comparison between our data for Fe/Cu_3Au(100) and the data for Fe/Cu(100) obtained by other groups is meaningful, we repeated the magnetic measurements [2] for Fe films on Cu(100) grown at room and low temperature.

The experiment consists of two parts: the magnetic studies using MOKE, and studies of the film morphology and growth mode applying STM. The magnetic measurements were carried out in a UHV chamber (base pressure, 2×10^{-8} Pa) equipped with facilities for MOKE, Auger electron spectroscopy (AES), low-energy electron diffraction (LEED) and thin film growth. To monitor the process of the film growth, medium-energy electron diffraction (MEED) was employed during the deposition of iron [6]. Studies of the film morphology were carried out in-situ at similar vacuum conditions in another UHV chamber equipped with STM, AES, LEED and an iron evaporator.

Prior to deposition of the iron films, the substrates were cleaned by 1.5 keV Ar^+ ion bombardment, and subsequently annealed to 900 K for 2 min. Cu_3Au(100) was additionally tempered at 600 K for 30 min to obtain a chemically well-ordered surface (Cu_3Au exhibits a chemical order/disorder transition at ≈ 660 K). The degree of ordering was checked with LEED and the diffraction pattern showed a clear c(2×2) superstructure. A detailed description of the chemical particularities and of the preparation of the substrate Cu_3Au(100) can be found elsewhere [6]. The iron films

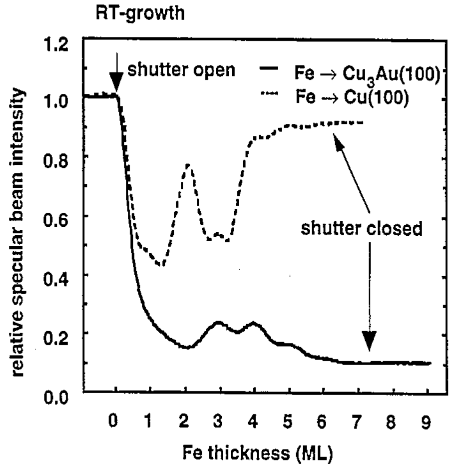
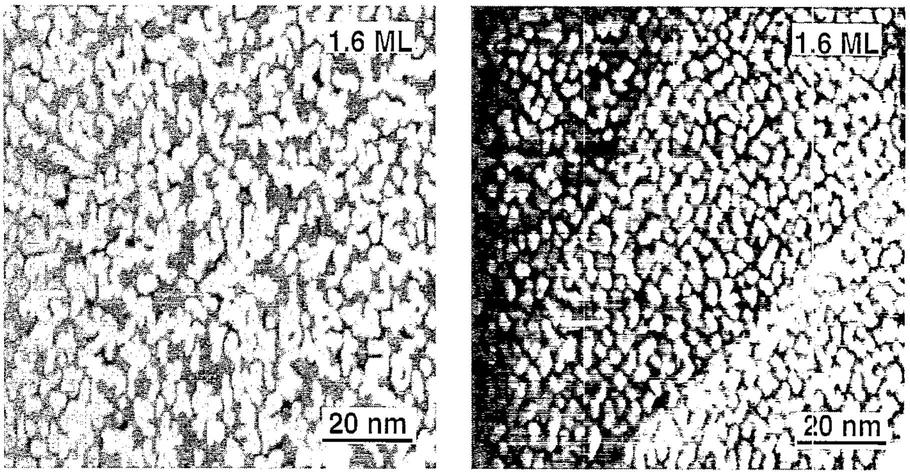


Fig. 1. MEED specular beam intensities for RT-grown Fe films on both Cu(100) and Cu$_3$Au(100).

were grown at different temperatures. The growth temperature was kept within 300 ± 5 K for the room-temperature (RT) growth. In the case of low-temperature (LT) growth the deposition temperature in the MOKE and the STM chamber was 160 K and 130 K, respectively. After evaporation the films were briefly annealed at 300 K. STM images were taken at room temperature.

