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Random telegraph noise investigation in irradiated digital SiPMs

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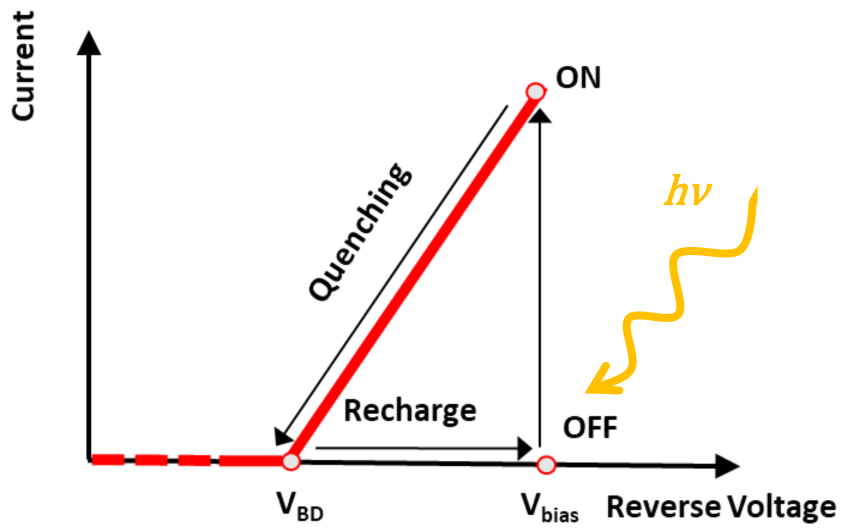
Single-Photon Avalanche Diodes

Single-Photon Avalanche Diodes (SPADs) are photodiodes biased above the breakdown voltage.

Working principle:

- A single photon hitting the sensitive area can trigger the self-sustaining avalanche;
- A quenching circuit stops the avalanche decreasing bias voltage;
- SPAD is again able to detect a new photon;

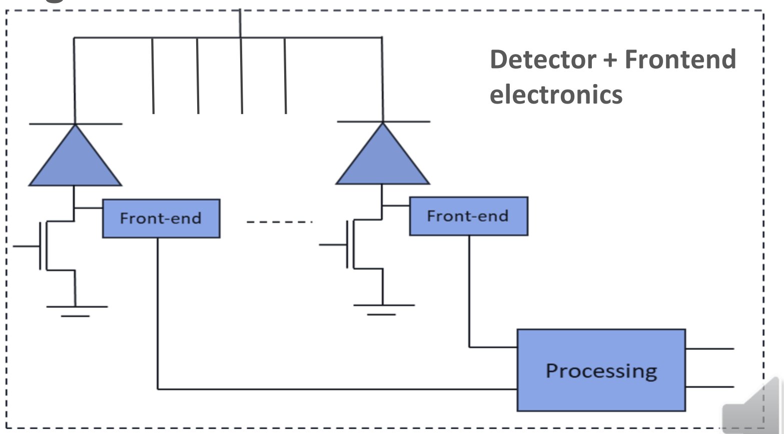
SPADs have sensitivity at the single-photon level with no need for amplification, and good timing resolutions.



First implementation of SPAD in CMOS technological process has been achieved in 2003:

- Excellent timing resolution;
- Position sensitive;
- SPADs individually selectable;
- Post-processing circuits integrated on chip;
- High DCR wrt custom processes;

