Jinst

PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *January 22, 2025*
REVISED: *March 3, 2025*
ACCEPTED: *March 3, 2025*
PUBLISHED: *April 8, 2025*

Effect of 1 MeV neutron-irradiation on the electrical properties of Si-based diodes

Joseph Oluwadamilola Bodunrin[*] **and Sabata Jonas Moloi**

Department of Physics, College of Science, Engineering and Technology, University of South Africa,
Private Bag X6, Florida, 1710, South Africa

E-mail: `ebodunjo@unisa.ac.za`

ABSTRACT: This study investigates the impact of 1 MeV neutron irradiation on the electrical properties of n-type silicon (n-Si) Schottky diodes, focusing on high fluences of 10^{15} and 10^{16} n/cm^2. Current-voltage (I-V) measurements were conducted on diodes before and after irradiation to assess changes in conduction behaviour. Results reveal a significant shift from exponential diode characteristics to ohmic conduction with increasing fluence, a phenomenon less explored compared to lower-fluence studies (e.g., $< 10^{14}$ n/cm^2) documented by the RD50 collaboration and CERN experiments. The reverse current increased by factors of 3.5 and 82 at 10^{15} and 10^{16} n/cm^2, respectively, attributed to radiation-induced defects generating minority carriers. In the forward bias, minimal change was observed at 10^{15} n/cm^2 (factor of 1.14 decrease), while a marked increase (factor of 3.64) occurred at 10^{16} n/cm^2, linked to enhanced majority carrier generation by defects. This transition to ohmic behaviour, corroborated by a reduction in rectification ratio from 45 (unirradiated) to 2 (10^{16} n/cm^2), reflects defect levels pinning the Fermi energy near the intrinsic position. These findings elucidate the effects of high-fluence neutron irradiation on silicon diodes, offering valuable insights for developing radiation-hard detectors for extreme environments, such as the High-Luminosity LHC.

KEYWORDS: Materials for solid-state detectors; Radiation damage to detector materials (solid state); Radiation-hard detectors; Solid state detectors

2025 JINST 20 P04007

---

[*] Corresponding author.

https://doi.org/10.1088/1748-0221/20/04/P04007

Contents

1 Introduction 1

2 Experimental details 2

3 Results and discussion 3

4 Conclusion 4

2025 JINST 20 P04007

1 Introduction

Silicon-based diodes are cornerstone devices in radiation detection, widely employed in applications such as space exploration, nuclear power plants, and particle accelerators due to their robust electrical properties and compatibility with integrated circuit technology [1–3]. However, prolonged exposure to extreme radiation environments, such as those encountered at the Large Hadron Collider (LHC), induces significant degradation in their performance, compromising reliability and data acquisition efficacy [4]. This decline stems from radiation-induced changes in the diodes' electrical properties, driven by defects that alter carrier dynamics and conduction mechanisms [4]. While pre-irradiation with fluences exceeding 10^{13} n/cm^2 has been shown to enhance radiation hardness in silicon detectors [5], the specific effects of higher neutron fluences beyond the conductivity-type inversion threshold of 1.4×10^{13} n/cm^2 [6, 7] remain underexplored, despite their relevance to next-generation facilities.

Extensive research, including efforts by the RD50 collaboration and experiments like ATLAS, CMS, and LHC at CERN, has characterized silicon diode degradation under various irradiation conditions, typically focusing on proton damage or neutron fluences below 10^{14} n/cm^2 [6, 7]. At these levels, damage scales linearly with fluence, and electrical properties such as leakage current and capacitance are well-documented [8]. However, at higher fluences (e.g., 10^{15}–10^{16} n/cm^2), the response of silicon diodes diverges, with evidence suggesting a saturation of damage effects and a potential shift in conduction mechanisms [8]. Few studies have systematically investigated this regime, particularly the transition from exponential diode behaviour to ohmic conduction, which may arise from defect-mediated Fermi-level pinning at the intrinsic position [8, 9]. This gap is critical, as future colliders like the High-Luminosity LHC (HL-LHC), set to operate from 2026 with radiation levels over ten times higher than the current LHC [10], will demand detectors resilient to such harsh conditions.

