Neutron irradiation effect on SiPMs up to
\[ \Phi_{\text{neq}} = 5 \times 10^{14} \text{ cm}^{-2} \]

M. Centis Vignali\textsuperscript{b}, E. Garutti\textsuperscript{a,}*, R. Klanner\textsuperscript{a}, D. Lomidze\textsuperscript{a}, J. Schwandt\textsuperscript{a}

\textsuperscript{a}Hamburg University, Luruper Chaussee 149, 22761 Hamburg, Germany
\textsuperscript{b}CERN, Geneva, Switzerland

Abstract

Silicon Photo-Multipliers (SiPM) are becoming the photo-detector of choice for increasingly more particle detection applications, from fundamental physics, to medical and societal applications. One major consideration for their use at high-luminosity colliders is the radiation damage induced by hadrons, which leads to a dramatic increase of the dark count rate. KETEK SiPMs have been exposed to various fluences of reactor neutrons up to \( \Phi_{\text{neq}} = 5 \times 10^{14} \text{ cm}^{-2} \) (1 MeV equivalent neutrons). Results from the I-V, and C-V measurements for temperatures between \(-30^\circ\text{C}\) and \(+30^\circ\text{C}\) are presented. We propose a new method to quantify the effect of radiation damage on the SiPM performance. Using the measured dark current the single pixel occupation probability as a function of temperature and excess voltage is determined. From the pixel occupation probability the operating conditions for given requirements can be optimized. The method is qualitatively verified using current measurements with the SiPM illuminated by blue LED light.

Keywords: SiPM, Radiation damage, Neutron irradiation

1. Introduction

Radiation damage of silicon by hadrons has been extensively studied for electronics and sensors \cite{1, 2}. In the Si bulk, defect states are formed, which change the effective doping, reduce the carrier mobilities and lifetimes, and

*Corresponding author

Email address: Erika.Garutti@physik.uni-hamburg.de (E. Garutti)
increase the generation rate. The increased generation rate causes an increase in dark-count-rate (DCR), which is the biggest limitation for use of SiPMs in a high radiation environment. To better quantify the effect of the DCR increase on the SiPM performance, the pixel occupation probability is determined using the measured dark current and the values of the quenching resistance. The pixel occupation probability is defined as the probability that a Geiger discharge occurs in a pixel in a given time interval. From the pixel occupation probability the decrease of the dynamic range of the SiPM due to dark counts can be determined. The results are compared to SiPM current measurements with the SiPM illuminated by a blue LED.

In this paper current-voltage measurements of SiPMs irradiated with neutrons to fluences between 0 and $\Phi_{eq} = 5 \times 10^{13}$ cm$^{-2}$, with and without illumination by a blue LED, and temperatures between $-30^\circ$C and $+30^\circ$C are presented. From these data the temperature and fluence dependence of characteristic SiPM parameters, like breakdown voltage, pixel occupancy, and reduction of the photo-detection efficiency are determined.

2. SiPMs, irradiation and measurements

The SiPMs investigated were fabricated by KETEK [3]. They consist of 4384 pixels of $15 \times 15$ $\mu$m$^2$, a breakdown voltage of about 27.5 V, a depth of the amplification region, as determined by capacitance-voltage (C-V) measurements, of $<1$ $\mu$m, and a poly-silicon quenching resistance of 550 k$\Omega$ with a sample-to-sample spread of $\pm30\%$. For more details see [4]. The neutron irradiations were performed at room temperature without applied bias at the TRIGA Research Reactor of the JSI, Ljubljana. The samples were transported cold to Hamburg after irradiation and stored in a refrigerator at $-30^\circ$C. No annealing was applied to the samples before measurement. However, each measurement cycle took approximately 2 hours at one given temperature, and in particular the measurements at $+30^\circ$C cause annealing. The sample are kept in the refrigerator when not being measured. The following measurements were performed on a temperature-controlled chuck in a dry atmosphere: current-voltage (I-V) for forward and reverse voltages; temperatures between $-30^\circ$C and $+30^\circ$C without and with illumination by LED light of 470 nm.
Figure 1: Measured I-V curves at various fluences, (a) at +20°C, in the dark, (b) at −30°C in the dark (solid lines) and with LED illumination (dashed lines). The related fluences are reported next to the curves.

