A process and a reactor for the quick, uniform and deep etching of a C-face 4H-silicon carbide layer were developed using chlorine trifluoride gas. Based on the concept that the etching rate profile of the rotating wafer was the average of that on a concentric circle, the uniform etching rate profile was obtained by the average between the multiple wavy etching rate profiles and by sufficiently spreading the chlorine trifluoride gas. The etching rate variation and RMS microroughness could be reduced to about 1.6% and about 0.2 nm, when the etching rate and depth were 20 μm/min and about 100 μm, respectively. The developed process could etch off the 150-μm-deep layer without deteriorating the RMS microroughness for the total etching time within 8 min.

The chlorine trifluoride gas etching design was systematically solved for the local chlorine trifluoride gas distribution during the etching process. For reducing the production cost of the electronic devices, any quick fabrication technique is effective and expected. For the same purpose, chlorine trifluoride gas etching was expected for many applications, such as that in the field of silicon carbide microelectronic devices. When the significant total etching time is 8 min or less, chlorine trifluoride gas etching is expected to be used for the mass production of silicon carbide devices.

Experimental

Figure 1 shows the vertical cross section of the silicon carbide dry etcher used in this study. The n-type C-face 4H-silicon carbide wafer (Tanke Blue Semiconductor Co., Ltd., Beijing, China) was placed on the rotation rod. The front and back sides of the 4H-silicon carbide wafer were finished to a mirror surface by means of chemical mechanical polishing (CMP). The wafer was heated from the bottom side using halogen lamps and a reflector made of gold. The wafer temperature was adjusted by the electric power supplied to the halogen lamps. The electric powers for the various wafer temperatures were preliminary measured and determined in ambient nitrogen at various gas flow rates using the R-type thermocouples attached at the wafer surface. The wafer temperature and the wafer rotation rate were 400 °C–500 °C and 10 rpm, respectively.

Figure 2 is the typical process for etching the 4H-silicon carbide dry etcher used in this study. The chlorine trifluoride gas underwent an exothermic chemical reaction to produce gaseous byproducts as described in Eq. 1.

\[ 3\text{ClF}_3 + 8\text{SiC} \rightarrow 3\text{SiF}_4 + 3\text{CF}_4 + 4\text{Cl}_2. \]

The chlorine trifluoride gas, nitrogen gas and gaseous byproducts were removed from the etcher through the exhaust.

In previous studies, the C-face of the 4H-silicon carbide could be quickly etched to produce a mirror surface at an etching rate higher than several μm/min. Using the chlorine trifluoride gas, a deep etching technique was expected for many applications, such that for thinning the wafer by removing the backside of the 4H-silicon carbide wafer after the power device fabrication on the front surface.

In previous studies, the average between different wavy etching rate profiles. In addition, the global etching rate non-uniformity from the center to the periphery of the wafer should be systematically solved by any technique. For this purpose, the two-layered gas distributor was designed. It contained the functions of spreading a heavy gas, such as chlorine trifluoride gas, over the entire reactor, and of the average of wavy etching rate profiles. When the significantly flat surface was obtained, the surface microroughness would be precisely evaluated. Additionally, the capability for the deep etching removal of a layer thicker than 100 μm should be studied.

This study thus used the two-layered gas distributor. The C-face 4H-silicon carbide wafer having the diameter of 50 mm was etched to evaluate the global, local and microscopic etching rate uniformity. The evaluated etching depth was up to 175 μm.
after the etching. The 50% chlorine trifluoride gas at 300 °C was used for 6 min in Step (III). The overall process was performed at atmospheric pressure. While the actual wafer surface temperature was not measured for avoiding any unexpected accident, it was assumed to be not significantly higher than that immediately before initiating the etching. The etching results in this study were shown as a function of the initial wafer temperature.

The etching rate was obtained using the difference in the wafer thickness before and after the etching. The wafer thickness was measured by the digimatic micrometer. The macroscopic surface condition was studied by a visual inspection using the image of an orthogonal cross pattern which was reflected at the mirror wafer surface. The microscopic condition of the etched surface was further evaluated using a phase shift interference microscope, ZYGO (Canon Inc., Tokyo, Japan).

