SiPM radiation damage

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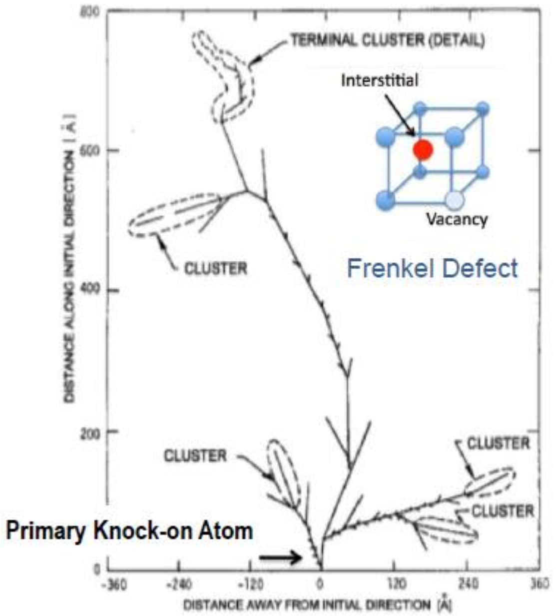
Outline

- Radiation induced damage in silicon
- Radiation damage of SiPMs by ionizing radiation
- Radiation damage effects in SiPMs (hadrons)
- Results on heavily irradiated SiPMs
- Self-heating effects in irradiated SiPMs
- Annealing of radiation damage
- Approaches to develop radiation harder SiPMs.
- Conclusion

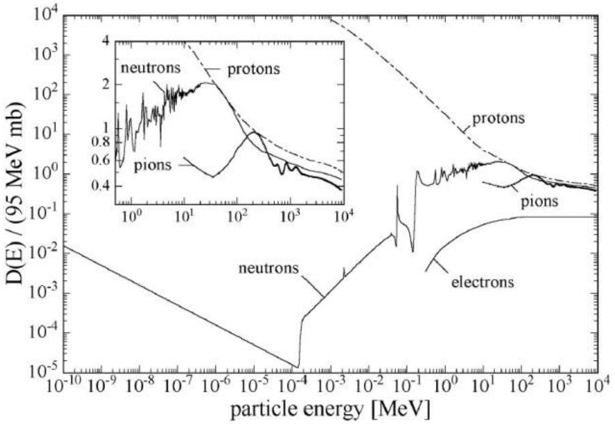
Review on SiPM radiation damage:
E.Garutti, Yu.Musienko, Radiation damage of SiPMs, NIM A926 (2019) 69

Radiation induced damage in silicon

Radiation induced damage in Silicon



G. Cibinetto, ANIMMA 2013
IEEE Conference Proceedings



Bulk damage:

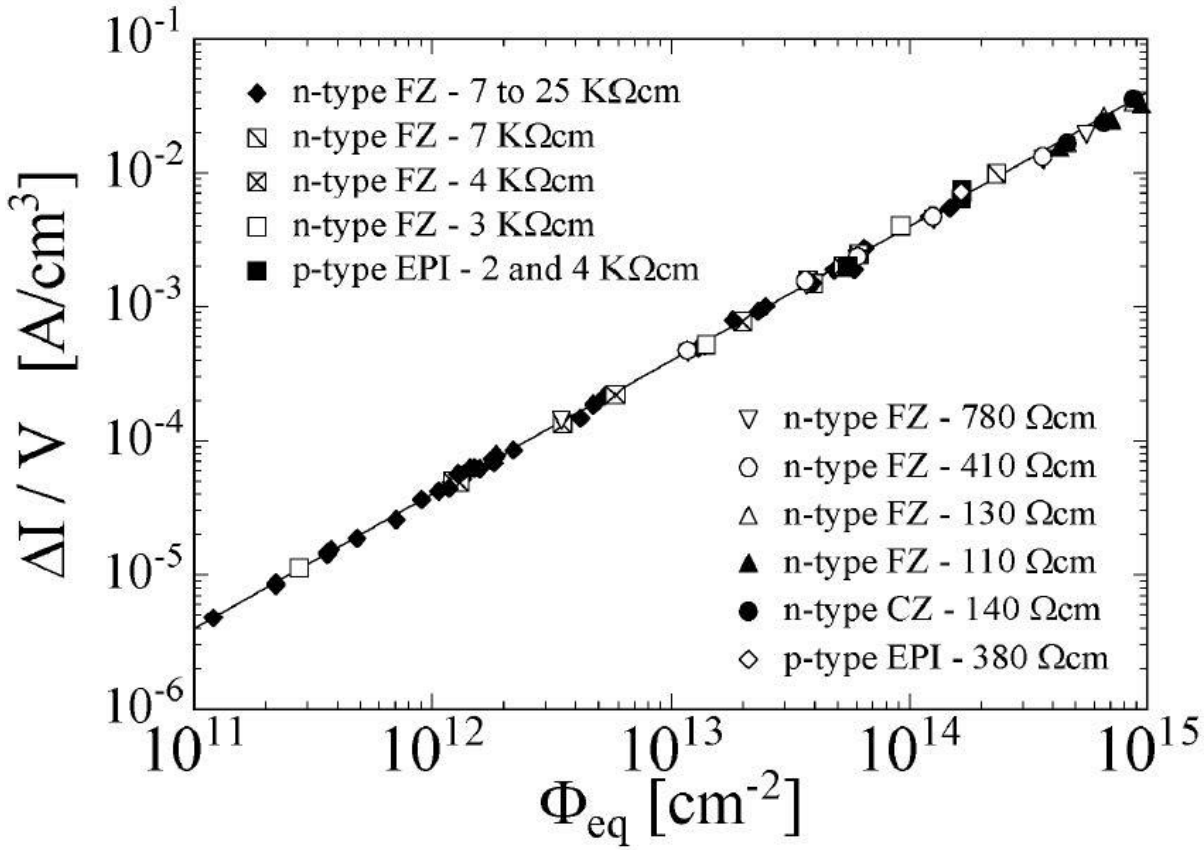
- Incoming particle transfers a certain amount of energy to atom
- If the energy transferred to the atom is large than the binding energy of a silicon atom (~190 eV) then the atom can be displaced, moving it to an interstitial site and leaving a vacancy → single point or cluster defects
- Number of defects 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: doping concentration change

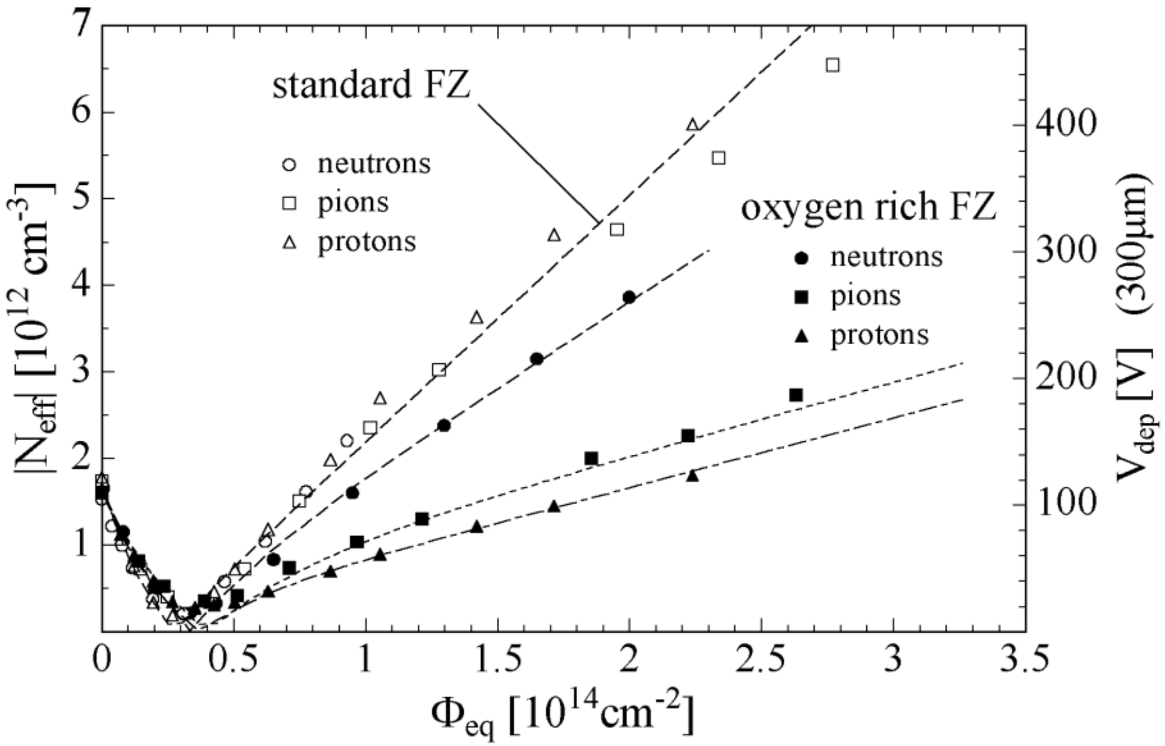
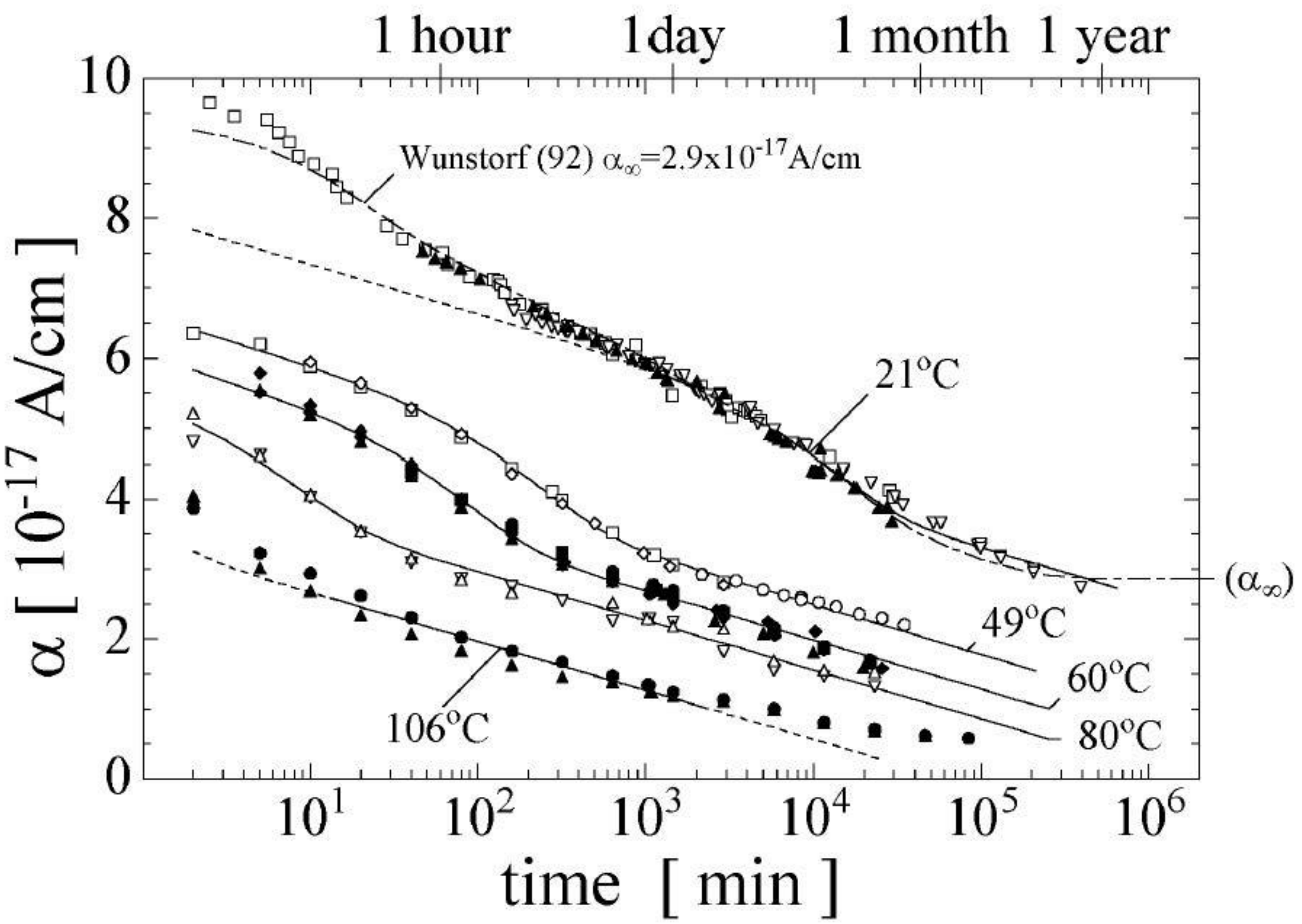


