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Uniformity of epilayer grown by ultrahigh-vacuum chemical vapor deposition

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Abstract

In this work, we explored the Ge fraction, layer thickness and dopant concentration uniformity of epilayers grown by an ultrahigh-vacuum chemical vapor deposition system (UHV/CVD). Three epilayers were grown for this study: a single epilayer of SiGe, a heavily boron doped Si epilayer and a Si/SiGe superlattice with p^+ Si cap. The uniformity in a wafer was measured to be less than $\pm 1.5\%$. In addition, we explored the wafer-to-wafer uniformity of a strained SiGe layer. The variations in thickness and composition between two samples grown in the same run were evaluated to be ± 1.3 and $\pm 1.2\%$, respectively. These results show that uniform layers can be simultaneously obtained on many wafers by the UHV/CVD system.

Keywords: Epilayers; Ultrahigh-vacuum chemical vapor deposition system; Uniformity

1. Introduction

In recent years, research into the growth of strained-layer superlattices (SLS) has greatly stimulated the development of heteroepitaxy, because of its possible applications in bandgap engineering. The $Si/Si_{1-x}Ge_x$ heterostructure has been studied extensively and new devices based on this material system have been proposed and fabricated [1–7].

For advanced Si/SiGe device fabrication, a low-temperature process is desirable for minimizing problems associated with lattice mismatch and interdiffusion. The UHV/CVD system is an important technique for low-temperature growth of Si and SiGe epitaxial layers. A particular advantage of this growth technique is the fact that uniform layers can be obtained on many wafers simultaneously. As a result, the growth technique is readily usable in manufacturing. Other alternative techniques for SiGe growth, such as molecular beam epitaxy (MBE), limited reaction process (LRP), or atmospheric pressure epitaxy, are usually performed in single wafer reactors. Recently, Greve et al. have investigated the uniformity of SiGe epitaxial layers grown by UHV/CVD [8]. However, only the uniformity of SiGe epilayer was studied in their work. In this work, we study the Ge fraction, layer thickness and dopant concentration uniformity of epilayers grown by the UHV/CVD system. These epilayers include a single epilayer of SiGe, a heavily boron doped Si epilayer and a Si/SiGe superlattice with p^+ Si cap.

2. Experimental

Three samples were grown on 3-in., (001) Si substrates using a home-made hot-wall multiwafer UHV/CVD system for this study. They are a single epilayer of

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SiGe, a heavily boron doped Si epilayer and a Si/SiGe superlattice with p^+ Si cap. In this work, the growth temperature was kept constant at 550 °C. Prior to the growth, the substrate was subjected to an H_2SO_4:$H_2O_2 = 3{:}1$ clean and a 10% HF dip. Silane (SiH_4) and 10% germane (GeH_4) in hydrogen were used as reactant gases. In addition, 1% diborane (B_2H_6) in hydrogen was used as the p-type dopant gas. The base pressure of the system was maintained at about 2×10^{-8} torr in the growth chamber. During growth, the system was operated at about 1.0 mtorr. Layer uniformity was evaluated by high-resolution double-crystal X-ray (HRXRD). Variations in the layer composition were found by collecting rocking curves from several locations spaced between the wafer edge ($r = 38$ mm) and the wafer center ($r = 0$ mm). Data was collected in four arcsec steps, with a count time of 18 s per step. The structural parameters were determined from a comparison between the experimental rocking curve and the simulated one.

3. Results and discussion

Fig. 1 shows the HRXRD (004) rocking curves obtained from several locations in the 370 nm thick $Si_{0.875}Ge_{0.126}$ epilayer. Nearly identical rocking curves were obtained, indicating good in-wafer uniformity in thickness and Ge fraction. In the full-strained SiGe case, the Ge composition x is directly related to the peak splitting $\Delta\theta$ by

$$x = \Delta\theta / 10480 \tag{1}$$

where $\Delta\theta$ is expressed in arcsec. Thickness (t) was determined using the period of intensity oscillations (Pendellösung fringes) between the layer and substrate peaks (see Eq. (2)):

$$t = \lambda \sin\theta_B / \Delta\theta \sin 2\theta_B \tag{2}$$

where θ_B is the Bragg's angle of Si (004).

