ASPIDES kickoff meeting

January 30th, 2025

Bulk damage study in CMOS SPADs

INSIDE project (CSN V)

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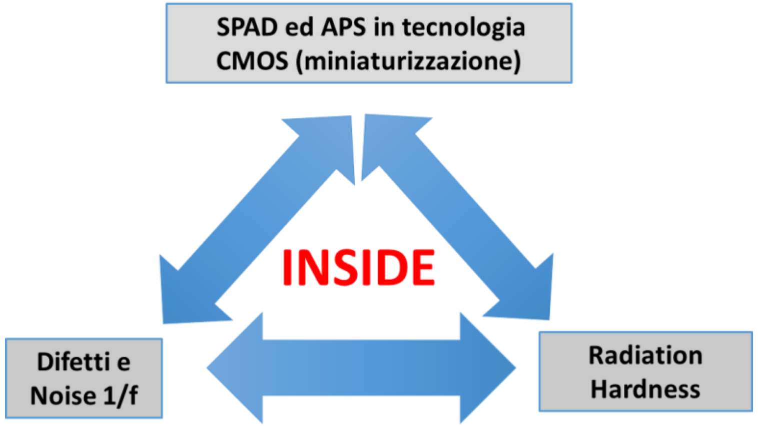
INSIDE project

INSIDE: FIIcker Noise Studies for Investigation of Detector pErformances

CSNV experiment in 2017-2020, PI: F. Di Capua

Study of radiation induced defects in photosensors

- Partnership with FBK (D. Stoppa)
- Few samples of 150-nm CMOS SPADs test chips



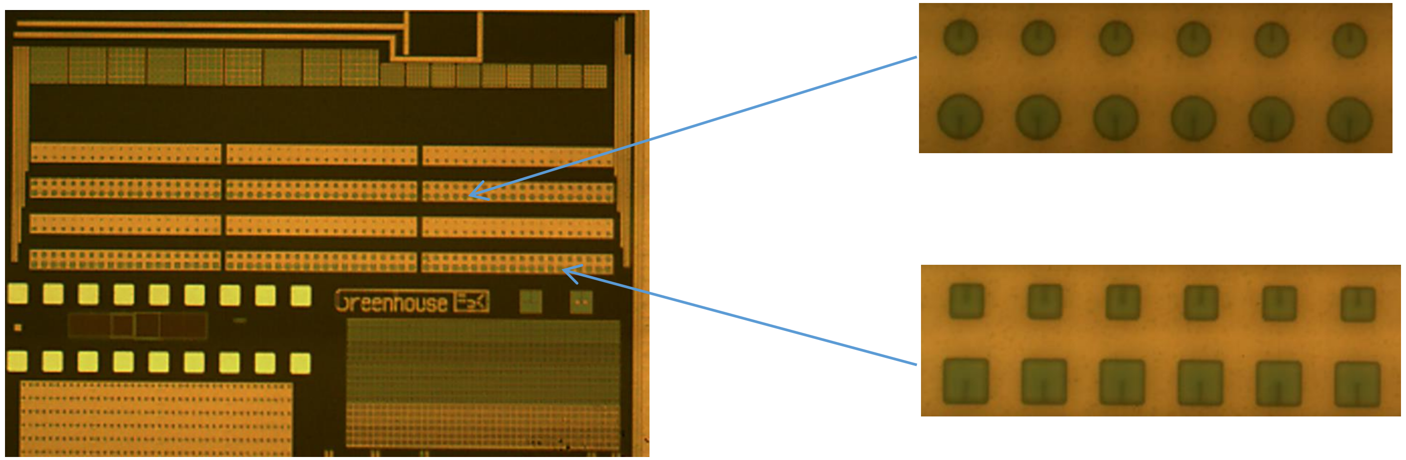
SPAD ed APS in tecnologia CMOS (miniaturizzazione)

INSIDE

Difetti e Noise 1/f

Radiation Hardness

FONDAZIONE BRUNO KESSLER



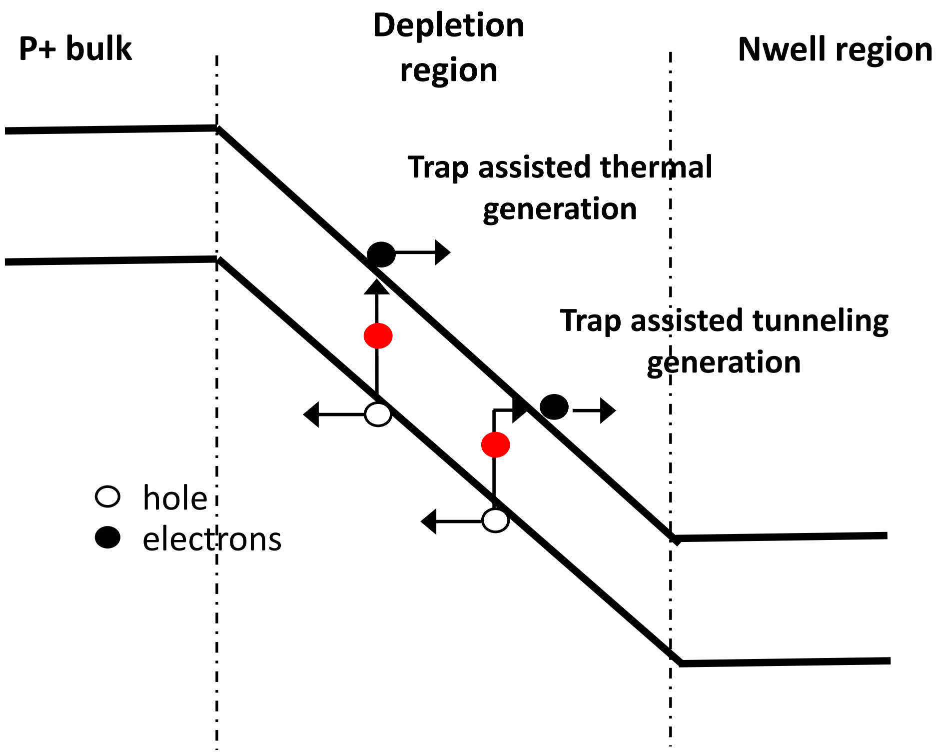
Dark counts and bulk damage

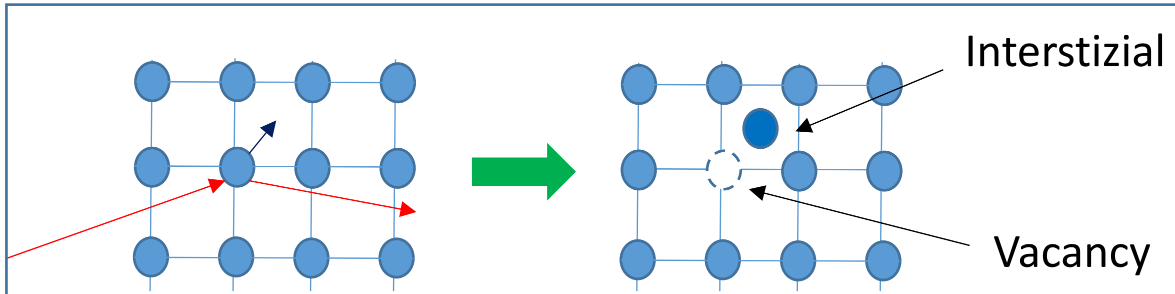
Dark Count Rate (DCR) enhanced by mid-gap energy levels in the depletion region through both

- **Thermal (Shockley–Read–Hall generation);**
- **Tunnelling processes;**

Mid-gap energy levels due to:

- Fabrication process impurities;
- **Radiation induced effects, displacement damage mainly**.





Displacement of Si-atoms from lattice structure due to incident particles.
Typical defects are dopant-related vacancy complexes, as phosphorus-vacancy (P-V), or di-vacancy (V-V) defects.

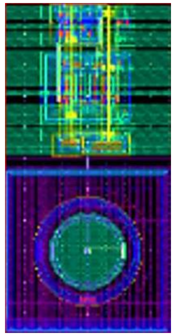
Devices Under Test

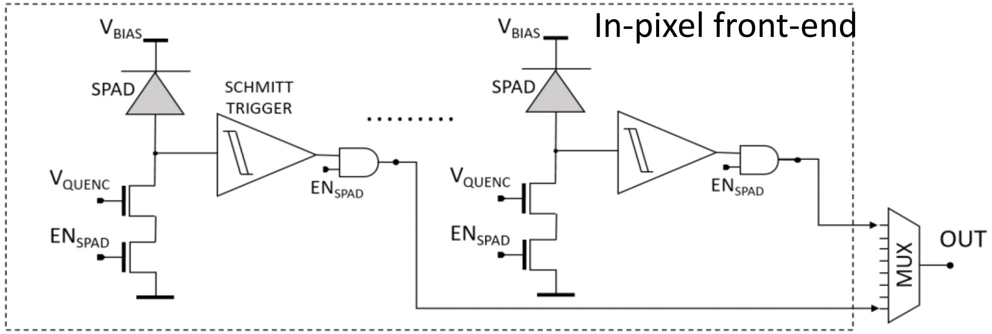
[1] L. Pancheri, D. Stoppa, Low-noise Single Photon Avalanche Diodes in 0.15 µm CMOS Technology,

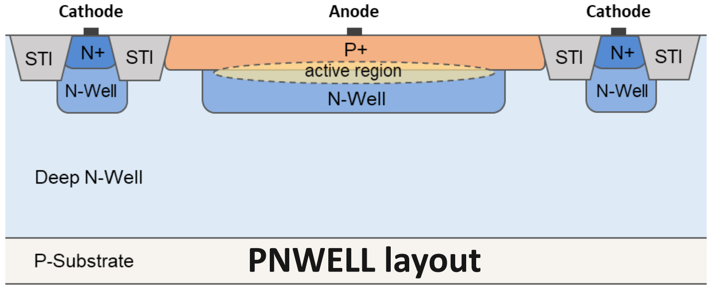
Devices designed by Fondazione Bruno Kessler (FBK) and implemented in a **150-nm CMOS process** [1]:

- **Three junction layouts: PNWELL and PWNISO1/2;**
- **Several active area sizes: 5x5, 10x10, 15x15, 20x20 µm^2;**

- **Each SPADs is implemented with its front-end electronics:**
  - A trigger to digitalize the pulse;
  - MUX to select one pixel at the time;

