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Study of ferromagnetic-paramagnetic phase transition in two-dimensional Fe/Mo(110) epitaxial films.

V. Usov, S. Murphy, I.V. Shvets

SFI Nanoscience Laboratories, Physics Department, Trinity College, Dublin 2, Ireland

Abstract

Epitaxial Fe films were grown on a Mo(110) single crystal surface at different temperatures. The relationship between magnetism and film morphology was studied *in situ* using scanning tunneling microscopy and Kerr magnetometry. For the films of the same thickness an increase of the Curie temperature by ~ 30 K and broader ferromagnetic-paramagnetic phase transition is observed for the room-temperature grown films compared to the films grown at elevated temperature.

Keywords: Ising model – spin 1/2., phase transitions – ferro-paramagnetic, Kerr effect, iron films.

Corresponding author: Victor Usov, Department of Physics, Trinity College Dublin, Dublin 2, Ireland. Tel.: 3531–6083139. Fax: 3531–6711759. Email address: oussovv@tcd.ie.

Introduction

Epitaxial ultrathin films exhibit strong correlation between the primary magnetic properties and the film morphology. Scanning tunneling microscopy (STM) and surface magneto-optical Kerr effect (SMOKE) are powerful techniques, which allow one to gain insights into the relations between structural, electronic and magnetic properties. Epitaxial Fe films on Mo (110) surfaces are particularly suited for such experiments. The higher surface energy of the substrate compared to the film makes the films thermodynamically stable [1]. There is no surface alloying or inter-diffusion up to about 900 K [2]. Thin and ultra-thin Fe/Mo(110) films possess a large in-plane uniaxial anisotropy. They also demonstrate the square hysteresis loops of full remanence M_r [3] indicating a single domain state. This makes Fe/Mo(110) a convenient system for studies of ferromagnetic to paramagnetic phase transition by means of SMOKE. Indeed, M_r coincides with the spontaneous magnetization and can be taken as the order parameter when the system is in a single-domain state and the measurements are performed along the easy axis [4]. In this paper we report on the critical behaviour of Fe ultrathin films grown on the Mo (110) surface. This is a follow up study of our recent investigation of the magnetic properties of epitaxial Fe/Mo (110) films.

Experiment

The Mo(110) substrate was prepared from a single Mo crystal, aligned to 0.65° off the (110) plane, yielding ~ 180 Å wide terraces running along [1-1-1] direction (Fig.1a). The cleaning procedure described in Ref. [5] was repeated until the surface produced a sharp 1 × 1 LEED pattern, consistent with the bulk termination of the Mo(110) surface

(Fig.1b). Fe films were deposited by electron beam evaporation of a 4N purity Fe rod. The deposition rates were monitored using a quartz crystal balance and were typically in the $0.5 \leq D \leq 0.7$ Å/min range.