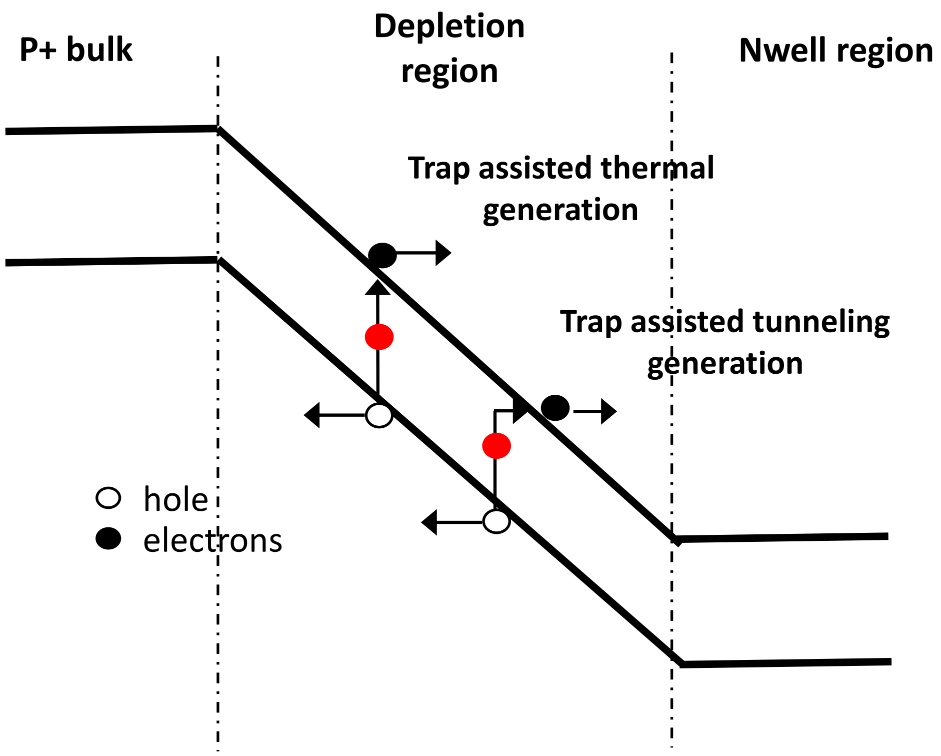
Digital SiPM



Dark Count Rate sources

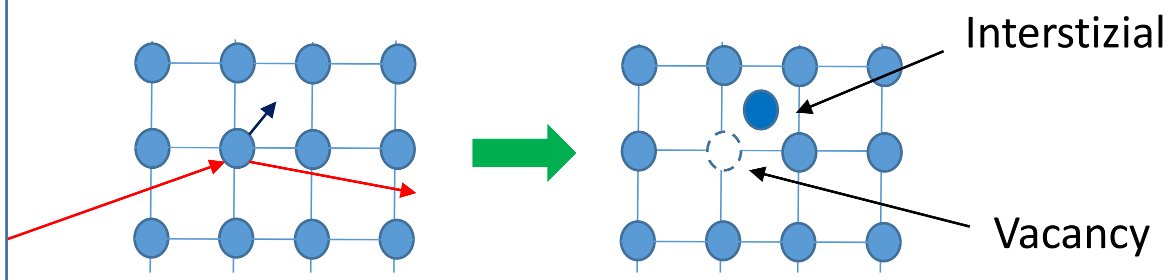
Dark Count Rate (DCR) strongly depends on the presence of mid-gap energy levels. They lead to an enhancement of the generation rate of carriers in depletion region through both

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



Mid-gap energy levels due to:

