Radiation damage of SiPMs

Y. Musienko *)

University of Notre Dame (Notre Dame)

*)*On leave from Institute for Nuclear Research RAS (Moscow)*

Outline

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- Radiation damage effects in SiPMs
  - radiation damage by hadrons
  - radiation damage by X-rays and gammas
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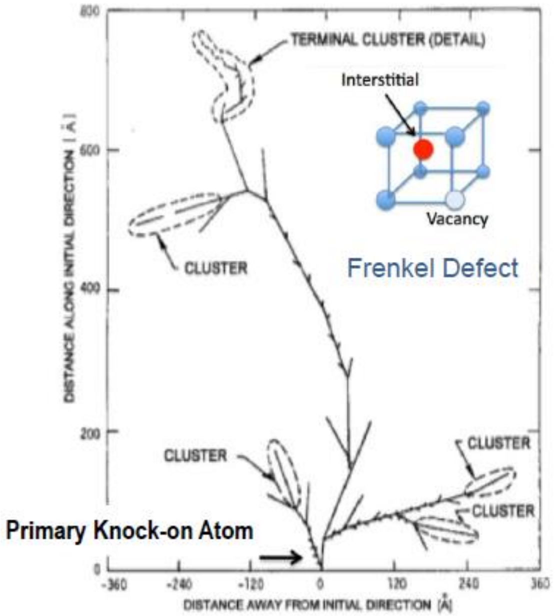
- Radiation damage of SiPMs at reduced temperature
- Approaches to develop radiation harder SiPMs
- Conclusion

Introduction

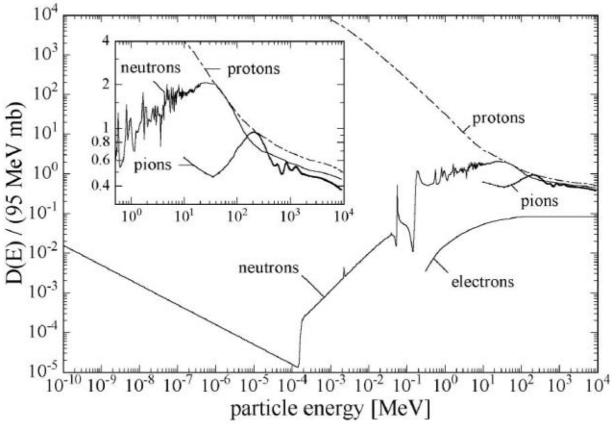
New detectors for the upgrade of the LHC experiments (CMS, LHCB) demand to operate SiPMs up to fluences of $10^{12} \div 10^{14}$ particles/cm^2. Application of SiPMs in this experiments requires understanding of the effects caused by different types of irradiation on SiPM parameters. This review is an attempt to summarize the current knowledge of radiation damage of SiPMs.

Radiation induced damage in silicon

Radiation induced damage in Silicon



G. Cibinetto, ANIMMA 2013
IEEE Conference Proceedings



Bulk damage:

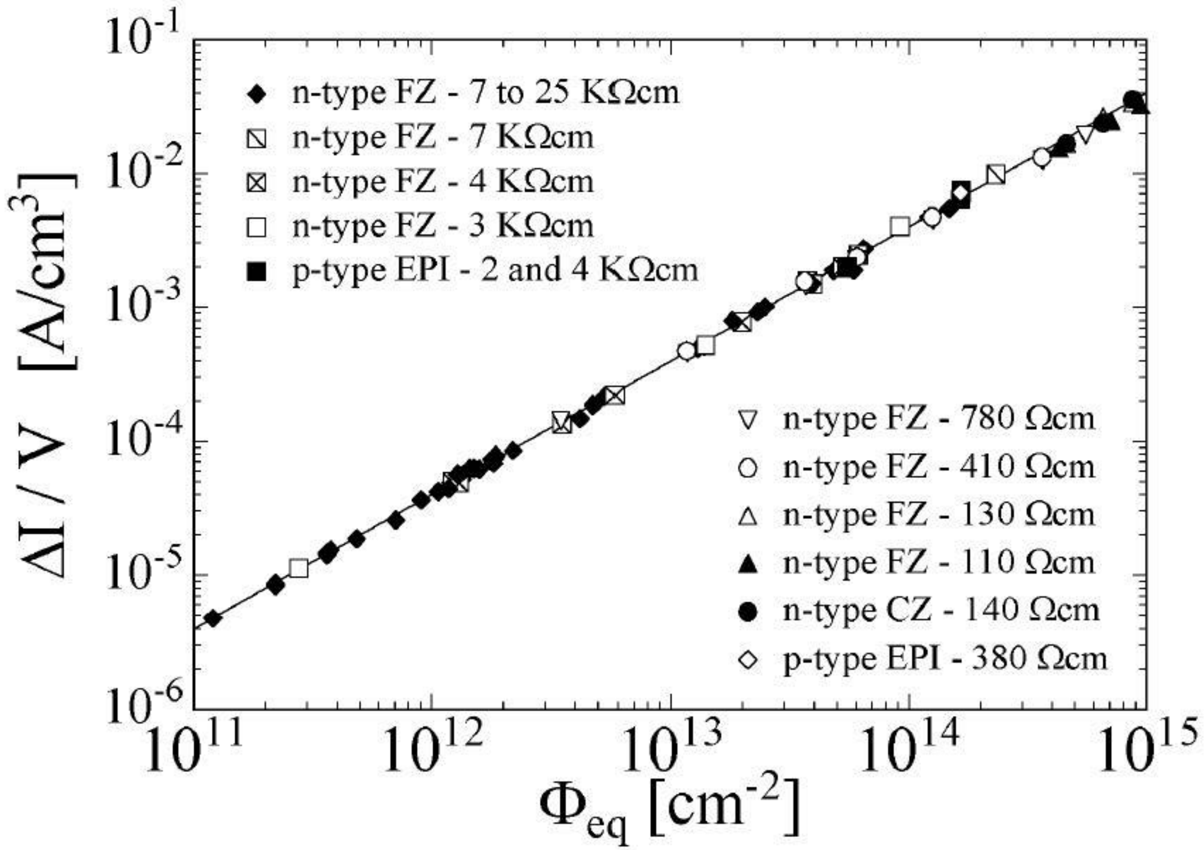
- Incoming particle transfers a certain amount of energy to atom
- If the energy transferred to the atom is larger than the binding energy of a silicon atom (~190 eV) then the atom can be displaced, moving it to an interstitial site and leaving a vacancy → single point or cluster defects
- Number of defects is proportional to the Non Ionizing Energy Loss (NIEL) – depends on incoming particle type and its energy

Surface damage:

- Low energy X-rays can produce surface damage affecting the SiO_2/Si_3N_4 layer
- Ionizing particles can produce charging up effects affecting the internal fields inside the device

(M. Moll, Radiation damage in silicon particle detectors,
Ph.D. thesis, Hamburg U. (1999) and references there in)

Radiation induced damage in Silicon: dark current increase



Measured after 80 min annealing at 60 °C

(M. Moll, Radiation damage in silicon particle detectors, Ph.D. thesis, Hamburg U. (1999) and references there in)

Dark current increase is proportional to the neutron fluence and depleted volume of silicon in a wide range of fluences ($10^{11} \div 10^{15}$):

$$\Delta I = \alpha\,\Phi_{eq}\,V$$

$$\alpha(80\,\mathrm{min}, 60°\mathrm{C}) = (3.99 \pm 0.03) \times 10^{-17}\mathrm{A/cm}$$

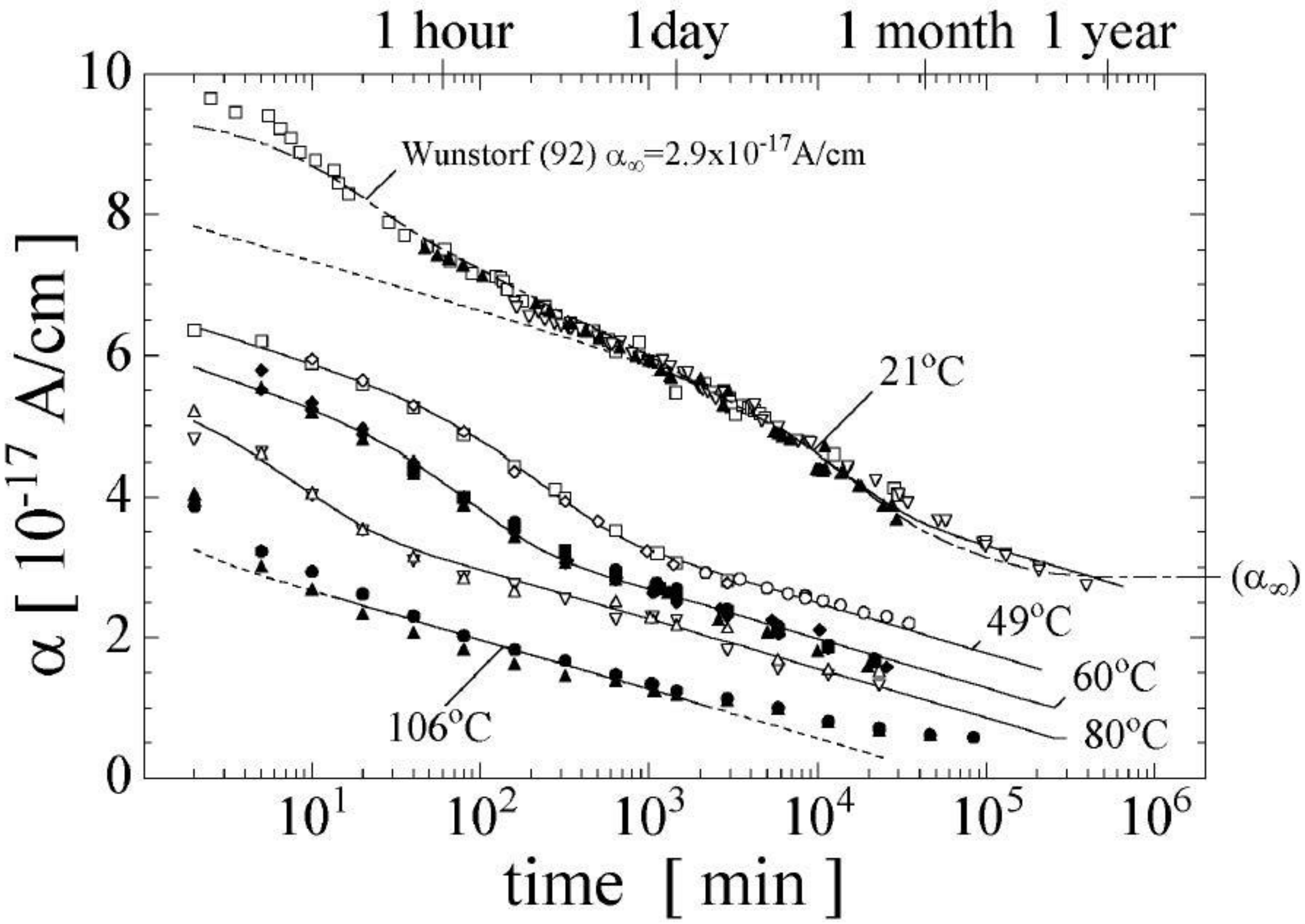
Dark current generation rate depends on temperature:

$$I_{gen} \propto T^2 e^{-\frac{E_a}{kT}}.$$

Activation energy E_a = 0.605 eV is close to the middle of the silicon bandgap

A. Chilingarov, Temperature dependence of the current generated in Si bulk, Journal of Instrumentation 8 (10) P10003.

Radiation induced damage in Silicon: dark current annealing



High temperature can significantly speed up process of dark current annealing in irradiated silicon devices

