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Investigation of avalanche photo-diodes after irradiation with neutrons up to $5x10^{14}$ n/cm²

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Results on the radiation hardness of avalanche photodiodes to fast neutrons are presented. APDs from Hamamatsu were irradiated with reactor neutrons up to 1 MeV equivalent fluence of $5x10^{14}$ n/cm^2 . Dark current and gain vs. bias dependence were measured at T=25 °C, 15 °C and 5 °C after several years of annealing at room temperature. The gain vs. bias and QE vs. wavelength dependences were compared with that before irradiation.

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1. Introduction

Resistance of the CMS ECAL APDs [1] to neutrons was previously studied in details up to $2x10^{13}$ neutrons/cm^2 (corresponds to 500 fb^{-1} at the LHC). It was found that QE and gain change was less than 5% at this neutron fluence. What will happen with the CMS APDs at 10 000 fb^{-1}? Will they survive? What will be the gain, dark current and QE change? To answer these questions we studied performances of 3 CMS APDs irradiated with $5x10^{14}$ n/cm^2 (1 MeV equivalent) at the Lubljana reactor. The APDs gain, dark current and quantum efficiency were measured before irradiation at 25 °C. The preliminary results on the APDs parameters after irradiation, irradiation facility and irradiation set-up were presented in ref. [2]. In this work we measured parameters of these APDs after several years of annealing at room temperature. The gain vs. bias and QE vs. wavelength dependences were compared with that of non-irradiated APDs.

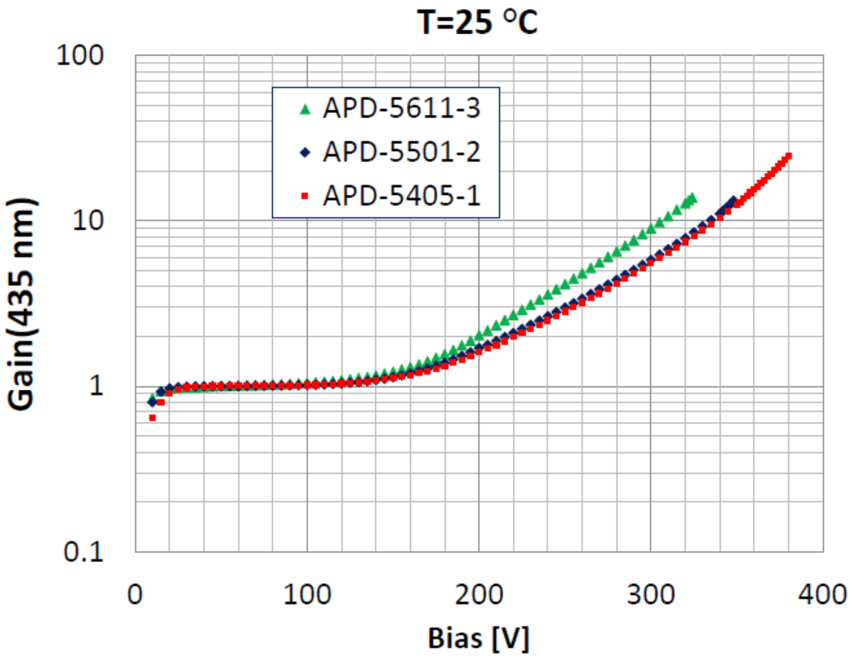

Figure 1: *Gain vs. bias for 3 APDs after irradiation (measured using 435 nm LED light).*

2. Dark current and Gain vs. Bias voltage.

Dependences of APDs dark current and photocurrent vs. bias voltage were studied using Keithley 6487 picoammeter/voltage source. The APDs were placed in a dark box inside an environmental chamber (Termacs, Kleiner AG). Temperature inside the chamber was controlled with precision ±0.1 °C. Blue (435 nm) LED light source was placed outside the chamber (in the temperature stabilized room). The LED light was sent to the APD via a 2 m long 1 mm quartz fiber. The way to evaluate the gain of an APD is to measure photocurrent (total current minus dark current) versus bias voltage. APD gain at certain bias can be calculated as a ratio of the photocurrent measured at this bias to the photocurrent measured at low bias (<100 V) [3]. Fig.1 shows gain vs. bias dependence measured at room temperature for 3 irradiated APDs. One can see that after $5x10^{14}$ n/cm^2 APDs are still operational as photo-sensors with gain. The maximum gain they reach is around 15÷25. At higher gains operation of irradiated APDs becomes non-stable. Dark currents vs. biases measured for 3 APDs are shown in Fig.2. At low biases this dependence is very similar for all the APDs. At higher biases differences in dark currents can be explained by