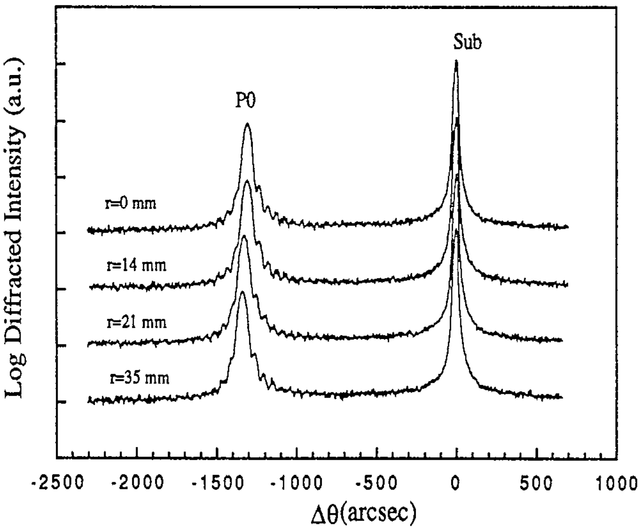

Fig. 1. The HRXRD (004) rocking curves obtained from several locations of in about 370 nm thick $Si_{0.875}Ge_{0.126}$ epilayer.

The variation in Ge composition versus distance from the center of the wafer, r, is presented in Fig. 2. The variation in Ge fraction is within ±1.5%. In this SiGe sample, no thickness variations were observed within the experimental error (±9 nm).

In order to study the uniformity of the dopant concentration, a 250 nm thick Si–B epilayer with a boron concentration of 8.1×10^{19} cm^{-3} was used. Fig. 3 shows the HRXRD (004) rocking curves obtained from several locations of this heavily boron-doped Si epilayer. Similarly, nearly identical rocking curves are obtained, indicating good in-wafer uniformity in thickness and boron

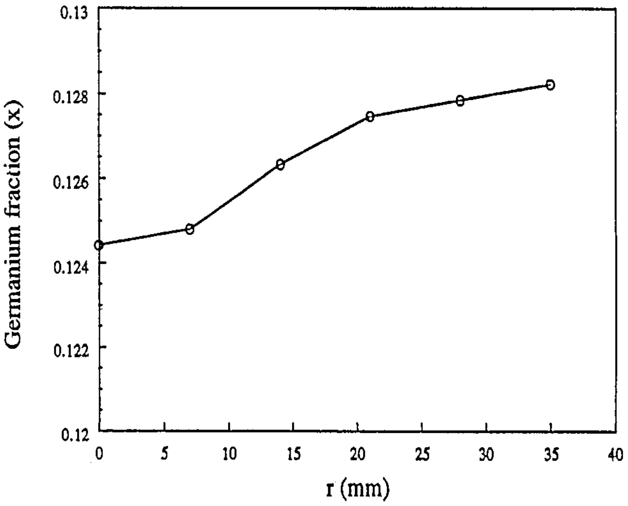

Fig. 2. The variation in Ge composition versus distance from the center of the wafer (r).

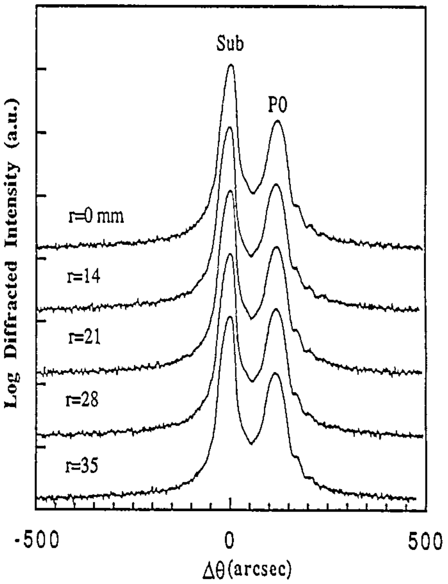

Fig. 3. The HRXRD (004) rocking curves obtained from several locations of a heavily boron-doped Si epilayer.

