Step Motion and Structure Transition on InAs and GaAs(001) Surfaces Observed by Scanning Tunneling Microscopy

Hiroshi YAMAGUCHI and Yoshiji HORIKOSHI

NTT Basic Research Laboratories, Musashino-shi, Tokyo 180, Japan

The step motion and structure transition on InAs and GaAs (001) surfaces are directly observed by scanning tunneling microscopy at high temperatures. A stable (2×4) structure is observed with the InAs surface even at temperatures high enough to cause the motion of monomolecular steps and kinks. At higher temperatures, domains with an In stable (4×2) structure (As desorbed region) are clearly observed in As stable (2×4) structures. These results differ from those for GaAs surfaces and indicate strong lateral interaction in (2×4) structures on InAs.

Understanding surface elementary processes at the atomic scale is important for elucidating and controlling the growth kinetics of molecular beam epitaxy (MBE). For that purpose, we must dynamically observe the behavior of atoms on the growing surface. One of the most powerful techniques of surface characterization is scanning tunneling microscopy (STM). STM makes it possible to observe atomic scale structures of III-V compound semiconductors surfaces.1,2 In this paper, we report on high-temperature STM observation of InAs and GaAs (001) surfaces by using an STM apparatus designed for studying heated samples.3 The change in surface structure due to thermal motion of surface atoms is observed dynamically using this technique. The results indicate a drastic difference between InAs and GaAs in surface structure transition at high temperatures.

The experimental setup was explained elsewhere in detail.4,5 Here, we simply mention sample preparation method. For both InAs and GaAs substrates, a protective layer of elemental As was formed by depositing As4 on the surface cooled to -10 °C after growing a 500-nm-thick buffer layer. The sample was then transferred, through air, to the STM system, and the protective layer was removed by heating the sample at about 300 °C for 15 minutes in the preparation chamber. During the STM observations, samples were heated by a current of less than 2.5 nA.

After removing the protective layer, (2×4) and c(4×4) structures appeared for InAs and GaAs surfaces respectively. With GaAs surfaces, (2×4) structures were observed after the sample was heated to about 370°C. A typical STM image of InAs (2×4) structures is shown in Fig. 1. The clearly visible straight rows with dark contrast probably correspond to the missing dimer rows as in the GaAs (2×4) structure. It should be noted that this structure has higher uniformity than that had obtained with GaAs surfaces. The reported GaAs (2×4) structure prepared by using a similar As passivation technique,6,7 is also less uniform than this InAs structure. Although long annealing is reported to improve the uniformity of GaAs,7 a highly uniform (2×4) structure was observed on InAs just after the protective layer was removed. This suggests that strong lateral interaction causes the coherence of surface reconstruction to be high for the InAs surface.

When the temperature was further increased, the

Fig. 1 STM image of an InAs (001) surface obtained at 260°C. The image area is 50×50 nm, the bias voltage was -3.0 V, and the tip current was 0.08 nA.
motion of monomolecular steps and kinks was observed. Figure 2 shows a series of STM images obtained at 330 °C. The time interval between sequential images is 35 s. The one-molecule-high kinks (A and B in the figure) move in the [110] direction. If we assume that the two defects C and D do not move, we can calculate the thermal drift between consecutive images to be less than 2 nm. These images, therefore, correspond to almost the same position on the surface, and the observed changes in step structure must be due to step motion. These images show that the motion of steps and kinks occurs in units of 1.6 nm in the [110] direction. In other words, kink depths are in units of 4× spacing. This is consistent with the results of static observation of GaAs misoriented surfaces.8) The resolution of the present images is not high enough to show whether or not the unit of the kink and step structure in the [110] direction is 2× spacing. 2× periodicity was observed for the (2×4) structure in terraces even at this temperature, but the periodicity was not clear at kink edges.

Although step motion has also been observed on GaAs (001) surface,9) that motion was observed after the (2×4) structure had disappeared (Fig. 3). This is very different from the motion on the InAs surface, which can be observed when there are stable (2×4) structures. The change in step structure indicates the surface diffusion of both As and In atoms. On the InAs surface, even at temperatures high enough to cause the diffusion of these atoms, (2×4) structures can exist stably because of the strong lateral interaction of the structure. In addition, the step motion for the GaAs surface was rather random in that no systematic behavior was observed. This means that the (2×4) structure also plays an important role in assuring the uniformity of step structure. In a usual MBE growth condition for GaAs, (2×4) structures are maintained by supplying As pressure on the surface. Therefore the step motion on GaAs during MBE growth should rather resemble to that of InAs surfaces.

The significant motion of steps and kinks in the [110] direction is consistent with the observation of anisotropic step-flow growth during MBE of GaAs.8-10) The step structures during growth are reported to be more straight for the surface misoriented to [110] than [110]. Even though the present results were obtained under ultrahigh vacuum rather than when molecular beams were supplied, they show that the (2×4) structure develops more easily along [110] than [110] and they directly show anisotropic step-flow growth on a misoriented surface. The step motion on GaAs surfaces with As pressure is considered to be similar with this InAs case. This observation
is consistent with our previous model for anisotropic step flow growth of GaAs surfaces.9)

When the sample temperature was further increased for an InAs surface, we investigated the structural changes occurring when the As atoms desorbed. The STM image of an InAs surface obtained at 350 °C (Fig. 4) shows that regions with (4×2) structures appeared in (2×4) structures. This result is consistent with the results of reflection high-energy electron diffraction observation and Monte Carlo simulation, and can be explained by strong lateral interaction between surface As units on the InAs (001) surface.11,12) Because these (4×2) domains form suddenly when we increase the sample temperature by only 10 °C, this change probably corresponds to a discontinuous phase transition.

Next, we discuss the physical origin of the strong lateral interaction on InAs (2×4) surfaces. One possible explanation is a difference in bond strength: As atoms on the InAs surface are more weakly bonded to In than they are to Ga atoms on the GaAs surface. The surface diffusion and desorption of As atoms, therefore, occurs at lower temperatures for InAs than for GaAs. On the other hand, the influence of the lateral interaction should be stronger at lower temperatures because it has an Arrhenius-type temperature dependence. Therefore, even if we assume a similar magnitude of lateral interaction energy between surface As units for both InAs and GaAs, the influence of the interaction should be stronger for InAs because surface processes can be observed at lower temperatures.

In conclusion, we used STM to observe InAs and GaAs (001) surfaces at temperatures up to 350 °C (InAs) and 450 °C (GaAs). The missing-dimer row structure of InAs surface was more uniform than that on a GaAs surface. The change in surface structure was observed when the sample temperature was increased to 330 °C (InAs) and 450°C (GaAs). Stable (2×4) structures were observed even at temperatures high enough to cause the motion of monomolecular steps and kinks with InAs. At higher temperatures, domains with (4×2) structures (corresponding to As desorbed regions on the surface) are clearly observed with InAs. These results differ from those for GaAs surfaces and indicate strong lateral interaction in the (2×4) structures on InAs.

We thank Dr. Tatsuya Kimura for his continuous encouragement of this work.

REFERENCES