Figure 5.21: Dependence of N_{eff} on the accumulated 1 MeV neutron equivalent fluence Φ_{eq} for *standard* and *oxygen enriched* FZ silicon irradiated with reactor neutrons

Under hadron irradiation doping concentration in silicon detectors changes due to acceptor/donor concentration change

(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 annealing

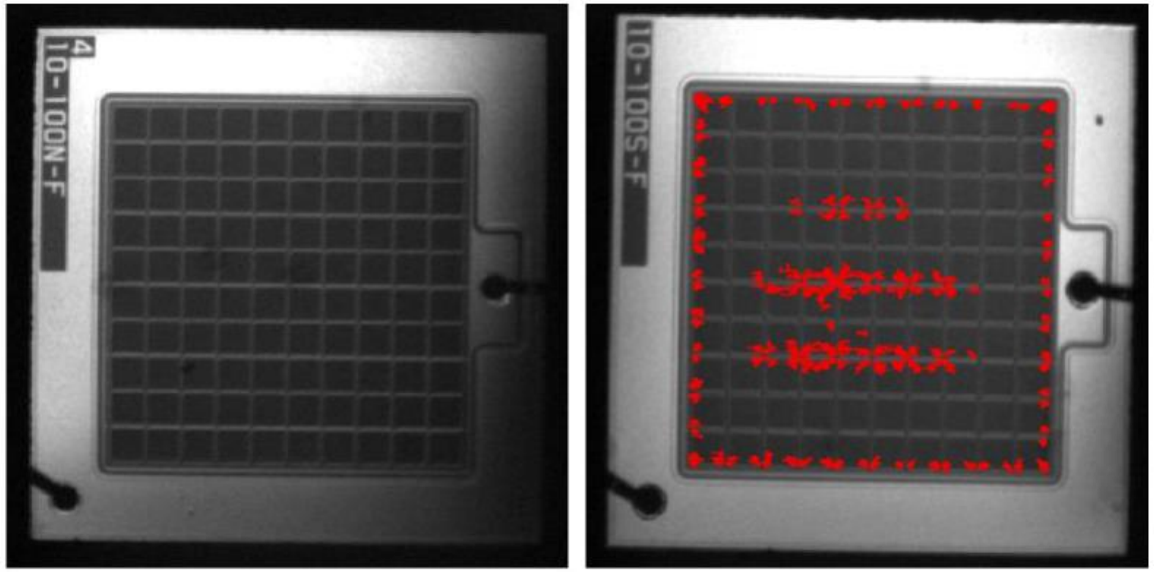


High temperature can significantly speed up process of dark current annealing in irradiated silicon devices

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

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

"Early" SiPMs under Co-60 gamma ray irradiation



Infrared camera 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 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

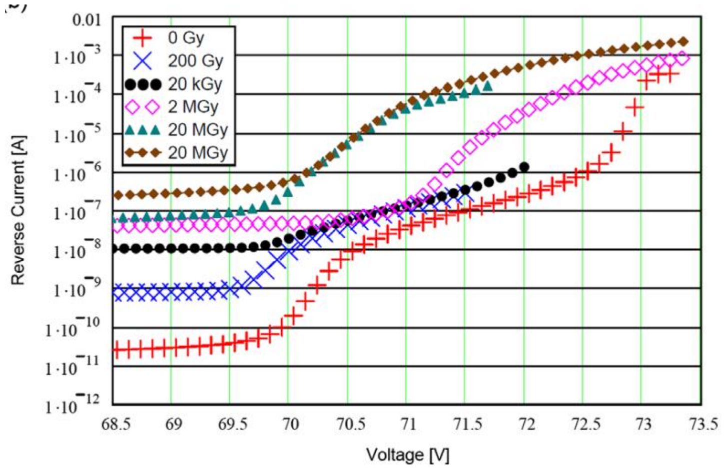
T. Matsubara, H. Tanaka, K. Nitta, M. Kuze, Radiation damage of MPPC by gamma-ray irradiation with Co-60, PoS PD07 (2007) 032.

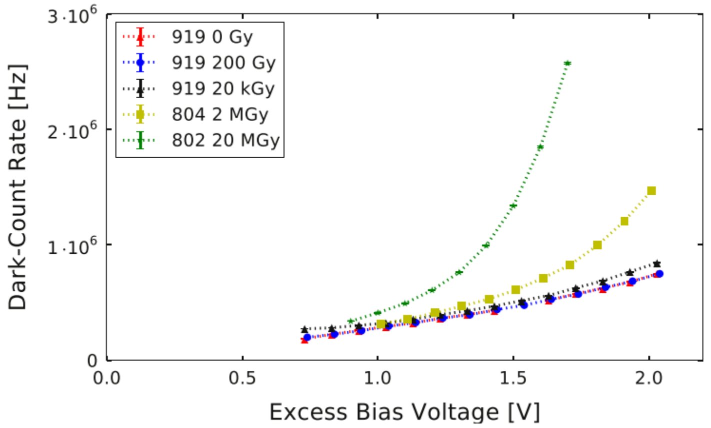
It is worth mentioning that in recent SiPMs such kind of damage is not observed

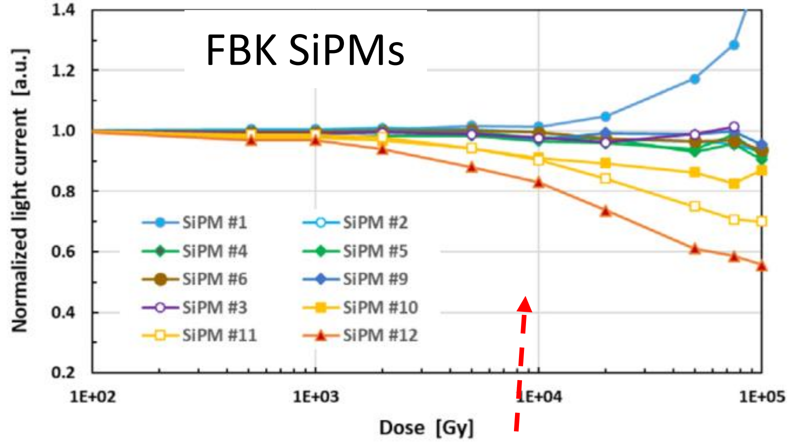
Effects of X-rays irradiation on recent SiPMs

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

(F. Acerbi et.al, NIM A1045 (2023) 2)







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 and to doses up to 100 kGy on the recent FBK SiPMs. The SiPMs were irradiated without applied bias. From current–voltage, capacitance/conductance–voltage, capacitance/conductance–frequency, pulse-shape, and pulse-area measurements, the SiPM characteristics below and above breakdown voltage were determined. 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.