Results and discussion

STM images of nearly complete 2 monolayer (ML) Fe films on Mo(110) substrate grown at 300 K and at 512 K are shown in Fig. 1c and 1d respectively. At room temperature (Fig. 1c) the second layer tends to grow in the layer-plus-island mode with increasing preferential growth along [00-1] axis. When the growing islands cross the atomic steps the film thickness locally increases from 2 to 3 ML. The second layer relaxes along [1-10] direction via formation of the dislocations appearing along [00-1] direction, which form favorable nucleation sites for the successive Fe layers leading to the formation of the third layer islands. At elevated temperatures, the first and the second Fe layers grow by the step-flow mechanism producing 1 and 2 ML thick Fe stripes. Second Fe layer stripes grow along the step edges without crossing them so that the formation of a third layer does not occur. The magnetic properties were studied *in-situ* using the longitudinal Kerr effect with magnetic filed applied along the easy [001] axis. An example of the hysteresis loops obtained from the film grown at 512 K is presented in Fig.2. Qualitatively the behaviour of the films deposited at room temperature was similar. We define the temperature at which the remanence vanishes as Curie temperature and for clarity denote it as T_c'. The thickness dependence of the Curie temperature for the films grown at 300 K is displayed in Fig. 3. As expected the Curie temperature is significantly reduced compared to the bulk value and decreases monotonically with decreasing Fe coverage. To observe the effect of the film structure on the magnetic properties, two films of the same thickness 3.35 Å (1.95 ML) were grown at 512 ± 15 K and 300 K. The temperature dependence of remanent Kerr intensity for these films is displayed in Fig. 4a. Both films undergo the second order phase transition. Since Kerr intensity is proportional to the magnetization M the data can be fit to the universal power law $M \propto (1 - T/T_c)^{\beta}$ according to which M approaches zero at a finite temperature T_c . β is the critical exponent which depends on the universality class. β equals 0.125 for the Ising model which describes a 2D system with two possible orientations (up-down) of the order parameter [6]. β value close to 0.125 given by the Ising model is expected for a 2 ML Fe/Mo(110) due to a large in-plane uniaxial anisotropy inherent to the system [7]. The fitting of the data in Fig.4a is accomplished by choosing T_c, *which* maximises the range of a straight line in a log(M) *versus* $\log(1 - T/T_c)$ plot, which is shown in Fig. 4b. The slope of the graph yields an effective critical exponent $\beta = 0.128 \pm 0.003$ for the film grown at high temperature and $\beta = 0.129 \pm 0.004$ for the film grown at room temperature which agrees with the Ising value of 0.125 within an error (only the fitting error is given). A detailed discussion on the fitting method can be found in Ref. [7]. The dependence of the magnetic properties on the film growth conditions is evident from the Fig.4a. The average number of the nearest neighbors is larger in the film grown at 300 K due to the local increase of the film thickness from 2 to 3 ML. As result T_c for this film is larger by approximately 30 K compared to the film grown in the layer-layer fashion at higher temperature despite the equal deposited thickness. The tail above the fitted T_c is also larger for the film deposited at room temperature (3.5 % against 2%, see Fig. 4a). This tail is generally attributed to the finite-size effect arising from the surface defects reducing the correlation length [7, 8]. This tail can be estimated as $(T_c^{'} - T_c)/T_c \sim a/l$ where a is the lattice parameter and l is the length scale of the coherent regions of the film [9]. The tail of 2% gives a finite size of ~ 150 Å which is in good agreement with the terrace width measured by STM (Fig. 1a). The increased density of the islands edges compared to the density of step edges in the film deposited at room temperature can explain the broader transition. The island edges serve as additional hindrances reducing propagation of the long-range fluctuations. However, the effect of non-homogeneous distribution of the film thickness cannot be excluded. The 3 ML thick film features have the T_c larger than 2 ML ones. Elmers *at. al.* demonstrated for an Fe monolayer on W(110) composed of the monolayer Fe stripes that the magnetisation tail above T_c can broaden as a result of the Curie temperature distribution of the stripes composing the film [10].

In conclusion: we have observed the dependence of the growth and magnetic properties of ultra-thin Fe films, grown on Mo(110) on the substrate temperatures. Below 2 ML the films prepared at 512 K grow in the layer-by-layer mode. The films deposited at 300 K grow in the layer-plus-island fashion. For the films of the same thickness grown at different temperatures a dramatic difference in T_c of ~ 30 K was measured. The broader transition at T_c is also observed for the room temperature grown films.

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Figure captions:

Figure 1. a) 500×500 nm STM image of the clean Mo(110) substrate. b) LEED pattern of a vicinal Mo(110) surface c) 80×80 nm^2 STM image of 1.85 ML Fe film grown on Mo(110) at 300 K d) 250×250 nm^2 STM image of 1.95 ML Fe film grown at 512 K; dislocations appear as white lines; arrows mark the step edges.

Figure 2. . Longitudinal hysteresis loops measured at indicated temperatures for a 1.95 ML Fe film grown on Mo(110) at 512 K.

Figure 3. Thickness dependence of the Curie temperature T_c' for Fe/Mo(110) films grown at 300 K.

Figure 4. a) Remanent Kerr intensity of 1.95 ML Fe films grown on Mo(110) at 300 K (circles) and at 512 K (squares); solid lines fit the data to the power law $M \propto (1 - T/T_c)^{\beta}$ with T_c and β used as fitting parameters. b) Log-log plots of the remanent Kerr intensity *versus* $(1 - T/T_c)$; T_g denotes the growth temperature. $\beta = 0.129$ and $\beta = 0.128$ were found from the slope of the graph for $T_g = 300$ K and $T_g = 512$ K respectively.