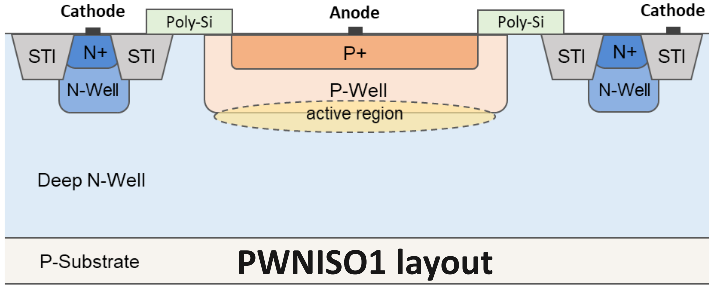






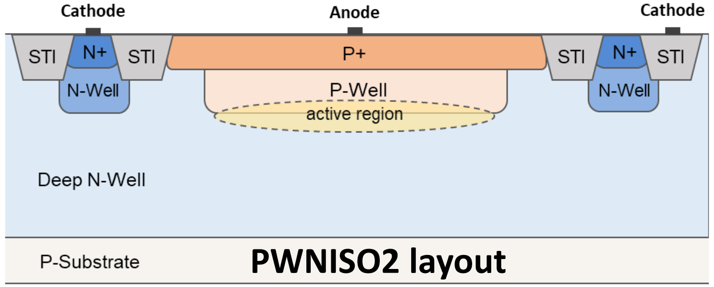
Deep graded junction

Active thickness ~ 0,66µm



Shallow step junction

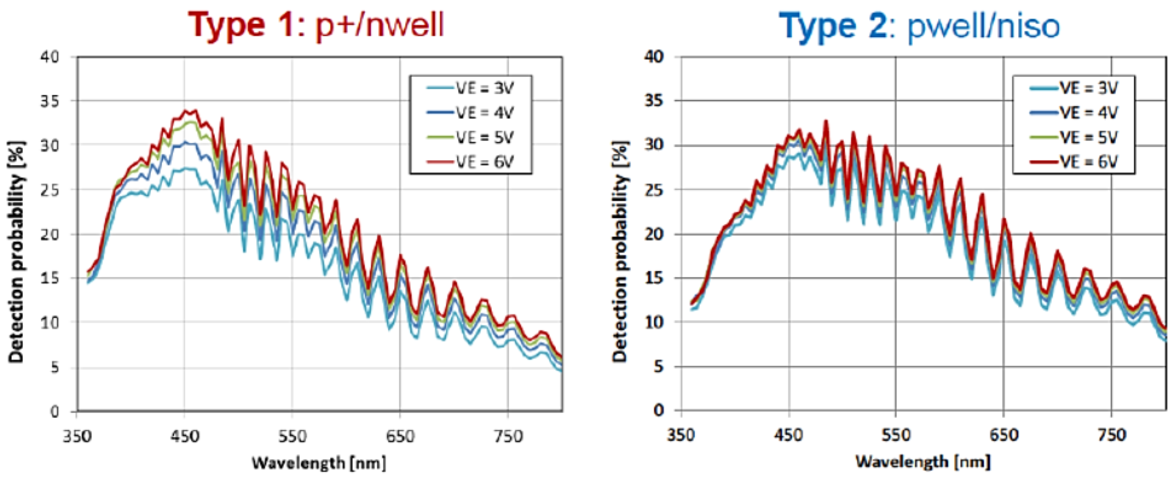
Active thickness ~ 0,85µm



Same of PWNISO1 without Poly-Si gate.

FBK CMOS SPAD

pde



“Solid-state single-photon Detectors and CMOS Readaout Circuits for Positron Emission Tomography Applications”, *Hesong Xu, et. Al.*

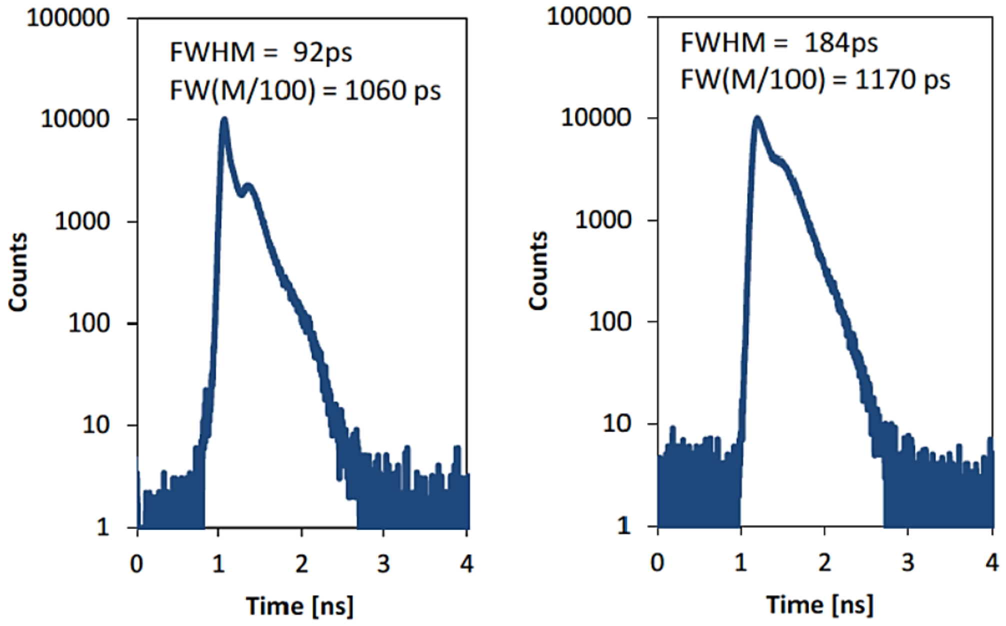
Time resolution

P+/Nwell junction

Type 1: **60ps FWHM**

Pwell/Niso junction

Type 2: **170ps FWHM**



“Low-noise Single Photon Avalanche Diodes in 0.15 µm CMOS Technology”, *L Pancheri, D Stoppa*

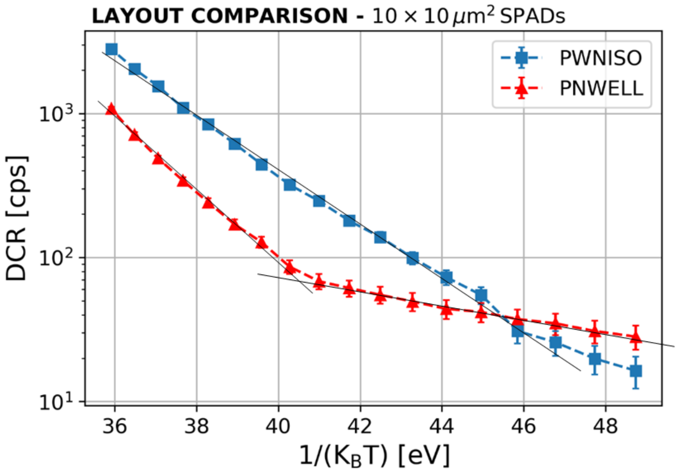
Pre-irradiation characterization

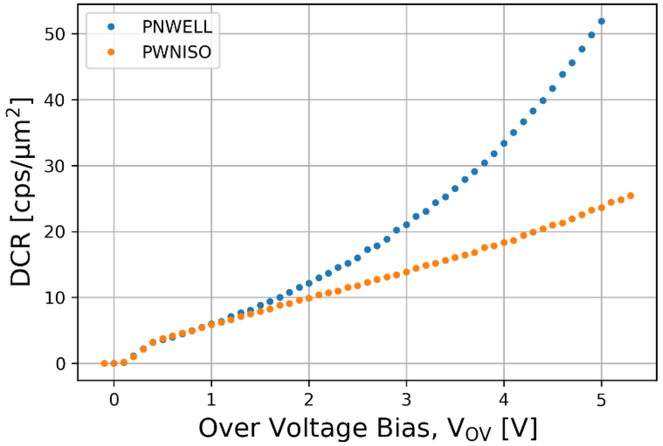
Device have been characterized before irradiation.

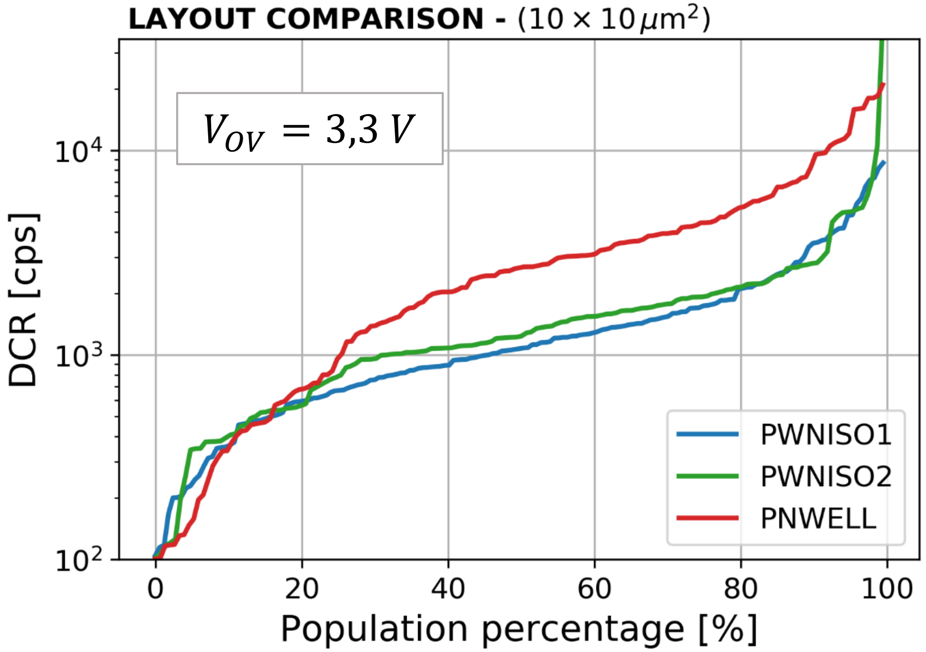
- **PNWELL shows a significant tunnelling contribution to the DCR.**

$10 \times 10\ \mu\mathrm{m}^2$ SPADs

	PNWELL	PWNISO1	PWNISO2
Mean DCR [cps]	~1400	~1700	~3600







Irradiation campaigns

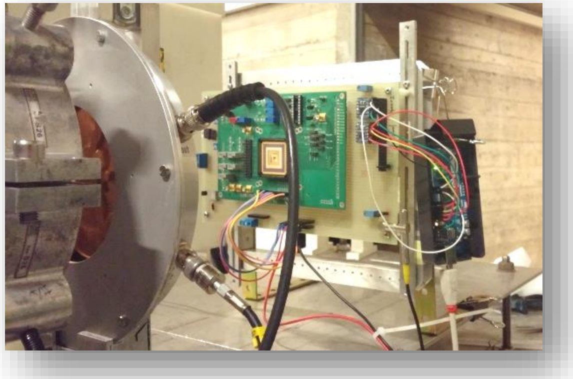
Proton test performed at INFN-LNS in Catania (Italy) using:

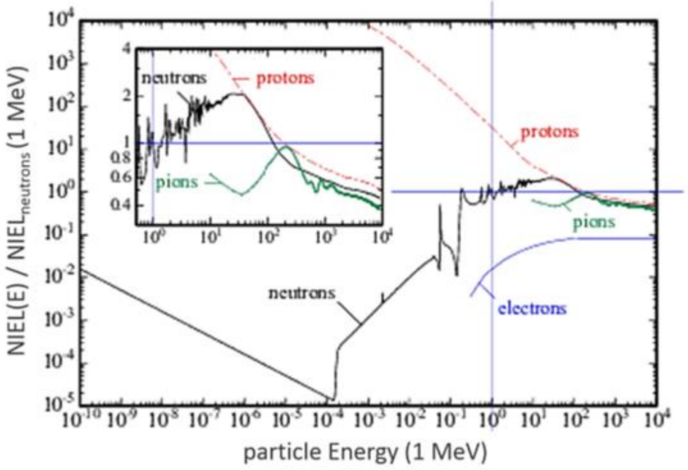
- 16 MeV proton beam;
- Delivered fluences: 10^{10} - 10^{11} p/cm^2

Electron test performed at ILU-6 accelerator at the Warsaw Institute of Chemistry and Nuclear Technology:

- 2 MeV electron beam;
- Delivered fluences: 10^{12} e/cm^2

particle	Fluence [e/cm²]	TID [krad]	DDD [TeV/g]
p^+	$6{,}7 \cdot 10^9$	2,3	45
p^+	$1{,}4 \cdot 10^{10}$	4,8	94
p^+	$2{,}0 \cdot 10^{10}$	7,1	139
p^+	$2{,}8 \cdot 10^{10}$	9,6	188
p^+	$4{,}1 \cdot 10^{10}$	14	283
e^-	$3{,}48 \cdot 10^{12}$	88	155
e^-	$6{,}92 \cdot 10^{12}$	173	309