(M. Moll, Radiation damage in silicon particle detectors, Ph.D. thesis, Hamburg U. (1999) and references there in)

Radiation induced damage in Silicon: doping concentration change

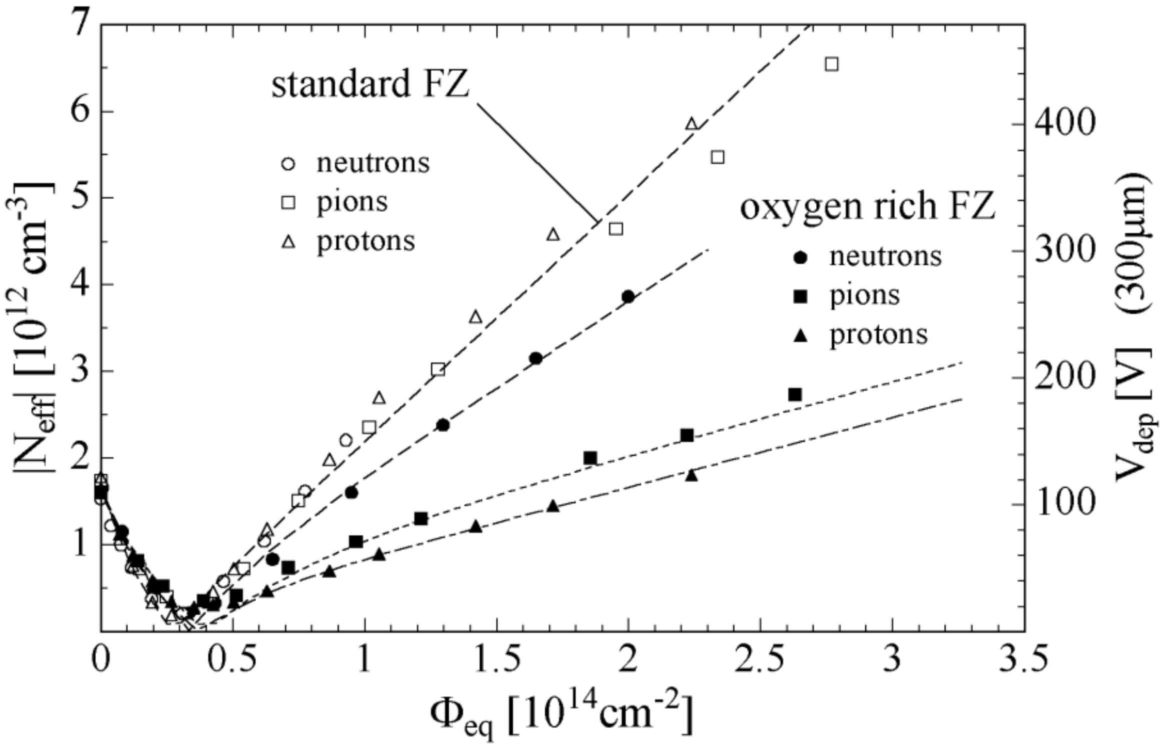


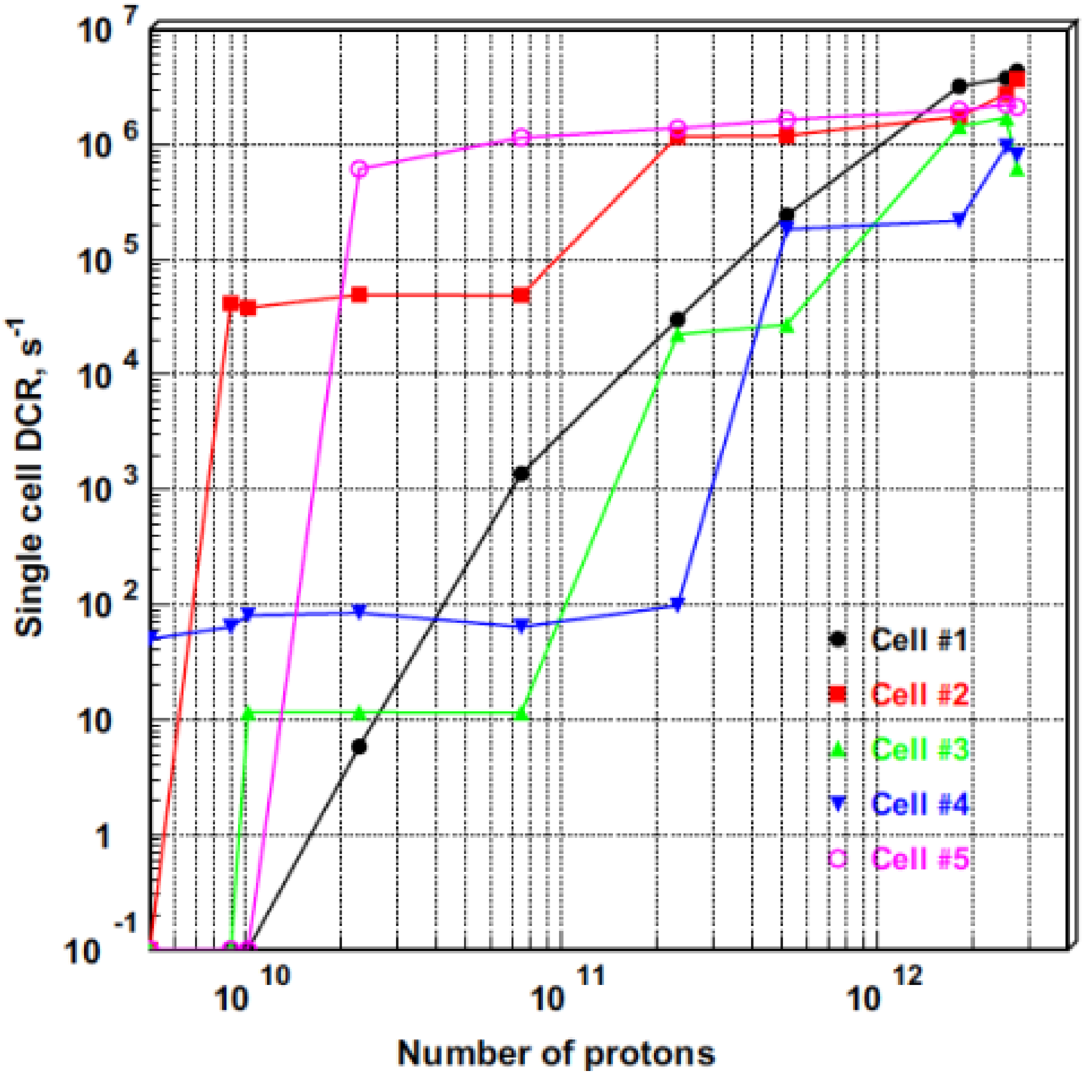
Figure 5.21: Dependence of N_{eff} on the accumulated 1 MeV neutron equivalent fluence Φ_{eq} for *standard* and *oxygen enriched* FZ silicon irradiated with reactor neutrons

Under hadron irradiation doping concentration in silicon detectors changes due to acceptor creation (donor removal) processes.

(M. Moll, Radiation damage in silicon particle detectors, Ph.D. thesis, Hamburg U. (1999) and references there in)

Radiation damage effects in SiPMs (hadrons)

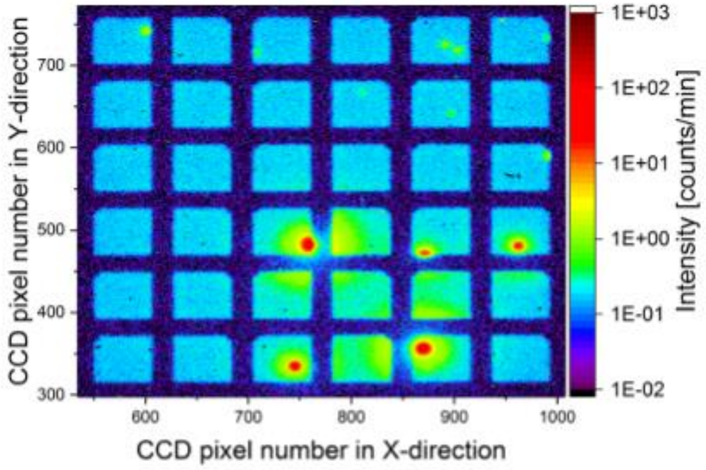
The dark count rate of individual cells of a Philips DSiPM as a function of total accumulated dose.



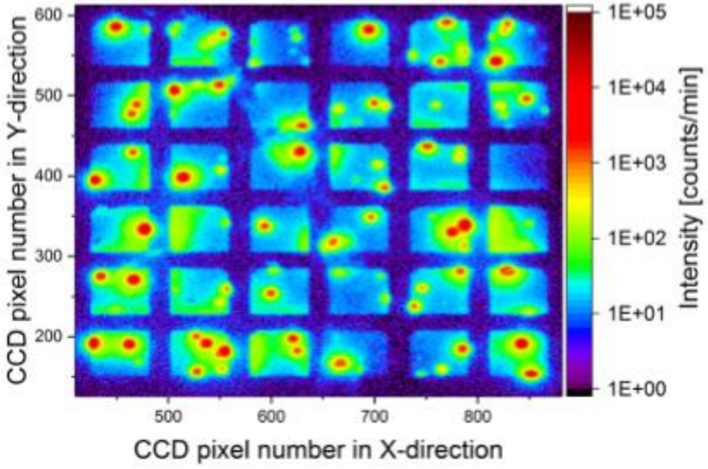
Barnyakov et. all have investigated the radiation damage of digital SiPMs exposed to 800 MeV protons. In a digital SiPM, the DCR of every individual cell can be monitored separately. The step-like increase of the DCR indicates that a single interaction of a proton with a Si atom may result in a drastic DCR increase and that the increase may differ by orders of magnitude for each proton interaction. Most likely this effect is linked to the formation of cluster-like defects in one pixel.
SiPMs help to understand radiation induced defects in silicon!

