G-APD radiation hardness

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Radiation damage in semiconductors (Si)

Radiation damage in silicon is strongly dependent on the type and energy of the radiation

Two types of radiation damage:

- ***Surface damage (ionizing damage in the Si/SiO_2 interface)***
- ***Bulk damage (crystal lattice defects: displacement of silicon atoms)***

Surface damage

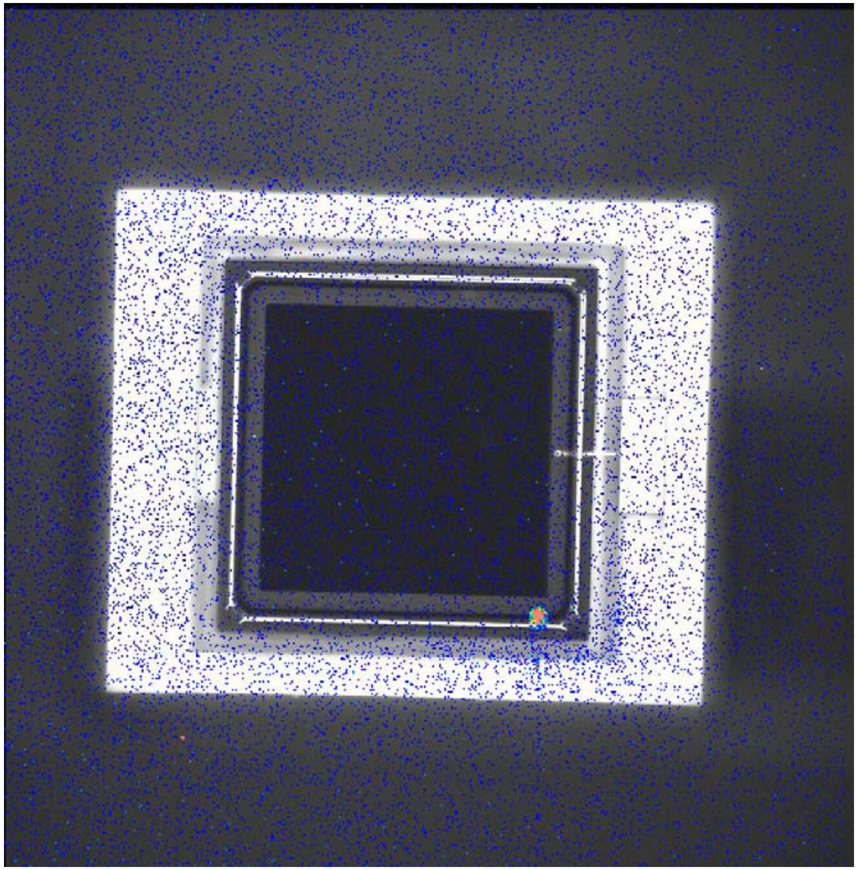
SiO_2 is a very good insulator (or a semiconductor with a large band gap of 8.8 eV). Electron/hole pairs created by ionizing particles can be trapped into very deep levels associated with the defects in oxide from which the emission back into conduction/valence band is very unlikely at room temperature

Ionizing radiation (charged particles, gammas) produces surface damage (damage in the Si/SiO2 interface) due to accumulation of positive charges in the oxide (SiO2) and the Si/SiO2 interface

This may cause:

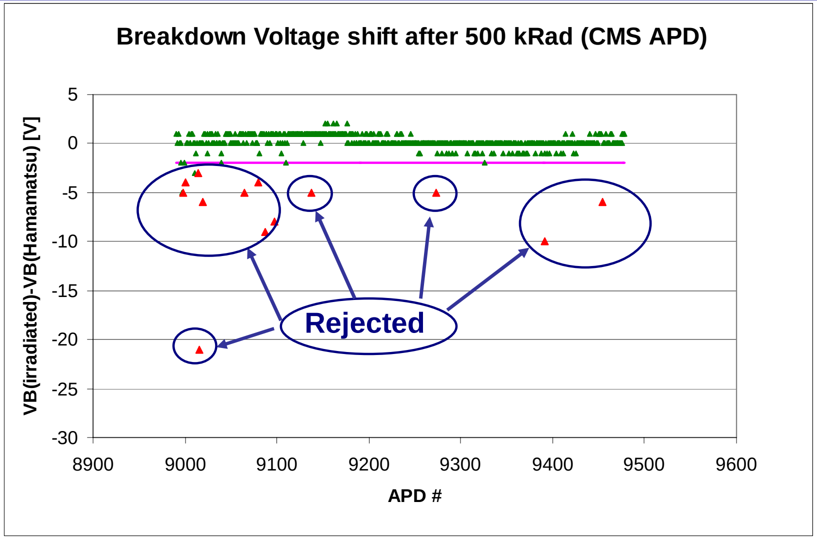
- breakdown voltage shift (early APD breakdown)
- QE reduction
- surface current increase

CMS APD irradiated with gammas from Co-60 source



Light is emitted from the point where the dielectric is broken by irradiation (HV is ON).

(Picture is taken with the CCD camera at Hamamatsu)



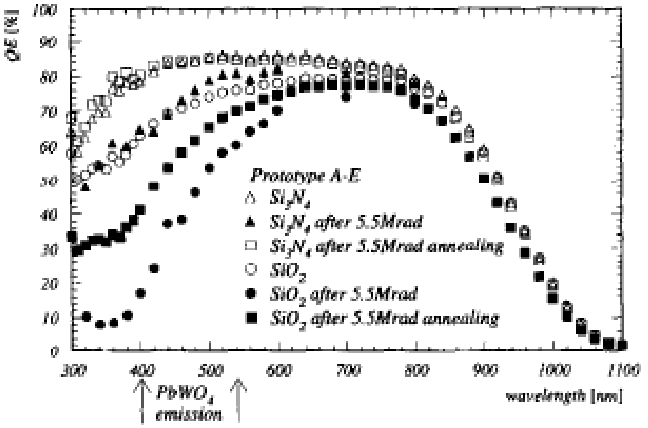
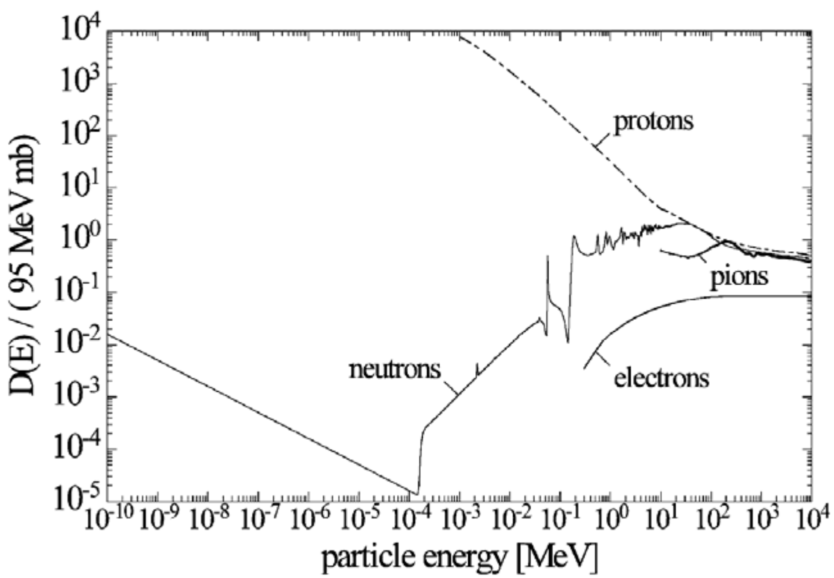


