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Study of radiation damage induced by 82 MeV protons on multi-pixel Geiger-mode avalanche photodiodes

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ABSTRACT

Results from a study on the radiation hardness of multi-pixel Geiger-mode avalanche photodiodes (G-APDs) are presented. Recently developed G-APDs from five manufacturers (Hamamatsu (Japan), CPTA/Photonique (Russia/Switzerland), Zecotek (Singapore), Pulsar (Russia) and FBK-IRST (Italy)) were exposed to 82 MeV protons at fluences up to 10^{10} protons/cm^2 at the Paul Scherrer Institute. The G-APD's main parameters were measured before and after irradiation. The effects of the proton radiation on breakdown voltage, quenching resistance value, gain, photon detection efficiency, dark current and dark count rate for these devices are shown and discussed.

1. Introduction

Recently developed multi-pixel Geiger-mode avalanche photodiodes (also known as G-APDs, SiPMs, SSPMs, MRS APDs, MAPDs, MPPCs, etc.) are very promising candidates for many high energy physics (HEP) applications. Many of the high energy physics experiments where G-APDs are planned to be used (ILC detectors, the CMS detector at LHC, etc.) operate in harsh radiation environments, which produce damage in different materials. As has been shown by many investigators, radiation (gammas, electrons, neutrons, charged hadrons, etc.) can produce defects in the silicon bulk or at the Si/SiO_2 interface [1]. Many of these defects are electrically active and can change doping concentration in the silicon as well as causing charge trapping effects. As a result, parameters of G-APDs such as breakdown voltage, leakage current, dark count rate, gain, and photon detection efficiency (PDE) may change during irradiation. Irradiation may also cause changes in the G-APD quenching resistors.

The change of the G-APD parameters during irradiation is one of the most important questions for application of G-APDs in high energy physics experiments. In our previous study [2] we reported on G-APD radiation damage studies using 28 MeV positrons. In this paper we present the results of proton irradiation of the G-APDs from five manufacturers (CPTA/Photonique (Russia/Switzerland) [3], MEPhI/Pulsar (Russia) [4], FBK-IRST (Italy) [5], Zecotek (Singapore) [6] and Hamamatsu (Japan) [7]). The G-APDs were exposed to 82 MeV protons with fluences up to 10^{10} protons/cm^2 at the Paul Scherrer Institute. The most important G-APD parameters were measured before and after irradiation.

2. Irradiation set-up and G-APDs under study

Five G-APDs from 5 producers (see Table 1) were irradiated with a 10 cm diameter high intensity beam of 82 MeV protons. The G-APDs developed by CPTA/Photonique, MEPhI/Pulsar, FBK and Zecotek were made on p-type silicon; the MPPC from Hamamatsu was made on n-type silicon. Most of these G-APDs were experimental devices, except the MPPC S10362-11-050C, which is a commercial device supplied by Hamamatsu. All the APDs were placed on a PCB board and connected in parallel to a Keithley 487 picoammeter/source and reverse-biased at 10 V. The total current delivered to the APDs was monitored during irradiation. The G-APDs were positioned to be in the center of the beam. Non-uniformity of the beam intensity over the whole area of APD location was measured to be below 20%.

3. Measurement set-up

The response of the G-APDs to a calibrated LED pulse, photon detection efficiency, breakdown voltage, dark current and count rate were measured as a function of bias voltage before and 90 days after irradiation at the CERN APD Lab. The bias voltage to the G-APDs was applied with the Keithley-487 picoammeter/voltage source. The signals from the G-APDs were amplified with a fast transimpedance amplifier (gain = 20) [8] and digitized with a Picoscope 5203 digital oscilloscope [9]. A Labview based code was written to analyze the recorded waveforms. The G-APDs were illuminated with small green

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(515 nm) LED pulses via a 0.5 mm collimator. The number of photons in the LED pulse was measured using a calibrated XP2020 photomultiplier. Fig. 1 shows the results of some of the measurements performed with the MEPhI/Pulsar G-APD. The temperature during the measurements was stabilized to 23 °C with the variation during the measurements not exceeding 1 °C.

