Proton Radiation Effects in 4H-SiC Diodes and MOS Capacitors

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***Abstract*—Proton irradiation is used to probe the physics of 4H-silicon carbide (SiC) Schottky barrier diodes (SBDs) and negative channel metal oxide semiconductor (nMOS) capacitors for the first time. Both 4H-SiC SBD diodes and SiC MOS structures show excellent radiation tolerance under high-energy, high-dose proton exposure. Unlike for SiC JBS diodes, which show a strong increase in series resistance after proton irradiation, these SiC SBDs show very little forward bias I–V degradation after exposure to 63.3 MeV protons up to a fluence of 5×10^{13} p/cm^2. An improvement in reverse leakage current after irradiation is also observed, which could be due to a proton annealing effect. The small but observable increase in blocking voltage for these SiC SBDs is attributed to a negative surface charge increase, consistent with earlier gamma results. The resultant $Q_{\rm eff}$ change of 4H-SiC nMOS capacitors under proton irradiation was used to quantify the radiation induced changes to the blocking voltage in the SBD diodes in MEDICI simulations, and showed a good agreement with the experimental data. Characterization of these capacitors also suggests that 4H-SiC MOS structures are radiation hard.**

***Index Terms*—Negative channel metal oxide semiconductor (nMOS) capacitors, Schottky barrier diodes (SBDs).**

I. Introduction

THE PHYSICAL and electronic properties of silicon carbide (SiC) make it an attractive semiconductor material for high-temperature, radiation resistant, and high-power-handling electronic devices [1]–[3]. Previous studies on radiation effects in SiC devices show that SiC-based neutron and charge particle detectors [4]–[6], dosimeters [7], and spectrometers, have excellent potential for operating in extreme radiation environments [6]–[9].

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High-energy particle bombardment, such as by proton, neutron, electron and pion irradiation, can create vacancies, interstitials, and their associated defects. These radiation-induced defects often produce energy states in the bandgap and therefore can influence the electrical properties of materials and devices. Different radiation-induced defects can be observed if the particle type, energy, fluences are changed, or if the exposure temperature and material processing differ [10]–[12]. We have previously studied the effects of high-dose gamma irradiation on 4H-SiC Schottky barrier diodes (SBD) and MOS capacitors [13], [14], and proton irradiation on 4H-SiC Junction Barrier Schottky (JBS) diodes [15]. There was little observed degradation for the SiC SBDs after gamma radiation, but interestingly, a significant degradation of series resistance (R_S) observed in forward voltage drop and an improvement in the reverse characteristics after proton irradiation of the JBS diodes, potentially compromising their usefulness in power switching systems operating in extreme environments. Given the closely related structure of SBD and JBS diodes (a JBS diode is composed of both pn and SBD diodes), this anomalous difference in their radiation response was particularly surprising, and has not to date been fully understood. In addition, the measured blocking voltages (BV) of the post proton-irradiated diodes consistently increased by about 200 V compared to the pre-irradiation devices, a rare instance when radiation exposure actually improves device performance [15]. In this paper, we present new results of proton radiation effects on both 4H-SiC SBDs and MOS capacitors aimed at providing a better understanding of these anomalous results and the unique physics of the SiC-SiO_2 interface.

II. Experiment

Circular SBD diodes with diameters ranging from 100 μm to 400 μm were fabricated on 4H SiC n^+ wafers with a 10 μm 1×10^{15} cm^{-3} nitrogen doped n^- epitaxial layer obtained from Cree, Inc. A high quality thermal oxide followed by 1 μm converted poly-Si layer was used for field passivation. Ni was deposited for the backside ohmic contacts and annealed at 1100 °C for 2 min in vacuum. Schottky contact openings were formed by selective reactive ion etching (RIE) followed by a buffered oxide etch (BOE) through the passivation, and immediate loading into the metallization chamber for Ni schottky contact evaporation. Schottky contacts were completed with Ti and Au overlayers. This SBD metallization scheme was also used in the JBS diodes to facilitate unambiguous comparisons.