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



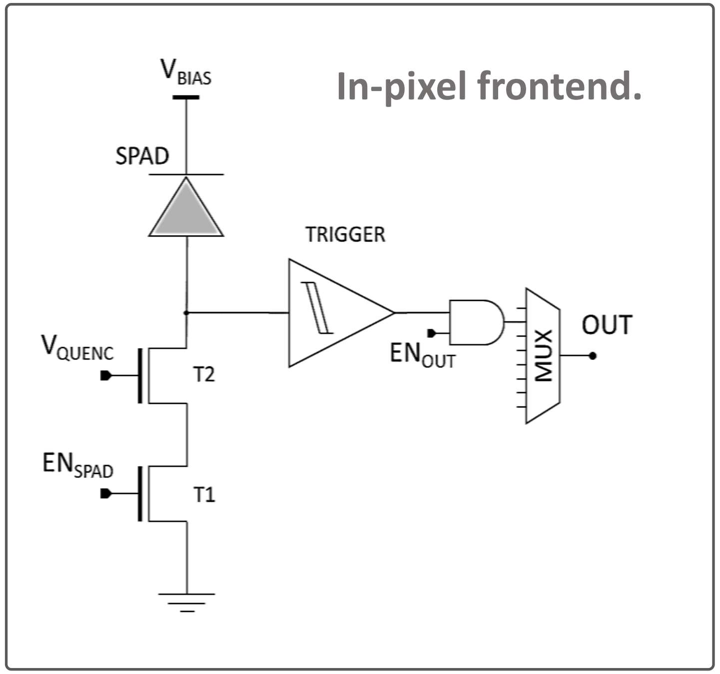
Displacement of Si-atoms from lattice structure due to incident particles. Typical defects are dopant-related vacancy complexes, as phosphorus-vacancy (P-V), or di-vacancy (V-V) defects.

Devices under test

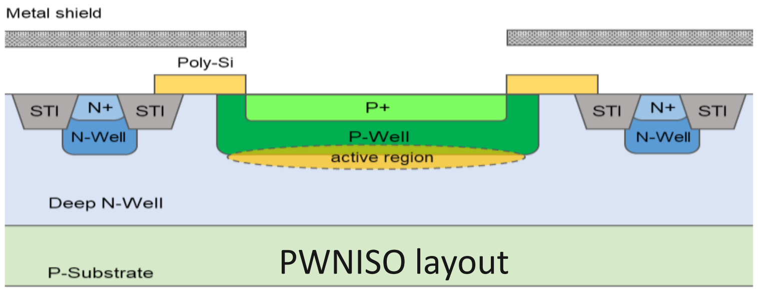
Devices designed by Fondazione Bruno Kessler (FBK), and implemented in a 150-nm CMOS process (LFoundry).

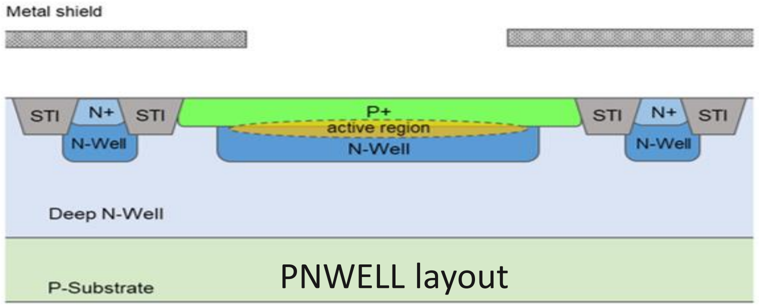
[*Low-noise Single Photon Avalanche Diodes in 0.15 µm CMOS Technology, L. Pancheri, D. Stoppa*]

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



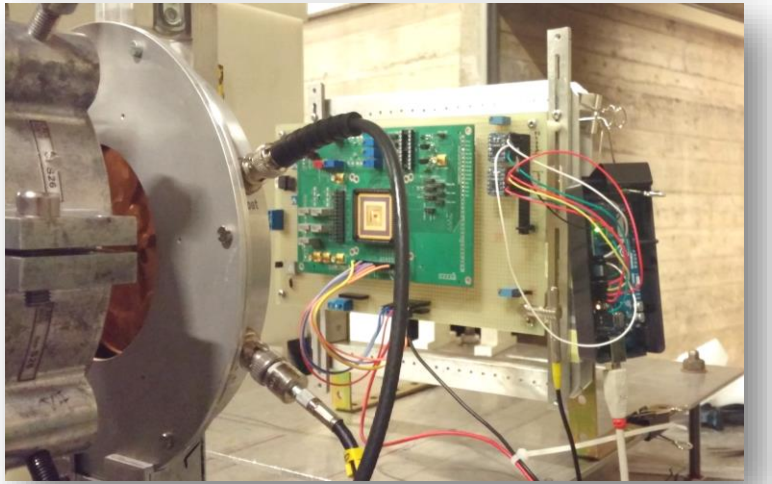
- Two junction layouts, and several active area sizes (5, 10, 15, 20 µm);





