# Heavy-Ion-Induced Charge Enhancement in 4H-SiC Schottky Barrier Diodes

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**Abstract**

Heavy ion induced anomalous charge collection was observed in 4H-SiC Schottky Barrier Diodes (SBDs). This result is a new process of Single Event Burnouts (SEBs) in the case of incident ions on SiC-SBDs. It is suggested that the range of the incident ions with respect to the thickness of the epi-layer, ion energy, and electric-field intensity of the SBD is key to understanding this observation and understanding the SEB mechanism.

## 1. Introduction

Silicon carbide (SiC) is regarded as a promising candidate for electronic devices requiring high radiation tolerance (rad-hard devices). Ohshima *et al*. [1] reported that SiC Metal-Oxide-Semiconductor (MOS) Field Effect Transistors (FETs) showed higher gamma-ray radiation resistance than Si MOSFETs. It was also reported that SiC Static Induction Transistors (SITs) [2] and Metal-Semiconductor FETs (MESFETs) [3]can be operated up to 10 MGy without significant degradation to their electrical characteristics. These results indicate that SiC has superior radiation tolerance from the point of view of Total Ionizing Dose effects (TIDs). For the development of rad-hard SiC devices, it is necessary to understand the response of their performance when dense charge is generated in them by an incident ion, resulting in Single Event Effects (SEEs). Permanent malfunctions are induced in power devices by SEEs, and the probability of SEEs increases with increasing electric field in the device. Since the electric field in SiC power devices must be higher than in Si power devices, it is very important to clarify SEEs in SiC devices. In a previous study on ion incidence effects, Nava *et al*. reported charge generated in SiC Schottky diodes by He ions and its response to damage creation for particle detector applications [4]. Charge generated in SiC pn diodes by heavy ions was also reported [5]. Previously, performance of the device was also affect by a high defect density. However, recently, several Schottky Barrier Diodes (SBDs) are commercially available by the improvement of crystalline quality.

For SEEs, Scheick*et al*. reported that a catastrophic failure appeared in SiC-SBDs caused by protons without any steady increase of leakage current, and a percolation theory was proposed to explain this effect [6]. The Single-Event Burnouts (SEBs) were also observed with high LET (>10 MeV•cm$^2$/mg) heavy ions in spite of the SiC-SBDs having no current sustaining mechanism such as in Bipolar Junction Transistors (BJTs) [7]. Kuboyama *et al*. showed that the SEB caused by anomalous charge collection by incident heavy ions with a high LET (>10 MeV•cm$^2$/mg) [8]. They proposed that the anomalous charge collection from SiC-SBD is caused by Trap Assisted Tunneling (TAT). At present, experimental data for understanding the exact mechanisms of SEEs in the SiC-SBDs are very scarce and SEB mechanisms of SiC-SBDs have not been fully understood.

The epitaxial layer (epi-layer) thickness of SiC-SBDs used in previous studies were thinner than the incident ion range [6, 8]. The thicker epi-layer is required for higher voltage devices. Therefore, in this study, we show the heavy ion induced charge collection from thicker epi-layer than previous studies. To reveal SEB mechanisms, we investigate the applied bias dependence of the charge collection on SiC-SBDs.

## 2. Experimental

The SiC-SBDs used in this study were fabricated on an n-type 4H-SiC epi-layer. The n-type epi-layer was grown on an n-type 4H-SiC substrate (Si-face, 8˚ off) using a Chemical Vapor Deposition (CVD) technique [9]. The thickness and doping concentration of the epi-layer are 30 μm and 2-3x10$^{15}$ cm$^{-3}$, respectively. A Mo contact with a thickness of 50 nm was used as the anode of the SiC-SBD. The bonding pad on the Mo contact was made by Al (2 μm thick). The bonding pad area is 1 mm$^2$. Generally, the electric-field is concentrated around the edge of the bonding pad.To avoid degradation of the breakdown voltage by the electric-field concentration, commercial SiC-SBDs have a Junction Termination Extension (JTE) or a guard ring structure near the edge of the bonding pad. In this study, the SiC-SBD has a 3zone-JTE structure around the edge of the bonding pad to moderate the electric-field concentrate.

Fig. 1 shows a schematic view of the experimental setup used in this study. We measured the collected charge induced by heavy ions in the SiC-SBD from its cathode in the same manner as Kuboyama *et al*. [8]. The SiC-SBD was mounted on a chip carrier with two strip-lines with short bonding wires from the anode to the strip-line kept under reverse bias conditions. The anode was grounded and the cathode biased from +400 V to +1000 V with 100 V to 200 V steps by a high-voltage supply via a charge-sensitive pre-amplifier. We used an ORTEC 142C for the charge-sensitive pre-amplifier. Collected charge signals from the pre-amplifier were shaped as voltage-pulses having pulse-heights proportional to the collected charges by an ORTEC 572 spectroscopic amplifier after attenuation by a 20 dB attenuator. The pulse-height distribution analyzed by PHA basically corresponds to the collected charge distribution. The absolute value of the collected charge was calibrated experimentally using ions from an accelerator incident on a Si-Solid State Detector (SSD) with the same measurement circuit used in this experiment. At the same time, the voltage-pulse waveform from the spectroscopic amplifier was stored by an oscilloscope to monitor pile-up waveforms and malfunction of the measurement circuit.