X-ray radiation can significantly change PDE of SiPMs due to damage of the SiO_2/Silicon interface and SiPM protection window.

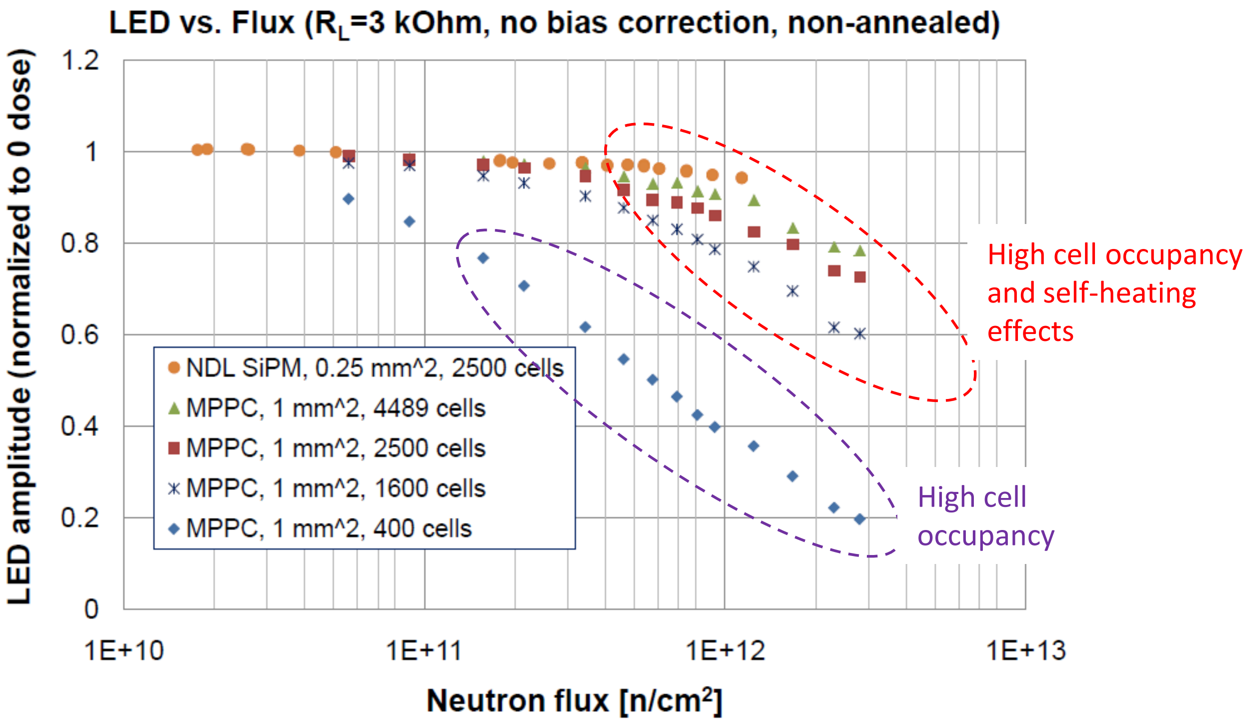
Radiation damage effects in SiPMs (hadrons)

SiPM radiation damage by hadrons

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 (high SiPM cell occupancy due to high induced dark carriers' generation-recombination rate and self-heating effects caused by high dark current in irradiated SiPMs)
- Breakdown voltage increase, PDE, Gain reduction due to donor/acceptor concentration change

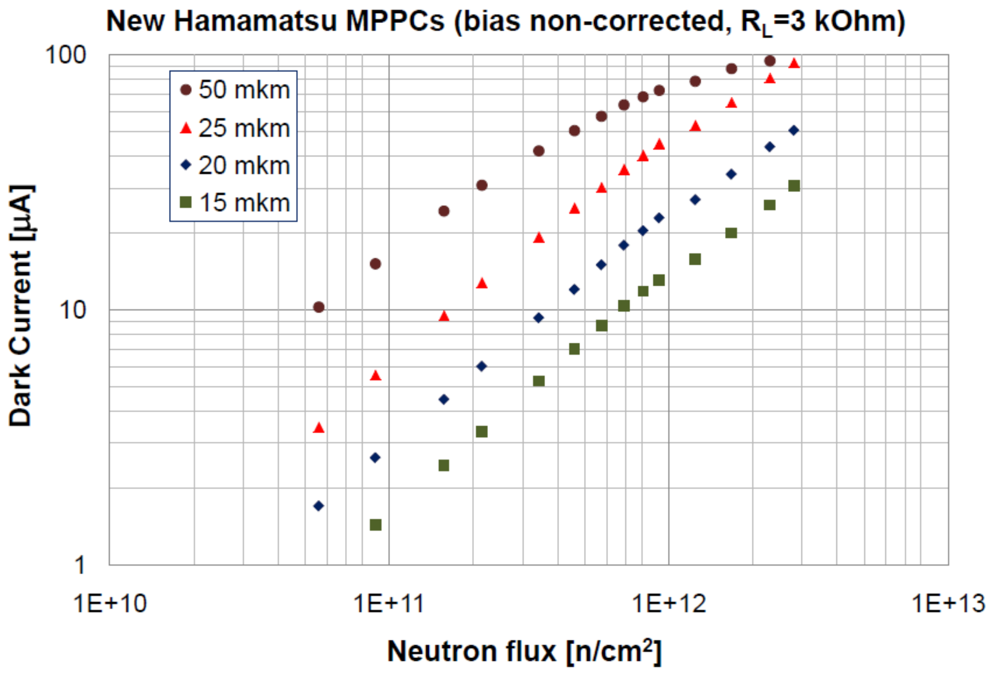
Relative response to LED pulse vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs measured at RT



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

SiPMs with high cell density (faster cell recovery time and smaller dark currents) can operate up to $3*10^{12}$ neutrons/cm^2 even at room temperature (gain change is < 25%).

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:

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

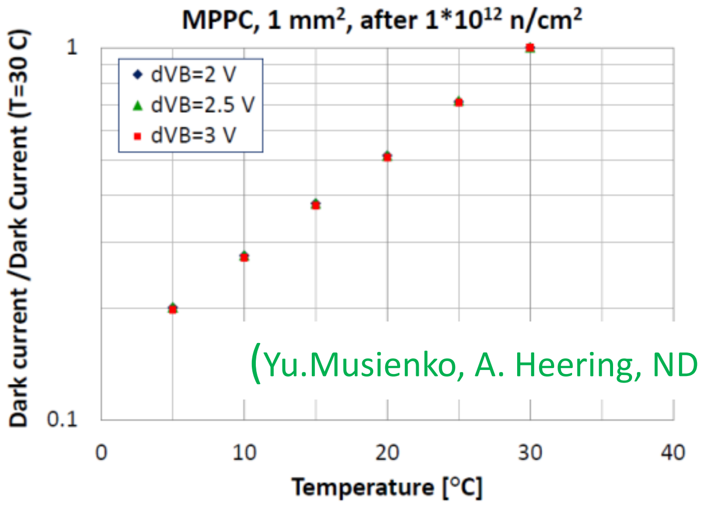
α – dark current damage constant [A/cm];
Φ – particle flux [1/cm^2];
V – "effective" silicon volume [cm^3]
M – SiPM gain
k – NIEL coefficient

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

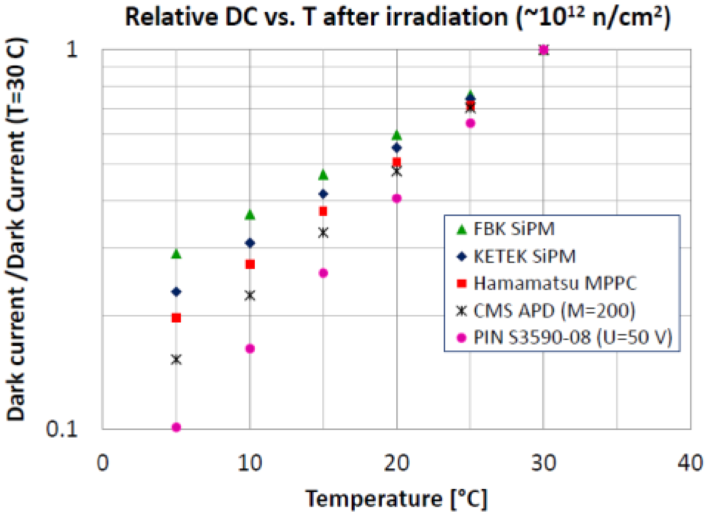
Thickness of the epi-layer for most of SiPMs is in the range of 1-2 µm, however d_{eff} ~ 4 ÷ 50 µm for different SiPMs. High electric field effects (such as phonon assisted tunneling) play significant role in the origin of SiPM's dark noise.

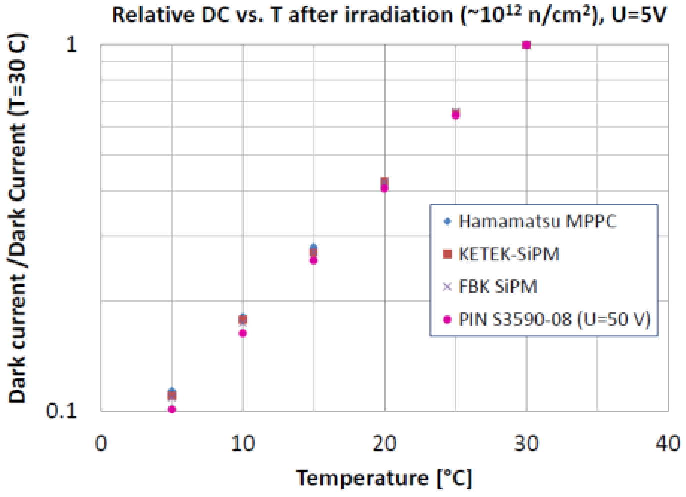
$V \sim S * G_f * d_{eff}$,
S - area
G_f - "effective" geometric factor
d_{eff} - "effective" thickness

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



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





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 significant difference of this dependence was observed 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.

