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Mesh Pattern of SPE-Grown Ge Islands on Si(111)

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Mesh patterns of Ge islands are grown on a Si(111) surface by using solid phase epitaxy. Typical experimental conditions for the formation of these mesh patterns are a substrate temperature of about 400°C and a Ge thickness of about 10 Å. The mesh pattern is due to the preferential crystallization of *a*-Ge films at steps and at out-of-phase boundaries of 7x7 reconstructions.

INTRODUCTION

Ge heteroepitaxial growth on a Si surface has been intensively studied, especially because Ge-Si heterostructures show promise for integrating light-emitting devices into Si-integrated circuits. However, due to a large lattice mismatch between Si and Ge, Ge grows on the Si surfaces in the Stranski-Krastanov mode. Ge grows in a layer-by-layer fashion up to only a few monolayers, and then the growth mode changes into island growth. Therefore, much attention has been paid to obtaining uniform Ge-grown layers on Si surfaces. However, controlling Ge islands themselves has not been tried. In this paper, we report on the possibility of controlling Ge island positions on a Si(111) surface by using solid phase epitaxy (SPE).

EXPERIMENTAL

Nominally flat Si(111) surfaces (B-doped, 1-10 Ωcm) were primarily used as the substrates for Ge growth. Vicinal Si(111) samples (B-doped, 1-10 Ωcm), however, were also used to investigate how steps affect Ge SPE growth. Samples were cleaned using the Shiraki method. After cleaning, Si buffer layers with a thickness of about 200 Å were deposited at 600°C to smooth the surface. After annealing at 900°C, the samples were cooled to room temperature (RT) at a typical cooling rate of 2 K/s. The Ge was grown at a rate of 0.1-0.3 Å/s by using an electron gun evaporator. Samples were annealed by radiation from a W filament placed behind the sample, and sample temperatures were measured using a W-WRe thermocouple welded to the sample holder. After sample preparation, the surface morphologies were *ex situ* investigated in real space by using atomic force microscopy (AFM) and transmission electron microscopy (TEM).

RESULTS and DISCUSSION

In reflection high-energy electron diffraction (RHEED) patterns, 7x7 spots from the original Si(111) surface remain after the Ge deposition at RT. This is because the 7x7 reconstruction is preserved at the *a*-Ge/Si interface.[1] When the surface was annealed at about 200°C, diffuse integral-order streaks appeared in the RHEED pattern, indicating *a*-Ge layers had begun to crystallize. The critical thickness for the relaxed island formation t_c was 4 monolayers. RHEED patterns from the 7Å-Ge sample grown using 400°C annealing still include 7x7 spots as well as transmission diffraction spots created in relaxed Ge islands. Ge islands are formed before the interface 7x7 reconstruction is totally destroyed. After 550°C annealing, the 7x7 reconstruction changes to 5x5 reconstruction.

Figure 1 shows an AFM image of the 10Å-

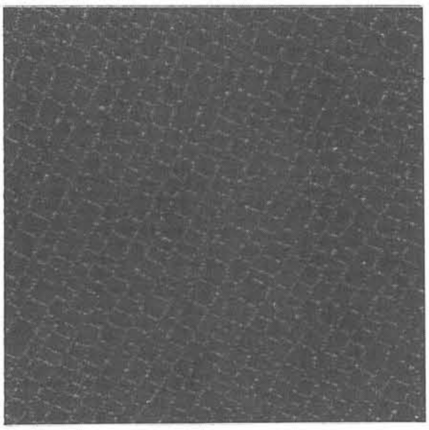

FIG.1. AFM image of SPE-grown Ge/Si(111) with 10-min annealing at 450°C. The Ge thickness is 10 Å. The scanning area is 9000 x 9000 nm.

Ge/Si(111) surfaces grown using 450°C, 10-min annealing. This figure clearly shows that Ge islands are arranged in a mesh pattern. Planar view TEM images also showed that Ge islands with Moiré fringes are arranged in such a mesh pattern. These images indicate that Ge layers do not crystallize uniformly; there are defined positions where Ge layers easily crystallize.

We next examined the conditions needed to obtain this mesh pattern. We investigated the temperature, thickness, and misorientation dependences of island patterns. Figures 2(a)-(c) show AFM images of Ge island patterns grown at 200, 450, and 650°C, respectively. The Ge thickness and annealing time were 10 Å and 10 min. The sample grown at 450°C shows the clearest mesh pattern. Figure 2(a) also shows the mesh pattern, but the island sizes are much smaller than those in Fig. 2(b). This is probably because *a*-Ge films were not perfectly crystallized. On the other hand, Ge islands in Fig. 2(c) are larger than those in Fig. 2(b) and positioned randomly. This is because smaller islands agglomerate into larger ones during annealing (Ostwald ripening).

