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Radiation tolerance comparison of silicon and 4H–SiC Schottky diodes

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ABSTRACT

In this paper, silicon and 4H-silicon carbide (4H–SiC) based Schottky barrier diodes (SBD) have been compared for their radiation hardness capabilities through technology computer aided design (TCAD) simulations, using the non-ionizing energy loss (NIEL) mechanism. Both the devices are modeled for radiation effects after choosing same design points through interplay of drift layer doping and thickness for a fair comparison. Device simulation results show the superior radiation tolerance of 4H–SiC SBDs when compared to silicon devices under proton irradiation. On-state simulations reveal that the performance of Si and 4H–SiC diodes begin to degrade at a 1 MeV proton fluence of $\sim 5 \times 10^{11}$ and $\sim 7 \times 10^{12}$ cm^{-2}, respectively. The higher radiation tolerance of 4H–SiC SBDs is also observed in off-state simulations. It is found that the reverse breakdown voltage decreases in silicon, whereas it increases in 4H–SiC devices under the effect of irradiation, mainly due to doping compensation mechanism. These observations validate experimental results available in literature and provide a way forward to use TCAD simulations for studying radiation effects in other devices.

1. Introduction

4H-Silicon Carbide (SiC) is a promising semiconductor material for power applications with an additional advantage for being useful in harsh environments such as high temperature [1–4] and radiation prone atmospheres [5]. This is possible due to the inherently wide bandgap of 4H–SiC, its low intrinsic concentration, high critical electric field and high thermal conductivity when compared to silicon. Over the recent years, 4H–SiC has found applications in radiation detectors [6] due to its significantly high radiation tolerance and has attracted outer space related industries, who have been studying the use of 4H–SiC devices and circuits extensively for their missions [7]. In this regard, the effects of different types of radiation on several 4H–SiC devices such as diodes [8–11], bipolar junction transistors (BJTs) [12,13], and junction field-effect-transistors (JFETs) [14] have been studied. However, these studies only cover a limited range of radiation types, fluences, and energies. Whereas, in order to assess the viability of these devices in a real space environment, the devices need to be irradiated with a wide range of particle energies and fluences which are not feasible to be simulated in a laboratory environment. In addition, there are very few experimental studies that provide a realistic comparison between the radiation hardness of silicon and 4H–SiC devices when they are subjected to the same radiation type [15,16].

The present work demonstrates a technology computer aided design (TCAD) based simulation framework that provides the flexibility to study the irradiation of the device of choice with a wide range of particle energies and fluences. This is then used to compare the radiation hardness of silicon and 4H–SiC Schottky barrier diodes (SBD) in terms of on-state and off-state performance. While the concept studying radiation effects on semiconductor devices through TCAD is not novel by itself [17], the present work attempts to describe a TCAD-based framework through which the radiation hardness of any Schottky diode can be gauged, without relying on previous experimental data. The presented framework uses the displacement damage dose or the non-ionizing energy loss (NIEL) concept to quantify and determine the extent of radiation damage. With the help of stopping range of ions in matter (SRIM) [18] calculations and the radiation effects' module (REM) in Silvaco TCAD tool [19], the NIEL concept is applied on 1200 V silicon and 4H–SiC SBDs to understand the effect of proton irradiation on the forward and reverse characteristics of both the devices. The effect of proton irradiation on the forward characteristics is gauged by recording the voltage (V_{F_1A}) at which the forward current flowing through the SBDs is 1 A - a methodology adapted from Ref. [16]. The off-state performance of the devices is evaluated through measuring the breakdown voltage after irradiation.

Simulation results clearly show the superiority of the 4H–SiC SBDs in

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both the on-state and off-state regimes. At forward voltages, the performance of both the devices degrade eventually, however, the deterioration of Si SBDs begins at a (1 MeV) proton fluence of $\sim 5 \times 10^{11}$ cm^{-2} whereas this value is $\sim 7 \times 10^{12}$ cm^{-2} for the 4H–SiC counterpart. Moreover, the breakdown voltage of 4H–SiC devices tends to increase due to proton irradiation while the performance of the silicon SBDs degrades significantly after irradiation. These observations can be explained in terms of the doping compensation mechanism and the factors that expedite the avalanche breakdown of the diodes.