Trap-assisted tunneling effects

(E.Garutti, Yu.Musienko, NIM A926 (2019) 69)

Hamamatsu S15408 25 um cell pitch SiPM, after 1E13 n/cm^2, dVB=1 V

Low electric field (PIN)

The diffusion and generation currents have the following temperature dependence [9]:

$$I_{diff} \propto T^3 e^{-\frac{E_g}{kT}}, \quad (1)$$

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

(T=-35 °C ÷ +25 °C)

For the activation energy, E_a a value of 0.605 eV is found by Chilingarov [10], which using the Shockley–Read–Hall (SRH) model corresponds to a trap energy $E_t = E_a + \frac{E_g}{2} = 45$ meV from mid gap.

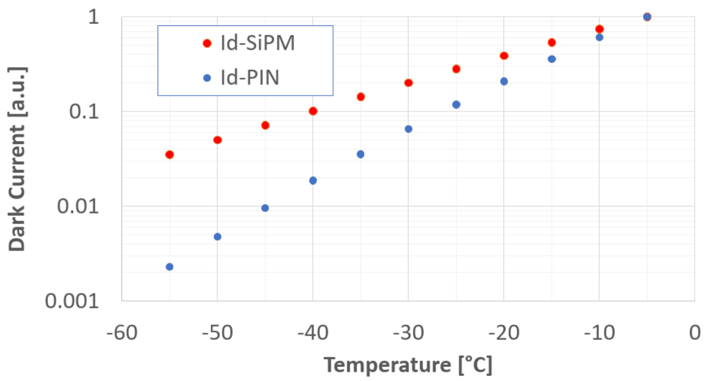
High electric field (APD&SiPM)

For electric fields of the order of 10^5 V/cm or higher Eq. (2) needs to be corrected by a trap-assisted tunneling term, $I_{gen+tat}$. The correction depends on the effective field strength, F_{eff} and modifies Eq. (2), as

$$I_{gen+tat} \propto (1+\Gamma) T^2 e^{-\frac{E_a}{kT}}, \quad (3)$$

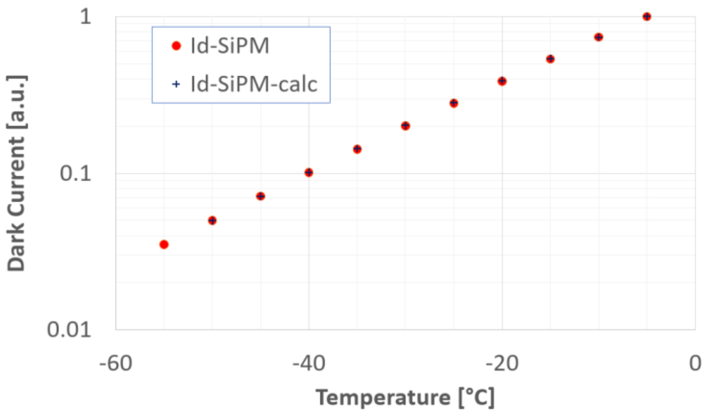
where $\Gamma \approx \frac{F_{eff}}{(kT)^{3/2}} e^{\left(\frac{F_{eff}}{(kT)^{3/2}}\right)^2}$ is the term defined by Hurkx [11], which accounts for the effects of tunneling.

Idark vs. T (SiPM&PIN) – relative to Idark at -5 °C



Calculation for PIN: E_a= 0.605 eV, $E_t = E_a + E_g/2 \approx$ 45 meV

Idark vs. T (SiPM-measured&calculated)



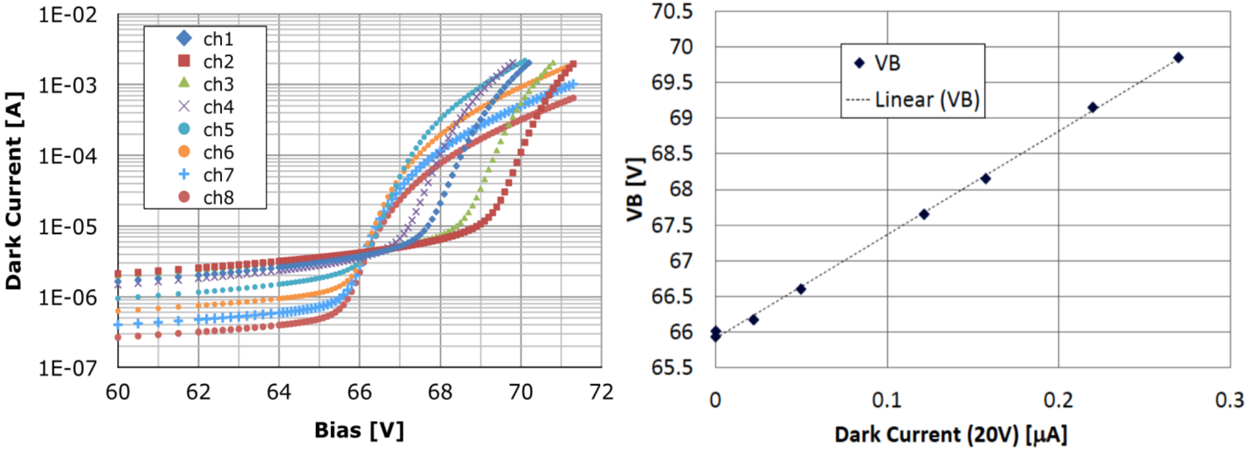
Calculation for SiPM: E_a= 0.415 eV, $E_t = E_a - E_g/2 \approx$ -151 meV, F_{eff}=0.0043 eV$^{1.5}$

Results on heavily irradiated SiPMs

Breakdown voltage change with hadron irradiation

2.8 mm dia., 10 um cell pitch Hamamastu MPPCs irradiated up to 2.2E14 n/cm², (A.Heering et al., NIM A824 (2016) 111)

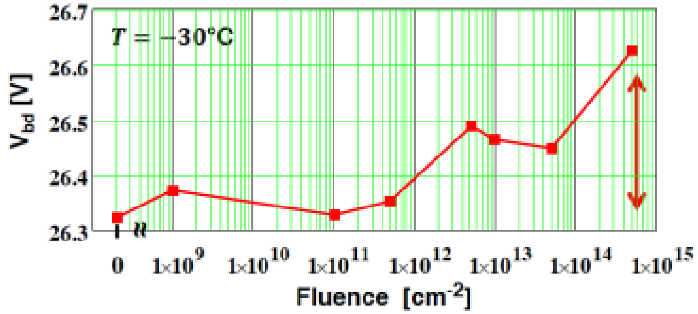
Ch.2 – irradiated with 24 GeV protons (~2.2E14 n/cm²)
Ch.8 – irradiated with 24 GeV protons (~7.5E12 n/cm²)



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

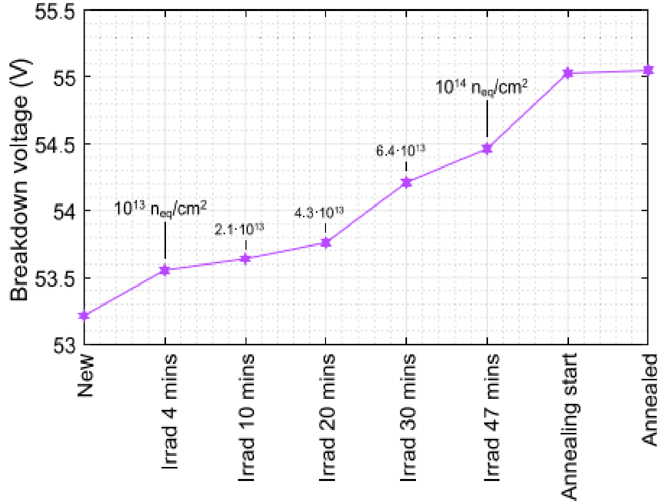
The same type as S12572-010C MPPC. 8-ch. array developed for the CMS HCAL Phase I Upgrade project. Non-uniform irradiation with 24 GeV protons (5 mm dia. FWHM spot size).
Change of the doping concentration: VB shift with fluence reaches 4 V at 2.2E14 n/cm².