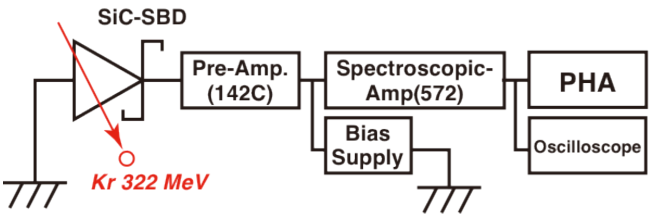


Fig. 1 The schematic view of experimental setup. The anode was grounded and the cathode biased by a high-voltage supply via a charge-sensitive pre-amplifier (ORTEC 142C). Collected charge signals from the pre-amplifier were shaped as voltage-pulses having pulse-heights proportional to collected charges by spectroscopic amplifier of an ORTEC 572. Pulse-heights were analyzed by the PHA. At the same time, voltage-pulses waveform from spectroscopic amplifier was stored by oscilloscope.

The heavy ion irradiation was performed using the AVF cyclotron at the Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) in Japan Atomic Energy Agency (JAEA), Takasaki [10]. The SiC-SBDs were irradiated i4cuum chamber with a broad beam of 322 MeV Krypton (Kr) at an irradiation angle of 0 degrees. The beam flux (7 ions/device/s) was low enough to avoid pile-up of the ion induced charge collection signals.
The absolute value of the beam flux was measured using a Si-SSD with the measurement circuit used in this experiment. The projected ion range in the SiC was 26 µm evaluated by a SRIM calculation and is almost the same as the thickness of the SiC epi-layer.

## 3. Experimental Results

Fig. 2 shows the collected charge spectra from the SiC-SBD. The vertical axes are ion induced pulse generation cross-section. The horizontal axis shows the collected charge. Normally the collected charge spectrum might have a mono-peak similar to that found in the Si-SSD spectrum. In fact, an ion-induced mono-peak in SiC-SBD was observed in a previous study [8]. However, we observe two major peaks under bias conditions higher than 400 V as shown in Fig.2. The first peak exists at the smaller value of 6.2 pC in every bias condition. The upper limit of the first peak (6.2 pC) corresponds to the fully-stopped 300 MeV of Kr ion induced charge in 4H-SiC.
The second peak value increases with applied reverse bias up to 600 V for the SiC-SBD, and finally saturated. The saturated second peak values are in the 15-18 pC range which is more than three times the charge induced by the Kr. A ratio between the total cross-section of the charge correction and ion fluence was almost one under all bias conditions. This result implies that an incident heavy ion induces a charge collection signal.

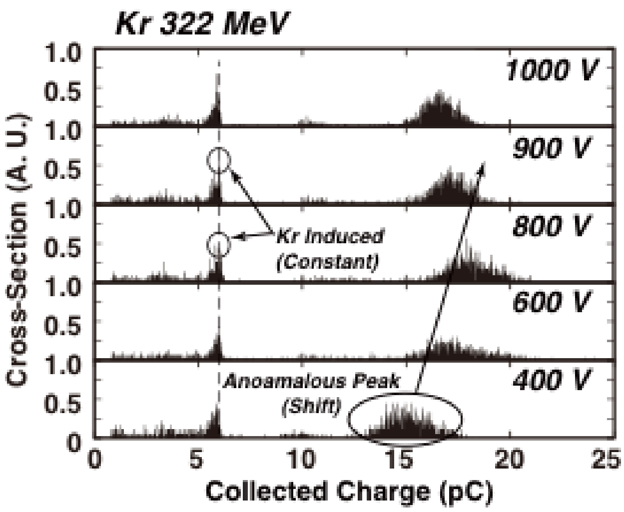


Fig. 2Collected charge spectra from the SiC-SBD.

We verify that the second peak was induced by the heavy ion. Fig. 3 shows examples of charge collection pulse-waveforms shaped by the spectroscopic amplifier. A bias of 400 V was applied to the SiC-SBD during the measurement. These pulse-heights correspond to the value of collected charge from the SiC-SBD. The black line shows the highest charge collection of the 2nd peak. For comparison, charge collection pulse-waveform of the first peak is superimposed in Fig. 3 as a gray line. These waveforms show typical pulse-waveforms without a pile-up of charge collection signal from the charge amplifier. If the second peak consists of pile-up components, the black waveform had an artifact shoulder at tail. For other waveforms, there were no artifact shoulders in this measurement. In addition, we could not find any malfunction of this measurement setup in pre- and post- energy spectrum measurements of Kr ions by using Si-SSD.