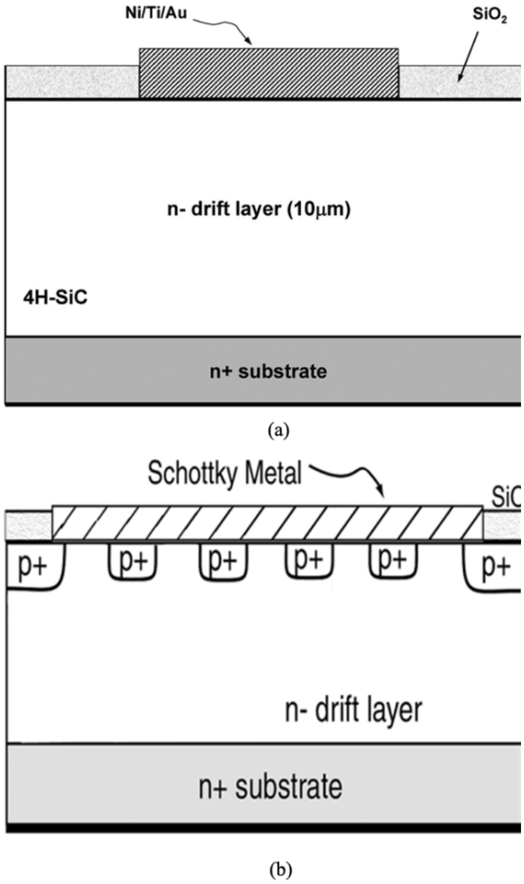

Fig. 1. (a) Schematic device cross section of the 4H-SiC SBD diode and (b) schematic device cross section of the 4H-SiC JBS diode.

A schematic cross section of the device structure is shown in Fig. 1(a). (b) is a schematic cross section of the JBS diode for later comparison. JBS diodes contain active p-n regions among n-SiC Schottky regions, which can help improve reverse leakage of SBDs while obtaining similar forward performance as SBDs at the same time. The design and fabrication of JBS diodes are more complicated than that of SBDs though. The space between each p-region and the width of the p-region need to be carefully optimized in order for the device to work properly.

4H-SiC nMOS capacitors were also fabricated to better understand the effects of radiation on the SiC-SiO_2 interface charge density. Prior to oxidation, the samples were cleaned using a standard RCA cleaning process followed by a dip in a buffered hydrogen fluoride solution. After the cleaning, the samples were immediately loaded into a double-walled oxidation furnace in an Ar atmosphere at room temperature for oxidation. Dry oxidation was performed at 1150 °C for 2 h to produce a 35 nm thick oxide layer. Samples were then loaded in Ar at 900 °C, and slowly raised to 1175 °C in Ar for the NO passivation step [16]. The temperature was kept at 1175 °C for 2 h in NO. Two gate metal layers (100 nm of Mo plus 100 nm of Au) were deposited onto the oxide by conventional sputtering to form the MOS capacitors. For detailed fabrication information on the 4H-SiC MOS structures, see [14]. All MOS capacitors were circular, with diameters of either 70, 200 or 340 μm.

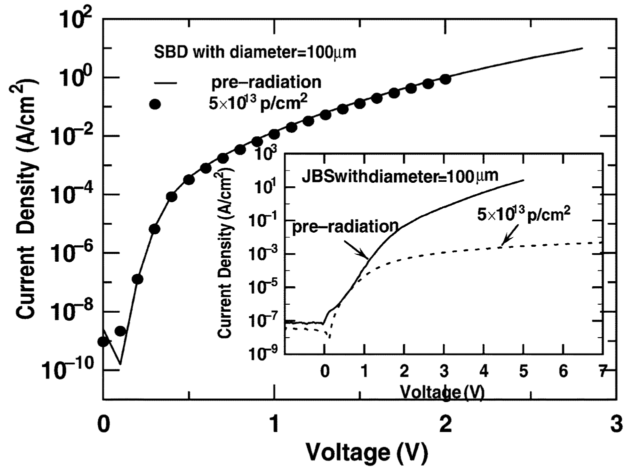

Fig. 2. Forward current-voltage characteristics of the 4H-SiC SBDs both before and after proton irradiation. Inset: forward current-voltage characteristics of 4H-SiC JBS diodes before and after proton irradiation.

