Nuclear Instruments and Methods in Physics Research B 507 (2021) 42–45

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, B

journal homepage: www.elsevier.com/locate/nimb

Bias-dependent displacement damage effects in a silicon avalanche photodiode

Robert M. Zedric [a], Sunil S. Chirayath [a,*], Craig M. Marianno [a], Yacouba Diawara [b], Natko Skukan [c]

[a] Department of Nuclear Engineering, Texas A&M University, College Station, TX 77843, USA
[b] Neutron Sciences Directorate, One Bethel Valley Road, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
[c] Nuclear Science and Instrumentation Laboratory, International Atomic Energy Agency, Friedensstrasse 1, 2444 Seibersdorf, Austria

ARTICLE INFO

Keywords:
IBIC
Displacement Damage
Avalanche photodiode
Bias effects

ABSTRACT

Radiation effects studies on a commercial beveled-edge avalanche photodiode (APD) showed that applying reverse bias to the device during irradiation enhanced the severity of apparent damage. Proton microbeam irradiations were made using a proton beam energy of 2 MeV and fluence ranging from 2.0×10^{10} to 5.1×10^{12} cm^{-2}. Charge collection measurements using the ion beam induced charge (IBIC) technique showed that relative losses increased by up to an order of magnitude when the reverse bias applied during irradiation increased from 50 to 1500 V. The presence of reverse bias also led to equivalent losses in charge collection that would only be seen in irradiations with an order of magnitude higher fluence in unbiased APDs. The results demonstrate that bias-enhanced irradiation damage is insufficiently understood and must be accounted for in characterizations of radiation effects.

1. Introduction

Radiation effects on electronics are important to understand when using various instrumentation and detection systems in nuclear safeguards, national security, and satellite applications. The accumulation of displacement damage within a semiconductor lattice leads to loss in performance and undesirable behavior of irradiated devices or their constituent components. Experimental studies typically focus on the particle types, energies, and fluence of incident radiation as well as the material type and doping profile of the target device. However, literature rarely discusses either the value or the effect of applied voltage during irradiation because this particular parameter tends to be inconsequential in the formation of displacement damage in silicon [1]. Past reports and new observations show that it merits further investigation.

Several irradiation studies using deep level transient spectroscopy (DLTS) reported that the relative concentrations of defects within irradiated devices were influenced by the bias applied during irradiation. Liu et al. showed that the populations of divacancy, vacancy-oxygen, and vacancy-phosphorus complexes were influenced by forward and reverse biases in a NPN transistor irradiated with Si ions [2]. Ravi et al. studied H and He implantation in PN diodes and found that while divacancy production remained constant, other types of defects were suppressed by the application of bias [3]. These included defects due to hydrogen implantation as well as a type of defect which was only observed following helium implantation. These reports show that displacement damage formation is clearly susceptible to the bias applied during irradiation.

2. Methodology

An commercially-available APD from Luna Optoelectronics with model number 630–70-73–500 (formerly Advanced Photonix, Inc) was used for our study because it was previously found to perform well in radiation detection applications. The APD studied had a large active area of 2 cm^2 and was designed to operate at reverse biases up to 2000 V. The design and operating characteristics of the APD are described elsewhere [4–6]. A set of spreading resistance measurements were conducted to determine the doping densities of the n and p-type regions. Uniform phosphorus doping at a density of 7.44×10^{13} cm^{-3} was present in the n-type float-zone region. Boron doping in the epitaxial p-type region was less uniform but was generally near 1.05×10^{15} cm^{-3}. The junction depth was 17.5 μm below the surface.

