A novel structure in Ge/Si epilayers grown at low temperature

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Abstract

We report the growth of Ge/Si strained layer at low temperature. A new growth mode is observed where ‘groove islands’ are formed beneath the Ge wetting layer. The new structure exhibits an Ge concentration dependent profile along the growth direction. This effect is tentatively attributed to the stress-driven intermixing of Ge/Si during the growth. © 2000 Elsevier Science S.A. All rights reserved.

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1. Introduction

Recently, Ge/Si quantum structures have attracted great attention due to its potential application in the monolithic integration of Si-based optoelectronic devices. As the growth techniques progress, the designed structure has moved from the two-dimensional quantum wells to zero-dimensional quantum dots system [1,2]. This is achieved by depositing a few monolayers of Ge on Si epilayer. The growth mechanism of the islanding has been extensively investigated, focusing on probing the channel for the relaxation of strain energy. With the advanced microscopic technique, such as scanning tunneling probe with atomic resolution (STM), it is found that the islands are energetically favor the formation of the so called ‘hut clusters’ with a side facets of {105} [3–5].

In most of the previous studies of Ge/Si epitaxy, the samples are prepared at high temperatures ranging between 500 to 750°C. In this paper, we report a new growth mode observed in samples grown at very low growth temperature. In contrast to the conventional Stranski–Krastanow self-organized growth mode (SK mode) where 3D Ge hut clusters develop at the top of a thin wetting layer [1,6], the new structure, as observed by the cross-sectional transmission electron microscope image (TEM), is formed beneath the flat Ge layer. It has a shape of a groove with its apex pointing toward the wafer (hereafter called ‘groove islands’). The structure exhibits a Ge concentration dependent profile along the growth direction as analyzed by an energy-disper-

sive X-ray microanalysis (EDS). Thus, it provides an unambiguous experimental evidence of intermixing in the Ge/Si heterostructure.

2. Samples and experiments

The samples were grown by molecular beam epitaxy (MBE) at a base pressure of 5×10^{-11} Torr using e-gun. N-type Si(001) substrates were used with a resistivity of 4.5 Ω cm. Substrates were initially cleaned using the standard procedure: the Si(001) surface was then prepared by desorbing the thin oxide layer at high temperature of 1100°C. Si and Ge are deposited at a growth rate of 2 and 0.5 Å/s, respectively. For the growth of each sample, it consist of four stages: (a) a thick Si buffer layer of 500 nm grown at 450°C (b) a thin Ge layer (c) a Si layer of 150 nm grown at 450°C (d) 19 periods of Ge/Si quantum dots. The nominal thickness is 4/16 nm. On the top, a thin capping layer of Si is deposited. Three samples N1, N2 and N3 were grown with different temperatures of procedure (d). It were grown at 250, 300 and 350°C. Prior to the deposition of each Ge layer, the Si surface exhibits a clear 2×1 reflection high-energy electron diffraction pattern (RHEED), indicating the surface was smooth. Microscopic analysis of TEM image and EDS were taken along the [011] direction. The probe beam diameter is about 15 Å.

3. Results and discussions

A typical cross-sectional transmission electron micro-

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Fig. 1. A cross-sectional TEM image of sample N1 grown at 300°C showing the novel ‘groove islands’ structure that formed beneath the wetting layers are marked by the two solid arrows.

scope image (TEM) is presented in Fig. 1. In the figure, the regions of dark contrast correspond to the thin Ge, while light contrast regions correspond to the Si spacer layer. It shows the layer structures as described above. Since we are interested in the quantum structure, we will focus on the layer structure of (d). The 19 periods of the Ge/Si heterostructure exhibit two characteristics: Firstly, a thin layer of Ge is clearly seen as marked by the dashed arrow (wetting layers). From the TEM image, the thickness is estimated to be 40 Å. Secondly, a series of groove islands is observed as marked by the solid arrows. These structures were developed along the growth direction [001] and formed beneath the wetting layer. A schematic diagram of the islands is depicted in the inset of Fig. 1. The average height of the groove is about 90 Å. This is far thicker than the wetting layer, suggesting a mixing between Ge and Si has occurred during the growth. EDS measurement is employed to analyze the composition of Ge inside the groove. The spectrum, probing at the center of the groove, is presented in Fig. 2. It shows that Si is the dominant specimen. By integrating the emitted signal, it yields a Ge composition of about 6.3%.

As has been well established, the epitaxy of Ge on Si(100) exhibits an SK growth mode with compressive strain presented in the Ge layer. (The lattice mismatch between the two materials is about 4%) Above a certain thickness, the strained 2D Ge wetting layer evolves into 3D islands by introducing either misfit dislocation or elastic

deformation to reduce the free energy of the epilayer [1,7]. The critical thickness of the 2D–3D transition is inversely proportional to the growth temperature, due to the reduction of surface thermal diffusivity of the deposited atom. The surface diffusivity of a deposited atom depends exponentially on temperature. In comparison with the conventional high temperature growth, the diffusion length of Ge atom at low temperature is considerably smaller. (see for example Ref. [8]). As a result, island formation is kinetically delayed or frozen out. For the Ge/Si system, it is about 10^{-3} monolayers at the temperature range of 500–750°C [9–11]. (one monolayer is 1.4 Å) For the sample growth in this study, the thickness of the wetting layers is far above the critical thickness, and therefore the formation of islands is expected. However, this is not observed suggesting a suppression of the conventional SK growth mode at low temperature. As shown by the EDS analysis described above, the groove islands show a characteristic of intermixing. In view of the large number of experiments, the discussion of intermixing is limited to the top few monolayers of the Ge/Si surface. Based on the observation of a change in the periodicity of the surface reconstruction pattern, the intermixing has been reported by Voigtlander et al. [12]. The effect of intermixing is to reduce the strain misfit at the interface, thus providing an effective channel for relieving the strain energy. With increasing Ge coverage, the strain energy of the 2D film increases. To relax the energy, as the diffusivity

Fig. 2. An EDS spectrum probing at the center of the groove island.

of the Ge atom is kinetically suppressed, this drives the Ge further into the Si layer forming a groove, leading to the observation reported here.

4. Conclusions

In conclusion, we have shown that the SK growth mode is effectively suppressed in Ge/Si heteroepilayers at very low temperatures. Intermixing is the dominant channel for strain relaxation. This leads to the observation of a new growth mode where groove islands are formed beneath the Ge wetting layer. A plausible explanation of the growth mechanism is proposed.

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