2. Proton irradiation of silicon and 4H–SiC SBDs

2.1. Device structure and models

To compare and evaluate the radiation tolerance of silicon and 4H–SiC, two SBDs are simulated in Silvaco ATLAS using both the semiconductor materials. The 4H–SiC SBD design is based on an experimentally characterized device [20] with a drift layer doping, thickness, and device area of 9.1×10^{15} cm^{-3}, 12.2 μm, and 9.5×10^{-3} cm^{-2} respectively. This design has an ideal breakdown voltage (V_{BR}) of ~1600 V [16], and the fabricated device in Ref. [20] demonstrated a V_{BR} of 1200 V. The models used in the simulation include band-to-band tunneling, and the anisotropic impact ionization model. Titanium is used as a Schottky contact with a work function of 4.33 eV, as Ti was used in the fabricated device in Ref. [20]. The device model parameters are adjusted so that a good agreement is obtained between the experimental reverse IV characteristics in Ref. [20] and the simulated IV curves.

Similarly, a silicon SBD is also simulated in ATLAS. The design point (i.e. the drift layer doping and thickness) is carefully chosen so that both the silicon and 4H–SiC diodes have the same ideal breakdown voltage. This is important to make a fair comparison between the radiation hardness of both the diodes. As demonstrated in Fig. 1, a silicon diode with drift layer doping of 1.2×10^{14} cm^{-3} and thickness of 100 μm also has an ideal V_{BR} of ~1600 V [21], hence it is selected as a design point. For the silicon diode, band-to-band tunneling, and Selberherr impact ionization models are primarily used in the simulations. Since the model parameters for silicon-based SBDs are quite well established, the default model parameters in ATLAS are used for the simulations. A platinum silicide electrode with a work function of 5.17 eV [22] is used to serve as a Schottky contact to the anode, as it is typically used in Si based SBDs [23]. The model parameters for both the silicon and 4H–SiC SBDs are listed in Table 1.

2.2. Simulation framework for proton irradiation

The present work proposes a framework for simulating irradiation

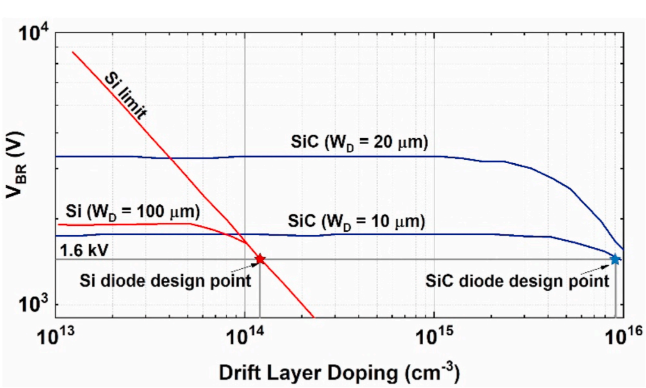

Fig. 1. Design points with an ideal V_{BR} of 1.6 kV of the silicon and SBDs used in this work. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Model parameters for the silicon and 4H–SiC SBDs.

Model parameters		Silicon Schottky barrier diode		4H–SiC Schottky barrier diode	
Drift Layer Thickness/Doping		100 μm/1.2×10^{14} cm^{-3}		12.2 μm/9.1×10^{15} cm^{-3}	
Schottky metal work function		Φ (Pt_2Si) = 5.17 eV [22]		Φ (Ti) = 4.33 eV	
Band-to-band tunneling [24]	BB.A (cm^{-1}V^{2}s^{-1})	9.66×10^{18}		7.5×10^7	
	BB.B (V/cm)	3×10^7		1×10^7	
	BB.GAMMA	2		2.6	
Impact Ionization		Selberherr model parameters [25]		Anisotropic model parameters [26]	
		AN1, AN2 (cm^{-1})	7.03×10^5	AE (cm^{-1})	3.82×10^8
		BN1, BN2 (V/cm)	1.23×10^6	AH (cm^{-1})	3.1×10^8
		AP1 (cm^{-1})	6.71×10^5	BE (V/cm)	2.18×10^7
		AP2 (cm^{-1})	1.58×10^6	BH (V/cm)	2.03×10^7
		BP1 (V/cm)	1.69×10^6	–	
		BP2 (V/cm)	2.04×10^6		

effects that does not rely on irradiating actual devices, hence saving significant amount of time and resources. In addition to introducing traps in the simulation setup, ATLAS also provides another way of introducing radiation through REM. REM requires the following parameters: incident particle type, particle energy, NIEL value, damage factor, and the irradiation fluence. The particle type, energy, and fluence are user-defined parameters, and the NIEL and damage factor can be calculated from the vacancies produced in the material by the incident particle. The damage due to irradiation in a material can be characterized by the density of Frenkel pairs (N_F) generated in the material [27]. N_F is determined using the displacement per atom from SRIM, which is then used as an input to the REM module to simulate the radiation effects. Degradation of silicon solar cells under radiation calculated using this method has qualitatively agreed well with previous experimental degradation results [28,29], demonstrating the validity of the framework. The REM also requires NIEL, which can be determined from the VACANCY. txt file in SRIM outputs using the method outlined in Ref. [30]. It is important that the NIEL values are normalized to the active depth of the device, as suggested by Messenger et al. [29]. In our case, the active depth of the device is the depletion width of the Schottky diode at the breakdown voltage. As demonstrated in Fig. 2, the active depth for the silicon and 4H–SiC diode is found to be 105 μm and 12 μm, respectively.