KETEK SiPM irradiated with neutrons (S.Cerioli et. all, ICASiPM (2019))



VB increase: ~1.3 V at 5E14 n/cm²

Hamamatsu S13360-1350CS SiPM irradiated with neutrons (M.Calvi et. al, NIMA922 (2019) 243)

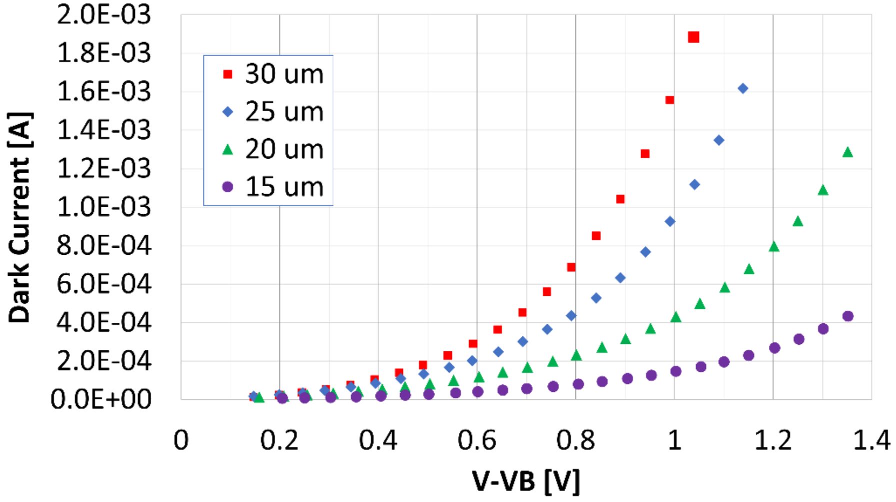


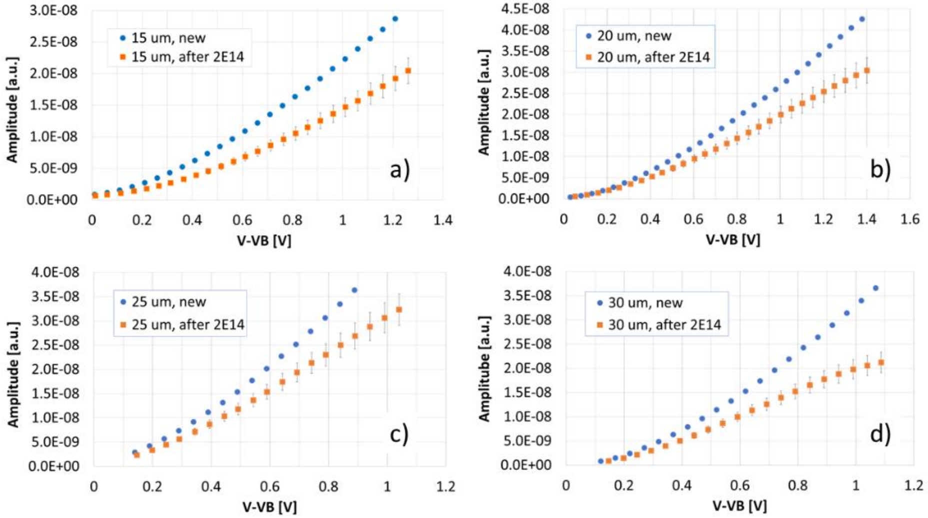
VB increase: ~1.2 V at 1E14 n/cm²

VB increase is smaller for SiPMs with thinner epi layer (smaller VB)

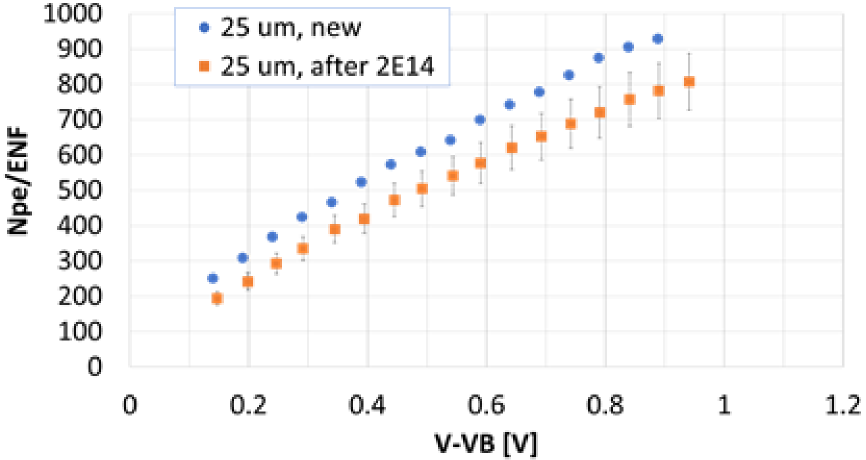
Changes in dark current and signal response at high neutron fluxes

Can SiPM survive very high neutron fluxes expected at high luminosity LHC? Recent Hamamatsu SiPMs (9 mm^2, 15, 20, 25, 30 μm cell pitch SiPMs developed for CMS BTL and HGCAL projects) were irradiated with reactor neutrons (2*10^{14} n /cm^2 1 MeV equivalent). SiPMs were measured at T=-45 °C. TECs were used to stabilize the SiPMs temperature





(Yu. Musienko et al., article in preparation)



The authors found:

- Increase of the dark current (up to ~1.6 mA for 30 um SiPM, at dVB=1 V)
- Increase of VB: 1 V for 20, 25, 30 um SiPMs and 2 V for 15 um SiPM
- Drop of the signal amplitude (25% ÷ 40 % depending on dVB and SiPM type)
- Reduction of PDE (for 25 um cell SiPM: 15 % ÷25 % depending on dVB)

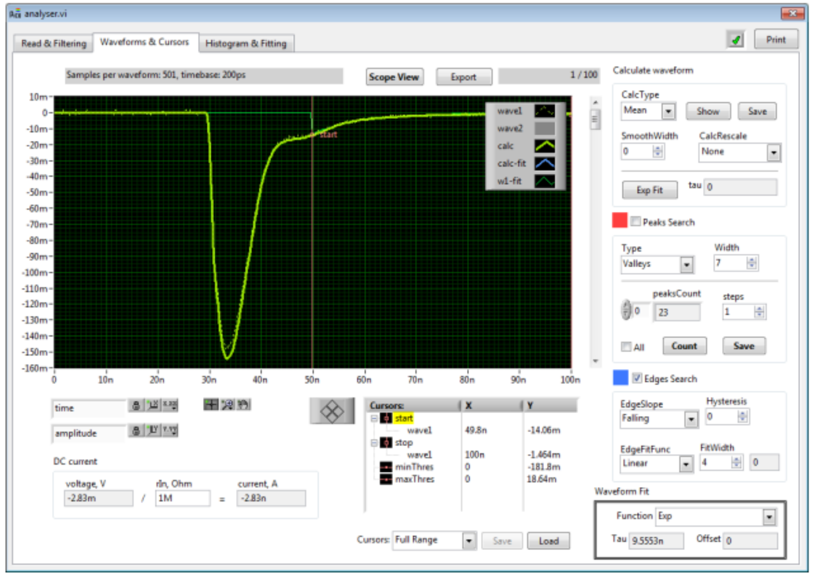
The main result is that SiPM survived this dose of irradiation and can be used as photon detector! (see presentation of M. Wayne at this conference)

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

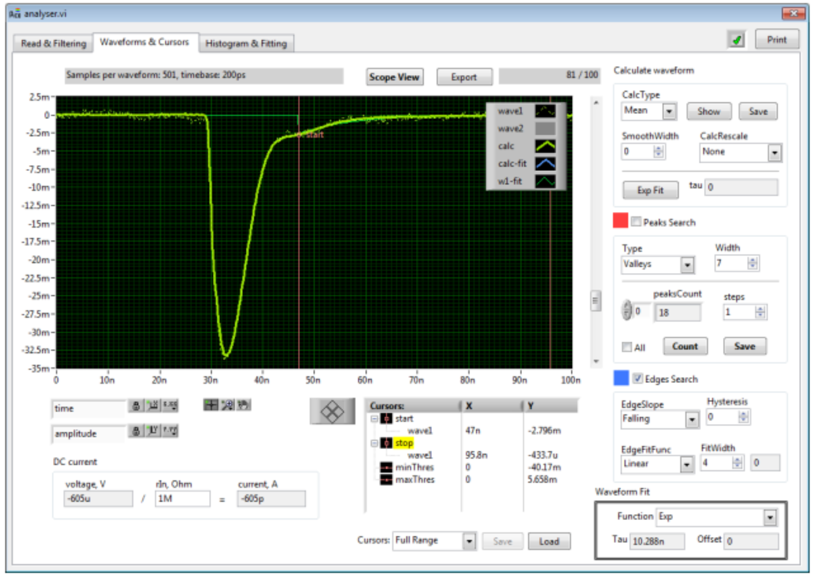
Does irradiation change the SiPM signal shape?

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

New



After 5E13 n/cm^2



- 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

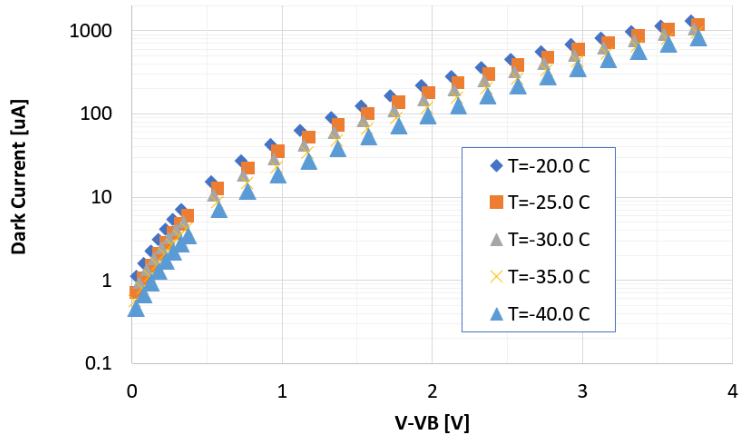
(Yu. Musienko, A. Heering, A. Karneyeu, M. Wayne, article in preparation)

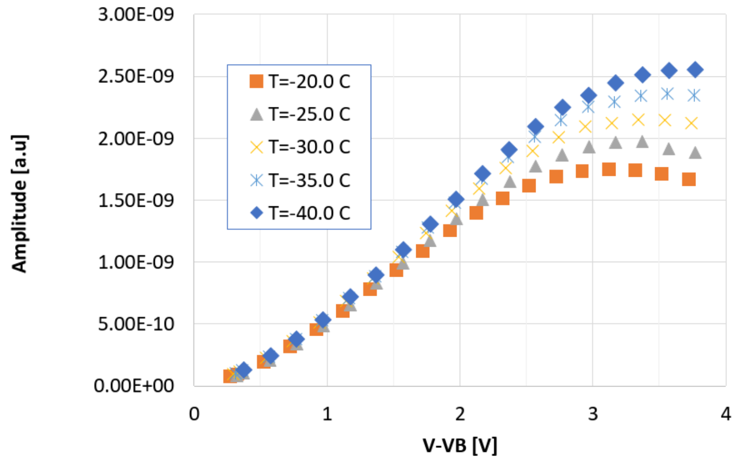
S10943-4732, 15 micron pixels, no trenches similar to S12572-015C SiPM