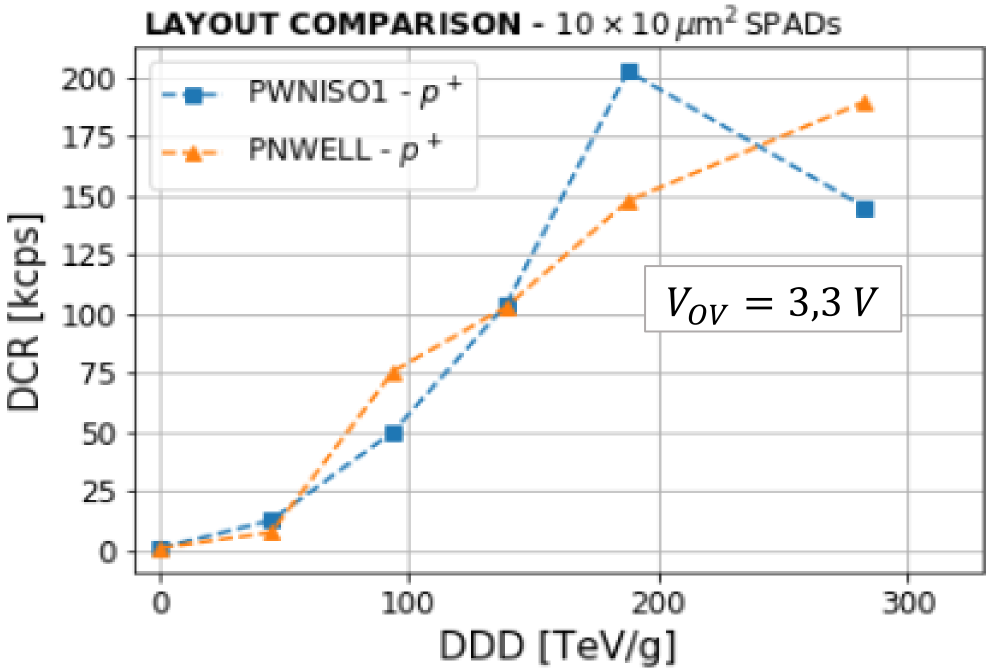


Claude Leroy, Pier-Giorgio Rancoita, "Principles of Radiation Interaction in Matter and Detection 2nd Edition", World Scientific Publishing, 2009.

Protons irradiation effects

Mean DCR increases up to two order of magnitude at maximum dose delivered;

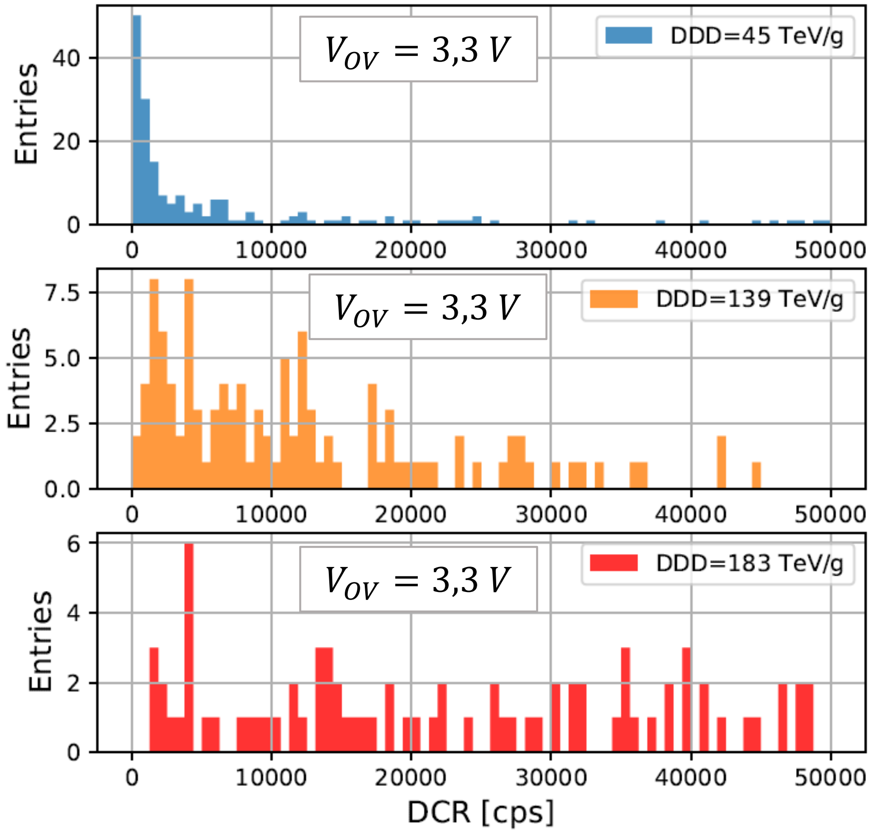
No relevant differences between PNWELL and PWNISO1/2 layouts.



$\frac{\Delta\,\mathrm{DCR}}{DDD}\left[\frac{cps}{TeV}g\right]$	PNWELL	PWNISO1	PWNISO2
	708	678	692

DCR increase factor from linear fit

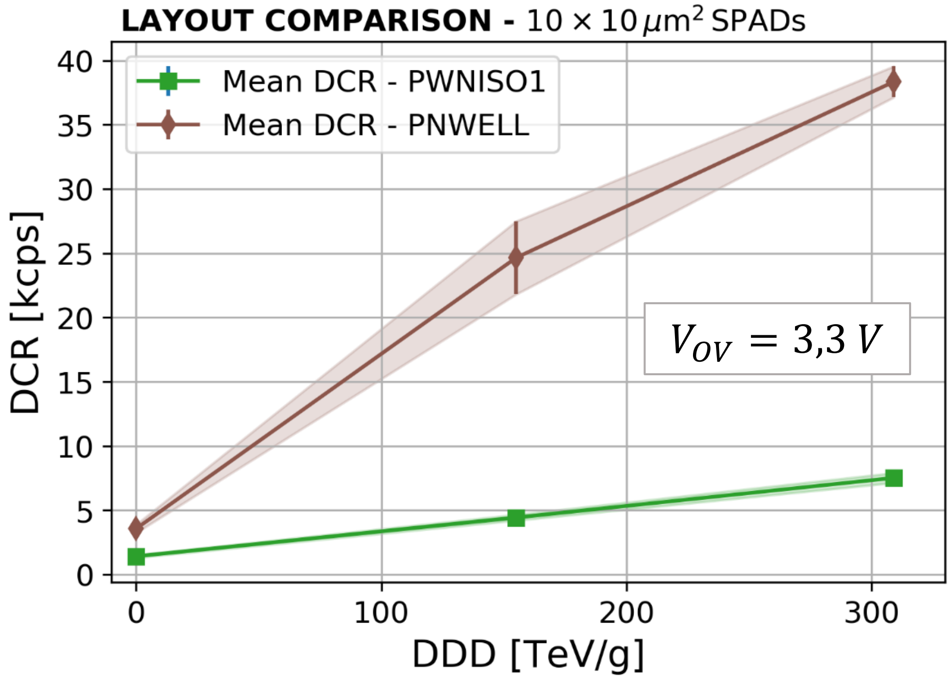
DCR distribution in PWNISO1 during irradiation

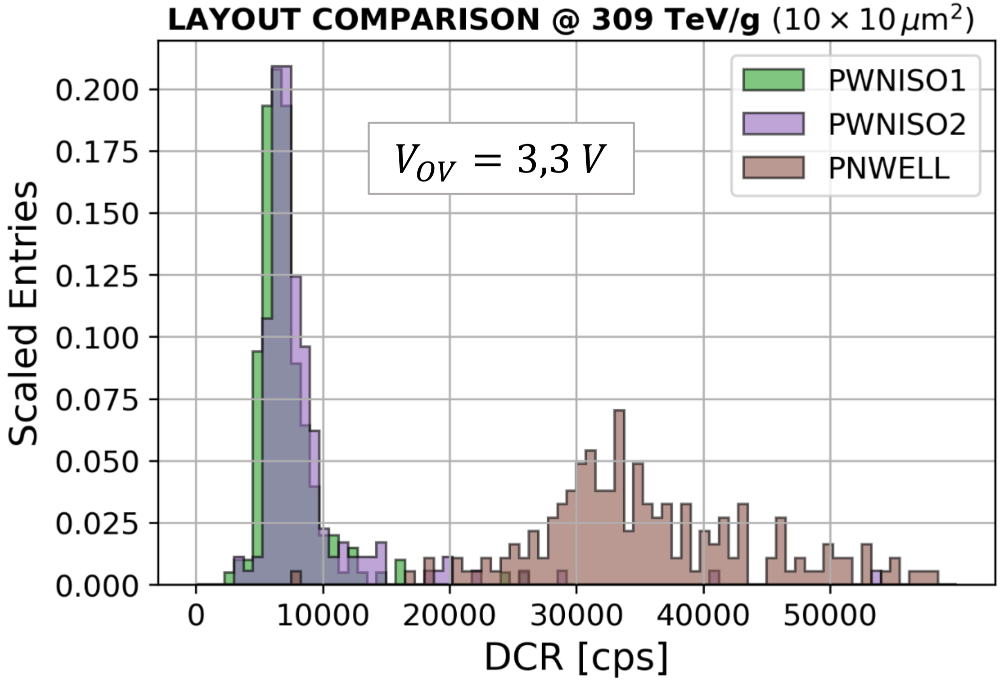


Electron irradiations effects

PWNISO1 and 2 shows no significant differences: no role due to defects created in the STIs;

For the PNWELL the DCR increase is 5 time larger than in PWNISO1-2, beside the smaller active volume.





$\frac{\Delta \text{DCR}}{DDD}\left[\frac{cps}{TeV}g\right]$	PNWELL	PWNISO1	PWNISO2
	112	19,8	20,1

DCR increase factor from linear fit

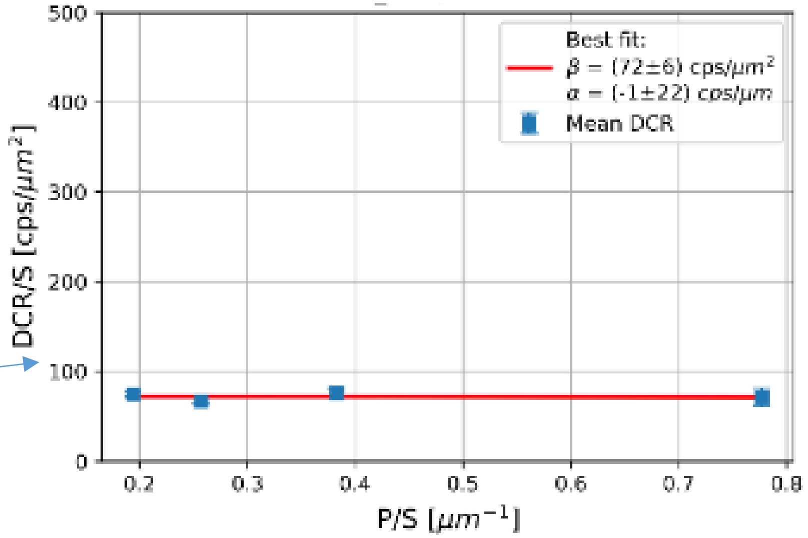
DCR induced degradation: P/S analysis

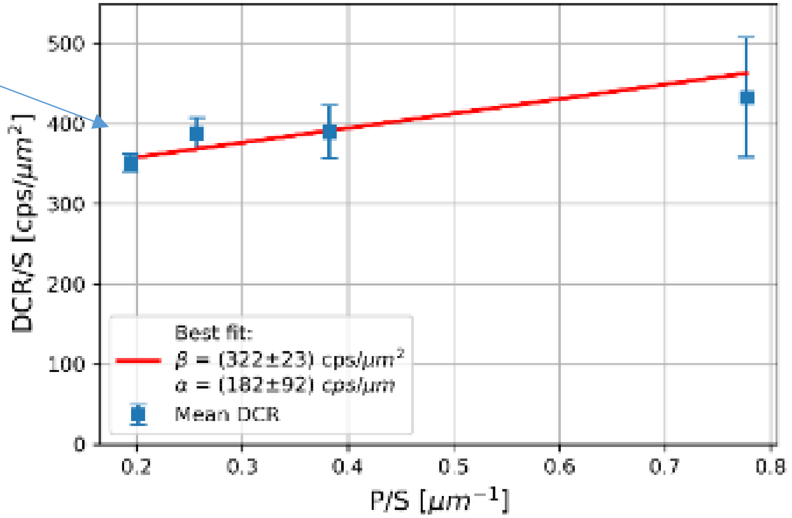
Possible indications about the origin of the damage, i.e., ionization and/or displacement from P/S dependence analysis.