(M. Yu. Barnyakov et. all, NIM A824 (2016) 83)

Using IR light emission to study neutron irradiated SiPMs



(a) Reference sample, $t_{exp} = 2$ h



(b) Neutron irradiated sample, $t_{exp} = 2$ min

Every Geiger discharge emits a certain number of optical and IR photons produced in the high field region. For randomly distributed DCR on the SiPM volume, the light emission is expected to be homogeneous. In the case of local defects in silicon, hotspots can form, which are more likely to generate Geiger avalanches in the dark.

Light intensity images for a non-irradiated (a) and a neutron irradiated SiPM test structure (b), operated at ΔV = 4 V. The irradiated SiPM was exposed to $\Phi_{eq} = 10^{10}$ cm^{-2} and no annealing was applied. The effect of radiation in increasing the number of hot-spots is evident in these images.

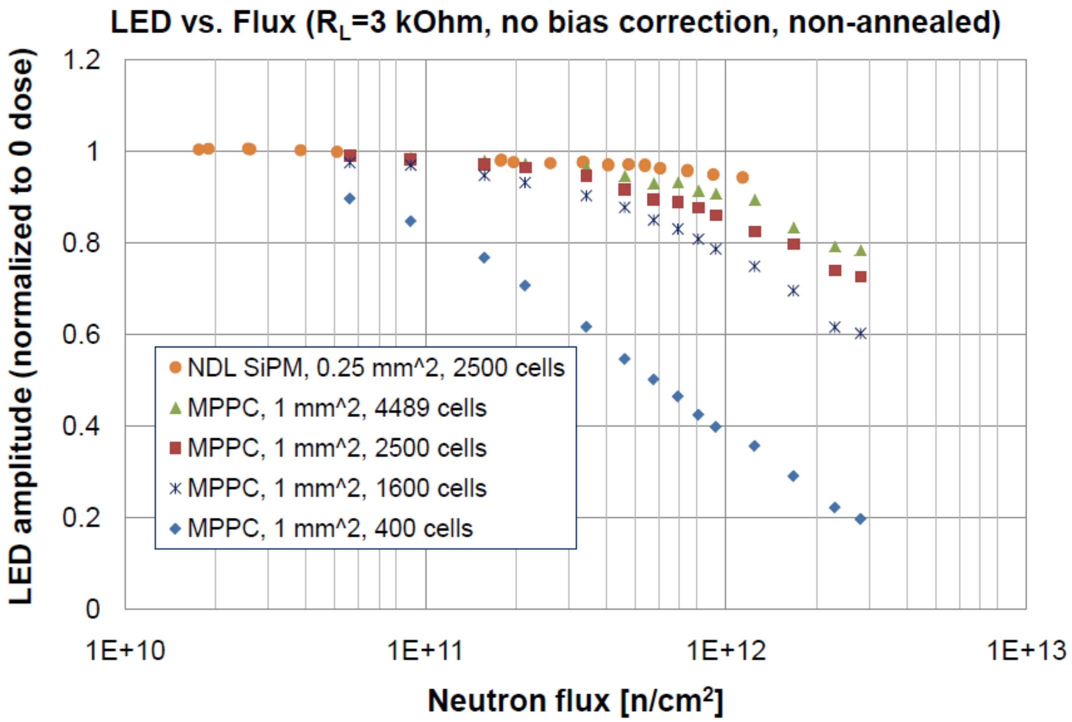
(*E. Engelmann, Dark count rate of silicon photo-multipliers, Ph.D. thesis, Universitt der Bundeswehr Mnchen (2018))*

SiPM radiation damage by neutrons: signal reduction

Radiation may cause:

- Fatal SiPMs damage (SiPMs are broken and can’t be used after certain absorbed dose)
- Dark current and dark count increase (silicon …)
- Change of the gain and PDE vs. voltage dependence (SiPM cell “blocking” effects due to high induced dark carriers generation-recombination rate)
- Breakdown voltage increase, PDE, Gain reduction due to donor/acceptor concentration change

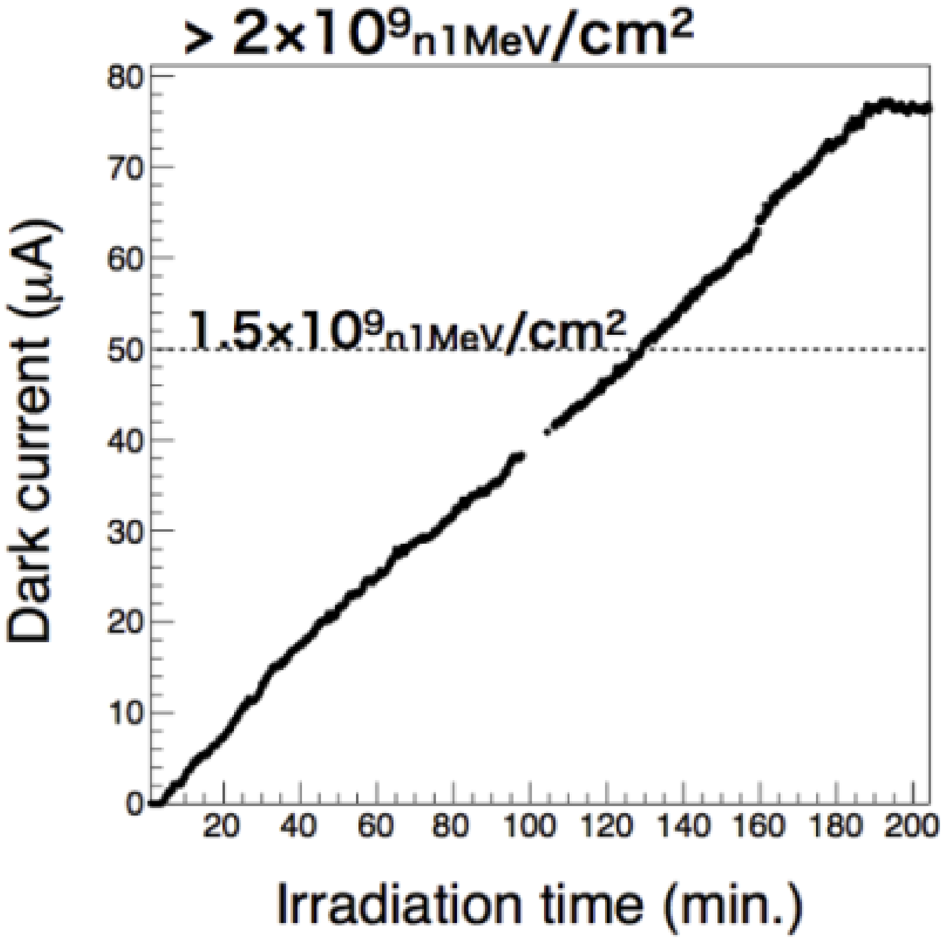
Relative response to LED pulse vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs

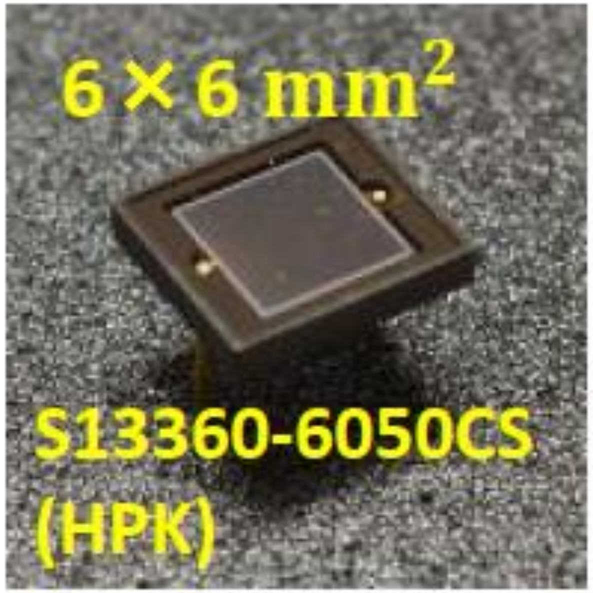


(Yu. Musienko, A. Heering, NDIP-2011, Lyon, France)

SiPMs with high cell density and fast recovery time can operate up to $3*10^{12}$ neutrons/cm^2 (gain change is< 25%).

Dark current increase with neutron fluence for Hamamatsu S13360-6050CS MPPC (dVB=3.0 V)

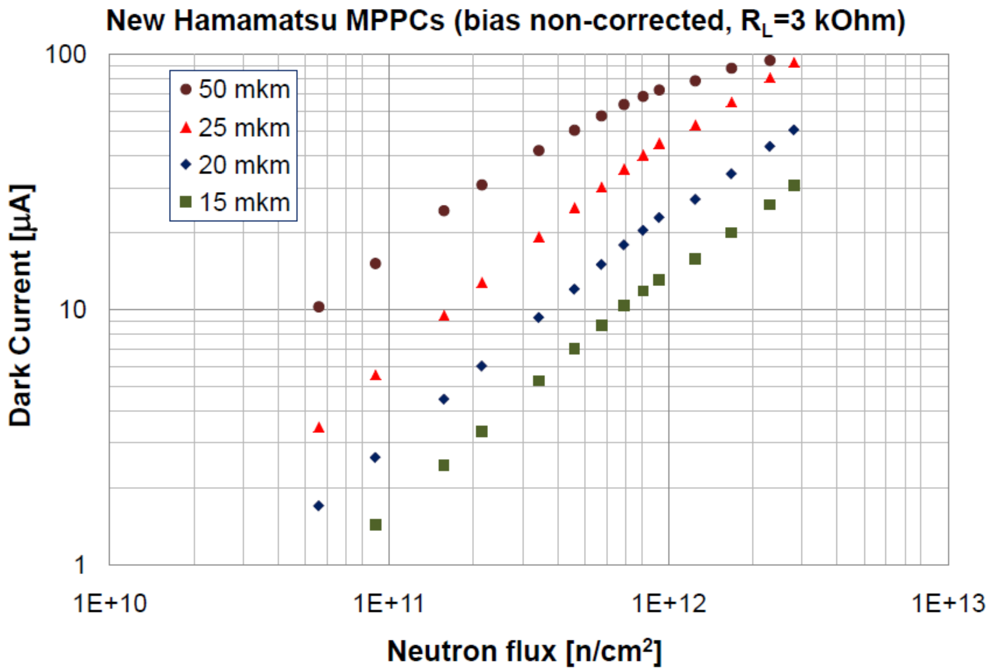




Dark current linearly increases with fluence

(Nobuhiro Shimizu, Upgrade of the Cesium Iodide calorimeter for the KOTO experiment., PD18, Tokyo)

