STM Observation of Bi line structures on the Si(100) surface with Ag deposition

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We report the dynamic process of Bi line structure (BLS) formation and the reaction dynamics of the BLS with foreign atoms on Si(100) surfaces by scanning tunneling microscopy (STM). The BLS consisting of Bi dimers is formed on the Si(100) surface after bismuth deposition at 400~500°C. From the consecutive STM images taken after Bi deposition on the surface, we found that BLSs are formed by expelling atoms that compose the Si terrace at the front of the BLS growth. When Ag atoms were deposited on the Si(100) surface with the BLSs, we found that Ag atoms are preferentially adsorbed on the Si terraces compared with BLSs.

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1. Introduction

The deposition of metal atoms on semiconductor surfaces has been investigated in many works. Among them, the behavior of Bi atoms on a Si(100) surface has recently attracted considerable attention on the grounds that Bi atoms act as a surfactant in heteroepitaxial systems such as Ge/Si(100) [1]. We have ever studied the surface structures of Bi-deposited Si(100) surfaces and have found a formation of a one-dimensional structure, namely, Bi line structure (BLS, in short) consisting of Bi dimers on the Si(100) surface [2]. The BLS has attracted considerable interest in recent years [3-16]. This structure consists of two chains of Bi dimers in the topmost layer, and stretches parallel to the ×2 direction of the terrace of the Si(100) (2×1) surface. The formation of such a one-dimensional structure was reported in Sb/Si(100) system [17]. However, the dynamic process of BLS formation has not been clarified. Therefore we performed a scanning tunneling microscopy (STM) experiment to observe reaction dynamics of Bi atoms on the Si(100) surface. We will discuss the process of BLS formation and the mechanism to induce such kinds of self-organization.

Ag/Si(100) system is expected for application in the silicon devices, because Si(100) is practically used as the substrates of microelectronics devices and Ag has a small electrical resistivity. Among the works concerning with the Ag/Si(100) system, Sakurai *et al.* have succeeded in fabricating Ag-atom wires on a Si(100) surface [18]. In their method of making a one-dimensional structure, they desorbed hydrogen atoms from a mono-hydride Si(100) surface by the STM tip to produce dangling-bond wires, on which Ag atoms preferentially adsorb. Fabrication of atomic-scale structures by using STM has attracted much attention from a viewpoint of making nano-scale devices on the semiconductor surfaces. However, such techniques of fabrication with STM tips may not be suitable for making a lot of atomic-scale devices on the substrate. Any other methods including self-organization mechanisms are expected to be improved.

If above-mentioned BLS can be used as a "template" during the formation of a one-dimensional structure of foreign atoms, we would obtain the way to make new devices. In the present study, we also observed the surface structure after Ag deposition on the Si(100) surface with BLS in order to investigate the reaction dynamics of the BLS with foreign atoms.

2. Experimental

The experiment has been performed in an ultra-high vacuum (UHV) chamber under a base pressure of 1×10^{-8} Pa. The chamber was equipped with a commercial STM (JEOL JSTM-4500XT), a rear-view low energy electron diffraction (LEED) (VG RVL-900) and sample-preparation facilities including heating, Bi deposition and Ag deposition. Tips for STM were made from W wire (0.3 mm in diameter), which were etched using 2N NaOH in a Pt loop electrode in direct current mode. The tips were baked out before being used for scanning.

Si(100) samples of $1\times7\times0.38$ mm^3 were cut from a p-type wafer (B-doped, ～7 Ωcm), and cleaned *in-situ* by direct-current heating at 900^{o}C followed by brief flashing at 1200^{o}C. After the cleaning procedure, well-developed STM images and (2×1) LEED patterns were observed. The sample temperature was measured in the range of 250～1000^{o}C with an optical pyrometer. Bi (99.999 % purity) or Ag (99.9999% purity) was deposited from a crucible made of thin Ta foil. The rate of Bi or Ag deposition was roughly 1 ML/min, where 1 ML was defined to be the ideal Si density in the (100) plane.

3. Results and Discussion

We have ever studied the BLS on a Si(100) surface by STM [2,3,6,9]. We found that BLS is imaged as consisting of two adjoining bright lines. Each bright line corresponds to a chain of Bi-dimers. The BLS is buried in the Si(100) topmost layer. The direction along BLS is perpendicular to the direction of the Si-dimer rows. The total width of a BLS is just four times the lattice constant of the Si(100) surface, and the length reaches the range 40~200nm or, sometimes longer than that. Both inside the BLS and in the terrace thereabouts, it was reported that there are few vacancy defects [3,13].

Figure 1(a) shows an STM image of a Si(100) surface after Bi deposition at 400°C. This image was observed at a specimen temperature of 400°C. Electronic noises from a power source used for substrate heating degraded severely the image quality. There have grown several BLSs in a terrace which contains many line defects parallel to BLS. Note that the BLSs themselves have no vacancy defects.