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

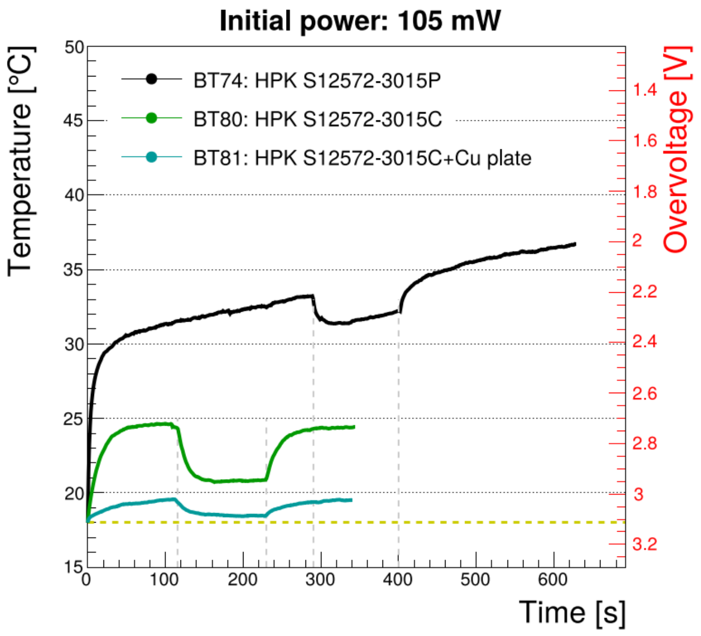
Self-heating effects in irradiated SiPMs

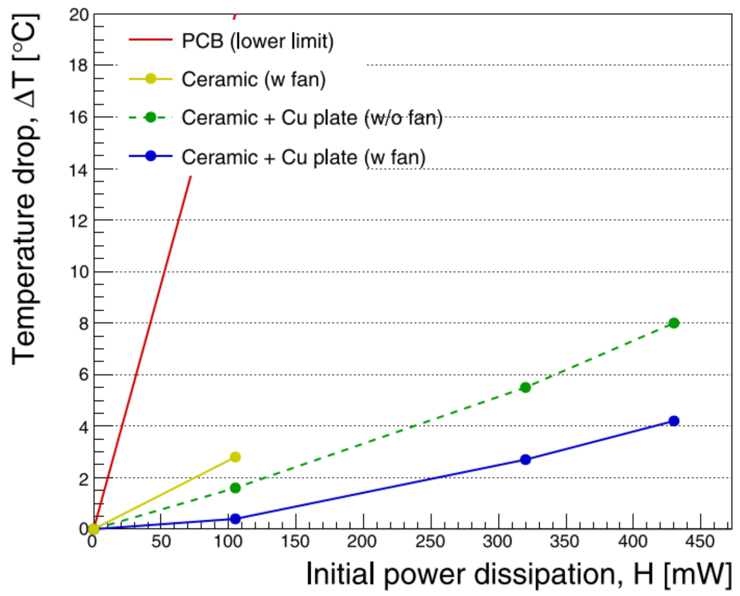
Self-heating effects in irradiated SiPMs





LED pulsed light was used to study amplitude to over-voltage dependence of S12572-1015P SiPM irradiated with 5E13 n/cm^2. Signal amplitude doesn't increase with dVB due to SiPM self-heating (PCB package with bad thermal conductivity).





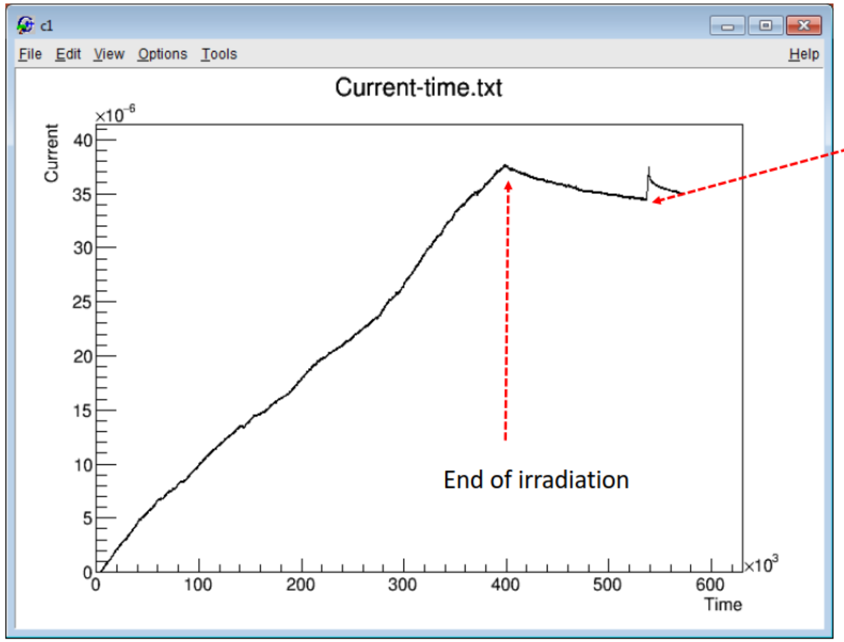
M. Lucchini, Yu. Musienko, A. Heering, NIM A997 (2020) 164300 proposed a method (using intense illumination with a LED) to evaluate the heat dissipation properties of different SiPM packages and the temperature stability of SiPMs during operation under extremely high dark count rates (larger than 30 GHz). Temperature variations as a function of time was tested for the three SiPM configurations (PCB package, ceramic package, ceramic package + Cu plate)

SiPM temperature can increase by >19°C in case of ~105mW power dissipation and PCB package.
PCB package can provide better thermal conductivity with large number of copper filled vias.

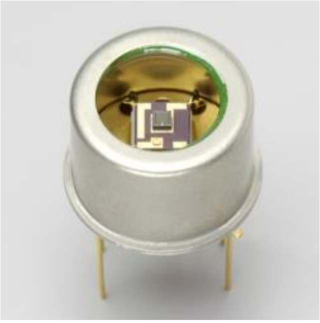
Annealing of radiation damage

Dark Current vs. Irradiation Time&Neutron Fluence

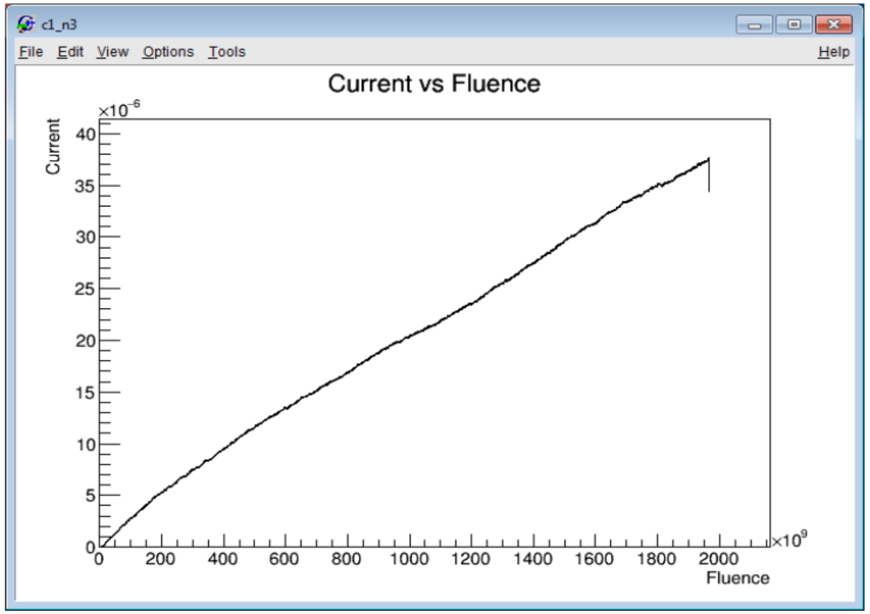
I_{dark} vs. Time, T=-30 °C, U=67.0 V (dVB=4.76 V)



Bias was set OFF and set to 67 V again

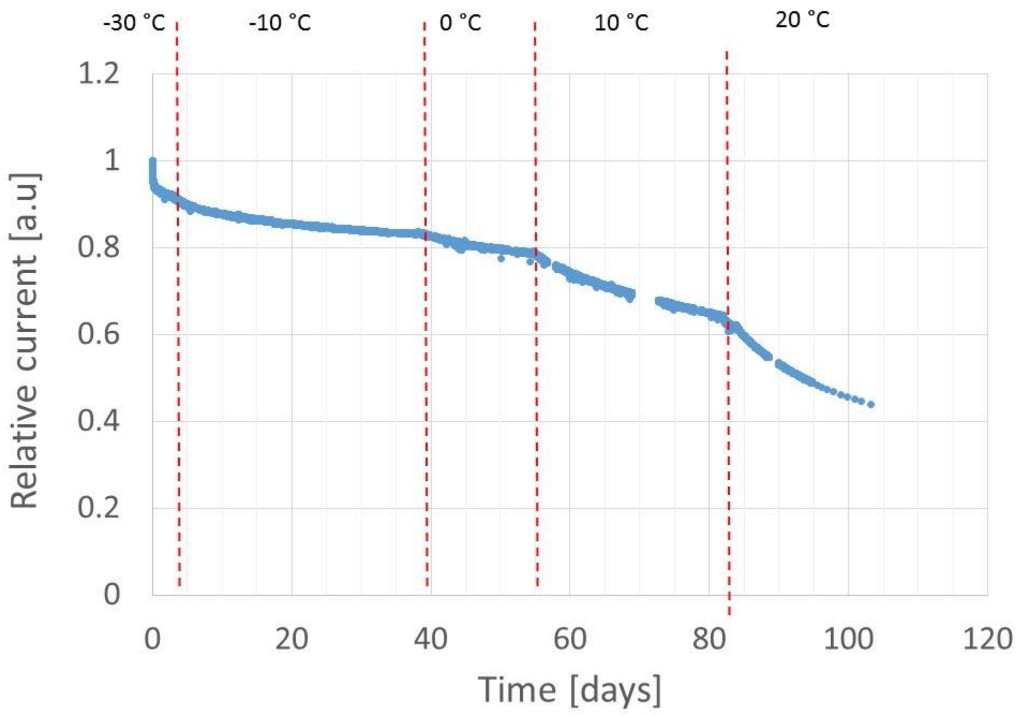


I_{dark} vs. Fluence, T=-30 °C, U=67.0 V (dVB=4.76 V)



To study the dark current annealing, a 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.