Proton irradiation was performed at the Crocker Nuclear Laboratory cyclotron located at the University of California at Davis, using 63.3 MeV protons. The SBDs and MOS capacitors were exposed to a fluences as high as 5×10^{13} p/cm^2. Dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. The radiation source (Ta scattering foils) located several meters upstream of the target establish a beam spatial uniformity of about 15% over a 2.0 cm radius circular area. Beam currents from about 5 pA to 50 nA allow testing with proton fluxes from 1×10^6 to 1×10^{11} $\mathrm{proton/cm^2 s}$. The dosimetry system is accurate to about 10%. At proton fluences of 1×10^{12} p/cm^2 and 5×10^{13} p/cm^2, the measured equivalent total ionizing dose was approximately 135 and 6,759 krad(Si), respectively. The SBDs and MOS capacitors were irradiated with all terminals floating. Previous results suggest that this does not have any impact on the results.

The forward and reverse current-voltage characteristics were measured with an Agilent 4155 Semiconductor Parameter Analyzer. Both forward and reverse characteristics were measured before and after irradiation. Reverse breakdown measurements were performed using a Tektronix 371 high-power curve tracer. The simultaneous Hi-Lo C–V (capacitance-voltage) method was used to measure effective oxide charge and the interface state density of the SiC-SiO_2 interface. High-frequency (Hi) C–V curves were measured at 100 kHz at room temperature to obtain the total effective oxide charge $(Q_{\rm eff})$, which includes the oxide fixed charge, the oxide trapped charge, and any mobile ionic charge. Simultaneous Hi-Lo measurements were made at room temperature in order to extract the interface trap density (D_{it}) near the semiconductor conduction band edge.

III. Results and Discussion

A. SBD Diodes

All results in this section are based on measurements of 12 Schottky Barrier Diodes with diameters of 100 μm, distributed across two different dies. The results were quite uniform among all of the diodes. Fig. 2 shows a typical forward-bias characteristics of a SBD with oxide passivation, both before and after proton irradiation. The magnitude of the forward current density is repeatably observed to be slightly decreased for the irradiated sample, and can be attributed to the introduction of radiation induced trap levels in the forbidden gap. Such trap levels can readily capture free majority carriers, leading to a lower net current conduction [15], [17], [18]. As can be seen, the low injection portion of the J–V curve changes very little after radiation, and the ideality factor remains about 1.02 while the barrier height remains around 1.05 V, suggesting that proton radiation didn't degrade the Schottky contact. This is consistent with our previous results on JBS diodes. Note, however, that the high injection portion of the J–V characteristics show only negligible changes at 5×10^{13} p/cm^2 fluence, which is profoundly different from that observed with proton irradiated JBS diodes (inset of Fig. 2), where the series resistance (R_S) increased dramatically following proton exposure [15]. The inset of Fig. 2 shows the I–V characteristics of a typical JBS diode both before and after proton irradiation. The R_s extracted from I–V curve based on thermionic-emission theory changes from 25 Ω to 7.2 mΩ for JBS diodes. Considering the differences in the structures of the SBD and JBS diodes, this suggests that the R_S change observed in the JBS diodes could be due to the radiation-induced degradation of the interface between metal and the p-type 4H-SiC. Another possibility is that the p-type 4H-SiC material itself (found in pn junction portion of the JBS device) responds differently to protons than does the n-type 4H-SiC region. Auger Electron Spectroscopy (AES) characterization of both the JBS diodes and the SBD diodes show no difference in the metal layers before and after proton irradiation. This suggest that there is no obvious metal composition change due to proton irradiation. However, during the process of preparing the sample for AES test we found that some clusters stay on the surface of JBS diodes that were not removable by metal removal steps. Similiar clusters of stack faults (SF) in the device active region of SiC pn diodes has been previously reported [19], [20]. These SF's are due to high current overstress and lead to a large forward voltage drop degradation. The origin of these clusters is not clear as yet and was suggested to be SF nucleations around the built-in defects along with structural irregularities during processing of p-type SiC formations. Clusters observed in the active region of JBS diodes after proton irradiation could be similiar and cause the degradation of forward voltage drop. These clusters could be due to: 1) degradation due to repeated measurements over time and 2) proton irradiation. The first possibility is highly unlikely since we only measured these diodes at room temperature and over a short time period. Thus, we propose that proton irradiation probably causes similiar SF defects in the p-region SiC as that produced by high current stress.

