High-quality homoepitaxial layers grown on 4H-SiC at a high growth rate by vertical LPCVD*

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Abstract: High quality, homoepitaxial layers of 4H-SiC were grown on off-oriented 4H-SiC (0001) Si planes in a vertical low-pressure hot-wall CVD system (LPCVD) by using trichlorosilane (TCS) as a silicon precursor source together with ethylene (C_2H_4) as a carbon precursor source. The growth rate of 25–30 μm/h has been achieved at lower temperatures between 1500 and 1530 ℃. The surface roughness and crystalline quality of 50 μm thick epitaxial layers (grown for 2 h) did not deteriorate compared with the corresponding results of thinner layers (grown for 30 min). The background doping concentration was reduced to 2.13×10^{15} cm^{-3}. The effect of the C/Si ratio in the gas phase on growth rate and quality of the epi-layers was investigated.

Key words: 4H-SiC; homoepitaxial growth; vertical hot wall CVD; crystal morphology
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1. Introduction

Silicon carbide (SiC) is a promising material for high-power and high-frequency devices, due to its superior characteristics, such as wide bandgap, high breakdown field and high thermal conductivity[1]. In the past few years, various SiC based electronic devices, like SBD, PIN and MPS, have been reported in Refs. [2–4]. Throughout the fabrication process of these SiC devices, thick SiC epitaxial layers with low background doping are required. In order to grow thick SiC layers cost effectively, high growth rates are desirable[5]. The simplest way to obtain a high growth rate is to increase the source amounts[6], which often results in several problems, such as poor quality of crystallization and deterioration of surface roughness. In order to avoid this kind of problem, the C/Si ratio, Si/H ratio, operational parameters, etc. need to be optimized.

In general, homoepitaxial growth is carried out by chemical vapor deposition (CVD) at around 1500–1600 ℃ utilizing step-controlled epitaxy and a typical growth rate of 2–6 μm/h[7]. Over the past few years, vertical hot-wall CVD reactors have achieved growth rates of up to 50–70 μm/h with growth temperatures between 1700 and 1800 ℃[8]. The addition of HCl to the conventional gas system or the use of a Cl-containing precursor has been reported to achieve the suppression of Si-cluster formation and high growth rates. Very high growth rates of >100 μm/h at 1600 ℃ are reported with the use of HCl, $SiHCl_3$ and CH_3SiCl_3[9].

In this paper, we employ a vertical, low pressure, hot-wall CVD reactor which can accommodate up to 4-inch diameter wafers. We have developed an optimized epitaxial growth process in vertical LPCVD system. The epitaxial growth rate is up to 30 μm/h at 1530 ℃, which is close to the highest growth rate with the comparable growth temperature. This paper shows the results of growing very thick 4H-SiC epilayers at a high growth rate and discusses the epitaxial surface morphology and crystalline quality based on an analysis of electrical and structural properties of the films.

2. Experiments

Epitaxial growth was performed in a vertical, low pressure, hot-wall CVD reactor with downward H_2 carrier gas flow (as shown in Fig. 1). The susceptor, made of graphite with a SiC coating, is inductively heated using RF power. This susceptor has the capacity for holding three 2-inch wafers and it can rotate during the epitaxy process at a controllable rotation speed. The growth temperature is measured by an infrared pyrometer.

The substrates were commercially available 2-inch, 8° off-axis, Si-face 4H-SiC purchased from Tianke. The pressure for all runs was 40 Torr. We used trichlorosilane (TCS) as a silicon precursor source together with ethylene (C_2H_4) as a carbon precursor source. Hydrogen (H_2), purified in a palladium diffusion cell was used as the carrier gas. The growth temperature ranged from 1500 to 1530 ℃.

The surface morphologies, thickness, crystalline quality and doping concentration of 4H-SiC epilayers were characterized by atomic force microscopy (AFM), X-ray diffraction, Raman scattering spectroscopy (RSS) and C–V measurement, respectively.