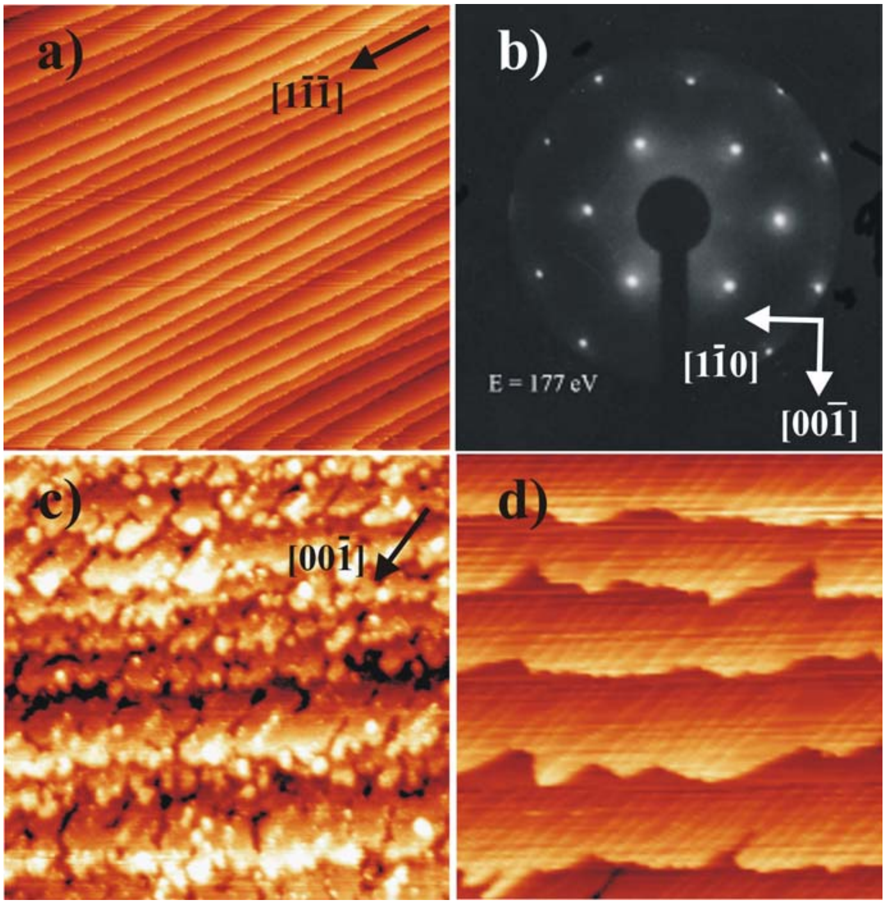

Figure 1.

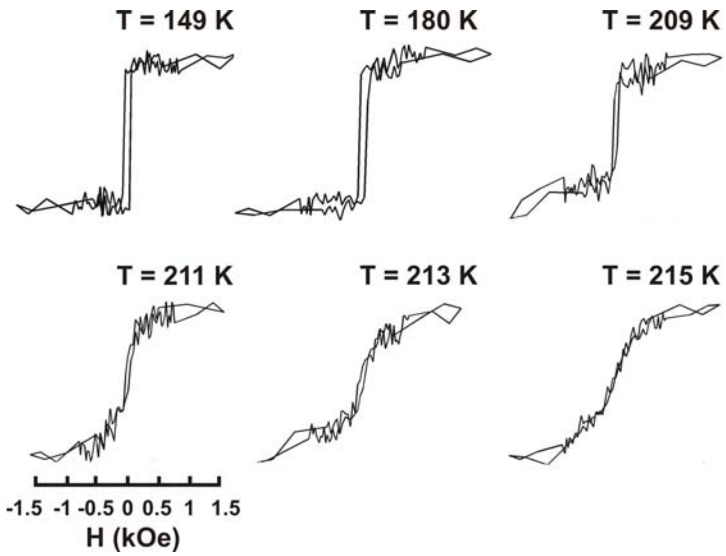

Figure 2.

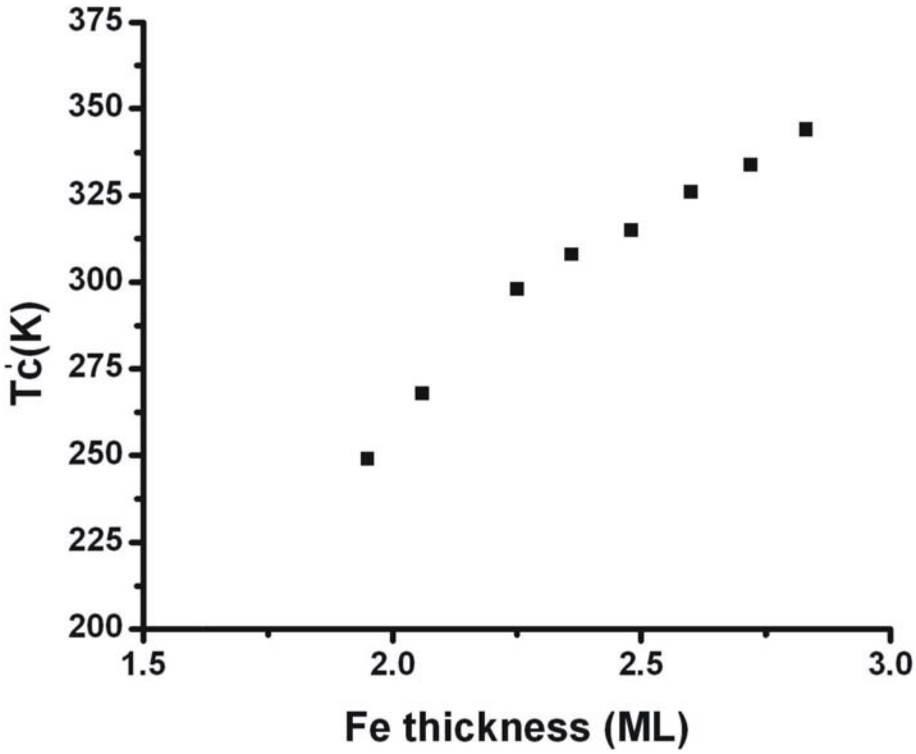

Figure 3.