Figure 1(b) shows an STM image observed 100s later over the same region as Fig. 1(a). In this figure, two white arrows indicate new BLSs which have formed after the previous observation (Fig. 1(a)). The lengths of the new BLSs are 4.7nm (left-hand side) and 16.4nm (right-hand side). These BLSs were stretched to 9.5nm and 17.4nm 20s later, shown in Fig. 1(c), respectively. Neither clusters nor islands of Bi that could be a source of Bi supply to growing BLSs are found on this surface. Bi atoms for new BLSs may be supplied either from the terrace or from a sub-layer lying under the topmost layer. We suggest these terraces consist of both Si and Bi atoms.

We can see that a protruded portion of the terrace between the two new BLSs, indicated with white arrows in Fig. 1(b), recedes. This terrace with protruded portion lies over the one that involves newly developed BLSs. At high temperature observation, atoms at the terraces easily detached from there, but the BLSs exist on the surface without vacancy defects at high temperature. Therefore the BLSs are more stable than Si terraces. In our previous paper [3], we described that the surface migration of both Bi and Si atoms is enhanced on the BLS, and that Si atoms must be expelled at the front of BLS growth. According this view, the transformation of terrace edges would be influenced by the formation of new BLSs. Both Si and Bi atoms in the terrace at the front of BLSs may be removed to diffuse to other places along BLS, or be desorbed from the terrace.

Figure 2 shows an STM image taken after Ag deposition for 60s on the Si(100) surface with BLSs. This image was observed at room temperature. The BLSs are indicated with white arrows in Fig. 2. The LEED pattern was changed from (2×1) to (1×1) by Ag deposition on the surface. In Fig. 2, Ag atoms were adsorbed on the terrace, however, Ag atoms were hardly adsorbed on BLSs. Therefore we estimate that the sticking coefficient of Ag atoms on the BLS is very low even at room temperature, compared with that on the Si terrace.

When more Ag atoms were deposited on the Si(100) surface with BLSs, we can not find the BLSs in the STM images. The LEED pattern showed (1×1). After annealing this surface, we could observe the BLS again. Figure 3 shows an STM image taken after Ag deposition for 90s on the Si(100) surface with BLSs followed by annealing at 470°C. Though much Ag atoms deposited on the surface covered with the BLS, the BLS reappeared after annealing the surface. We can estimate that Ag atoms on the BLS are preferentially removed in the annealing process. As a reason for this phenomenon, we estimate that the combination of Ag atoms and BLSs are weak because the BLSs are more stable than Si terraces. In this experiment, superstructure of Ag/Si couldn't be observed. Bi atoms of the BLSs are supplied to growing wires from terraces or from sub-layers under the topmost layer. In other words, terraces include not only Si atoms but also Bi atoms. Therefore we estimate that superstructure of Ag/Si cannot be observed. It is necessary to investigate the interaction of atoms except for Ag atoms with BLS to clarify the character of BLS.

4. Conclusions

The consecutive STM observations of Bi-deposited Si(100) surfaces at 400°C revealed the dynamical process of BLS formation. Bi atoms are supplied to growing BLSs from terraces or from sub-layers under the topmost layer. The BLSs are more stable than Si terraces. We investigated the reaction dynamics of the BLS with foreign atoms on Si(100) surfaces. When Ag atoms were deposited on the Si(100) surface with the BLSs, we found that Ag atoms are preferentially adsorbed on the Si terraces compared with BLSs.

Acknowledgments

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Figure Captions

Fig. 1. (a) STM image after Bi deposition at 400°C. (b) STM image observed after annealing the specimen (a) at 400°C for 100s. (c) STM image observed after annealing the specimen (b) at 400°C for 20s. All STM images were taken at sample bias $V_{\mathrm{S}} = +1.7\mathrm{V}$, tunneling current $I = 0.3\mathrm{nA}$, and image area $S = 40\times40\mathrm{nm}^2$.

Fig. 2. STM image taken after Ag deposition for 60s on the Si(100) surface with BLSs. $V_{\mathrm{S}} = -2.0\mathrm{V}$, $I = 0.3\mathrm{nA}$, $S = 80\times80\mathrm{nm}^2$.

Fig. 3. STM image taken after Ag deposition for 90s on the Si(100) surface with BLSs followed by annealing at 470°C. $V_{\mathrm{S}} = -2.0\mathrm{V}$, $I = 0.3\mathrm{nA}$, $S = 80\times80\mathrm{nm}^2$.

