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Nucleation, growth and magnetic properties of Fe ultrathin films grown on InAs(1 0 0)-4 × 2

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Abstract

We have studied the magnetic and structural properties of epitaxial BCC Fe grown at room temperature on InAs(1 0 0)-4 × 2 substrates using the magnetooptic Kerr effect (MOKE) in situ and scanning tunneling microscopy (STM). Growth occurs by the Volmer–Weber mode with the Fe islands nucleating in the channels between the first layer In dimer rows. With increasing Fe coverage a superparamagnetic to ferromagnetic phase transition is found to occur at a critical thickness d_c of 3.5 ± 0.05 ML consistent with a 2D percolation phase transition. The directly measured STM feature sizes are in excellent agreement with the size of the superparamagnetic islands estimated by fitting the M–H loops with a Langevin function below the critical thickness.

Keywords: Iron films; Film growth; Interfaces—metal–semiconductor; Critical phenomena—magnetic phase trasition

Ferromagnetic metal (FM)/semiconductor heterostructures have attracted great attention recently for the study of fundamental magnetic properties of ultrathin films and for the development of the next generation magneto-electronic devices [1–3]. For these future magnetoelectronic devices spin-dependent transport is an essential property of the device function, requiring systems with well-defined and magnetic interface layers. The most extensively studied FM/semiconductor system to date is Fe on GaAs. Epitaxial BCC Fe has been stabilised early [4,5] on GaAs using molecular beam epitaxy (MBE) growth, due in part to the fact that the lattice constant of GaAs ($\alpha_0 = 5.654$ Å) is almost exactly twice that of BCC Fe ($\alpha_0 = 2.866$ Å). Although the Fe/GaAs system has been extensively studied the structure of the interface is still unclear [6,7]. Furthermore, Fe forms a rectifying contact on GaAs, while metals on narrow-gap semiconductors on the other hand, such as InAs, form low-resistance contacts [8] which may make InAs a better candidate for electronic devices. Our preliminary results show that despite the large mismatch (5.4%) BCC Fe can be grown epitaxially on InAs surface at elevated temperatures [9]. Here we present a study of the correlation of the magnetic properties and growth morphology of ultrathin films of BCC Fe grown at room temperature on InAs(1 0 0)-4 × 2.

Fe films were grown on InAs substrates at room temperature in a molecular beam epitaxy chamber using an e-beam evaporator with a depositon rate of 0.5 ML min^{-1}. During growth the pressure was below 7×10^{-10} mbar. Details about substrate preparation can be found in Ref. [9]. The surface structure of the substrate and the Fe films was determined by LEED. The magentic properties of the Fe films were studied using in situ MOKE during growth. The loops were collected in the longitudinal geometry. STM measurements were done after transferring the samples under UHV conditions in the stage of the Burleigh microscope on selected thicknesses.

Fig. 1 shows the evolution of the ferromagnetic phase. At a thickness of 2.5 ML the intensity is linear with the applied field. With further Fe deposition (3.0 ML) the MOKE loop is just becoming S-shaped and shows no hysteresis. Fitting the M–H curves with Langevin function, in the range of ± 1 kOe, the average value of the effective magnetic moment per cluster is estimated to be 0.4×10^4 and $1.85 \times 10^4 \mu_B$, after 2.75 and 3.0 ML

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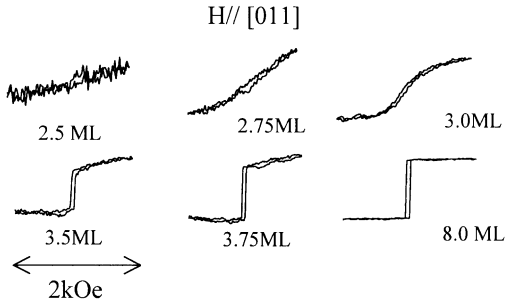

Fig. 1. In situ MOKE loops for the Fe/InAs(1 0 0)-4 × 2 for different Fe thicknesses.

deposition, respectively. Assuming a bulk moment for the Fe clusters and an island height of ~5.0 ML, we estimate the island size to be ~80 Å × 80 Å for the 2.75 ML and ~110 Å × 110 Å for the 3.0 ML Fe film. With further increase in the coverage, long-range ferromagnetic order develops at a thickness of 3.5 ML. The hysteresis loops after the onset of the ferromagnetic phase in Fig. 1 show that the films have a well-defined magnetic coercivity and remanence ratio.