3. Breakdown voltage

The breakdown voltage $V_{bd}$ for each set of measurement is determined using the method of the minimum of the inverse logarithmic derivative (ILD) as discussed in [4]. Fig. 2 (a) presents ILD for the I-V curves shown in Fig. 1 (a). The difference of $V_{bd}$ after and before neutron irradiation as function of irradiation fluence are presented in Fig. 2 (b) for $T = +20°C$. Up to $\Phi_{neq} = 5 \times 10^{13} \text{ cm}^{-2}$, no change is observed in the value of $V_{bd}$ within the uncertainty of about 40 mV. The value of $V_{bd}$ after irradiation with $\Phi_{neq} = 5 \times 10^{14} \text{ cm}^{-2}$ neutrons is higher by about 350 mV compared to the non-irradiated SiPM. Note that in [4] we reported a difference of about 1 V for the $V_{bd}$ determined from I-V curves and the $V_{G}^{bd}$ determined from gain ($G$) vs. voltage curves, for this specific SiPM. Therefore the results from of Fig. 2 (b) do not allow to draw conclusions on the fluence dependence of the SiPM gain, which is expected to be proportional to $V - V_{G}^{bd}$. Further work is required to establish a method to determine $V_{G}^{bd}$ for irradiated SiPMs.

4. Photo-detection

One relevant question for SiPM applications is, how does the photo-detection change as a function of fluence and temperature either because of changes in the SiPM electronic parameters (signal duration, $\tau$, electric field, $V_{bd}$, $PDE$, correlated noise ($CN$)) or because of the increase in $DCR$. Fig. 3 presents the normalized photo-current
Figure 2: a) ILD curves computed from the I-V curves of Fig. 1 (a). b) difference of $V_{bd}$ after and before neutron irradiation as function of fluence.

\[
I_{LED}^{norm} = \frac{I_{LED}^{meas}(V_{bias}) - I_{dark}(V_{bias})}{I_{LED}^{meas}(V_{bias} = 10 \, V) - I_{dark}(V_{bias} = 10 \, V)} \tag{1}
\]

of the SiPM before and after irradiation to $\Phi_{neq} = 5 \times 10^{13} \, \text{cm}^{-2}$. At $V_{bias} = 10 \, V$ the SiPM gain is assumed to be 1. If the additional pixel occupancy by the LED photons is ignored $I_{LED}^{norm}$ can be related to SiPM parameters by $I_{LED}^{norm} \approx A^{*}_{\text{prob}} \cdot G \cdot (1 + CN)$, with $A^{*}_{\text{prob}}$ being the Geiger discharge probability multiplied by the probability that the corresponding pixel is not occupied by a Geiger discharge. The ratio

\[
R = \frac{I_{LED}^{norm}(\Phi_{neq})}{I_{LED}^{norm}(\Phi_{neq} = 0)} \tag{2}
\]

should be equal to 1 if the product $A^{*}_{\text{prob}} \cdot G \cdot (1 + CN)$ is not affected by the irradiation. While this was the case within $< 10\%$ up to $\Phi_{neq} = 10^{12} \, \text{cm}^{-2}$, as demonstrated in [5], it is not anymore true for $\Phi_{neq} = 5 \times 10^{13} \, \text{cm}^{-2}$. Above breakdown $R$ drops quickly to zero, indicating a rapid decrease in effective photo-detection efficiency. Cooling to $-30^\circ \text{C}$ increases the excess voltage range for a given lower limit of $R$. To understand the cause of this signal loss the pixel occupation probability is investigated.

5. Pixel occupation probability

We introduce the pixel occupation probability due to dark counts $\eta_{DC}$, as the probability of a Geiger discharge in a pixel in a time interval $\Delta t$. It is
related to the $DCR$ by

$$DCR \cdot (1 + CN) \approx \frac{N_{pix}}{\tau} \cdot \eta_{DC},$$

where we have taken $\Delta t = \tau = R_q \cdot C_{pix}$ the recovery time of the SiPM pulse. One can express the measured $I_{dark}$ in terms of the pixel occupation probability:

$$I_{dark} = q_0 \cdot G \cdot DCR \cdot (1 + CN) \approx q_0 \cdot \frac{C_{pix} V_{ex}}{q_0} \cdot \frac{N_{pix}}{\tau} \cdot \eta_{DC}.$$  \hspace{1cm} (4)

Eq. 4 can be rewritten as:

$$\eta_{DC} = \frac{I_{dark}}{V_{ex}} \cdot \frac{R_q}{N_{pix}}.$$  \hspace{1cm} (5)

We note that all quantities in Eq. 5, $I_{dark}$, $R_q$ and $V_{bd}$ can be determined from I-V measurements for forward and reverse bias. In particular, $R_q$ is taken from $\frac{dI}{dV}$ calculated at the highest forward bias voltage below current limit of 1.7 V.