This study addresses this gap by examining the electrical properties of *n*-Si Schottky diodes irradiated with 1 MeV neutrons at fluences of 10^{15} and 10^{16} n/cm^2. Using *I*-*V* measurements, we explore how high-fluence neutron irradiation alters diode behaviour, focusing on the emergence of ohmic conduction and its implications for radiation hardness. Unlike lower-fluence studies where defect generation scales predictably, our results indicate that at these elevated levels, defect densities drive a fundamental change in carrier transport, offering insights into device performance in extreme environments. By analysing these changes across fluences, this work advances the understanding of radiation effects on silicon-based diodes and provides a foundation for designing more robust detectors for future high-radiation applications.

2 Experimental details

This study utilized Schottky-based diodes fabricated on *n*-Si substrates to investigate the effects of 1 MeV neutron irradiation. The *n*-Si wafers, with a resistivity of 1–20 Ω cm, were diced into 1 cm × 1 cm pieces using a diamond cutter. To ensure clean surfaces, samples were ultrasonically cleaned in acetone, methanol, and deionized water for 5 minutes each, then blow-dried with nitrogen gas. Schottky contacts were formed by thermally evaporating 130 nm of gold (Au) onto the polished front side of the *n*-Si at a rate of 1 Å/s under a vacuum of 10^{-6} mbar, through a mask with 0.6 mm radius circular apertures. Ohmic contacts were created by depositing 100 nm of aluminium (Al) onto the entire backside, using the same deposition conditions. These Au/*n*-Si/Al devices are structurally identical to those in ref. [11], though fabricated independently for this study. A schematic of the diode structure is provided in figure 1.

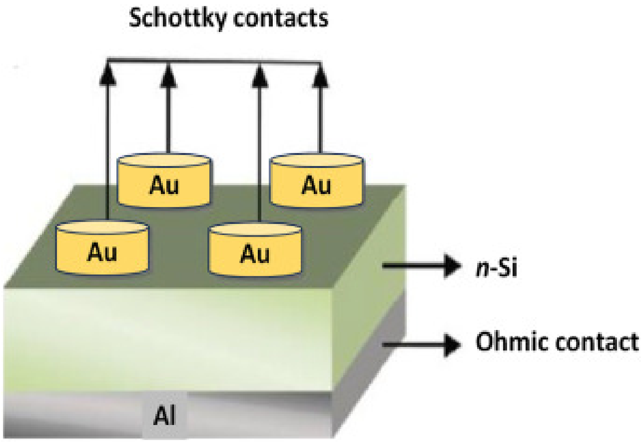

Figure 1. The schematic of fabricated diode with Au and Al as Schottky and ohmic contact, respectively.

Four diodes were prepared for each condition: unirradiated and irradiated to fluences of 10^{15} and 10^{16} n/cm^2. Irradiation was performed at the National Energy Corporation of South Africa (NECSA) using a 1 MeV neutron beam generated by a deuterium-tritium source, with fluence accuracy of ±10% verified via foil activation dosimetry. The beam flux was maintained at approximately 10^9 n/cm^2/s, and samples were irradiated at room temperature (300 K). Post-irradiation, diodes were stored at room temperature for 48 hours to allow short-term defect stabilization, with no intentional annealing applied. This storage period was chosen to minimize self-annealing effects prior to electrical characterization, though minor ambient annealing cannot be excluded.

Electrical properties were assessed via *I*-*V* measurements conducted before and after irradiation for all devices. Measurements were performed using in-house-made meters for current measurements, replicating the setup described in ref. [11]. The system was calibrated to supply voltages from −4 V to +4 V in 0.01 V steps. Tests were conducted in a controlled environment at room temperature and under dark conditions to eliminate photogeneration effects. Capacitance-voltage (*C*-*V*) measurements were planned but omitted due to equipment malfunctions post-irradiation; this limitation will be addressed in future studies. *I*-*V* measurements were conducted on all four diodes per condition (unirradiated, 10^{15} n/cm^2, and 10^{16} n/cm^2), with data initially averaged to account for variability, yielding error bars of ±5% based on the standard deviation from repeated tests. However, the trends in *I*-*V* behaviour, were remarkably consistent across diodes fabricated from the same *n*-Si material and exposed to identical irradiation fluences. Given this uniformity, we selected one representative diode for each condition.