* Corresponding author.
E-mail address: sunilsc@tamu.edu (S.S. Chirayath).

https://doi.org/10.1016/j.nimb.2021.09.013
Received 2 July 2021; Received in revised form 18 September 2021; Accepted 21 September 2021
Available online 4 October 2021
0168-583X/

Proton irradiations were made using the microbeam end station at the Ruđer Bošković Institute [7]. Two MeV energy protons were implanted in 100 × 100 μm^2 squares on the APD using a raster scanning method. Transport of ions in matter (TRIM) simulations predicted an average final proton depth of 48 μm and an average of 54 vacancies created per incident proton. Irradiation fluence ranged from 2.0×10^{10} to 5.1×10^{12} cm^{-2}, average flux ranged from 4.6×10^7 to 1.6×10^{10} cm^{-2}s^{-1}, and reverse biases applied during irradiation ranged from 0 to 1500 V. Typical uncertainties for the fluence and flux were below 3%. Ion beam induced charge (IBIC) measurements using 2 and 4 MeV protons assessed the change in signal response from irradiated regions, with a beam energy spread of about 1 keV. The IBIC measurements carried out at the Ruđer Bošković Institute typically had a resolution of 20 to 40 keV for the Si detectors. Measurements biases included 40, 1200, 1600, and 1800 V, with only the latter two biases producing any band-to-band impact ionization. Ratios were then taken of the post-damage IBIC response to the pre-damage response to give the charge collection ratio (CCR). CCR was used to describe IBIC responses in this paper instead of charge collection efficiency (CCE) because the latter is traditionally used in the context of devices which do not have gain from impact ionization. CCR provides greater flexibility for analysis because the normalizing factor in the denominator can express the time-integrated current (aka induced charge) in the electrodes at biases where impact ionization occurs. Following IBIC measurements, data were extracted from the center of each irradiated region during post-processing to avoid edge effects. Uncertainties given for CCR values were calculated using list mode data within the central regions and expressed using one sigma standard deviations.

3. Results and discussion

The CCR values (in percent) of eight irradiations made over a range of reverse biases from 0 to 1500 V are depicted in Fig. 1a and 1b. Irradiation fluence and flux values were kept constant between regions, with values of 6.4×10^{11} cm^{-2} and 1.6×10^{10} cm^{-2}s^{-1}, respectively. IBIC scans using 2 and 4 MeV protons with measurement biases of 1200, 1600, and 1800 V revealed the CCR of the irradiated regions.

The degradation in signal response from the APD was greatly amplified when large reverse biases were applied during irradiation. This was observed for all irradiation biases at or above 250 V. Only the 50 V irradiation had a higher CCR than the 0 V irradiation. In the 2 MeV scans, the drop in CCR for the 1500 V irradiation was 4 times greater than the drop in CCR for the 0 V irradiation when measured at 1800 V. When measured at 1600 V, the irradiation bias-induced drop was 5 times greater, and at 1200 V it was nearly 7 times greater.

The CCR values showed a remarkable sensitivity to the applied bias during the measurement. This behavior indicated that radiation damage affected impact ionization rates. The introduction of defects caused trapping and increased scattering which reduced both the concentration and average velocity of conduction band electrons compared to pre-damage conditions. These effects worked together to reduce the CCR at higher biases by suppressing the effective electron ionization coefficient for impact ionization.

Similar trends were seen between the IBIC scans made with 4 MeV protons in Fig. 1b as those made with 2 MeV protons in Fig. 1a. For a given irradiation and measurement bias combination, the CCR values were up to 13% higher in Fig. 1b. than in Fig. 1a. The 2 MeV probing ions delivered the greatest IBIC sensitivity because its Bragg peak overlapped with the depth of maximum irradiation damage, and all electron-hole pairs were created within the damaged volume. In contrast, the 4 MeV probing ions generated a significant amount of charge beyond the damaged volume, as deep as 148 μm below the surface. The resulting loss in sensitivity was strong enough in the 1200 V scan in Fig. 1b for the loss in CCR to appear almost negligible compared to the pre-damaged state. It is important to note that the edge of the depletion region, also known as the space charge region (SCR), was deeper than the end of range for a 4 MeV proton for measurement biases at 1200 V and above.