**Results and Discussion**

**Gas distributor design.**—In this study, the silicon carbide wafer diameter was 50 mm. The diameters of the gas distributor and the pinhole diameter were 50 mm and 1.1 mm, respectively. For the gas distributor design, the etching was assumed to locally occur at the wafer position beneath the pinhole of the gas distributor, through which the chlorine trifluoride gas flowed downward. The etching rate at various distances from the center of the rotating wafer was assumed as the average value along the concentric circle, similar to...
Local etching rate $\propto N/(2\pi r)$

$N$: Number of pinholes on concentric circle

$r$: Distance from wafer center (x)

Following Eq. 2, the etching rate profile was calculated for Distributors A and B,\textsuperscript{9} which had the orthogonal and the slanted pinhole arrangements, as shown in Figs. 4a1 and 4b1, respectively. The calculated etching rate profiles are shown in Figs. 4a2 and 4b2. Both profiles were wavy with the period of 2–3 mm. The amplitude was 2.8 and 1.6 for Distributors A and B, respectively. Such a wavy profile was considered to be produced due to the accumulation of the etching rates caused by the pinholes on the same concentric circle.

While the accumulation of the etching rate could be moderately diverged and reduced by slanting the pinhole arrangement, the wavy profile still remained, as shown in Fig. 4b2. As reported in a previous study,\textsuperscript{9} the high gas flow rate could make the wavy etching rate profile flat. However, because the high gas flow rate simultaneously influences the global etching rate profile, it should be limited to a fine adjustment.

For systematically designing the pinhole arrangement in this study, the wavy profile was intentionally averaged and compensated with the different wavy profiles. As shown in Fig. 5a, the circular-shaped gas distributor was evenly divided into four regions, such as (i)–(iv). As shown in Figs. 5a and 5b, in the (i)–(iv) regions, the pinhole position was horizontally and vertically shifted so that the etching rate waves shift a quarter period from each other. Figure 5c shows the flat image of the etching rate profile which is the average of those in the (i)–(iv) regions.

The calculated etching rate by Distributor C is shown in Fig. 4c2. The etching rate was not wavy along with showing a significantly small scattering. Additionally, the amplitude was 0.8 which was significantly lower than those of Distributors A and B. Based on these results, Distributor C was chosen for the experimental evaluation.

Figure 6a1 shows a schematic of the two-layered gas distributor which consists of upper and lower gas distributors. Figures 6b and 6c are photographs of the upper and lower gas distributors, respectively. The upper gas distributor had pinholes only along the periphery of the circular plate. The lower gas distributor was Distributor C.

As shown in Fig. 6a2, the upper gas distributor widely transported and spread the injected gas to the periphery of the reactor so that the heavy etching gas does not flow straight down toward the wafer. Through the circular-arranged pinholes, the gas enters the thin space between the upper and lower gas distributors. The gas uniformly spread over the top surface of the lower gas distributor due to the gas-flow resistance cause by the pinholes. The gas uniformly flowed down through the pinholes over the wafer surface. The etching reaction locally occurs at the positions corresponding to...
the pinholes located above; the wafer rotation gives the average etching rate on the concentric circle.

The gas distributor design concept in this study is expected to be available and effective for the wafers and pinholes having the different diameters from 50 mm and 1.1 mm, respectively, for pursuing the optimum condition.

**Etching rate.**—Using the two-layered gas distributor, shown in Fig. 6, the etching rate was obtained at various wafer temperatures and at the various gas flow rates. The etching time was 2–20 min, typically 2–5 min. Figure 7 shows the etching rates at the chlorine trifluoride gas concentrations of 20, 50 and 100% and at the wafer temperatures of 400, 450 and 500 °C. In Fig. 7, the chlorine
trifluoride gas flow rate was fixed at 300 sccm and the concentration was adjusted by adding nitrogen gas. At each temperature, the etching rate increased with the increasing chlorine trifluoride gas concentration. The maximum etching rate was about 2, 10 and 16 $\mu$m min$^{-1}$ at 400, 450 and 500 °C, respectively, at the chlorine trifluoride gas concentration of 100%.