3 Results and discussion

Figure 2(a) presents the semilogarithmic I-V characteristics of unirradiated and neutron-irradiated n-Si Schottky diodes at fluences of 10^{15} and 10^{16} n/cm^2. Neutron irradiation markedly increases the reverse current, rising by factors of 3.5 and 82 at 10^{15} and 10^{16} n/cm^2, respectively, compared to the unirradiated diode's baseline of 4.5 µA at −4 V. This escalation is attributed to radiation-induced defects in the silicon bandgap, which act as generation centres for minority carriers [11]. The defect density scales with fluence, amplifying carrier generation and thus leakage current, consistent with trends observed in proton-irradiated silicon diodes [11], albeit at lower fluences (e.g., 10^{14} n/cm^2 in ref. [9]). In forward bias, the current decreases slightly at 10^{15} n/cm^2 (factor of 1.14, from 189 µA to 166 µA at 4 V), suggesting minor disruption of majority carrier flow, but increases significantly at 10^{16} n/cm^2 (factor of 3.64, to 688 µA), indicating that high-fluence defects also enhance majority carrier contributions. Compared to p-type silicon (p-Si), where leakage typically dominates due to higher minority carrier generation [4], n-Si shows a balanced response, reflecting its doping characteristics.

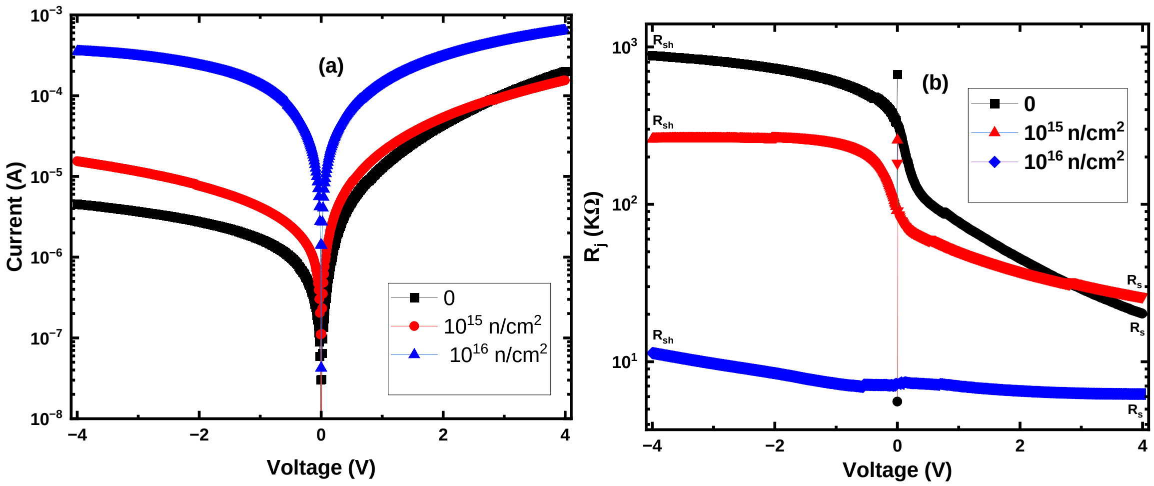

Figure 2. $\ln(I) - V$ characteristics (a) and $\ln(I) - V$ characteristics (b) of unirradiated and neutron-irradiated n-Si diodes.

The rectification ratio, defined as the forward-to-reverse current ratio at ±4 V, quantifies diode quality and its ability to block reverse current; a critical metric for detector applications [12]. This ratio drops from 45 for the unirradiated diode to 10 and 2 at 10^{15} and 10^{16} n/cm^2, respectively, signalling a loss of rectification due to radiation damage. This aligns with findings in ref. [11], where high-fluence irradiation similarly degrades diode behaviour, though our study uniquely highlights the transition to ohmic conduction at these levels.

Figure 2(b) illustrates junction resistance (R_j) versus voltage, derived as $R_\mathrm{j} = dV/dI$, offering insight into diode quality [12]. The shunt resistance (R_sh), taken as the maximum R_j in reverse bias, reflects leakage suppression and should be maximized, while the series resistance (R_s), the minimum R_j in forward bias, indicates contact efficiency and should be minimized [13]. For the unirradiated diode, R_sh and R_s at ±4 V are 919.95 kΩ and 19.06 kΩ, respectively. Post-irradiation, these values shift to 279.62 kΩ and 26.45 kΩ at 10^{15} n/cm^2, and 11.95 kΩ and 6.35 kΩ at 10^{16} n/cm^2, reflecting increased leakage and altered carrier transport. The R_sh decrease parallels proton irradiation studies (e.g., ref. [8]), though the R_s reduction at 10^{16} n/cm^2 suggests defect-enhanced conductivity.