Irradiation test

Test at Tandem Accelerator line @ LNS

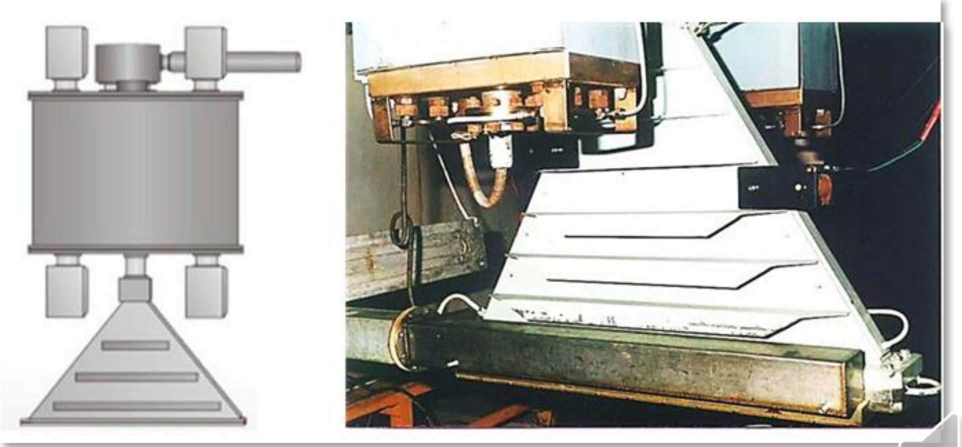


Irradiation test with protons and electrons.

- Proton test performed at INFN-LNS in Catania (Italy) using:
    - 21 and 16 MeV proton beam;
    - Delivered fluences: 10^{10} - 10^{11} p/cm^2
    - Displacement Damage Dose (DDD) up to 600 TeV/g

- 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
    - Displacement Damage Dose (DDD) up to 300 TeV/g