Using this methodology, both the silicon and 4H–SiC SBDs are irradiated in ATLAS using the REM module, with protons having fluences up to 10^{14} cm^{-2} and energies of 1 MeV and 5 MeV. This range of fluences is chosen considering the typical fluence of protons present in space [16]. The proton energies are carefully chosen so that both the following cases are covered: *(i)* the maximum damage caused by the irradiation is inside the active depth (1 MeV) and *(ii)* the maximum damage is outside the active depth of the devices (5 MeV). The projected range (R_P) of 1 MeV protons in silicon is ~16.3 μm and 4H–SiC is ~10.7 μm, whereas R_P for 5 MeV protons in silicon and 4H–SiC is ~216 μm and ~145.5 μm, respectively. The forward and reverse IV characteristics for both the diodes are then compared as a function of proton energy and fluence.

3. Simulation results and discussion

3.1. Proton irradiation effects on the forward characteristics of Si and 4H–SiC SBDs

Fig. 3(a) and (b) shows the impact of 1 MeV proton irradiation on the

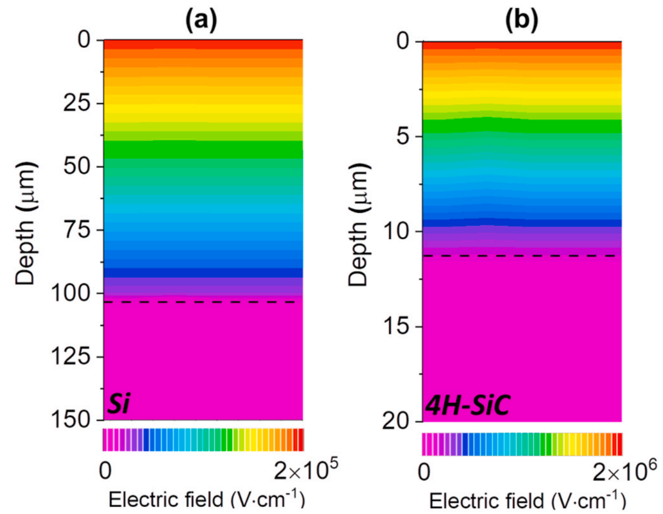

Fig. 2. Electric field contour plot for (a) silicon and (b) 4H–SiC Schottky barrier diode at a reverse bias voltage of 1200 V. The active depth is marked with a dashed line in both the devices. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

forward characteristics of Si and 4H–SiC SBDs, respectively. A substantial drop in the forward current and increase in the turn-on voltage is observed for the Si based diode at fluences $>10^{12}$ cm^{-2}. This decrease in the forward current and increase in the forward voltage drop after irradiation is attributed to the vacancies created by the impinging particles which in turn increase the resistance of the drift layer. A similar trend is seen for the 4H–SiC SBD as well, however, the impact is much less severe when compared to the Si diode, due to the higher radiation tolerance of the material.

The radiation tolerance of both the diodes can also be compared by measuring the forward voltage (V_{F_1A}) required to generate a current of 1 A across the devices [16]. A higher voltage required to generate the same current indicates an increase in the resistance of the drift layer, which compromises the device reliability. Fig. 4 shows the effect of 1 and 5 MeV proton irradiation on V_{F_1A} of Si and 4H–SiC SBDs, for a wide range of particle fluences.

The V_{F_1A} for the Si and 4H–SiC SBDs without any irradiation is 0.76 and 0.77 V, respectively. As proton fluence increased, this voltage naturally increases for both the devices. However, the trend with which V_{F_1A} increases for both the devices is not the same. In case of the Si diode, negligible increase in V_{F_1A} is observed for proton fluences up to $\sim 5 \times 10^{11}$ cm^{-2}, irrespective of the particle energy, after which the voltage begins to increase exponentially with the fluence. On the other hand, there is no change in V_{F_1A} for the 4H–SiC SBDs up to 1 MeV proton fluences of $\sim 7 \times 10^{12}$ cm^{-2}, after which the V_{F_1A} increases sharply. Furthermore, at 5 MeV, the fluence level after which the reliability of the 4H–SiC SBD is compromised, is almost an order of magnitude higher. The impact of irradiation is less severe for higher energy protons as the region of maximum damage for 5 MeV protons lies outside the device thickness in both the devices. These observations suggest that 4H–SiC SBDs can operate reliably, without any substantial change in the forward characteristics, for a wider range of proton fluences. Moreover, unlike the Si SBDs, 4H–SiC diodes exhibit greater radiation tolerance against highly energetic particles. The qualitative trends of V_{F_1A} for the 4H–SiC SBDs with respect to proton fluence agree well with the experimental data reported in Ref. [16]. It is worth mentioning that the change in V_{F_1A} for the Si SBD in Fig. 4, somewhat resembles the data reported for Si p-n diodes in Ref. [16]. This is attributed to the fact that Si SBDs typically exhibit a dual Schottky and p-n behavior in the forward bias mode, as evident through the dual forward slope in Fig. 3(a), and as pointed out through SPICE fitting of Si SBDs in Ref. [31].