2025 JINST 20 P04007

To elucidate conduction mechanisms, double logarithmic I-V plots are shown in figures 3(a)–(c). For the unirradiated diode (figure 3(a)), two linear regions emerge in forward bias: from 0 to 0.18 V with a slope of 1.22, indicating ohmic conduction dominated by thermally generated carriers over injected ones across the space charge region (*SCR*) [14], and from 0.19 to 4 V with a slope of 1.75 (near 2), suggesting space-charge-limited current (SCLC) [15, 16]. Post-irradiation (figures 3(b)–(c)), a single linear region with a slope of $\sim$ 1 dominates at both fluences, confirming a shift to ohmic conduction. This transition, absent in lower-fluence proton studies (e.g., ref. [11]), narrows the gap between forward and reverse currents, especially at 10^{16} n/cm^2 (figure 3c), where currents align from 0 to $\sim$ 1 V. Figure 3(d) plots the forward bias slope versus fluence, decreasing from 1.22 (unirradiated) to 1.08 and 1.03 at 10^{15} and 10^{16} n/cm^2, respectively.

This ohmic shift is explained by relaxation theory [17], where high-density defect levels, positioned near the bandgap centre, pin the Fermi energy at the intrinsic position, enhancing conductivity and resembling semi-insulating behaviour [18]. Unlike p-Si, where recombination dominates, n-Si's defect states facilitate both generation and conduction, a distinction critical for radiation-hard detectors [18]. Table 1 summarizes key parameters: ideality factor (η), Schottky barrier height (ϕ_B), and saturation current (I_s), calculated via thermionic emission fits (ref. [8]). For the unirradiated diode, $\eta = 2.11$, $\phi_B = 0.78$ eV, and $I_s = 32.3$ nA; at 10^{15} n/cm^2, $\eta = 2.26$, $\phi_B = 0.73$ eV, $I_s = 17.6$ nA; and at 10^{16} n/cm^2, $\eta = 3.89$, $\phi_B = 0.65$ eV, $I_s = 231$ nA, reflecting defect-driven deviations from ideal behavior, comparable to ref. [11].

Table 1. The diode parameters for unirradiated and neutron-irradiated to the fluences of 10^{15} and 10^{16} of Au/n-Si/Al Schottky diodes.

Diode	η	I_s **(A)**	ϕ_B **(eV)**
0	2.11	3.23×10^{-8}	0.71
$\mathbf{10^{15}}$	2.26	1.76×10^{-8}	0.73
$\mathbf{10^{16}}$	3.89	2.31×10^{-6}	0.60
Ref. [11]	2.72	3.13×10^{-9}	0.77

Temperature influences leakage current significantly, as defect activation scales with thermal energy. Measurements at 300 K show pronounced increases, but lower temperatures may reduce this effect by stabilizing defect levels, a hypothesis for future study. The observed ohmic trend at high fluences aligns with radiation-hardness goals, suggesting potential for stable detector operation in harsh environments like the HL-LHC.

4 Conclusion

This study has elucidated the profound effects of 1 MeV neutron irradiation on the electrical properties of n-Si Schottky diodes, particularly at high fluences of 10^{15} and 10^{16} n/cm^2. I-V measurements reveal a clear transition from exponential diode behaviour to ohmic conduction as fluence increases, driven by radiation-induced defects that pin the Fermi energy near the intrinsic position. The reverse current rises sharply by factors of 3.5 and 82 at the respective fluences due to minority carrier generation, while forward current shifts from a slight decrease at 10^{15} n/cm^2 to a significant increase at 10^{16} n/cm^2, reflecting enhanced majority carrier contributions. This shift, accompanied by a rectification ratio drop from 45 to 2, underscores a defect-mediated change in conduction mechanism, distinct from the