A small but repeatable decrease in the low voltage reverse-bias leakage current after proton exposure was also consistently observed (Fig. 3). The reverse current density of these SiC diodes decreases from 3.54×10^{-8} A/cm^2 to 1×10^{-8} A/cm^2 at 10 V of reverse bias. This result is similar to what was observed in the proton-irradiated JBS diodes. Fig. 4 shows the measured reverse leakage and breakdown characteristics both before and after proton irradiation. The reverse leakage after irradiation remains smaller than its pre-radiation values, although the pre-irradiation reverse current shows two clear and repeatable "kinks" at around 50 V and 270 V for these diodes. Interestingly, these kinks disappeared after proton exposure, suggesting that proton exposure has an annealing effect on certain deep level traps in 4H-SiC. Similar types of annealing effects using electron irradiation on SiC has been previously reported by [21], and similar radiation-induced reverse leakage improvements have also been observed [10].

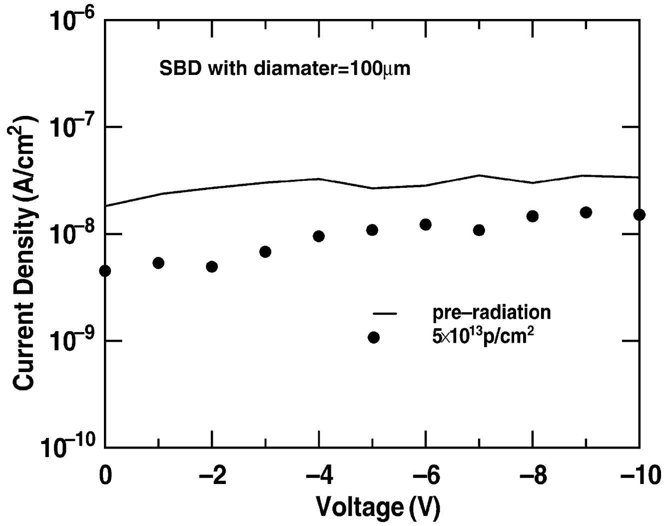

Fig. 3. Reverse current-voltage characteristics of the 4H-SiC SBDs both before and after proton irradiation.

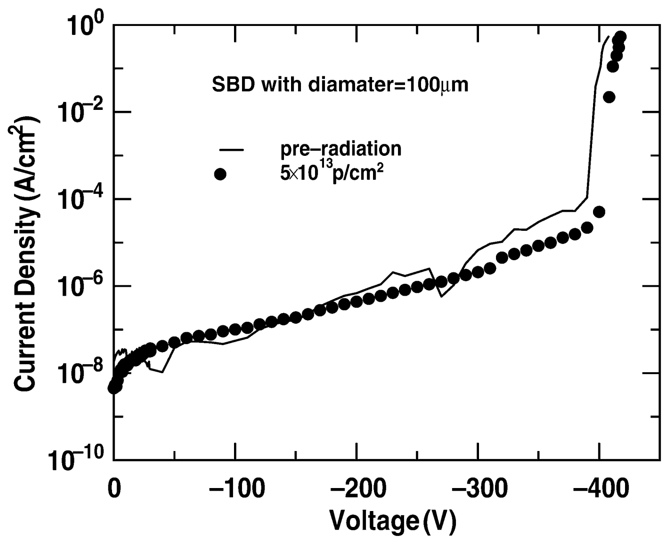

Fig. 4. Measured reverse leakage and blocking characteristics both before and after proton irradiation.