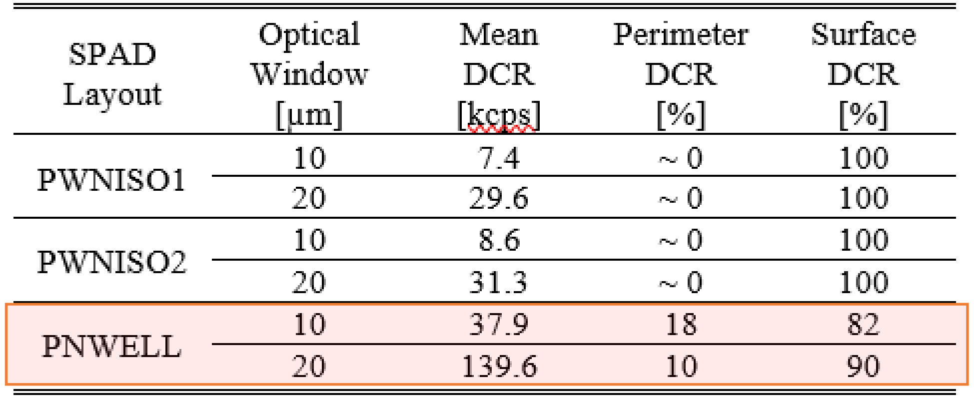
- TID effects expected at the perimeter of the SPAD, due to trapped interface states induced in the STI leads
- Non-ionizing effects expected from defects distributed in entire p-n depletion volume.

Only surface dependence in the PWNISO junction.

Some perimeter contribution observed in the PNWELL junction.







SPAD Layout	Optical Window [μm]	Mean DCR [kcps]	Perimeter DCR [%]	Surface DCR [%]
PWNISO1	10	7.4	~ 0	100
	20	29.6	~ 0	100
PWNISO2	10	8.6	~ 0	100
	20	31.3	~ 0	100
PNWELL	10	37.9	18	82
	20	139.6	10	90

TABLE II. Dark Count Rate analysis on different SPAD structures irradiated at a displacement damage dose of 309 TeV/g.

DCR induced degradation: NIEL scaling

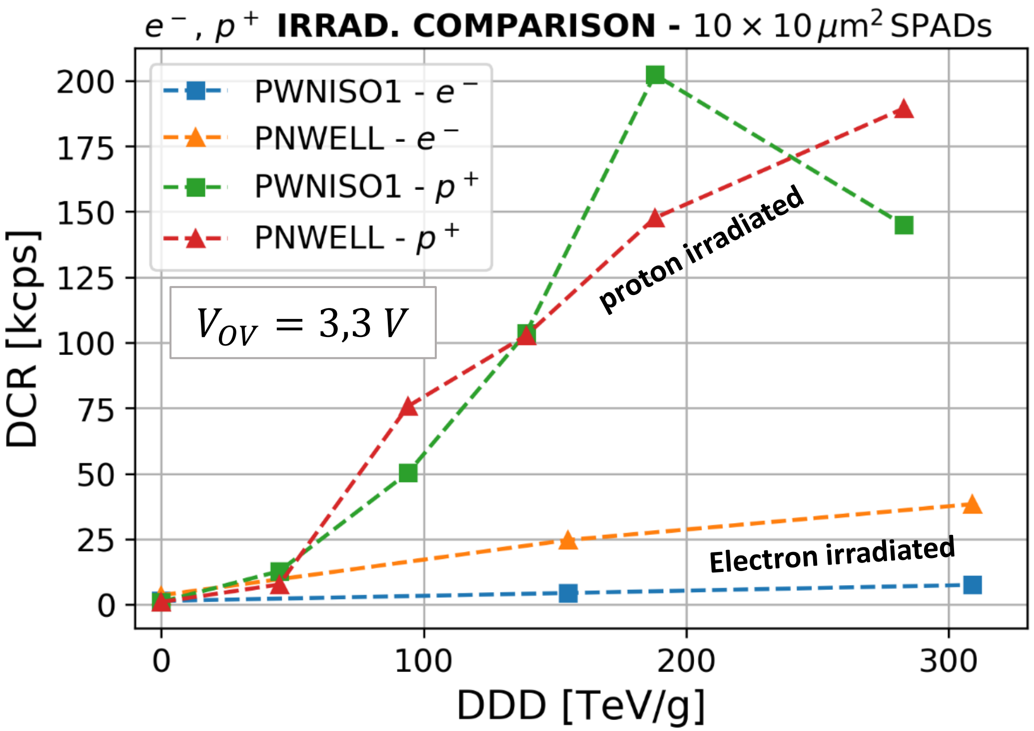
Effects induced by 2 MeV and 16 MeV protons in comparison

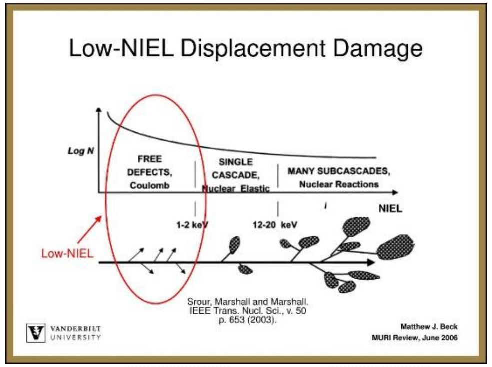
- **degradation after electron irradiation lower wrt proton irradiation**

Similar effects reported in literature for various devices.
In [1] an effective NIEL for electrons has been proposed.

Might depend on the induced defect type:

- Low-Energy electrons produce mainly isolated defects (point-like defects).
- Protons produce defects relatively close together to form a local region of disorder (defect cluster).


e^-, p^+ **IRRAD. COMPARISON -** $10 \times 10\,\mu m^2$ SPADs


Low-NIEL Displacement Damage

Srour, Marshall and Marshall.
IEEE Trans. Nucl. Sci., v. 50
p. 653 (2003).

Matthew J. Beck
MURI Review, June 2006

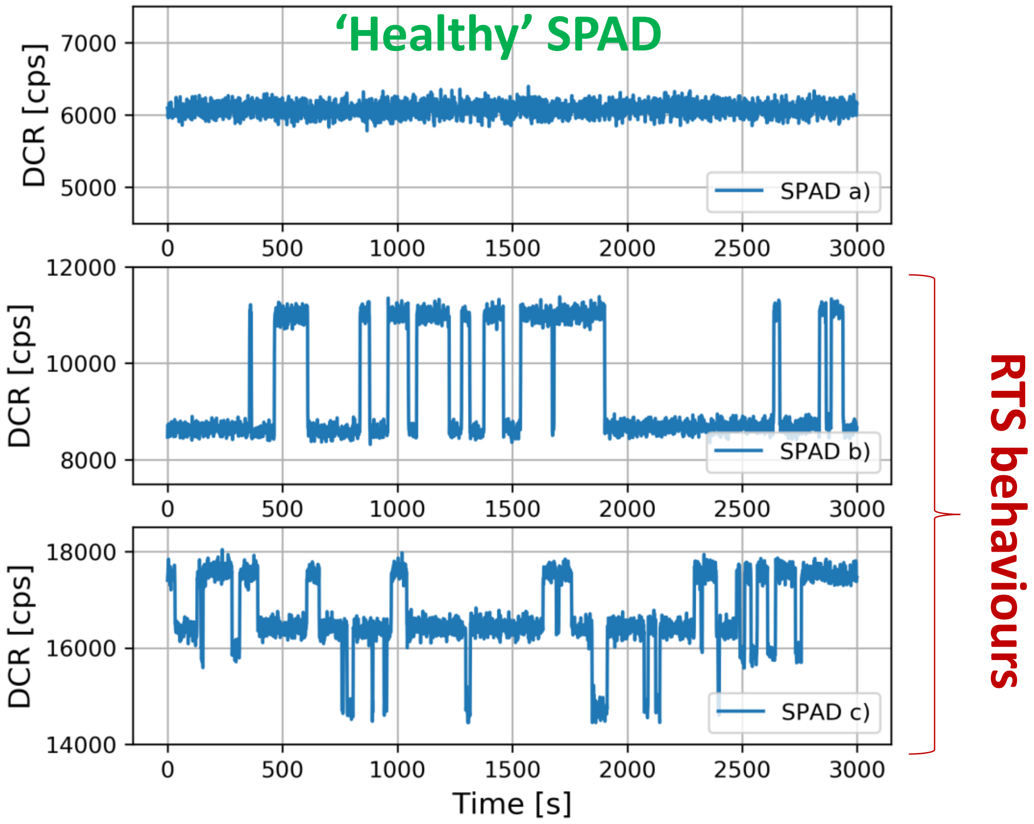
[1] *P. Arnolda, et al.,* NIEL Scaling: Comparison With Measured Defect Introduction Rate in Silicon

Random Telegraph Signals observation

After irradiation discrete fluctuation of DCR between two or more levels have been observed.

This phenomenon is known in literature as **Random Telegraph Signal Noise**.

DCR vs observation time



Similarities to the RTS effects observed in MOS devices, at the origin of the flicker noise.

In MOS, due to charge trapping/detrapping in defects at SiO2 interfaces

In SPADs, it is related to metastable defects located in the device bulk region.