Test at ILU-6 accelerator @ ICNT

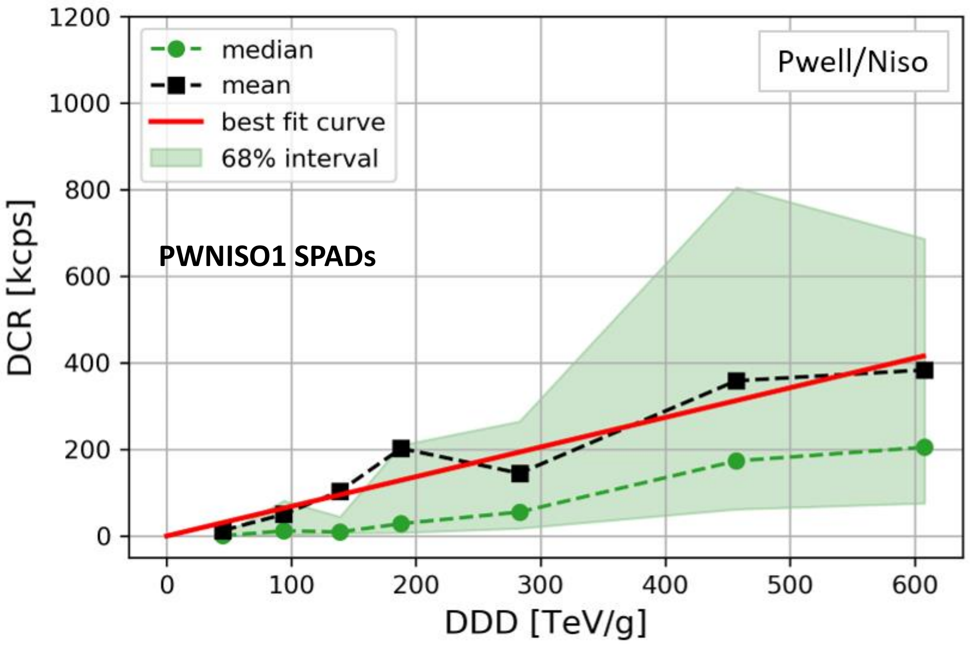


DCR Induced Degradation

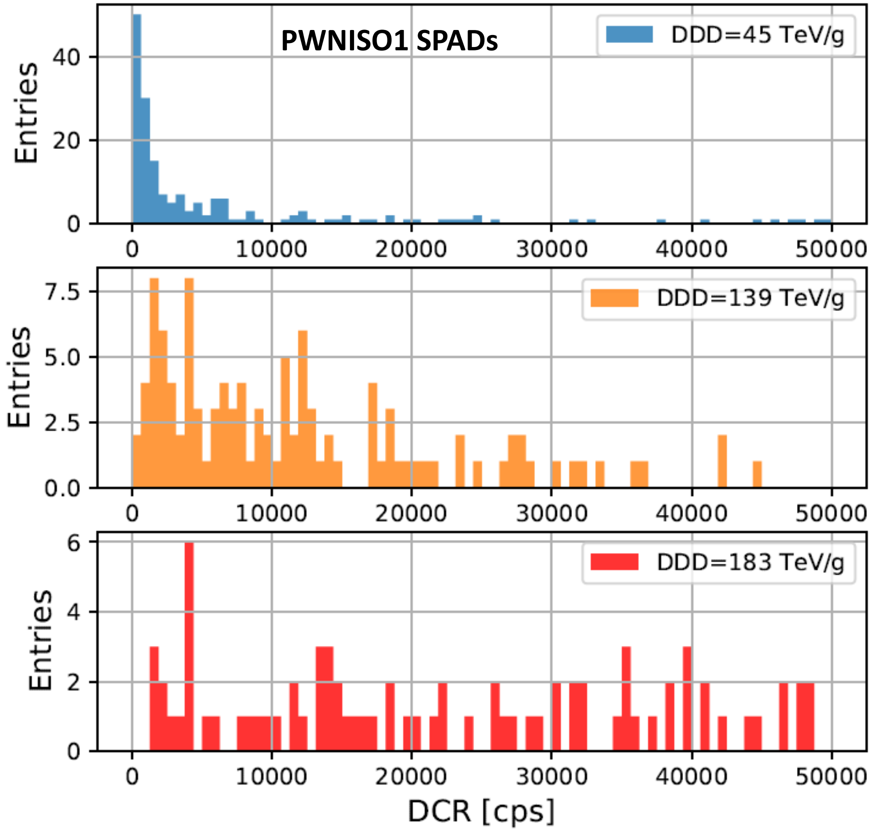
High susceptibility to the DCR increase as a function of the displacement dose induced by protons:

- Mean DCR increases up to two order of magnitude at maximum dose delivered;
- No significative changes in the breakdown voltage.