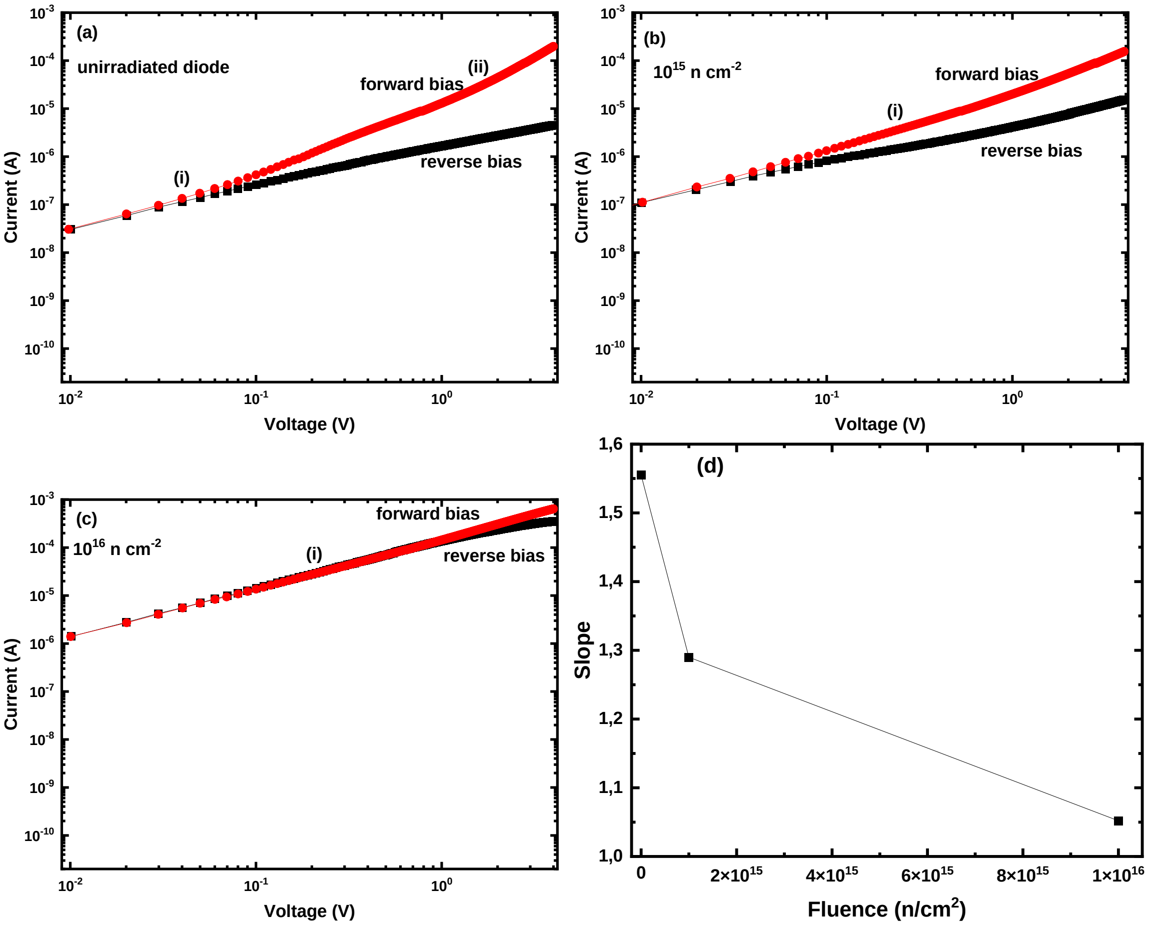

Figure 3. Current-voltage characteristics of (a) unirradiated, (b) neutron-irradiated n-Si diode to a fluence of 10^{15}, (c) 10^{16} n/cm^2 in a double logarithmic scale and (d) plot of slope against fluence.

linear damage trends observed at lower fluences (e.g., $< 10^{14}$ n/cm^2) in prior studies. These findings offer a nuanced understanding of silicon diode behaviour under extreme irradiation, beyond the scope of typical proton-focused research. The observed ohmic behaviour at high fluences aligns with the requirements for radiation-hard detectors, suggesting potential resilience in harsh environments like the High-Luminosity LHC. However, the temperature dependency of leakage current, measured here at 300 K, warrants further exploration, as lower temperatures may mitigate defect activation and slow the ohmic transition. Future studies should incorporate C-V measurements omitted here due to equipment constraints to probe defect densities directly, alongside temperature-dependent I-V analyses to refine defect dynamics models. These insights not only advance the understanding of neutron irradiation effects but also provide a foundation for designing robust semiconductor devices for next-generation high-radiation applications.