3.2. *Proton irradiation effects on the reverse characteristics of Si and 4H–SiC SBDs*

Fig. 5(a) shows the effects of 1 MeV protons on the silicon Schottky diode. As evident from the figure, the performance of the diode starts to

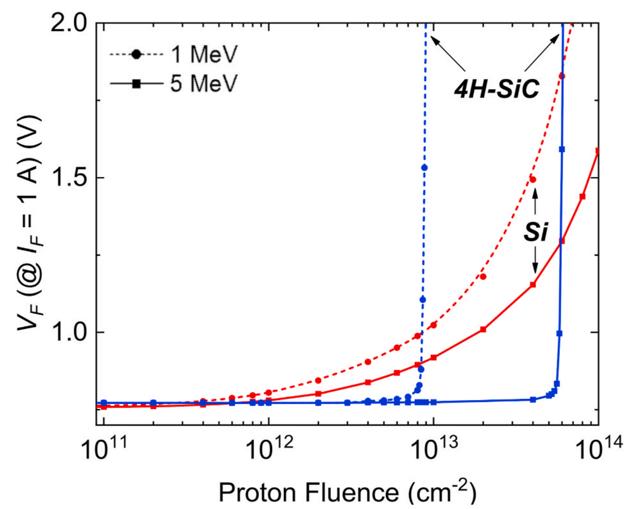

Fig. 4. Change in the forward voltage at 1 A against proton fluence for Si and 4H–SiC SBDs.

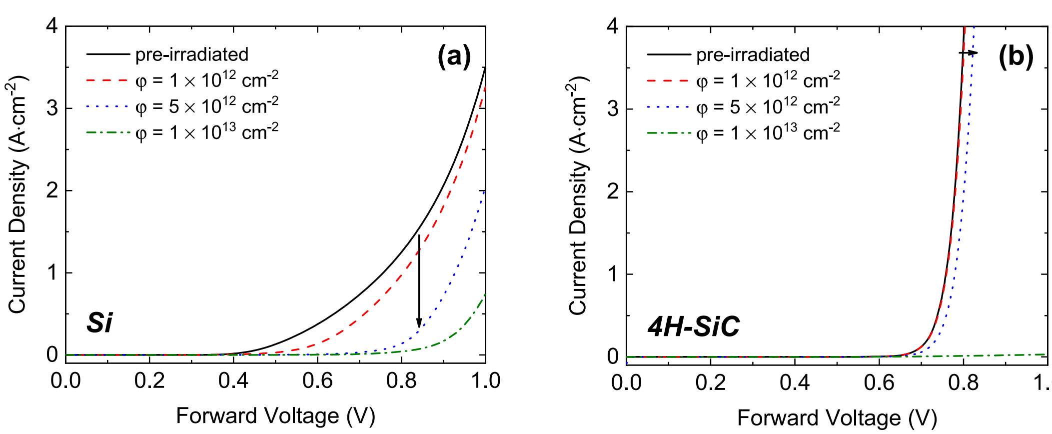

Fig. 3. Forward IV characteristics of (a) silicon and (b) 4H–SiC Schottky barrier diodes after 1 MeV proton irradiation. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

degrade, and the V_{BR} reduces when the proton fluence exceeds 1×10^{11} cm^{-2}. In fact, at a proton fluence of 1×10^{12} cm^{-2}, the V_{BR} already reduces by ~21% from 1200 V to ~950 V. This trend of degradation in V_{BR} of the silicon SBDs with increasing fluence is in line with experimental results [32]. Fig. 5(b) shows the impact of irradiating the silicon SBD with 5 MeV protons. Once again, the V_{BR} reduces with increasing fluence, however, the degradation in this case is less severe. At a proton fluence of 1×10^{13} cm^{-2}, the V_{BR} reduces to ~700 V, which corresponds to a degradation of ~42% when compared to the pre-irradiated V_{BR}.

