Unusual island formations of Ir on Ge (111) studied by STM

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Island formation on the Ir/Ge(111) surface is studied using ultrahigh vacuum scanning tunneling microscopy. Ir was deposited at room temperature onto a Ge (111) substrate with coverages between 0.5 and 2.0 monolayers (ML). The samples were annealed to temperatures between 550 and 800 K, and then cooled prior to imaging. With 1.0 ML Ir coverage, at annealing temperatures 650–750 K, round islands form at locations where domain boundaries of the substrate reconstruction intersect. Both the substrate and the islands display a (√3x√3)R30° reconstruction. Additionally, a novel surface formation is observed where the Ir gathers along the antiphase domain boundaries between competing surface domains of the Ge surface reconstruction. This gives the appearance of the Ir in the domain boundaries forming pathways between different islands. The islands formed at higher annealing temperatures resulted in larger island sizes, which is evidence of Ostwald ripening. We present a model for the islands and the pathways which is consistent with our observations.

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1. Introduction

The restructuring of semiconductor surfaces, upon adsorption of metals, is of fundamental interest in surface physics. A practical application is the fabrication of electronic devices. Our group has done much work recently on studying and characterizing different low-index single crystal surfaces of clean Ge [1]. We have also studied the surface characteristics arising from the evaporation of different metals onto a Ge substrate [2–8].

In addition to Frank-Van der Merwe (layer-by-layer), Volmer-Weber (three-dimensional (3D) islands), and Stranski-Krastanov (layer plus islands) growth, [9] other interesting growth modes are sometimes observed, such as 1D growth (islands with high aspect ratios in preferred directions) [5,10]. The growth type depends on the combination of the metal and semiconductor chosen, the Miller indices of the substrate, and the dosing and annealing temperatures. The sizes of the islands generally increase with higher annealing temperatures for cases which can be described by Ostwald ripening [11]. The local geometry of the surface, such as the existence of steps or defects, also has a clear role in the types of islands formed.

Ir surface structures have been studied relatively little despite the many interesting metals located nearby on the periodic table [12–14]. For this paper, we studied Ir/Ge(111) with Ir coverage between 0.5 and 2.0 monolayers (ML), and annealing temperatures between 550 and 800 K. With 1.0 ML Ir coverage, at annealing temperatures 650–750 K, round islands form at locations where domain boundaries intersect. Both the substrate and the islands display a (√3x√3)R30° (hereafter referred to simply as √3) reconstruction. Additionally, a novel surface formation is observed where the Ir gathers along the antiphase domain boundaries between competing surface domains of the Ge surface reconstruction. This gives the appearance of the Ir in the domain boundaries forming pathways between different islands.

2. Experimental details

The instrumentation we use is the first apparatus that combined a low energy electron microscope (LEEM) [15,16], X-ray photoemission spectrometer (XPS), and a scanning tunneling microscope (STM) [17], into a common ultrahigh vacuum (UHV) system [18], with a base pressure of 2 × 10⁻¹⁰ torr. Using a modified sample holder which is compatible with all three instruments, an identical sample can be observed using LEEM, XPS, and STM without breaking vacuum.

Ge(111) samples were placed into UHV, where the samples were sputtered using Ar+ ions with 250 eV energy and ~4 μA sputtering current. Subsequently, they were annealed at ~800 °C until they were clean and displayed the c(2x8) surface reconstruction [19,20], as viewed by STM. A clean Ge sample was used for each annealing experiment.

The Ge(111) samples were dosed with monolayer (ML) and submonolayer coverages of Ir and then annealed to a temperature between 550 K and 800 K in the STM. The samples were heated by resistive heating of a filament located near the sample; a thermocouple attached to
the sample allowed measurement of the temperature. The samples were heated at a constant rate, and it took between 8 and 15 min to heat the sample to the target temperature, with the longer times corresponding to higher temperatures. The sample was held at the final annealing temperature for 5 min. The sample was cooled in UHV conditions and imaged at either 400 K or room temperature (RT). After the sample cooled, it was imaged using STM. Because the samples were only annealed for 5 min, it is likely that longer annealing times would produce some observations similar to higher annealing temperatures. Data were analyzed and plotted using WSxM software [21].

The dosing rate of the homebuilt Ir electron beam evaporator was determined by comparing experimental XPS spectra [8] to simulated spectra computed using Sessa [22]. The Ir coverage for completion of an observed $\sqrt{3}$ overlayer in LEEM was determined to be $\sim 2.0$ ML [8]. With the assumption that the deposition rate maintained a constant flux, this calibration was used for the STM data presented in this paper.

