Technology for Controlling Trench Shape in SiC Power MOSFETs

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1. Introduction

As the worldwide consumption of energy is increases and the global environment steadily deteriorates, society must find more efficient ways to utilize energy in order to achieve sustainable advances. Accordingly, the field of power electronics is of vital importance, and huge advances in power semiconductor devices are anticipated. Power semiconductor devices that use silicon (Si) are said to be approaching the limits of their inherent characteristics, and although technical developments such as the SJ-MOSFET (super junction metal-oxide-semiconductor field-effect transistor) and FS-IGBT (field stop insulated gate bipolar transistor) have resulted in improved characteristics, further improvement will be difficult to realize. Silicon carbide (SiC), a compound that combines silicon and carbon, has physical properties that are superior to those of Si, and is capable of achieving high voltage, low on-resistance, low loss and high-speed operation. The application of SiC devices enables power supplies to be made smaller in size, have lower loss, operate at high temperatures (with a simplified the cooling mechanism), and also enables electric power energy to be utilized more effectively.

As devices that use SiC material, some Schottky barrier diodes are being sold commercially, and as switching devices, MOSFETs have been much researched, but are not yet being used in practical applications. Trench-type MOSFET (UMOSFET) devices promise to realize lower on-resistance than the planar types, but require SiC-specific dry etching technology. Being physically hard and chemically stable, SiC material is difficult to etch, and even with an etching machine that uses high density plasma, the etching rate is slow and the etching shape is difficult to control. A trench sidewall or bottom surface formed by dry etching exhibits surface roughness and areas with sharp angles remain at the opening portion. In a UMOSFET, because a channel is formed in the trench sidewall, the smoothness affects electron mobility and the presence of sharp angles in the trench invites decreased withstand voltage capability due to the concentration of electric fields. Thus, smoothing of the trench inner wall and rounding of the corner shapes of the trench opening and bottom are essential. However, it is difficult to obtain an ideal shape and smoothness by only optimizing the dry etching conditions.

On the other hand, high-temperature annealing in a hydrogen (H_2) atmosphere is known to improve the trench shape and smoothness of Si trench devices.[1][2] SiC is also stable at high temperatures, and there have been no reports of this type of approach applied to SiC. This paper examines technology for simultaneously performing high-temperature annealing of SiC trenches and performing process optimization in order to control trench shape and improve sidewall smoothness.

2. Experimental Procedure

A sample was prepared by forming SiO_2 film at a thickness of 2 µm on a 4H-SiC (see explanatory note on page 73) substrate (8° off the C face), and then patterning the resist with a line width of 1 to 3 µm. Next, the resist was worked as a mask and dry etching was performed to pattern the SiO_2. After the resist was removed, the SiO_2 worked as a mask and then the SiC was dry etched. The etching depth ranged from 3 to 8 µm. After hydrofluoric acid was used to remove the SiO_2 film, annealing was performed for 1 to 30 minutes in an atmosphere of argon (Ar), silane-added argon (SiH_4/Ar) and hydrogen (H_2) at 1.5 to 760 Torr using a CVD (chemical vapor deposition) apparatus capable of achieving temperatures of up to approximately 2,200 °C. For evaluation purposes, a scanning electron microscopy (SEM) was used to observe the trench inner wall and a cross-section thereof before and after the annealing, and an atomic force microscope (AFM) was used to measure the substrate surface roughness and the roughness of the trench sidewall. For some samples, X-ray photoelectron spectroscopy (XPS) was used to analyze Si and C binding and composition on the substrate surface.

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3. Results and Considerations

3.1 Pressure dependency of annealing

Figure 1 shows cross-sectional and plane surface SEM photographs of trenches annealed in an Ar atmosphere at 1,700 °C at the different pressures of 1.5 Torr, 80 Torr and 760 Torr.

Figure 1(a) shows the cross-section and bottom of a trench that has not been annealed after the trench etching. It can be seen that without annealing, the corners of the trench opening are formed from nearly right-angles, and the trench bottom is rough. In the case of annealing at 1,700 °C in an Ar atmosphere at 1.5 Torr, the trench shape and the trench bottom surface exhibit little change, but at 80 Torr and 760 Torr, the corners of the trench opening become rounded and the trench bottom becomes smooth.