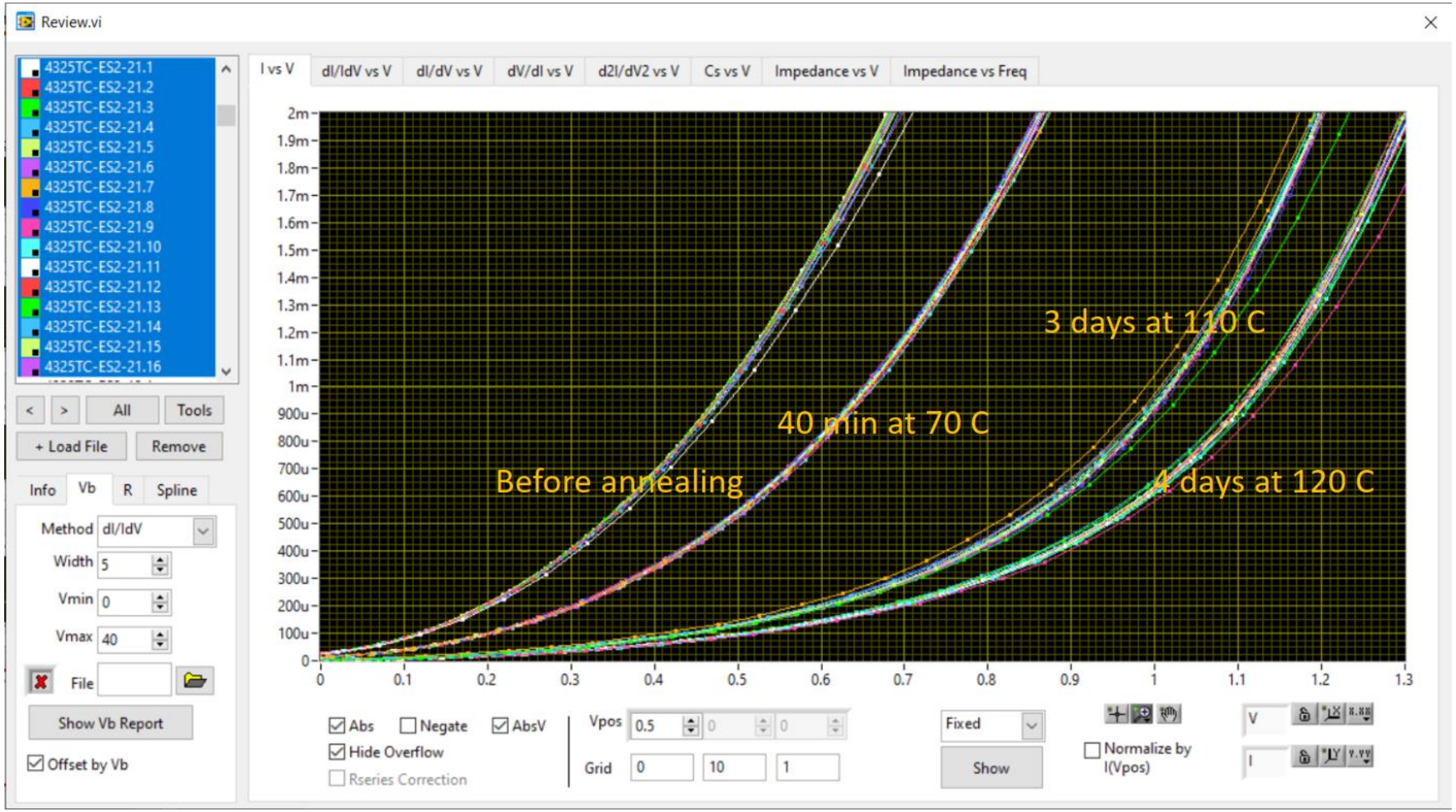
Dark Current annealing at T=-30 °C and 20 °C



The SiPM was kept at T=-30 C after irradiation. During annealing we changed SiPM temperature using TEC integrated in the SiPM package. This figure shows the relative change of dark current with time. The annealing of dark current accelerates with increasing temperature.

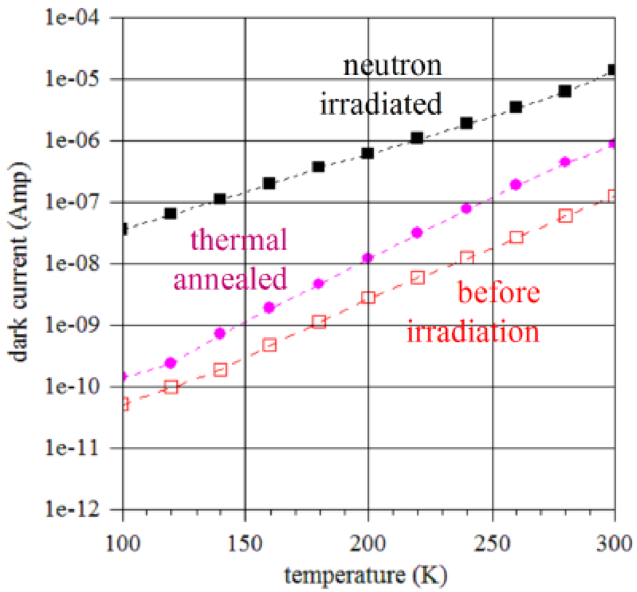
~60% of dark current is annealed when the temperature changes from -30 °C to +20 °C

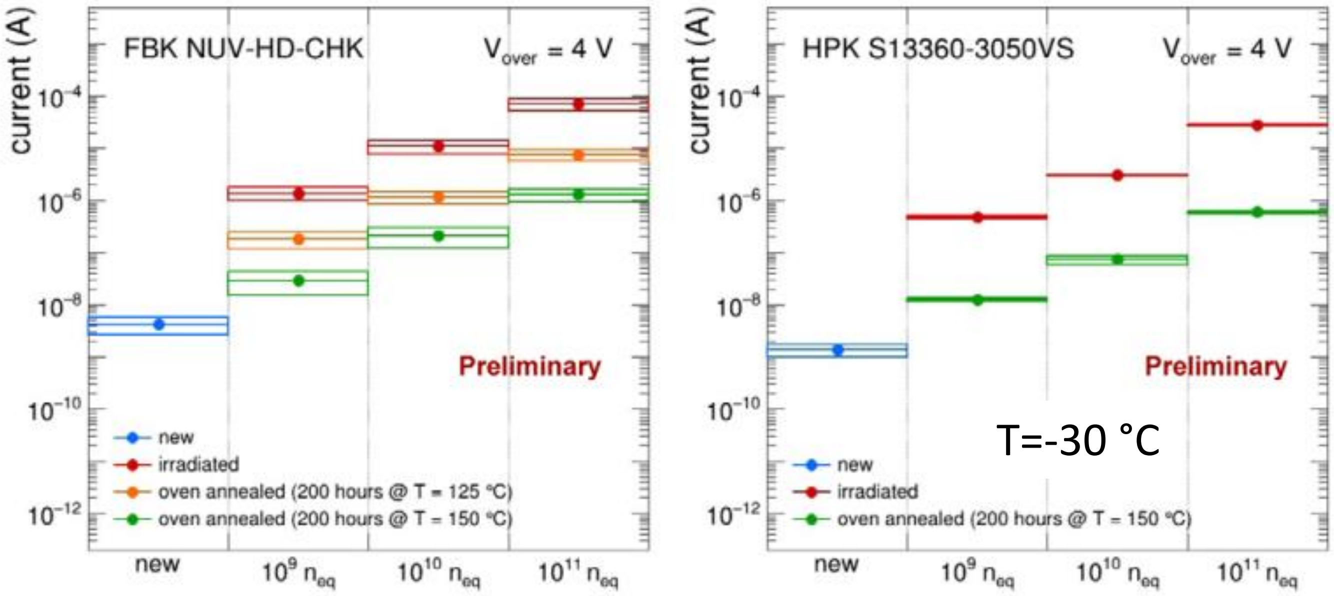
Dark Current annealing at elevated temperature



Annealing factor ~7.5 was achieved for 9 mm^2 S15408 25 um cell pitch SiPMs (16 channel BTL array) cell size SiPM irradiated with 2E14 n/cm^2 after 4 days of annealing at 120 °C (measured at T=-45 °C)

Dark current annealing at very high temperature



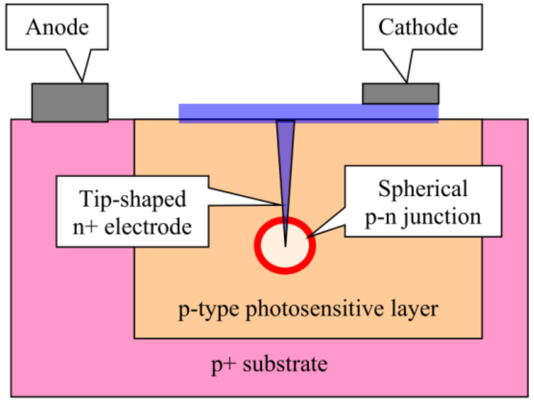


Tsang et. all (JINST 11 (12) P12002) performed 3 days annealing at +250 °C, using forward bias with the SiPM current reaching 10 mA. A remarkable effect of this high temperature annealing was demonstrated: >20 fold reduction of the dark current at room temperature. Single photo-electron resolution was recovered after this procedure for devices irradiated up to $\Phi = 10^{12}$ $n*cm^{-2}$ with cooling them to about -50 °C.

