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Formation of epitaxial defects by threading screw dislocations with a morphological feature at the surface of 4° off-axis 4H-SiC substrates

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Abstract. In this paper, we present the formation of extended epitaxial defects, such as carrot defects, from threading screw dislocations (TSDs) with a morphological feature at the surface of the substrates. It was confirmed using highly sensitive surface observation, atomic force microscopy (AFM) and KOH etching that the surface roughness around a TSD was observed as the morphological feature and TSDs with such a morphological feature formed extended epitaxial defects with high frequency of appearance compared to usual TSDs without any features. The density of TSDs with such morphological feature depended on the polishing methods. Furthermore, we observed that the formation and shapes of extended defects from TSDs with such morphological feature were affected by step-bunching at the surface of the epilayers.

Introduction

Silicon carbide (SiC) power devices are regarded as key components of high-voltage and low-loss power conversion equipment. Epitaxial growth by "step-controlled epitaxy" on off-axis substrates is an essential technique in SiC device fabrication [1]. It is important for high-power applications to reduce the number of large epitaxial defects, such as triangular defects and carrot/comet defects, which act as device-killer defects [2]. Recently, it has been reported that triangular defect density can be reduced to less than 1 cm^{-2} via epitaxial growth with the addition of HCl [3]. However, further reduction of these large epitaxial defects is required in order for SiC devices to handle higher power densities. In this paper, we describe the formation of extended epitaxial defects, such as carrot defects, from threading screw dislocations (TSDs) with a morphological feature at the surface of the substrates. Atomic force microscopy (AFM) was used to confirm the shape of the morphological feature. Using an advanced microscope with a stage controller, the positions of the TSDs with a morphological feature at the substrate surface were mapped, and the positions were compared to the starting positions of the extended defects after epitaxial growth. The frequency of the appearance of the extended defects from the TSDs with a morphological feature was compared to that from usual TSDs without any features. Furthermore, the influence of step-bunching of the epilayers was studied on the appearance and shapes of the extended defects.

Experimental

Epitaxial growth was carried out in an inductively heated hot-wall reactor. The growth was conducted at a pressure of 1×10^{3}–1×10^{4} Pa and a temperature of 1550–1600 °C. The C/Si ratios were 0.5–1.0, and the growth rate was ~5 μm/h. The substrates used in this study were 4-inch, 4° off-axis, Si-face 4H-SiC wafers. The epilayers obtained were analyzed by Fourier transform infrared spectroscopy (FTIR) for the thickness and by mercury probe C-V measurements for the doping concentration. The thickness and doping concentration of the epilayers was ~10 μm and ~1×10^{16} cm^{-3}, respectively. Highly sensitive observation of surface morphologies, such as pits and bumps, was performed with high precision to determine their positions on the wafers. An area of 10 μm×10 μm was evaluated using atomic force microscopy (AFM). Etching of the substrates and epilayers was carried out with molten KOH to reveal any dislocations.

Results and Discussion

TSDs with a morphological feature. The white arrow in Fig. 1(a) indicates the observed morphological feature at the surface of the substrate, and Fig. 1(b) shows an image of the KOH-etched substrate in the same area as seen in Fig. 1(a). The etch pit of the TSD can be seen in Fig. 1(b), and its position corresponds to that of the morphological feature in Fig. 1(a). The same type of morphological feature as in Fig. 1(a) is shown by the black arrow in Fig. 2(a), and Fig. 2(b) shows, as an example of extended defects, a carrot defect that appears at the morphological feature in Fig. 2(a) after epitaxial growth. Figure 2(c) shows the etch pits after KOH etching of the carrot defect in Fig. 2(b). From Figs. 2(a)-(c), it was confirmed that a TSD with the morphological feature formed a carrot defect in the same way as a usual TSD without any features at the substrate surface [4-6]. AFM measurements were carried out to confirm the shape of this morphological feature and an example of AFM images is indicated in Fig. 3, which shows that the shape is concave and has the size of 0.5−1 μm in both length and width, with a depth of ~100 nm. From further AFM measurements, the surface roughness around a TSD, especially a surface pit, is considered responsible for this morphological feature.

Frequency of the appearance of extended epitaxial defects from TSDs. We then compared the frequency of the appearance of extended epitaxial defects from TSDs with the morphological feature to that from usual TSDs without any features which are generally observed in our substrates. The results are summarized in Table 1 where it can be seen that TSDs with the morphological feature formed extended epitaxial defects with a much higher frequency than usual TSDs. The density of TSDs with a morphological feature was 5−10 cm^{-2} in this study. Taking into account that the density of usual TSDs is 500−1000 cm^{-2}, TSDs with a morphological feature can form extended

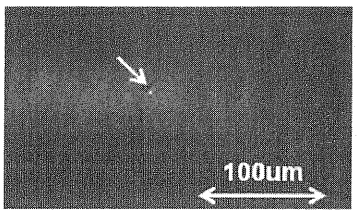

Fig. 1(a)

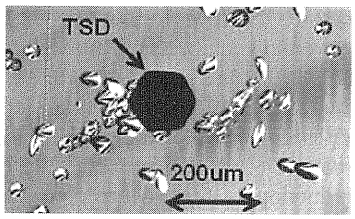

Fig. 1(b)

Fig. 1 Optical images of (a) the observed morphological feature at the surface of a substrate, and (b) the KOH-etched substrate in the same area as (a).