Figure 2 shows the XPS measurement results for carbon at the substrate surface of these samples. For the sample without annealing and those with annealing at 80 Torr and 760 Torr, a peak binding energy due to the SiC was observed, but for the sample annealed at 1.5 Torr, the binding energy peak was shifted toward the high energy side. This shifted peak is for graphite, confirming that when annealing is performed at 1.5 Torr, the Si sublimates from the substrate surface and the surface becomes nearly entirely composed of C. Based on these results, we found that improvements in the trench shape and smoothness could not be realized at low pressures, and that a suitable annealing pressure is at least 80 Torr. Subsequent experiments were conducted at 80 Torr.

Fig.1 Pressure dependency of shape of SiC trench annealed in an Ar atmosphere at 1,700 °C

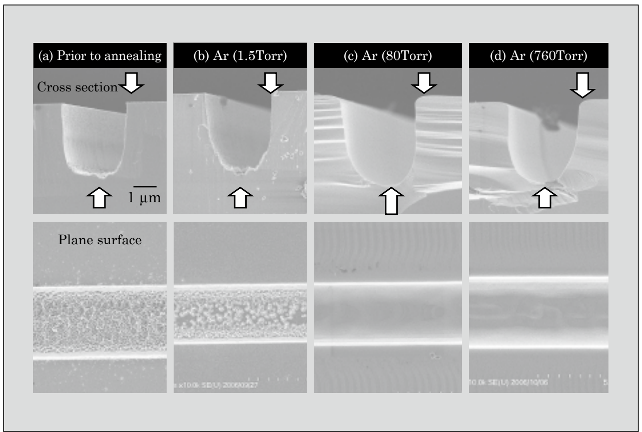
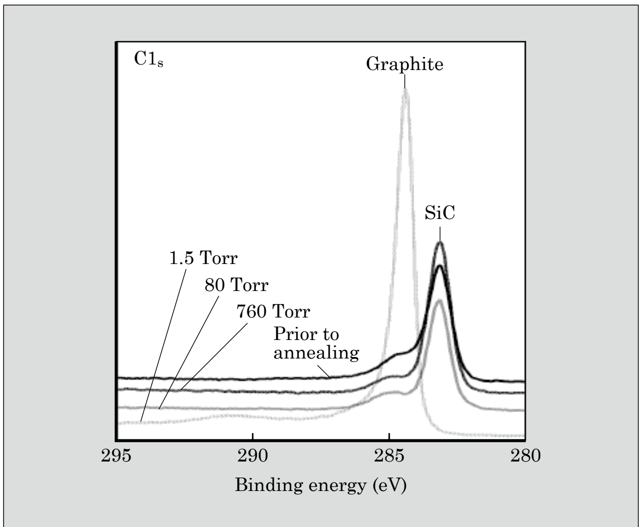


Fig.2 XPS measurement results of $C1_s$ peak on SiC surface



3.2 Dependency on annealing atmosphere

Figure 3 shows cross-sectional and plane surface SEM photographs of trenches annealed at a temperature of 1,700 °C, a pressure of 80 Torr and in the different annealing atmospheres of Ar, SiH_4/Ar and H_2.

The samples annealed in atmospheres of Ar and SiH_4/Ar exhibited rounded trench corners and smooth trench bottoms. However, the sample annealed in a H_2 atmosphere had a smooth trench bottom, but areas in the vicinity of the trench opening and sidewall exhibited signs of significant etching.[3] Due to the significant trench sidewall etching that occurs during annealing in a H_2 atmosphere at 1,700 °C, temperature optimization is required. Optimization of the annealing temperature was examined below for the cases of annealing in a SiH_4/Ar atmosphere and in a H_2 atmosphere.

3.3 Temperature dependency of annealing in a SiH_4/Ar atmosphere

Figure 4 shows cross-sectional and plane surface SEM photographs of trenches annealed in a SiH_4/Ar atmosphere at 80 Torr at various temperatures ranging between 1,500 °C and 1,800 °C.

As the annealing temperature rises, the corners of the trench opening become more rounded, and surface roughness on the trench bottom decreases and becomes smoother. In order to make the trench corners become rounded, a temperature of at least 1,700 °C is required. In the plane surface SEM photographs, step bunching (a phenomenon of waviness caused by an aggregation of atomic steps) was observed in substrate surfaces

