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Study of spiral growth on 4H-silicon carbide on-axis substrates

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ABSTRACT

We grew epitaxial layers on on-axis carbon-face 4H-silicon carbide substrates and investigated the growth conditions for the generation of spiral growth. We discovered that spiral growth occurs in regions where the local off-angle is less than 0.05° and when the spiral hillocks have a tilt angle of 0.06°. Moreover, we found that each spiral hillock coalesced without causing dislocation in the areas where the spiral growth occurred. Our results indicate that spiral growth is dominant when the spiral hillocks have a tilt angle greater than the off-angle of the substrate. Step-flow growth is overcome by spiral growth because the rate of spiral growth is greater than that of step-flow growth.

1. Introduction

Power devices are necessary to control various high-voltage components efficiently. Silicon carbide (SiC) allows high-efficiency, high-temperature operation, and the miniaturization of power devices because of its physical properties such as a wide bandgap and high thermal conductivity. Consequently, SiC power devices are widely used, and SiC unipolar power devices such as Schottky barrier diodes and metal-oxide-semiconductor-field-effect-transistors (MOSFETs) are commercially available for use, for example, in air-conditioning equipment and as train components.

Currently, SiC epitaxial growth has been achieved by using step-flow growth on 4° off-angle substrates to enhance the polytype stability [1,2], but there are some problems caused by the off-angle. The development of trench MOSFETs leads to increase in the current density of normal MOSFETs. However, it has been reported that the anisotropic channel properties on the trench sidewalls, such as the channel mobility and threshold voltage, are caused by the large off-angle of 4° [3]. Reducing the off-angle is effective in suppressing the anisotropic properties [3]. Moreover, SiC bipolar power devices such as PiN diodes and insulated gate bipolar transistors (IGBTs), which can control ultra-high-voltages, are expected to be achieved. However, it has been reported that the generation of stacking faults, which originate from basal plane dislocations (BPDs) in epitaxial layers, results in the degradation of bipolar device performance in the forward voltage direction [4]. Consequently, the number of BPDs in the epitaxial layers must be reduced to achieve PiN diodes and IGBTs. There are no BPDs in epitaxial layers grown on on-axis substrates because BPDs in the substrate cannot propagate to the epitaxial layers. In fact, it has been reported that the formation of stacking faults originating from BPDs was not observed for PiN diodes fabricated on on-axis SiC substrates [5]. Thus, epitaxial growth on on-axis SiC substrates eliminates the problems of trench MOSFETs, PiN diodes, and IGBTs.

Several groups have reported SiC epitaxial growth on on-axis substrates [6–12]. Leone et al. studied the on-axis silicon-face (Si-face) and carbon-face (C-face) epitaxial growth of 6H- and 4H-SiC [6–8]. On-axis substrates have different off-angles. Leone et al. reported that spiral growth was the dominant mechanism when the off-angle was less than 0.15°, and both step-flow growth and spiral growth occurred when the off-angle was 0.15–0.5° for Si-face growth [6–8]. In addition, they reported that the morphology was characterized by very smooth polygonized islands regardless of the off-angle for C-face growth, even though the off-angle was less than 0.15° [8]. In this past report, the growth temperature was significantly high and the C/Si ratio was very low compared to common SiC chemical vapor deposition (CVD) process [8]. Hassan et al. studied the on-axis Si-face 4H-SiC epitaxial growth [9]. They reported that spiral growth is dominant in areas with an almost perfectly on-axis surface orientation [9]. In addition, Kojima et al. reported that the growth mechanism was step-flow growth when a C-face 4H-SiC substrate with the off-angle of 0.3° was used [10]. Thus, in on-axis Si-face epitaxial growth, spiral growth occurs when the off-angle is almost perfectly on-axis, for example, less than 0.15°, but the reason for this boundary value is unknown. On the other hand, spiral growth has not been observed regardless of the off-angle in on-axis C-face epitaxial growth.

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In this study, we carried out the epitaxial growth on on-axis 4H-SiC substrates to investigate the growth conditions for the occurrence of spiral growth and to characterize the spiral growth using X-ray topography. Moreover, we discuss the important factors leading to spiral growth.

2. Experimental procedure

Homoepitaxial layers were grown on commercially available 3 inch on-axis 4H-SiC substrates after chemical mechanical polishing. We used C-face because spiral growth has not been observed in the past. A close-spaced vertically blown CVD system, where substrates were oriented perpendicular to the gas flow, was used [13]. H_2 was used as the carrier gas, and SiH_4 and C_3H_8 were used as the precursors. In situ H_2 etching and the epitaxial growth were carried out at 1570°C and 2.7 kPa. The in situ H_2 etching time was 15 min. The epitaxial layers were grown for 3 h at a growth rate of about 15 μm/h. The thicknesses were about 45 μm. The H_2 flow rate was 20 slm. The SiH_4 and C_3H_8 flow rates were 30 sccm and 10 sccm, respectively, for the growth procedure. We used the relatively high C/Si ratio of 1.0 for growth on on-axis substrates to obtain low background carrier concentrations. The background carrier concentrations calculated by capacitance-voltage measurements were about 1×10^{14} cm^{-3}.

