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Gas-Source Molecular Beam Epitaxial Growth of Crescent-Shaped SiGe Quantum Wire Arrays on a V-Groove Patterned Si Substrate

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We report the successful fabrication of crescent-shaped SiGe quantum wire (QWR) arrays on a V-groove patterned Si (100) substrate with Si (111) facets, and on a sawtooth patterned Si substrate by gas-source Si molecular beam epitaxy. Excellent crescent-shaped SiGe quantum wire arrays were evidenced by cross sectional transmission electron microscopy (TEM). Selective epitaxial growth (SEG) technique with SiO_2 mask layer was also found to be applicable to the QWR fabrication. Photoluminescence (PL) spectra indicated the existence of quantized states associated with QWR.

1. Introduction

High quality heterointerfaces are thought to be a requirement for observing novel optical properties of quantum wire (QWR) based upon the quantum confinement effect. Hence, realization of semiconductor quantum wire (QWR) arrays by utilizing growth alone has attracted great interest since it is free from damage, and high quality heterointerfaces are expected to be obtained. Recently, Kapon *et al.* reported the successful fabrication of QWR arrays on a V-groove patterned GaAs substrate by metal-organic chemical vapor deposition (MOCVD) where they clearly showed the existence of quantized states related with QWR at the bottom of the groove by cathode luminescence (CL)[1]. Tsukamoto *et al.* utilized the selective growth technique in MOCVD for GaAs "arrowhead-shaped" QWR[2]. As seen in these reports, there has been great progress in the *in-situ* fabrication of QWR in GaAs/AlGaAs system[3)-5)]. However, to the best of our knowledge, *in situ* fabrication of SiGe/Si QWR has not been achieved yet.

We report the first successful fabrication of SiGe/Si QWR arrays on a V-groove patterned Si substrate, and a sawtooth (W-groove) patterned Si substrate using gas-source Si molecular beam epitaxy (GS-SiMBE). Anisotropy of growth rate on the different crystallographic orientation in GS-SiMBE made it possible to obtain a crescent shaped SiGe layer, the profile of which was clarified by transmission electron microscopy (TEM) cross-sectional imaging. Selective growth technique (SEG) was also applied to the *in-situ* fabrication of QWR. Photoluminescence (PL) of the SiGe QWR is also reported.

2. Experimental

The starting material is nominally on-axis p-type Si (001) wafer with resistivity of 5-10 Ωcm. On this wafer, a 1350Å SiO_2 film is deposited by thermal oxidation technique. Subsequently, by using a standard electron beam (EB) lithography technique, line-and-space patterns along the [110] direction with period of 0.6-4.0 μm are generated. For the V-groove pattern formation, the substrate is dipped in N_2H_4-based solution after removing resist. In the case of a W-groove patterned Si substrate, Si_3N_4 is deposited by low pressure chemical vapor deposition (LPCVD) on the corrugated SiO_2. Combination of anisotropic dry etching and dipping in HF leaves narrow Si_3N_4 with width of about 50Å, which acts as a mask for chemical etching in N_2H_4-based solution. Figure 1 shows cross sectional scanning electron microscopy (SEM) image of (a) V-groove and (b) W-groove patterned Si substrate. As shown in this figure, two kinds of patterned Si substrates are reproducibly obtained by this lithography processing. We can expect SiGe quantum wire structures by transferring substrate geometry during MBE growth. For this purpose, epitaxial growth was performed in a purpose-built GS-SiMBE (Daido Hoxan VCE S2020) system using disilane (Si_2H_6) and germane (GeH_4) as gaseous sources. The detail of the system has already been reported elsewhere[6]. Photoluminescence (PL) spectra was measured in standard lock-in configuration and detected by a liquid-nitrogen-cooled Ge photodetector. Excitation was supplied by an Ar ion laser.