4. Experimental results

4.1. Dependences of dark currents and dark counts on the bias voltage

A significant increase of the dark current and dark count rate was measured for all the devices. Figs. 2 and 3 show the dependences of the dark current and dark count on the bias voltage measured with four G-APDs before and after irradiation. The discriminator threshold was set to half the single pixel signal level. The dark counts were corrected for the dead time of the counting system that was measured to be ~8 ns.

4.2. Dependences of the G-APDs responses to LED signals on the bias voltage

Responses of the G-APDs to calibrated LED pulses as functions of bias voltage were measured before and after proton irradiation. The green (515 nm) LED was driven by a Philips PM 5786 pulse generator. The amplitude of the LED pulse (~50 photons/pulse) was adjusted by HP 355C attenuators. The amplitude was within 5% precision the same for the measurements done before and after irradiation. The duration of the LED pulse was measured to be 10 ns FWHM. The calibration of the LED pulses was done with the reference XP2020 PMT. The waveforms recorded by a Picoscope 5203 were integrated during a 120 ns gate. The results are shown in Fig. 4 (for the MEPhI/Pulsar G-APD see Fig. 1). One can see that at low overvoltages (V–VB < 2 V) the changes of the measured LED signals for the irradiated MEPhI/Pulsar, CPTA/Photonique, Hamamatsu and FBK G-APDs are small (less than 10%). Significant reduction of the detected LED signal amplitude (> 10%) was measured with the irradiated MEPhI/Pulsar and CPTA/Photonique G-APDs at high overvoltages (V–VB > 4 V). The change of the response of Zecotek G-APD is large even at low overvoltages. The LED signal amplitude measured by this irradiated G-APD was reduced by more than 30% in the range of bias voltages 34.2–35.2 V.

4.3. Changes of the breakdown voltages after irradiation

The change of the G-APDs breakdown voltage VB after irradiation was calculated using the results of the measurements of the G-APDs amplitudes shown in Figs. 1 and 4. The VB was defined as a crossing of the straight line passing through the two first experimental points with bias axis. The VB changes were found to be less than 50 mV for all the devices.

4.4. Dependences of the photon detection efficiencies on the bias voltage

High dark count rates of irradiated G-APDs do not allow the separate measurements of the G-APDs photon detection efficiency and its excess noise factor F [10]. However their ratio can be measured even for noisy G-APDs. This ratio can be expressed by Eq. (1) (see, for example, [11]) as

$$PDE^* = \frac{PDE}{F} = \frac{A^2}{(\sigma_A^2 - \sigma_p^2)N_\gamma} \quad (1)$$

Table 1
Geometrical and electrical characteristics of the G-APDs.

G-APD	Area (mm^2)	Number of pixels	VB (V)	R_{pix} (MΩ)
CPTA/Photonique	1	556	30.1	7.1
MEPhI/Pulsar	1	1024	56.4	0.4
FBK	1	400	30.75	0.43
Zecotek	1.1	576	33.85	?
Hamamatsu	1	400	69.05	0.11