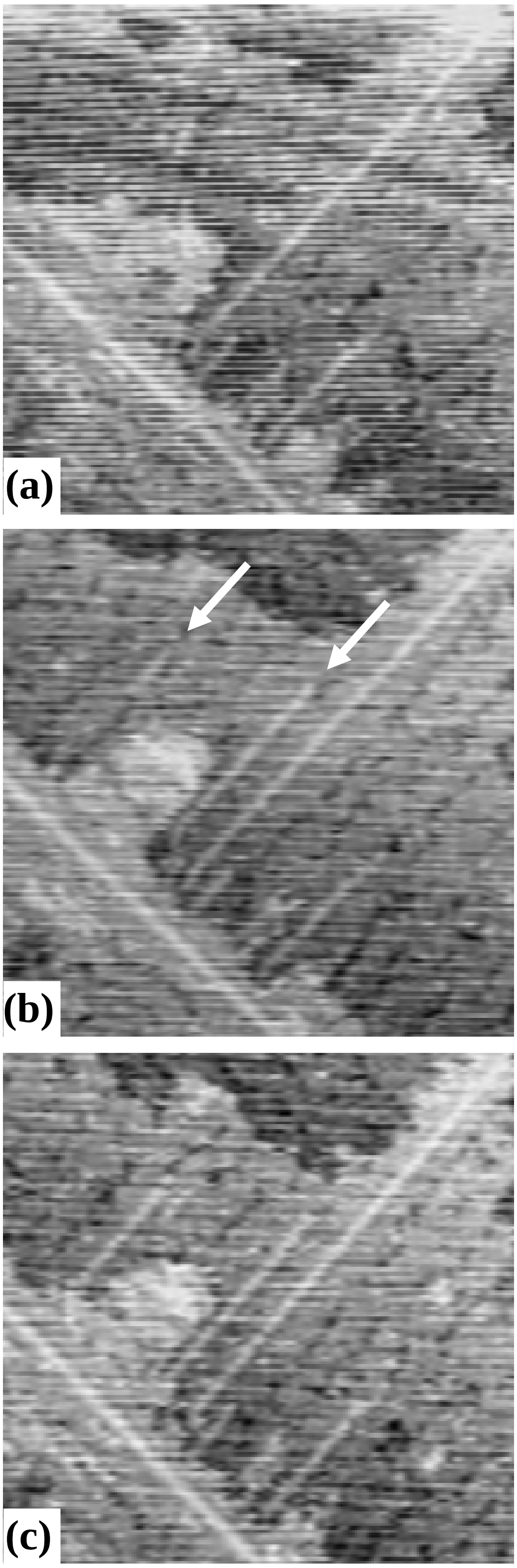

Fig. 1. T. Itoh et al.

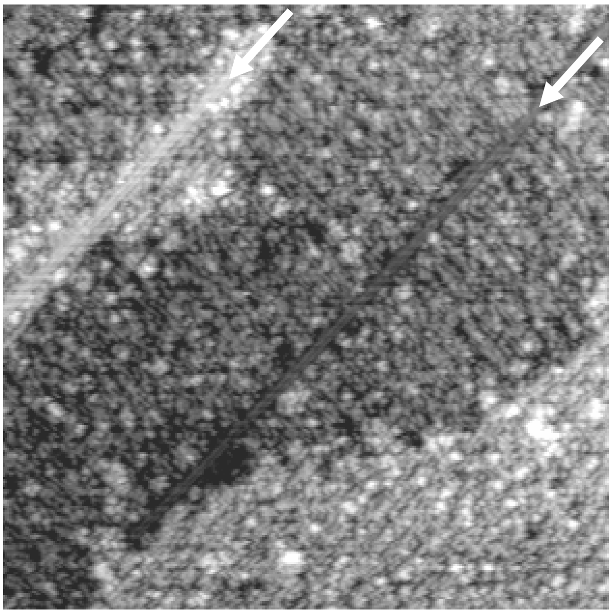

Fig. 2. T. Itoh et al.

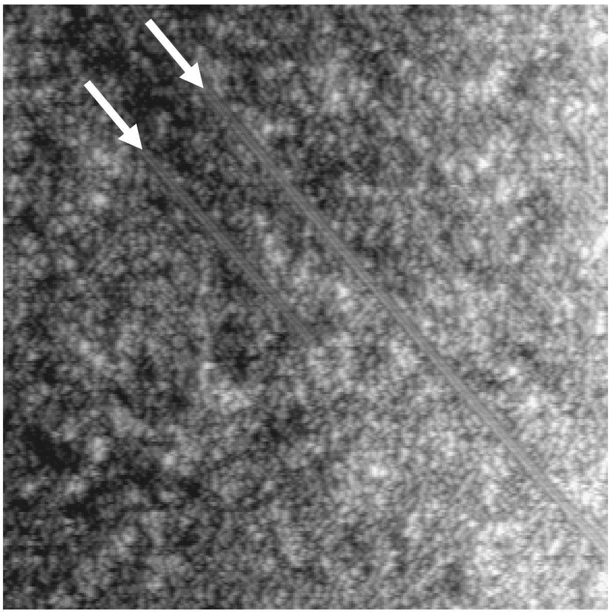

Fig. 3. T. Itoh et al.