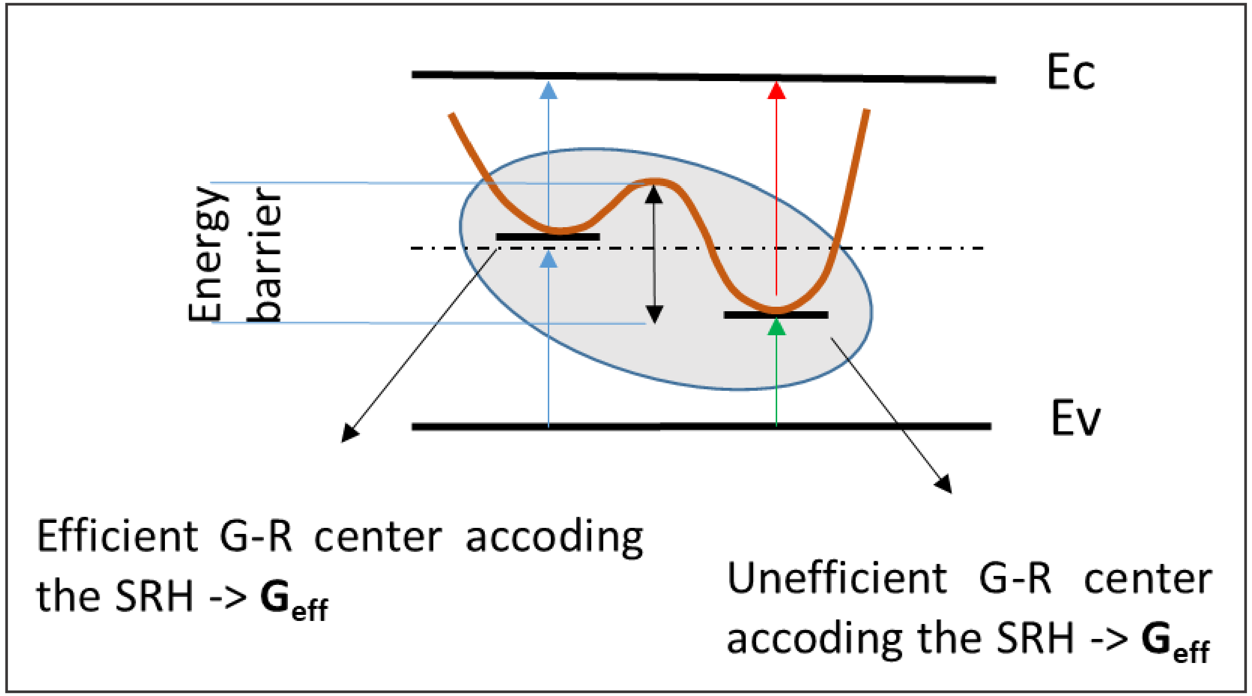
Random Telegraph Signal: defects

In bulk devices RTS origin due to defects which exists in two or more stable configurations.

Metastable defects can randomly change their configuration:

- As a consequence, the *e-h* generation rate can change, resulting a ‘jump’ in the level of DCR.
- An energy barrier must be overcome to switch from one configuration to another: for this reason the RTS switching frequency is expected to depend on the temperature.

Bi-stable complex defect schematization



Efficient G-R center accoding the SRH -> $\mathbf{G}_{\mathrm{eff}}$

Unefficient G-R center accoding the SRH -> $\mathbf{G}_{\mathrm{eff}}$

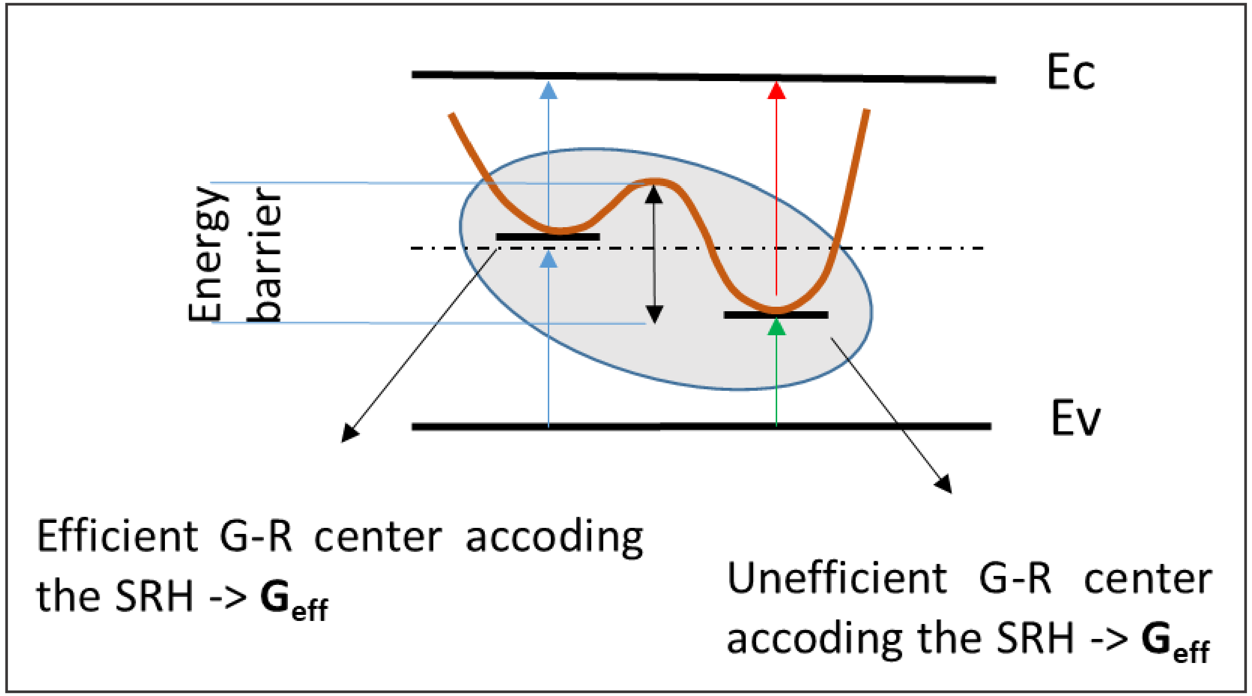
Random Telegraph Signal: defects

In bulk devices RTS origin due to defects which exists in two or more stable configurations.

Possible sources:

- **Phosphorus-Vacancy (P-V) defects** have a dipole structure. The dipole axis can change with the vacancy position and may induce RTS. [G. D. Watkins and J. W. Corbett, 1964; H. Hopkins, G.R. Hopkinson, 1995, T. Nuns, 2007]
- The interaction of neutral **di-vacancies in cluster defects** can produce a reaction called “Inter-center transfer” which has the effect of increase the generation rate.

Bi-stable complex defect schematization



Efficient G-R center accoding the SRH -> $\mathbf{G}_{\mathbf{eff}}$

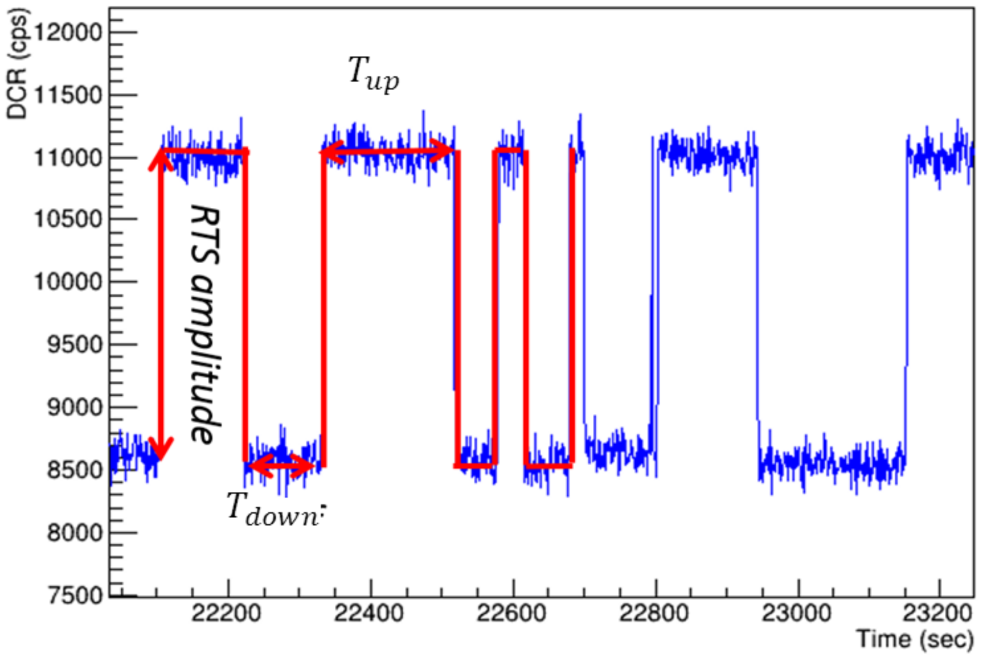
Unefficient G-R center accoding the SRH -> $\mathbf{G}_{\mathbf{eff}}$

RTS time analysis

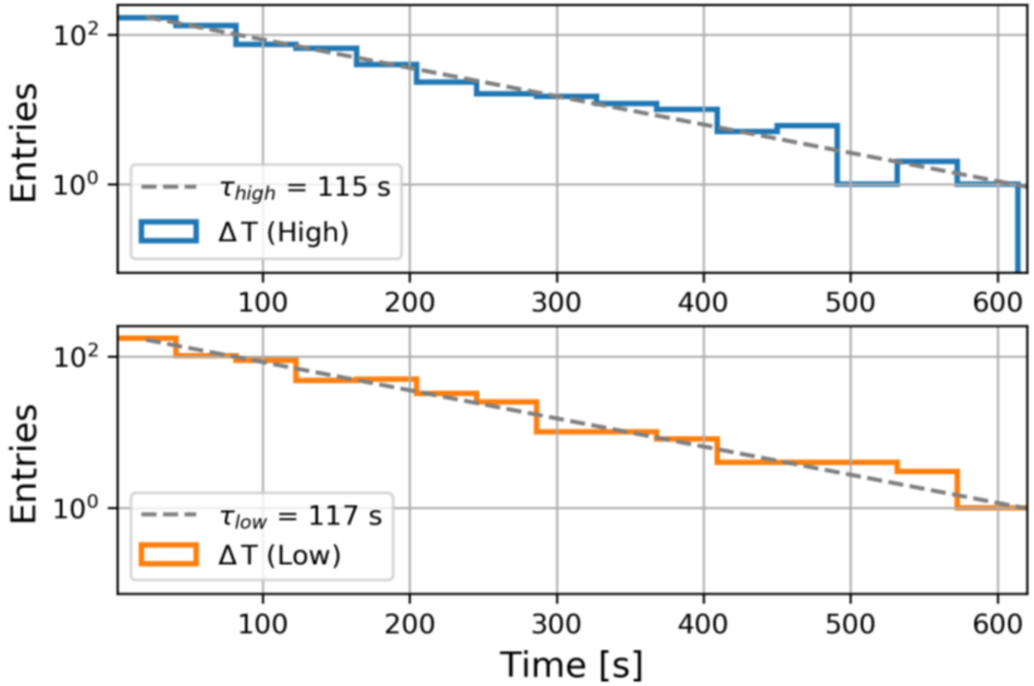
For the two-level case, **RTS behaviours analysed as a function of observation time**.

- Follow Poisson distribution law for random switching events.
    - Times between RTS transitions are exponentially distributed.

