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Charge Distribution in Termination Area of 4H-SiC Diodes Analyzed by Measuring Depletion-layer Capacitance

Hiroyuki Matsushima[1], Hiroyuki Okino[1], Kazuhiro Mochizuki and Renichi Yamada[1]

[1] Hitachi, Ltd., Research & Development Group, Center for Technology Innovation - Electronics,
1-280, Higashi-koigakubo, Kokubunji-shi, Tokyo, 185-8601 Japan
Phone: +81-42-323-1111 E-mail: hiroyuki.matsushima.fw@hitachi.com

Abstract

A distribution of positive charge density was analyzed in the SiO_2/SiC interface of the termination area after reverse-bias stressing. An increase in positive-charge density caused a change in breakdown voltage of test 4H-SiC PN diodes. By using Measuring Depletion-layer Capacitance (MDC) of the diodes, a change in capacitance after bias stressing was measured. This result showed that the distribution of positive charge was not uniform but a large quantity at the termination area applied with a high electric field.

1. Introduction

Silicon-carbide (SiC) power devices have several reliability issues that silicon power devices do not. One is a decrease in breakdown voltage (V_{BD}) under reverse-bias stressing at high temperature [1]. The V_{BD} decrease was considered to be due to a change in charge density in the termination area. However, an accurate position of a change in a charge was not clarified since the change was only indicated by *I-V* characteristics. To show the positions of the changes experimentally, the authors previously proposed a novel method: Measuring Depletion-layer Capacitance (MDC) in the termination area of SiC-PN diodes [2]. The measurements showed that positive-charge density increased in the SiO_2/SiC interface of the termination area after reverse-bias stressing. It was concluded that this increase changes the distribution of the electric field in the termination area and thus causes a change in V_{BD}.

In this study, a distribution of positive charge density after reverse-bias stressing was clarified by using MDC in the termination area of SiC-PN diodes with different termination structures. A change in capacitance (ΔC) after stressing showed that the positive charge density in the SiO_2/SiC interface of the termination area was not uniform but a large quantity at the termination area applied with a high electric field.

2. Experimental method

Schematic cross sections of test PN diodes are shown in Fig. 1. The diodes were fabricated on n-type epitaxial layers grown on 4°-off-axis 4H-SiC (0001) substrates. The donor concentration of the epitaxial layers was 3.0×10^{15} cm^{-3}, and the thickness of the layers was 30 µm. The termination structure in the diodes was a two-zone junction-termination extension (JTE) [3]. The JTE was formed by aluminum implantation. The lower and higher accepter concentration areas were named “TM1” and “TM2”, respectively. Three structures of the JTE were fabricated, which were formed that has different TM1 width (W_{TM1}) and TM2 width (W_{TM2}) but the same total width of the termination area. A bias stress of 2.6 kV was applied to the diodes at 150°C for a stress time of 96 hours.

3. Results and discussion

Characteristics before bias stressing

C-V characteristics before bias stressing of PN diodes with different W_{TM1} and W_{TM2} are shown in Fig. 2, which shows no capacitance difference under 1100 V but a difference above 1100 V. The authors’ previous work indicated that capacitance was changed by increasing positive charge density in the termination area [2]. However, the quantity of charge density was the same since the characteristics were measured before bias stressing. For this rea-

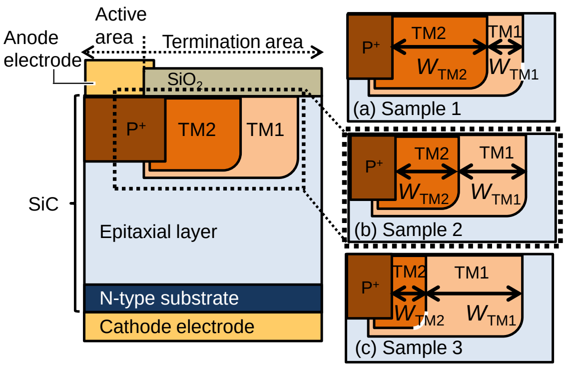

Fig. 1 Schematic cross sections of test PN diodes with different TM1 width (W_{TM1}) and TM2 width (W_{TM2}) but the same total width of termination area.