Dark current vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs



(Yu. Musienko, A. Heering, NDIP-2011, Lyon, France)

High energy neutrons/protons produce silicon defects which cause an increase in dark count and leakage current in SiPMs:

$$I_d \sim \alpha * \Phi * V * M * k,$$

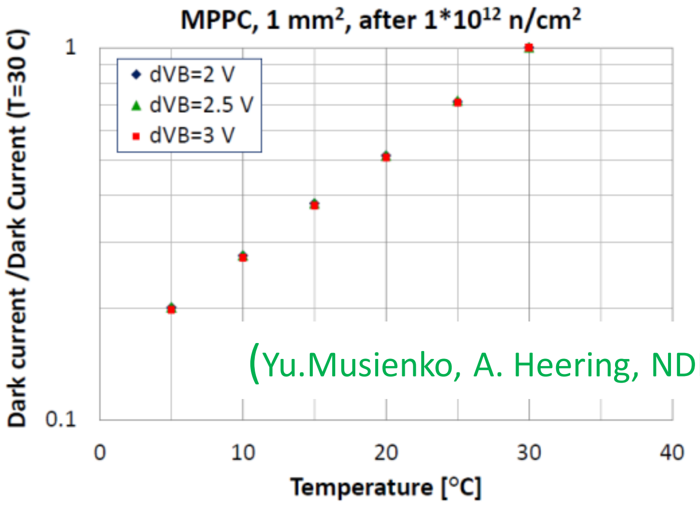
α – dark current damage constant [A/cm];
Φ – particle flux [1/cm^2];
V – “effective” silicon volume [cm^3]
M – SiPM gain
k – NIEL coefficient

α_{Si} ~4*10^{-17} A*cm after 80 min annealing at T=60 °C (measured at T=20 °C)
Damage produced by 40 neutrons (1 MeV) in 1 µm thick Si → 1 dark count/sec at 20 °C

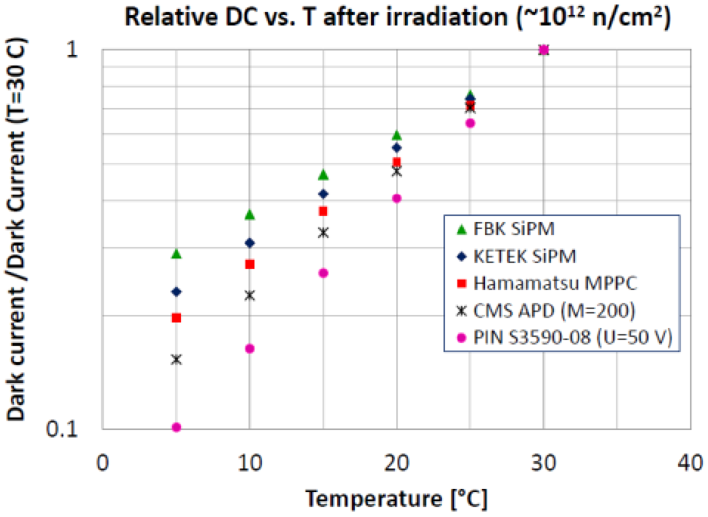
Thickness of the epi-layer for most of SiPMs is in the range of 1-2 µm, however d_{eff} ~ 4 ÷ 50 µm for different SiPMs. High electric field effects (such as phonon assisted tunneling and field enhanced generation (Pool-Frenkel effect) play significant role in the origin of SiPM’s dark noise.

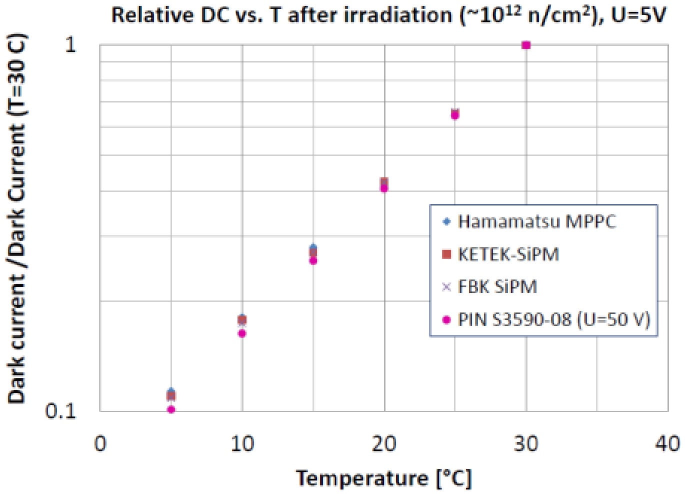
$V \sim S * G_f * d_{eff}$,
S - area
G_f - “effective” geometric factor
d_{eff} - “effective” thickness

Dependence of the SiPM dark current on the temperature (after irradiation)


MPPC, 1 mm², after 1*10¹² n/cm²

(Yu.Musienko, A. Heering, NDIP-2014)

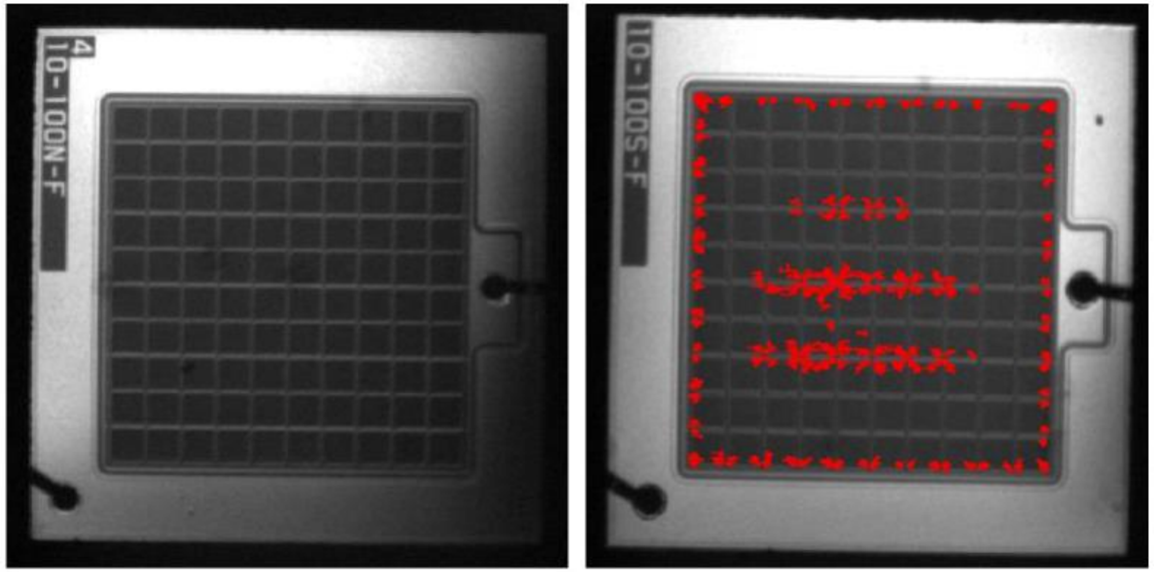

Relative DC vs. T after irradiation (~10¹² n/cm²)


Relative DC vs. T after irradiation (~10¹² n/cm²), U=5V

It was observed a rather weak dependence of the SiPM's dark current decrease with temperature on the dVB value. SiPM dark currents at low voltage (5V) behave similar with temperature to that of the PIN diode. However we observed significant difference of this dependence for differenet SiPM types when they operate over breakdown! General trend is that SiPMs with high VB value have faster dark current reduction with the temperature.

Radiation damage effects in SiPMs (X-rays and gammas)

“Early” SiPMs under Co-60 gamma ray irradiation



Infrared pictures of a new sample and the irradiated with 240 Gy dose. Infrared light is emitted due to heat produced by high leakage current (red points).

Matsubara and co-authors in have irradiated a prototype SiPM from Hamamatsu (Type No. T2K-11-100C) under bias up to 240 Gy of 60-Co γ-rays and measured the dark current, dark-count rate, gain, and cross talk. Whereas gain and cross talk did not significantly change with dose, large dark count pulses and localized spots with leakage current along the outer edge of the active region and the bias lines were observed for about half an hour after irradiation for doses above 200 Gy

T. Matsubara, H. Tanaka, K. Nitta, M. Kuze, Radiation damage of MPPC by gamma-ray irradiation with Co-60, PoS PD07 (2007) 032.

Effects of X-rays irradiation on recent SiPMs

(C. Xu, R. Klanner, E. Garutti, W.-L. Hellweg, NIM A762 (2014) 149)