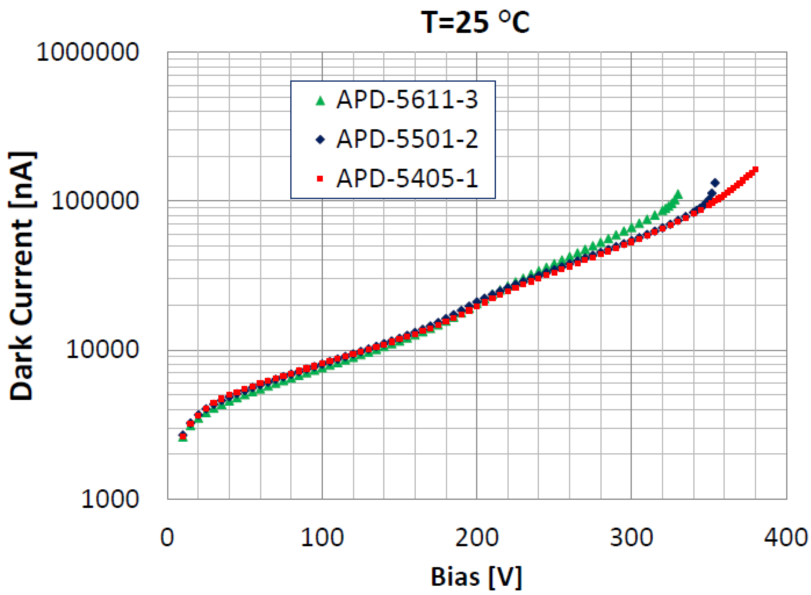

Figure 2: *Dark current vs. bias measured for 3 APDs after irradiation.*

difference in the APDs gain. Fig.3 shows gain vs. bias dependence for the 5405-1 APD measured at 25 °C before and after irradiation. There is a distinctive feature of the gain curve measured after irradiation: in the region of high bias voltages (>100 V) the gain curve after irradiation is shifted in comparison to that measured before irradiation by ~27 V (see Fig. 4). A similar effect was previously seen with the irradiated E&G APDs [4]. This effect was related to a change of the doping concentration inside the depletion region of the APD due to creation of acceptor-like states [4, 5]. Dark current as a function of bias voltage for the 5405-1 APD measured before and after irradiation is shown in Fig. 5.

