In order to evaluate the potential of a non-plasma dry etcher for silicon carbide, a 50-mm-diameter C-face 4H-silicon carbide wafer was etched using chlorine trifluoride gas at 500°C. The wafer deformation was sufficiently small after the repetitive etching, even though the wafer was very thin, that is, about 160-μm thick. When the wafer surface was significantly etched, concentric-circle-shaped valleys were formed at the radii corresponding to the circular-shaped arrays of pinholes at the gas distributor. Because the local pattern of the 4H-silicon carbide wafer etching rate corresponded to that of the chlorine trifluoride gas supply, the etching rate distribution was determined to be mainly governed by the chlorine trifluoride gas flow. Because the surface morphology and roughness after the etching was comparable to that of the mirror-polished wafer surface, the etcher evaluated in this study was expected to have a significant potential for mirror etching.

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In order to reduce the electric energy loss, power electronics1–3 is currently playing major roles and making enormous contributions over the world. The power devices have various key positions to govern and improve the overall power consumption efficiency. They will have more functions and capabilities achieved by advancing the technologies of material production and device designs.

The power devices are made of semiconductor materials,2,3 such as silicon (Si), silicon carbide (SiC) and gallium nitride (GaN). The silicon carbide power devices have been developed by many researchers and engineers due to their fascinating nature, such as a high dielectric breakdown voltage, for high voltage use. The silicon carbide power devices are actually installed and currently working in trains and vehicles.2,3 Because the power device demand will further increase in the future, the process of silicon carbide material production should be improved.

The significantly hard and nonreactive properties of the silicon carbide very often make the device fabrication processes long and complex. When the wafer back side is thinned by mechanical or chemical mechanical polishing after the device fabrication, the thinning processes require several hours or more. The removal rate is still about 0.2 μm/min when the plasma and Pt catalyst are used for the polishing.11–13 For developing a high speed process, an alternative high speed process, such as chemical etching, is expected.

For improving the removal rate by the chemical approach, chlorine trifluoride (ClF3) gas4–10 is expected to be useful. The chlorine trifluoride gas has been reported to quickly etch the Si- and C-faces single-crystalline 4H-silicon carbide (SiC) material at a high rate, such as 5 μm/min.11 The C-face 4H-silicon carbide could be etched while maintaining the mirror-polished surface.14,17

In order to realize an industrial-scale wafer etching process, the SiC single-wafer dry etcher has been designed, fabricated and evaluated15–16 in this reactor, the entire etching rate profile over the 50 mm-diameter polycrystalline 3C-silicon carbide wafer depended on the concentration and flow of the chlorine trifluoride gas. Based on a numerical calculation accounting for the transport phenomena,14,15 the relationship between the local etching rate profile and the chlorine trifluoride gas transport was determined. For further development, the single-crystalline 4H-silicon carbide wafer should be used for evaluating the influence of the chlorine trifluoride gas transport. Additionally, the surface morphology and the wafer deformation formed by the etching should be evaluated.

Generally, the mirror etching is effective for improving the quality of electronic devices, such as the electron mobility, the leakage current and the gate oxide integrity.18 For other applications, the quick mirror etching with the simultaneous light-weighting will effectively produce the high performance optical applications made of silicon carbide.19 The mirror etching technique will expand various possibilities of silicon carbide.

In this study, as an extension of previous studies,13–16 the C-face 4H-silicon carbide single-crystalline wafer was etched using the chlorine trifluoride gas. The relationship of the etching rate profile with the chlorine trifluoride gas supply was studied using a significantly deep etching condition. Using the same conditions, the surface roughness after the etching was compared with that of a polished wafer. Additionally, the wafer deformation was evaluated by repetitive heating, etching and cooling.

**Experimental**

The 4H-silicon carbide wafers having the off-orientation of 4° were cut from the n-type single-crystalline ingot (TankeBlue Semiconductor Co., Ltd., Beijing, China). The Si- and C-faces were polished by a chemical mechanical polishing (CMP) technique.20 In this study, the C-face 4H-silicon carbide wafer was etched, because the back side (C-face) etching is usually performed for the wafer thinning after fabricating the device structure.

Figure 1 shows a cross-sectional view of the silicon carbide dry etcher. The chlorine trifluoride gas was introduced from two gas injectors at the top of the reactor. The chlorine trifluoride gas flowed into the etcher and was distributed after the etching of the wafer.
Gas distributor used in the silicon carbide dry etcher.