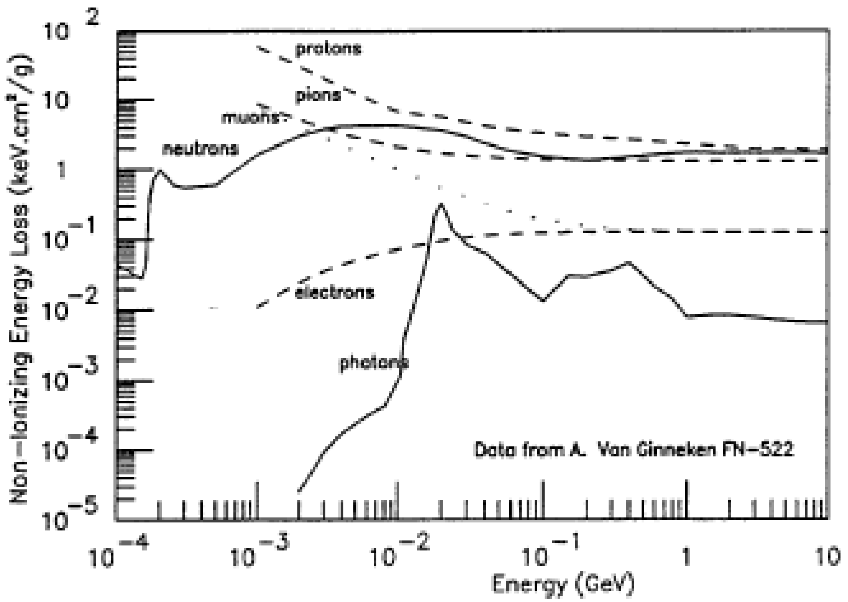
Fig. 1. Quantum efficiency of APDs with different passivation layers before and after gamma irradiation and annealing.

Bulk damage and NIEL function

Bulk damage scales linearly with the amount of Non Ionizing Energy Loss (NIEL hypothesis), which is very dependent on the particle type and its energy



A. Vasilescu, Fluence normalization based on the NIEL scaling hypothesis, 3rd ROSE Workshop on Radiation Hardening of Silicon Detectors, DESY Hamburg 12–14 February 1998, DESY-PROCEEDINGS-1998-02.



A. Van Ginneken. Fermilab Note. FN-522 (1989).

NIEL(1 MeV gammas) ~ 10^{-5} * NIEL(1 MeV neutrons)

Bulk damage effects

Increase of the dark current generated in the silicon bulk (multiplied current):

$$I = \alpha \Phi_{\mathrm{eq}} V$$

***Φ_{eq}* – 1 MeV neutron equivalent total flux**

***V* – silicon active volume**

***α* – dark current damage constant (~4*10^{-17} A/cm for 1 MeV neutrons after 80 min annealing at 60 °C or ~10^{-16} A/cm after few days annealing at room temperature)**

Changes in the effective doping concentration (creation of acceptor-like states) a few weeks after irradiation:

$$\Delta N = N_0 (1 - \mathrm{e}^{-c\Phi}) + b\Phi$$

where $N_0 = 3.36(\pm 0.03) \times 10^{11}\,\mathrm{cm}^{-3}$, $c = 3.58$ $(\pm 0.2) \times 10^{-13}\,\mathrm{cm}^2$, $b = 0.0171(\pm 0.0001)\,\mathrm{cm}^{-1}$, and Φ is the total neutron fluence in neutrons/cm^2.[5]

HERA-B Design Report, DESY–PRC 95/01, 1995.

Multipixel Geiger-mode APDs (G-APDs)

Model

Active G-APD volume:

$V = S*G*L = s*L$

S - total area

s - active area (total area minus non-sensitive area between pixels)

G - geometric factor

L - depletion layer thickness

Expected G-APD dark current increase after irradiation:

$\Delta I = \alpha * M * P_G * \Phi_{eq} * V$

α - dark current damage constant

M – G-APD gain

P_G – Geiger discharge probability (is a f [V-VB])

Φ_{eq} – 1 MeV neutron equivalent total flux

G-APD radiation hardness studies

G-APD's radiation hardness was studied with:

28 MeV positrons (PSI)

- *Hamamatsu MPPCs, CPTA/Photonique SSPMs, Dubna/Micron AMPDs*

200 MeV protons (ITEP)

- *MEPhI/Pulsar SiPMs*

53.3 MeV protons (Osaka Univ.)

- *Hamamatsu MPPCs*

0.1-1 MeV neutrons (reactor (YAYOI))

- *Hamamatsu MPPCs*

290 MeV/nucleon $C6^{+}$ ions (HIMAC)

- *Hamamatsu MPPCs*

Co^{60} ~1 MeV gammas (Tokyo Tech)

- *Hamamatsu MPPCs*

28 MeV positrons (PSI)

The reason we used 28 MeV positrons for APD irradiation:

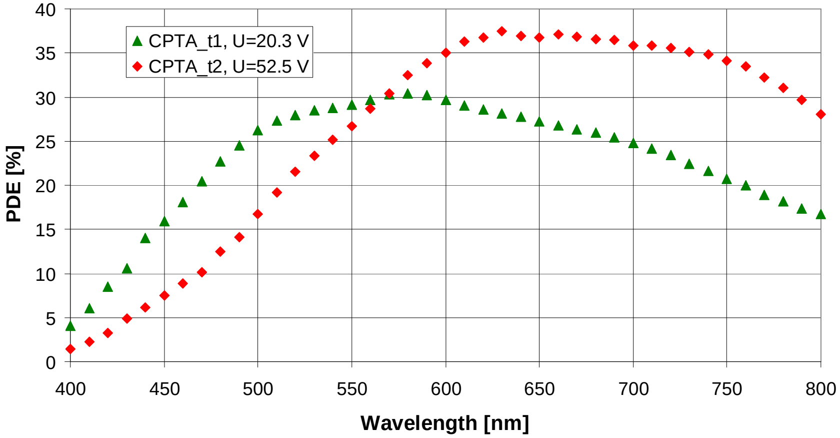
- Excellent positron beam available at Paul Scherrer Institut (Villigen, Switzerland)
- Possibility to monitor and control beam intensity
- APDs are not activated during irradiation and measurements can be performed immediately after irradiation

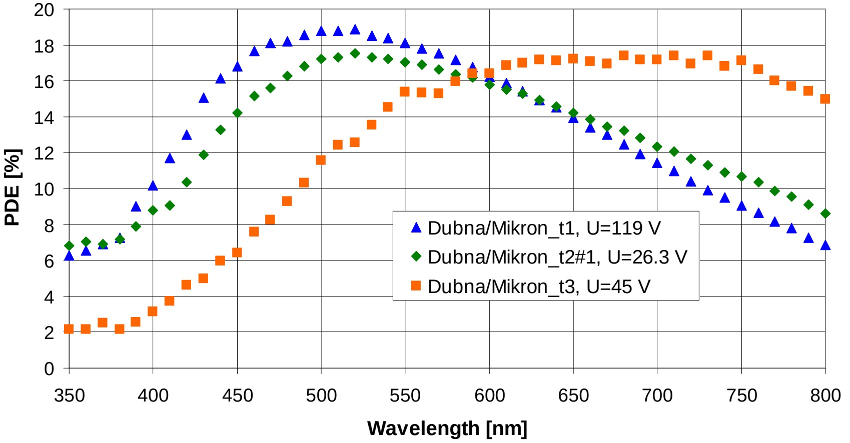
G-APDs and their parameters before irradiation (T=22 C)