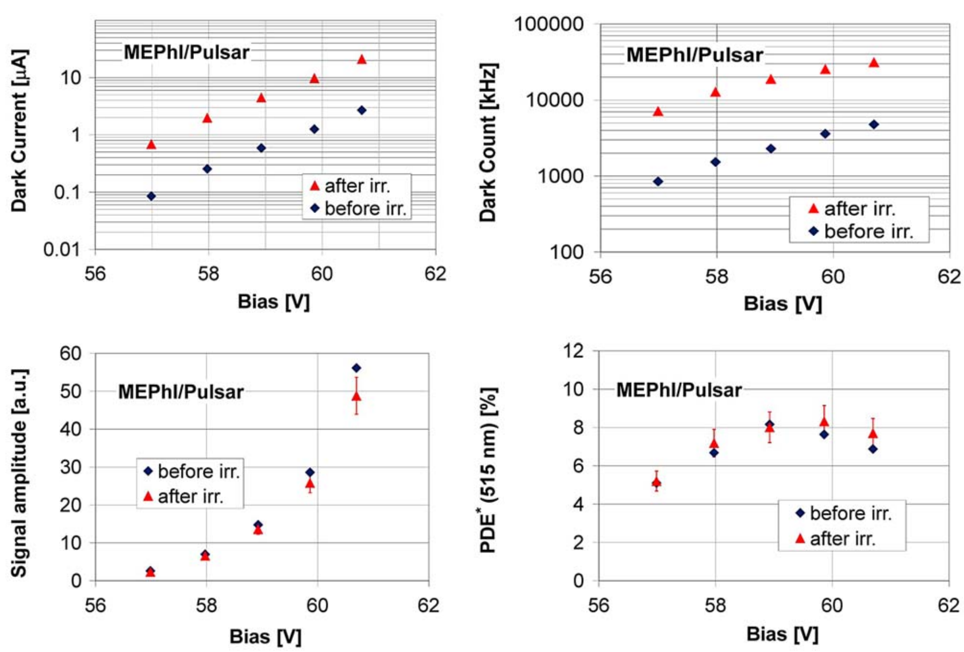

Fig. 1. Dependences of the dark current, signal amplitude, dark count and PDE^* (see formula (1) for the definition) on the bias voltage, measured for MEPhI/Pulsar G-APD before and after proton irradiation.

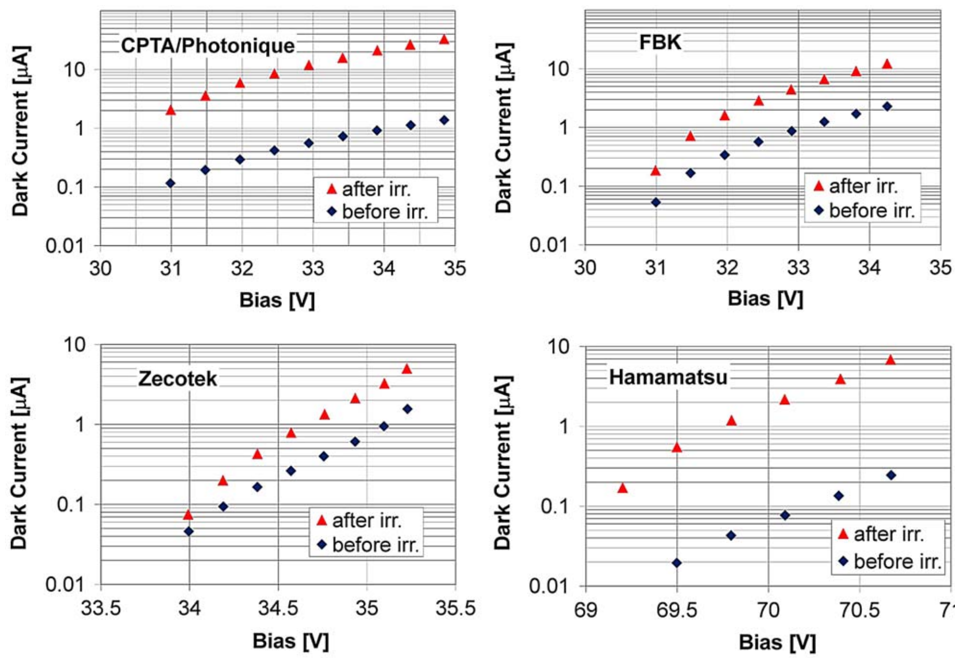

Fig. 2. G-APDs dark currents vs. bias voltage, measured before and after proton irradiation for G-APDs from 4 manufacturers.