Fig.3 Atmosphere dependency of shape of SiC trench annealed at 1,700 °C

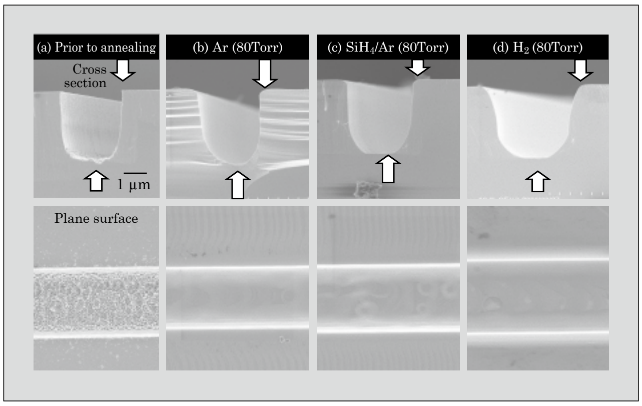


Fig.4 Temperature dependency of SiC trench shape with annealing in SiH_4/Ar atmosphere

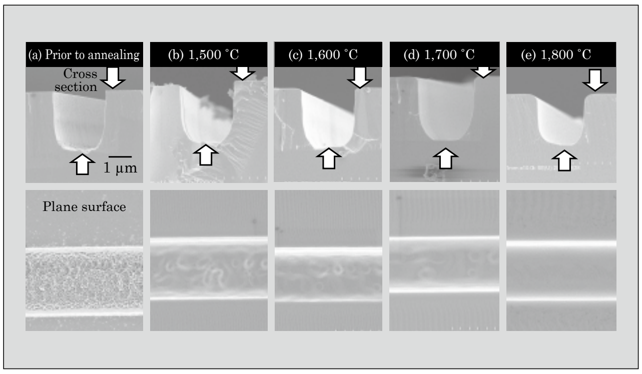
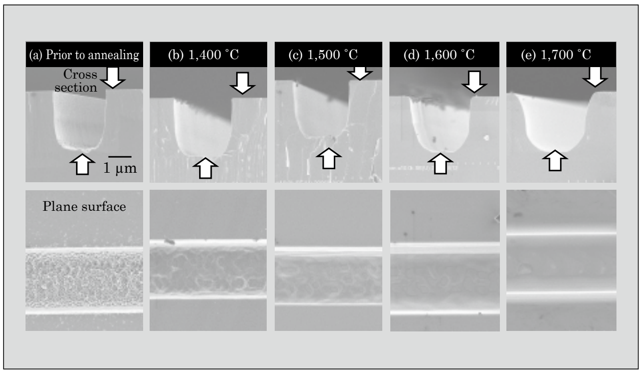


Fig.5 Temperature dependency of SiC trench shape with annealing in H_2 atmosphere



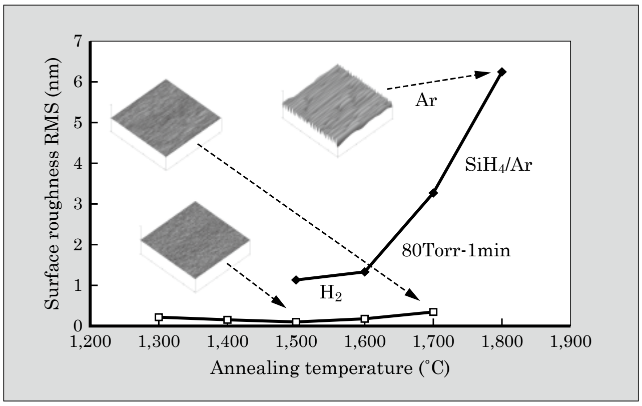
that had been annealed at temperatures of 1,700 °C or higher. This step bunching is believed to be due to an 8° offset of the substrate, and is caused by the release of strain incurred during polishing as a result of the annealing. Measurement of the roughness of the substrate surface with an AFM indicated greater roughness as the annealing temperature increased. From these results, we found that an annealing temperature of 1,700 °C is suitable for obtaining rounded trench corners, a smooth trench bottom surface and reduced substrate surface roughness.

3.4 Temperature dependency of annealing in a H_2 atmosphere

Figure 5 shows cross-sectional and plane surface SEM photographs of trenches annealed in a H_2 atmosphere at 80 Torr at various temperatures ranging between 1,400 °C and 1,700 °C.

We verified that as the annealing temperature increases, the bottom of the trench becomes smoother, but if the annealing is performed at a temperature of 1,600 °C or above, the sidewalls become etched and thereby increase the width of the trench. We also found that rounded trench corners could not be obtained by annealing at temperatures of 1,500 °C and below. Measurement of the roughness of the substrate surface with an AFM revealed a RMS (root mean square) roughness of 0.3 nm or less regardless of the

Fig.6 Surface roughness for various annealing conditions



annealing temperature, and that the annealing did not generate any additional roughness.