Fig. 2 shows in situ STM images for room-temperature Fe deposition on InAs(1 0 0)-4 × 2. Images from the substrate after annealing reveal that the surface is well ordered with terraces separated by monoatomic steps extending over 500 Å. Higher-resolution images exhibit a row-like corrugation with a height variation of ~2–3 Å and a separation between the rows of 17 Å corresponding to the four-fold reconstruction. Fig. 2a shows an image of 0.05 ML of Fe, the substrate corrugation is still clearly visible underneath. Fe even at this low coverage forms three-dimensional islands approximately 14 Å in diameter and 4.2 Å (3 ML) when measured with respect to the lower part of the corrugations. The clusters are always found to be confined in the channels between the first layer In dimer rows, indicating that this is the preferred nucleation site. With increasing coverage the cluster size increases; at 2.3 ML (Fig. 2b) the cluster size is now ~40 Å × 40 Å. At 3.5 ML (Fig. 2c) a number of islands have coalesced and are part of bigger clusters with an average size of ~140 Å × 140 Å although a number of smaller islands can be seen with sizes comparable to the cluster size of the 2.3 ML. For the narrow thickness range between 2.75 and 3.0 ML, therefore the mean cluster size deduced from the Langevin function (between 80 and 110 Å) and that from the STM images are quite similar i.e ~1000 atoms per cluster, indicating that these particles give rise to the superparamagnetic response at this thickness. Beyond this thickness at 5 ML (not shown) and 8 ML (Fig. 2d) the cluster sizes increases further to ~180 and ~200 Å, respectively, although it becomes increasingly difficult to distinguish them as such as many more clusters have now coalesced. At 8 ML extensive

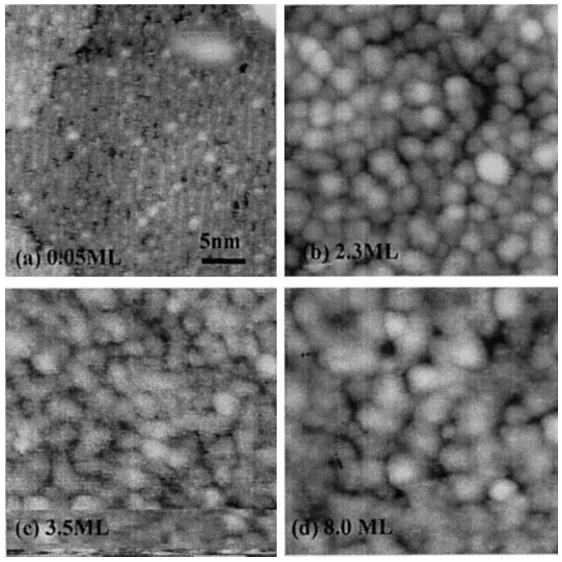

Fig. 2. STM images from Fe films grown on InAs(1 0 0)-4 × 2 surface with thicknesses of (a) 0.05 ML, (b) 2.3 ML, (c) 3.5 ML and (d) 8 ML. All image sizes are 44 nm × 44 nm (sample bias of 1.7 V and $I_T = 1.0$ nA).

colescence has resulted in almost all of the islands being interconnected.

In order to learn more about the nature of the phase transition we study the behaviour of one of the order parameters in the critical region, the susceptibility χ which is defined as the derivative of the magnetisation with respect to the applied field, evaluated at zero field. By assuming that the percentage of Fe coverage on the substrate is directly proportional to the thickness of the deposited Fe, we can apply a power law model in analysing the thickness-induced transition in the susceptibility data. The susceptibility around the transition follows a scaling behaviour, $\chi \sim (1 - d/d_c)^{-\gamma}$, with $\gamma = 2.21 \pm 0.25$. The percolation model predicts $\gamma = 2.389$ for two dimensions suggesting that the transition observed can be described by a two-dimensional percolation phase transition. Percolation theory deals with the clusters formed by the statistically random occupation of lattice sites; at a critical concentration p_c there exists a finite probability of a cluster extending across the entire area of the lattice. In this case, it is the superparamagnetic 3D islands created during Fe deposition, randomly located on the surface, that coalesce to form a giant magnetic island marking the onset of magnetic order. Although the growth is 3D it is still the interconnection of clusters in a plane which determines the onset of magnetic order and so we can still observe a 2D percolation phase transition.

In summary, a superparamagnetic phase was observed to develop within a narrow thickness range before the

onset of long-range ferromagnetic ordering. The transition to ferromagnetism at the critical thickness of 3.5 ML, can be described by a 2D percolation phase transition. We conclude that a coalescing array of superparamagnetic 3D islands exhibits a critical behaviour consistent with a 2D percolation phase transition.

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