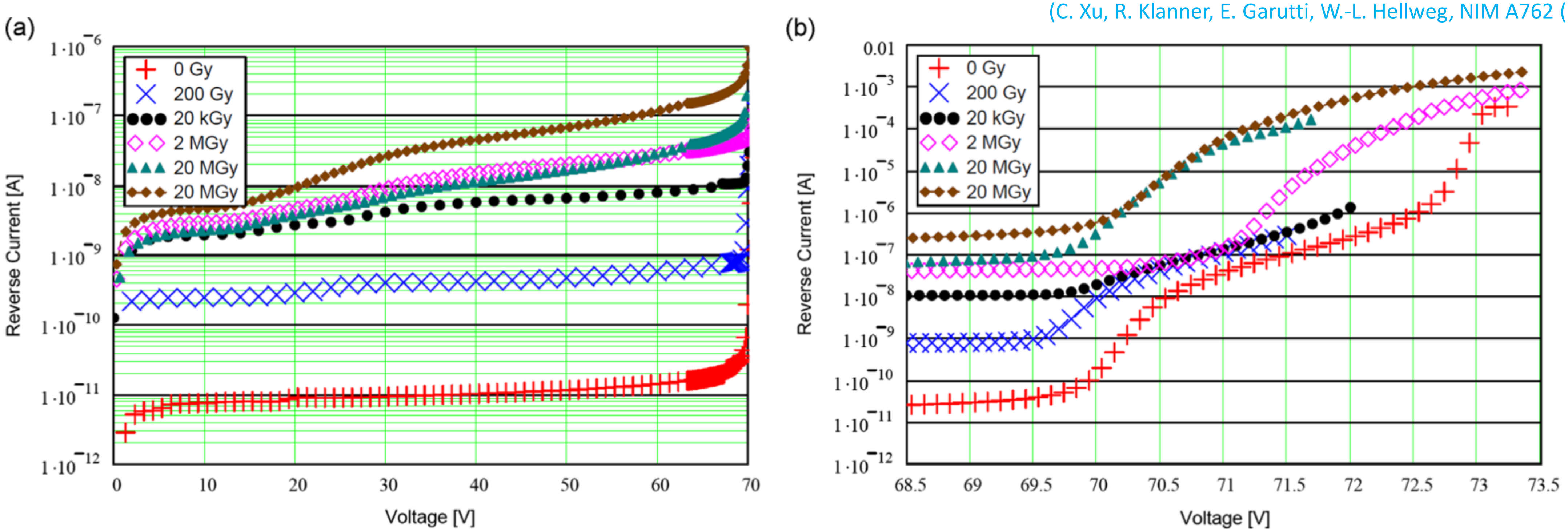


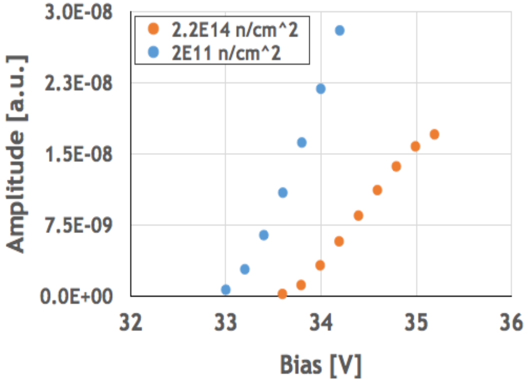
Fig. 6. Reverse currents of SiPMs as a function of voltage before, and after irradiation with X-rays to 200 Gy 20 kGy, 2 MGy, and 20 MGy (a) below the breakdown voltage, and (b) in the region of and above the breakdown voltage.

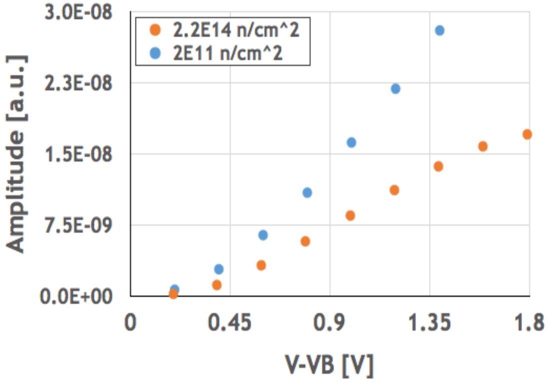
The effects of X-ray irradiation to doses of 0, 200 Gy, 20 kGy, 2 MGy, and 20 MGy investigated on the Hamamatsu silicon-photomultiplier (SiPM) S10362-11-050C. The SiPMs were irradiated without applied bias voltage. Up to a dose of 20 kGy the performance of the SiPMs is hardly affected by X-ray radiation damage. For doses of 2 and 20 MGy the SiPMs operate without any change in gain, but with a significant increase in dark count rate.

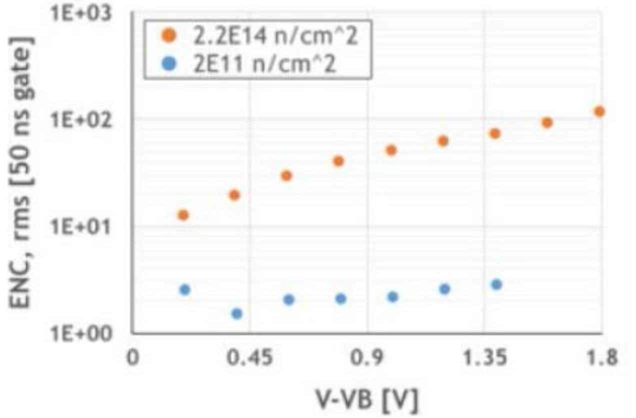
Results on heavily irradiated SiPMs

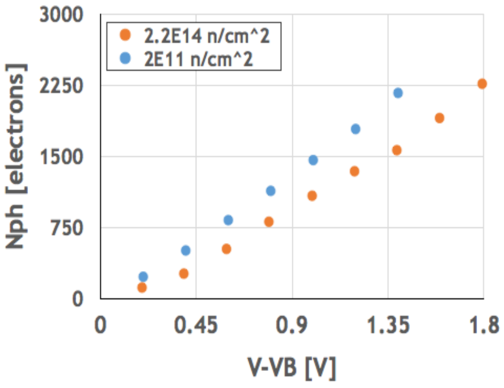
SiPM irradiated up to $2.2*10^{14}$ n /cm^2

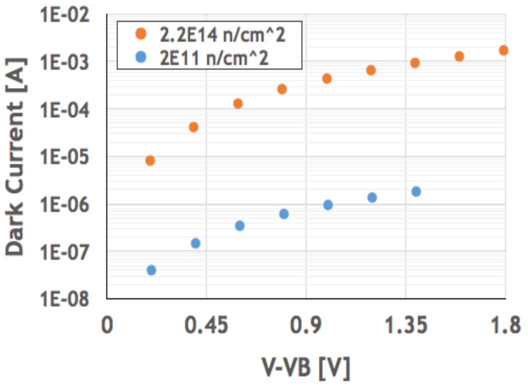
Can SiPM survive very high neutron fluences expected at high luminosity LHC? FBK SiPM (1 mm^2, 12 μm cell pitch was irradiated with 62 MeV protons up to $2.2*10^{14}$ n /cm^2 (1 MeV equivalent).











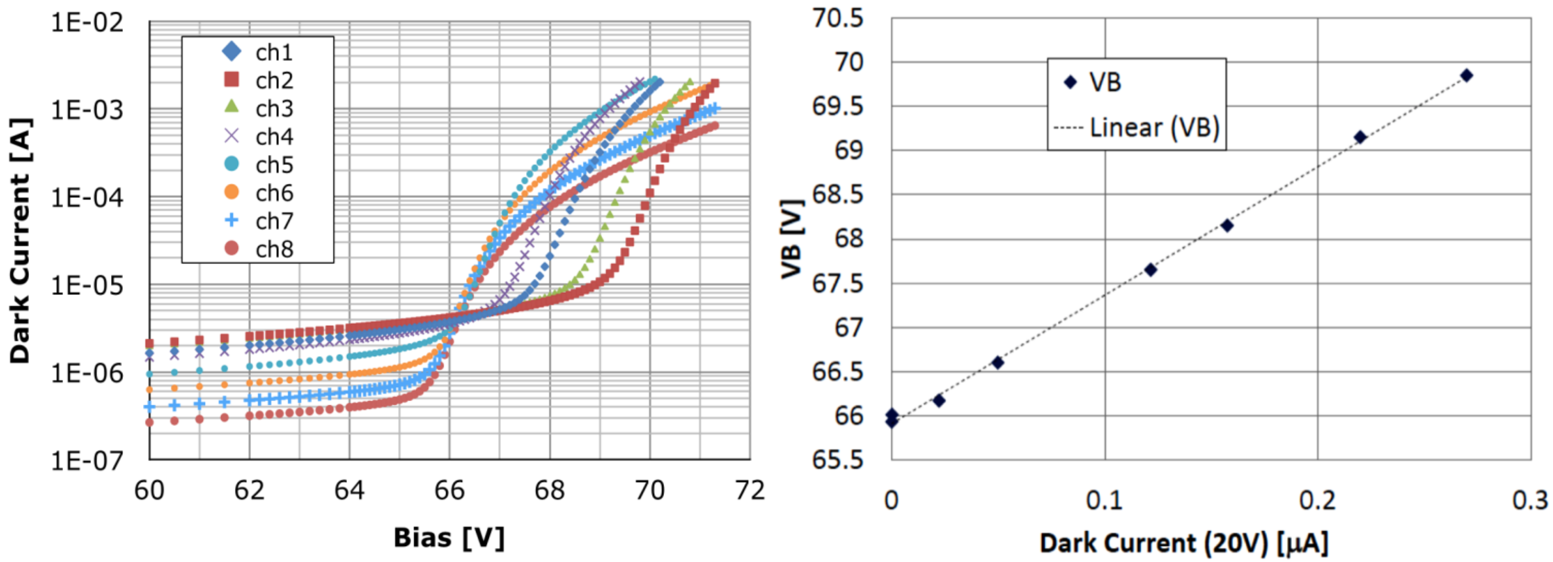
(A.Heering et al., NIM A824 (2016) 111)

The authors found:

- Increase of VB: ~0.5 V
- Drop of the amplitude (~2 times)
- Reduction of PDE (from 10% to 7.5 %)
- Increase of the current (up to ~1mA at dVB=1.5 V
- ENC(50 ns gate, dVB=1.5V)~80 e, rms

The main result is that SiPM survived this dose of irradiation and can be used as photon detector!

2.8 mm dia., 10 um cell pitch Hamamastu MPPCs irradiated up to 2.2E14 n/cm^2



(a) Dark current vs. bias voltage. (b) VB shift vs. dark current at gain 1

Ch.2 – irradiated with 24 GeV protons (~2.2E14 n/cm^2)
Ch.8 – irradiated with 24 GeV protons (~7.5E12 n/cm^2)

Hamamatsu S12572-010C 8-ch. MPPC array developed for the CMS HCAL Phase I Upgrade project was exposed to non-uniform irradiation with 24 GeV protons (5 mm dia. Spot size).

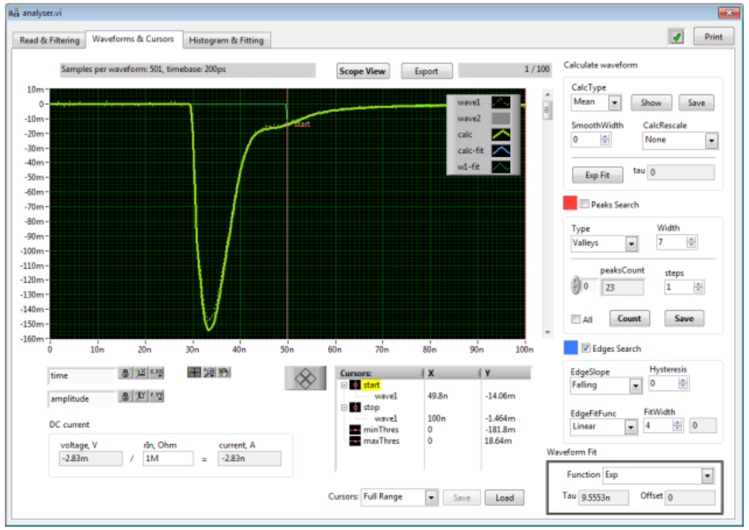
Change of the doping concentration: VB shift with fluence reaches 4 V at 2.2E14 n/cm^2. SiPMs with thicker depletion region has larger VB shift in comparison to the “thin” SiPMs.