Eighteen additional irradiations were made to assess the combined effects of fluence and bias and are depicted in Fig. 2a, 2b, and 2c. Nine irradiations were made at zero bias and nine at 500 V reverse bias. Each set covered a range of fluence values from 2×10^{10} to 5.1×10^{12} cm^{-2} with proton flux varying from 4.6×10^7 to 1.1×10^{10} cm^{-2}s^{-1}.

For each fluence value in Fig. 2, the irradiations made at 500 V had the lower CCR values compared to 0 V irradiations for all cases except the fluence of 2x10^{10} cm^{-2}. The CCR values in Fig. 2a for zero-bias irradiations exhibited a monotonous decrease as fluence increased. These trends contrasted with the CCR vs fluence behavior for 500 V irradiations in Fig. 2b, which showed unexpected increases in CCR at high fluences. As reference, Pastuovic et al. showed that irradiations made with zero bias on standard photodiodes would consistently give monotonous decreases in CCE for an increasing fluence for all measurements [8]. While standard photodiodes and APDs operate differently, the resemblance in behavior for zero-bias irradiations shows that the former can be a useful starting point in understanding the latter.

The differences between the CCR values seen in Fig. 2a and 2b were not as great as those seen within Fig. 1a and 1b, but they still showed substantial decreases. The region irradiated at 500 V with a fluence of 1.3x10^{12} cm^{-2} showed a reduction in CCR that was more than three times greater than a region irradiated at zero bias with the same fluence. The measurements at 1800 V exhibited a CCR value of 87.1% in the 0 V irradiation which then fell to 55.3% in the 500 V irradiation. Fig. 2a and

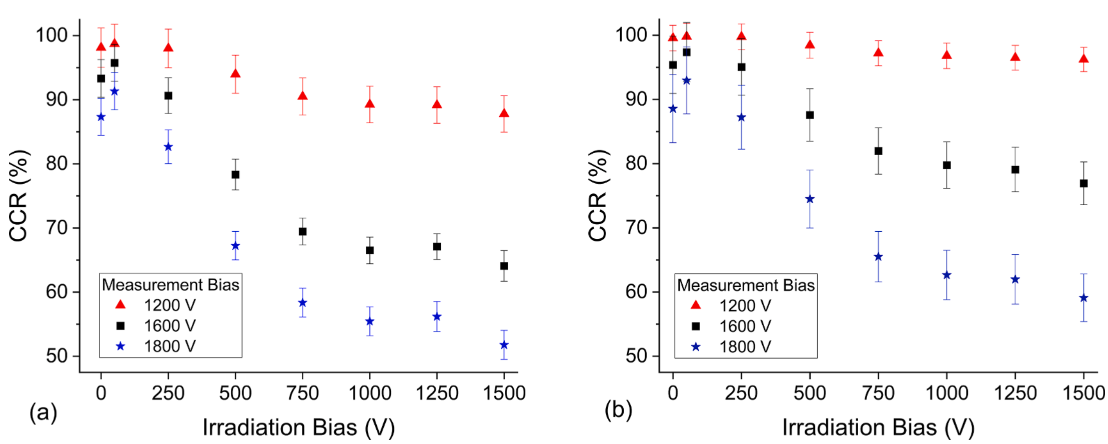

Fig. 1. CCR values from eight irradiations made with a fluence of 6.4×10^{11} cm^{-2}, flux of 1.6×10^{10} cm^{-2}s^{-1}, and reverse biases from 0 to 1500 V. The IBIC probe used 2 MeV energy protons in (a) and 4 MeV protons in (b).