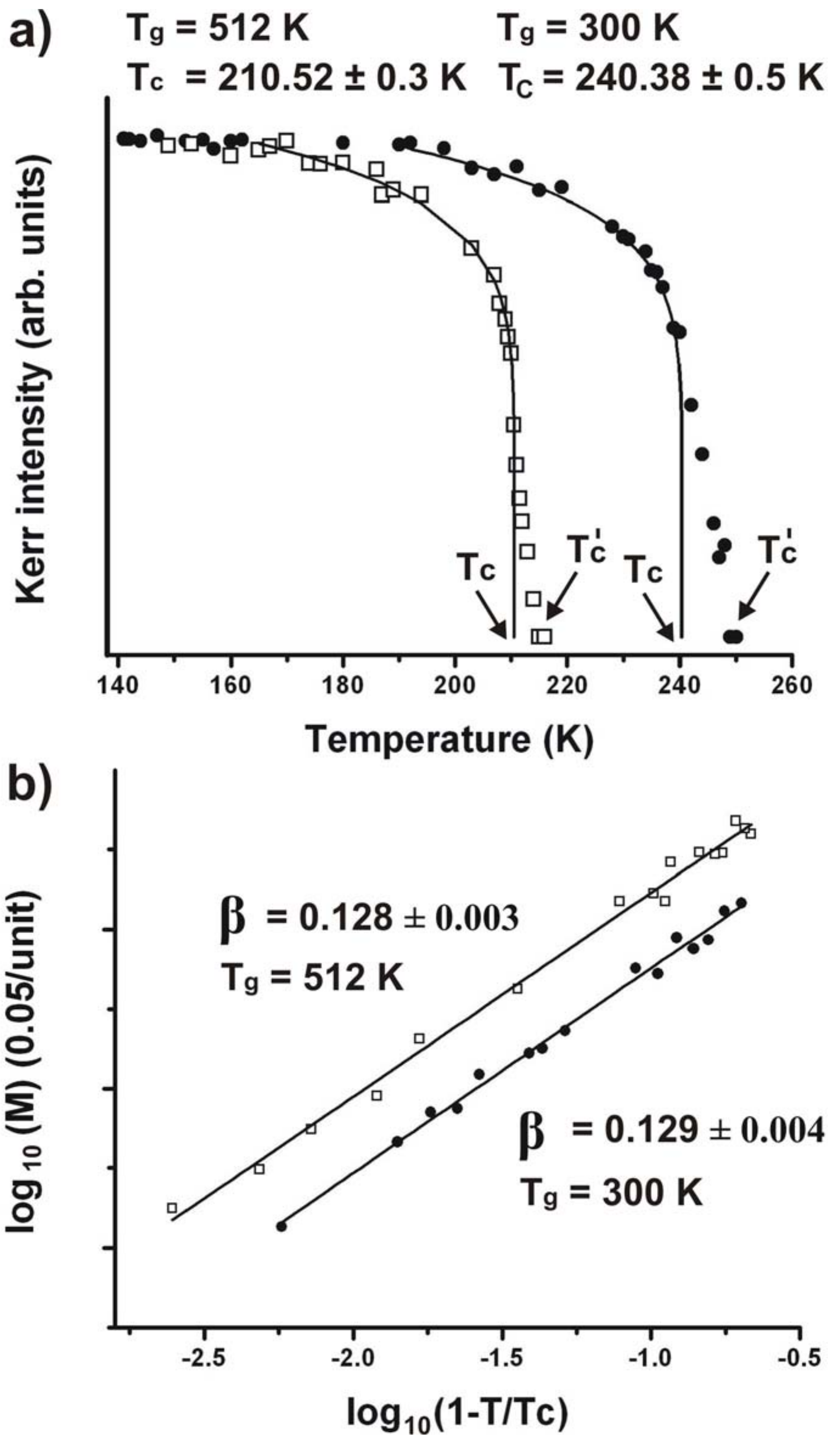
a)
Tg = 512 K
Tc = 210.52 ± 0.3 K
Tg = 300 K
TC = 240.38 ± 0.5 K
Kerr intensity (arb. units)
Tc
Tc'
Tc
Tc'
140
160
180
200
220
240
260
Temperature (K)
b)
β = 0.128 ± 0.003
Tg = 512 K
β = 0.129 ± 0.004
Tg = 300 K
log10 (M) (0.05/unit)
-2.5
-2.0
-1.5
-1.0
-0.5
log10(1-T/Tc)

Figure 4.