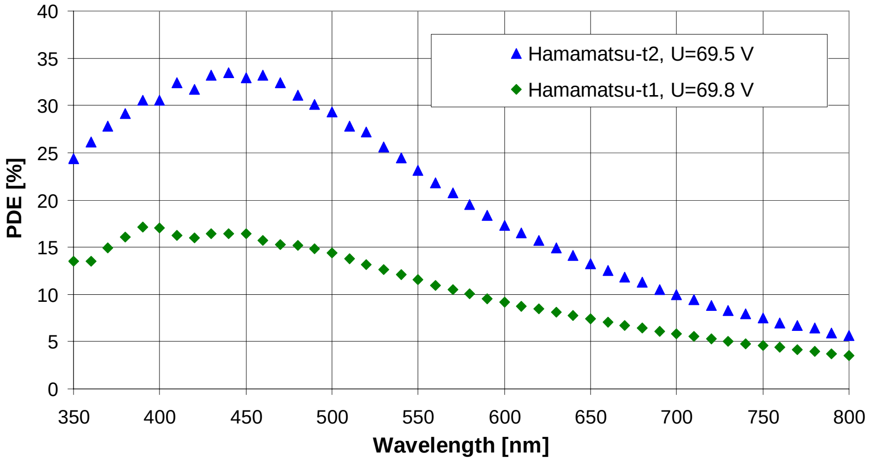
G-APDs	Producer's reference	Substrate	Area [mm²]	# of pixels	Uop [V]	Gain*10^6 (Gate=60 ns)	PDE(515 nm) [%]	Dark Count [MHz]
CPTA-t1	SSPM-0606BG4MM-PCB*	p-type	4.41	1748	21	0.2	32	20
CPTA-t2	F1707	p-type	1	556	52.5	1.2	20	4
Dubna/Mikron-t1	MW-3	n-type	1	10 000	119	0.05	19	7
Dubna/Mikron-t2#1	p-INT-2	p-type	3.24	2436	26.5	1.5	18	8
Dubna/Mikron-t2#2	p-INT-2	p-type	3.24	2436	26	1.5	18	8
Dubna/Mikron-t3	pMP-3d-11	p-type	1	1024	45.5	0.9	12	5
Hamamatsu-t1	311-31A-001	n-type	1	1600	69.5	0.5	12	0.5
Hamamatsu-t2	311-53-1A-001	n-type	1	400	69.5	3.5	27	1.3

*Photonique SA reference

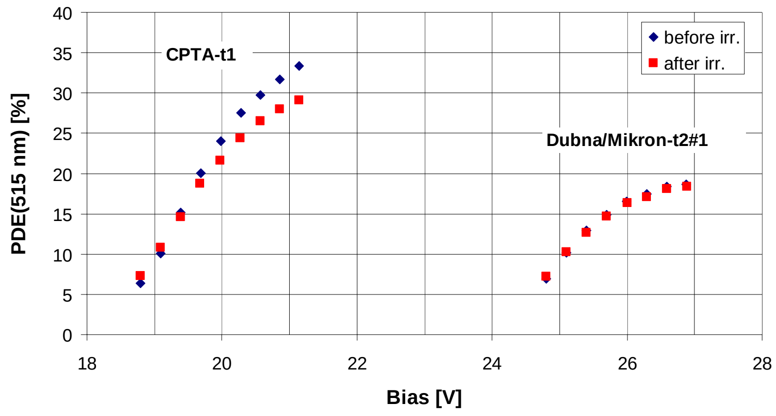
G-APDs spectral responses - measured at T=22 ºC

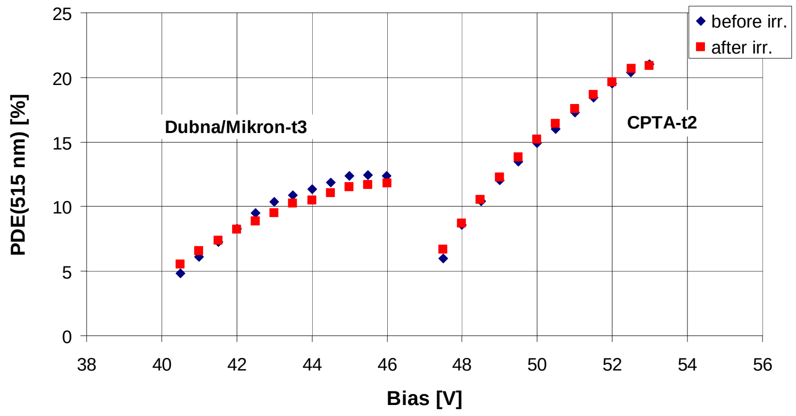


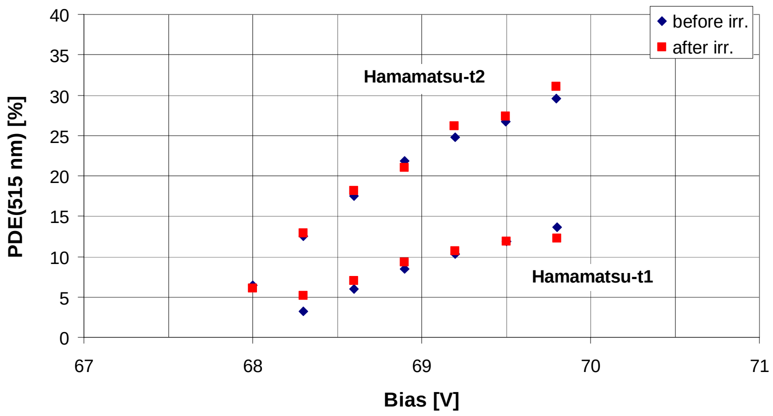


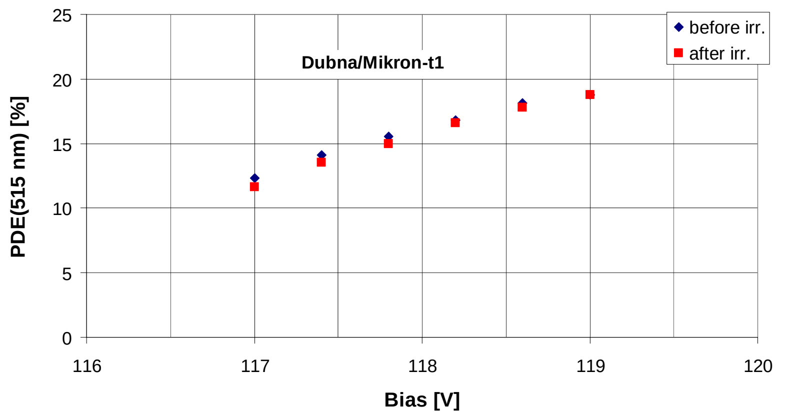


Photon detection efficiency vs. bias voltage dependence (before and after $8*10^{10}$ positrons/cm^2) measured at T=22 ºC

