TECHNICAL REPORT

An induced annealing technique for SiPMs neutron radiation damage

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ABSTRACT: The use of Silicon Photo-Multipliers (SiPMs) has become popular in the design of High Energy Physics experimental apparatus with a growing interest for their application in detector area where a significant amount of non-ionising dose is delivered. For these devices, the main effect caused by the neutron fluence is a linear increase of the leakage current. In this paper, we present a technique that provides a partial recovery of the neutron damage on SiPMs by means of an Electrical Induced Annealing. Tests were performed, at the temperature of 20°C, on a sample of three SiPM arrays (2×3) of 6 mm² cells with 50 μm pixel sizes: two from Hamamatsu and one from SensL. These SiPMs have been exposed to neutrons generated by the Elbe Positron Source facility (Dresden), up to a total fluence of \(8 \times 10^{11}\) \(n_{\text{MeV-eq}}/\text{cm}^2\). Our techniques allowed to reduced the leakage current of a factor ranging between 15-20 depending on the overbias used and the SiPM vendor. Because, during the process the SiPM current can reach O(100 mA), the sensors need to be operated in a condition that provides thermal dissipation. Indeed, caution must be used when applying this kind of procedures on the SiPMs, because it may damage permanently the devices themself.

KEYWORDS: Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc); Radiation damage to detector materials (solid state); Photon detectors for UV, visible and IR photons (solid-state)

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1 Introduction

A Silicon Photo-Multiplier (SiPM) is a novel semiconductor photo-detector composed by a matrix of pixels operating few volts above the breakdown voltage (Geiger-Mode Avalanche Photo-Diode). Distinctive features of such technology are: single photon detection capability, high gain ~ $10^6$ and good time resolution (< 1 ns) [1]. In addition SiPMs present small size and customisable granularity, insensitivity to magnetic fields and are relatively un-expensive. For these reasons several current and planned High Energy Physics experiments employ SiPMs in their experimental setup [4, 5]. A growing interest exists in their application when a high level of non-ionizing dose is expected to be delivered to the SiPMs.

Different studies showed a correlation between the bulk defects in the Silicon structure due to the radiation damage and the deterioration of the photo-detector performances [6, 7]. Hadrons and high energy leptons can produce point defects as well as cluster related defects in the photo-detector active volume. In particular, neutrons travelling within the Silicon lattice induce many displacements of Silicon atoms that, at the end of the path, form a disordered agglomeration of atoms called cluster [8]. From the macroscopic point of view, some of these defects act as charge carriers generator centers, producing an increase of dark noise. The current state of the art technology does not provide any method to fully recover neutron induced damage in Silicon based photo-detectors. Thermal annealing can partially recover the neutron induced damage, as shown in ref. [9], where after several days of thermal treatment at different temperatures, the dark current got reduced by a factor of about 10. Our tests reported in the next sections indicate that an important recovery of the SiPM damage can be achieved also by means of an electrical induced annealing in few minutes of treatment. Two different methods have been tested: a direct and an inverse polarization of the SiPM using a non conventional over voltage - larger than the usual 5 V limit indicated by several vendors [1, 2]. We believe that this technique may combine two effects: the thermal annealing induced by heating the Silicon lattice and the presence of a strong electric field to re-order the atoms in the Silicon lattice displaced by the neutron-induced bulk damage [10].
2 Experimental setup

The measurements described in this paper were performed at the Silicon Detector Facility of the Fermi National accelerator Laboratory.\(^1\) Two different sets of SiPM arrays were studied: Hamamatsu [1] and SensL [2]. A sample from each vendor has been exposed to neutrons generated by the Elbe Positron Source facility (Dresden), up to a total fluence of \(8 \times 10^{11} \text{n}_{\text{MeV}_{\text{eq}}} / \text{cm}^2\) \([3]\). The average energy of neutrons produced has been estimated by a full FLUKA simulation; the spectrum, figure 1, is well centred around 1 MeV.

![Fluka simulation of the neutrons energy spectrum at the SiPMs position.](image)

The tests described in this paper has been conducted after 3 months from the irradiation. During most of the time, the SiPMs were kept at room temperature of about 20 °C and in a dark box.

These SiPMs consist of a \(2 \times 3\) array of \(6 \times 6 \text{mm}^2\) monolithic cells with pixel sizes of 50 \(\mu\)m. Both SiPM arrays have a custom design, developed for the electromagnetic calorimeter of the Mu2e experiment [11, 12]. To improve the thermal dissipation capabilities compared to commercial designs,\(^2\) they have been built with a thermal resistance of about \(5 \times 10^{-4} \text{m}^2\text{K}/\text{W}\). The experimental setup consisted of:

- light tight thermal chamber TestEquity Model 140 [13];
- power supply PLH250 [14] to bias the SiPMs and measure their current;
- \(30 \times 20 \text{ cm}^2\) Cu plate, 3 mm thick, used as thermal support for the SiPMs;
- 3 PT1000 [15] thermistors used to measure the temperatures of the SiPM and of the Cu support.

