Growth Process of Silicon on the Si(111) $\sqrt{3} \times \sqrt{3}$-Ag Surface at Room Temperature

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The growth process of silicon on the Si(111)$\sqrt{3} \times \sqrt{3}$-Ag surface (hereafter $\sqrt{3}$Ag surface) has been studied by scanning tunneling microscopy (STM). Islands of one bilayer thickness with infinite form and triangular geometry are observed for 0.32 ML (ML: 1 ML = $7.8 \times 10^{14}$/cm$^2$) deposition of silicon on the $\sqrt{3}$Ag surface. The orientation of two dimensional islands with triangular geometry is the same as that of unfaulted half unit of the Si(111)$7 \times 7$ structure (hereafter $7 \times 7$ structure). The surface structure of the Si islands is characterized as the $\sqrt{3}$ structure by analysis of STM images of the island. It is believed that Ag atoms segregate on the deposited silicon islands and the island surfaces become the $\sqrt{3}$Ag structure. In comparison with densities of the islands on the $7 \times 7$ and $\sqrt{3}$Ag surfaces, it is concluded that the diffusion coefficient of Si atoms on the $\sqrt{3}$Ag surface is about 60 times larger than that of Si atoms on the $7 \times 7$ surface. The value of the diffusion coefficient is independence on deposition rates. We also discuss a possibility of the Schwoebel effect on the $\sqrt{3}$Ag surface for Si atoms because populations of the islands at step edges of upper terraces are higher than those at lower step edges.

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I. INTRODUCTION

It is considered that there are no dangling bonds on the Si(111)$\sqrt{3} \times \sqrt{3}$-Ag (hereafter $\sqrt{3}$Ag) surface. Therefore it is known that Ag growth on the surface is three dimensional (3D) island growth [1]. For Ag deposition on the $\sqrt{3}$Ag surface at substrate temperature of 150 K, however, the Si(111)$\sqrt{21} \times \sqrt{21}$-Ag structure appears at 0.2 monolayer and subsequently one dimensional islands are formed on the surface [2]. One dimensional islands evolve into 3D islands by annealing to room temperatures. For Au deposition on the $\sqrt{3}$Ag surface at room temperature, the Si(111)$\sqrt{21} \times \sqrt{21}$ structure also appears at 0.14 ML as in the case of Ag [3]. For further deposition of Au on the surface, 2D growth takes place unlike in the case of Ag [4]. It is considered that gold 2D islands are formed on the $\sqrt{3}$Ag surface with layer-by-layer growth, since Si atoms segregate on the Au surface as a surfactant. In other example of the surfactant, it has been reported by Nakahara et al. [5] that Molecular beam epitaxial growth of Si on the Ga-activated Si(111) surface. When Si atoms are deposited on the Si(111)$\sqrt{3} \times \sqrt{3}$-Ga surface (hereafter $\sqrt{3}$Ga surface), Si 2D islands are formed on the $\sqrt{3}$Ga surface. Iwanari et al. [6] have reported surfactant epitaxy of Si on Si(111) mediated by Sn. For Si deposition on the Si(111)$\sqrt{3} \times \sqrt{3}$-Sn($\sqrt{3}$Sn), Si 2D islands are formed on the $\sqrt{3}$Sn surface and step flow occurs. In the case the $\sqrt{3}$Sn structure is formed on the Si 2D islands. They have reported that densities of Si 2D islands at the upper step edges are higher than those at lower step edges. It is possible to be considered that this effect is due to the Schwoebel effect [7, 8]. Ichimiya et al. have reported that the Schwoebel effect is observed for Si diffusion process on the Si(111)$7 \times 7$ surface [9].

It is interested in silicon growth on the $\sqrt{3}$Ag surface how the Si islands are grown on the surface including the Schwoebel effect. In the present work, we study a growth process of Si on the $\sqrt{3}$Ag surface by using an STM.