Although it may seem counter-intuitive, it is the low energy protons (in the range of keV) that are more detrimental to the silicon SBDs in comparison to high energy protons (several MeVs). This is because, the irradiation damage primarily depends on the R_P of the impinging protons and the active depth of the device. For the silicon Schottky diode presented in this paper, the thickness of the depletion width at breakdown voltage is ~105 μm. This means that the 1 MeV protons ($R_P \approx$ 16.3 μm) will create the maximum damage peak within the active region of the device. On the other hand, the range of the 5 MeV protons is ~216 μm which indicates that only some damage takes place as the protons traverse through the active depth and the maximum damage occurs outside the active device region. This observation is supported by the simulation results shown in Fig. 5(a) and (b) where the degradation in V_{BR} by 5 MeV protons is less than the damage caused by 1 MeV protons for the same proton fluence.

Moving on to the studying radiation effects on 4H–SiC SBD, Fig. 6(a) shows the effect of 1 MeV protons on the reverse IV characteristics of 4H–SiC Schottky diode. Unlike the deterioration of V_{BR} observed in silicon diodes, the blocking capability of 4H–SiC diodes actually improves with increasing fluence. At an incident proton energy of 1 MeV and at a fluence of 1×10^{13} cm^{-2}, the V_{BR} of the 4H–SiC diode increases by ~42% from 1200 to ~1700 V. Moreover, at least an order of magnitude reduction is observed in the leakage current of the device in the pre-breakdown regimes. The substantial decrease in the leakage current corroborates well with the sharp increase in the V_{F_1A} (and hence an increase in the drift layer resistance) observed in Fig. 4. Both these observations are also reported in literature when actual 4H–SiC diodes are irradiated with protons [11]. It is postulated that exposure to protons has an annealing effect on the deep level traps found in 4H–SiC which leads to a slight reduction in leakage current when the diode is reverse biased [33]. In addition, the increase in V_{BR} in the 4H–SiC diodes can be attributed to an increase in the resistance of drift layer caused by the carrier compensation due to irradiation [11].

Despite the fact that irradiation causes carrier compensation in both the silicon and 4H–SiC diodes, only the breakdown voltage of silicon diodes degrades with increasing fluence. This is because, the energy required to generate an electron-hole (e-h) pair in 4H–SiC is ~7.8 eV [34] which is more than 2 × the energy required to produce an e-h pair in silicon (~3.6 eV [35]). Hence, even if the density of defects introduced in both the devices is similar after irradiation, the number of incident protons that will have sufficient energy to create e-h pairs in silicon is much higher than that in 4H–SiC. This implies that the generation of carriers when the diodes are reverse biased is substantially greater in silicon SBDs when compared to the 4H–SiC diodes. In addition, the high concentration of e-h generated in silicon is compounded by its 3 × smaller bandgap when compared to 4H–SiC, which interestingly accelerates the avalanche breakdown of the silicon diodes. Therefore, any increase in resistance of the drift layer via carrier compensation in silicon is dominated by the significant generation of e-h pairs due to the irradiation process. On the other hand, carrier compensation dominates the e-h generation process in the 4H–SiC SBDs, thereby increasing its V_{BR} under the proton irradiation. Fig. 6(b) shows the reverse IV curves for the 4H–SiC SBD irradiated with 5 MeV protons for difference fluences. As expected, the trend with respect to fluence remains the same, though the impact of irradiation is lower when compared to the 1 MeV case, as the maximum density of defects introduced by the 5 MeV protons lies outside the device active thickness.

In summary, the change in V_{BR} of silicon and SBDs after simulating proton irradiation at 1 MeV and 5 MeV is shown in Fig. 7. It is evident from the figure that 4H–SiC SBDs demonstrate a much higher radiation tolerance irrespective of the incident proton energy, when compared to similar Si based devices as the V_{BR} of Si SBDs reduces severely due to the irradiation process.

4. Conclusion

It has been concluded that 4H–SiC Schottky barrier diodes are more robust and offer better radiation tolerance in on-state and off-state modes, when compared to similar devices made from silicon. This has been demonstrated by simulating proton irradiation in both devices of same rating. For a meaningful comparison, the design points for both the diodes are chosen such that they have the same breakdown voltage prior to irradiation. To simulate the radiation effects in TCAD, NIEL phenomenon is considered. Simulation results show that the 4H–SiC SBDs operate reliably and are more robust against particle irradiation for a wider range of proton fluence, when compared to their silicon counterparts. With regards to the off-state performance, breakdown characteristics of the 4H–SiC SBDs improve because of the carrier compensation effect, whereas the V_{BR} of silicon SBDs expectedly reduces after proton irradiation due to the substantial generation of e-h pairs. To the best of our knowledge, this is the first time that the effect of particle irradiation on the on-state and off-state performances of same rating Si and 4H–SiC SBDs are compared. The presented results validate the potential of 4H–SiC devices in radiation rich space environments.