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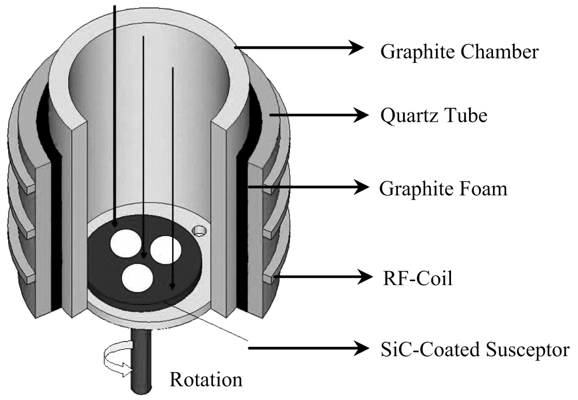

Fig. 1. Schematic diagram of the epi-reactor.

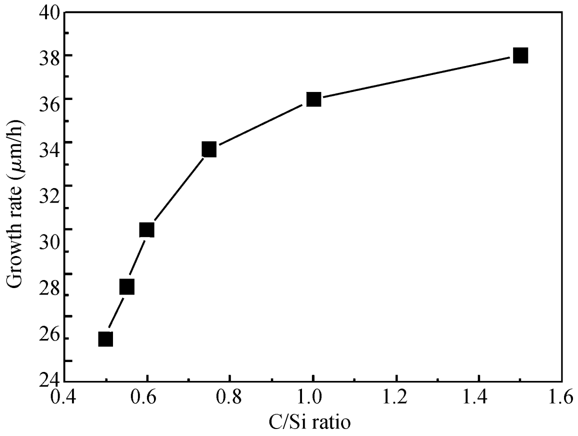

Fig. 2. C/Si ratio dependence of growth rate in vertical LPCVD of 4H-SiC (0001).

3. Results and discussion

3.1. Growth rate

In this reactor, growth rates strongly depend on the C/Si ratio, as shown in Fig. 2. The growth rate increases followed by the C/Si ratio increasing, as suggested by Fujiwara *et al.*[10]. At a C/Si ratio of 0.5, excellent surface morphology with a low density of defects was obtained. With a further increase in the C/Si ratio, the quality of the epilayer began to deteriorate and the density of triangular defects and carrot defects increased. When the C/Si ratio increased to 1, inclusions of 3C-SiC were observed in large area of epilayers. So the optimized C/Si ratio is 0.5. The thickness of 4H-SiC epilayers can be determined from a cross-sectional view of cleaved 4H-SiC samples with a scanning electron microscope. As shown in Fig. 3(a), the growth rate is up to 25 μm/h at 1500 ℃. In Fig. 3(b), an SEM cross section of an epitaxial layer with a thickness of 50 μm is shown. The growth rate of 30 μm/h can be obtained when the growth temperature reaches 1530 ℃ (Fig. 3(c)). The net donor concentration of the epilayer which was grown for 30 min is 8.45×10^{15} cm^{-3}, as shown in Fig. 4. With the growth time up to 2 h, the net donor concentration was reduced to 2.13×10^{15} cm^{-3}. One of the reasons for this phenomenon is considered to be a baking effect. Residual nitrogen in the reactor is removed during a CVD run, and therefore the incorporation of N gradually decreases with increasing growth time.

