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CHARACTERIZATION OF EPITAXIAL Fe ON GaAs(110) BY SCANNING TUNNELING MICROSCOPY

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ABSTRACT

Iron on GaAs(110) comprises an interesting system not only due to small lattice mismatch, 1.4%, but also because of the magnetic properties of the overlayer. In the present work, scanning tunneling microscopy (STM) was used to investigate bcc Fe films in the 0.1 Å to 20 Å thickness range, grown at 300 K and 450 K substrate temperatures. STM images show Volmer-Weber growth with the formation of 3-D Fe islands 20–30 Å in diameter for 0.1–1 Å deposition at 300 K, increasing to 40–50 Å for thicker films. Iron island sizes at low coverage and thin film roughness at higher coverages both show significant dependence upon growth temperature.

INTRODUCTION

There is considerable interest in understanding the growth and properties of small metal structures on semiconductor surfaces. In particular, a system such as Fe on GaAs, which exhibits a small lattice mismatch, is interesting because of the possibility of growing Fe films or structures with novel properties.[1,2] The (110) face of fcc GaAs has a basis vector of 5.654 Å in the [001] direction, which is nearly twice the unit cell spacing of bulk bcc Fe (a_o = 2.866 Å). The lattice mismatch between Fe and GaAs in the [001] direction is 1.4% with an equivalent mismatch in the $[1\bar{1}0]$ direction. Single-crystal bcc Fe films have been successfully grown on GaAs(110) using molecular beam epitaxy with a substrate growth temperature of 450–500 K.[1-3] In this paper, we report the observation by scanning tunneling microscopy (STM) of the growth of Fe on GaAs(110) substrates. The initial growth is found to be in the form of 3-D Fe clusters characteristic of the Volmer-Weber growth mode.[4] The degree of 3-D growth is found to be dependent on the substrate temperature, and the GaAs substrate exhibits no apparent disorder in the vicinity of the Fe clusters. It was also found that the surface roughness of thin Fe films is dependent on substrate temperature during growth.

EXPERIMENTAL

The experiments were performed in an ultra-high vacuum chamber with a base pressure $< 4 \times 10^{-11}$ torr. The scanning tunneling microscope, similar to the IBM/Zurich design,[5] consists of a glass frame support with a double spring suspension for vibration isolation, a piezoelectric/electrostatic clamping device for coarse sample motion and a piezoelectric tripod for tip motion along the sample surface. All STM images were recorded at room temperature. Fe clusters and films were grown by molecular beam

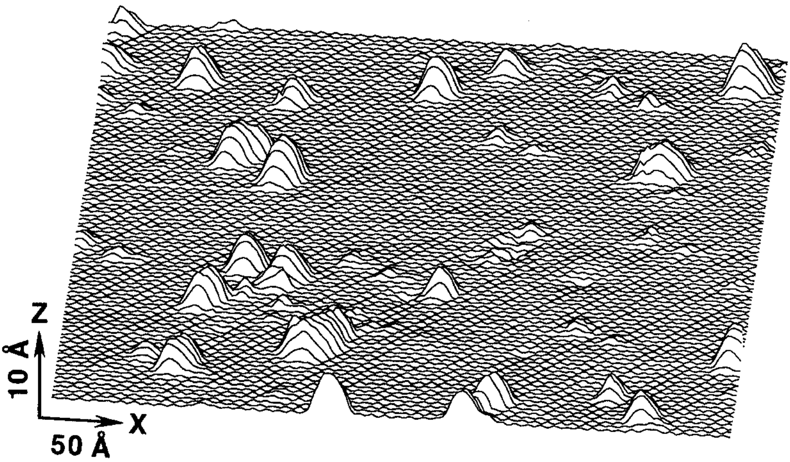

Figure 1: STM image, 400 × 384 Å, of 0.1 Å Fe/GaAs(110) epitaxially grown at 300 K substrate temperature. The sample bias was −2.5 V. The image is displayed by line scans with hidden line removal showing a 3-D perspective of the surface. Fe clusters, substrate As rows, and surface defects are observed in the STM image. (Note the Z scale magnification.)

epitaxy with GaAs substrate temperatures of 300 K and 450 K. Fe evaporation was monitored using a quartz microbalance, but for small depositions, coverages were estimated by measuring cluster volumes. Coverages are specified as the equivalent thickness of a uniform Fe layer (1 monolayer = 2 Å). Surface order and cleanliness were monitored with low energy electron diffraction (LEED) and Auger spectroscopy before and after growth. The substrates consisted of *p*-type GaAs, Zn doped at a concentration of 2×10^{19} cm^{-3}.