Author statement

Amna Siddiqui: Methodology. Investigation, data curation, formal analysis, writing the original draft.

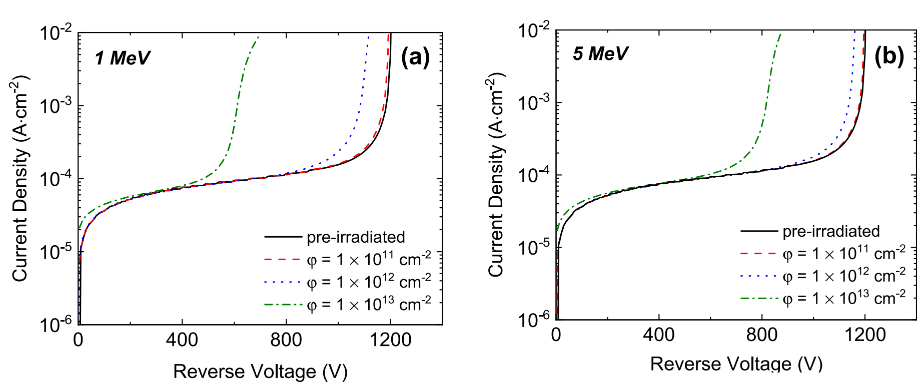

Fig. 5. Reverse IV charactersitics of the silicon SBDs after (a) 1 MeV and (b) 5 MeV proton irradaition with varying fluences. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

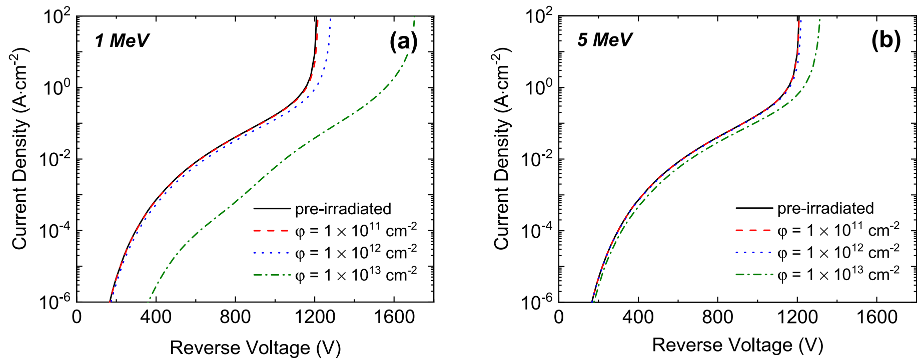

Fig. 6. Reverse IV charactersitics of the 4H–SiC SBDs after (a) 1 MeV and (b) 5 MeV proton irradaition with varying fluences.

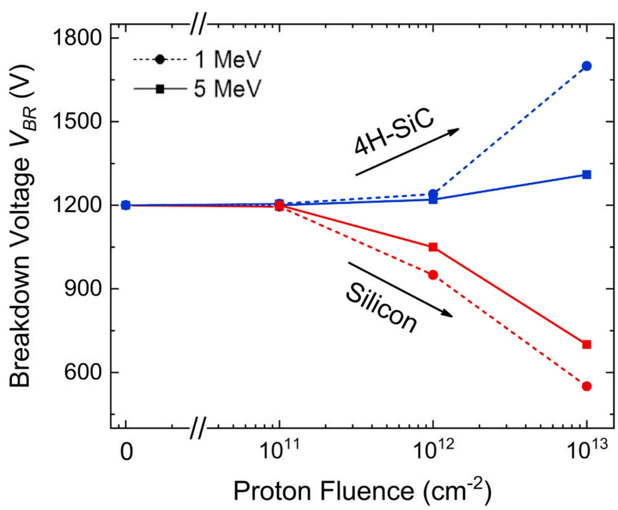

Fig. 7. Comparison of change in V_{BR} for Si and 4H–SiC based SBDs due to 1 MeV (dashed) and 5 MeV (solid) proton irradiation.

Muhammad Usman: Conceptualization, validation, review and editing, resources, supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] D.J. Spry, P.G. Neudeck, D. Lukco, L.Y. Chen, M.J. Krasowski, N.F. Prokop, C. W. Chang, G.M. Beheim, Prolonged 500°C operation of 100+ transistor silicon carbide integrated circuits, Mater. Sci. Forum 924 (2018) 949–952. https://doi.org/10.4028/www.scientific.net/MSF.924.949.

