Nuclear Inst. and Methods in Physics Research, A 936 (2019) 671–673

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

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

Low temperature characteristics of SiPMs after very high neutron irradiation

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ARTICLE INFO

Keywords:
Silicon photomultiplier
MPPC
GAPD
CMS
Radiation damage

ABSTRACT

The design of the CMS phase II upgrade for the HL-LHC uses SiPMs for the Barrel Timing Layer (BTL) and the Behind HCAL detector (BH or CEH). In both sub-detectors the SiPMs will see a 1 MeV equivalent dose of around 10^{14} n/cm^2. To lower the noise in the SiPMs the design is to keep the SiPMs at a low temperature of −30 °C. Different samples from two manufactures of SiPMs were irradiated to a total dose of resp. 2×10^{12}, 5×10^{13} at the TRIGA reactor at the JSI in Slovenia. The noise in SiPMs is dominated by trap assisted tunneling which is a result of the high internal electric field in SiPMs. We therefore studied the noise behavior from +10 °C to −40 °C from standard high internal field and specially designed low field SiPMs from FBK-irst and Hamamatsu. After the initial characterization before annealing the noise decrease in SiPMs was also studied using accelerated annealing.

Contents

1. Introduction

During the CMS Phase 1 upgrade R & D we performed many irradiation measurements on SiPMs from different companies [1–9]. We observed an expected current increase due to defects created by irradiation of the silicon. We compared this current increase with the data from existing PIN diodes at room temperature [10]. In general we expect the SiPMs to be much more irradiation resistant (lower dark count rate) than PIN diodes because they have a much thinner epitaxial layer, in the order of a few microns, than PIN junctions that are typically 100 to 300 μm. Experimentally we found much higher current increase in the different SiPMs than expected for a 2 μm epitaxial layer. A possible explanation is that the generation of electron–hole pairs due to defects in the depletion region is enhanced by a high electric field (> 10^5 V/cm) leading to the mechanism of trap-assisted tunneling or the Poole–Frenkel effect. [11,12]. The future phase II projects in CMS are considering the use of SiPMs in very high irradiation areas. To lower the noise after irradiation, cooling to −30 °C was proposed. We studied the current decrease vs temperature for SiPMs after irradiation (10^{14} n/cm^2). Because of the internal electric field effects inside the SiPMs we collaborated with FBK-irst to produce, in addition to the standard field (SF), also low internal electric field (LF) SiPMs and compared them to the Hamamatsu (S10943-4732) production SiPM produced for the Hadronic Endcap in the CMS experiment [13]. Here we refer to it as the HE SiPM.

Because the wavelength of interest of both BTL and BH is around 410 nm we used the NUV SiPMs from FBK-irst. In Fig. 1 we show the PDE vs wavelength of the 15 μm cell devices from FBK and HPK at 3 V over-voltage before irradiation. At 3 V over-voltage we found

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https://doi.org/10.1016/j.nima.2018.09.111
Received 30 June 2018; Received in revised form 21 September 2018; Accepted 24 September 2018
Available online 28 September 2018
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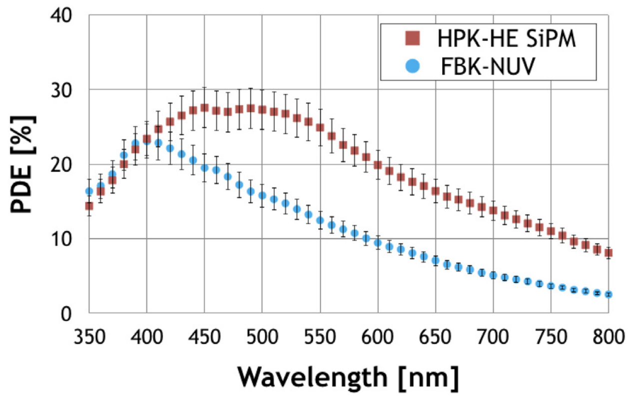

Fig. 1. Measured PDE vs wavelength at 3 V over-voltage.