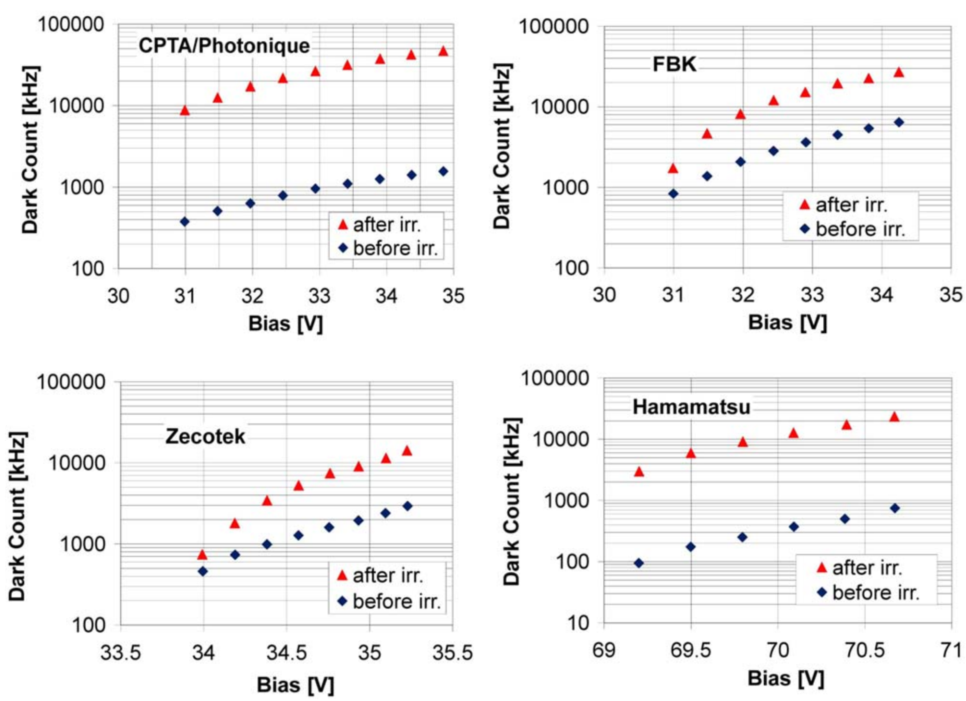

Fig. 3. G-APDs dark counts vs. bias voltage, measured before and after proton irradiation.

where A is the measured LED amplitude (after pedestal subtraction), σ_A^2 is its variance, σ_p^2 is the variance of the pedestal value, N_γ is the number of photons in the LED pulse. The calculated dependencies of the *PDE**s on the bias voltages for four G-APDs are shown in Fig. 5 (for MEPhI/Pulsar G-APD see Fig. 1). The measurements of the responses of the G-APDs to calibrated LED pulses were used for the calculations. It is interesting to notice that the *PDE* as a function of bias voltage for all the G-APDs remained unchanged after irradiation within a precision of our measurements (~10%). This is probably due to fact that sensitivity of *PDE** to a voltage change is much smaller than that of the gain.

4.5. G-APDs quenching resistors after irradiation

The values of the G-APD quenching resistors (see Table 1) were found from the measurements of the G-APD currents when a forward bias was applied to the G-APDs. The results of these measurements for four G-APDs (performed before and after

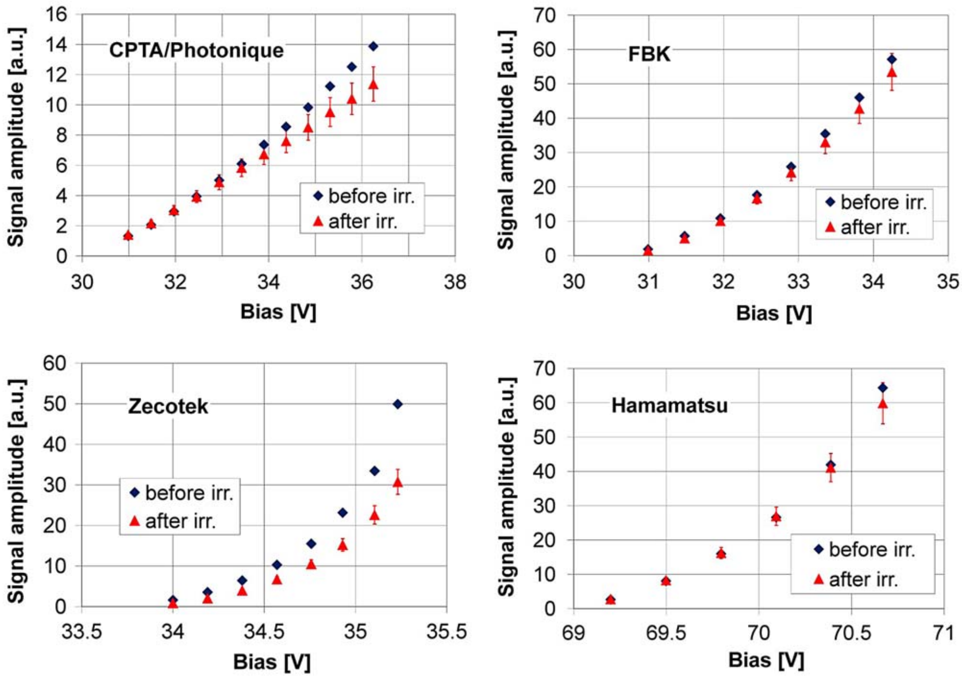

Fig. 4. G-APDs signal amplitudes vs. bias voltage, measured before and after proton irradiation for G-APDs from 4 manufacturers.