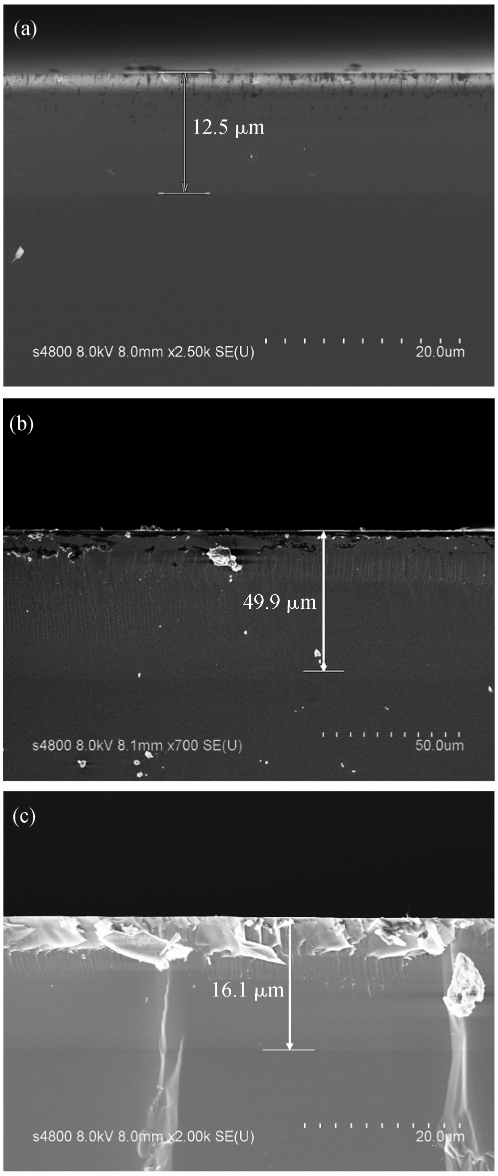

Fig. 3. Cross-sectional SEM micrographs of the three samples grown for (a) 30 min, (b) 2 h and (c) 30 min at 1530 ℃.

3.2. Surface morphology

Maintaining allowable roughness and low density of growth pits is expected for thick epitaxial growth[11]. All of the epilayers (C/Si ratio: 0.5 to 0.8) are mirror-like in Nomarski microscopy observation. Figure 5 presents the AFM results of the epilayers which were grown at a rate of 25 μm/h (C/Si ratio: 0.5) for various times, producing film thicknesses between 12 and 50 μm. The thick epilayer grown for 2 h obtained a RMS roughness of 1.29 nm, while the thin epilayer grown for 30 min had an RMS value of 1.26 nm. These experimental results indicated that the surface roughness does not deteriorate with the growing time.

3.3. Crystalline quality

To measure the structural quality of the 4H-SiC films, X-ray diffraction and Raman scattering spectroscopy of the epitaxial layers were used. Figure 6 shows a typical XRD wide

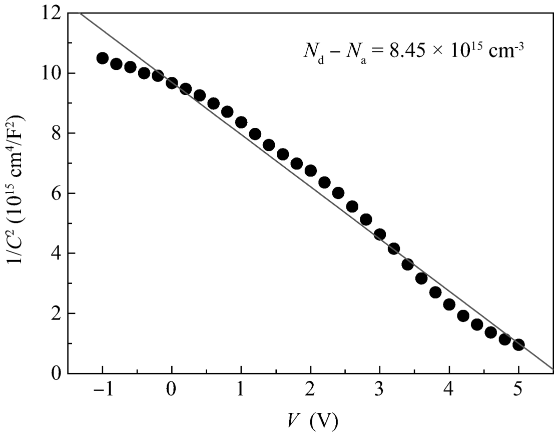

Fig. 4. C–V characteristic of 4H-SiC epilayer grown for 30 min.

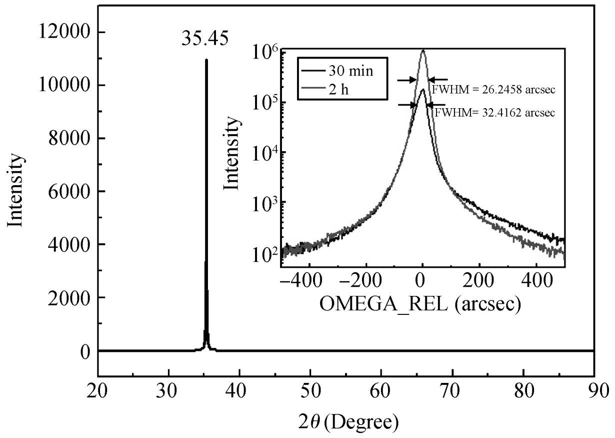

Fig. 6. XRD diffraction pattern between 20°– 90° of 4H-SiC epilayer. Inset shows the rocking curves.