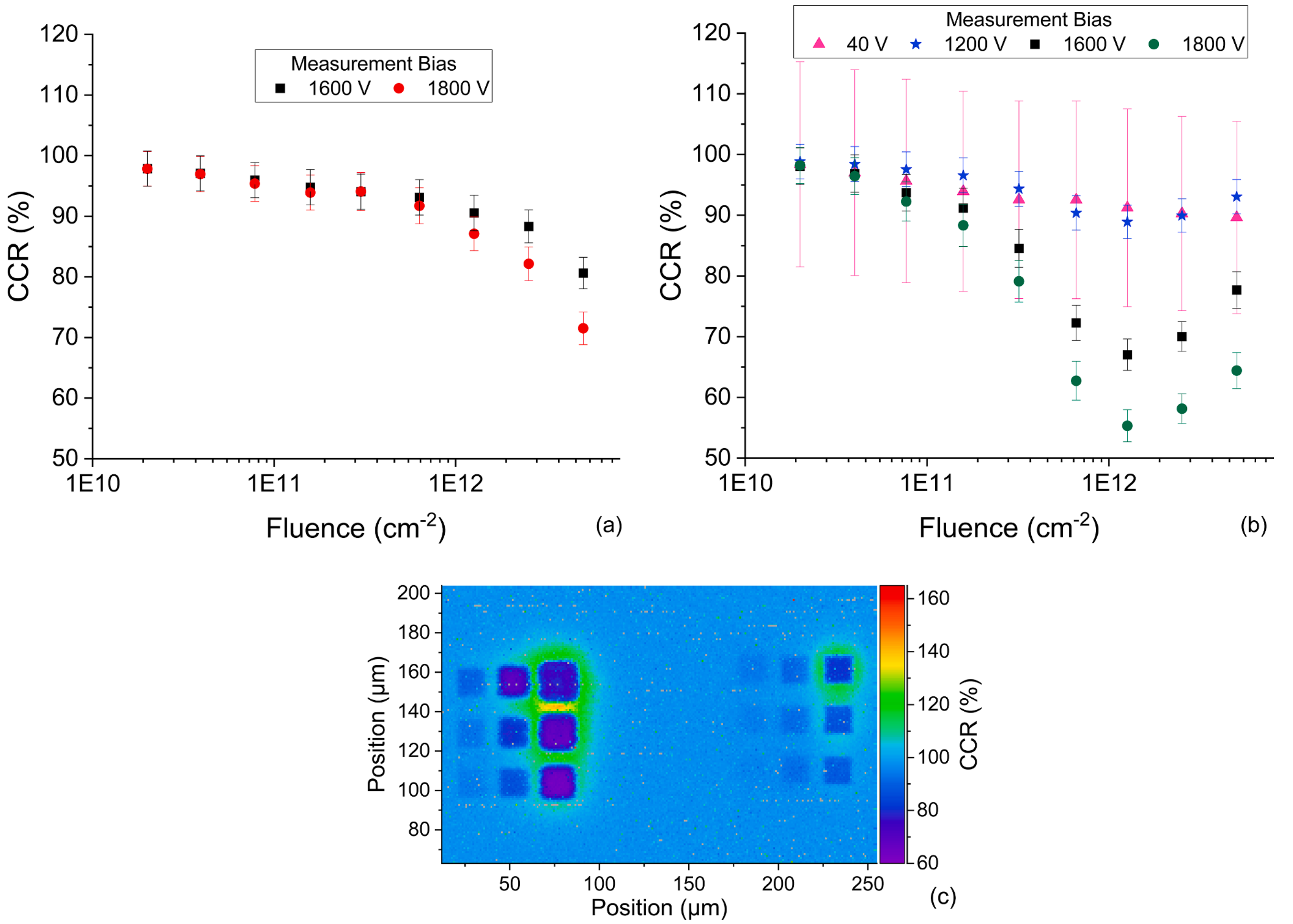

Fig. 2. IBIC response from 18 regions irradiated and measured with 2 MeV protons for a range of fluence values from 2×10^{10} to 5.1×10^{12} cm^{-2}. (a) shows IBIC measurements at 1600 and 1800 V for a set of irradiations made at zero bias. (b) shows similar data for irradiations at 500 V reverse bias while including IBIC scans at 40 and 1200 V. An IBIC scan at 1600 V of all 18 irradiated regions is seen in (c), with 0 V irradiations on the right and 500 V irradiations on the left.