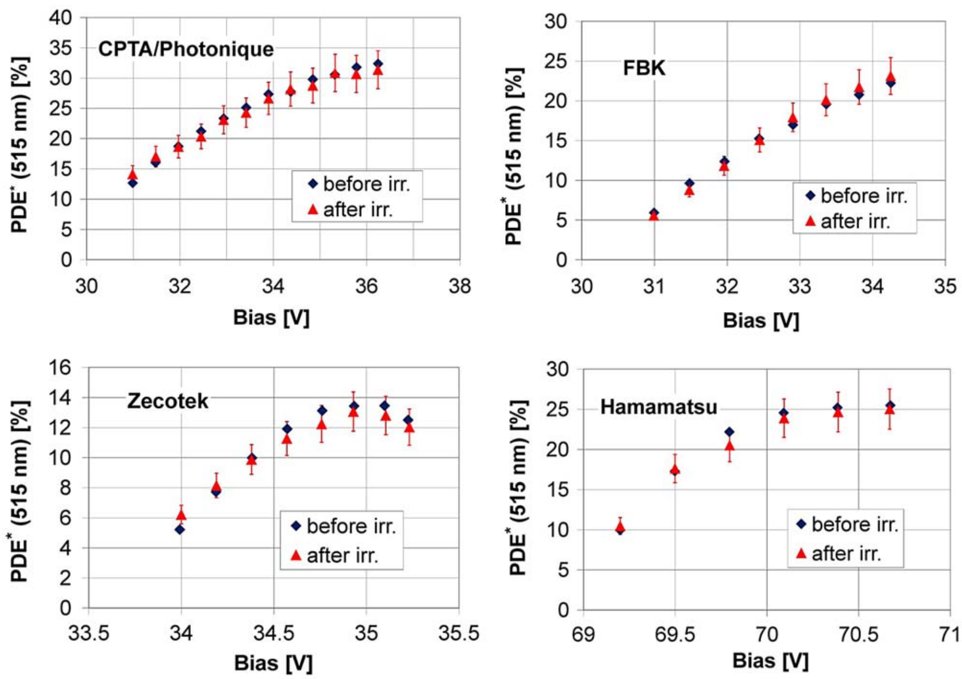

Fig. 5. *PDE**s vs. bias voltage, measured for the four G-APDs before and after proton irradiation.

irradiation) are shown in Fig. 6. From this figure one can see that for the CPTA/Photonique, FBK and Hamamatsu G-APDs the dependences of the currents on the forward bias voltages is linear for bias voltages of >0.7 V. From the linear part of the curves we calculated the corresponding resistor values. The G-APDs quenching resistor values were found dividing the resistor values found from these curves by the total number of pixels constituting the G-APDs. For the Zecotec device this dependence is not linear. This is probably due to the non-ohmic quenching resistor implemented into the structure of this G-APD. One can also notice that the dependencies of the current on the forward voltage remain unchanged after irradiation. This is also true for the MEPhI/Pulsar G-APD (the results are not shown). One can conclude that the structures of quenching resistors of these G-APDs were not damaged by proton irradiation.