II. EXPERIMENTAL

Mirror-polished n-type silicon wafers were used as substrates. A P-doped 10 Ω-cm Si(111) wafer was cut into 0.5×2.0×1.5 mm$^3$. Clean silicon surface were obtained by resistively heating above 1200°C in a UHV chamber. After the flashing, Ag was deposited at the substrate temperature of 500°C to form the entire surface to the $\sqrt{3}$Ag structure. Silicon was deposited onto the substrate at the room temperature by evaporating Si atoms from a Si wafer using resistive heating. Pressure during the Ag and Si deposition was $3.0 \times 10^{-8}$ Pa as the same that in the STM chamber. Deposition rates of silicon atoms are determined by coverage, height of silicon islands and deposition time.

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III. RESULTS

Figure 1(a) shows an STM image with the image size of 50×50 nm$^2$ that Si atoms are deposited 0.32 ML on the $\sqrt{3}\text{Ag}$ surface. The deposition rate was $3.12 \times 10^{-1}$/nm$^2\cdot$s. The islands of triangular and infinite forms are observed. As the profile of an island shown in Fig. 1(b) the height of the islands is about 0.3 nm which is the height of one bilayer of Si(111). The Si islands are scattered on the surface and the mean interisland distance is about 5.4 nm which is measured by densities of the islands on the terraces. The orientation of triangular islands is the same as that of unfaaulted half unit of the $7\times7$ structure. Figure 1(c) shows an STM image that Si atoms are deposited 0.14 ML on the $7\times7$ surface. The deposition rate was $2.2 \times 10^{-2}$/nm$^2\cdot$s. By comparing Fig. 1(a) with Fig. 1(c), the density of Si islands on the $7\times7$ surface is higher than that of Si islands on the $\sqrt{3}\text{Ag}$ surface, while the deposition rate for the former case is about 14 times larger than that for the latter case.

Figure 2 shows an STM image with the image size of 100×100 nm$^2$ that Si atoms are deposited 0.96 ML on the $\sqrt{3}\text{Ag}$ surface. The mean interisland distance is about 5.6 nm so that nucleation density on the $\sqrt{3}\text{Ag}$ surface is independent on the amount of Si deposition for the same deposition rate. The Si islands contact but do not coalesce each other. It is considered that periphery diffusion along the islands occurs slowly at the room temperature. Figure 3 shows that density of the Si islands is higher than that at the bottom step edges. It is considered that Si atoms nucleate easily at the upper step edges.

IV. DISCUSSION

Table I shows the incorporation region of Si on the $\sqrt{3}\text{Ag}$ surface and the $7\times7$ surface, measured in the present experiment. The incorporation region, $\lambda^2$, for Si on the surface is smaller than that for Si in the $\sqrt{3}\text{Ag}$ surface. The $\lambda^2$ for 0.96 ML deposition is nearly the same as that for 0.32 ML deposition. When the deposition rate and the substrate temperature are constant, the incorporation region is not changed even if the coverage is changed. Since the region becomes smaller for larger
deposition rate, it is considered that the region for the case of Si growth on the 7×7 surface is smaller than the value in Table I for the same deposition rate of Si growth on the $\sqrt{3}$Ag surface. Similarly Iwanari et al. determined the incorporation region of Si on the $\sqrt{3}$Sn surface and $\sqrt{3}$Ga surface, respectively [6]. These are larger than the incorporation region of Si atoms on the 7×7 surface.

If the critical nucleation is assumed to be due to one atom, a relation between incorporation region, $\lambda^2$, and the diffusion coefficient, $D$, is given by Irisawa-Kuroda theory [10] as

$$\lambda^2 = \left( \frac{D}{J} \right)^{\frac{1}{2}}. \tag{1}$$

Here $J$ is the deposition rate. Values of diffusion coefficients for Si atoms on the 7×7 and $\sqrt{3}$Ag surfaces shown in Table I are about 5 nm$^2$/s and about 3×10$^2$ nm$^2$/s respectively. Therefore the diffusion coefficient on the $\sqrt{3}$Ag is about 60 times larger than that on the 7×7 surface. Since the diffusion coefficient on the $\sqrt{3}$Ag surface does not depend on the deposition rates shown in Table I, it seems that the Irisawa-Kuroda theory is available for the present system.