2b also show that applying bias during irradiations reduced the amount of fluence required to reach a certain level of damage. Measurements at 1800 V showed that a 0 V irradiation with a fluence of 5.1x10^{12} cm^{-2} reached a CCR of 71.5%. A greater level of damage was reached when a 500 V irradiation with a fluence of 6.4x10^{11} cm^{-2} yielded a CCR of 62.7%. This produced stronger damage with an order of magnitude less fluence.

The IBIC scan in Fig. 2c shows a visual representation of the damaged regions and their relative loss in CCR. Halo-like regions were seen around regions with high fluence and their overlapping effects are thought to be responsible for the upward curve in CCR seen in higher fluence values in Fig. 2b. The mechanism behind the halos and their effect on CCR could not be explained at this time, although they are not the first halo-like effect seen in proton-irradiated diodes. Barbero et al. reported similar phenomena but with a reverse effect [9]. Instead of observing a stark increase in charge collection as seen in Fig. 2c, Barbero found that the CCE decreased over an area 12 times larger than the original irradiated zone. These effects were attributed to electric field bending from changes in the effective doping concentration.

The bias applied during irradiation may have affected defect formation both directly and indirectly. The direct mechanism may have involved the drift of charged interstitials (I) and vacancies (V) in the SCR. This likely promoted the motion of defects along the electric field and affected the spatial distribution of defect complexes, which could have formed. The indirect mechanism may have involved the alteration of defect charge states due to the greatly reduced concentrations of charge carriers within the SCR. This likely altered the formation of defect complexes because charge states determine the mobility of V and I defects and interstitial hydrogen. Charge states also affect their probability of interaction with other defects. A compounding factor within this particular device may have been the relative lack of oxygen within the epitaxial and float-zone regions of the device. This is believed to have enhanced the mobility of vacancies compared to devices made of Czochralski silicon, enabling the effects of applied bias to be more pronounced. Based on the dependence of the CCR with irradiation bias as seen in Fig. 1, it seems probable that both the direct and indirect mechanisms were at play [10,11]. Another potential possible cause for the CCR degradation might be also the formation of an n + layer induced by hydrogen implanted into the float zone (FZ) region of the diode. Deep level transient spectroscopy (DLTS) studies are necessary to determine the role which various defects play in these observations.

4. Conlusion

In conclusion, this study demonstrated a case where applying bias to a device during exposure to radiation caused a drastic change in apparent damage. Losses in CCR when measured at 1200 V were seen to increase by an order of magnitude when the irradiation bias increased from 50 to 1500 V. An irradiation at 0 V had less damage than a similar irradiation at 500 V with an order of magnitude lower fluence. While it is not certain why the device under test exhibited such sensitivities to the applied bias during irradiation, this research shows that this parameter must be considered more carefully in future studies involving displacement damage.

CRediT authorship contribution statement

Robert M. Zedric: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing original draft. **Sunil S. Chirayath:** Project Administration, Formal analysis, supervision, review & editing. **Craig M. Marianno:** Project Administration, Formal analysis, supervision, review & editing. **Yacouba Diawara:** Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, review & editing. **Natko Skukan:** Conceptualization, Data curation, Investigation, Methodology, review & editing.

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.

Acknowledgements

This research was performed under appointment to the Nuclear Nonproliferation International Safeguards Fellowship Program sponsored by the Department of Energy, National Nuclear Security Administration's Office of International Nuclear Safeguards (NA-241). It has also been partially conducted and supported by the International Atomic Energy Agency, Nuclear Science and Instrumentation Laboratory, Physics Section. Special thanks to Milko Jakšić at the Ruđer Bošković Institute for support and guidance during the experiments.

References

[1] M.S. Robbins, L.G. Rojas, An assessment of the bias dependence of displacement damage effects and annealing in silicon charge coupled devices, IEEE Trans. Nucl. Sci. 60 (6) (2013) 4332–4340, https://doi.org/10.1109/TNS.2013.2287255.