4.6. G-APDs recovery time

G-APD cell recovery times have been studied using a two light source method (see for example [12]). The G-APDs were illuminated with light pulses from two blue LEDs. The first LED

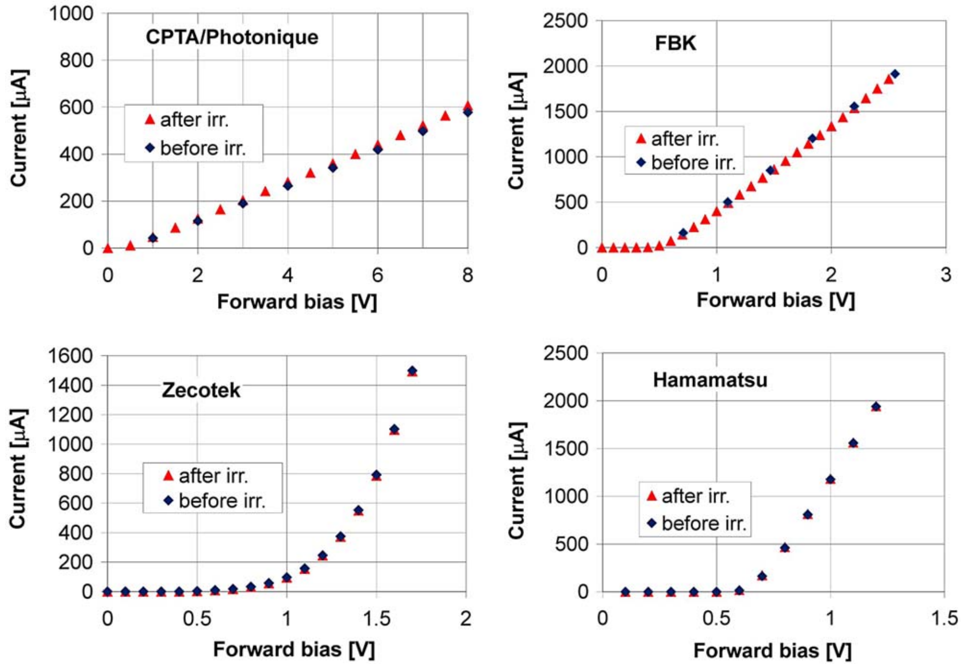

Fig. 6. G-APDs currents vs. forward bias voltage, measured before and after proton irradiation.

pulse was generated by an LP103 LED driver (produced by the PSI). One of the outputs of the LP103 LED driver was used as a trigger for the PM 5786 pulse generator. The delayed signal of the PM 5786 pulse generator triggered the second LED. The delay between LED signals was varied using the internal PM 5786 delay in the range from 20 ns to 100 µs. The intensity of the first LED pulse was ~200,000 photons/pulse in order to saturate the response of all G-APDs studied. The second LED pulse was adjusted to a significantly smaller number of photons ~200 photons/pulse. Durations of the LED pulses were 10 ns FWHM. The response of the G-APD to the second LED pulse was measured as a function of the pulse delay. The G-APDs operated at 1.5–3 V above their breakdown voltages.

The amplitudes of the G-APD pulses were normalized to the amplitudes measured when the time delay between the LED pulses was 1 ms. The results are shown in Fig. 7. As expected, the G-APDs with smaller quenching resistors had faster recovery times. It can be noticed that the recovery of the G-APDs (especially for the CPTA/Photonique and Zecotek devices) cannot be explained by a single time constant. The pixel dead time of 200–300 ns should be introduced to describe the recovery behavior of the CPTA/Photonique device. The very long pixel recovery time for the Zecotek G-APD is probably due to the non-ohmic quenching resistor implemented in the design of this APD. It might also be responsible for the significant reduction of the G-APDs signal amplitude after irradiation (see Fig. 4).

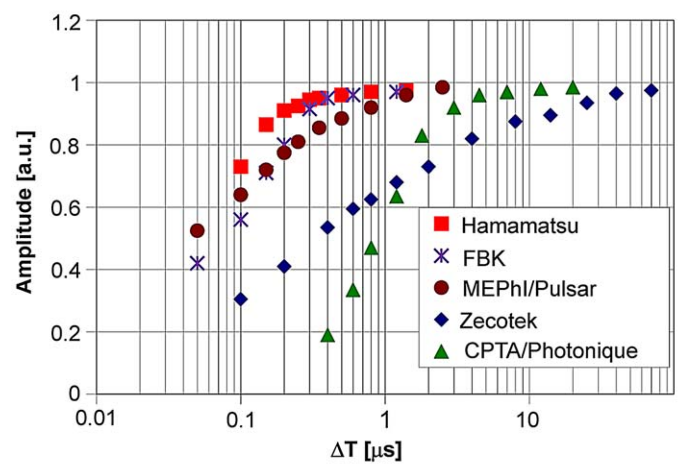

Fig. 7. Normalized amplitude of the second LED pulse measured by five G-APDs as a function of the delay between two LED pulses (measurements of the G-APD recovery time).