RESULTS

Figure 1 shows an STM line scan of the GaAs(110) surface with 0.1 Å coverage of Fe grown at 300 K. The GaAs substrate appears as rows of atoms along the $[1\bar{1}0]$ direction, which is at 45° with respect to the $+x$ direction. Only the substrate As atom locations are observed in the bare surface regions, since the image was obtained at negative sample bias.[6] A variety of different size Fe clusters are observed in the image. Many of the cluster heights are greater than the 2 Å interplanar spacing of Fe, indicating 3-D cluster growth. LEED observations of coalesced clusters (see Fig. 2) showed the bcc Fe diffraction pattern, consistent with previous work which determined the growth to be epitaxial.[3] Volume estimates of the clusters were achieved by integrating the STM height contours of the clusters. This is a good estimate since the charge density contours of metals closely follow the positions of the metal atoms. For very small clusters, this method overestimates the volume due to the finite resolution of the tunneling probe. The volumes of the clusters shown in Fig. 1 range from 100–1500 Å^3, corresponding to 9–127 atoms per cluster.

Figure 2 shows an STM image in 3-D perspective view of a 10 Å Fe film grown on a GaAs(110) surface at 300 K. The Fe clusters range in diameter from 40–50 Å and fill the entire surface. Since the GaAs substrate cannot be imaged with this coverage of Fe, volume calculations could not be made for these crystallites. Even though the Fe

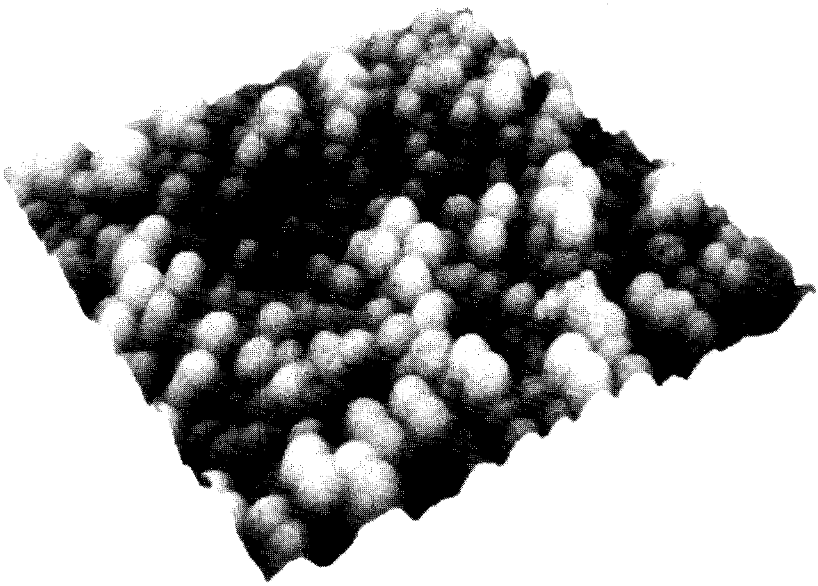

Figure 2: STM image (3-D perspective view with gray scale height shading, 740 × 750 Å) of 10 Å Fe/GaAs(110) shows Fe crystallites 40–50 Å in diameter. The sample bias was +1.5 V, and the substrate temperature during film growth was 300 K.

clusters are in contact with neighboring clusters, the Fe does not coalesce into a smooth film with the substrate temperature at 300 K during evaporation; the small crystallites appear to be distinct. The surface roughness of the image in Fig. 2 was calculated to be ~ 3 Å rms. In Figure 3, two contours are shown for Fe films grown on GaAs(110) at substrate temperatures of 300 K and 450 K. The contour from the 17 Å film grown at 450 K is clearly smoother than that of the film grown at 300 K. The surface roughness of the Fe film grown at 450 K was calculated to be ~ 1 Å rms. Thus, it appears that at an elevated substrate temperature, the Fe clusters tend to coalesce into a more uniform epitaxial film. Further work is in progress to determine the effect of film thickness on the surface quality.

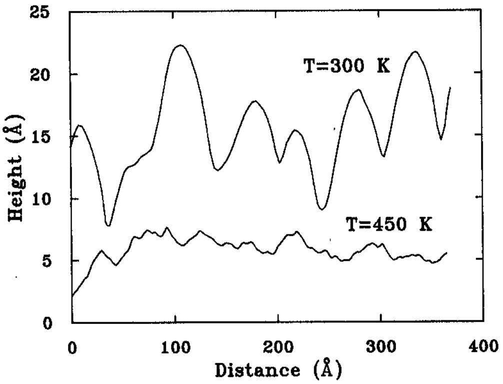

Figure 3: Height versus distance profiles taken from STM images of Fe films epitaxially grown on a GaAs(110) surface. The top curve is a profile from a 10 Å Fe film grown at 300 K with a surface roughness of ~ 3 Å rms. The bottom curve is a profile from a 17 Å Fe film grown at 450 K with a surface roughness of ~ 1 Å rms.