[2] H. Elgabra, S. Singh, High temperature simulation of 4H-SiC bipolar circuits, IEEE J. Electron Devices Soc. 3 (3) (2015) 302–305, https://doi.org/10.1109/jeds.2015.2407380.

[3] H. Elgabra, A. Siddiqui, S. Singh, Simulation of conventional bipolar logic technologies in 4H-SiC for harsh environment applications, Jpn. J. Appl. Phys. 55 (4S) (2016), 04ER08, https://doi.org/10.7567/jjap.55.04er08.

[4] D. Johannesson, M. Nawaz, S. Norrga, A. Hallen, H.-P. Nee, Static and dynamic performance prediction of ultrahigh-voltage silicon carbide insulated-gate bipolar transistors, IEEE Trans. Power Electron. 36 (5) (2021) 5874–5891, https://doi.org/10.1109/tpel.2020.3027370.

[5] A.A. Lebedev, V.V. Kozlovski, N.B. Strokan, D.V. Davydov, A.M. Ivanov, A. M. Strel'chuk, R. Yakimova, Radiation hardness of wide-gap semiconductors (using the example of silicon carbide), Semiconductors 36 (11) (2002) 1270–1275, https://doi.org/10.1134/1.1521229.

[6] L. Liu, A. Liu, S. Bai, L. Lv, P. Jin, X. Ouyang, Radiation resistance of silicon carbide Schottky diode detectors in D-T fusion neutron detection, Sci. Rep. 7 (1) (2017) 13376, https://doi.org/10.1038/s41598-017-13715-3.

[7] P.G. Neudeck, R.D. Meredith, L. Chen, D.J. Spry, L.M. Nakley, G.W. Hunter, Prolonged silicon carbide integrated circuit operation in Venus surface atmospheric conditions, AIP Adv. 6 (12) (2016) 125119.

[8] S. Popelka, P. Hazdra, V. Záhlava, Characterization and simulation of neutron irradiated JBS silicon carbide diode structures, Key Eng. Mater. 605 (2014) 151–154.

[9] A.A. Lebedev, K.S. Davydovskaya, V.V. Kozlovski, O. Korolkov, N. Sleptsuk, J. Toompuu, Degradation of 600-V 4H-SiC Schottky diodes under irradiation with 0.9 MeV electrons, Mater. Sci. Forum 897 (2017) 447–450, https://doi.org/10.1063/1.4973429.

[10] O.M. Korolkov, V.V. Kozlovski, A.A. Lebedev, N. Sleptsuk, J. Toompuu, T. Rang, Low-temperature annealing of lightly doped n-4H-SiC layers after irradiation with fast electrons, Semiconductors 53 (7) (2019) 975–978, https://doi.org/10.1134/s1063782619070133.

[11] L. Zhiyun, C. Tianbing, A.C. Ahyi, A.K. Sutton, B.M. Haugerud, J.D. Cressler, D. C. Sheridan, J.R. Williams, P.W. Marshall, R.A. Reed, Proton radiation effects in 4H-SiC diodes and MOS capacitors, IEEE Trans. Nucl. Sci. 51 (6) (2004) 3748–3752, https://doi.org/10.1109/tns.2004.839254.

[12] M. Usman, M. Nawaz, A. Hallen, Position-dependent bulk traps and carrier compensation in 4H-SiC bipolar junction transistors, IEEE Trans. Electron. Dev. 60 (1) (2013) 178–185, https://doi.org/10.1109/ted.2012.2226586.

[13] M. Usman, B. Buono, A. Hallen, Impact of ionizing radiation on the SiO_2/SiC interface in 4H-SiC BJTs, IEEE Trans. Electron. Dev. 59 (12) (2012) 3371–3376, https://doi.org/10.1109/ted.2012.2222414.

[14] J.M. McGarrity, F.B. McLean, W.M. DeLancey, J. Palmour, C. Carter, J. Edmond, R. E. Oakley, Silicon carbide JFET radiation response, IEEE Trans. Nucl. Sci. 39 (6) (1992) 1974–1981, https://doi.org/10.1109/23.211393.

[15] T. Ohshima, S. Onoda, N. Iwamoto, T. Makino, M. Arai, Y. Tanak, Radiation Response of Silicon Carbide Diodes and Transistors, Physics and Technology of Silicon Carbide Devices, IntechOpen, 2012, https://doi.org/10.5772/51371.

[16] R.D. Harris, SiC vs. Si for High Radiation Environments, Jet Propulsion Laboratory, California Institute of Technology Pasadena, California, 2008.