Acknowledgments

The research presented in this study was fully sponsored by the National Research Foundation of South Africa (Grant numbers 105292 and 114800).

References

[1] H.F.W. Sadrozinski, *Applications of silicon detectors*, *IEEE Trans. Nucl. Sci.* **48** (2001) 933.

[2] H.S. Bennett et al., *Device and Technology Evolution for Si-Based RF Integrated Circuits*, *IEEE Trans. Electron Devices* **52** (2005) 1235.

[3] M. Bruzzi et al., *Radiation-hard semiconductor detectors for SuperLHC*, *Nucl. Instrum. Meth. A* **541** (2005) 189.

[4] M.K. Parida, S. Tripura Sundari, V. Sathiamoorthy and S. Sivakumar, *Current-voltage characteristics of silicon PIN diodes irradiated in KAMINI nuclear reactor*, *Nucl. Instrum. Meth. A* **905** (2018) 129.

[5] V. Sandeep, J.C. Pravin and S.A. Kumar, *Ionizing radiation defects and reliability of Gallium Nitride-based III-V semiconductor devices: A comprehensive review*, *Microelectron. Reliab.* **159** (2024) 115445.

[6] A.R. Altamura et al., *Characterization of Silicon Photomultipliers after proton irradiation up to 1014neq/cm2*, *Nucl. Instrum. Meth. A* **1040** (2022) 167284 [`arXiv:2106.12344`].

[7] M. Moll, *Displacement damage in silicon detectors for high energy physics*, *IEEE Trans. Nucl. Sci.* **65** (2018) 1561.

[8] J.O. Bodunrin and S.J. Moloi, *Current-Voltage Characteristics of 4 MeV Proton-Irradiated Silicon Diodes at Room Temperature*, *Silicon* **14** (2022) 10237.

[9] S.J. Moloi and M. McPherson, *The current and capacitance response of radiation-damaged silicon PIN diodes*, *Physica B Condens. Matter* **404** (2009) 3922.

[10] M. Bianco, *Upgrade of the CMS Muon Spectrometer in the forward region with the GEM technology*, 2020 *JINST* **15** C09045.

[11] D.A. Oeba, J.O. Bodunrin and S.J. Moloi, *Electrical properties of 3 MeV proton irradiated silicon Schottky diodes*, *Physica B Condens. Matter* **610** (2021) 412786.

[12] G.F. Dalla Betta et al., *Investigation of leakage current and breakdown voltage in irradiated double-sided 3D silicon sensors*, 2016 *JINST* **11** P09006.

[13] E.Q.B. Macabebe and E.E. Van Dyk, *Parameter extraction from dark current-voltage characteristics of solar cells*, *S. Afr. J. Sci.* **104** (2008) 401.

[14] R. Kumar and S. Chand, *Fabrication and electrical characterization of nickel/p-Si Schottky diode at low temperature*, *Solid State Sci.* **58** (2016) 115.

[15] Ö Sevgili, *On the examination of temperature-dependent possible current-conduction mechanisms of Au/(nanocarbon-PVP)/n-Si Schottky barrier diodes in wide range of voltage*, *J. Mater. Sci. Mater. Electron.* **32** (2021) 10112.

[16] Ş. Çavdar, P. Oruç, S. Eymur and N. Tuğluoğlu, *Frequency-dependent capacitance and conductance characteristics and current transport mechanisms of Schottky diodes with TPA-IFA organic interfacial layer*, *Phys. Scripta* **99** (2024) 095986.

[17] B.K. Jones, J. Santana and M. McPherson, *Semiconductor detectors for use in high radiation damage environments — Semi-insulating GaAs or silicon?*, *Nucl. Instrum. Meth. A* **395** (1997) 81.

[18] M. McPherson, *Fermi level pinning in irradiated silicon considered as a relaxation-like semiconductor*, *Physica B Condens. Matter* **344** (2004) 52.