(A.Heering et al., NIM A824 (2016) 111)

Laser response of the CMS HE SiPM after irradiation with 5E13 n/cm^2

R_{load} = 16.7 Ohm, average of 100 waveforms

New



Samples per waveform: 501, timebase: 200ps

1 / 100

CalcType: Mean

SmoothWidth: 0

CalcRescale: None

tau: 0

☐ Peaks Search

Type: Valleys

Width: 7

peaksCount: 0 23

steps: 1

☐ All

☑ Edges Search

EdgeSlope: Falling

Hysteresis: 0

EdgeFitFunc: Linear

FitWidth: 4 0

Cursors:	X	Y
start		
wave1	49.8n	-14.06m
stop		
wave1	100n	-1.464m
minThres	0	-181.8m
maxThres	0	18.64m

Cursors: Full Range

DC current

voltage, V: -2.83m / rIn, Ohm: 1M = current, A: -2.83n

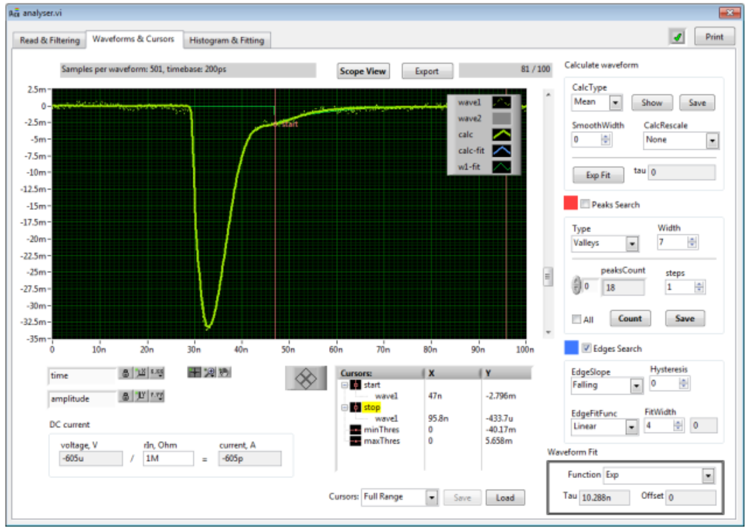
Waveform Fit

Function: Exp

Tau: 9.5553n

Offset: 0

After 5E13 n/cm^2



Samples per waveform: 501, timebase: 200ps

81 / 100

CalcType: Mean

SmoothWidth: 0

CalcRescale: None

tau: 0

☐ Peaks Search

Type: Valleys

Width: 7

peaksCount: 0 18

steps: 1

☐ All

☑ Edges Search

EdgeSlope: Falling

Hysteresis: 0

EdgeFitFunc: Linear

FitWidth: 4 0

Cursors:	X	Y
start		
wave1	47n	-2.796m
stop		
wave1	95.8n	-433.7u
minThres	0	-40.17m
maxThres	0	5.658m

Cursors: Full Range

DC current

voltage, V: -605u / rIn, Ohm: 1M = current, A: -605p

Waveform Fit

Function: Exp

Tau: 10.288n

Offset: 0

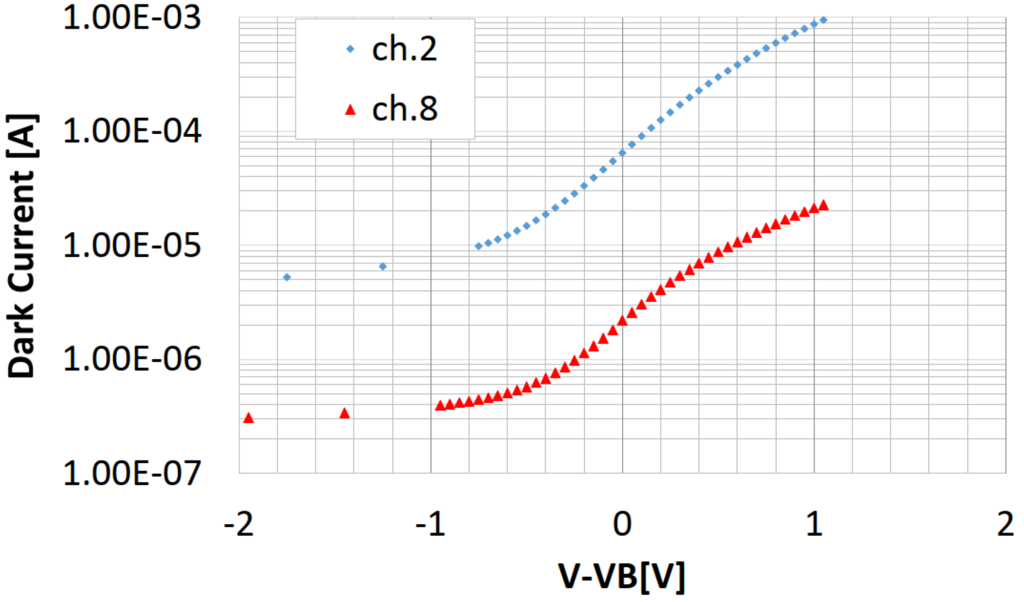
- HE 2.8 mm dia., 15 cell pitch SiPMs
- Laser 405 nm, 25 psec FWHM
- Quartz fiber 2 m long
- Picoscope 6404D, BW=500 MHz, 5 Gs/sec
- Loads: 50 Ohm, 25 Ohm, 16.7 Ohm

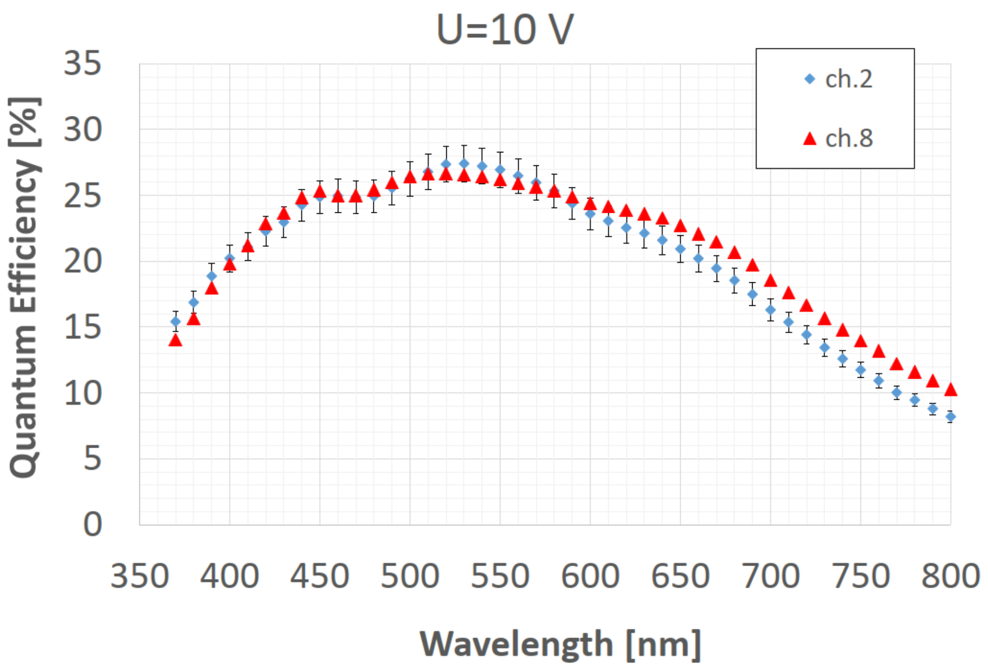
(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)

S10943-4732, 15 micron pixels, no trenches similar to S12572-015C SiPM

The SiPM response remains unchanged after 5E13 n/cm^2 (irradiated at Ljubljana reactor)

S12572-010C (quartz window) MPPC: dark currents and spectral response after irradiation





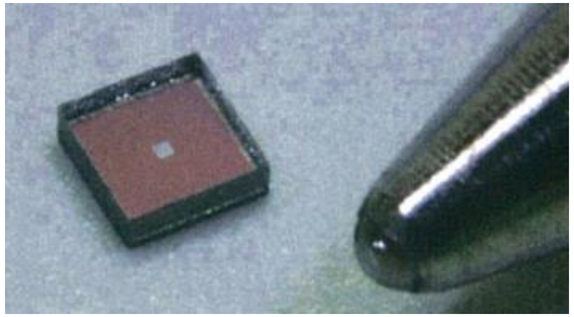
S12572-010C MPPC: dark currents vs. V-VB

S12572-010C MPPC: QE(10 V) s vs. wavelength

Ch.2 – irradiated with 24 GeV protons (~2.2E14 n/cm²)
Ch.8 – irradiated with 24 GeV protons (~7.5E12 n/cm²)

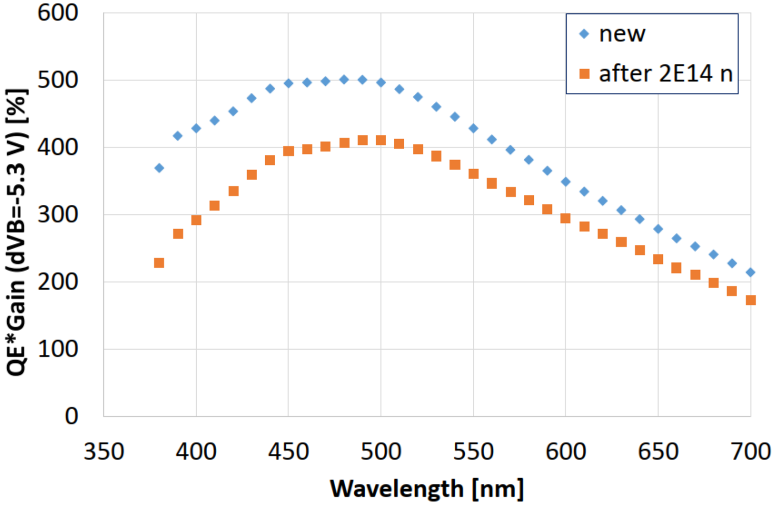
(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)