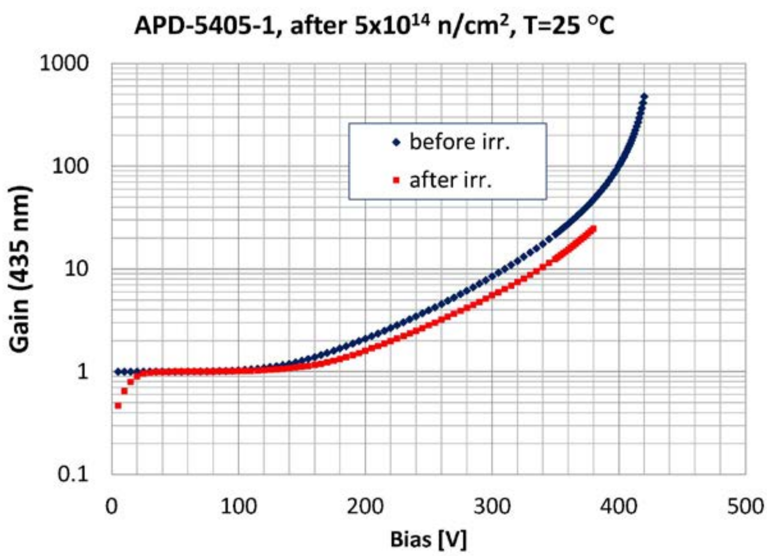

Figure 3: *Gain vs. bias before and after irradiation.*

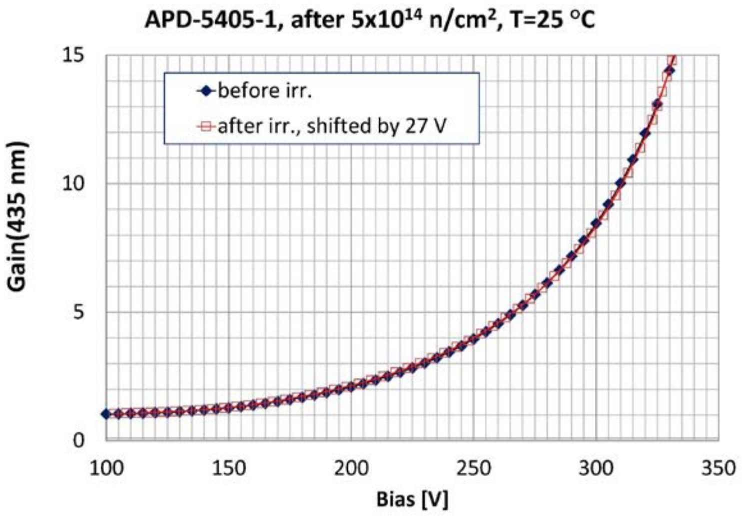

Figure 4: *Gain vs. bias before and after irradiation (shifted by 27 Volts).*

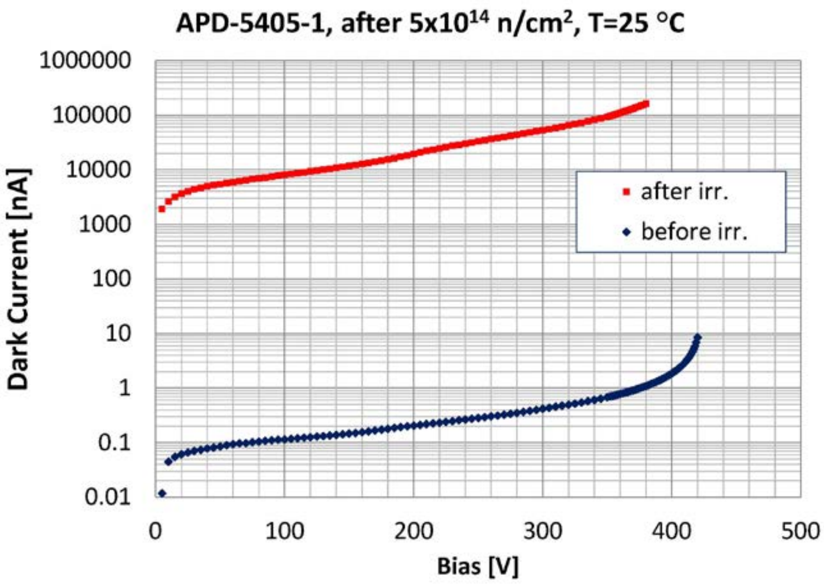

Figure 5: *Dark current vs. bias before and after irradiation.*

3. APD measurements at reduced temperature.

To understand dependence of the APD dark current on the temperature a set of measurements at 5, 15 and 25 °C was performed with the irradiated 5405-1 APD placed inside an environmental chamber. Fig. 6 shows the APD's dark current as a function of bias voltage measured at 3 temperatures.

Leakage current is an important parameter of an irradiated APD since it determines the noise. It consists of two components: surface current and current generated in the bulk region of the