5. Discussion of the results

G-APDs have different structures, areas, numbers of cells, operating voltages, gains, *PDE*'s, etc. How can one compare the dark count increase produced by radiation in different G-APDs? Radiation damage in silicon devices was extensively studied by many groups (see for example review [13]). A linear relationship was found between the volume-generated leakage current ΔI and particle fluence Φ:

$$\frac{\Delta I}{V} = \alpha \times \Phi \tag{2}$$

where V is the active volume of the silicon detector and α is the leakage current damage constant. The thermal component of the leakage current in silicon detectors has a very strong dependence on the temperature—it doubles every 8 °C. A partial recovery of the leakage current was found after irradiation. It was also found that the damage produced by particles in silicon depends on their energy and type. The damage constant $\alpha = 4 \times 10^{-17}$ A/cm was measured 10 days after irradiation with 1 MeV neutrons at 20 °C [14]. Using the recovery data and the temperature dependence of the leakage current from Ref. [14] one can find approximately the same value of α at $T = 23$ °C and 3–4 months after irradiation. The damage produced in silicon by the 82 MeV protons used for these studies is about twice that produced by 1 MeV neutrons [13].

Assuming that every generated electron produces a dark pulse, the frequency of the dark pulses of an irradiated APD can be found from equation

$$\Delta N = \frac{\Delta I}{q} = \frac{\alpha \times V \times \Phi}{q} \quad (3)$$

where q is a value of an electron charge. Taking into account that the active volume of a G-APD is proportional to its geometric factor one can modify Eq. (3) as follows:

$$\Delta N(U) = \frac{\alpha \times S \times G \times P_G(U) \times \Phi}{q} \Delta l \quad (4)$$

where S is the G-APD area, Δl is the thickness of the G-APD depletion volume, G is a geometric factor, $P_G(U)$ is a voltage dependent probability of the G-APD cell to be fired by charge carriers generated inside its active volume. Taking into account that the *PDE* is equal to the product of the quantum efficiency *QE*, $P_G(U)$ and G [15], one can write

$$\Delta N(U) = \frac{\alpha \times S \times PDE(U) \times \Phi}{q \times QE} \Delta l \quad (5)$$

From (5) one can see that the ratio $\Delta N/PDE/S$ should have a weak dependence on the bias voltage.

To compare the damage produced by protons in different G-APDs in paper [2] we proposed to use the normalized value of the dark count increase, i.e. the increase of the dark count divided by the area S and photon detection efficiency of the G-APD:

$$\Delta N^*(U) = \frac{(N(U)_{after} - N(U)_{before})}{S \times PDE^*(U)} \quad (6)$$

where $N(U)_{after}$ and $N(U)_{before}$ are the G-APDs dark counts measured before and after irradiation at bias voltage U. As was already mentioned in Chapter 3 it is difficult to measure the *PDE* for irradiated G-APDs. In Eq. (6) it was replaced by PDE^*, which is the ratio of the PDE and the excess noise factor F. Such a replacement is valid for G-APDs with low values of the excess noise factors, which is true for most of the G-APDs studied in this work. Fig. 8 shows the results of the calculations of ΔN^* as a function of the PDE^* for the 5 tested G-APDs. It is seen that ΔN^* increases with the increase of the PDE^* for all the G-APDs. These increases are much higher than expected from the increases of the excess noise factors, which increase from 1 at small *PDE*s to 1.2–1.4 at maximum values of PDE reachable by the G-APDs studied in this paper [10,16]. From Fig. 8 one can see more than a factor of two increase of the ΔN^*s for all the devices studied in this work. Such behavior cannot be explained if one takes into account only the generation–recombination process. Some other effects, probably related to the very high electric fields inside the G-APDs, can be responsible for such ΔN^* vs. PDE^* dependence.