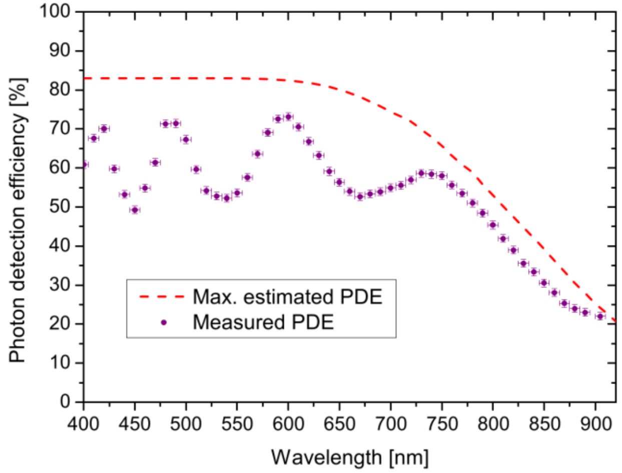
R. Preghenella et. all (NIM A1056 (2023) 168578) observed >30 fold reduction of the dark current after 200 hours annealing at 150 °C (measured at T=-30 °C)

Recent and future developments of rad. hard SiPMs

Tip Avalanche Photodiode—A spherical-junction SiPM concept

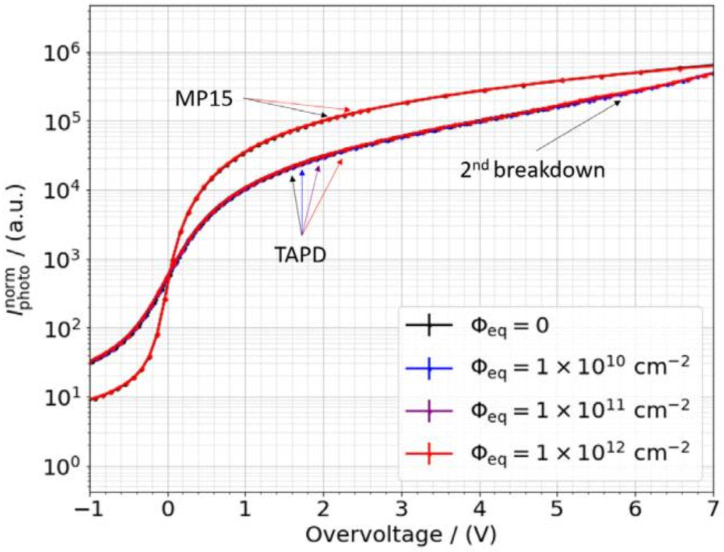


S. Vinogradov (NIM A1045 (2023) 167596) proposed a new design of SiPM (produced by KETEK) with spherical p-n junction, 15 um cell, τ=4 ns

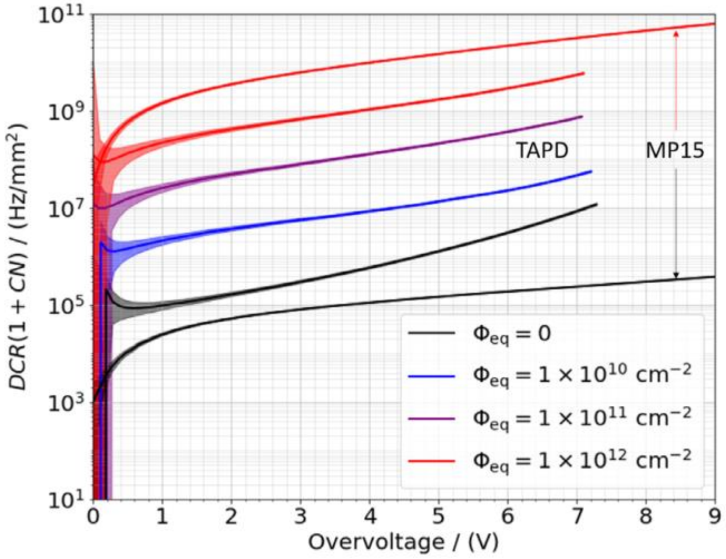


PDE vs. wavelength at dVB=5 V and T=21 °C

J. Römer et. al (NIM A 1045 (2023) 167792) studied radiation damage of TAPD by neutrons



No change in photocurrent vs. dVB dependence after 1E12 n/cm^2.



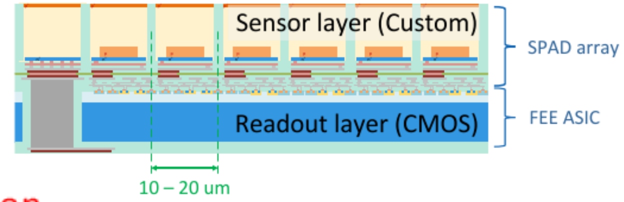
The dark count rate at 20 °C calculated normalized to a detector area of 1 mm^2 for the TAPD and the KETEK MP15 15 cell pitch “classical” SiPM.

A factor of 10 smaller dark current compared to a “classical” KETEK SiPM of the same area and cell pitch. This reduction is likely due to the smaller area of the avalanche region ➔ smaller trap assisted tunnelling effects.

FBK Backside Illuminated SiPM

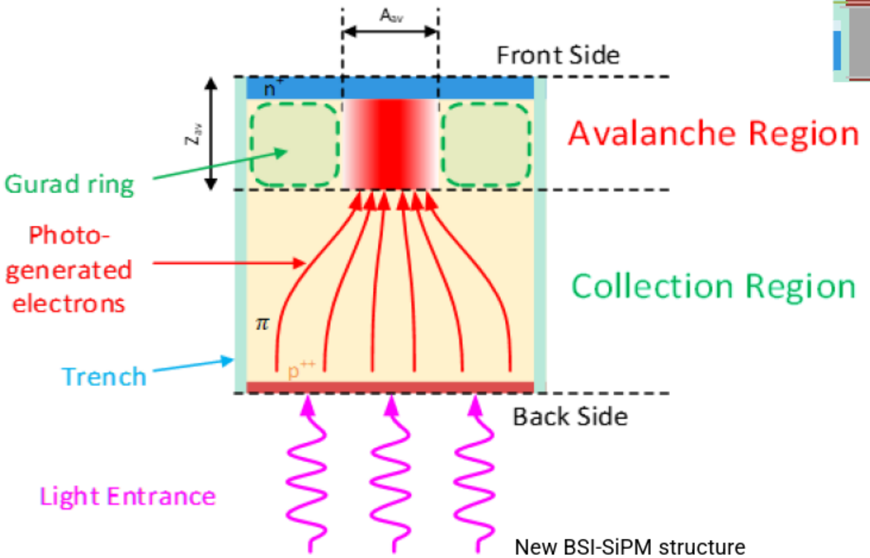
The next-generation of developments, currently being investigated at FBK, is building a *backside-illuminated, NUV-sensitive SiPM*. Several technological challenges should be overcome.

Clear *separation between charge collection and multiplication regions*.



Potential Advantages:

- Up to 100% FF even with small cell pitch
- Ultimate Interconnection density: < 15 um
- High speed and dynamic range
- Low gain and external crosstalk
- (Uniform) entrance window on the backside, ideal for enhanced optical stack (VUV sensitivity, nanophotonics)
- Local electronics: ultra fast and possibly low-power.



Development Risks:

- Charge collection time jitter
- Low Gain → SPTR?
- Effectiveness of the new entrance window

Radiation hardness:

- The SiPM area sensitive to radiation damage, is much smaller than the light sensitive area
- **Assumption**: the main source of DCR is field-enhanced generation (or tunneling).

Alberto Gola - FBK SiPM roadmap - Photodetection with semiconductors - LPSC meeting 03/06/2024

Instead of a conclusion: Approaches to develop radiation harder SiPMs

❖ Dark noise reduction

Optimization of the electric field profile (especially for smaller cells) to obtain a uniform electric field across the cell (no regions with higher or lower electric field values). Reducing the maximum electric field (trap-assisted tunnelling!), while keeping the depletion layer thickness thin to reduce the generation volume. TAPD or back-side illuminated SiPM structure are very promising for reducing high electric field effects.

❖ Cell occupancy reduction

Cell occupancy can be reduced developing SiPMs with small cell size and small 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 (A contradiction arises with the possibility of reducing the electric field.)

❖ 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 avoid trapping in front SiPM layer

❖ Optimization of SiPM package

Package of SiPM has to allow:

- ✓ SiPM operation in wide range of temperatures (-200 °C ÷ 200 °C);
- ✓ SiPM protective layer/epoxy must be radiation resistant
- ✓ Easy heat removal (to reduce SiPM self-heating)
- ✓ Integrated temperature sensor (can be integrated on the same chip as SiPM)
- ✓ Integrated heater (for faster and easy dark current annealing)?