3.5 Annealing conditions and substrate surface roughness

Figure 6 shows the results of measurement of SiC substrate surface roughness with an AFM in the cases where annealing was performed at various temperatures in Ar, SiH_4/Ar and H_2 atmospheres. The analysis range is a 10 μm square.

With H_2 annealing, the substrate surface was extremely smooth, even at high annealing temperatures. With SiH_4/Ar annealing, as the temperature increased, step bunching occurred and RMS deteriorated rapidly. At the same temperature, surface roughness was greatest with Ar annealing.

3.6 Results of two-step annealing with SiH_4/Ar and H_2

Annealing in a high temperature SiH_4/Ar atmosphere is effective for obtaining rounded trench corners, and annealing in a low temperature H_2 atmosphere is effective for obtaining a smooth substrate surface without changing the trench shape. Based on these results, we examined the feasibility of annealing in a SiH_4/Ar atmosphere to obtain rounded trench corners and smooth trench inner walls, and then annealing in a H_2 atmosphere to obtain a smooth substrate surface. Figure 7 shows cross-sectional and plane surface SEM photographs of trenches that have been annealed in two steps, first for 10 minutes at 1,700 °C in a SiH_4/Ar atmosphere and then for 10 minutes at 1,500 °C in a H_2 atmosphere.

It can be seen that the trench corner is rounded to a radius of curvature of 0.6 μm and that the bottom of the trench is extremely smooth. Measurement of the roughness of the substrate surface with an AFM verified that the RMS roughness has been improved to 1.59 nm. Thus, the consecutive implementation of annealing at 1,700 °C in a SiH_4/Ar atmosphere and then annealing at 1,500 °C in a H_2 atmosphere enables an improvement in the trench corner shape and substrate smoothness.

Using an SEM and AFM, the smoothness of the

Fig.7 Improvement in trench shape due to two-step annealing

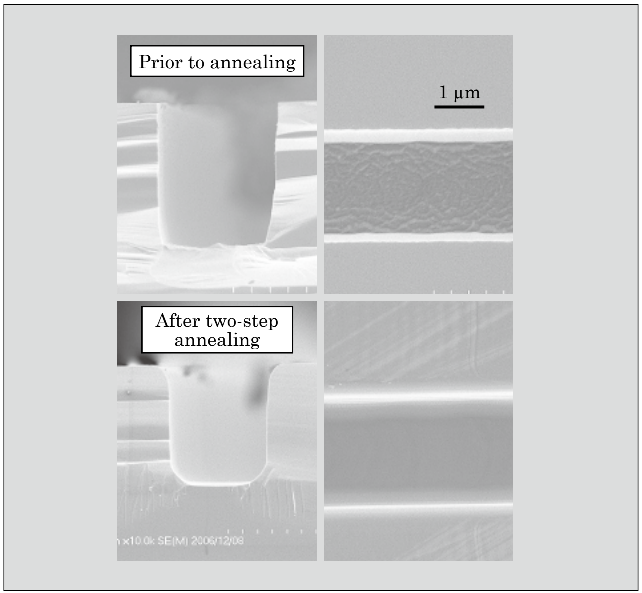
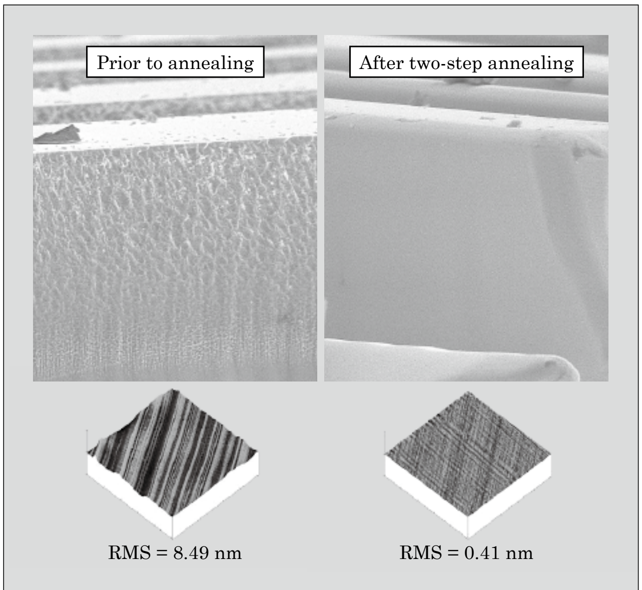