concentration. In a lightly doped epilayer, the distortion of the lattice constant by the incorporation of a dopant is negligible. However, the incorporation of a dopant can strongly distort the lattice in a heavily doped epilayer [9,10]. In Fig. 3, peak Sub and peak P0 represent the reflection of substrate and Si–B epilayer, respectively. Since the lattice constant of Si–B is smaller than that of Si–Si, the peak P0 appears on the high angle side of the substrate peak Sub. The boron concentration can be determined by the angle separation between peak P0 and peak Sub. The variation in boron concentration versus distance from the center of the wafer, *r*, is demonstrated in Fig. 4. The variation in boron concentration is about ±1.6%. The variation in boron concentration is a little higher than that in the Ge fraction. However, such observed variations were within the experimental error (±9 nm).

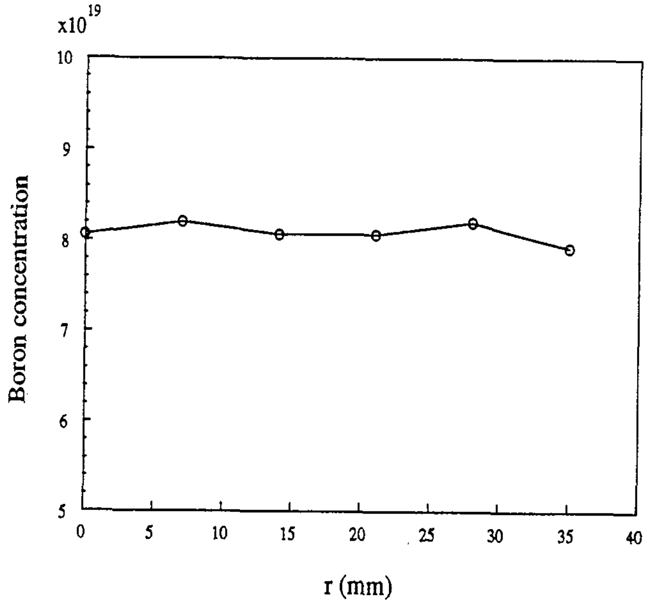

Fig. 4. The variation in boron concentration vs. distance from the center of the wafer (*r*).

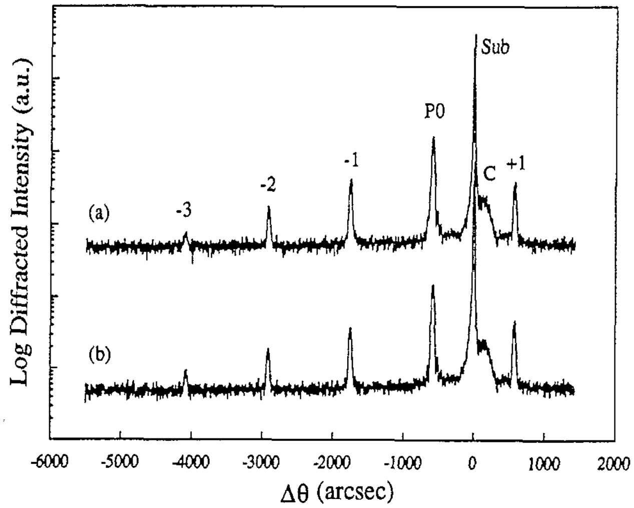

Fig. 5. (a) The HRXRD (004) rocking curves obtained from a Si/SiGe SLS of 20 periods with Si-12 nm, SiGe-5.1 nm, 17.7% Ge, and boron doped Si cap layer ($N = 1.12 \times 10^{20}\,\mathrm{cm}^{-3}$)-96 nm; (b) simulated rocking curve.