Fig. 1 shows the MEED results of Fe films on Cu(100) and Cu$_3$Au(100) for RT growth. After opening the shutter the intensity of the specularly diffracted beam for Fe/Cu$_3$Au(100) drops abruptly, reaches a minimum at 2 ML, and then slightly recovers with maxima at coverages of 3 and 4 ML. This is interpreted as a multilayer growth up to 3 ML followed by a quasi layer-by-layer growth up to ≈ 5 ML [6]. The MEED results of RT-grown Fe/Cu(100) show a curve similar to that reported in Ref. [2]. The lower average MEED intensity for Fe/Cu$_3$Au(100) is thus due to a rougher film surface, in contrast to the finding in Fe/Cu(100), which reveals a better layer-by-layer growth. This interpretation of the MEED measurements agrees well with our STM data as discussed in the following. Fig. 2(a)–2(d) show the STM images of 1.6 ML Fe films on Cu(100) and Cu$_3$Au(100) for both RT and LT growth. For RT growth the islands in the Fe film on Cu(100) (Fig. 2(a)) are much larger than those on Cu$_3$Au(100) (Fig. 2(b)). In the former case the first layer is more than 95% closed (dark gray), the second layer about 65% closed (light gray), and the layer filling of the third

(a) Fe/Cu(100) RT-growth (b) Fe/Cu$_3$Au(100) RT-growth



(c) Fe/Cu(100) LT-growth (d) Fe/Cu$_3$Au(100) LT-growth

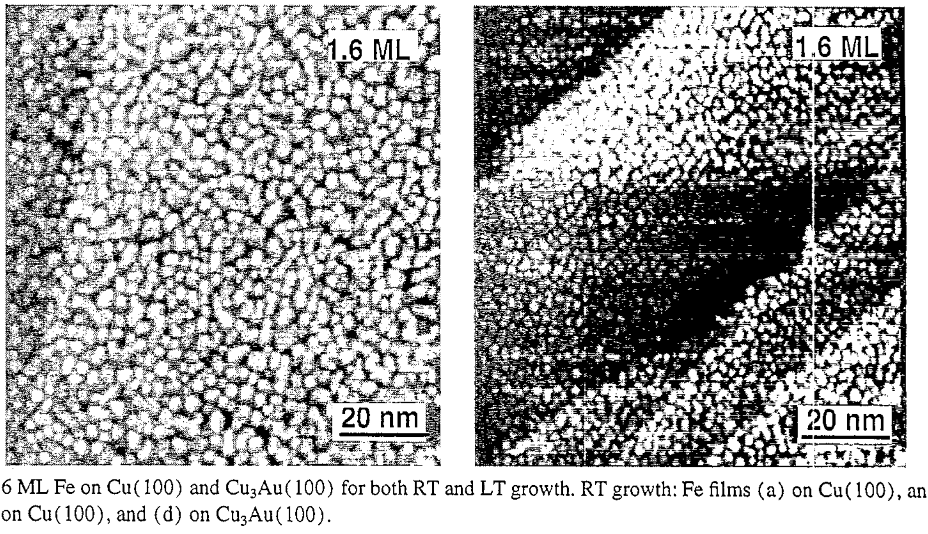


Fig. 2. STM images of 1.6 ML Fe on Cu(100) and Cu$_3$Au(100) for both RT and LT growth. RT growth: Fe films (a) on Cu(100), and (b) on Cu$_3$Au(100); LT growth: Fe films (c) on Cu(100), and (d) on Cu$_3$Au(100).

layer is less than 5% (small white patches). The latter case indicates, however, a distinct multilayer growth, in which only ≈80% of the first layer are closed and already many third-layer islands (brightest areas on each terrace) with more than 25% layer filling are observed. This situation causes the drastic drop of the MEED intensity, as shown in Fig. 1. The analysis of the height distribution of further STM images of Fe/Cu_3Au(100) at higher coverages shows that at a coverage of 3 ML (4 ML), where the maxima of the MEED intensity are found, only about 80% of the third (fourth) layer are closed, showing a mixing of the multilayer and layer-by-layer growth modes. The corresponding values of Fe/Cu(100) are found to be larger than 90%. A good layer-by-layer growth of Fe films as on Cu(100) is thus not encountered on Cu_3Au(100). The enhanced mismatch of fcc-Fe on Cu_3Au(100) (4.2% compared with 1% on Cu(100)) could be responsible for this complex growth behaviour.