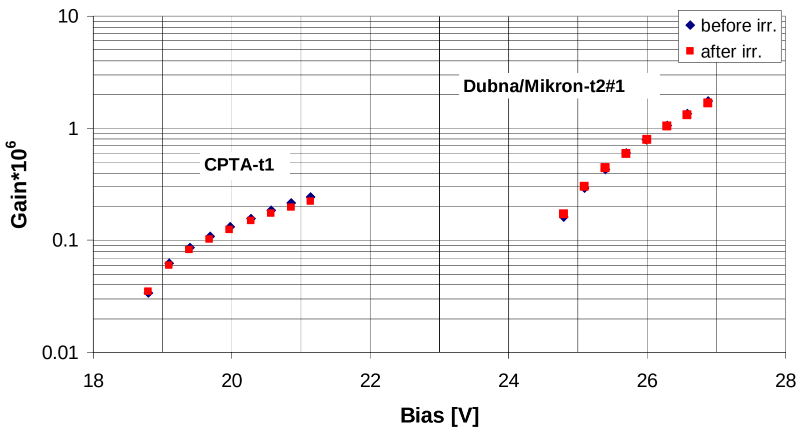


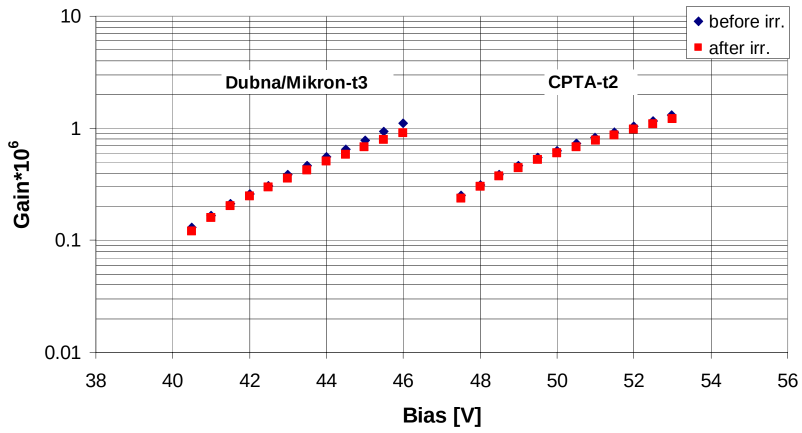


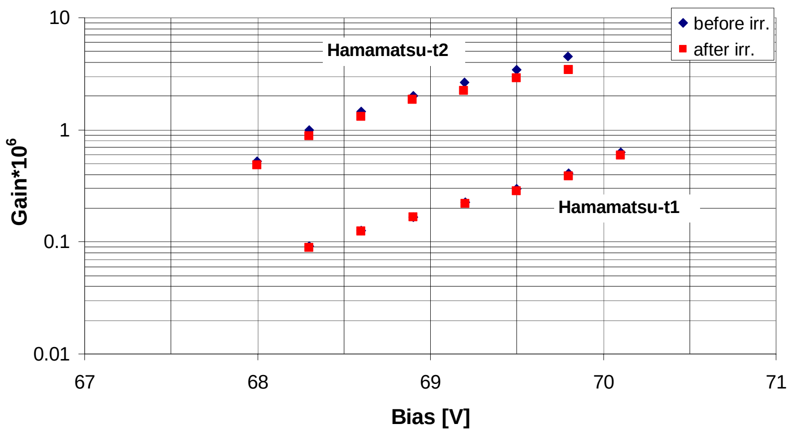


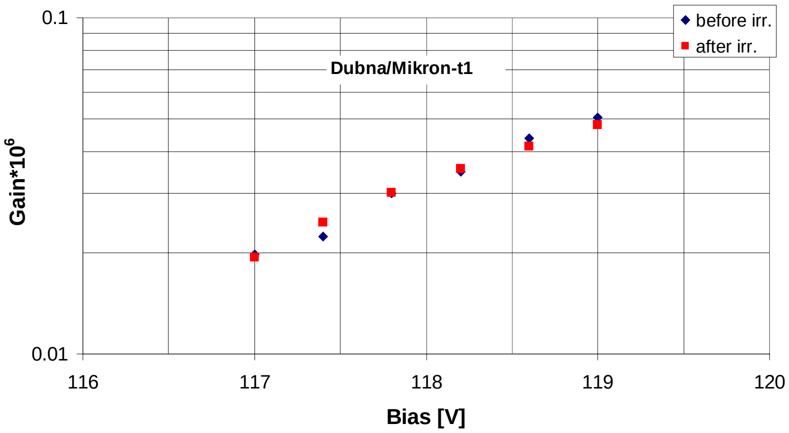


Gain vs. bias voltage dependence (before and after $8*10^{10}$ positrons/cm^2) measured at T=22 ºC

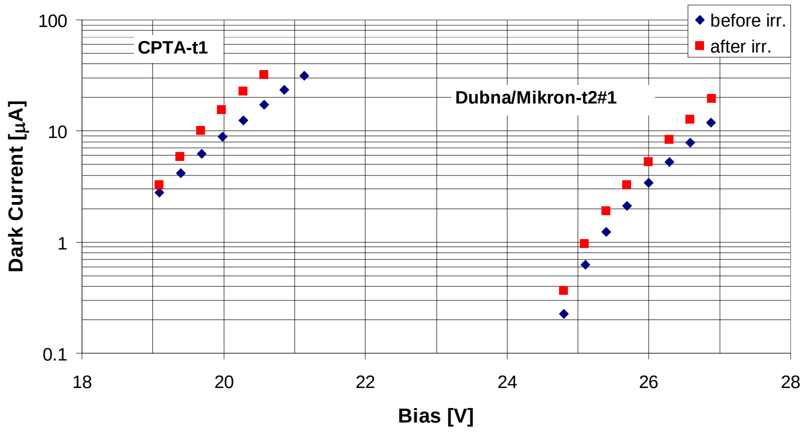


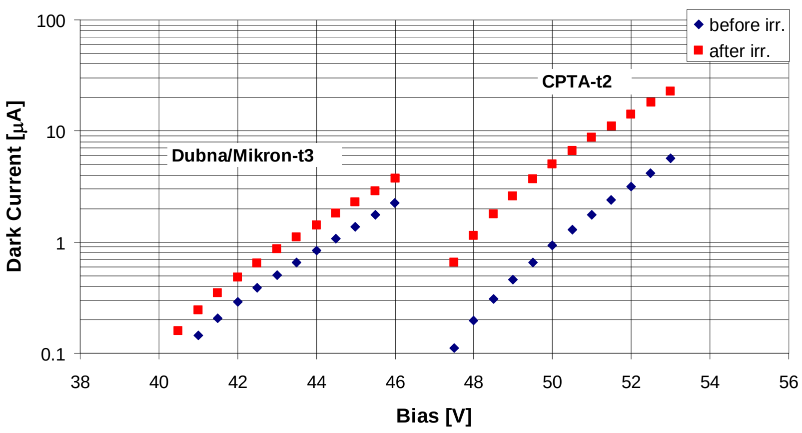


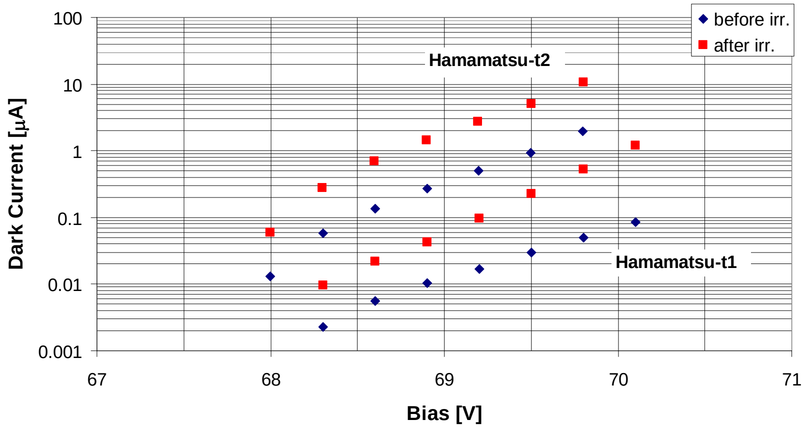


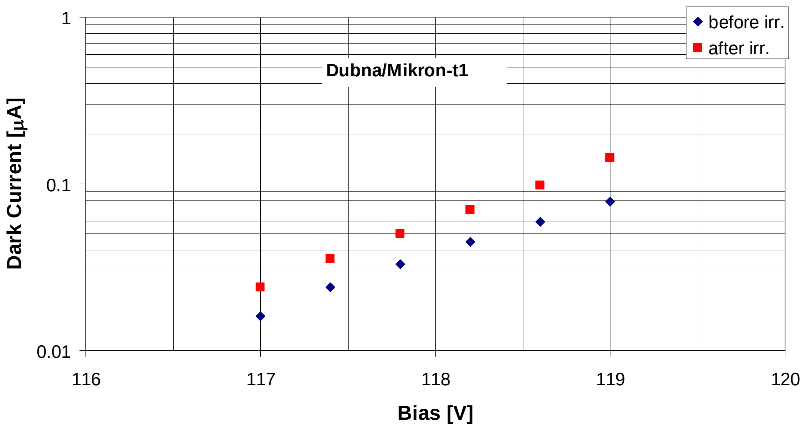


Dark current vs. bias voltage dependence (before and after 8*10^{10} positrons/cm^2) measured at T=22 ºC