DISCUSSION

For low coverages of Fe on GaAs(110), the growth of single clusters on the bare semiconductor surface can be observed with the STM. Even for coverages as low as 0.1 Å of Fe, 3-D Volmer-Weber growth[4] is observed. Using high-energy-resolution x-ray photoelectron spectroscopy, Ruckman *et al.* and Chambers *et al.* have reported that Fe grown on the (110) and (001) faces of GaAs at room temperature contain Ga and As impurities in the interstitial face-center sites of the bcc Fe.[7,8] However, Carbone *et al.* have reported that a photoemission study with synchroton radiation revealed no intermixing of Fe (deposited at 450 K) with the GaAs(110) substrate for Fe coverages of less than one monolayer.[9] The STM measurements (Fig. 1 and higher resolution images) reveal no disruption of the GaAs substrate immediately surrounding the Fe clusters. (Due to the finite size of the STM tunneling tip, a small portion of the substrate near a cluster can not be imaged.) Thus, if there is intermixing at the Fe/GaAs interface, the disorder is primarily localized at the Fe/GaAs interface, or extends into the GaAs crystal, producing no long range surface disorder.

In order to better characterize the cluster growth, the areas and volumes of clusters were determined from the STM data for isolated Fe clusters grown on GaAs(110) at 300 K and at 450 K (Fig. 4). For comparison, the data have been fit with a two parameter power law, $V = cA^n$, where V is the cluster volume and A is the cluster area. For 2-D growth the parameter n is 1.0, whereas for 3-D growth, $n = 1.5$. The dashed line in Figure 4 shows the relationship for theoretical hemispherical growth with $V = (2/3\sqrt{\pi})A^{1.5}$. As shown in Fig. 4, clusters grown at a substrate temperature of 300 K best fit the volume-area equation with $n = 1.2$, while clusters grown at the elevated temperature yield $n = 1.4$. Thus, even though the 300 K clusters exhibit 3-D structure, the nature of the growth is more two-dimensional; whereas, the growth pattern of the 450 K clusters is more representative of 3-D growth.

As the isolated clusters merge with increasing Fe deposition, the character of the resultant thin film is also dependent on the substrate temperature. The results presented in this paper agree with earlier work[3] in concluding that evaporation onto a 450 K substrate produces smoother films than a substrate temperature of 300 K. The crystalline structure of the Fe films could not be resolved with the STM, but the surface roughness

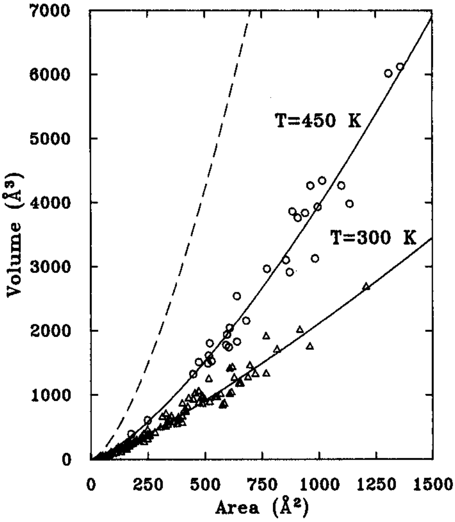

Figure 4: Cluster volume (V) versus cluster area (A) calculated from STM images of Fe on GaAs(110). Different growth modes are observed (with the data being fit to a power law) for substrate temperatures of 300 K (Δ; $V \propto A^{1.2}$) and 450 K ($\bigcirc$; $V \propto A^{1.4}$) during epitaxial growth. The dashed line represents hemispherical growth with $V = (2/3\sqrt{\pi})A^{1.5}$.

decreases by a factor of three and the clusters appear to coalesce into a uniform layer for the case of Fe deposition at the elevated temperature. LEED measurements established the crystalline nature of the Fe films. The diffuse LEED spots of the 10 Å, 300 K Fe film are indicative of small ($<$ 100 Å) crystalline clusters in registry; whereas the 17 Å, 450 K Fe film exhibited sharper LEED spots, characteristic of a uniform crystalline film.

The temperature dependence of the growth patterns of the Fe clusters at low coverages (Fig. 4) and the character of the thin Fe films at higher coverages (Fig. 3) is consistent with the temperature dependence of the Fe atom mobility on the substrate. At an elevated temperature, the Fe atoms will have an increased surface diffusion rate, thereby driving the system closer to a minimum in the surface free energy of the Fe clusters or films. For low coverages, the surface free energy is minimized by the formation of clusters on the surface. As the coverage is increased the clusters contact one another, and the configuration of minimum surface free energy becomes a uniform, flat film. The data reported here are consistent with this simple model in that the clusters deposited at 450 K exhibit a greater mean height (volume/area) than those grown at 300 K, and the film grown at 450 K is smoother ($\sim$ 1 Å surface roughness) than that film deposited at 300 K ($\sim$ 3 Å surface roughness).

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