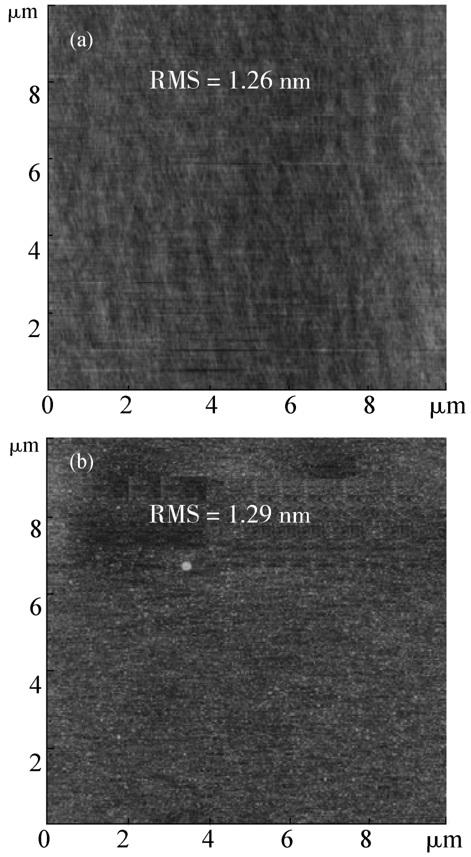

Fig. 5. AFM micrographs of the sample grown for (a) 30 min obtained an RMS roughness of 1.26 nm, and the one grown for (b) 2 h yielded a result of 1.29 nm.

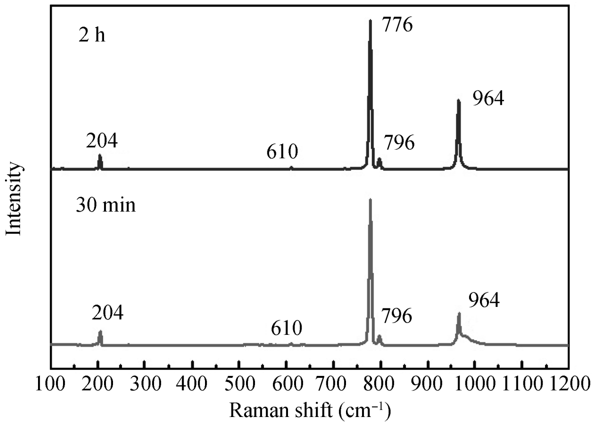

Fig. 7. Raman spectra of the epitaxial layers grown for 30 min and 2 h.

scan between 20°– 90° for an epilayer. A strong peak at 35.45° with a full width at half maximum of 0.14° is due to diffraction from the (0004) planes of 4H-SiC. No other feature is evident besides the (0004) patterns, thus indicating good 4H-SiC crystalline structure. Rocking curves at the [0004] refection peak of the epitiaxial layers which were grown for 2 h and 30 min were obtained from high resolution X-ray diffraction techniques. As shown in the inset of Fig. 6, the FWHM of these curves are 26.2 arcsec and 32.4 arcsec, respectively. The FWHM of the substrate is 35 arcsec. This suggests that the crystallinity of the epilayer is better than the substrate. And with the growing time increasing, the crystallinity of the epilayer became better. Raman scattering spectroscopy is a powerful tool to characterize SiC non-destructively. Figure 7 shows the Raman spectrum of the epitaxial layers grown for 30 min and 2 h obtained at room temperature in the back-scattering configuration. Typical Raman peaks of 4H-SiC polytype at 204 (TA, E_2), 610 (LA, A_1), 776 (TO, E_2), 796 (TO, E_1), and 964 (LO, A_1) cm^{-1} corresponding to the reasonably well-ordered 4H-SiC (with in 0.5 cm^{-1}) are observed, as described in Ref. [12]. These results confirm further that the thick 4H-SiC epilayers can be grown successfully on the off-orientation 4H-SiC substrates with high crystal quality.

4. Conclusions

A vertical LPCVD system was developed by the authors' group. An optimized epitaxial growth process was demonstrated, which produced epilayers with mirror-like morphology at a high growth rate of up to 30 μm/h (25 μm/h in typical) in this vertical LPCVD. We succeeded in growing a thick epilayer (50 μm) with a small RMS of 1.29. Results of X-ray diffraction and Raman scattering indicate that 4H-SiC can be homoepitaxially grown on off-oriented substrates, and high quality 4H-

SiC epilayers were obtained. Low background doping at low 10^{15} cm^{-3} was achieved.

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