As we can see from Fig. 4, the blocking voltages for this SBD increase from 389 to 413 V after proton exposure. The average increase for all the diodes is only 23 V, but statistically repeatable, and is much smaller than that observed for the JBS diodes. This is reasonable considering the high series resistance of JBS diodes after proton irradiation. The relatively small blocking voltage increase of SBDs in the present work can also be attributed to the radiation-induced excess charge in the surface passivation layers [13]. To better understand these results, we

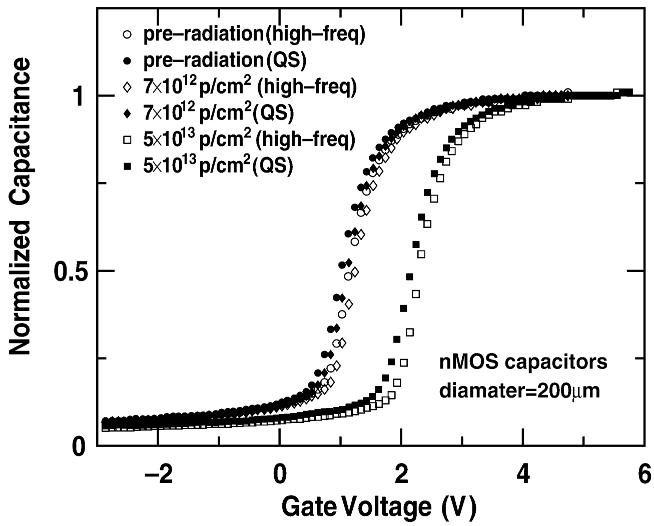

Fig. 5. Influence of proton irradiation on the C–V characteristics of the 4H-SiC nMOS capacitors passivated with NO.

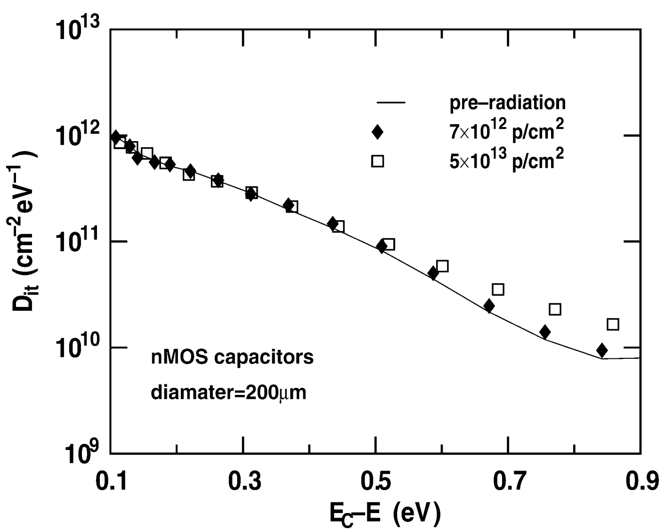

Fig. 6. Extracted interface state density of the 4H-SiC nMOS capacitors passivated with NO both before and after proton irradiation.

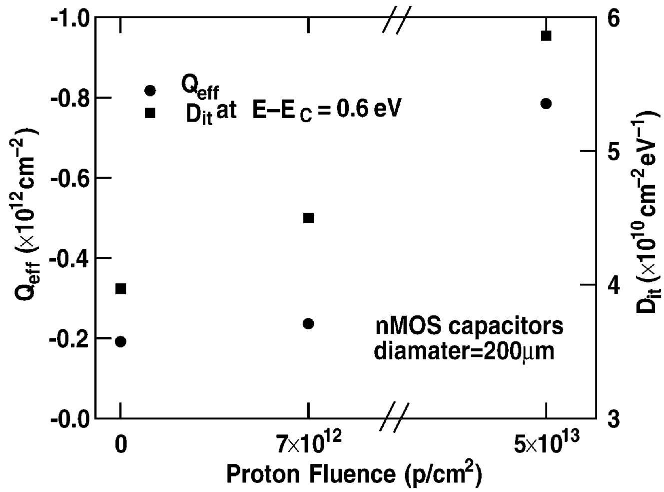

Fig. 7. Effective charge density and interface state density as functions of proton fluence.