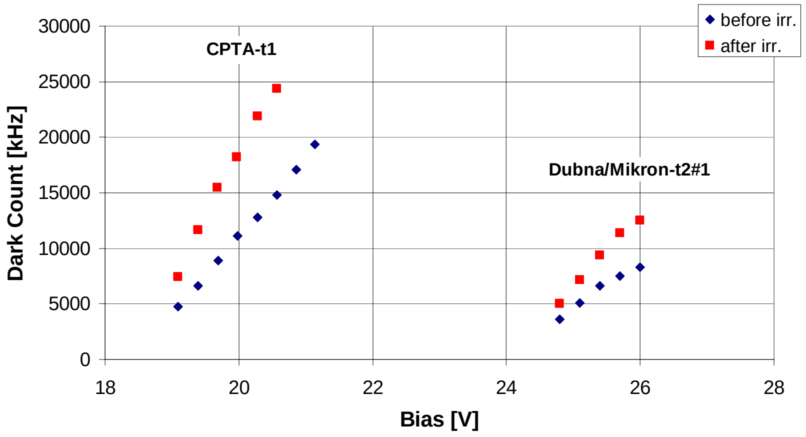


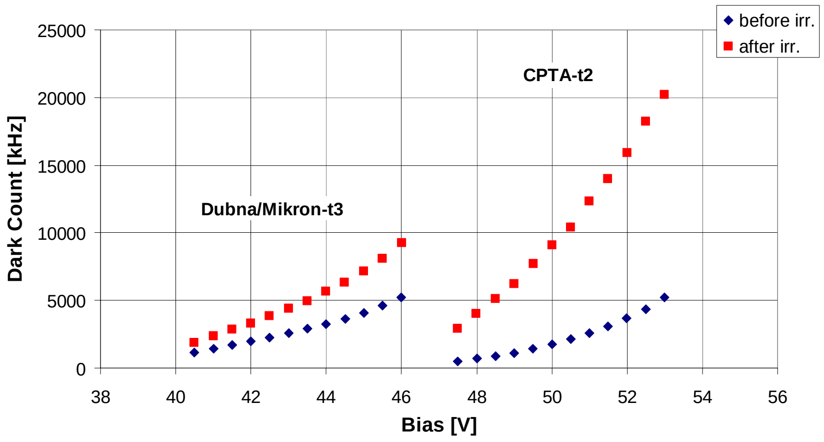


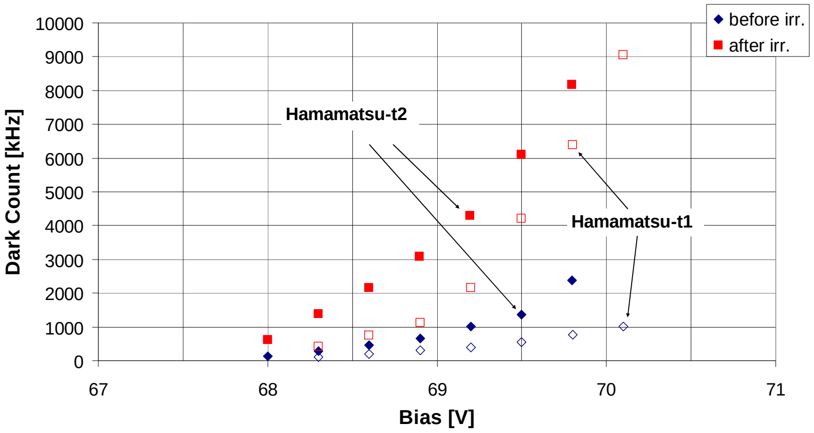


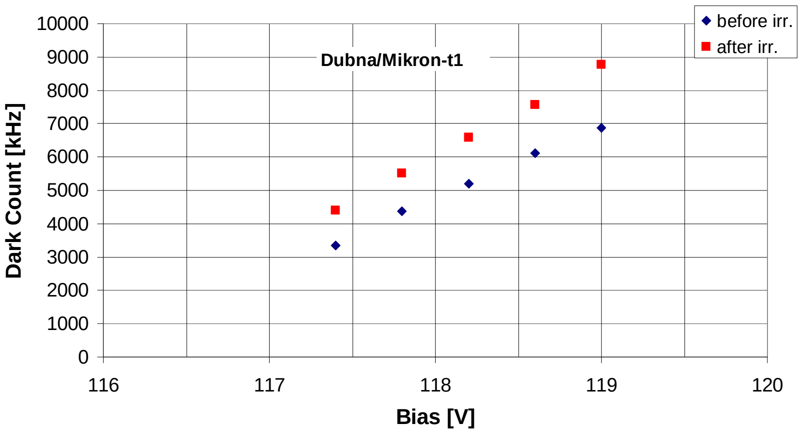


Dark count rate vs. bias voltage dependence (before and after $8 \cdot 10^{10}$ positrons/cm^2) measured at T=22 ºC









Dark Count Increase/PDE/Area

G-APDs studied have different area, geometric factor, depletion volume, etc. How to compare the dark count increase produced by radiation in different G-APDs?

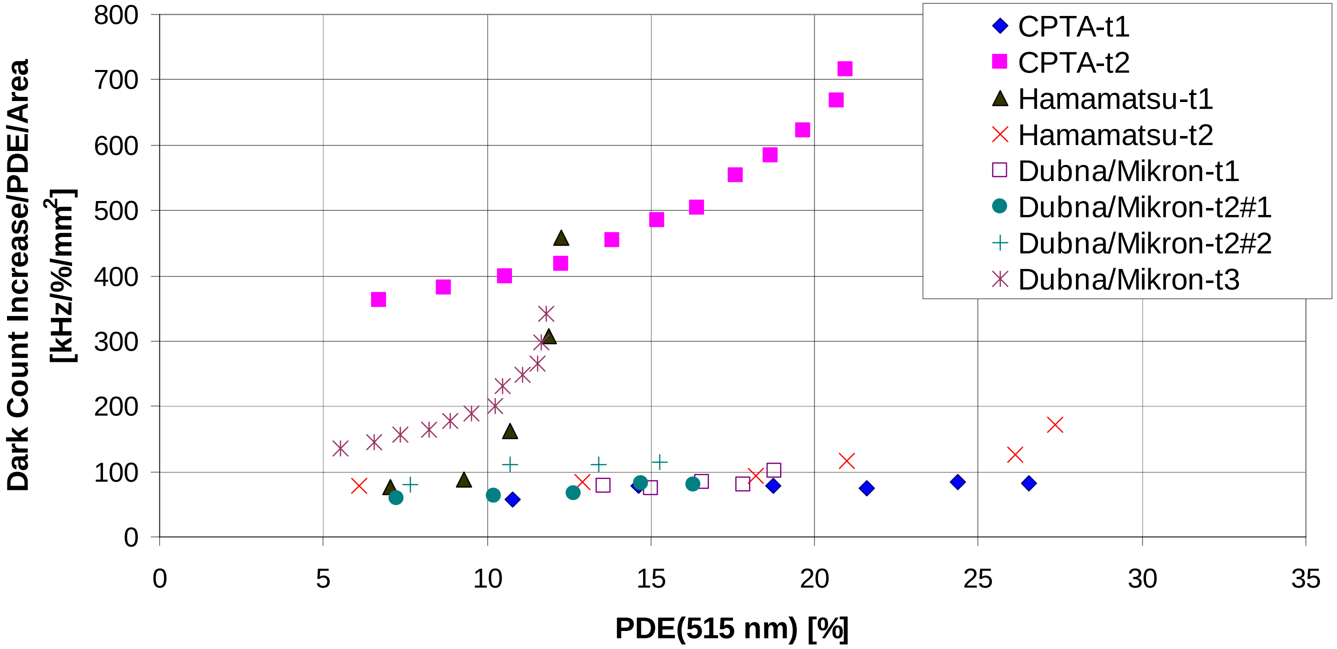
Expected G-APD dark count increase after irradiation:

$\Delta N=\Delta I/q/M=\alpha*M*P_G*\Phi_{eq}*V/q/M=\alpha*P_G*\Phi_{eq}*S*G*L/q$, *q – electron charge*

Assuming that PDE is proportional to P_G*G:

$\Delta N \sim \alpha*PDE*\Phi_{eq}*S*L/q \rightarrow \Delta N/PDE/S \sim \alpha*\Phi_{eq}*L/q$

This ratio is expected to have weak dependence on the G-APD PDE, geometric factor and sensitive area. Dependence on the depletion thickness remains.



Dark count damage constant (DCDC) evaluation

The ratio **ΔN/PDE/S** was found to be in the range of 70÷110 kHz/%/mm^2 for 5 G-APDs out of 8 (see figure). For these G-APDs at T=22C:

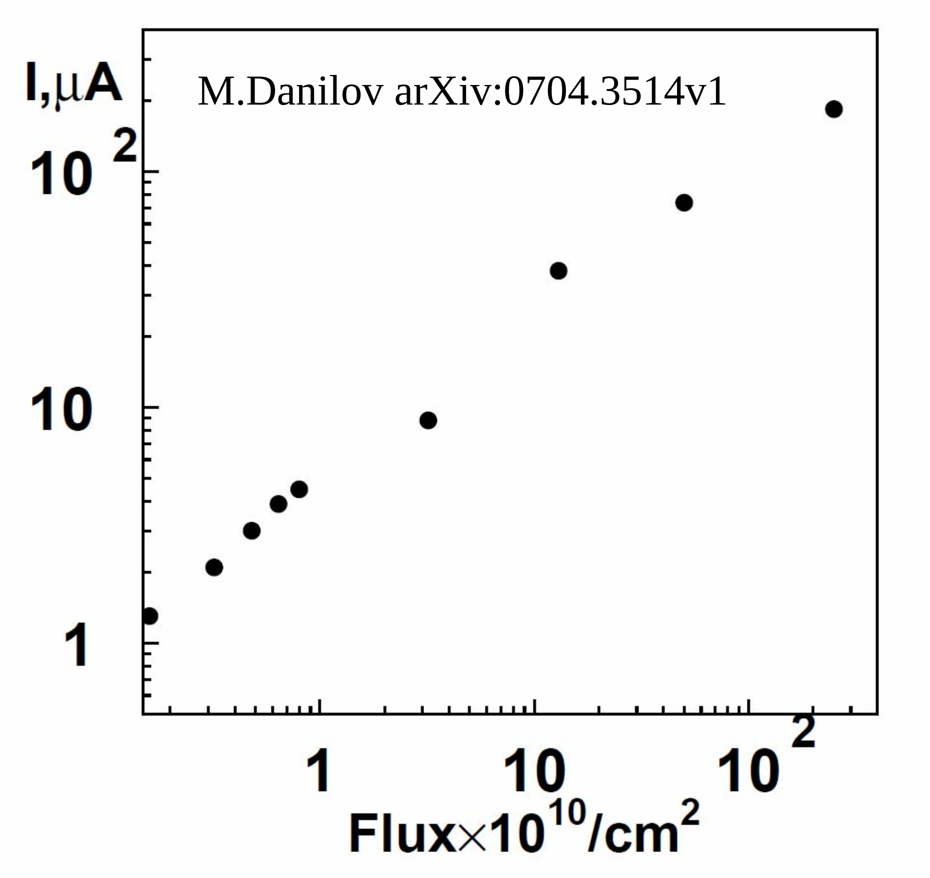
DCDC(28 MeV positrons)~0.9÷1.4*10^{-4} Hz/%/positron.

NIEL factor for 28 MeV positrons is ~30 times smaller than for 1 MeV neutrons (this was verified by irradiating S8148 Hamamatsu APD with 28 MeV positrons and 1 MeV neutrons). One can calculate:

DCDC(1 MeV neutrons)~2.7÷4.2*10^{-3} Hz/%/neutron

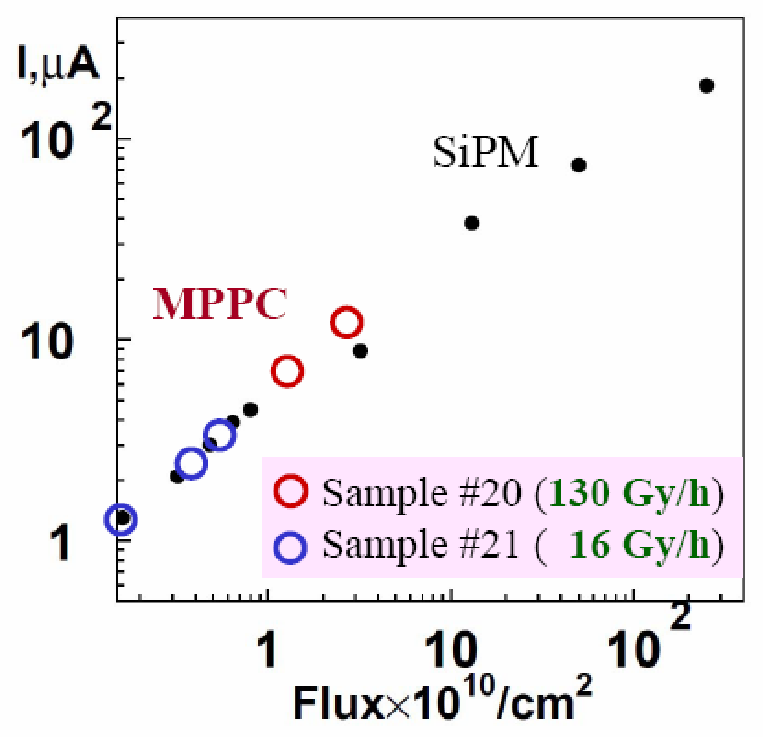
This corresponds to the current ~ 4.3 ÷ 6.7*10^{-20} A/neutron (assuming PDE=100%). Such current will be produced in silicon bulk if we assume the thickness of the depletion layer in the range of 4 ÷ 7 μm and α~10^{-16} A/cm/neutron. This is somewhat higher then the thickness of the epitaxial films used to produce G-APDs (~2-4 μm)

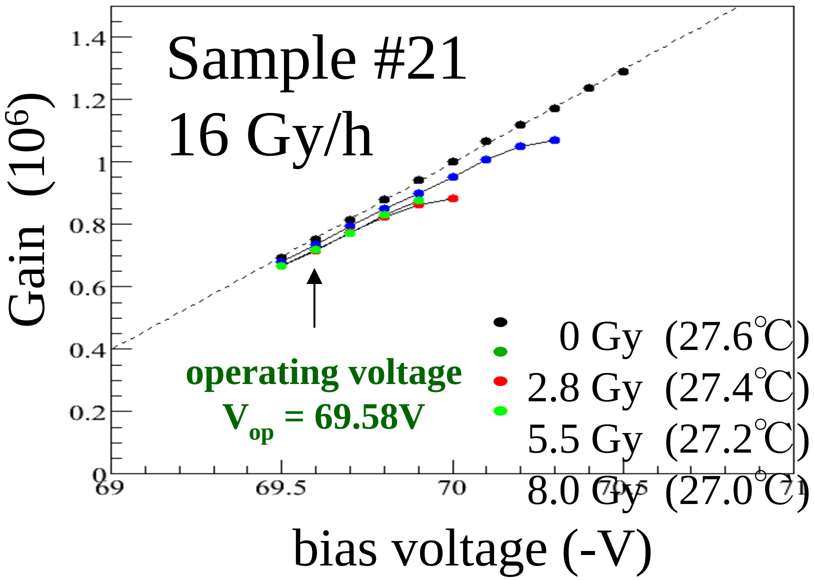
200 MeV protons (MEPHI/Pulsar SiPMs)



- $\Delta I^*M = 4\ \mu A$ after 10^{10} p/cm^2
- M ~10^6, PDE(515nm) ~15%, S~1.2 mm^2
- NIEL(200 MeV protons)~ NIEL(1 MeV neutrons)
- ➔ L~25 μm? Too thick. No annealing?