The slight off-angles of the on-axis substrates were calculated by measuring the step heights and terrace widths using tapping mode atomic force microscopy (AFM). The surface morphologies of the epitaxial layers were observed using Nomarski optical microscopy and AFM. The polytype of the epitaxial layers was determined by photoluminescence (PL) spectroscopy at 325 nm using He-Cd laser excitation at room temperature. Reflection X-ray topography measurements were performed to investigate the spiral growth area using synchrotron X-rays of the 11-2-8 reflection at the beam line BL 15 of the SAGA Light Source with the approval of the Kyusyu Synchrotron Light Research Center.

3. Results

3.1. Epitaxial growth on on-axis C-face 4H-SiC substrates

The local small off-angles of the on-axis C-face substrates were measured by AFM after chemical mechanical polishing. Fig. 1(a) and (b) show an example of the AFM images, and a cross-sectional profile of the bar labeled b after the flattening procedure, respectively. The three red[1] arrows show the positions of the steps in these figures. Fig. 1(b) shows that the step height shown by the red vertical solid line is 0.25 nm, which corresponds to the single Si-C bilayer height, and the terrace width shown by the blue horizontal dashed line is about 360 nm. The local off-angle θ is defined by Eq. (1).

$$\theta = Tan^{-1}(h/\lambda), \tag{1}$$

where h is the step height and λ is the terrace width. The local off-angle of this area was calculated to be about 0.04°.

Fig. 2 shows AFM images and local off-angles of two 3 inch on-axis substrates. These off-angles were obtained by the same method as above. Nine points were measured per substrate, and the measurement interval was 2 cm. The wafer depicted in the left of Fig. 2 has off-angles of 0.02–0.14°, whereas that on the right has off-angles of 0.01–0.03°. Thus, on-axis substrates have different local off-angles. We grew epitaxial layers on these wafers and found that there were two different growth modes depending on the local off-angles. Fig. 3(a) shows a Nomarski optical microscopic image of the epitaxial layer grown on the region that is surrounded by a red solid line in Fig. 2, where the local off-angle is 0.01–0.05°. Many spiral hillocks and a defect can be seen in Fig. 3(a). Some spiral hillocks are indicated by arrows and the defect is surrounded by a red dashed line. We found that spiral growth is dominant in this area even though the defect generated. We describe the area where many spiral hillocks generated as spiral growth area. Fig. 3(b) and (c) show the PL spectra of the spiral growth area and the defect, respectively. The spiral growth area luminesces at 390 nm, which corresponds to the luminescence of 4H-SiC [14,15], thus confirming that the polytype of the spiral growth area is 4H. The luminescence at about 500–600 nm arises from impurities in the substrate, which was confirmed by measuring the PL spectrum of the substrates. Fig. 3(c) shows that the defect is a 3C inclusion because the luminescence emission occurred at 540 nm, which corresponds to the luminescence of 3C-SiC [14–16]. Fig. 4(a) shows a Nomarski optical microscopic image of the epitaxial layer grown on the area that is surrounded by a blue dashed line in Fig. 2, where the local off-angle is 0.06–0.14°. The layer has a polycrystalline structure. Fig. 4(b) shows the PL spectrum of the layer. It luminesces at 540 nm, which correspond to the luminescence of 3C, indicating that a 3C-SiC layer had grown in the area where the local off-angle is 0.06–0.14°. The 3C-SiC growth, such as the 3C inclusion in Fig. 3(a) and the 3C-SiC layer in Fig. 4(a), was spontaneously generated. It has been reported that two-dimensional nucleation occurs because of high supersaturation on the substrate surface when large terraced regions exist, and the polytype of the nucleus is determined mainly by the growth temperature [1]. This leads to 3C-SiC growth because 3C-SiC is stable during CVD growth performed at 1500–1700 °C [1,17]. Therefore, it is thought that 3C inclusions, which are attributed to 3C-SiC nucleation, are induced by the wide terraces of the spiral hillocks in the spiral growth area shown in Fig. 3(a). In the 3C-SiC layer area shown in Fig. 4(a), step-flow growth and step bunching might occur, which would generate wide terraces. Consequently, the 3C-SiC layer growth would occur because of 3C-SiC nucleation. In this area, the 3C-SiC nucleation density was higher than that in the spiral growth area. It is thought that step-flow growth generated wider terraces because of step bunching in contrast to the spiral growth area where each spiral hillock coalesces before step bunching occurs. It has been reported that HCl addition is needed to elude 3C-SiC nucleation in on-axis growth [6]. HCl suppresses the generation of the 3C inclusion and the 3C-SiC layers.

As described above, 4H-SiC spiral growth occurred when the off-angle was less than 0.05° in growth on the C-face on-axis substrates. Thus, we found that spiral growth occurs in some conditions in C-face on-axis growth, as is the case with Si-face on-axis growth.

3.2. Investigation of the spiral growth area

As indicated in Section 3.1, spiral growth occurred when the off-angle was less than 0.05°. We investigated the structure of a spiral hillock to discuss the growth conditions for spiral growth. Moreover, the dislocation distribution in the spiral growth area was measured by reflection X-ray topography to investigate the crystalline quality.

Fig. 5(a) and (b) show AFM image of a spiral hillock around its top and the cross-sectional profile of the bar labeled b after the flattening procedure, respectively. This figure indicates that the step height shown by red vertical solid line is 0.5 nm, which corresponds to half one unit cell of 4H-SiC, and the terrace width shown by blue horizontal dashed line is about 450 nm. Therefore, the spiral hillock has a tilt angle of about 0.06°. This tilt angle value is con-

[1] For interpretation of color in Fig. 1 and 6, the reader is referred to the web version of this article.