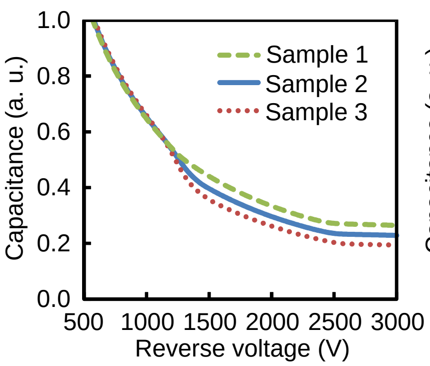

Fig. 2 *C-V* characteristics before bias stressing of PN diodes with different W_{TM1} and W_{TM2}.

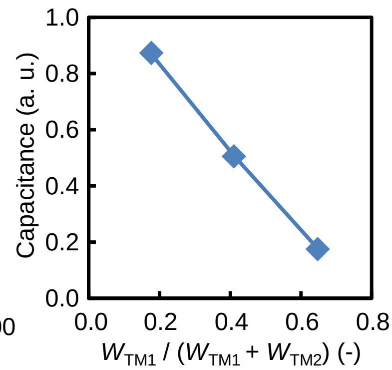

Fig. 3 Dependency of capacitance at 1500 V on W_{TM1} / (W_{TM1} + W_{TM2}).

son, the difference shown in Fig. 2 reflects the difference in termination structure. To clarify where the difference occurred in the termination area, dependency of capacitance at 1500 V on W_{TM1} / (W_{TM1} + W_{TM2}) is plotted in Fig. 3. When the W_{TM1} becomes wide, the capacitance becomes small. Simulated cross sections of the diodes are shown in Fig. 4. Three simulations were performed with the same charge density. When reverse voltage was 1500 V, TM1 depleted fully in the three different structures. From these results, the difference shown Fig. 2 indicates the depletion of TM1.

Characteristics after bias stressing

I-V characteristics of the PN diode before and after stressing are shown in Fig. 5. This figure shows that V_{BD} of the diode changed after stressing. *C-V* characteristics of the diode before and after bias stressing are shown in Fig. 6. The inset in Fig. 6 shows ΔC-V characteristic. These figures show that two changes appeared at around 1100 V (ΔC_1) and around 2500 V (ΔC_2). To clarify where the two changes occurred, *C-V* characteristics of diodes with different W_{TM1} and W_{TM2} were measured. Dependencies of ΔC_1 on W_{TM1} / (W_{TM1} + W_{TM2}) and ΔC_2 on W_{TM2} / (W_{TM1} + W_{TM2}) are plotted in Fig. 7. When W_{TM1} becomes wide, ΔC_1 becomes large. When W_{TM2} becomes small, ΔC_2 becomes small. From these results, it is concluded that ΔC_1 and ΔC_2 were caused by changes in charges in TM1 and TM2, respectively.

The relationships between simulated full depletion voltages (V_{FD}) and a change in positive charge (ΔQ) are shown in Fig. 8. The V_{FD} was defined in a voltage at which TM1 or TM2 depleted fully. In the simulation, positive-charge density was set uniformly in the SiO_2/SiC interface of the termination area. TM2 was not depleted fully when ΔQ was under 5.0 × 10^{12} cm^{-2}. When ΔQ becomes large, V_{FD} becomes small. In the case of the same positive-charge density, V_{FD} of TM2 was higher than that of TM1 because acceptor concentration of TM2 was higher than that of TM1. From *C-V* characteristics (Fig. 6), the V_{FD} of TM1 and that of TM2 were 1160 V and 2400 V, respectively. The V_{FD} were obtained by ΔC_1 and ΔC_2. When the V_{FD} of TM1 was 1160 V, ΔQ was 1.0 × 10^{12} cm^{-2}. When the V_{FD} of TM2 was 2400 V, ΔQ was 9.0 × 10^{12} cm^{-2}. Since the electric field in TM2 region was higher than that in TM1 (inset in Fig. 8), ΔQ in the SiO_2/SiC interface on the TM2 was larger than that on the TM1. From the results, the distribution of positive charge was not uniform but a large quantity at the termination area applied with a high electric field.

