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<td>Author(s)</td>
<td>Hiyoshi, Toru; Hori, Tsutomu; Suda, Jun; Kimoto, Tsunenobu</td>
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Simulation and Experimental Study on the Junction Termination Structure for High-Voltage 4H-SiC PiN Diodes

Toru Hiyoshi, Tsutomu Hori, Jun Suda, and Tsunenobu Kimoto, Senior Member, IEEE

Abstract—Designing and fabrication of 10-kV 4H-SiC PiN diodes with an improved junction termination structure have been investigated. An improved bevel mesa structure and a single-zone junction termination extension (JTE) have been employed to achieve a high breakdown voltage ($\geq 10$ kV). The improved bevel mesa structure, nearly a vertical sidewall at the edge of the p-n junction and a gradual slope at the mesa bottom, has been fabricated by reactive ion etching. The effectiveness of the improved bevel mesa structure has been experimentally demonstrated. The JTE region has been optimized by device simulation, and the JTE dose dependence of the breakdown voltage has been compared with experimental results. A 4H-SiC PiN diode with a JTE dose of $1.1 \times 10^{13}$ cm$^{-2}$ has exhibited a high blocking voltage of 10.2 kV. The locations of electric field crowding and breakdown are also discussed.

Index Terms—Bevel mesa, junction termination extension (JTE), PiN, silicon carbide (SiC), simulation.

I. INTRODUCTION

Silicon carbide (SiC) is an attractive semiconductor for high-voltage, high-temperature, and high-frequency devices due to its excellent electrical and physical properties [1], [2]. In recent years, high-voltage 4H-SiC Schottky barrier diodes are in the market [3], and SiC junction field-effect transistors (JFETs) [4] and metal–oxide–semiconductor FETs (MOSFETs) [5], [6] have been intensively developed as power switches, mainly for 600- to 1700-V applications. To realize advanced electric power networks, very high-voltage (more than several-kilovolts) SiC bipolar devices are superior to unipolar devices in terms of lower on-resistance, owing to the effect of conductivity modulation.

In the literatures, several SiC diodes and switches with a very high breakdown voltage greater than 10 kV have been demonstrated [7]–[12]. However, fundamental studies on the junction termination structure for such very high voltage devices are still limited. Several edge termination structures have been investigated, involving guard rings [13], [14], multijunction termination extensions (multi-JTEs) [15]–[17], multi-JTEs combined with guard rings [18], and mesa combined with JTEs [7], [19]. Among these termination structures, the mesa structure combined with JTEs has been accepted as one of the most effective structures for very high voltage devices [20]. Effects in reducing electric field crowding should strongly depend on the mesa shape and the JTE dose, details that have not been reported.

In this paper, the mesa shape has been improved for the alleviation of electric field crowding at the mesa edge. The improved bevel mesa structure, formed by reactive ion etching (RIE), has a nearly vertical sidewall at the edge of the p-n junction and a gradual slope at the mesa bottom. A single-zone JTE has been employed, and the optimization of the JTE is also investigated by means of device simulation. Employing the improved bevel mesa structure combined with an optimized JTE, a 10-kV 4H-SiC PiN diode is realized. The fabrication process and the effectiveness of the improved bevel mesa structure are presented. In addition, a comparison between the simulated and experimental blocking voltages of PiN diodes is also discussed.

II. CONCEPT AND FABRICATION PROCESS OF THE IMPROVED BEVEL MESA STRUCTURE

Fig. 1 shows various termination structures employed for high-voltage SiC PiN diodes (the JTE region is not indicated). In the planar structure shown in Fig. 1(a), the electric field crowding takes place at the edge of the p-n junction (dotted circle A). In the vertical mesa structure shown in Fig. 1(b), the electric field crowding may occur at the right-angled corner of the mesa bottom, shown as the dotted circle B. By employing the bevel mesa structure shown in Fig. 1(c), the electric field crowding at the right-angled corner (dotted circle C) can be alleviated. However, the negative bevel mesa structure near the p-n junction (dotted circle D) enhances the electric field crowding. The improved bevel mesa structure fabricated in this paper is shown in Fig. 1(d): a rounded corner at the mesa bottom and a nearly vertical sidewall at the edge of the p-n junction are
Fig. 1. Various PiN structures. (a) Planar structure. (b) Vertical mesa structure. (c) Bevel mesa structure. (d) Improved bevel mesa structure.