3. Growth of QWR

A good Si buffer layer without losing the substrate geometry is essential to the realization of QWR. For this purpose, one should understand the growth kinetics in GS-SiMBE. It is well known that there is an anisotropy of growth rate (GR) along the different substrate orientation in GS-SiMBE, which depends on the growth temperature[7]. With increasing growth temperature, anisotropic factor which is defined by GR_{111}/GR_{100} decreases. Therefore, low temperature growth is favored to maintain the substrate geometry. On the other hand, PL efficiency strongly depends on the growth temperature[8], and a high growth temperature environment is desirable. In order to satisfy these two claims, we selected the growth temperature of 740 °C and a thin buffer layer less than 300Å.

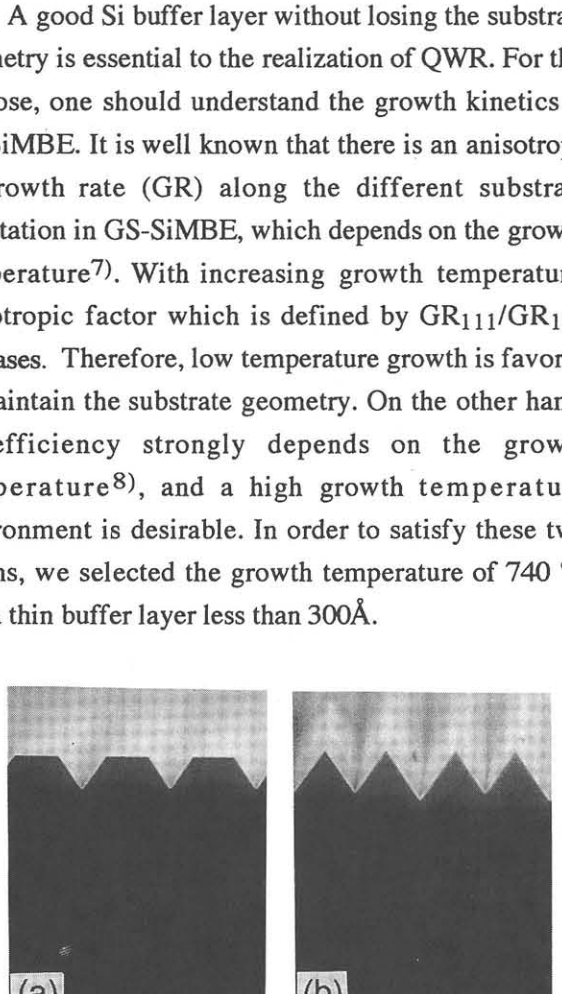

Fig.1 Cross sectional SEM image of (a) V-groove and (b) W-groove patterned Si substrate.

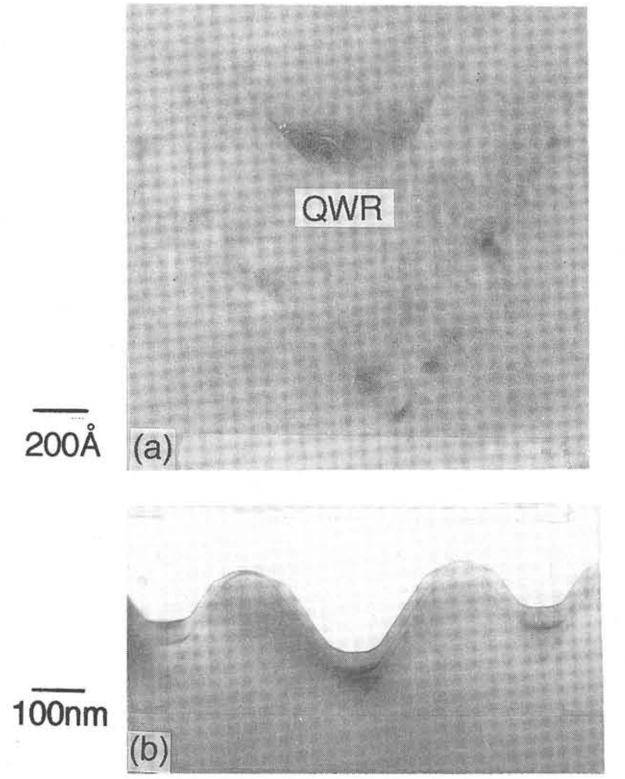

Fig.2 Cross sectional TEM image of SiGe QWR grown on (a) V-groove and (b) W-groove patterned Si substrate.