S13190-1015 TSV MPPC: spectral response after 2E14 n/cm^2

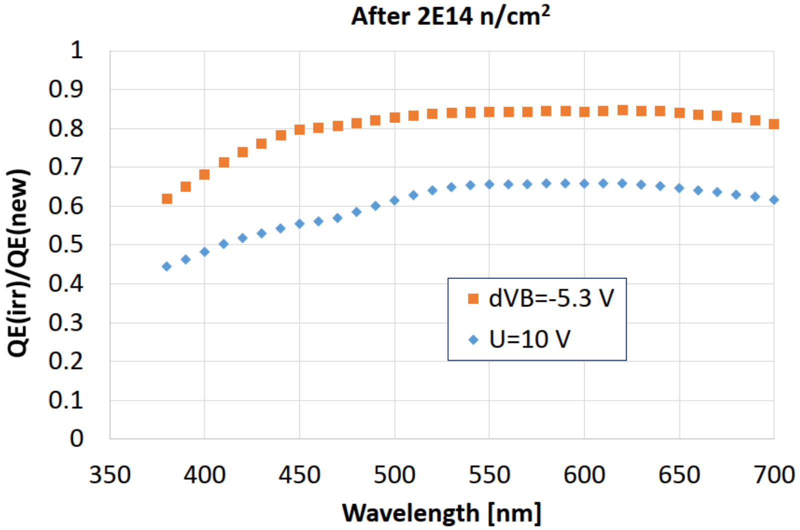


TSV design, SiPM is protected by ~300 um thick glass window

(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)



*QE*Gain vs. wavelength (new and irradiated)*



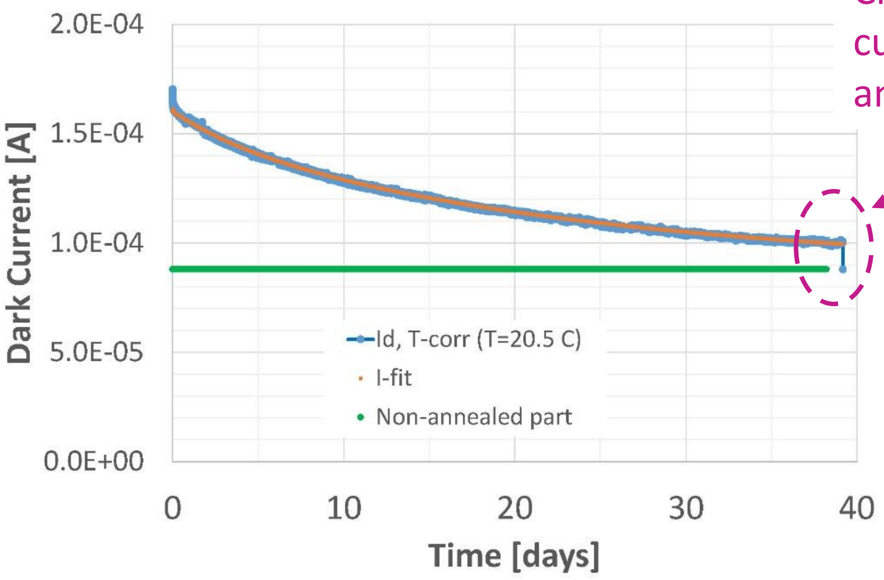
QE(irr.)/QE(new) vs. wavelength (new and irradiated)

20% ÷ 30 % loss of the QE after irradiation is probably due to darkening of the entrance glass window after irradiation

Annealing of the radiation damage

SiPM dark current annealing after irradiation

S10943-4732, 15 micron pixels, no trenches similar to S12572-015C SiPM



Change of the dark current after 16 hours annealing at 70 °C

HE-P-10935 array (2.8 mm dia., 15 μm cell pitch) was passively irradiated at CHARM up to 1.4E12 n/cm^2 (1 MeV equivalent, CHARM calibration!!). Irradiation took ~5 days. Annealing study (at T=20.5 °C) started 1 day after end of irradiation.

- SiPM bias - 66.8 V (dVB=0.98 V)
- T=20.5 °C
- Duration of measurement – 39.2 days

After that SiPM was annealed at T=70 °C during 16 hours. I-V curves were measured before and after annealing.

After 39.2 days of annealing at T=20.5 °C the SiPM dark current reduced from 160 mA to 100.5 mA. Additional 16 hours annealing at 70 °C reduced the SiPM dark current from 100.5 mA to 88 mA (~13 %).

6 days after irradiation the dark current vs. time annealing can be described by 3 time components:

τ = 4 days	τ = 23.5 days	Non-anneal. part	Total (I(0)=160 uA)
0.069	0.382	0.549	1.000

(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)

Dark current annealing at elevated temperature

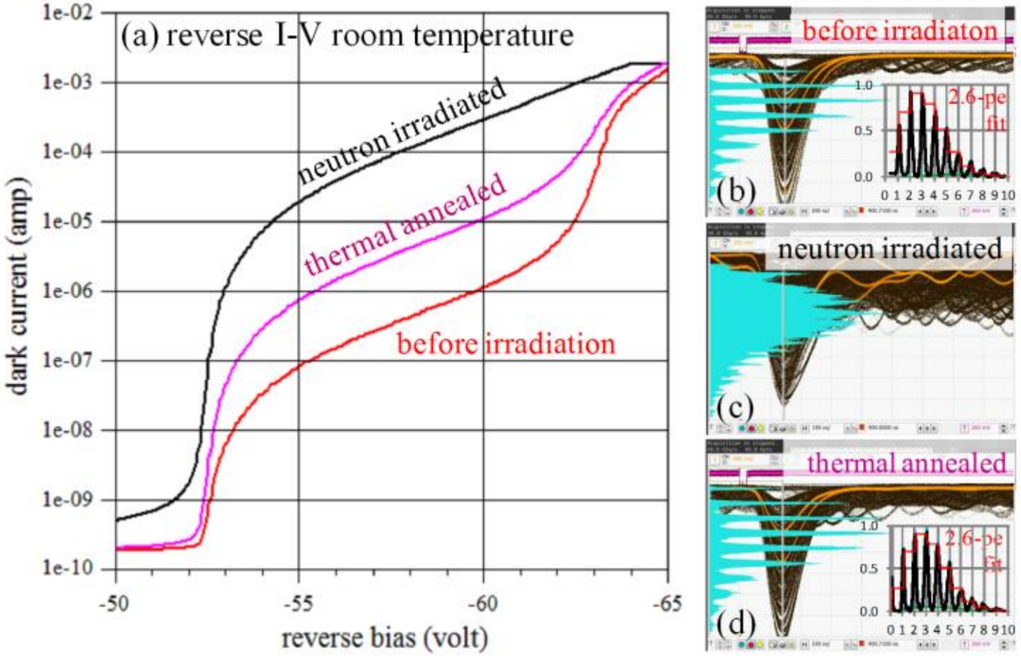


Figure 3. (a) Representative reverse I–V characteristic of SiPM at room temperature, and its cumulative collection of the photoelectron histogram sampled at the peak of the time-gated single photoelectron charge signal pulses at ~ 3 volt over-voltage (b) before irradiation, (c) after neutron irradiation to a dosage of 10^9 n/cm^2, and (d) followed by 250°C thermal annealing, respectively. Single photoelectron histograms are in cyan, insets in (b) & (d) are the corresponding Poisson fitted photon number resolving histograms to ~ 2.6 photoelectrons (red).

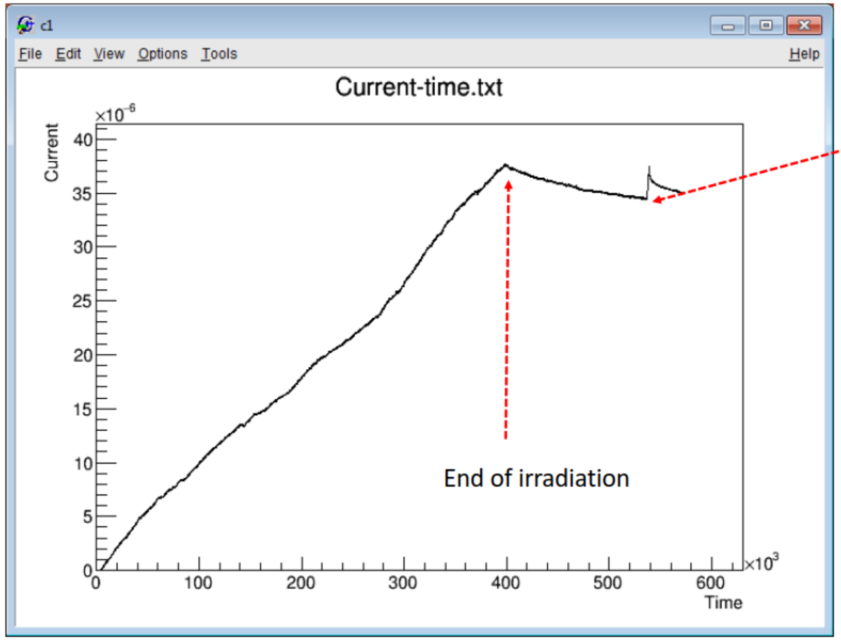
T. Tsang et. all performed annealing at +250 °C, using forward bias with the SiPM current reaching 10 mA. A remarkable effect of this high temperature annealing was demonstrated: >20 fold reduction of the dark current. Single photo-electron resolution was recovered after this procedure for devices irradiated up to $\Phi_eq = 10^{12}$ cm^{-2} with cooling them to about -50 °C.

T. Tsang, T. Rao, S. Stoll, C. Woody, Neutron radiation damage and recovery studies of sipms, Journal of Instrumentation 11 (12) (2016) P12002.