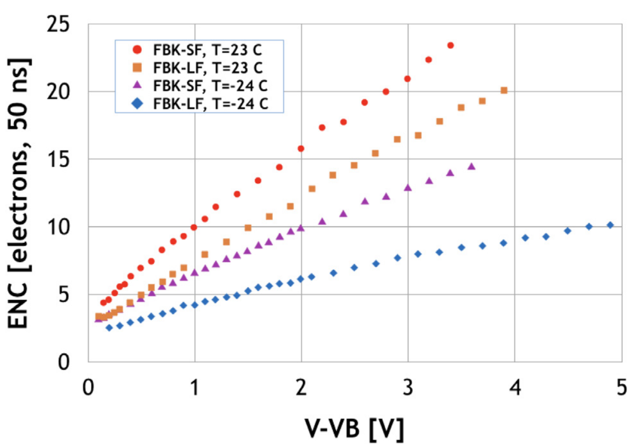

Fig. 2. ENC noise vs over-voltage for LF and SF 1 mm^2 FBK SiPMs at after a dose of 2×10^{12} n/cm^2 ($T = -24$ °C is non-annealed).

that the PDE to be very comparable, around 20% at 410 nm for both manufactures.

2. Radiation damage after 2×10^{12} 1 MeV eq. n/cm^2

In January 2017 we exposed the FBK NUV and Hamamatsu HE SiPMs to a total dose of 2×10^{12} 1 MeV eq. n/cm^2 at the TRIGA reactor at the JSI. These SiPMs were initially kept cold after irradiation and the noise was measured at −24 °C before annealing. After this initial measurement we annealed the devices at 70 °C for 24 h. The samples were analyzed using pulsed LED. We found no gain or PDE change up to 3 V over-voltage.

Fig. 2 shows the ENC noise of the of 1 mm^2 FBK low field and FBK standard field devices in a 50 ns gate after irradiation at $T = 23$ °C after annealing and $T = -24$ °C before annealing. We observed that the noise ratio of the SF vs LF at room temperature is 1.27 and we found a much bigger ratio of 1.63 between SF and LF at $T = -24$ °C. This shows different temperature coefficients between the low field and standard field devices. The Hamamatsu HE SiPM had a similar noise performance as the FBK LF SiPM of 12 p.e. noise/mm^2 at 2 V over-voltage at $T = 23$ °C after annealing.

3. Radiation damage after 5×10^{13} 1 MeV eq. n/cm^2

A second set of identical samples were irradiated to a total dose of 10^{13} 1 MeV equivalent n/cm^2. The samples were sent from JSI radiation facility to CERN chilled and were kept cold at CERN to avoid annealing.