DCR vs observation time



Up/Down state time distribution

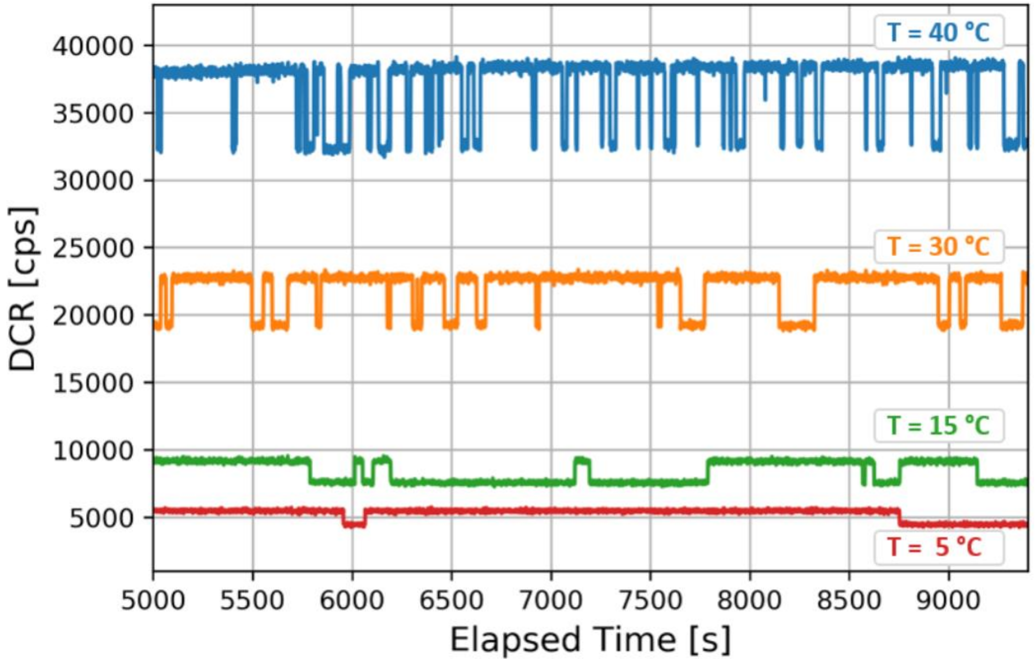


RTS vs temperature

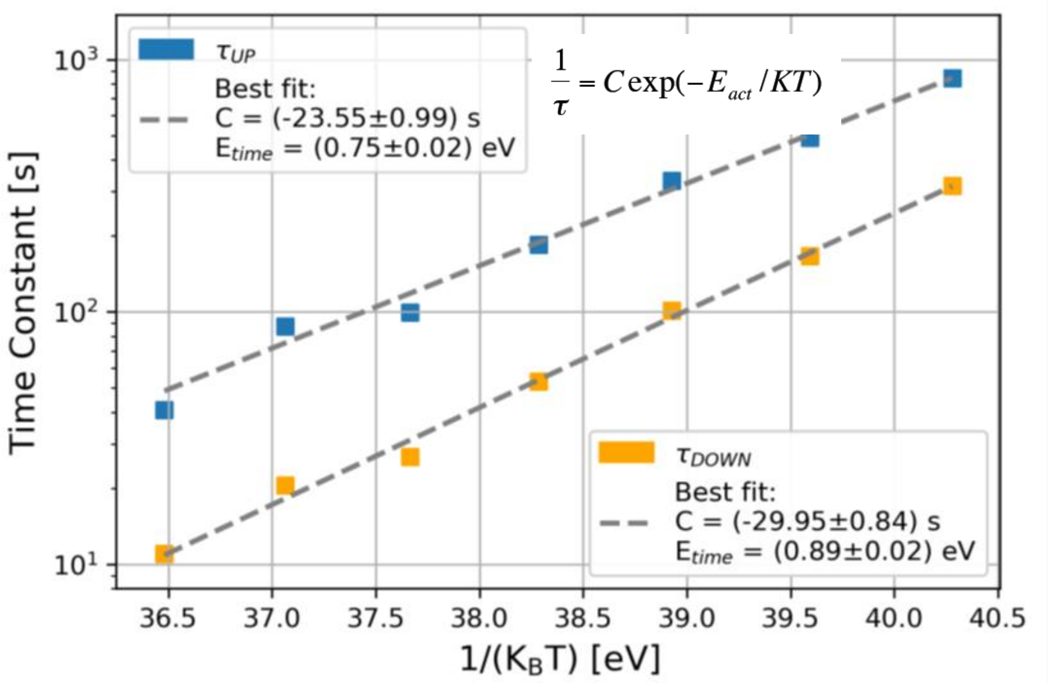
For the two-level case, **RTS behaviours analysed as a function of temperature**.

- RTS amplitude and switching probability increase with temperature, following an exponential dependence.

RTS as a function on Temperature



RTS time constant vs. Temperature

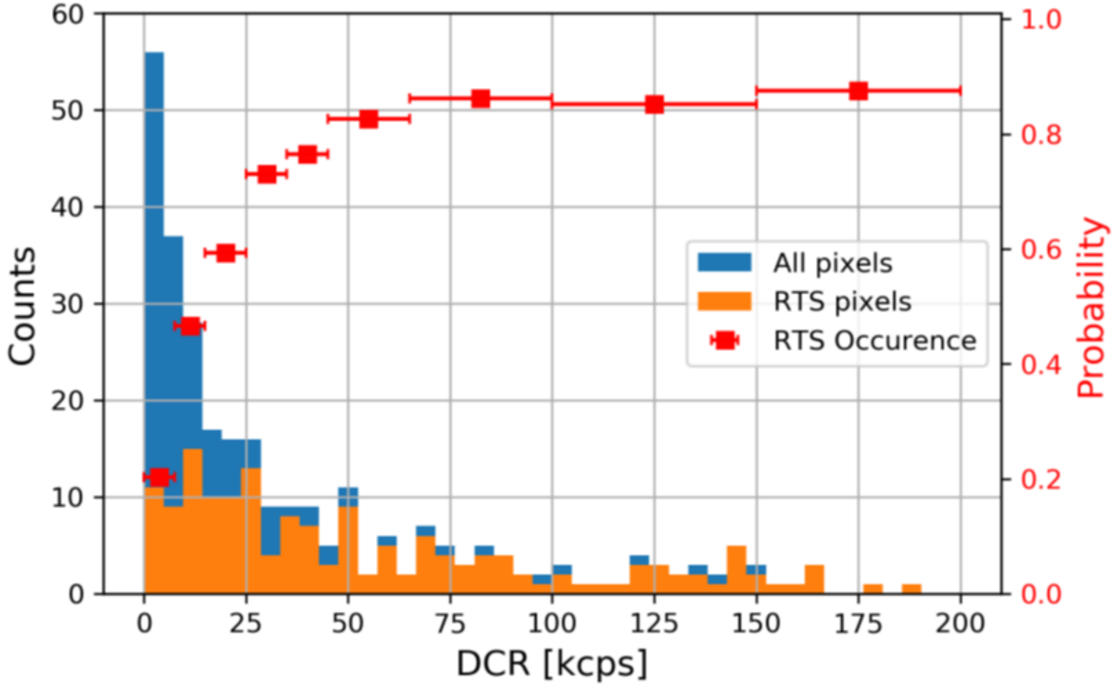


RTS occurrence

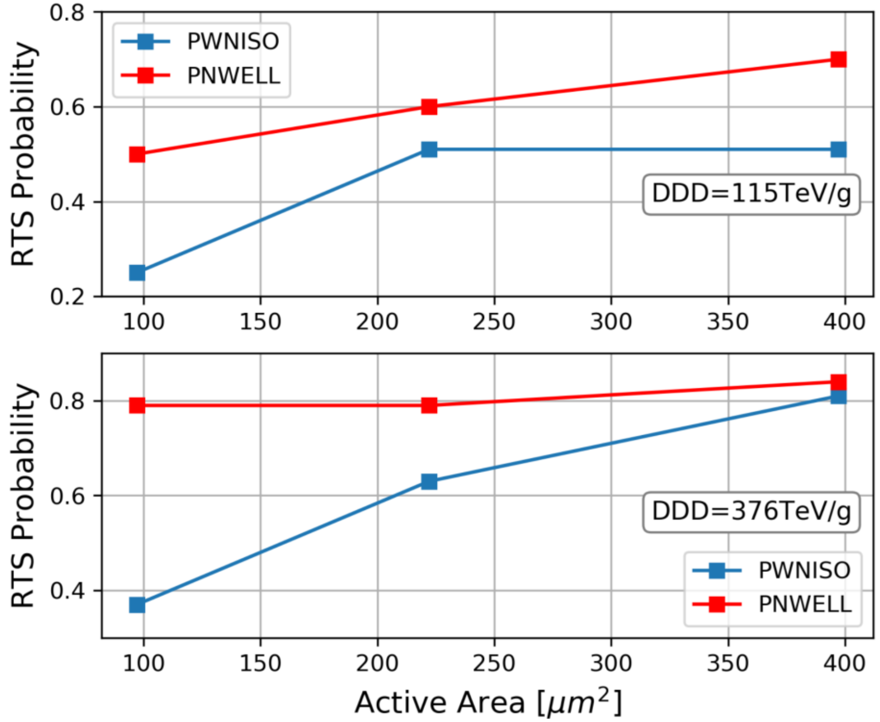
RTS occurrence studied for different SPAD layouts:

- higher probability to observe RTS occurrence for pixels that exhibit high DCR after irradiation.
- probability of having RTS increases with the SPAD sensitive area and with the DDD level.

RTS probability vs SPAD DCR



RTS probability vs SPAD area



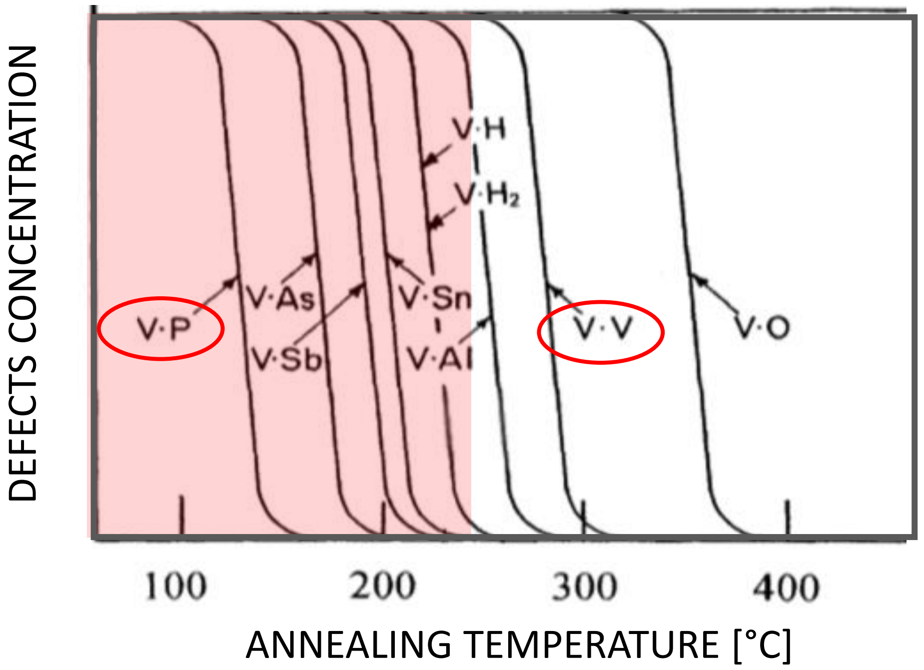
Isochronal Annealing

The annealing procedure is a useful tool to investigate the defects responsible for DCR and RTS.

- Different bound energy of the defects results in different annealing temperature:
  - P-V centers anneal at about 130°C
  - Di-Vacancies anneal at 270°C

Our results suggest the P-V complex defects as a candidate responsible for DCR increase and Random Telegraph Signal behaviour.