Studies of radiation damage to SiPMs at low temperatures

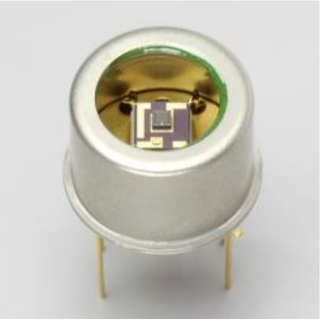
Dark Current vs. Irradiation Time&Neutron Fluence

I_{dark} vs. Time, T=-30 °C, U=67.0 V (dVB=4.76 V)

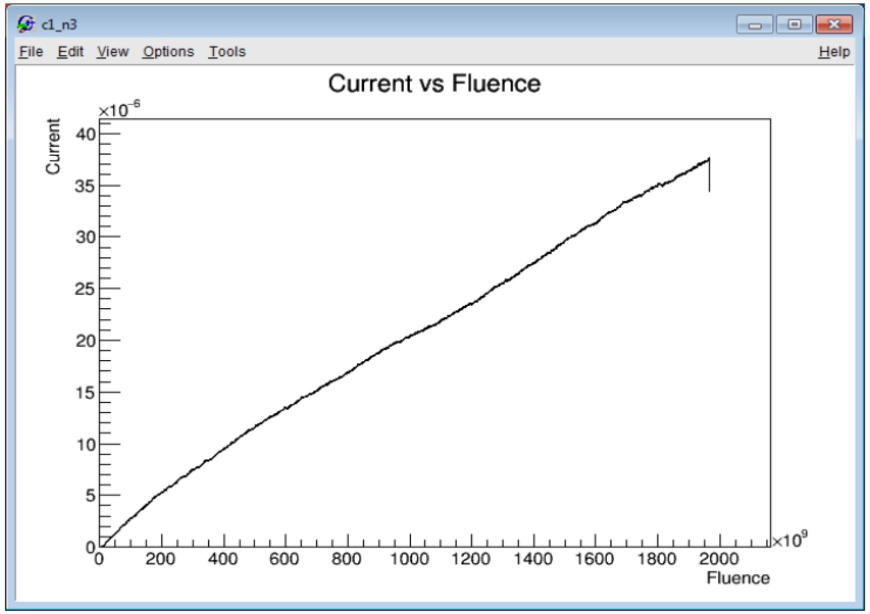


End of irradiation

Bias was set OF and set to 67 V again



I_{dark} vs. Fluence, T=-30 °C, U=67.0 V (dVB=4.76 V)



HPK 1 mm^2, 15 um cell pitch SiPM (HE/HB type) was irradiated under bias (U=67 V, dVB=4.76 V) in cold **(T=-30 °C, Peltier thermoelectric cooler)** at CERN CHARM irradiated facility up to **2.E12 n/cm^2** (1 MeV neutron equivalent) total fluence. The SiPM dark current was monitored during irradiation.

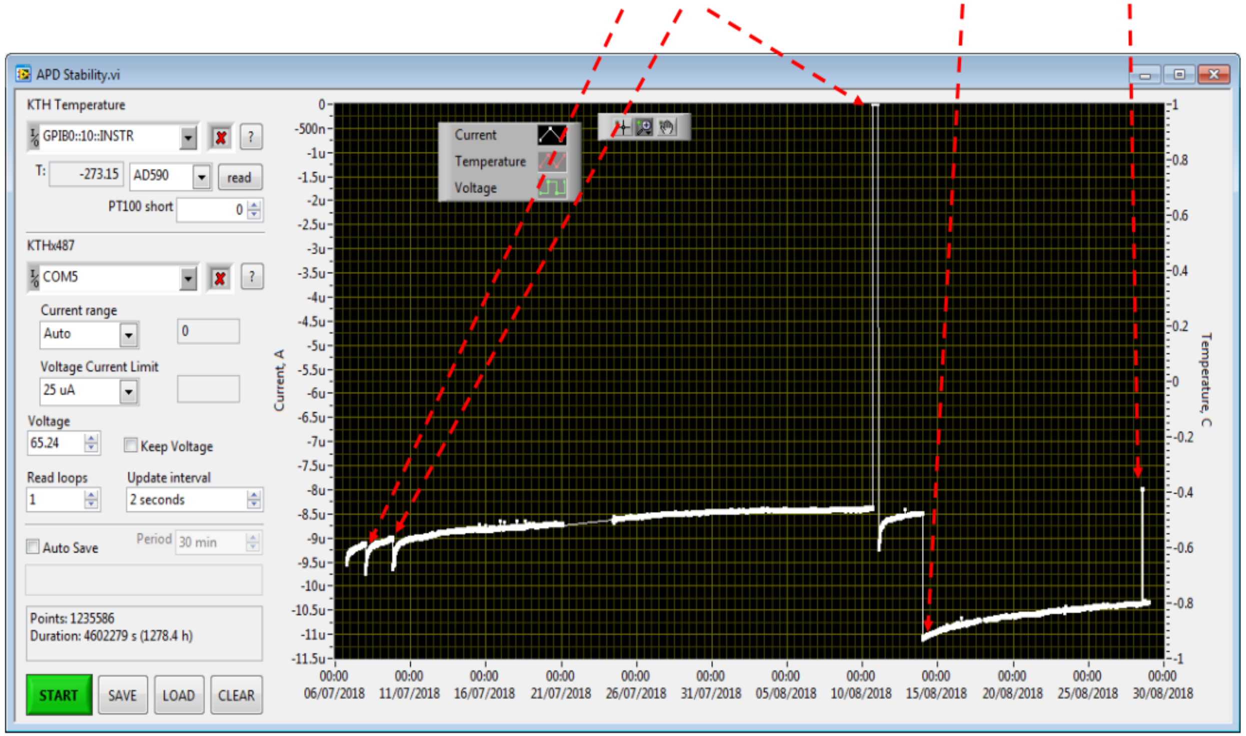
Dark Current annealing at T=-30 °C and -10 °C

Dark Current annealing at U=65.24 V (T=-30 °C and T=-10 °C)

Bias OFF for short time

T=-10 °C

T=-30 °C



APD Stability.vi

KTH Temperature

GPIB0::10::INSTR

T: -273.15 AD590

PT100 short 0

KTHx487

COM5

Current range: Auto 0

Voltage Current Limit: 25 uA

Voltage: 65.24

☐ Keep Voltage

Read loops: 1

Update interval: 2 seconds

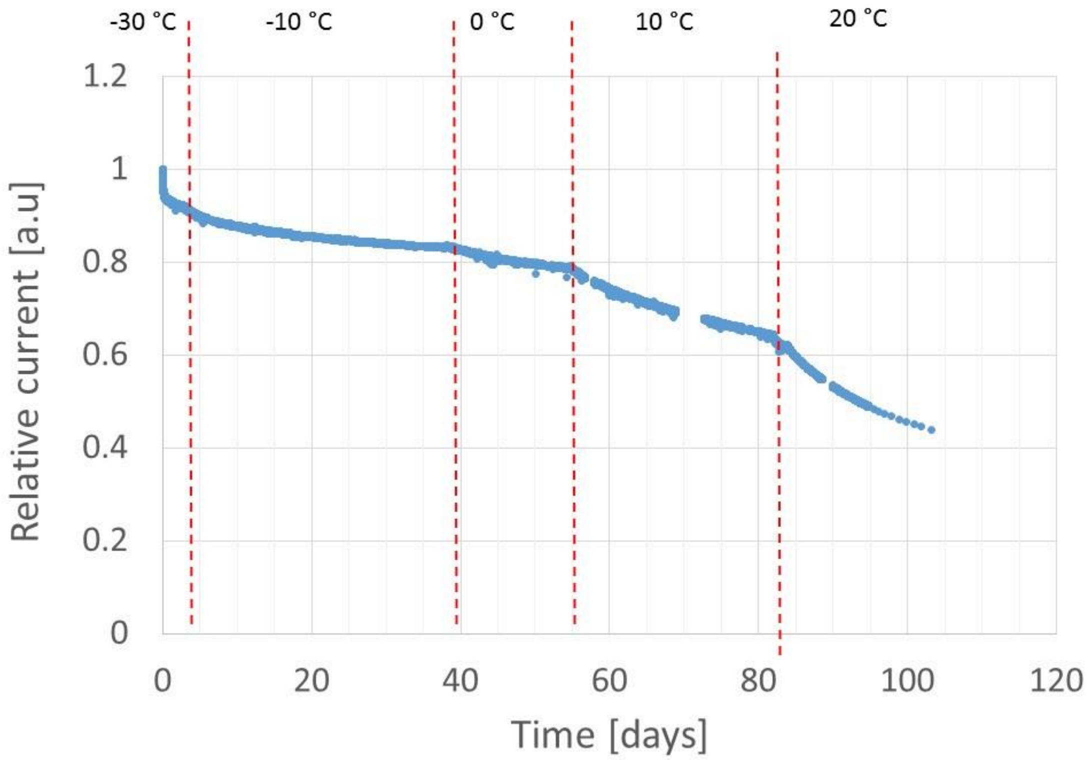
☐ Auto Save

Period: 30 min

Points: 1235586
Duration: 4602279 s (1278.4 h)

We studied annealing of the dark current at T=-30 °C during >38 days. Less than 25% of the dark current annealed at this temperature. We increased the temperature up to -10 °C and found another 7% reduction of the dark current after 2 weeks of annealing at this temperature.

Dark Current annealing at T=-30 °C and 20 °C



We calculated relative dark current change with time: ~60 % of dark anneals if temperature changes from -30 °C to +20 °C.

Approaches to develop radiation harder SiPMs

- Dark noise reduction

Optimization of the electric field profile (especially for smaller cell size) to get uniform electric field across the cell (no regions with higher or lower electric field values). Reduction of the maximum electric field value (trap-assisted tunneling, Pool-Frenkel effect), while keeping thickness of the depletion layer thin to reduce generation volume

- Cell occupancy reduction

Cell occupancy can be reduced developing SiPMs with smaller cell size and smaller recovery time

- Power consumption reduction

Reduction of SiPM gain (smaller cell size, smaller cell capacitance) and dark current generation

- Breakdown voltage increase minimization

It can be reduced by reducing the thickness of the depletion region. Compromise with the electric field reduction is required.

- Reduction of the damage in SiPM entrance window

Optimization of the $SiO_2/S_3N_4/Si$ interface to reduce light losses in an entrance window and to avoid trapping in front SiPM layer

- Optimization of SiPM package

Package of SiPM has to allow:

- ✓ SiPM operation in wide range of temperatures (-50 °C ÷ 200 °C);
- ✓ Easy heat removal (to reduce SiPM self-heating)
- ✓ Integrated temperature sensor (can be integrated on the same chip as SiPM)
- ✓ Integrated heater?

Summary

This review is an attempt to summarize the current knowledge of radiation damage of SiPMs. The main issues with heavily irradiated SiPMs are the increase of dark count rate and Gain&PDE reduction due to high cell occupancy and self-heating effects caused by high currents of irradiated SiPMs. Recently developed SiPMs from several producers demonstrated they ability to operate up to 1E14 n/cm^2. R&D on radiation hard SiPMs continue. Approaches to develop radiation harder SiPMs are defined.

I would like to thank all the people whose slides (shown at PhotoDet-2012, PhotoDet-2015, PhotoDet-2018, NDIP-2014, VCI-2016, Elba-2015, 2nd SiPM Advanced workshop-Geneva-2014, CPAD-2016, RICH-2016, IEEE-NS/MIC-2016, INSTR-2017, SENSE-2018, ICASiPM-2018 conferences etc.) are used in this presentation.