\(^1\)http://www.fnal.gov.
\(^2\)Hamamatsu and SensL, private communication.
Figure 2 shows a picture of the Cu support with the PT1000, used to measure the temperature of the support, and one SiPM array plugged in. All the tests were performed inside a thermal chamber at a temperature of 20 °C. This setup allowed us to monitor the temperature of the SiPM active region and of the Cu support during all the measurements and bias the SiPM with a current limitation of few hundreds mA. A second PT1000 sensor was placed on the top of the silicon resin of the SiPMs; the third PT1000 sensor was used to check that the temperature drop on the pin-side of the SiPM was within 2 °C with respect to the one measured on the active region.

3 SiPM recovery measurements

Two different configurations for biasing the SiPMs were tested: direct and inverse polarization using an over-voltage larger than 5 V.

So, we define:

- $V_{\text{DIR}}$ as the direct voltage, positive voltage applied between anode and cathode;
- $\Delta V_{\text{IND}}$ as the reverse over voltage with respect to the breakdown voltage, $V_{\text{br}}$, positive voltage applied between cathode and anode;
- $I_{\text{TEST}}$ as the photo-detector current during the annealing procedures;
• $I_{\text{dark}}$ as the leakage current measured in the standard reverse configuration of the SiPM at the operation voltage $V_{\text{op}} = V_{\text{br}} + 3$ V.

All the results shown in the following are relative to the $I_{\text{dark}}$ at this operational voltage point. At each annealing step, the determination of $I_{\text{dark}}$ has been done stopping the annealing, carrying the device at 20 °C with the thermal chamber and then measuring the current.

### 3.1 Induced annealing in direct polarization

Figure 3 shows the results obtained with one cell of a Hamamatsu SiPM array polarized in direct configuration at $V_{\text{DIR}} = 10$ V. The $I_{\text{dark}}$ shows an exponential trend with a decay time of $\tau = 500$ s and a constant current term $I_{0{\text{dark}}}$ = 5.2 mA.\(^3\) A reduction of ~ 40% in $I_{\text{dark}}$ after ~ 5 min of direct polarization was achieved. In this configuration the SiPM was generating a $I_{\text{TEST}}$ of ~ 530 mA, corresponding to a power of ~ 5 W, that is the power needed to recover the damage of a factor of about 2.

![Figure 3](image)

*Figure 3. $I_{\text{dark}}$ as a function of the exposure time for a direct polarisation. Points were fit with an exponential curve.*

### 3.2 Induced annealing in reverse polarization

To quote the performance of the recovery method in inverse polarization two different settings of over voltage were tested. Both Hamamatsu and SensL SiPMs have been checked in this configuration. Figure 4 shows the $I_{\text{dark}}$ variation as a function of the exposure time for a Hamamatsu SiPM. The first four measurements were taken at $\Delta V_{\text{IND}} = 10$ V, then we improved the recovery by increasing the over voltage up to $\Delta V_{\text{IND}} = 14$ V. After about 13 min at the described conditions, the SiPM $I_{\text{dark}}$ reached about 1 mA that corresponds to a reduction of a factor of 10 when compared to the starting value. Finally, we tried to increase the over-voltage up to $\Delta V_{\text{IND}} = 17$ V, but at this value the SiPM got broken. The $I_{\text{TEST}}$ measured during this operation was 130 (186) mA for a $\Delta V_{\text{IND}}$ of

\(^3\)Fit function used: $I_{\text{dark}} = I_{0{\text{dark}}} \cdot (1 + \exp(-t/\tau))$.
Figure 4. $I_{\text{dark}}$ as a function of the exposure time for a Hamamatsu SiPM cell for an inverse polarization. The two different settings for the over-voltage used during the test are separated by the vertical red line and indicated in the legends.

10 (14) V, corresponding to a dissipated power of about 8 (12) W. The temperature measured on the SiPM active region with the PT1000 was $\sim 150$ °C.

After the learning phase, we tested another Hamamatsu SiPM cell of the same device setting $\Delta V_{\text{IND}}$ at 14 V. Figure 5 shows the results of the $I_{\text{dark}}$ measurement operated every 2 min; from the fit\(^4\) we observe that a rapid reduction of the leakage current occurs with a $\tau$ of the order of 25 seconds. After about 6 min of electrical annealing, a total reduction of a factor 15 on the leakage current was observed, thus indicating a good agreement with the previous test done on the same SiPM model.