Figures 3(a)-(c) show AFM images of Ge layers of 7, 12, and 30 Å thick, respectively. The annealing temperature and time were 400°C and 10 min. The 12-Å Ge/Si(111) surface shows the clearest pattern. The mesh pattern does not look clear at smaller thicknesses because the island sizes are varied. On the other hand, because the island density increases as thickness increases, the pattern is buried in Fig. 3(c). On vicinal Si(111) surfaces misoriented 1° to the [11$\bar{2}$] and [$\bar{1}\bar{1}$2] directions, we could not observed such mesh patterns. These investigations show

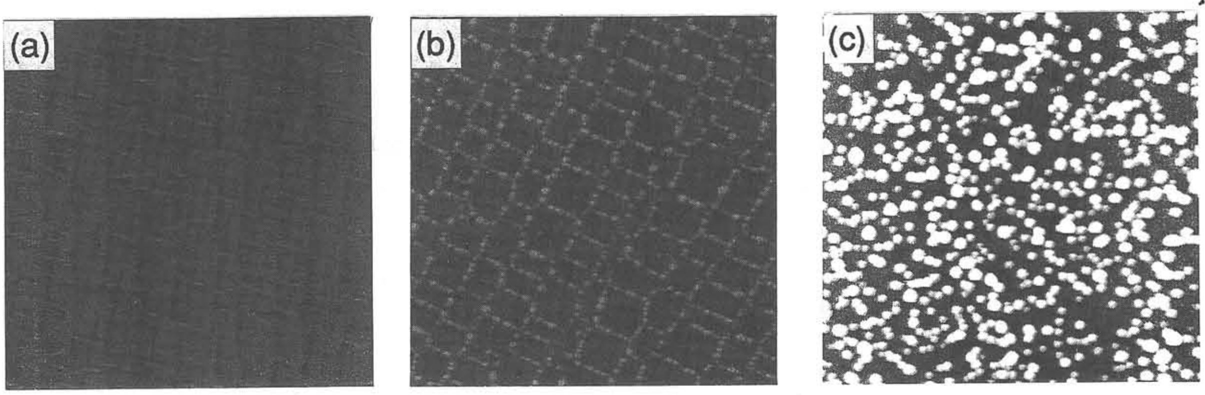

FIG.2. AFM images of SPE-grown 10-Å Ge/Si(111) surfaces. Annealing temperatures were (a) 200°C, (b) 450°C, and (c) 650°C. The annealing time was 10 min and the scanning area is 4500 x 4500 nm.

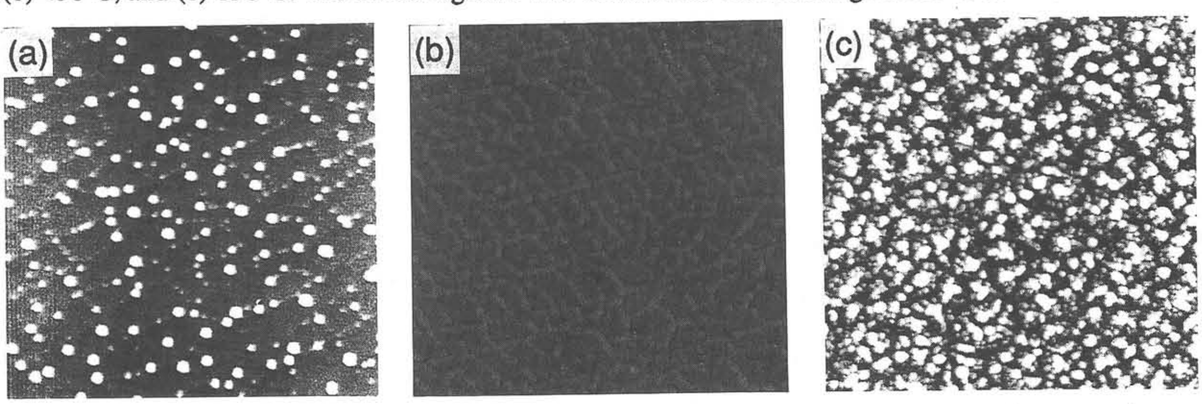

FIG.3. AFM images of SPE-grown Ge/Si(111) surfaces with Ge thicknesses of (a) 7 Å, (b) 12 Å, and (c) 30 Å. The annealing was at 400°C for 10 min and the scanning area is 4500 x 4500 nm.