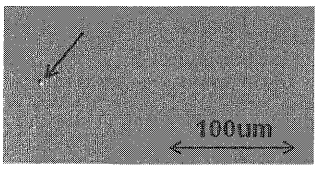

Fig. 2(a)

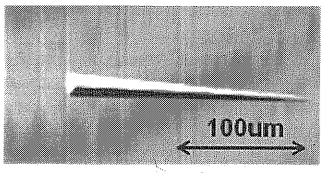

Fig. 2(b)

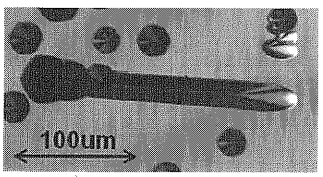

Fig. 2(c)

Fig. 2 Optical images of (a) the same type of morphological feature as that in Fig. 1(a), (b) a carrot defect that appeared at the position of the morphological feature after epitaxial growth, and (c) etch pits after KOH etching of the carrot defect in (b).

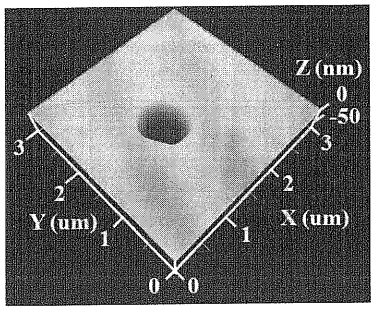

Fig. 3 An example of AFM images of the morphological feature around a TSD of a substrate.

epitaxial defects on the same level as usual TSDs. This means that the density of the extended defects increases because of the existence of TSDs with a morphological feature. It is considered that the morphological feature is caused by surface polishing, especially chemical-mechanical polishing (CMP), at TSD sites. Several types of CMP methods of a CMP manufacturer were compared based on the density of TSDs with a morphological feature, and the results are listed in Table 2. It can be seen that the density varied from less than 1 cm^{-2} to over 50 cm^{-2} depending on the CMP method, which demonstrates that CMP causes the morphological feature. The density sometimes varied in a single processing lot even when an identical method was used. Therefore, high quality and stability of CMP is necessary to obtain smooth surfaces of the substrates and a low density of extended defects after epitaxial growth.

Table 1 Comparison of the frequency of the appearance of extended epitaxial defects from TSDs with and without a morphological feature.

	From TSDs with morphological feature	From usual TSDs without any features
Frequency of the appearance of extended epitaxial defects (%)	~80	< ~1

Table 2 Variation of the density of TSDs with morphological feature depending on the CMP methods.

	Method A	Method B	Method C
Density of TSDs with morphological feature (cm^{-2})	< 1	5–10	> 50

Extended epitaxial defects and step-bunching. With respect to the data in Table 1, 27 sites where TSDs existed with the morphological feature were checked, and it was confirmed that extended defects appeared in 21 sites. At the 6 sites that did not form extended defects, we observed step-bunching after epitaxial growth. The white arrow in Fig. 4(a) shows the morphological feature at one of the 6 sites, and Fig. 4(b) shows the surface morphology after epitaxial growth in the same area. The dotted circle corresponds to the position of the morphological feature. Figure 4(c) is an image of etch pits after KOH etching in the area shown in Fig. 4(b). Figures 4(a)-4(c) point out that a TSD with the morphological feature cannot generate extended defects after epitaxial growth when step-bunching occurs at the surface. In some cases, extended epitaxial defects from TSDs with such morphological feature had indistinct shapes at the occurrence of step-bunching. The results mean that the condition of step-flow growth is related to the formation and shapes of extended epitaxial defects from TSDs.

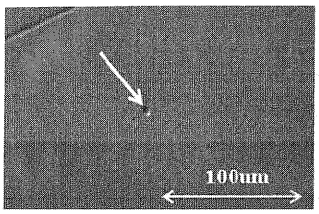

Fig. 4(a)

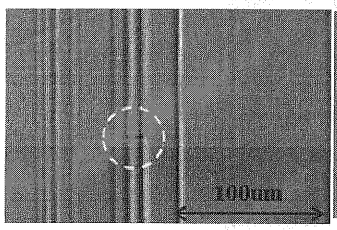

Fig. 4(b)

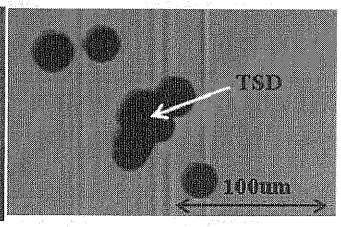

Fig. 4(c)

Fig. 4 Optical images of (a) the same type of morphological feature as that in Fig. 1(a) and Fig. 2(a), (b) surface morphology after epitaxial growth, and (c) etch pits after KOH etching. (b) and (c) are the same area as that shown in (a). A dotted circle in (b) corresponds to the position of the morphological feature seen in (a).

Conclusions

The formation of extended epitaxial defects, such as carrot defects, by TSDs with a morphological feature was studied. It was confirmed using highly sensitive surface observation, AFM and KOH etching that the surface roughness around a TSD was observed as a morphological feature and TSDs with this morphological feature formed extended epitaxial defects with high frequency of appearance compared to usual TSDs without any features. The density of TSDs with the morphological feature varied depending on CMP methods and it was pointed out that the high quality and stability of CMP was essential to reduce the extended defects. The formation and shapes of extended defects from TSDs with such morphological feature were affected by step-bunching.

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