In the case of LT growth a multilayer growth of the Fe films is found on both Cu(100) and Cu_3Au(100) (Fig. 2(c) and 2(d)). Compared with RT growth, a high island density in Fe films on both substrates is observed, which is caused by the reduced mobility of Fe adatoms at low temperature. In the Fe film on Cu(100) islands of the second layer have, however, more tendency to connect to each other than on Cu_3Au(100) and we can already find the third-layer islands at a coverage of 1.6 ML. The Fe film on Cu_3Au(100) at 1.6 ML has a higher island density than that on Cu(100) and only few islands in the third layer are found, exhibiting more a bilayer growth.

Fig. 3(a) shows the remanence Kerr signal of Fe films on Cu(100) as a function of thickness for both RT growth and LT growth, giving a result consistent with the findings in Refs. [1–3]. For RT growth Fe films exhibit a perpendicular magnetization up to about 4 ML with the remanence linearly increasing with Fe thickness, corresponding to a ferromagnetic phase. Films in the range from 5 ML to about 10 ML have reduced Kerr signals, indicating the existence of an antiferromagnetic phase, as reported in Refs. [1] and [2]. In the case of LT growth the perpendicular remanence Kerr signal linearly increases with the Fe thickness up to ≈5.5 ML as expected for a ferromagnetic film. It then goes to zero with a spin reorientation transition, changing the easy axis of the magnetization from a perpendicular into an in-plane direction [3]. The critical thickness for Fe/Cu(100), defined as the thickness for the onset of the spin reorientation transition, is thus 10 and 5.5 ML for RT and LT growth [2,3], respectively. Fig. 1(b) displays Kerr signals for Fe/Cu_3Au(100) as a function of Fe thickness for both growth temperatures. We find a perpendicular magnetization for RT growth up to a critical thickness of 3.5 ML. The corresponding value for LT growth is 5.5 ML. Films thicker than this critical thickness show a spin reorientation from perpendicular to in-plane magnetization in a narrow thickness region of about 0.5 ML. Note that RT-grown Fe/Cu_3Au(100) exhibits clearly the smallest value of the critical thickness. The antiferromagnetic phase which was found in Fe/Cu(100) for RT growth is not present in Fe/Cu_3Au(100) for both RT and LT growth. We tentatively attribute the absence of an antiferromagnetic phase in Fe/Cu_3Au(100) to the expanded lattice parameter. Cu_3Au(100) with a larger lattice constant cannot stabilize relaxed fcc Fe films as appear in Fe/Cu(100). The relaxation leads to a smaller lattice parameter of the films, supporting the antiferromagnetic phase mentioned above.

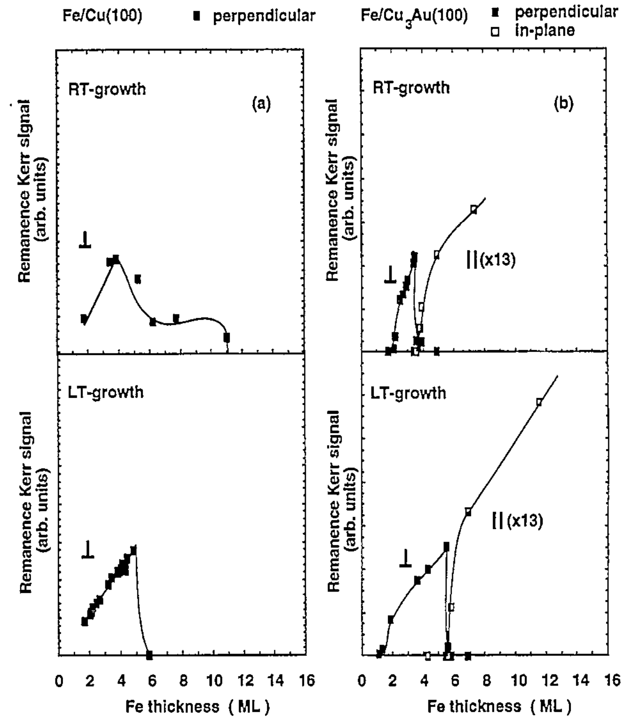


Fig. 3. Kerr signal at remanence as a function of Fe thickness for both RT and LT growth: (a) for Fe/Cu(100) and (b) for Fe/Cu_3Au(100). The solid and open squares denote data taken in the perpendicular and in-plane geometry, respectively. The measurements were carried out at 130 K in (a) and 160 K in (b). The solid lines serve as guides to the eyes.