Fig. 2. Fabrication process of the improved bevel mesa structure. (a) SiO$_2$ deposition and resist patterning. (b) SiO$_2$ wet etching. (c) RIE after resist removal. (d) SiC-improved bevel mesa structure.

Fig. 3. Cross-sectional SEM images of SiC mesa structures after RIE. (a) SiO$_2$ bevel mask formed by BHF etching. (b) Nearly vertical mesa formed by the nonoptimized RIE condition. (c) Improved bevel mesa formed with the optimized RIE condition.

Fig. 4. Structure of the 4H-SiC PiN diode.

III. DEVICE SIMULATION FOR THE OPTIMUM JTE REGION

Fig. 4 shows the schematic illustration of a 4H-SiC PiN diode simulated and fabricated in this paper. The JTE region was introduced in addition to the improved bevel mesa structure. To achieve high breakdown voltages, the JTE dose and the JTE length have been optimized by 2-D device simulation (ISE-DESSIS). The JTE dose should be optimized so that the JTE region is completely depleted at the desired reverse voltage to spread the equipotential lines toward the lateral direction. In the device simulation, the thickness and the donor concentration of the n$^-$ layer were fixed at 95 $\mu$m and $4 \times 10^{14}$ cm$^{-3}$, respectively. The height of the improved bevel mesa is 2 $\mu$m. The depth and the acceptor concentration of the p-layer were 0.8 $\mu$m and $1 \times 10^{20}$ cm$^{-3}$, respectively. The JTE dose was formed. With this structure, the electric field crowding caused by a right-angled corner and a negative bevel mesa structure can be minimized.

In this paper, the improved bevel mesa structure was formed by RIE with a SiO$_2$ bevel mask. Fig. 2 shows the fabrication process of the improved bevel mesa structure. The process consists of the following steps.

— SiO$_2$ was deposited on a SiC epilayer by plasma-enhanced chemical vapor deposition (PECVD), and a photoresist was patterned on SiO$_2$.
— SiO$_2$ was etched by BHF, and a SiO$_2$ bevel mask was formed.
— The photoresist was removed, and the SiC epilayer was etched by RIE with a CF$_4$–O$_2$ chemistry.
— SiO$_2$ was removed by BHF, leaving the improved bevel mesa structure.

The cross-sectional SEM image of a SiO$_2$ bevel mask formed by BHF etching is shown in Fig. 3(a). The rounded sidewall of SiO$_2$ was formed by isotropic wet etching. Fig. 3(b) and (c) shows the cross-sectional SEM images of SiC mesa structures after RIE. The shape of the SiC mesa structures strongly depends on the conditions of RIE. In the case of the nonoptimized RIE conditions, i.e., high RF power and high etching selectivity (CF$_4$: 5 sccm; O$_2$: 10 sccm; pressure: 50 Pa; RF power: 150 W; etching selectivity SiC/SiO$_2$: 1.8; etching rate of SiC: 310 nm/min), the rounded corner of the improved bevel mesa structure is not formed due to the high etching selectivity, as shown in Fig. 3(b). By optimizing the RIE conditions, i.e., low RF power and low etching selectivity (CF$_4$: 5 sccm; O$_2$: 10 sccm; pressure: 50 Pa; RF power: 75 W; etching selectivity SiC/SiO$_2$: 1.0; etching rate of SiC: 75 nm/min), the shape of the SiO$_2$ bevel mask is reproduced in the etched SiC.