Figure 2 (a) shows cross-sectional transmission electron microscopy (TEM) image of $Si/Si_{0.82}Ge_{0.18}/Si$ heterostructures grown on a V-groove patterned Si substrate. The V-shape dark line delineates the interface between the substrate and the buffer layer. At the bottom of the groove, we can clearly observe a crescent-shaped SiGe QWR with vertical and lateral dimension of less than 150Å. Since the QWR was fabricated by utilizing the growth alone and free from subsequent etching, no processing damage is induced and an excellent quality of crystallinity is likely to be established.

Epitaxial QWR growth on a W-groove patterned Si substrate was also carried out. In this case, the QWR formation is expected at the top and the bottom of the groove. Hence, we can increase the density of the QWR. Figure2 (b) shows cross-sectional TEM image of a SiGe QWR grown on a W-groove patterned Si substrate. Against the prediction, the QWR was only formed at the bottom of the groove. Interestingly, Si (311) facet formation occurred at the top of the groove.

4. Photoluminescence

Photoluminescence (PL) measurement was carried out for $Si/Si_{0.82}Ge_{0.18}/Si$ heterostructures grown on a V-groove patterned Si substrate. The thickness of the SiGe layer is nominally 32.4Å for Si (100) flat region. No phonon (NP) transition and its transverse optical (TO) phonon replica can be clearly identified from standard quantum wells (Note that our samples contain ordinary SiGe/Si quantum well structures formed over Si (100) flat region between neighboring grooves.) as shown in Fig.3 (a). However, we can hardly identify the emission from the QWR due to the strong emission from the standard quantum well.

In order to form only QWR at the bottom of the groove, SEG was utilized. In this case, the SiO_2 layer between the neighboring grooves was not removed before the growth. Figure3 (b) shows PL spectra of the QWR grown by SEG under the same growth conditions of the sample of Fig.3 (a). Interestingly, a pair of peaks can be found with higher emission energy than that of the standard quantum well. Since the energy separation (58meV) between the two peaks is in good agreement with Si-Si TO phonon energy, we can understand that the newly found peaks are NP and its TO phonon replica which come from the quantized state formed in the QWR.

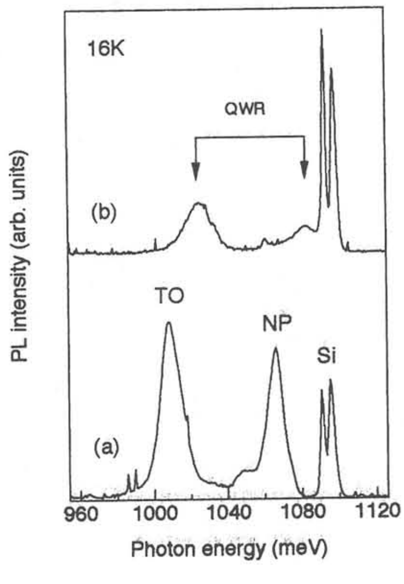

Fig.3 PL spectra of SiGe QWR grown (a) on a V-groove patterned Si substrate and (b) using SEG.

5. Summary

In summary, we succeeded in growing SiGe/Si QWR arrays on a V-groove patterned Si substrate by GS-SiMBE. Excellent crescent shaped SiGe layer was evidenced by TEM cross sectional image. Anisotropy of growth rate on the different orientation in GS-SiMBE made it possible to form the crescent shaped SiGe layer. The existence of quantized state in QWR was evidenced by photoluminescence measurement of the QWR formed by selective epitaxial growth.

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