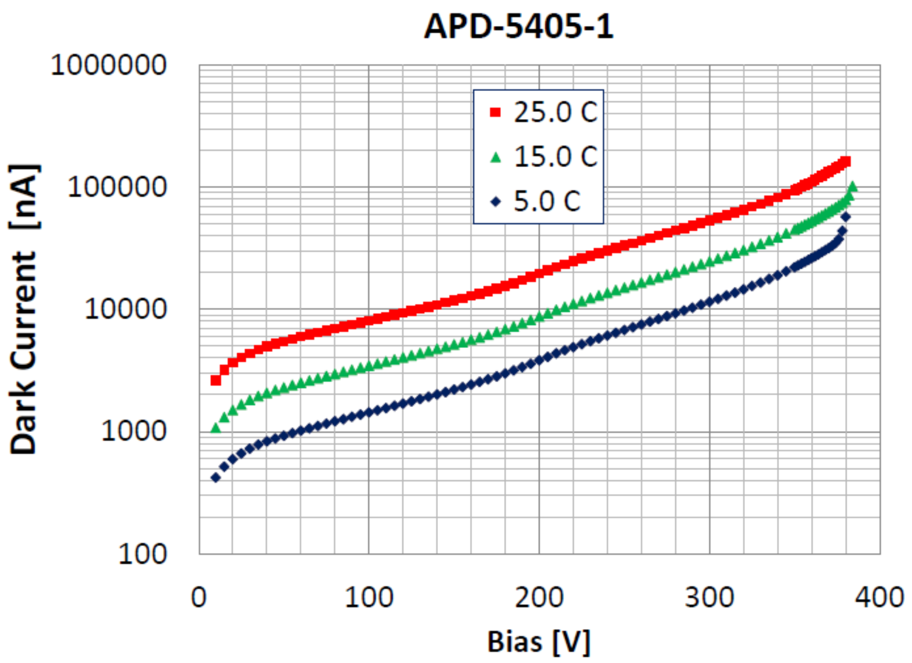

Figure 6: *Dark current vs. bias measured at 3 temperatures after irradiation.*

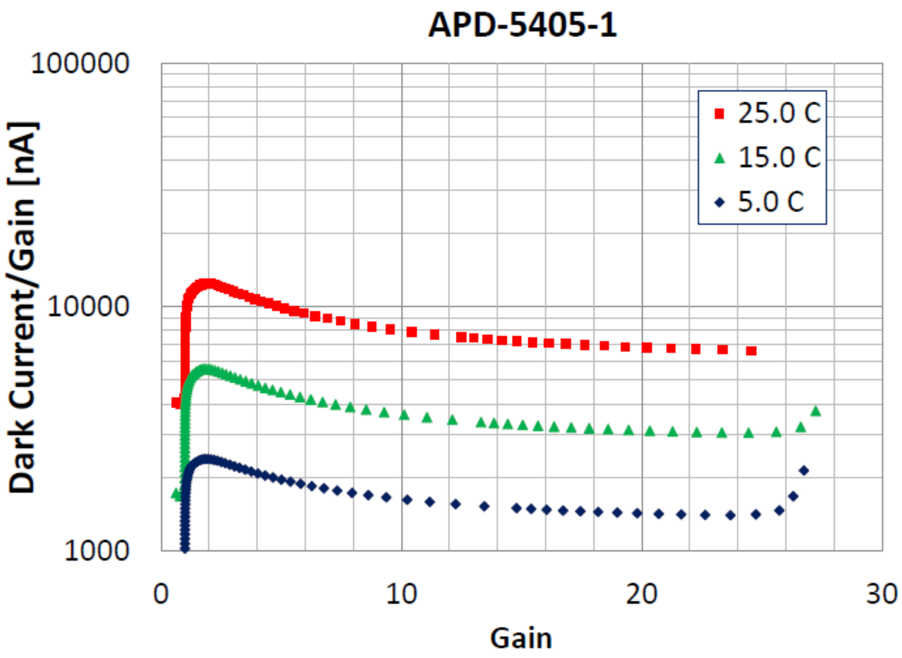

Figure 7: *Dark current divided by gain vs. gain measured at 3 temperatures.*

APD. Surface current does not go into the avalanche region. Usually it rises linearly with the applied bias. On the other hand, bulk current goes into the avalanche region and undergoes multiplication. One can assume that at high biases (close to the breakdown) APD's dark current is proportional to the gain. In other words, ratio of the APD dark current to the gain becomes constant. This is a way to calculate the initial APD bulk current before it undergoes multiplication. Fig.7. shows dark current divided by gain vs. gain for the 5405-1 APD at 5, 10 and 15 °C. From this figure one can notice that the APD's bulk dark current can be significantly reduced by reducing temperature (~2.2 times per 10 °C).

4. Quantum efficiency vs. wavelength

For the spectral response measurements an "Optometrics" SDMC1-03 spectrophotometer was used. We also used a calibrated PIN photodiode (Newport, model 818-UV) as a reference.