The bevel angle of the present mesa structure was about 70°.

as shown in Fig. 3(c). The bevel angle of the present mesa structure was about 70°.
changed from $0.3 \times 10^{13}$ to $2.0 \times 10^{13}$ cm$^{-2}$ to investigate the dependence of the breakdown voltage on the JTE dose. The JTE length was changed from 100 to 300 $\mu$m to investigate the JTE length dependence. The SiC/SiO$_2$ interface charge was not considered in the simulation. A more accurate breakdown voltage should be obtained from the ionization integral in the simulation. However, the breakdown of a simulated device was defined when the maximum electric field in SiC reaches 3.0 MV/cm to simplify the simulation.

Fig. 5(a) shows the simulated breakdown voltage as a function of the JTE dose. The open circles, open triangles, and open squares denote the simulated breakdown voltage for the JTE length of 300, 200, and 100 $\mu$m, respectively. The simulated breakdown voltage exhibited a maximum value at the optimum JTE dose of $1.0 \times 10^{13}$ cm$^{-2}$ irrespective of the JTE length.

Fig. 5(b) depicts the JTE length dependence of the breakdown voltage with the optimum JTE dose of $1.0 \times 10^{13}$ cm$^{-2}$. The highest simulated voltages are 11.4, 13.5, and 14.0 kV for JTE lengths of 100, 200, and 300 $\mu$m, respectively. The simulated breakdown voltage begins to saturate at a JTE length of 200 $\mu$m, indicating that a 200-$\mu$m-long JTE region may be sufficient to realize 10-kV SiC devices.

IV. DIODE FABRICATION

Thick (90–125 $\mu$m) n$^-$ epilayers intentionally doped to $(2–7) \times 10^{14}$ cm$^{-3}$ have been grown on n-type 8° off-axis 4H-SiC(0001) substrates. Epitaxial growth was performed by horizontal hot-wall chemical vapor deposition (CVD) with a high growth rate of 45 $\mu$m/h [21]. The p-anode (depth: 0.8 $\mu$m) and the contact layer (depth: 0.2 $\mu$m) were formed by Al ion implantation with a concentration of $2 \times 10^{18}$ and $2 \times 10^{20}$ cm$^{-3}$, respectively. The single-zone JTE region (depth: 0.8 $\mu$m) was also formed by Al ion implantation at room temperature. The JTE dose was changed from $0.4 \times 10^{13}$ to $1.6 \times 10^{13}$ cm$^{-2}$ to investigate the dependence of the breakdown voltage on the JTE dose. After Al ion implantation, all the implanted species in the anode and in the JTE region were activated by annealing at 1700 °C for 30 min with a carbon cap to suppress surface roughening [22], [23]. The typical JTE length $L_{JTE}$ and the mesa diameter were (100–300) and (300–800) $\mu$m, respectively. For surface passivation, thermal oxidation was carried out in dry N$_2$O ambient at 1330 °C for 4 h [24], and, subsequently, a 2.0-$\mu$m-thick SiO$_2$ layer was deposited by PECVD. Ti/Al and Ni annealed at 1000 °C for 3 min were used as ohmic contacts on the anode and the cathode, respectively.

Fig. 6. Simulated equipotential lines (pitch: 250 V) in 4H-SiC PiN diodes for (a) low JTE dose of $0.4 \times 10^{13}$ cm$^{-2}$, (b) high JTE dose of $1.6 \times 10^{13}$ cm$^{-2}$, and (c) optimum JTE dose of $1.0 \times 10^{13}$ cm$^{-2}$.
V. Experimental Results and Discussion

To experimentally investigate the effectiveness of the improved bevel mesa structure, the breakdown voltages of the two mesa structures shown in Fig. 1(c) and (d) were compared. A thick n⁻ epilayer (donor concentration: $2 \times 10^{14}$ cm⁻³; thickness: 100 μm) was used. The diodes were processed at the same time except for the mesa formation. The bevel mesa structure has a bevel angle of 35°. Both diodes have a mesa height of 1.5 μm. The JTE dose of these diodes was $0.7 \times 10^{13}$ cm⁻², so that the electric field crowding should occur at the mesa edge.