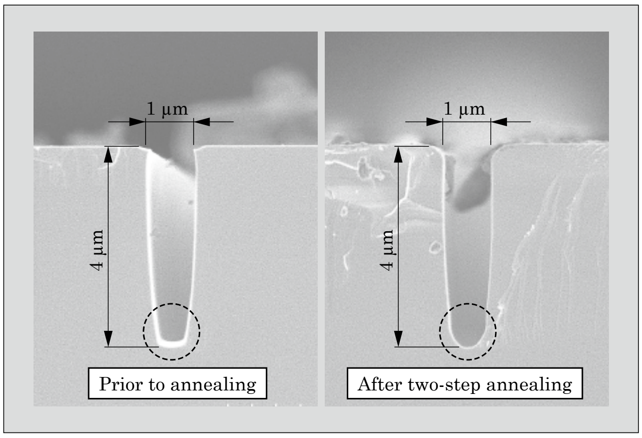
Fig.8 Improvement in trench sidewall due to two-step annealing



trench sidewall of a sample was evaluated both before and after performing two-step annealing with SiH_4/Ar and H_2, and the results are shown in Fig. 8.

The sample had a trench depth of 8 μm, and the AFM analysis range was 1 μm square. Prior to annealing, i.e., immediately after etching, a significant amount of roughness on the trench sidewall could be observed even when using a SEM. With the AFM, large surface unevenness was observed in stripe shapes, and the RMS value was 8.49 nm. After annealing, the sample was smooth without any roughness that could be observed with the SEM. With the AFM, the extreme degree of smoothness was verified and the RMS value had decreased to 0.41 nm. Thus, we were able to verify that the two-step annealing process resulted in extremely smooth trench sidewalls.

Fig.9 Change in trench shape and dimensions before and after two-step annealing



3.7 Application of two-step annealing to small trenches

The effectiveness of two-step annealing on small trench sizes (widths) was also verified. Figure 9 compares the trench shape and trench size before and after two-step annealing.

We verified that a suitable roundness of the trench corners and a semicircular-shaped trench bottom were obtained without any change to the width or depth of the trench. As a result of these improvements, the trench shape compares favorably to that of a Si trench device.

4. Conclusion

We verified the effectiveness of high temperature annealing for improving the trench shape and inner wall smoothness of trenches formed by dry etching SiC material. By annealing at a pressure of 80 Torr and temperature of 1,700 °C in a SiH_4/Ar atmosphere, rounded trench corners and smooth inner walls of the trench could be obtained. However, surface roughness caused by step bunching occurred on the substrate surface. We also verified that annealing at a pressure of 80 Torr and temperature of 1,500 °C in a H_2 atmosphere results in improved smoothness only, without any change to the trench shape. In order to realize both shape and smoothness improvements for a trench, we found that a two-step process of annealing in a SiH_4/Ar atmosphere followed by annealing in a H_2 atmosphere enables improvements in the shape of trench corners, the smoothness of trench inner walls and the smoothness of the substrate surface. After the formation of a SiC trench, the implementation of annealing at a high temperature is believed to result in improved withstand voltage capability and electron mobility for a SiC-UMOSFET.

Reference

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(2) Sudoh. K. et al. Numerical Study on Shape Transformation of Silicon Trenches by High-Temperature Hydrogen Annealing. Jpn. J. Appl. Phys. Vol. 43, no. 9 A, 2004, p. 5937-5941.

(3) Karlsson, S., Nordell, N. AFM Study of In Situ Etching of 4H and 6H SiC Substrates. Mater. Sci. Forum vols. 264-268, 1998, p. L363-366.

Explanation **4H-SiC**

Silicon carbide (SiC) is known to take more than 200 polytypes (crystal forms). Research activities with practical interests have been focused on three polytypes, 3C-, 4H-, and 6H-SiC, due to their high probability in occurrence. Here, the initial numbers stand for the repetition period of unit cell along the c-axis, and the letters for the crystal system: C for cubic and H for hexagonal.

4H-SiC is most hopeful for power semiconductors, owing to its superior properties including approximately ten times as high breakdown field, three times as high bandgap, twice as high electron saturation velocity, and three times as high thermal conductivity, as those of silicon. 4H-SiC has higher electron mobility and smaller anisotropy therein than 6H-SiC. Availability of high-quality single-crystalline wafers in recent years has opened employment mainly in power devices.

Polarity in SiC crystals provides two selections in using the {0001} plane: Si face and C face. Difference in crystal orientation is known to bring about, for example, different behaviors in epitaxial growth and different thermal oxidation rate. It is still under argumentation which face is more suitable for device fabrication.