Figure 8 shows the etching rate profile at the wafer temperature of 500 °C. For increasing the etching rate at 500 °C, the chlorine trifluoride gas flow rate was increased to 500 sccm. The etching rate for the 20, 50 and 100% chlorine trifluoride gas was 10, 16 and 20 $\mu$m min$^{-1}$, respectively, which were higher than those in Fig. 7. As shown in Fig. 8, the etching rate at each concentration of the chlorine trifluoride gas was uniform over the wafer. In Fig. 8, the percent values in the brackets were the etching rate variations which were evaluated by Eq. 3:

$$\text{Etching rate variation}\% = 100 \times \frac{(\text{Max} - \text{Min})}{(\text{Max} + \text{Min})}. $$

The etching rate variation was 3.6, 3.1 and 1.6% at the chlorine trifluoride gas concentration of 20, 50 and 100%, respectively. The etching rate profile was significantly uniform in contrast to those reported in previous studies.9,12

In this study, the wafer rotation rate was fixed at 10 rpm. Because the wafer rotation at around 10 rpm takes the average of the etching rate along the concentric circle,10,15 the window of the allowable and effective wafer rotation rate is very wide, probably those between 1 and several tens rpm.

**Surface morphology.**—The etched surface was macroscopically and microscopically evaluated. Figure 9 shows an image of the orthogonal cross pattern reflected at the 50-mm-diameter C-face 4H-silicon carbide wafer surface after the etching. A 42-$\mu$m thick layer

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**Figure 7.** C-face 4H-silicon carbide etching rate at various temperatures and chlorine trifluoride gas concentrations. The chlorine trifluoride gas flow rate was fixed at 300 sccm.

**Figure 8.** C-face 4H-silicon carbide etching rate at 500 °C and at various chlorine trifluoride gas concentrations. The chlorine trifluoride gas flow rate was fixed at 500 sccm. Values in bracket are the etching rate variations.

**Figure 9.** Reflected image of orthogonal cross pattern on the 50-mm-diameter C-face 4H-silicon carbide wafer surface after 42-$\mu$m thick layer was etched off by 100% chlorine trifluoride gas at 500 °C.
of the wafer surface was etched off at 500 °C for 2 min by the 100% chlorine trifluoride gas at the flow rate of 500 sccm. As shown in this figure, the orthogonal cross pattern was clearly reflected at the overall etched surface from the center to the periphery. Additionally, the lines of the cross pattern were straight without bending as shown in the magnified images of Figs. 9b–9d at the center, half radius and periphery, respectively. The visual inspection showed that the etched surface was globally and locally flat and non-wavy, consistent with the etching profiles shown in Fig. 8.

The RMS surface microroughness was evaluated and shown in Figs. 10 and 11. The microscopic surface images at the (C) center, (L) left, (R) right, (T) top, and (B) bottom were very flat with significantly small hills and valleys. As shown in Fig. 10 (C), (L), (R), (T) and (B), the RMS microroughness was 0.225, 0.207, 0.220, 0.244, and 0.211 nm, respectively.

The RMS surface microroughness was further evaluated after removing the various thicknesses by the 100% chlorine trifluoride gas at 500 °C, as shown in Fig. 11. The chlorine trifluoride gas flow rate was 300 and 500 sccm. The dotted line shows that the RMS microroughness is almost 0.2 nm before the etching. The RMS surface microroughness was evaluated as the average value of five points, such as the center, left, right, top, and bottom, over the wafer.

After the etching at the chlorine trifluoride gas flow rate of 300 sccm, the RMS surface microroughness remained near 0.2 nm with the increasing etching depth up to 175 μm. Similarly, at the flow rate of 500 sccm, the RMS surface microroughness remained near 0.2 nm, even when a 160 μm-thickness was etched off. This result indicated that the surface microroughness did not deteriorate up to the etching depth of 160–180 μm.

The obtained results concluded that the etching rate under wide conditions was uniform along with maintaining the original surface microroughness over the 50-mm-diameter wafer. The obtained surface microroughness was comparable to those finished by means of the chemical-mechanical polishing. The etching rate and the etched surface obtained in this study were considered to be advanced from the notable study which showed the etching rate of 15 μm min⁻¹ and the etching depth variety (max - min) of about 30 μm after removing the 200 μm thickness by 20 min.
Conclusions

A uniform and high etching rate of the 50-mm-diameter C-face 4H-silicon carbide wafer was obtained with no change in the surface microroughness after removing the 160–180-μm-thick layer using the chlorine trifluoride gas. The gas distributor was designed based on the average between the various wavy etching rate profiles and based on the widely spreading heavy etchant gas. The etching rate variation and the RMS microroughness could be reduced to 1.6% and about 0.2 nm when the etching rate and depth were 20 μm min⁻¹ and about 40 μm, respectively. The developed process enables the etching rate of 20 μm min⁻¹ and the etching depth of 160–180 μm, while maintaining the original RMS surface microroughness.

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