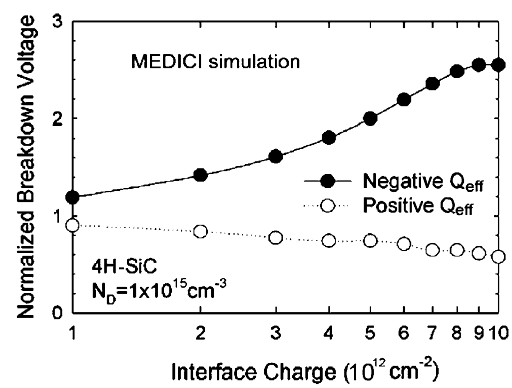

Fig. 8. Breakdown voltage change as a function of the radiation-induced interface charge density.

determined the change in the oxide charge by analyzing the effects of proton irradiation on 4H-SiC MOS capacitors.

B. MOS Capacitors

The radiation results reported here on nMOS capacitors are based on fourteen 200 μm diameter structures distributed on two different dies, and the results are again quite uniform among these devices. Typical normalized CV curves from the nMOS capacitors before and after irradiation are shown in Fig. 5. The results show that the 4H-SiC nMOS capacitors are radiation tolerant up to 7 $\times 10^{12}$ p/cm^2 fluence. There is a very small positive shift in the CV curves after 7 $\times 10^{12}$ p/cm^2 but a much large positive shift after 5 $\times 10^{13}$ p/cm^2. The V_{FB} after the 5 $\times 10^{13}$ p/cm^2 exposure shifts from 1.22 to 2.34 V, and shows that the total proton exposure resulted in a net negative charge increase, consistent with our earlier results using gamma rays.

Fig. 6 shows the extracted interface state density (D_{it}) as a function of energy level before and after irradiation. At energy levels close to the conduction band edge, D_{it} remains unchanged even after 5 $\times 10^{13}$ p/cm^2 fluence. As the energy level moves more deeply into the bandgap, however, the effects of radiation on D_{it} become distinct. Beyond $E_C - E = 0.85$ eV, D_{it} become roughly constant for both the pre- and post-radiation samples. Since the response time of interface states increases as energy level goes deeper, the D_{it} extracted from room temperature Hi-Lo CV mesurements with 100 kHz used as the high frequency may not be accurate at energy higher than about 0.6 eV [22]. To probe D_{it} at deep energy levels more accurately, the same technique at elevated temperatures can be used. The $Q_{\rm eff}$ and D_{it} at $E_C - E = 0.6$ eV as a function of proton fluence is shown in Fig. 7. As can be seen, both $Q_{\rm eff}$ and D_{it} change only slightly after 7 $\times 10^{12}$ p/cm^2 proton exposure, but more significantly after a fluence of 5 $\times 10^{13}$ p/cm^2. $Q_{\rm eff}$ decreases (becomes more negative) by about -7.1×10^{11} cm^{-2} at 5 $\times 10^{13}$ p/cm^2, while D_{it} increases by 2 $\times 10^{10}$ cm^{-2}eV^{-1}.

The measured changes in $Q_{\rm eff}$ were used to simulate the anticipated blocking voltage change in the SBD using MEDICI simulations [23]. Fig. 8 shows the simulated effects on blocking voltage of radiation-induced negative and positive $Q_{\rm eff}$ as a function of interface charge density [13]. The measured change of -7.1×10^{11} cm^{-2} in effective interface charge leads to an increase of about 20 V in blocking voltage [13], [14], consistent with our SBD device measurements. Thus, we believe that the measured SBD blocking voltage increase is primarily the result of the negative increase in oxide charge. With the increased negative surface charge, the potential contours under reverse bias are significantly spread out, thereby reducing the electric field crowding which leads to breakdown. This increase, however, is relatively small compared to that for SBDs irradiated with gamma rays [13], consistent with the differences in induced surface charge for both radiation types.

IV. Conclusion

4H-SiC SBDs and nMOS capacitors show a high level of radiation tolerance after proton exposure. Unlike for SiC JBS diodes, SiC SBDs show very little forward I–V degradation after exposure to proton fluences as high as 5×10^{13} p/cm^2, suggesting that the proton-induced high R_S of the SiC JBS diodes after proton exposure is probably due to radiation-induced damage related to the p-type SiC. The reverse leakage current of post-irradiated SiC SBDs shows a decrease (improvement) after proton exposure, which could be due to proton annealing effects. The observed slight increase in blocking voltage for SiC SBDs after proton exposure is attributed to to an increase in negative surface charge.

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