[17] S. Onoda, T. Ohshima, T. Hirao, K. Mishima, S. Hishiki, N. Iwamoto, K. Kawano, Impact of auger recombination on charge collection of a 6H-SiC diode by heavy ions, IEEE Trans. Nucl. Sci. 54 (6) (2007) 2706–2713, https://doi.org/10.1109/tns.2007.908459.

[18] J.F. Ziegler, J.P. Biersack, The stopping and range of ions in matter, in: D. A. Bromley (Ed.), Treatise on Heavy-Ion Science: Volume 6: Astrophysics, Chemistry, and Condensed Matter, Springer US, Boston, MA, 1985, pp. 93–129.

[19] Silvaco. ATLAS User's Manual, Silvaco International, Santa Clara, CA, 2016.

[20] L. Di Benedetto, G.D. Licciardo, T. Erlbacher, A.J. Bauer, S. Bellone, Analytical model and design of 4H-SiC planar and trenched JBS diodes, IEEE Trans. Electron. Dev. 63 (6) (2016) 2474–2481, https://doi.org/10.1109/ted.2016.2549599.

[21] S.M. Sze, K.K. Ng, Physics of Semiconductor Devices, Wiley-Interscience, 2007.

[22] T.J. Drummond, Work Functions of the Transition Metals and Metal Silicides, Albuquerque, New Mexico, 1999.

[23] T.S. Natarajan, Functional nanofibers in microelectronics applications, in: Q. Wei (Ed.), Functional Nanofibers and Their Applications, Woodhead Publishing, 2012, pp. 371–410, https://doi.org/10.1533/9780857095640.2.371.

[24] G.A.M. Hurkx, D.B.M. Klaassen, M.P.G. Knuvers, A new recombination model for device simulation including tunneling, IEEE Trans. Electron. Dev. 39 (2) (1992) 331–338, https://doi.org/10.1109/16.121690.

[25] S. Selberherr, A.C. Eringen, Analysis and Simulation of Semiconductor Devices, Springer-Verlag, 1984.

[26] T. Hatakeyama, J. Nishio, C. Ota, T. Shinohe, Physical Modeling and Scaling Properties of 4H-SiC Power Devices, 2005, pp. 171–174, https://doi.org/10.1109/sispad.2005.201500.

[27] E. Donegani, Energy-dependent Proton Damage in Silicon, University of Hamburg, 2017.
[28] A. Siddiqui, M. Usman, Reliability of PERC solar cells under alpha irradiation: a simulation-based study for space applications, ECS J. Solid State Sci. Technol. 10 (1) (2021), 015003, https://doi.org/10.1149/2162-8777/abdadf.
[29] S.R. Messenger, E.A. Burke, G.P. Summers, R.J. Walters, Application of displacement damage dose analysis to low-energy protons on silicon devices, IEEE Trans. Nucl. Sci. 49 (6) (2002) 2690–2694, https://doi.org/10.1109/tns.2002.805359.
[30] S.R. Messenger, E.A. Burke, G.P. Summers, M.A. Xapsos, R.J. Walters, E. M. Jackson, B.D. Weaver, Nonionizing energy loss (NIEL) for heavy ions, IEEE Trans. Nucl. Sci. 46 (6) (1999) 1595–1602, https://doi.org/10.1109/23.819126.
[31] R.D. Harris, A.J. Frasca, Proton irradiation of silicon Schottky barrier power diodes, IEEE Trans. Nucl. Sci. 53 (4) (2006) 1995–2003, https://doi.org/10.1109/tns.2006.880934.
[32] R.D. Harris, A.J. Frasca, Proton Irradiation of Silicon Schottky Barrier Power Diodes, 8th European Conference on Radiation and its Effects on Components and Systems, IEEE, Cap d'Agde, France, 2005, https://doi.org/10.1109/radecs.2005.4365615. PG6-1-PG6-6.
[33] F. Nava, E. Vittone, P. Vanni, G. Verzellesi, P.G. Fuochi, C. Lanzieri, M. Glaser, Radiation tolerance of epitaxial silicon carbide detectors for electrons, protons and gamma-rays, Nucl. Instrum. Methods Phys. Res. Sect. A Accel. Spectrom. Detect. Assoc. Equip. 505 (3) (2003) 645–655, https://doi.org/10.1016/s0168-9002(02)01558-9.
[34] T.R. Garcia, A. Kumar, B. Reinke, T.E. Blue, W. Windl, Electron-hole pair generation in SiC high-temperature alpha particle detectors, Appl. Phys. Lett. 103 (15) (2013) 152108, https://doi.org/10.1063/1.4824774.
[35] M. Jaksic, Z. Pastuovic, T. Tadic, Characterisation of semiconductor materials and devices by the IBIC technique, Vienna (Austria). Available: https://www.osti.gov/etdeweb/servlets/purl/20267247.