Fig. 5(a) shows the HRXRD (004) rocking curves obtained from a Si/SiGe superlattice of 20 periods with Si-12 nm, SiGe-5.1 nm, 17.7% Ge, and boron doped Si cap layer ($N = 1.12 \times 10^{20}\,\mathrm{cm}^{-3}$)-96 nm. In this figure, peak Sub represents the Si substrate reflection, peak P0 the zeroth-order superlattice reflection, and the other main peaks are satellite peaks (−3, −2, −1, +1) resulting from the periodicity of the superlattice. In addition, a broad peak labeled peak C on the right side of the substrate resulted from the p$^+$ Si cap, which is used to form an ohmic contact for the devices. Fig. 5(b) shows the simulated rocking curve for this $\mathrm{Si}_{1-x}\mathrm{Ge}_x$/Si superlattice. In this simulated rocking curve, we have considered the effect of diffused scattering from the first crystal and substrate [11]. As compared to Fig. 5(a), excellent matches between experiment and simulation in terms of peak position, peak intensity, and full width at half maximum (FWHM) of each main peak are clearly observed. Therefore, we can conclude that strained Si/SiGe superlattice with excellent interfaces and crystalline quality could be achieved by UHV/CVD [12–14].

Fig. 6 shows the HRXRD (004) rocking curves obtained from several locations of this Si/SiGe superlattice. Fig. 7 and Fig. 8 show the variations in average Ge

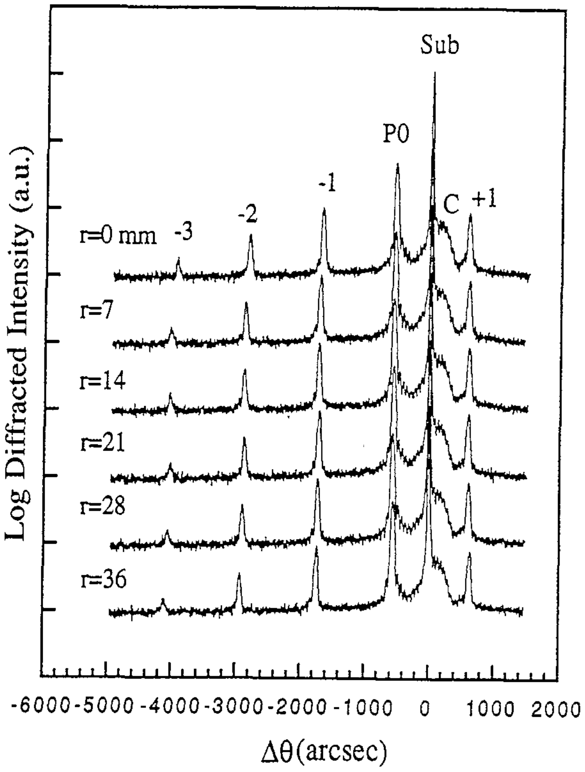

Fig. 6. The HRXRD (004) rocking curves obtained from several locations of a Si/SiGe SLS of 20 periods with Si-12 nm, SiGe-5.1 nm, 17.7% Ge, and boron doped Si cap layer ($N = 1.12 \times 10^{20}\,\mathrm{cm}^{-3}$)-96 nm.

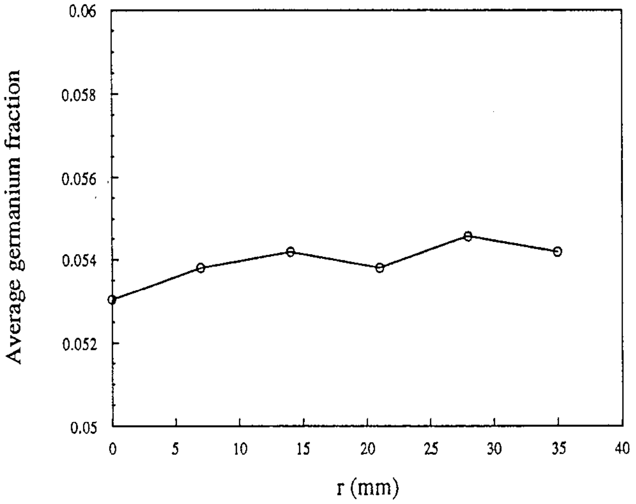

Fig. 7. The variation in average Ge fraction of strained Si/SiGe superlattices.

fraction and thickness of period of these superlattices, respectively. The average Ge fraction of SLS can be determined directly from Eq. (1). The thickness of period (T) can also directly be determined from Eq. (3).

$$2(\sin\theta_n - \sin\theta_0) \times T = n\lambda \qquad (3)$$

where n is the order of the satellite peak, T the periodicity of the superlattice, θ_n and θ_0 the diffraction angles of nth-order and zeroth-order satellite peaks, respectively, and λ the wavelength of the incident X-ray. The variations in the average Ge fraction and periodicity of the SLS are ±1.4 and ±2%, respectively.