We also note that for $\eta_{DC} \to 1$ the voltage drop due to $I_{dark}$ over $R_q/N_{pix} = V_{ex}$; thus the pixel voltage never recovers, i.e. $V_{bias} - V_{ex} = V_{bd}$.

Assuming Poisson statistics, we calculate $\mu_{DC} = -ln (1 - \eta_{DC})$, the average number of $e - h$ pairs which in a time interval $\tau$ would produce a Geiger discharge in a pixel not already occupied by a discharge. The quantity $\mu_{DC}/\tau$
Figure 4: a) $I_{\text{dark}}$ versus excess bias voltage for a SiPM irradiated to $\Phi_{\text{neq}} = 5 \times 10^{13} \text{ cm}^{-2}$. b) Pixel occupation probability $\eta_{\text{DC}}$ for various temperatures from $+20 ^\circ\text{C}$ to $-30 ^\circ\text{C}$.

is directly related to the charge carrier generation rate (and thus can be simulated using Shockley-Read-Hall statistics including field enhancement).

Fig. 4a shows the measured $I_{\text{dark}}$ versus excess bias voltage for a SiPM irradiated to $\Phi_{\text{neq}} = 5 \times 10^{13} \text{ cm}^{-2}$ for various temperatures from $+20 ^\circ\text{C}$ to $-30 ^\circ\text{C}$. Fig. 4b presents the results for the pixel occupation probability $\eta_{\text{DC}}$ extracted from Fig. 4a. The curves indicate that for instance for an operation temperature of $-30 ^\circ\text{C}$, this particular SiPM has a pixel occupation probability of 20% if operated at 2.5 V excess bias. We conclude that the increase of the pixel occupation probability, $\eta_{\text{DC}}$, with temperature and fluence is responsible for the rapid decrease of the photo-detection efficiency, as function of fluence and temperature, as demonstrated by the decrease of $R$ shown in Fig. 3.

6. Conclusions

Different characteristics of KETEK SiPMs irradiated with neutrons up to a fluence of $\Phi_{\text{neq}} = 5 \times 10^{14} \text{ cm}^{-2}$ were extracted from current-voltage measurements with and without illumination with a blue LED and temperatures between $-30 ^\circ\text{C}$ and $+30 ^\circ\text{C}$. The values of the breakdown voltage is not changed up to $\Phi_{\text{neq}} = 5 \times 10^{13} \text{ cm}^{-2}$, whereas an increase of $V_{\text{bd}}$ is observed for $\Phi_{\text{neq}} = 5 \times 10^{14} \text{ cm}^{-2}$. For high neutron fluences, the $\text{DCR}$ by far exceeds the values for which the standard methods of $\text{DCR}$ determination using pulse-height spectra can be applied. Therefore the method of pixel occupation probability is introduced, which allows to characterize the reduction of photo-detection efficiency due to high DCRs. As an example, the
specific KETEK SiPM irradiated to $\Phi_{neq} = 5 \times 10^{13}$ cm$^{-2}$ has a pixel occupation probability of 20% if operated at $V_{ex} = 2.5$ V at $-30^\circ$C, and thus can be used as photo-detector, however with a significantly reduced dynamic range compared to the non-irradiated SiPM.

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References

[1] J. R. Srour, J. W. Palko, Displacement Damage Effects in Irradiated Semiconductor Devices, IEEE Transactions on Nuclear Science 60 (2013) 1740–1766. doi:10.1109/TNS.2013.2261316.

[2] G. Lindström, Radiation damage in silicon detectors, Nuclear Instruments and Methods in Physics Research A 512 (2003) 30–43. doi:10.1016/S0168-9002(03)01874-6.

[3] KETEK, Hofer Str. 3, D-81737 Munich, Germany, 2017. URL: https://www.ketek.net.

[4] V. Chmill, E. Garutti, R. Klanner, M. Nitschke, J. Schwandt, Study of the breakdown voltage of SiPMs, Nucl. Instrum. Meth. A845 (2017) 56–59. doi:10.1016/j.nima.2016.04.047 arXiv:1605.01692.

[5] M. Centis Vignali, V. Chmill, E. Garutti, R. Klanner, M. Nitschke, J. Schwandt, Neutron Induced Radiation Damage of KETEK SiPMs, IEEE conference records (2016).