A similar test has been carried out also for the SensL device [2]. Figure 6 shows the measured $I_{\text{dark}}$ for two different settings of $\Delta V_{\text{IND}}$: 5 and 8 V. After 22 min we measured on overall reduction factor $\sim 16$ on $I_{\text{dark}}$ (from 40.2 to 2.5 mA). Unfortunately after 22 min the SiPM got unplugged from the Cu plate, reached a temperature larger than 200 °C and got broken. Figure 7 shows the localization of the heating induced by the over voltage condition on the single cell under bias. During the annealing treatment, we have measured a $I_{\text{TEST}}$ current of 200 (400) mA for $\Delta V_{\text{IND}}$ of 5 (8) V, corresponding to a dissipated power of about 6 (13) W. The temperature measured on the SiPM active region was $\sim 150$ °C.

We repeated the measurement on another cell of the same device at $\Delta V_{\text{IND}} = 8$ V. Figure 8 shows the $I_{\text{dark}}$ variation as a function of the exposure time; also in this case, we observe that a rapid reduction of the leakage current occurs with a $\tau$ of the order of 25 seconds, consistent with the value observed in figure 5. After $\sim 17$ min the $I_{\text{dark}}$ was reduced from 42.9 to 2.7 mA that is compatible with the reduction observed in the previous test.

\(^4\)Fit function used: $I_{\text{dark}} = N_1 \cdot \exp(-t/\tau_1) + N_2 \cdot \exp(-t/\tau_2)$.

\(^5\)The breakdown voltage of the SensL SiPM at 20 °C is 24.87 V [2].
Figure 5. $I_{\text{dark}}$ as a function of the exposure time for a Hamamatsu SiPM cell applying an over-voltage of 14 V during the recovery.

Figure 6. $I_{\text{dark}}$ as a function of the exposure time for a SensL SiPM cell. The two different settings for the over-voltage used during the test are separated by the vertical red line and indicated in the legends.

4 Comparison between induced and thermal annealing

To understand if the observed reduction of $I_{\text{dark}}$ was due only to the related thermal annealing, we exposed the SiPM to high temperatures at $V_{\text{op}}$. Since the breakdown voltage of SiPMs changes in an inversely proportional way with the temperature following a rule of about 0.1%/°C, during the test we have adjusted the breakdown voltage with respect to the temperature of the test. For this test we used a different cell of the Hamamatsu SiPM array. We started keeping the SiPM at 80 °C for 19 min, then increased the temperature up to 120 °C, following the procedures explained in [9]. Results are summarised in table 1.
Figure 7. SiPM array on the Cu support at the end of the tests.

Figure 8. $I_{\text{dark}}$ as a function of the exposure time for a SensL SiPM cell applying an over-voltage of 8 V during the recovery.

In 30 minutes, the thermal annealing alone provided a recovery of about 25% that is much smaller than the one observed with electrical induced annealing in a much shorter time.

5 Conclusions

We have presented an electrical induced annealing technique that allows to partially recover neutron damage of SiPM. Tests of such a technique were performed on two different sets of SiPM arrays from
Table 1. $I_{\text{dark}}$ measured @ 54.7 V, 20°C after exposure of the SiPM at different thermal conditions.

| SiPM T [°C] | Exposure time [s] | $I_{\text{dark}}$ [mA] |
|-------------|-------------------|------------------------|
| 20 ± 0.5    | 0                 | 12.33 ± 0.01           |
| 80 ± 0.5    | 1120              | 9.93 ± 0.01            |
| 120 ± 0.5   | 600               | 9.50 ± 0.01            |

Hamamatsu and SensL. The benefit of the observed method is that it allows to partially recover (up to a factor 15-20) the bulk damage in the SiPM exposed to a neutron fluence of $8 \times 10^{11} \text{n}_{1 \text{MeV}_{\text{eq}}/\text{cm}^2}$, thus improving the results one may get with the conventional thermal annealing. A remarkable recovery related to high temperature annealing is presented in [16], where results of few days of annealing at +250 °C, using forward bias with the SiPM current reaching 10 mA, are shown. By comparison, the biggest advantage of our technique resides in the possibility to be used in an installed detector “in situ” with an application of few minutes. In particular, we have observed that a rapid reduction of the leakage current occurs with a $\tau$ of the order of 25 seconds.

However, since during this process the SiPM current can reach $O(100 \text{ mA})$, the sensors need to be operated in a condition that provides thermal dissipation. This precaution will avoid the sensors heating up to breaking temperatures or damage permanently the device hosting the sensors.

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