4. Conclusions

A distribution of positive charge density after reverse-bias stressing was clarified by using Measuring Depletion-layer Capacitance (MDC) in the termination area of SiC-PN diodes with different termination structures. The distribution of positive-charge density was not uniform but a large quantity at the termination area applied with a high electric field. This result indicates that MDC is an effective method to analyze changes in charge density of the termination area.

References

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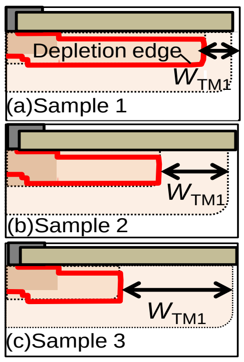

Fig. 4 Simulated cross sections of diodes at 1500 V.

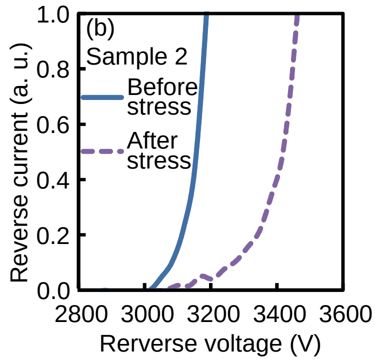

Fig. 5 *I-V* characteristics of PN diode before and after bias stressing.

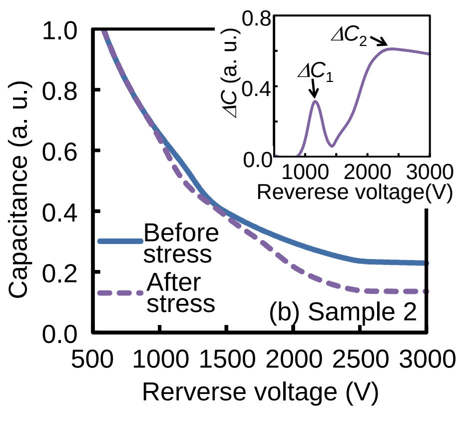

Fig. 6 *C-V* characteristics of PN diode before and after bias stressing. Inset shows ΔC-V characteristic.

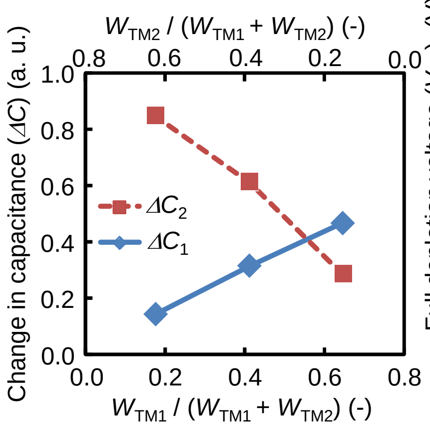

Fig. 7 Dependencies of ΔC_1 and ΔC_2 on W_{TM1} / (W_{TM1} + W_{TM2}) and W_{TM2} / (W_{TM1} + W_{TM2}), respectively.

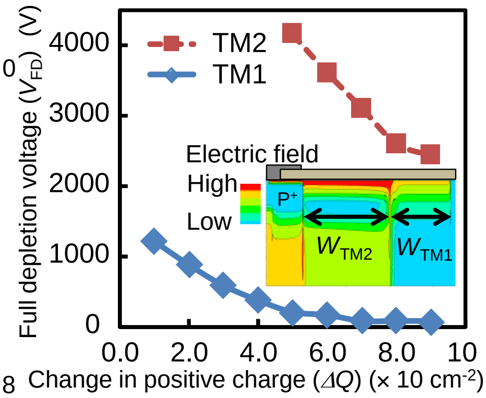

Fig. 8 Relationships between simulated full depletion voltage (V_{FD}) and change in positive charge (ΔQ). Inset is simulated cross section at 2600 V.