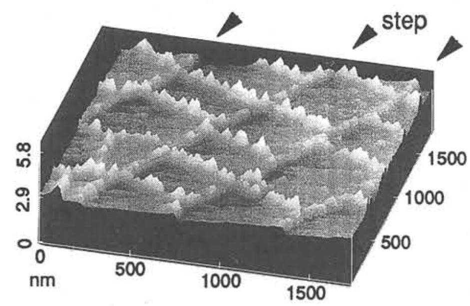

FIG. 4. AFM image of SPE-grown Ge/Si(111) with 1-min annealing at 200°C. The Ge thickness is 10 Å.

that the SPE conditions needed to obtain a mesh pattern are an annealing temperature of about 400°C, a Ge thickness of about 10 Å, and the substrate surface must be nominally flat.

Why are Ge islands arranged in a mesh pattern? An AFM image in the initial stage of SPE shown in Fig. 4 clearly indicates island formation at steps. We speculate that the Ge arrangement normal to steps is caused by island formation at the out-of-phase boundaries (OPB) of the 7x7 reconstruction on the substrate. It has been reported that the OPB crosses the terrace almost normal to the step.[2] STM observation shows that 2-dimensional Ge islands prefer to nucleate on the OPB of a Ge-MBE-grown Si(111) surface.[3] Moreover, Ge islands grown on the substrate quenched from 900°C were roughly arranged probably due to a smaller domain size of the 7x7 reconstruction. These observations support the occurrence of Ge island formations on the OPB.

The mesh pattern formation process is schematically shown in Fig. 5. As shown in Fig. 5(a), during the 1x1-to-7x7 phase transition, the 7x7 reconstruction is nucleated at an upper step edge and grows into a terrace.[4] The growth of the 7x7 reconstruction ends when the 7x7 reconstruction reaches a step or meets a different domain of the 7x7 reconstruction. When the domains are connected out-of-phase, the atomic structures at the step and domain boundary (OPB) are disordered. OPBs that cross the terraces normal to the steps are energetically the most favorable because their lengths are the shortest. Therefore, a mesh pattern is formed by the steps and OPBs, as shown in Fig. 5(b). After *a*-Ge deposition, the 7x7 reconstruction is preserved at the interface [Fig. 5(c)]. The Ge crystallization is initiated at the step and OPB because Ge is incorporated into crystal without destroying the

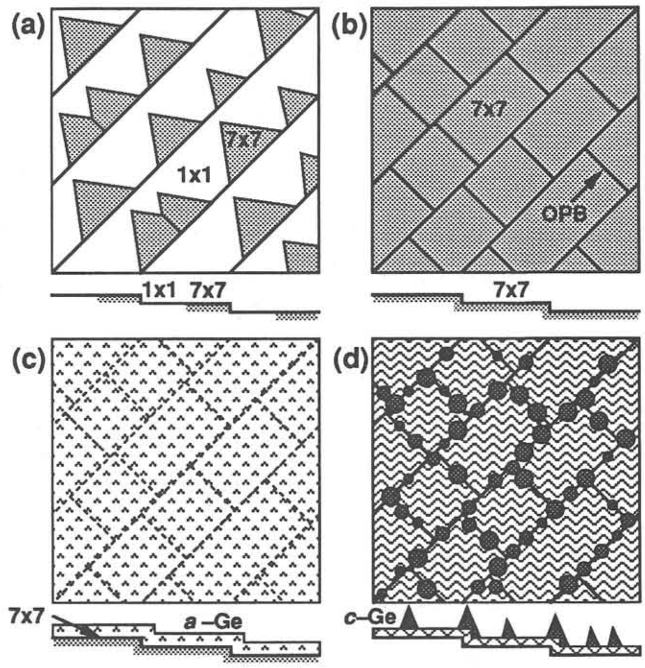

FIG. 5. Schematic views of surface structures. (a) during 1x1-to-7x7 phase transition, (b) after the transition, (c) after *a*-Ge deposition, and (d) after SPE.

7x7 reconstruction. When the Ge layers are thicker than t_c, Ge islands are formed at the position where crystallization is initiated. In this way the Ge islands are arranged in a mesh pattern [Fig. 5(d)].

CONCLUSION

In this paper, we examined mesh pattern formation of SPE-grown-Ge islands on Si(111). Typical conditions are an annealing temperature of about 400°C and a Ge thickness of about 10 Å. The mesh pattern is due to the preferential crystallization of *a*-Ge films on the steps and OPBs of the 7x7 reconstruction. This result shows that we can use Ge islands to decorate the irregularities on the original surface. In other words, we can control the Ge island positions by controlling surface irregularities, enabling the creation of ultra-fine Ge island structures without the aid of lithography.

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