Figure 2. Gas distributor used in the silicon carbide dry etcher.

downward through the gas distributor. The gas distributor had 3-mm-diameter pinholes arranged along concentric circles, as shown in Fig. 2. This figure shows that the distances between the pinhole centers were 6 mm along the same concentric circle, and 5 mm between the next concentric circle. The gas distributor and chamber wall were made of stainless steel. The chlorine trifluoride gas was used often after being diluted. The gas mixture of chlorine trifluoride and nitrogen approached and etched the C-face 4H-silicon carbide wafer, which had a mirror-polished surface with a 50-mm diameter. The wafer thickness was 100–200 μm, typically about 160 μm. The rotation rate of the silicon carbide wafer was 10 rpm. The susceptor under the wafer was made of quartz glass. The hollow-shaped susceptor contained three halogen lamps and a cylindrical gold reflector.

The wafer was etched, without a help of plasma, along with producing the gaseous by-products of silicon tetrafluoride (SiF₄), carbon tetrafluoride (CF₄) and chlorine (Cl₂).

\[
3\text{SiC} + 8\text{ClF}_3 \rightarrow 3\text{SiF}_4 \uparrow + 3\text{CF}_4 \uparrow + \text{Cl}_2 \uparrow \tag{1}
\]

The etching process is shown in Fig. 3. The wafer was typically heated to 500 °C from room temperature in ambient nitrogen. At 500 °C, the chlorine trifluoride gas was introduced. The flow rate and concentration of the chlorine trifluoride gas were typically 50 sccm and 50–100%, respectively, at atmospheric pressure. The nitrogen gas was used at the flow rate of 50 sccm for diluting the chlorine trifluoride gas to 50%. After the etching, the wafer temperature was adjusted to 400 °C. At this temperature, the wafer surface was again exposed to the chlorine trifluoride gas at 100% for 5 minute in order to remove the carbon film formed on the wafer surface during the etching at 500 °C. The carbon removal process is recommended after the quick etching. The temperature effective for removing the carbon film is 300–400 °C. After terminating the chlorine trifluoride gas, the wafer was cooled to room temperature in ambient nitrogen. The wafer was then removed from the reactor. The etching rate of the silicon carbide was determined by the decrease in weight and thickness of the wafer.

Because the chlorine trifluoride gas could be easily transported through the formed carbon film which was significantly thin, the etching rate was not influenced by the carbon film formation. The etching rate might be influenced by various crystalline defects. For C-face 4H-silicon carbide surface, the screw dislocations caused the etching pits, while the threading edge dislocations did not. Thus, the influences of crystalline defects on the etching rate and the etching pit formation should be carefully evaluated, in future.

The wafer deformation was visually evaluated over entire wafer, using an image of the cross-hatched patterns which was reflected at the wafer surface after the etching, as shown in Fig. 4. The significant etching depth pattern was visualized and evaluated by observing the distorted image of the bar-shaped light reflected at the etched wafer surface. The surface morphology and roughness were measured by phase shift interference microscopy, ZYGO (Canon Inc., Tokyo, Japan). The vertical and lateral resolution are 0.5 nm and 0.3 μm, respectively. The RMS value was evaluated over 140 μm length.

**Results and Discussion**

**Wafer deformation.**—The wafer deformation was first evaluated, because it often caused very serious practical problems for the wafer operation. The silicon carbide wafer was sequentially etched four times at 500 °C. Each of the etchings was performed following the process shown in Fig. 3. Figure 5 shows photographs of the cross-hatched patterns reflected at the wafer surface (a) before etching, (b) after the first etching by 50% chlorine trifluoride gas for 5 minutes, (c) after the second etching by 50% chlorine trifluoride gas for 4 minutes, (d) after the third etching by 50% chlorine trifluoride gas for 2 minutes, and (e) after the fourth etching by 50% chlorine trifluoride gas for 5 minutes.
The wafer was etched by chlorine trifluoride gas at 100% and at slightly higher than 500°C for 4 minutes, (d) after the third etching by 100% chlorine trifluoride gas for 2 minutes, and (e) after the fourth etching by 100% chlorine trifluoride gas for 4 minutes. The numerical value written at the top right position in each photograph is the wafer thickness after the etching. Figures 5b–5e show that the etched wafer surfaces were specular and clearly reflected the cross-hatched patterns. All the horizontal and vertical lines were observed to be straight; the shape of the cross-hatched patterns shown in Figs. 5b, 5c and 5d were recognized to be the same as those in Fig. 5a. In contrast, Fig. 5e shows that the reflected cross-hatched patterns were very slightly bent particularly near the wafer edge, and at the right top position of the wafer edge. This indicated that the four repeated processes of the heating, etching and cool down did not cause a significant deformation. Because the chemical etching generally causes no stress at the etched surface, different from the mechanical method,9,10 the wafer deformation could be small even for the very thin wafer of about 160 μm thickness, which is significantly thinner than that typically used.12 The deformation for the standard thick wafers was thus expected to be smaller than that in this study, although the wafer deformation was not quantitatively evaluated.