There is also a significant difference in ΔN^* measured for different G-APDs at the same values of the PDE^*s. From the results of the ΔN^*s shown in Fig. 8 and from Eq. (5) one can get an estimate of the depleted region thickness of the G-APDs. The dark current damage constant of 4×10^{-17} A/cm corresponds to the ~250 Hz/cm dark count rate. After irradiation with the 10^{10} protons/cm^2 (which is equivalent to 2×10^{10} neutrons/cm^2) the dark count rate should increase to ~5 MHz/μm/mm^2 or ~70 kHz/μm/mm^2/% (here we took into account the 70% maximum value of the *QE*, which can be achieved with the 2–4-μm-thick silicon detectors for green light [17]). For the PDE^*s in the range from 10% to 20% the values of the ΔN^*s are in the range from 200 to 1400 kHz/μm/mm^2/%. These values correspond to depletion depths from 3 to 20 μm. The smaller value looks reasonable, but the larger value is much higher than is expected from the thicknesses of the epitaxial films (2–4 μm) used to produce these G-APDs.

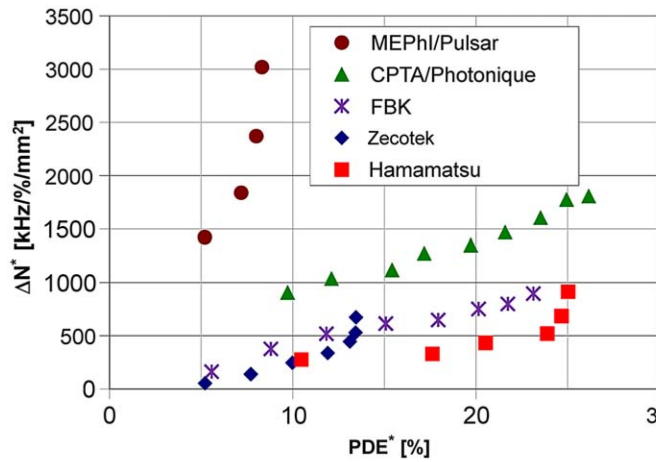

Fig. 8. Normalized dark count increase vs. PDE^* calculated for five irradiated G-APDs.

6. Conclusion

Five G-APDs (produced by CPTA/Photonique, MEPhI/Pulsar, FBK-IRST, Zecotek, and Hamamatsu) were irradiated with 82 MeV protons up to 2×10^{10} 1/cm^2 of 1 MeV neutron equivalent flux. The G-APD's response to green LED pulses, the *PDE/F* ratio, breakdown voltage, quenching resistor value, dark current and count rate were measured before and after irradiation. A significant increase in the leakage current and dark count rate was measured for all the devices. There was no change of breakdown voltage and quenching resistor value found at the precision of our measurements. The change of *PDE/F* ratio as a function of voltage was found to be less than 10%. Significant reduction (>10%) of the signal amplitude was measured with some of the irradiated G-APDs.

References

[1] G. Lutz, Semiconductor Radiation Detectors, Springer, Berlin, 1999, pp. 275–303.
[2] Y. Musienko, et al., Nucl. Instr. and Meth. A 581 (2007) 433.
[3] http://photonique.ch/.
[4] http://pc3k40.exp.mephi.ru/.
[5] Fondazione Bruno Kessler, Trento, Italy 〈http://sipm.itc.it/〉.
[6] http://www.zecotek.com/.
[7] http://www.hamamatsu.com.
[8] http://photonique.ch/Prod_AMP_0600.html.
[9] http://www.picotech.com/picoscope5000.
[10] Y. Musienko, S. Reucroft, J. Swain, Nucl. Instr. and Meth. A 567 (2006) 57.
[11] E. Guschin, et al., Nucl. Instr. and Meth. A 567 (2006) 250.
[12] I. Britvitch, D. Renker, Nucl. Instr. and Meth. A 567 (2006) 260.
[13] G. Lindstrom, Nucl. Instr. and Meth. A 512 (2003) 30.
[14] G. Lindstrom, M. Moll, E. Fretwurst, Nucl. Instr. and Meth. A 426 (1999) 1.
[15] D. Renker, Nucl. Instr. and Meth. A 567 (2006) 48.
[16] Y. Musienko, S. Reucroft, J. Swain, PoS (PD07) 012 〈http://pos.sissa.it〉.
[17] G.W.C. Dash, R. Newman, Phys. Rev. 99 (1955) 1151.