For Si deposition on the $\sqrt{3}$Ag surface, the $\sqrt{3}$Ag structure is formed on the surface of Si islands. The cohesive energy of Si-Si bonding is larger than that of Si-Ag one, so Si atoms prefer to make bonds with Si atoms rather than with Ag atoms, and Ag atoms segregate on the islands surfaces [11, 12]. Therefore it is believed that the $\sqrt{3}$Ag surface is formed on the Si islands. The $\sqrt{3}$Ag structure is disordered because the mobility of Si and Ag atoms are very low at the room temperatures.

It is expected that nucleation density of islands at the step edges of upper terraces are the same as those of the lower terraces. In the STM images of Fig. 3, however, it is revealed that Si islands are more nucleated at the step edges of the upper terraces than those of lower terraces. There are two possibilities for the effect. One is that nucleation occurs due to many defects at the upper step edges. Another one is due to the Schwoebel effect. In the former case, it is hardly to find defects at the upper step edges in STM images. So it seems that the effect is due to the Schwoebel effect [7, 8]. When the mean potential of the step is assumed to become as shown in Fig. 5, Si atoms at lower terraces go up to the edge while the Si atoms at the upper terraces stop by the barrier of potential in the step. Therefore the growth nuclei are formed at the upper step edges and Si islands are grown there.

Finally, it is expected that the Si 2D islands with triangular geometry prefer the orientation which is rotated by 30 degree for the triangular geometry of 7×7 surface. So it is difficult to understand why the orientation of the islands with triangular geometry is the same as that of unfaulted half unit on the 7×7 surfaces. A possible explanation is that the $\sqrt{3}$ step edges along (112) form zig zag arrangement to ⟨110⟩ direction in average. Similarly, for deposition on the 7×7 surface, In islands form triangular geometry. The orientation is the same for Si deposition on the $\sqrt{3}$Ag surface [13].

|                | $\lambda^2$ [nm$^2$] | $\lambda$ [nm] | $J$ [nm$^2$/s] | $D$ [nm$^2$/s] |
|----------------|-----------------------|----------------|---------------|---------------|
| Si/Si          | 11                    | 3.3            | $2.2 \times 10^{-2}$ | 5.3           |
| Si/Ag/Si (Amount of deposition: 0.32 ML) | 29                    | 5.4            | $3.12 \times 10^{-1}$ | 2.6 $\times 10^{2}$ |
| Si/Ag/Si (Amount of deposition: 0.96 ML) | 31                    | 5.6            | $3.12 \times 10^{-1}$ | 3.0 $\times 10^{2}$ |
| Si/Ag/Si (Amount of deposition: 0.38 ML) | 100                   | 10             | $3.8 \times 10^{-3}$ | 3.0 $\times 10^{2}$ |

V. CONCLUSION

For Si deposition on the $\sqrt{3}$Ag surface, islands of 1 BL thickness with infinite form and triangular geometry are observed. The diffusion coefficient of Si on the $\sqrt{3}$Ag surface is about 60 times that of 7×7 surface at the room temperature. The region is not changed when the coverage is changed with the same deposition rate. The diffusion coefficient analyzed by Irisawa-Kuroda theory is independent on deposition rates. Therefore the theory is
available in the present system. Island densities at the upper step edges are larger than those at the lower step edges. Therefore it is considered that the Schwoebel effect for silicon atoms is occurred at the step. The surface of Si islands has the same periodicity of the $\sqrt{3}$Ag surface. It is believed that the $\sqrt{3}$Ag structure is formed on Si islands. This means that the cohesive energy of Si-Si is larger than that of Si-Ag so that silicon atoms prefer to make bonds with silicon ones rather than with silver atoms.

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