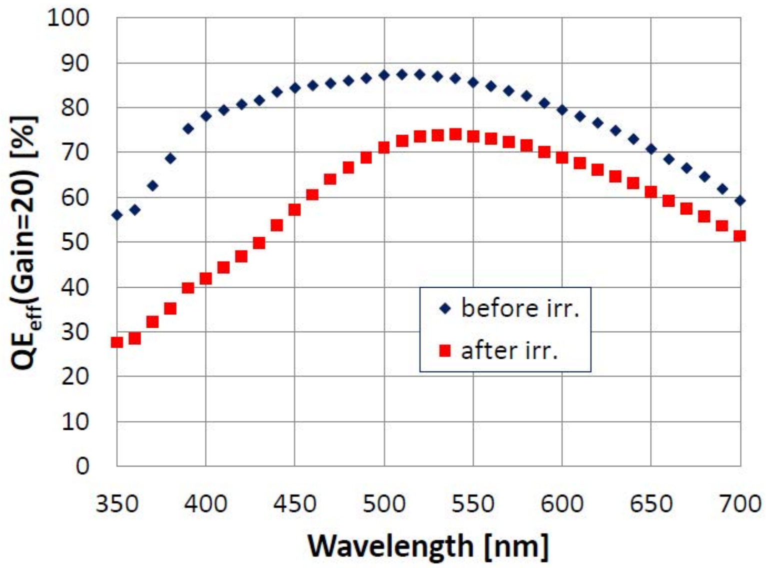

Figure 8: *"Effective" quantum efficiency vs. wavelength before and after irradiation (Gain=19, T=25 °C)*

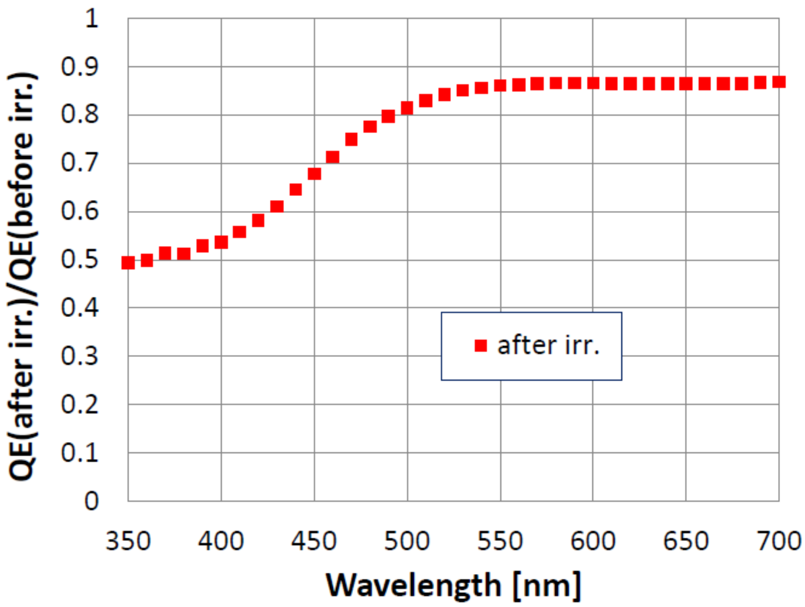

Figure 9: *Quantum efficiency losses vs. wavelength after irradiation (Gain=19, T=25 °C)*

Photosensors were illuminated with light via 2 m long and Ø1mm quartz fiber. Photocurrent measured with the APD was compared with that of the PIN photodiode. The APD gain depends on the wavelength of incident light [3]. As a result an "effective" quantum efficiency (EQE) should be introduced to describe an APD spectral response at high voltages (details on the "effective" quantum efficiency measurements can be found in [4]). The EQE vs. wavelength dependences for new and irradiated APDs are shown in Fig.8 Using this data we calculated the ratio of the EQE(after)/EQE(before) as a function of wavelength. It is shown in Fig.9. Significant reduction of the EQE at short wavelength is clearly seen. Protective epoxy transparency loses (which are more pronounced at short wavelength) can be a possible explanation of this result.

4. Conclusion

The CMS ECAL APDs (produced by Hamamatsu) were irradiated up to 5x10^{14} n/cm² (1 MeV equivalent). This corresponds to > 10 000 fb^{-1} at the LHC. Dark current and gain vs. bias dependences were measured at T=25 °C, 15 °C and 5 °C after several years of annealing at room temperature. The gain vs. bias and QE vs. wave-length dependences were compared with that of non-irradiated APDs.

Main results of the study are:

- APDs are still operational as a light detector with gain>15 at T=25 °C;
- QE losses of ~40% were found for $PbWO_4$ crystal light (400-500 nm);
- The APD gain was substantially reduced due to doping profile change, caused by creation of active acceptor like states in the APD depleted region (effect was previously seen with the EG&G APDs [3]). Problem can be solved by ~30 V bias voltage increase;
- The APD's dark current increased by 80 μA (Gain=10, T=25 °C) in comparison to that before irradiation;
- The APD's dark current can be significantly decreased by reduction of temperature (~2.2 times per 10 °C).

Acknowledgments

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