Mean DCR increase vs DDD



DCR distribution after *p+* irradiation

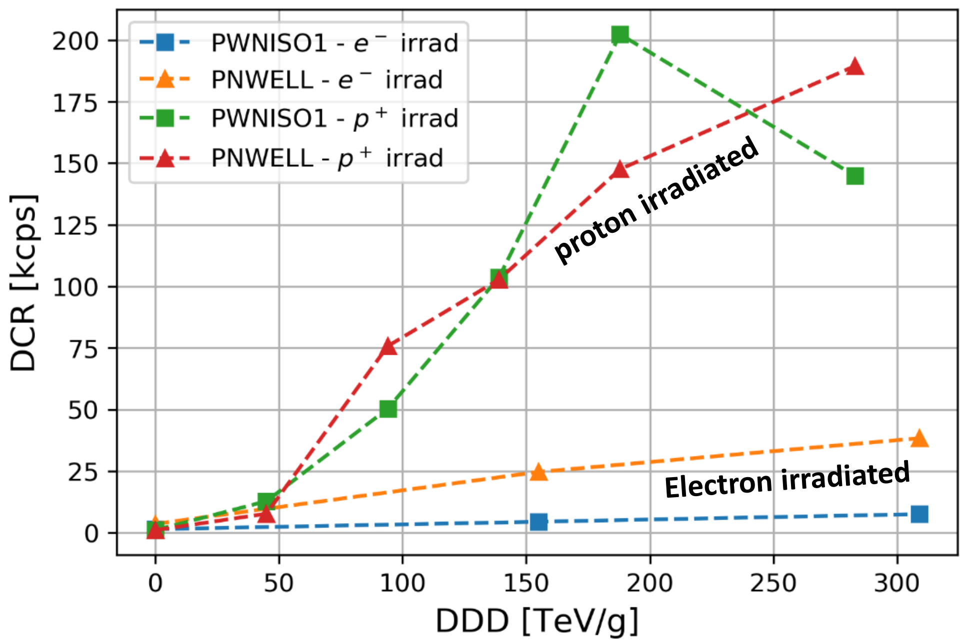


DCR Induced Degradation

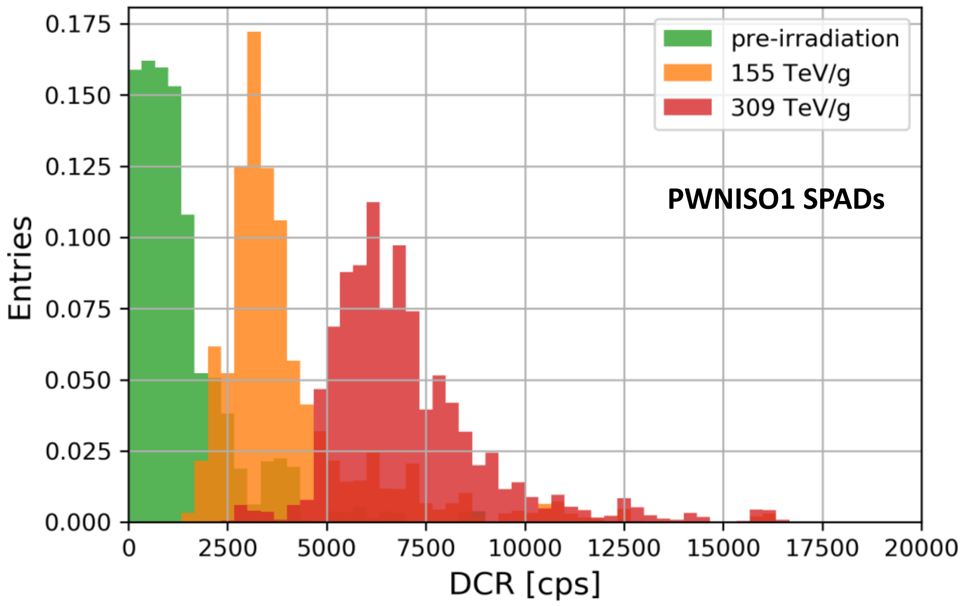
A minor degradation has been observed in electron irradiated SPADs.

- Electrons with energy less than about 2 MeV, produce relatively isolated defects (point-like defects).
- Defects induced by protons may be produced relatively close together and form a local region of disorder (defect cluster).