We will now discuss some significant findings by comparing Fe/Cu(100) and Fe/Cu_3Au(100). First, we find that the choice of the substrate for RT-grown Fe films strongly influences both magnetic properties (with respect to the magnetic phase and the critical thickness) and morphology. As discussed above the antiferromagnetic phase is related to the relaxed fcc Fe films with a smaller lattice parameter. A complex growth mode in RT-grown Fe/Cu_3Au(100) due to the large lattice mismatch is, however, unable to stabilize such a relaxed fcc film. This leads to the absence of the antiferromagnetic phase. The explanation for the small value of the critical thickness in RT-grown Fe/Cu_3Au(100) is, however, more complex. It was reported for the Fe/Cu(100) system that the spin reorientation transition is attributed to a fcc–bcc phase transition rather than to the growing influence of the shape anisotropy [7]. If this is also the driving force of the magnetization reorientation in the Fe/Cu_3(100) system, then one should already observe the fcc–bcc transition at coverages around 3.5 ML. The layer distances extracted from STM and LEED I/V data for RT-grown Fe films on Cu_3Au(100) show a coexistence of the fcc and bcc structure at coverages from 3.5 to 6 ML. The fcc phase in the film at 3.5 ML is, however, still predominant. This is quite different from the finding in the RT-grown Fe/Cu(100), in which many bcc Fe patches at the critical thickness (10 ML) are already found [8]. A more quantitative analysis of the percentage of the bcc phase at coverages in the vicinity of the critical thickness and its influence on the magnetic anisotropy is thus still necessary. The magnetoelastic anisotropy due to the larger strain in RT-grown Fe/Cu_3Au(100) gives, on the other hand, a contribution to the in-plane anisotropy. This could also lead to a reduction of the critical thickness. It is often assumed that a different surface roughness can modify the surface magnetocrystalline and magnetostatic anisotropy. An estimate of the roughness-induced contribution to the perpendicular anisotropy can be obtained considering theoretical models by Bruno [9]. Taking the actual roughness of RT-grown Fe/Cu_3Au(100) from our STM data yields only a $\approx 10\%$ difference as compared with an ideal flat surface. Furthermore, although LT-grown Fe films on both substrates have much rougher film surfaces than RT-grown films, the critical thickness of the former is still larger than that of the latter. We thus conclude that the roughness may not be the main origin of the reduced critical thickness in RT-grown Fe/Cu_3Au(100), but most probably the influence of the magnetoelastic anisotropy.

Second, LT-grown Fe films exhibit a surprising insensitivity of the magnetic phase and the critical thickness to the substrate. LT-grown Fe films on both substrates reveal only a ferromagnetic phase and a similar critical thickness. The multilayer growth at low temperature due to the reduced diffusion of Fe adatoms on the substrate leads to the absence of relaxed fcc films, precluding an antiferromagnetic phase in LT-grown films even on Cu(100). Furthermore, since for LT growth the Fe adatoms have a much smaller mobility and tend to form islands, the island growth of Fe films at low temperature on both substrates (with different island densities, though) could diminish the influence of the particularities of the substrate surface (e.g. Schwoebel barrier potential) on morphology and crystalline structure. The diminished influence of the substrate on the film growth at low temperature leads then to a lesser sensitivity of the magnetic properties to the choice of the substrate.

In conclusion, we do not find the antiferromagnetic phase, as found in RT-grown Fe/Cu(100), in Fe/Cu_3Au(100), related to the absence of a good layer-by-layer growth due to the enhanced lattice mismatch. The small value of the critical thickness in RT-grown Fe films on Cu_3Au(100) is attributed to an enhancement of the in-plane anisotropy, which may be related to magnetostriction due to the enhanced strain. The influence of an fcc–bcc transition on the spin reorientation transition in the Fe/Cu_3Au(100) system needs further investigation. A decisive correlation of the surface roughness with the critical thickness, however, is not encountered. Finally, RT-grown films show a pronounced substrate dependence of the morphology, the growth mode and the magnetic properties. LT-grown Fe films reveal comparable magnetic properties on both substrates, which may be related to a similar crystalline structure and morphology of the Fe layers on both substrates at low temperature.

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