Schematic of vacancy-defect annealing *



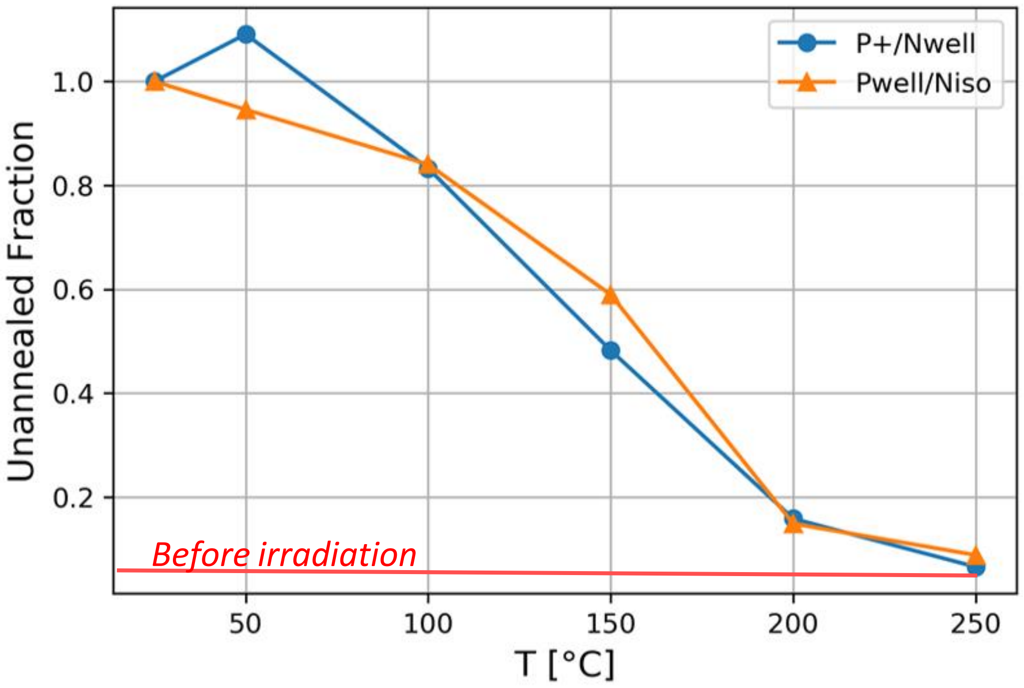
***“Annealing of Proton-Induced Random Telegraph Signal in CCDs” ,** T. Nuns et al.

Isochronal Annealing

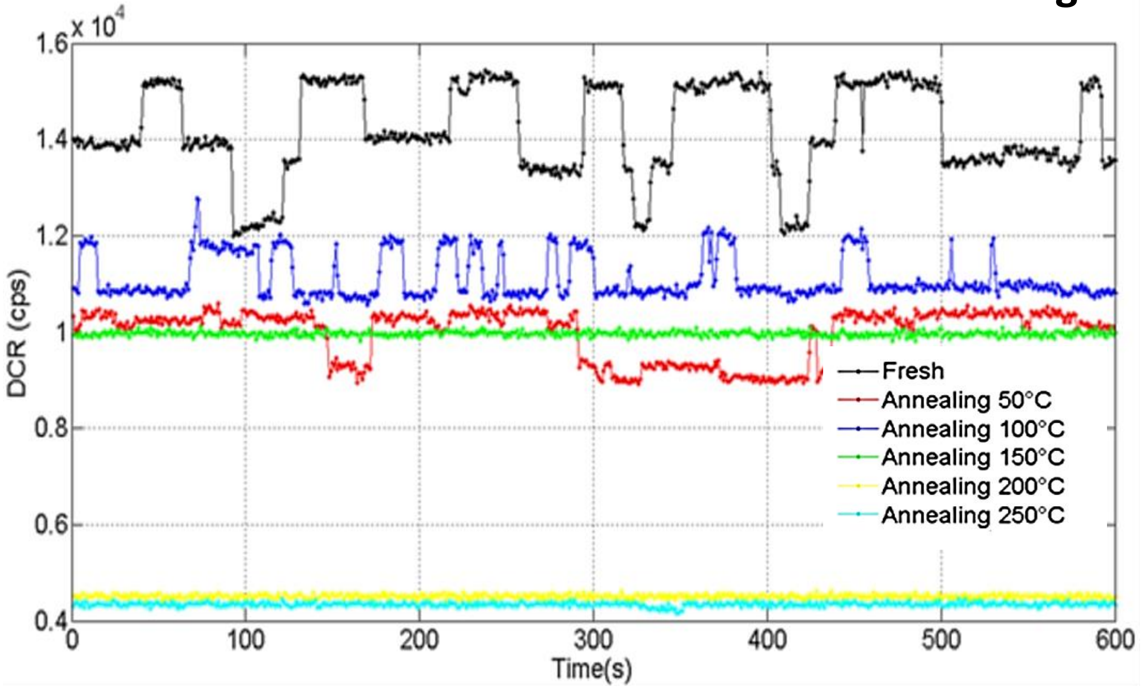
DCR of irradiated SPAD has been measured after several annealing steps between 50°C and 250°C.

- After annealing the mean DCR recovered its initial value, while multi-level RTS transformed into lower level and less frequent RTS, before completely disappear.

Mean DCR vs annealing step



Evolution of DCR vs Time as a function of Annealing



Backup

References

“Proton induced dark count rate degradation in 150-nm CMOS single-photon avalanche diodes”, *M. Campajola et al.*

“Random Telegraph Signal in Proton Irradiated Single-Photon Avalanche Diodes”, *F. Di Capua et al.*

Random Telegraph Noise

- Phosphorus-Vacancy (P-V) defects can be generated in doped silicon devices. It can be formed at any of four Si-atoms around the P-atom.
- P-V center has a dipole structure. The dipole axis can change with the vacancy position and may induce RTS.
- Calculation on kinetics of reorientation predicts 0.9 eV for activation energy. [G. D. Watkins and J. W. Corbett, 1964; H. Hopkins, G.R. Hopkinson, 1995, T. Nuns, 2007]

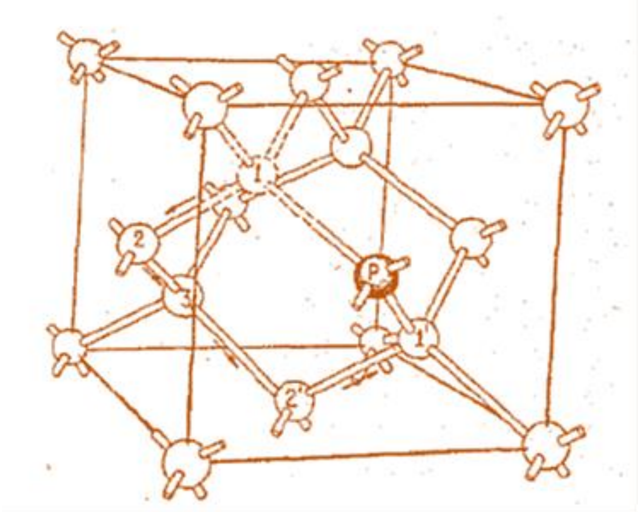


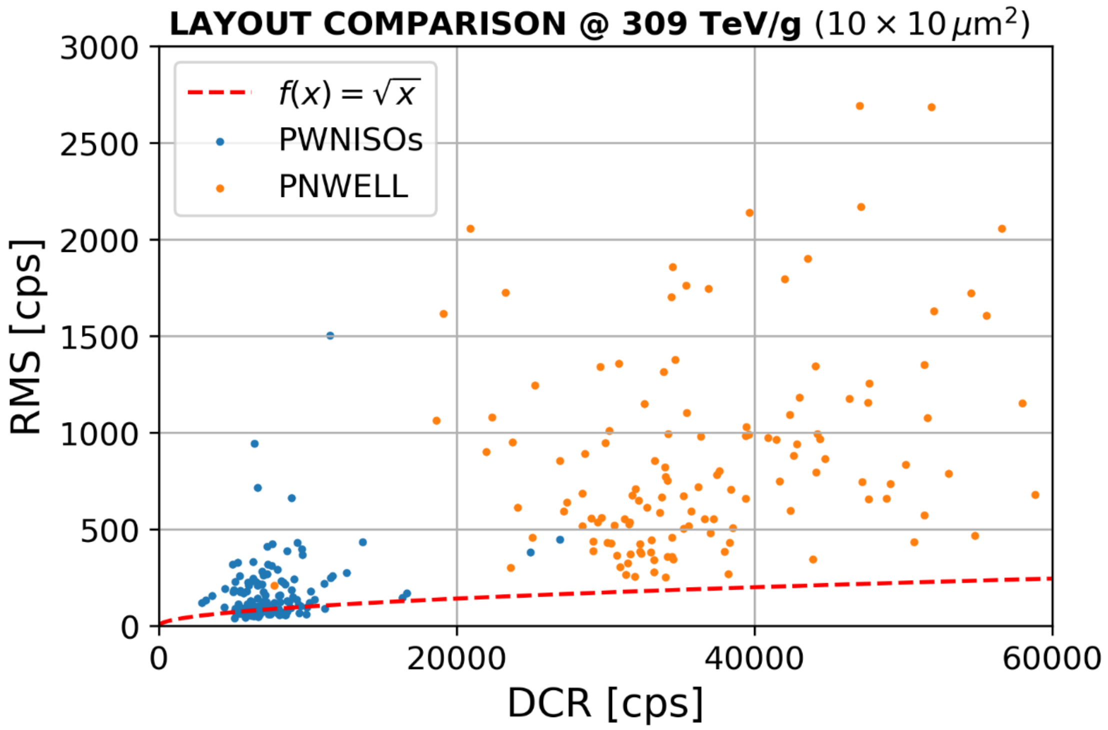
Figure from Watkins & Corbett (1964)

- Di-Vacancies cluster: these defects have three energy levels and four charge states (+,0,-,2-).
- The interaction of neutral di-vacancies (the most probable state) can produce a reaction called “Inter-center transfer” which has the effect to increase the generation rate.
- The rearrangement of defects can create configuration in which inter-center transfer is possible and in other no, giving rise to RTS.

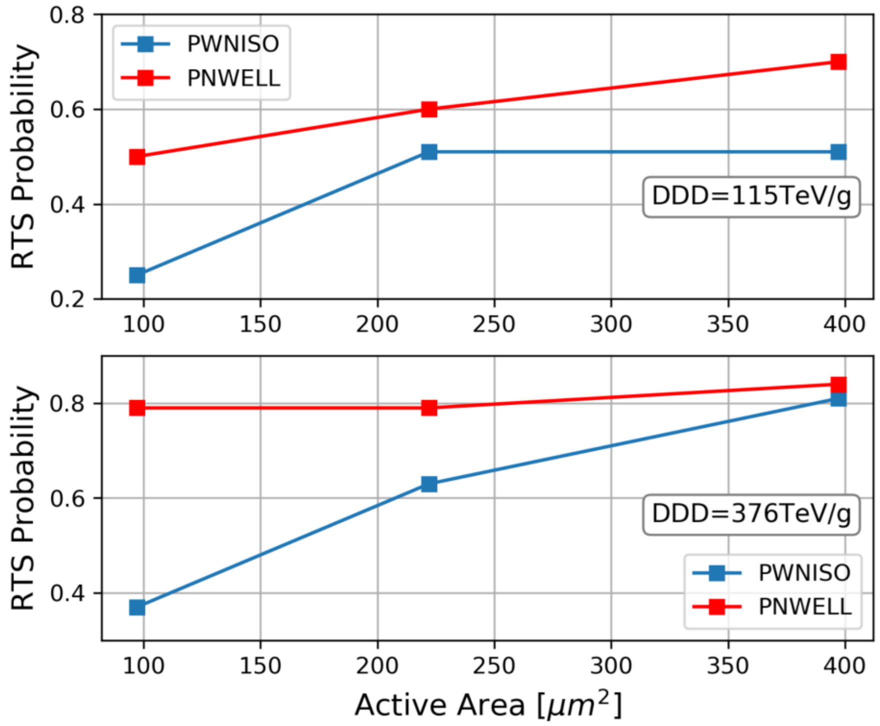
RTS occurrence

RTS occurrence studied for different SPAD layouts:

- higher probability in PN junctions


LAYOUT COMPARISON @ 309 TeV/g $(10 \times 10\,\mu m^2)$

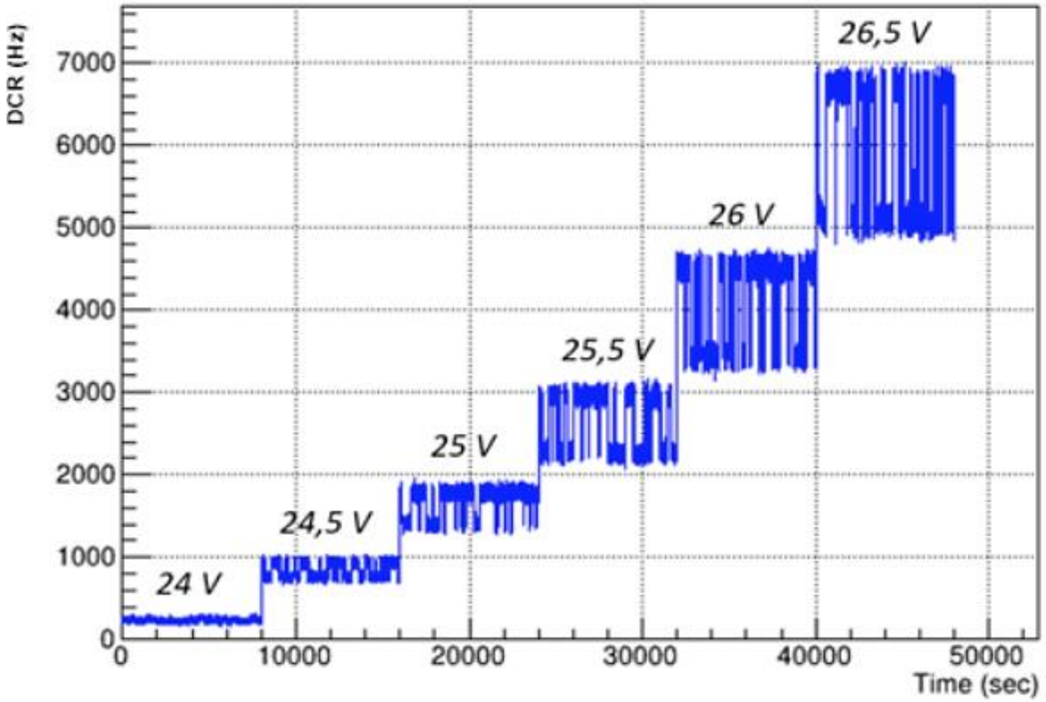
RTS probability vs SPAD area



Random Telegraph Noise

- RTS amplitude increase with the overvoltage

RTS amplitude vs overvoltage

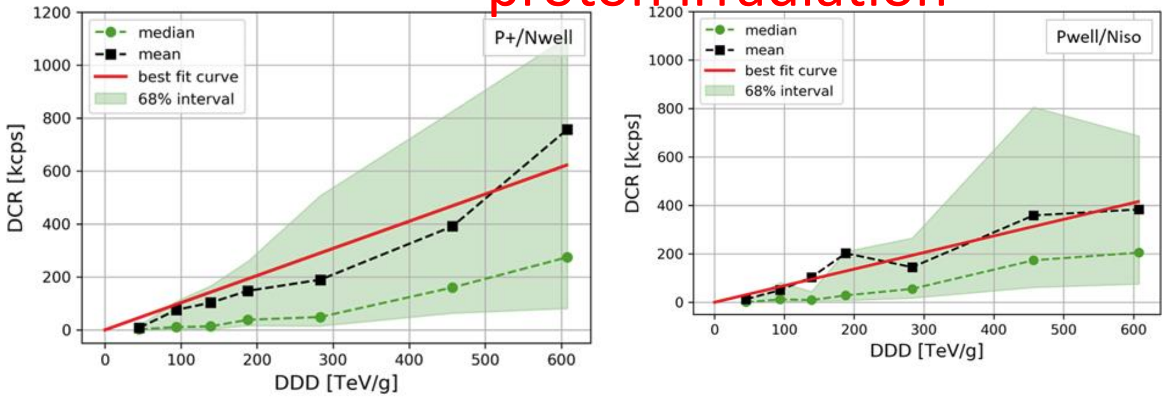


Radiation damage studies

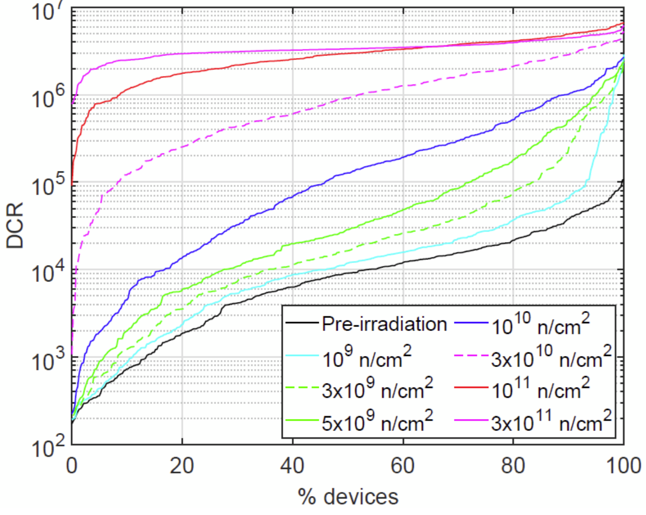
Large degradation observed in previous studies [1]:

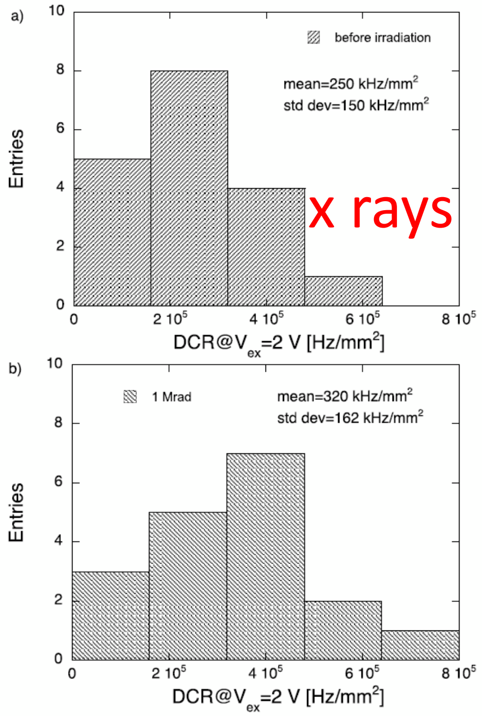
- First 150 nm devices -> few MHz/mm^2
  - ∽ GHz/mm^2 at 10^{10} p/cm^2
- APIX 180 nm devices: 1 MHz/mm^2 [2,3,4]
  - ∽ GHz/mm^2 at 10^{11} n$_{eq}$/cm^2
  - +30% DCR increase with 1 Mrad

proton irradiation



neutron irradiation



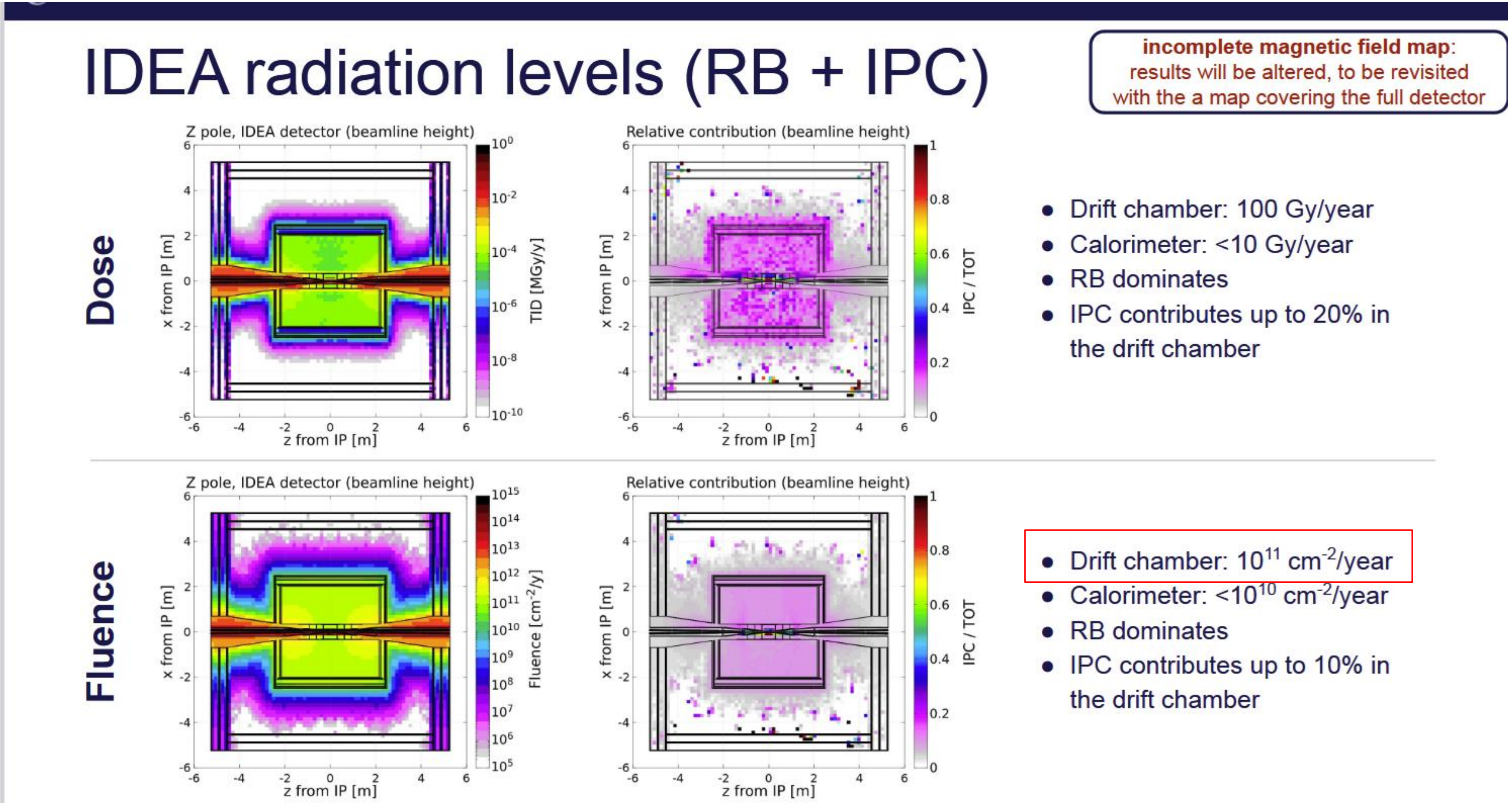


x rays

[1] M. Campajola, et al., Proton induced dark count rate degradation in 150-nm CMOS single-photon avalanche diodes, NIMA
[2] M. Musacci, et al. "Radiation tolerance characterization of Geiger-mode CMOS avalanche diodes for a dual-layer particle detector." NIMA
[3] L. Ratti, et al. “Dark Count Rate Degradation in CMOS SPADs Exposed to X-Rays and Neutrons” TNS
[4] A. Ficorella, APPLICATION OF AVALANCHE DETECTORS IN SCIENTIFIC AND INDUSTRIAL MEASUREMENT SYSTEMS, PhD thesis

FCC doses

link



IDEA radiation levels (RB + IPC)

incomplete magnetic field map:
results will be altered, to be revisited
with the a map covering the full detector

Dose

- Drift chamber: 100 Gy/year
- Calorimeter: <10 Gy/year
- RB dominates
- IPC contributes up to 20% in the drift chamber

Fluence

- Drift chamber: 10^{11} cm^{-2}/year
- Calorimeter: <10^{10} cm^{-2}/year
- RB dominates
- IPC contributes up to 10% in the drift chamber