Fig. 7 shows the dependence of the breakdown voltage on the JTE length of the bevel mesa and the improved bevel mesa. The breakdown voltage of the improved bevel mesa is clearly higher than that of the bevel mesa at any JTE length. This result means that the electric field crowding at the mesa edge in the normal bevel mesa was enhanced by the shallow bevel angle.

Fig. 8 shows the current density versus voltage characteristics of a 10-kV 4H-SiC PiN diode (at 10.2 kV). The donor concentration and the thickness of the n⁻ layer are $4 \times 10^{14}$ cm⁻³ and 92 μm, respectively. The diode has a mesa diameter of 350 μm and a mesa height of 2.0 μm. The JTE dose is $1.1 \times 10^{13}$ cm⁻² (700 keV; $3.19 \times 10^{12}$ cm⁻²; 450 keV; $2.78 \times 10^{12}$ cm⁻²; 280 keV; $2.1 \times 10^{12}$ cm⁻²; 170 keV; $1.28 \times 10^{12}$ cm⁻²; 100 keV; $7.91 \times 10^{11}$ cm⁻²; 55 keV; $4.69 \times 10^{11}$ cm⁻²; 26 keV; $2.57 \times 10^{11}$ cm⁻²; 10 keV; $1.34 \times 10^{11}$ cm⁻²), and the JTE length is 200 μm. The differential on-resistance obtained from forward characteristics was 95 mΩ·cm². Under the forward-bias condition, blue electroluminescence was mainly observed in the p-type anode layer.

The diode has exhibited a high blocking voltage of 10.2 kV, which corresponds to about 72% of a parallel-plane breakdown voltage for the epilayer. The reverse characteristics were measured by the dc voltage supply; thus, the breakdown was mostly destructive.

Fig. 9 represents the dependence of the experimental breakdown voltage on the JTE dose, measured at room temperature. Closed triangles and closed circles denote the experimental results for JTE lengths of 200 and 300 μm, respectively. The thickness and the donor concentration of an n⁻ layer are (85–100) μm and (3–5) $\times 10^{14}$ cm⁻³, respectively. With these epilayers, almost the same parallel-plane breakdown voltage of 14.0 kV is expected. A mesa diameter and a mesa height of a diode are 350 and 2.0 μm, respectively. The experimental results showed a good agreement with the simulated results in the trend. The difference in the absolute values of the breakdown voltage between simulated and experimental results may be caused by RIE damage or differences between the simulated model and the real device. For example, the mesa structure of the simulated model does not perfectly reproduce the shape of the experimental diodes, and the experimental donor concentration of n⁻ layer is not exactly the same as the value of $4 \times 10^{14}$ cm⁻³ in the simulation.

Fig. 10 reveals the photographs of PiN diodes just before breakdown for a low JTE dose of $7 \times 10^{12}$ cm⁻² ($V_B = 4.0$ kV; Fig. 10(a)) and a high JTE dose of $1.6 \times 10^{13}$ cm⁻² ($V_B = 3.0$ kV; Fig. 10(b)). Electroluminescence, as a result of impact ionization, was observed on the diode just before breakdown.
multiplication, was observed at the mesa edge for the low JTE dose [Fig. 10(a)] and at the outer edge of the JTE region for the high JTE dose [Fig. 10(b)]. This observation is in good agreement with the simulation, as shown in Fig. 6.