3. Results and discussion

3.1. Observations of Ir features as a function of coverage

STM images of Ge samples with 0.5, 1.0, and 2.0 ML Ir coverage are shown in Figs. 1(a)–(c). For 0.5 ML, small round islands are seen which appear tall compared to the substrate. For 1.0 ML, round islands are observed which are larger and cover a greater surface area, compared to the sample with 0.5 ML. Even though a complete ML of Ir is deposited in Fig. 1(b), the islands cover about half of the surface. Fig. 1(b) also shows two step edges of the Ge substrate. Fig. 1(c) shows 2.0 ML Ir coverage, for which a nearly-complete overlayer of Ir is formed. Vacancy islands form at locations where the overlayer is not complete; two of the vacancy islands are outlined in Fig. 1(c). The overlayer observed in Fig. 1(c) correlates with the coverage at which a completed overlayer was observed in LEEM images, [8].

The arrows in Figs. 1(a) and (b) point to features which appear at an intermediate height between the Ge substrate and the islands. These features typically appear as thin lines connecting different islands. We call these features pathways. The arrows in Fig. 1(c) point to intermediate features located inside the vacancy islands next to the perimeter. Similar to the features indicated by arrows in Figs. 1(a) and (b), the features in Fig. 1(c) appear at an intermediate height between the Ge substrate and the overlayer; in contrast, however, these features have lower aspect ratios and cover a larger surface area. Many vacancy islands in Fig. 1(c) are completely filled with this feature. As discussed in Section 3.2, we suspect that both the islands and the intermediate features, such as pathways, are primarily composed of Ir.

Figs. 2(a) and 2(b) show magnified images of different regions of Fig. 1(b), and Fig. 2(c) shows a magnified image of a region of Fig. 1(c). The arrows in Fig. 2(a) show the location of a Ge step edge. Pathways are often found along upper step edges (middle arrow) except for locations where islands border the step-edge on the lower step (upper and lower arrow). The islands seen along the lower step-edge often protrude into the upper step-edge. The model we present for the islands in Section 3.5 includes 1.0 ML of Ge as part of the island structure. The protrusion of the islands into the step edge may be due to the abundance of Ge available to diffuse from the step edge. The absence of pathways along the upper step edge at these locations may similarly be due to the diffusion of Ir into the island structure.

The arrows in Figs. 2(b) and (c) point to small features which become apparent with higher magnification; we call these dots. The appearance of dots in both Figs. 2(b) and (c) indicates that the corresponding surfaces are similar. The dots appear dispersed on the substrate without long-range order.

The line profile in Fig. 2(d) shows that the height of the island appears slightly lower than the height of the Ge step edge; the surfaces are easily distinguished in Fig. 2(a) because dots only appear on the substrate. The line profiles in Figs. 2(e) and 2(f) show that the height of the island (b) is similar to the height of the overlayer (c). Since the overlayer corresponds to 2.0 ML Ir coverage, the round islands likely correspond to 2.0 ML Ir. The line profiles (e) and (f) also show the apparent heights of some intermediate features. The pathways are similar in height to the intermediate features inside the perimeter of the vacancy islands. The dots appear slightly lower than the other intermediate features. The difference in apparent height between the intermediate features and the tall features may be attributed either to a change in the surface composition, or to a change in physical height, or both.

3.2. High resolution STM image: chemical effects and $\sqrt{3}$ reconstruction

Fig. 3 shows an STM image of 1.0 ML Ir on Ge(111) which was annealed to 700 K. Although the tip bias was held constant during the acquisition, the resulting image shows surface features appearing differently in the three sections labeled I, II, and III. The borders between different sections run horizontally across the image, suggesting that a change in the tunneling tip must have occurred. Presumably, the addition or removal of a contaminant could cause a change in the work function, as well as the form of the local density of states of the tip for different regions of the image.

In section I of Fig. 3, the Ir features appear tall with respect to the Ge substrate, with distinct dots, pathways, and islands evident. In section II, typical pathways and dots are not clearly distinguishable. In section III, the pathways are clearly seen, but the dots are not evident. The height of the round islands in section I measures $2.6 \pm 0.1\,\text{Å}$ above the substrate reconstruction, while round islands in sections II and III measure $2.0 \pm 0.1\,\text{Å}$ and $2.2 \pm 0.1\,\text{Å}$, respectively. The height of the pathways depends on the tip state in a similar manner to the islands; pathways were typically about $1.5 \pm 0.3\,\text{Å}$ lower than the height of comparable islands.

It is likely that similar surface features (round islands, dots, and pathways) are present in all three sections of Fig. 3, but tip contamination
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