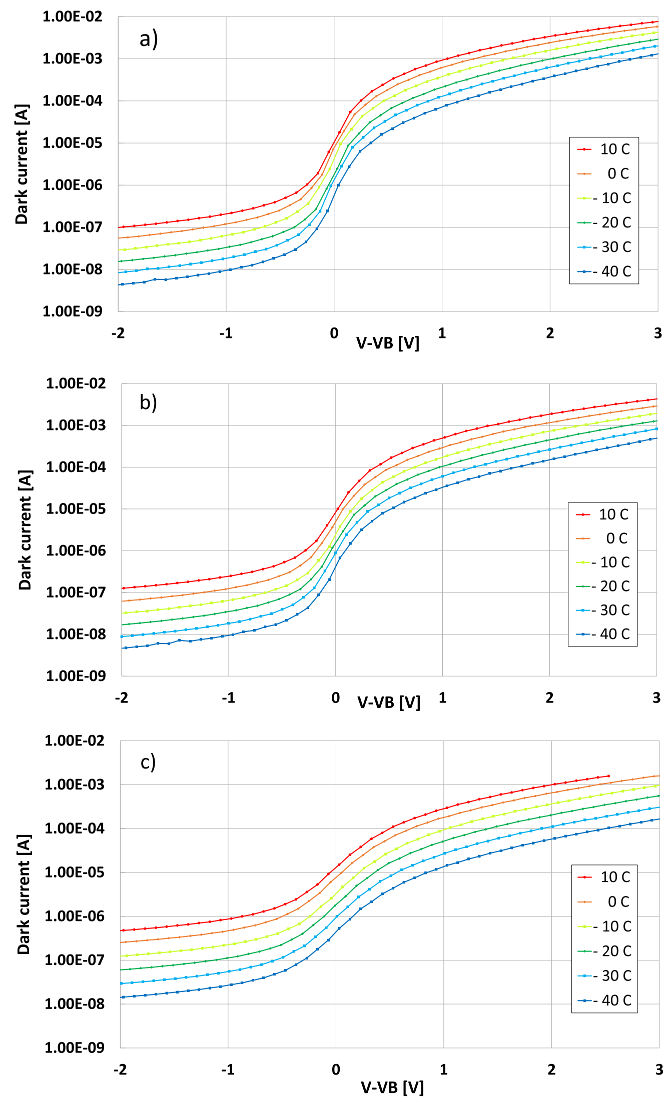

Fig. 3. Non annealed current per mm^2 at different temperatures after dose of 5×10^{13} n/cm^2. (a) 15 μm FBK SF (b) 15 μm FBK LF (c) 15 μm HE SiPM.

To study the noise decrease vs temperature in more detail we measured the leakage current vs temperature of these samples in a climate chamber variating the temperature between +10 °C and −40 °C. Fig. 3a, 3b and 3c show the leakage current measurements of respectively FBK SF, FBK LF and Hamamatsu HE SIPM. The breakdown voltages were respectively 26.4 V, 36.6 V and 66.1 V at 10 °C.

Fig. 4 shows the current decrease with decreasing temperature of the different SiPMs at 2 V over-voltage. At higher over-voltages and at the higher temperatures we find saturation in the devices due to occupancy and self heating effects after this high dose [10]. Because of this the points at +10 °C were disregarded in the fits. We found a temperature decrease coefficient of 1.65, 1.77 and 1.90 per 10 °C, showing better temperature coefficients for the higher breakdown voltage devices. However if we compare these values to PIN diodes operating at unity gain of typically 2.42 per 10 °C we suspect that the high electric field in SiPMs play a big role in this effect.

The gain of the FBK SF, FBK LF and HE SiPM were measured at 240×10^3, 220×10^3 and 200×10^3. Using the leakage current and gain the Dark Count Rate (DCR) can be estimated to be 16 GHz, 7 GHz and 3.5 GHz or an ENC noise in a 50 ns gate of 28 p.e., 19 p.e. and 13 p.e.

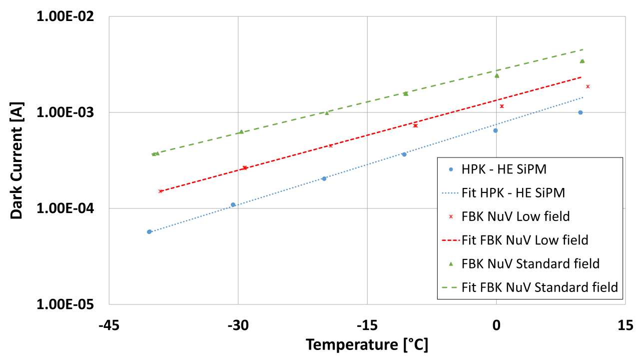

Fig. 4. Non annealed current per mm^2 at different temperatures after dose of 5×10^{13} n/cm^2. Current vs temperature at 2 V over-voltage.