VI. CONCLUSION

We have simulated and fabricated high-voltage 4H-SiC PiN diodes with an improved junction termination structure. The fabrication process of an improved bevel mesa structure, a nearly vertical sidewall at the p-n junction and a rounded corner at the mesa bottom, was presented. For the mesa preparation, a SiO$_2$ bevel mask was used in the RIE process. The key RIE conditions for the formation of the improved bevel mesa structure were low RF power (75 W) and low SiC/SiO$_2$ etching selectivity of 1.0. The dose and the length of a single-zone JTE were optimized by means of device simulation. The minimum JTE length and the optimum JTE dose obtained from the simulation of 10-kV PiN diodes were 200 $\mu$m and 1.0 $\times$ 10$^{13}$ cm$^{-2}$, respectively. 4H-SiC PiN diodes with a JTE dose of (0.4–1.6) $\times$ 10$^{13}$ cm$^{-2}$ have been fabricated on thick and lightly doped epilayers grown at a high growth rate of 45 $\mu$m/h. A 4H-SiC PiN diode (n$^+$ layer: 4 $\times$ 10$^{15}$ cm$^{-3}$, 92 $\mu$m) with an improved bevel mesa structure (JTE dose: 1.1 $\times$ 10$^{13}$ cm$^{-2}$; JTE length: 200 $\mu$m) exhibited a high blocking voltage of 10.2 kV. The dependence of the breakdown voltage on the JTE dose observed in the fabricated diodes showed a good agreement with the simulated results in the trend. The location of breakdown was discussed in terms of simulated equipotential lines and luminescence observed in experiments.

REFERENCES


Toru Hiyoshi was born in Shizuoka, Japan, on August 14, 1984. He received the B.E. degree in electrical engineering in 2007 from Kyoto University, Kyoto, Japan, where he is currently working toward the M.E. degree.

His current research activity includes fabrication and designing of high-voltage SiC PiN diodes, SiC device simulation, and the characterization of deep levels in SiC.

Tsunomo Hori was born in Osaka, Japan, on September 11, 1977. He received the B.S. and M.S. degrees from Kyoto University, Kyoto, Japan, in 2000 and 2002, respectively.

Since April 2002, he has been with Sumitomo Special Metals, Ltd. (now Hitachi Metals, Ltd.), Osaka, Japan. From October 2004 to March 2007, he was dispatched to Kyoto University as a Corporate Researcher and was engaged in the research on chemical vapor deposition of 4H-SiC. His current research activity includes chemical–mechanical polishing and the characterization of SiC.
Jun Suda was born in Ashikaga, Japan, in 1969. He received the B.E., M.E., and Ph.D. degrees from Kyoto University, Kyoto, Japan.

From 1992 to 1997, he worked on the growth of ZnSe-based semiconductors by molecular-beam epitaxy and the characterization of ZnMgSSe strained quantum well structures for optoelectronic applications. In 1997, he began the research on group-III nitride semiconductors (III-N) and SiC as a Research Associate with Kyoto University, where he is currently an Associate Professor with the Department of Electronics Science and Engineering. He has authored or coauthored over 55 publications in peer-reviewed journals and international conferences. His research interests include the heteroepitaxial growth of III-N, the functional integration of III-N and SiC materials by precise control of the heterointerface, the design of wide bandgap semiconductor devices, and the characterization of device structures by scanning-probe microscopy.

Tsunenobu Kimoto (M’03–SM’06) received the B.E. and M.E. degrees in electrical engineering in 1986 and 1988, respectively, and the Ph.D. degree based on his work on SiC epitaxial growth, characterization, and high-voltage diodes in 1996 from Kyoto University, Kyoto, Japan.

In April 1988, he joined Sumitomo Electric Industries, Ltd., where he conducted research on amorphous Si solar cells and semiconducting diamond materials. In 1990, he started his academic career as a Research Associate with Kyoto University, where he is currently a Professor with the Department of Electronic Science and Engineering. From September 1996 through August 1997, he was a Visiting Scientist with Linköping University, Linköping, Sweden, where he was involved in fast epitaxy of SiC and high-voltage Schottky diodes. He has authored over 250 papers published in scientific journals and presented in international conference proceedings. His main research activity includes SiC epitaxial growth, optical and electrical characterization, ion implantation, MOS physics, and high-voltage devices. He has also been involved in nanoscale Si devices and novel materials for nonvolatile memory.

Dr. Kimoto is a member of Japan Society of Applied Physics, the Institute of Electronics, Information, and Communication Engineering, and the Institute of Electrical Engineering.