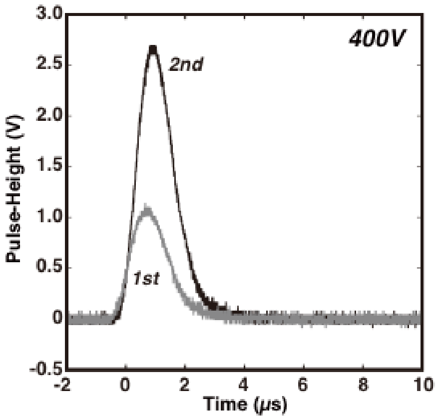


Fig. 3Charge collection pulse-waveforms shaped by the spectroscopic amplifier under the bias condition of 400 V. The black line shows the highest charge collection in the charge collection distribution under the bias condition of 400 V. Charge collection pulse-waveform of first peak in the charge collection distribution is superimposed.

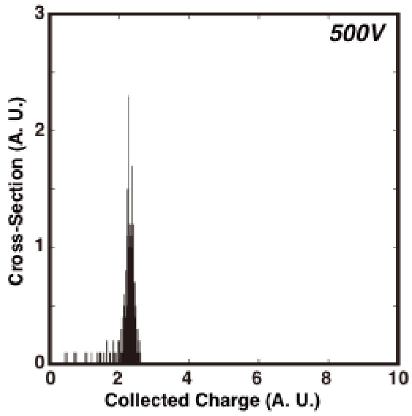


Fig. 4The collected charge spectrum from the post-irradiated the SiC-SBD induced by 5.4 MeV α particle from $^{241}$Am under the bias condition of 500 V.

We measured the collected charge induced by heavy ions with lower energy. Fig. 4 shows the collected charge spectrum from the post-irradiated SBD induced by 5.4 MeV α particle from $^{241}$Am under the bias condition of 500 V with the same measurement setup. The projected range of α particle in the SiC was evaluated to be 16 μm by SRIM calculation and is longer than the depletion width. There was no anomalous second peak in the α particle induced charge spectrum. We obtained typical 5.4 MeV α particle induced charge spectrum in SiC devices with low noise. This result also indicates that the measurement system works well.
From comparison between pre- and post- irradiation I-V characteristics of the SiC-SBD, we could not detect any permanent damage, i.e., a short of the Schottky contact. Therefore, we conclude that the second peaks are neither due to pile-up signals of ion induced charge collection nor steady leakage current signal. In other words, we can say that the anomalous charge collection signals were triggered by heavy ion incidence. We observed the anomalous collected charge peaks (2nd peaks) induced in SiC-SBDs by heavy ions in the case of the ion range nearly equal to epi-layer thickness.

## 4. Discussion

The experiment showed the anomalous charge collection peak. Moreover, the ion induced charge was enhanced in the SiC-SBD. The anomalous charge collection from SiC-SBDs was not observed in a previous reported study [8]. We can explain this discrepancy by a difference in the epi-layer thickness.
The epi-layer thickness of the SiC-SBD used in this study is 30 μm, while the epi-layer thickness of SDP06S60 is 3.7 μm. The depletion region of the SiC-SBD in this study is longer than SDP06S60. Thus the SDP06S60 could not collect the separate anomalous charge collection signal [8] even if the ion induced charge was enhanced in the epi-layer since the biased region was too short to a collect sufficient number of carrier. In other words, we could obtain the detail process of SEB by using the thick epi-layer. This result is a new process of the SEB in the case of incident ions in thick epi-layer of SiC-SBDs.
We would like to mention mechanisms of the charge enhancement in this section. In the case of Si power MOSFETs and BJTs, ion induced second peaks as an injection charge due to an activated parasitic bipolar transistor in the devices were reported [7, 11]. Constitutionally, however, parasitic bipolar effects dose not appear in SBDs.
Kuboyama *et al*. suggested that the anomalous charge collection in SiC-SBDs caused by Trap Assisted Tunneling (TAT) [8]. The TAT occurs under a high electric-field condition induced by ion incident. In addition, as shown in the previous simulation in [8], the high electric-field intensity produced by ion reached to a high enough electric-field intensity to induce impact ionization in epi-layer. These previous results suggest that the high electric-field induced by an incident ion in the SiC-SBD may be a possible reason for the charge enhancement since the higher electric-field induced the impact ionization and/or the TAT. Although future studies will have to reveal the effective mechanisms for the charge enhancement, ion induced electric-field may trigger charge enhancement and anomalous charge collection. In the case of α particles, we could not obtained

the second peak. Thus, we can conclude that key of this anomalous charge collection mechanism is related to the range of incident ions with respect to the thickness of the epi-layer, ion energy, and electric-field concentration.

## 5. Conclusion

We measured the bias dependence of the collected charge distribution induced by heavy ions in SiC-SBD fabricated in thick epi-layer. Anomalous collected charge peaks (2nd peaks) induced by the heavy ions were observed for the first time. The new process of the SEB was observed in the case of incident ions on thick epi-layer of SiC-SBDs. Previous results suggest that the high electric-field induced by incident ion on the SiC-SBD may be a possible reason for the charge enhancement. The higher electric-field may enhance the ion induced charge due to impact ionization and/or the TAT. Future studies will have to reveal the effective parameter for the anomalous charge collection on the SiC-SBD, since an increase of the collected charge may trigger SEB in any devices whatever the charge collection mechanism.

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