Finally, we explored the wafer-to-wafer uniformity of strained SiGe layers grown by UHV/CVD. Two strained SiGe epitaxial layers, about 380 nm thick and with 0.125 Ge composition, were grown on two different Si wafers in the same run. Fig. 9(a) and (b) shows the HRXRD rocking curves obtained from the center position of these two samples. Nearly identical rocking curves were observed. The structural parameters were determined form a comparison between the experimental rocking curve and the simulated one. The variation in composition between these two samples was evaluated to be ±1.2%. This result shows that uniform layers can be obtained simultaneously on many wafers by the UHV/CVD technique. As a result, the UHV/CVD technique is readily usable in manufacturing.

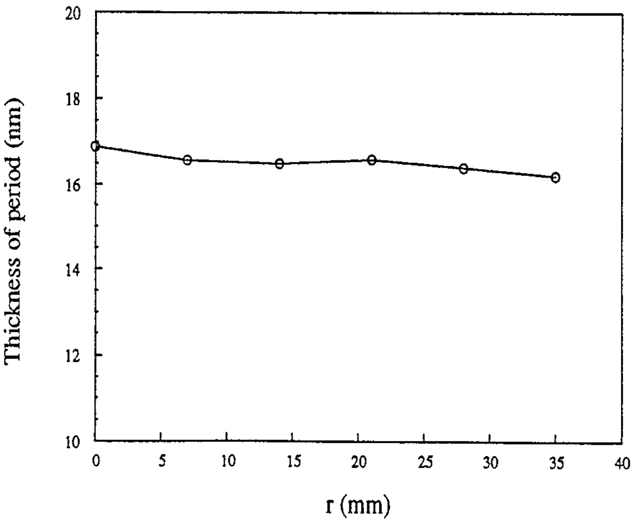

Fig. 8. The variation in thickness of period of strained Si/SiGe superlattices.

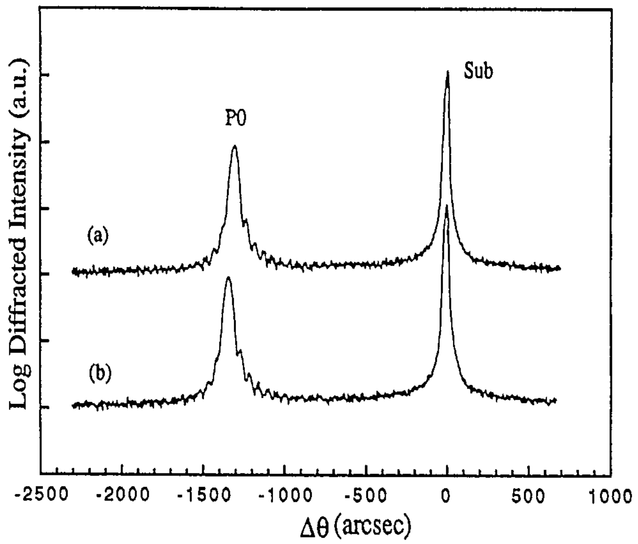

Fig. 9. HRXRD rocking curves for two strained SiGe epitaxial layers, labelled as (a) and (b), grown on two different Si wafers during the same run.

4. Conclusions

In this work, we explored the Ge fraction, layer thickness and dopant concentration uniformity of epilayers grown by an ultrahigh-vacuum chemical vapor deposition system (UHV/CVD). Three epilayers were grown for this study: a single epilayer of SiGe, a heavily boron doped Si epilayer and Si/SiGe superlattices with p^+ Si cap. The uniformity in a wafer was measured to be less than ±1.5%. In addition, we explored the wafer-to-wafer uniformity of the strained SiGe layer. The variations in thickness and composition between two samples grown during the same run were evaluated to be ±1.3 and ±1.2%, respectively. This result shows that uniform layers can be obtained simultaneously on many wafers by the UHV/CVD system.

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