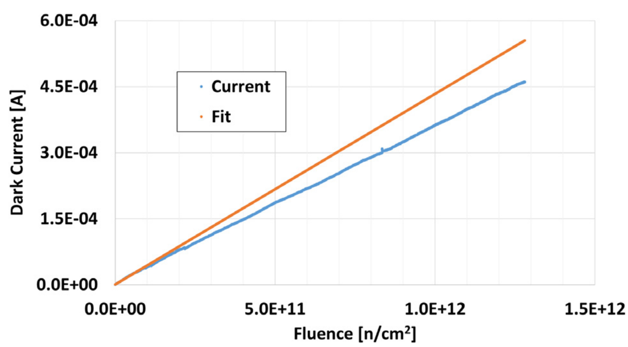

Fig. 5. Dark current increase vs dose of a 3×3 mm^2 Ketek SiPM cooled to −22 °C during radiation.

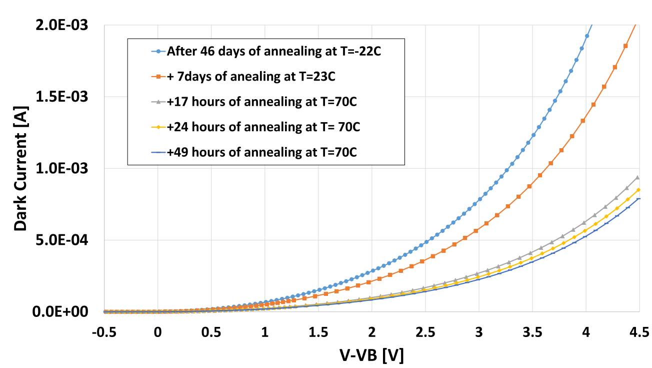

Fig. 6. Annealing of KETEK 3×3 mm^2 SiPM at various temperatures.

at 2 V over-voltage and −30 °C before annealing. This is consistent with the noise measured using a pulsed method in Fig. 2 at −24 °C with a 25 times lower dose.

4. Annealing

The HE SiPM was left at room temperature for 103 days. We found an annealing factor of 2.5 times of the current when it was remeasured.

To get more detailed information on annealing of SiPMs we put a KETEK 3×3 mm 15 μm SiPM mounted on a Peltier cooler in the CHARM facility at CERN. We irradiated the SiPM to a total dose 1.3×10^{12} n/cm^2 in 5 days while keeping the SiPM at −22 °C during the radiation. Fig. 5 shows the current increase vs dose. When we compare the data with a fit of the slope of the first initial small dose points, we can see significant annealing during the irradiation even at −22 °C.

Fig. 6 shows the annealing after 7 days at 23 °C and accelerated annealing at 70 °C for 17 h and longer periods after that. All the data was taken at −22 °C. We found a total annealing of a factor of 3 and the annealing starts to saturate after accelerated annealing of 17 h at 70 °C.

5. Conclusion

Results from a study of the noise due to high radiation damage of SiPMs up to 5×10^{13} cm^2 1 MeV equivalent neutrons/cm^2 at different temperatures are presented. Recently developed NuV low field SiPMs from FBK were compared with the FBK standard field SiPMs. Better noise performance was found in the low field SiPM especially at lower temperatures. The Hamamatsu CMS HE SiPM, which has an even higher breakdown voltage and lower internal field, still has the best temperature coefficient. To reach higher irradiation tolerance we propose to even further reduce the SiPM gain and work on electric field shaping.

No side effects during annealing were found besides the annealing of the current by a factor of three, so it would be beneficial if the detectors could be kept at room temperature during long LHC shutdowns.

Acknowledgments

The authors would like to express their gratitude to the JSI and CERN CHARM Facility team for their help in irradiations and hospitality. This project has received funding from the European Union's Horizon 2020 under Grant Agreement no. 654168. This work was supported by the U.S. National Science Foundation (grant number NSF-PHY-1312842) and by the Ministry of Education and Science of the Russian Federation (Russian state grant RFMEFI61014X0004).

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