53.3 MeV protons (Hamamatsu MPPC)

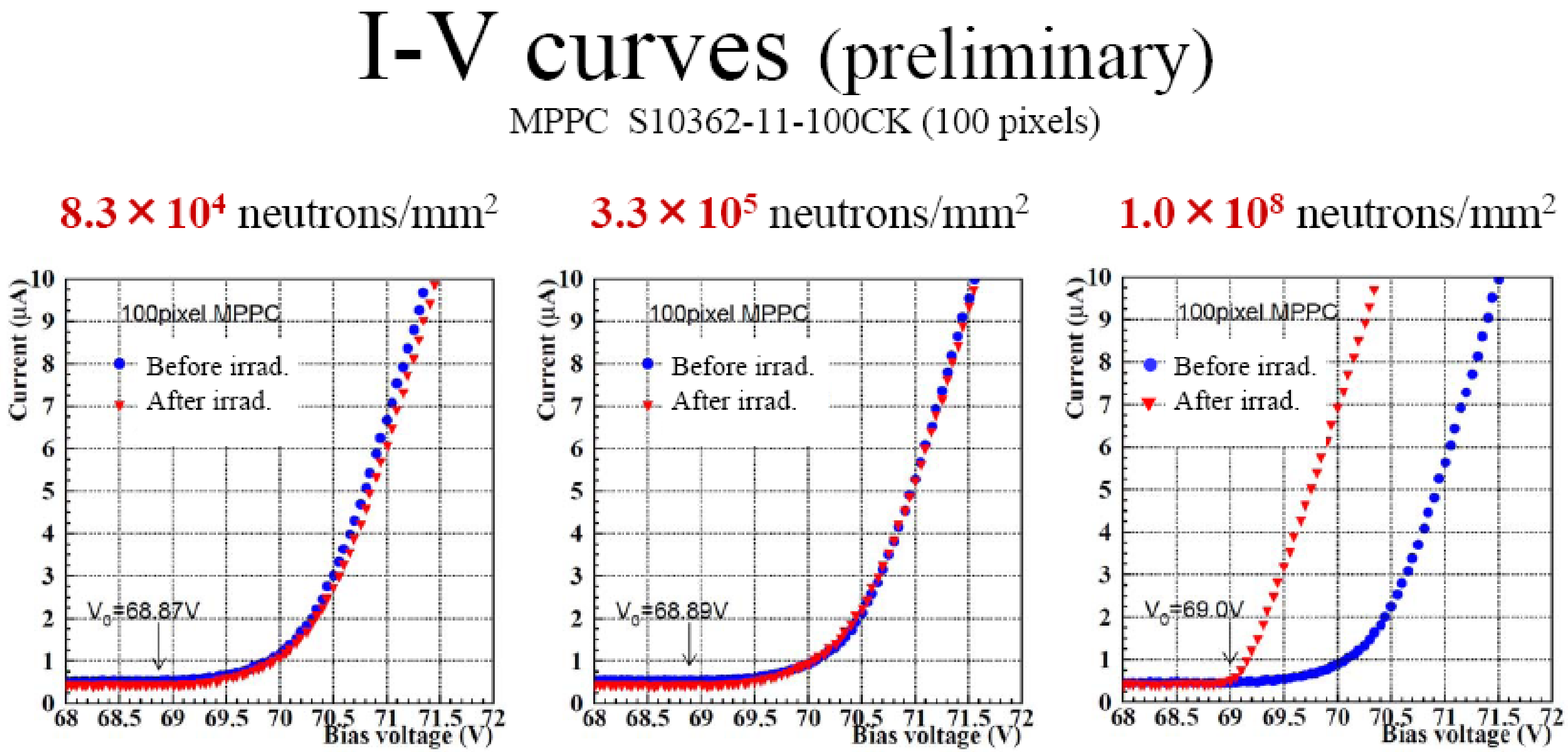




(From talk of T. Matsumura at PD-07)

- $\Delta I*M \sim 4\ \mu A$ after $10^{10}\ p/cm^2$
- $M \sim 10^6$, PDE(515nm) ~30%, $S=1\ mm^2$
- NIEL(53 MeV protons)~ 2*NIEL(1 MeV neutrons)
- ➔ L~6 μm (similar to the results with 28 MeV positrons)

Reactor neutrons

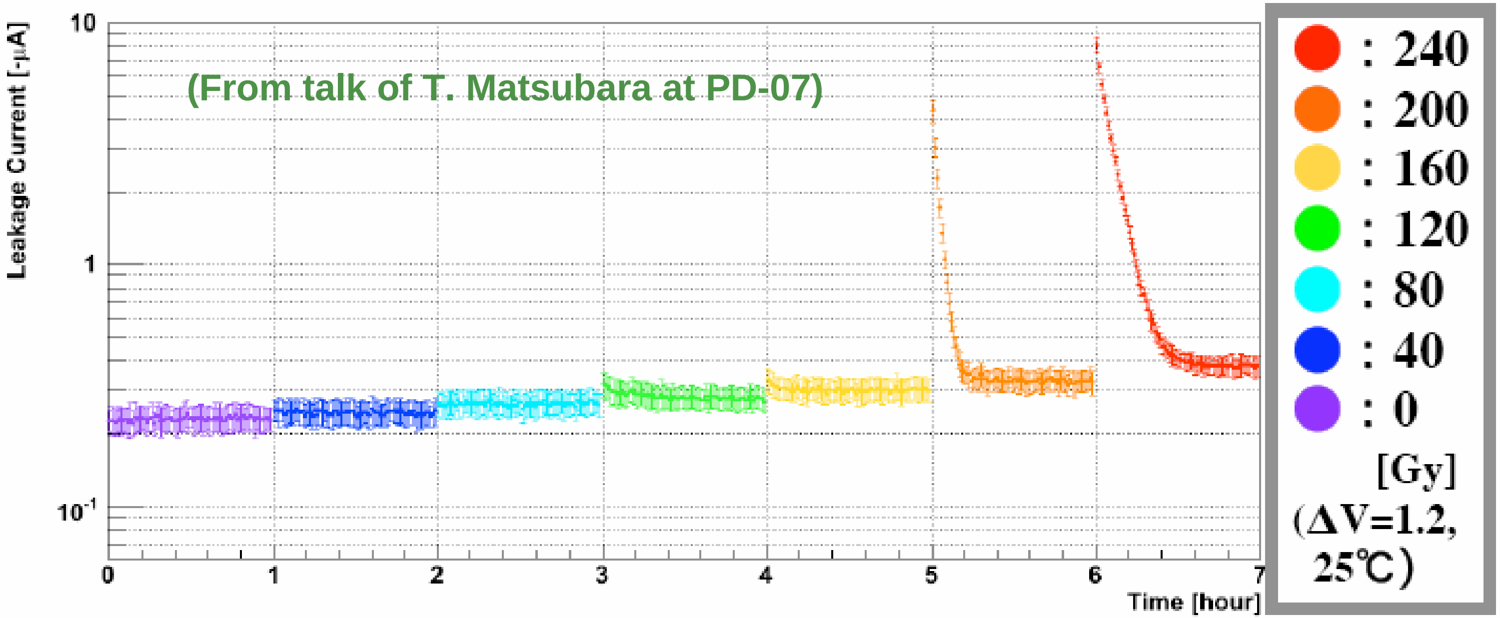


(From talk of T. Matsumura at PD-07)