**Etching depth pattern.**—In order to study the relationship between the etching depth profile and the arrangement of the pinhole of the gas distributor, the wafer was significantly etched by the 100% chlorine trifluoride gas at a temperature slightly higher than 500°C for 4 minutes. After the etching, the wafer center region was fully etched off to form a hole, as shown in Fig. 6, which is a photograph of the etched wafer. In this figure, the white zig-zag line is the reflected image of the bar-shaped light. The dotted lines show the positions of the pin-holes arranged on the gas distributor. This figure shows that the wafer surface was specular even after the significantly deep etching. Additionally, the straight shape of the bar-shaped light was recognized as a zig-zag shape, the turning positions of which coincided with the dotted lines. Because the wafer after the etching was significantly thin and fragile, the wafer thickness could not be measured. The periodically arranged circle-shaped valleys at the etched surface were considered to be formed along the circles of the pinhole arrangement for the chlorine trifluoride gas supply, because the wafer deformation cannot be periodic. These results verified that the etching depth profile could be locally formed on the single crystalline 4H-silicon carbide, corresponding to the local supply of chlorine trifluoride gas from the gas distributor, similar to the polycrystalline 3C-silicon carbide wafer.15 Thus, the local etching profile is expected to be adjusted by optimizing the gas supply design. The etching depth slope is expected to be adjusted by the distance between the pin-holes at the gas distributor.

**Surface roughness.**—The surface roughness after the etching was evaluated. Figure 7 shows the surface of the mirror polished wafer before the etching. Figure 7a shows the surface morphology as a contour diagram of the surface height. While there were very shallow hills and valleys, the wafer was totally flat. Figure 7b shows the height profile along the dotted line in Fig. 7a. The surface height was between −1 nm and +1 nm. The RMS roughness was 1 nm.

Figure 8 shows that the wafer surface after the etching at 500°C for 5 minutes by the 50% chlorine trifluoride gas. Figure 8a shows the contour diagram of the surface height. From the right top to the left bottom, the same color regions, that is, the same height regions are distributed. Figure 8b shows the surface height, which was between −1 nm and +1 nm, along the dotted line in Fig. 8a. While there was a weak surface pattern, the surface height profile was similar to that of the polished wafer, as shown in Fig. 7. The RMS surface roughness was still 1 nm. Although there was a blue colored point showing the pits, the rest of the region was recognized to be entirely flat.

Figure 9a shows the surface of the wafer shown in Fig. 6. Because this wafer was significantly etched, the etching influence on the surface morphology was expected to be significant. The measured point was indicated by the letter X in Fig. 6. As shown in Fig. 9a, the surface consisted of a flat region indicated by the color red and the pits indicated by the color blue. Because the wafer surface shown in Fig. 6 contained hills and valleys, the surface consistently had a slope, as shown in Fig. 9b. Along the slope, the surface height showed the shallow and local up-down. Here, the two parallel white dotted lines show the height range, the distance of which was nearly 2 nm. Thus, the surface was recognized to be rather smooth, similar to that of

**Figure 6.** Significantly-etched wafer surface reflecting the bar-shaped light. The wafer was etched by chlorine trifluoride gas at 100% and at slightly higher than 500°C for 4 min.

**Figure 7.** Surface morphology of the polished C-face 4H-SiC wafer without etching.

**Figure 8.** Surface morphology of C-face 4H-SiC wafer after etching by chlorine trifluoride gas at 50% and at 500°C for 5 min.
This study is expected to have a significant potential for the mirror fabrication of lightweight silicon carbide mirrors. The surface roughness after the etching was recognized to be similar to that of the mirror polished wafer. The etching reactor evaluated in this study is expected to have a significant potential for the mirror etching of C-face 4H-silicon carbide wafers.

Conclusions

In order to develop a non-plasma wafer etcher using the chlorine trifluoride gas, a 50-mm-diameter single crystalline C-face 4H-silicon carbide wafer was etched at 500°C. The wafer deformation was very small after four times heat treatments, etchings and coolings, even though the wafer was very thin. The etching depth profile corresponded to the circular-shaped array of the pinhole arrangement of the gas distributor. Thus, the pinhole arrangement is one of the key parameters for adjusting and flatting the local etching depth profile. The surface roughness after the etching was recognized to be similar to that of the mirror polished wafer. The etching reactor evaluated in this study is expected to have a significant potential for the mirror etching of C-face 4H-silicon carbide wafers.

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