[2] C. Liu, X. Li, H. Geng, E. Rui, J. Yang, L. Xiao, DLTS Studies of bias dependence of defects in silicon NPN bipolar junction transistor irradiated by heavy ions, Nucl. Instrum. Methods A 688 (2012) 7–10, https://doi.org/10.1016/j.nima.2012.05.073.

[3] J. Ravi, Y. Erokhin, S. Koveshnikov, G.A. Rozgonyi, The influence of an in-situ electric field on H^+ and He^+ implantation induced defects in silicon, Mater. Res. Society Symposium Proc. 316 (1994) 105–110, https://doi.org/10.1557/PROC-316-105.

[4] M. Moszynski, M. Kapusta, M. Balcerzyk, M. Szawlowski, D. Wolski, I. Wegrzecka, M. Wegrzecki, Comparative study of avalanche photodiodes with different structures in scintillation detection, IEEE Trans. Nucl. Sci. 48 (4) (2001) 1205–1210, https://doi.org/10.1109/TNS.2310.1109/23.958751.

[5] M. Moszyński, M. Szawlowski, M. Kapusta, M. Balcerzyk, Large area avalanche photodiodes in scintillation and X-rays detection, Nucl. Instrum. Methods Phys. Res. A 485 (3) (2002) 504–521, https://doi.org/10.1016/S0168-9002(01)02117-9.

[6] L.M.P. Fernandes, F.D. Amaro, A. Antognini, J.M.R. Cardoso, C.A.N. Conde, O. Huot, P.E. Knowles, F. Kottmann, J.A.M. Lopes, L. Ludhova, C.M.B. Monteiro, F. Mulhauser, R. Pohl, J.M.F.D. Santos, L.A. Schaller, D. Taqqu, J.F.C.A. Veloso, Characterization of large area avalanche photodiodes in X-ray and VUV-light detection, J. Instrum. 2 (08) (2007) P08005, https://doi.org/10.1088/1748-0221/2/08/P08005.

[7] M. Jakšić, I. Bogdanovic Radovic, M. Bogovac, V. Desnica, S. Fazinic, et.al, "New capabilities of the Zagreb ion microbeam system," Nuclear Instruments and Methods in Physics Research Section B, 260 (2007) 114-118. doi: 10.1016/j.nimb.2007.01.252.

[8] Z. Pastuovic, M. Jaksic, G. Kalinka, M. Novak, A. Simon, Deterioration of electrical and spectroscopic properties of a detector grade silicon photodiode exposed to short range proton, lithium and oxygen ion irradiation, IEEE Trans. Nucl. Sci. 56 (4) (2009) 2457–2464, https://doi.org/10.1109/TNS.2009.2023123.

[9] N. Barbero, J. Forneris, V. Grilj, M. Jakšić, J. Räisänen, A. Simon, N. Skukan, E. Vittone, Degradation of the charge collection efficiency of an n-type Fz silicon diode subjected to MeV proton irradiation, Nucl. Instrum. Methods Phys. Res., Sect. B 348 (2015) 260–264, https://doi.org/10.1016/j.nimb.2014.11.019.

[10] R.A. Brown, G.A. Rozgonyi, J. Ravi, Y. Erokhin, C.W. White, Charge state defect engineering of silicon during ion implantation, MRS Proc. 438 (1996) 39, https://doi.org/10.1557/PROC-438-39.

[11] J. Härkönen, E. Tuominen, E. Tuovinen, P. Mehtälä, K. Lassila-Perini, V. Ovchinnikov, P. Heikkilä, M. Yli-Koski, L. Palmu, S. Kallijärvi, H. Nikkilä, O. Anttila, T. Niinikoski, V. Eremin, A. Ivanov, E. Verbitskaya, Processing of microstrip detectors on Czochralski grown high resistivity silicon substrates, Nucl. Instrum. Methods A 514 (1-3) (2003) 173–179, https://doi.org/10.1016/j.nima.2003.08.102.