ΔI*M~10 μA (V-VB~1.4V) after 10^{10} n/cm^2
M ~2.5-3*10^6 , PDE(515nm) ~35%, S=1 mm^2
➔ L~4-5 μm (consistent with the results with 28 MeV positrons)

1 MeV gammas from Co-60 source

Leakage current after each irradiation

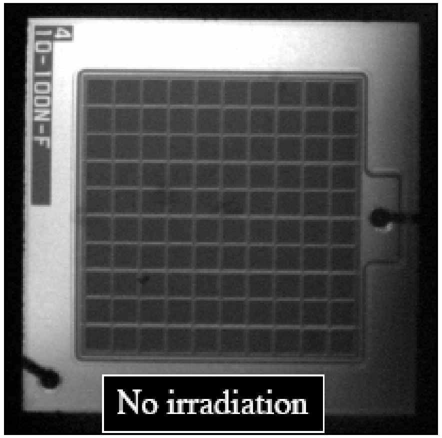


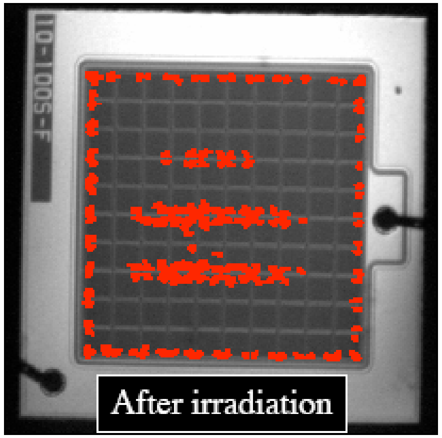
- Leakage current at V_{op} increased ~1.7 times by these irradiations comparing the second half of each data
- Annealing effect were observed from 120Gy irradiation
- Leakage current changed so much just after 200Gy and 240Gy

MPPC damaged by gamma irradiation

Infrared emission

- We took a picture by infrared camera, supplying bias voltage in order to look at where the high dark noise generated
- A large current flows in the red area





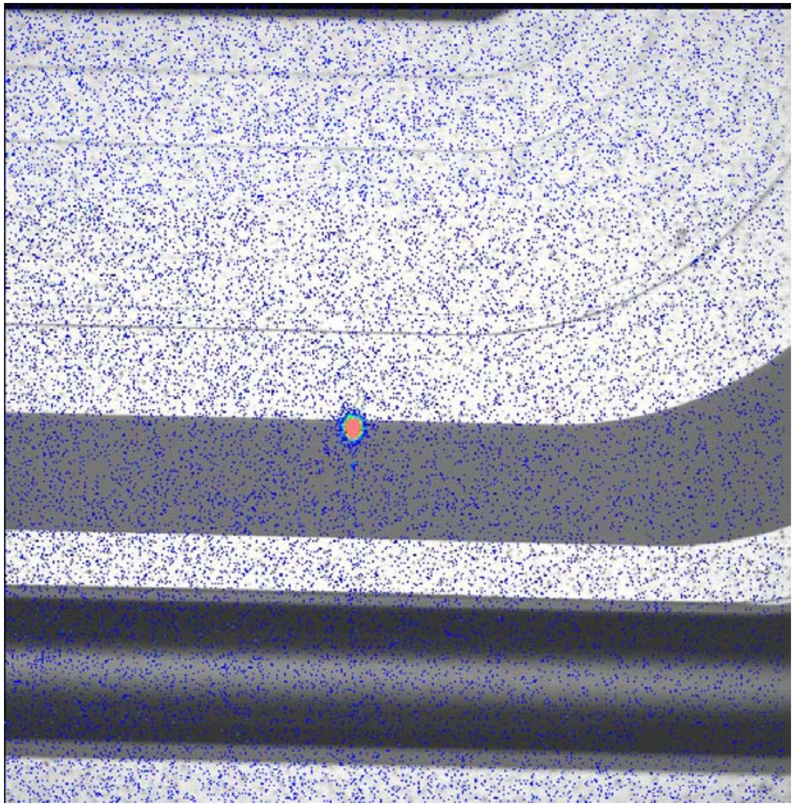
- We find the localized spot where the high dark noise generated
  - Outer edge of device and along the bias lines (to see full device)
  - Edge of a pixel (to see 1 pixel)

(＊)Bias lines exist alternately

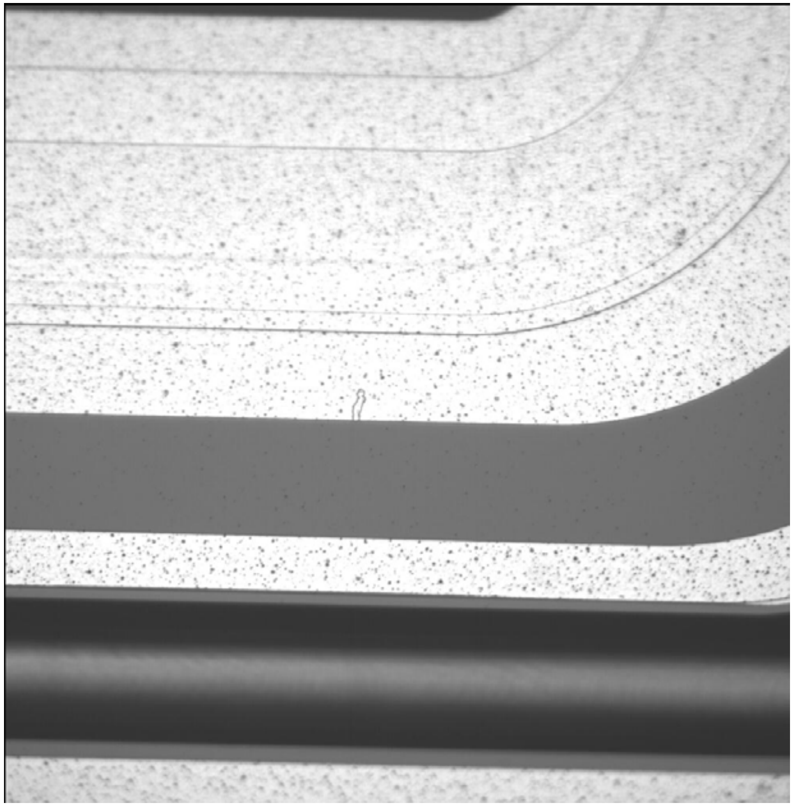
(From talk of T. Matsubara at PD-07)

CMS APD damaged by 1 MeV gammas

Bias "ON"



Bias "OFF"



"Defect" is seen on all APD`s from the same position on the wafer - defect of the mask

Summary

Damage caused by ionizing radiation (^{60}Co) should not be a real problem. A proper design of the cell edges and maybe a different crystal orientation will make the G-APD`s insensitive. Unavoidable defects on the surface might force a screening procedure.

Displacement damage cannot be avoided. The dark count damage constant is $(3.5\pm0.5)*10^{-3}$ Hz/%/neutron. Only a reduction of the contributing volume can keep the dark counts in a tolerable range.