Mean DCR increase as a function of the dose



DCR distribution after *e-* irradiation

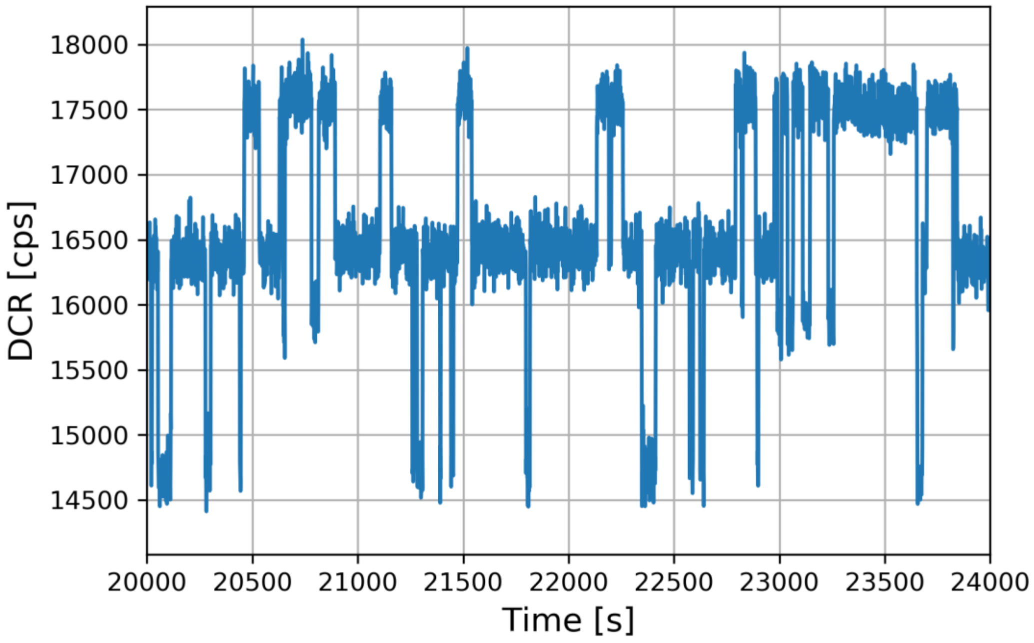


Random Telegraph Signal Noise

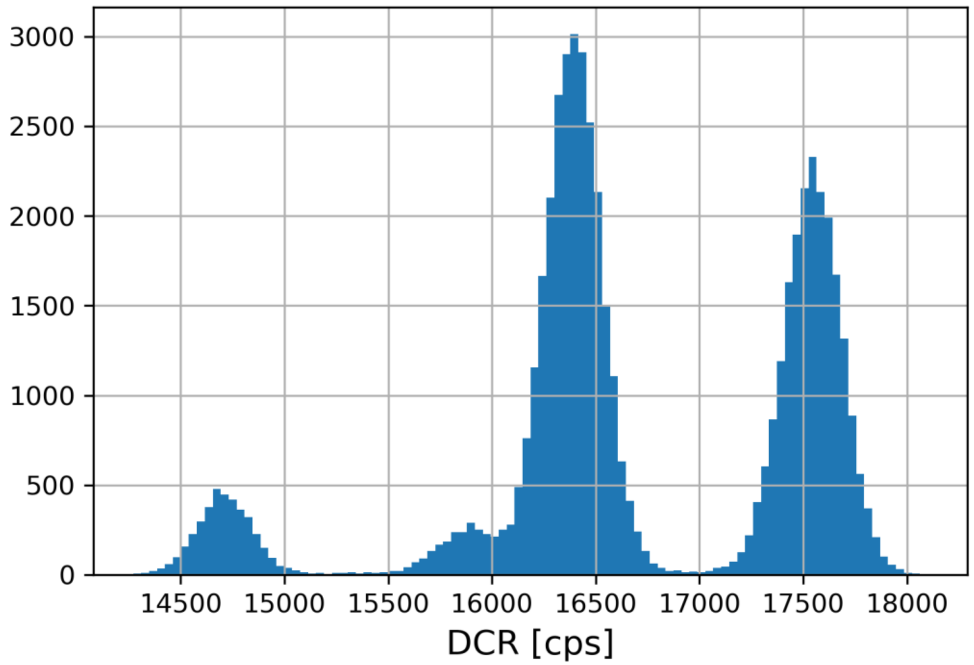
After irradiation discrete fluctuation of DCR between two or more levels have been observed.

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

DCR vs observation time



DCR distribution

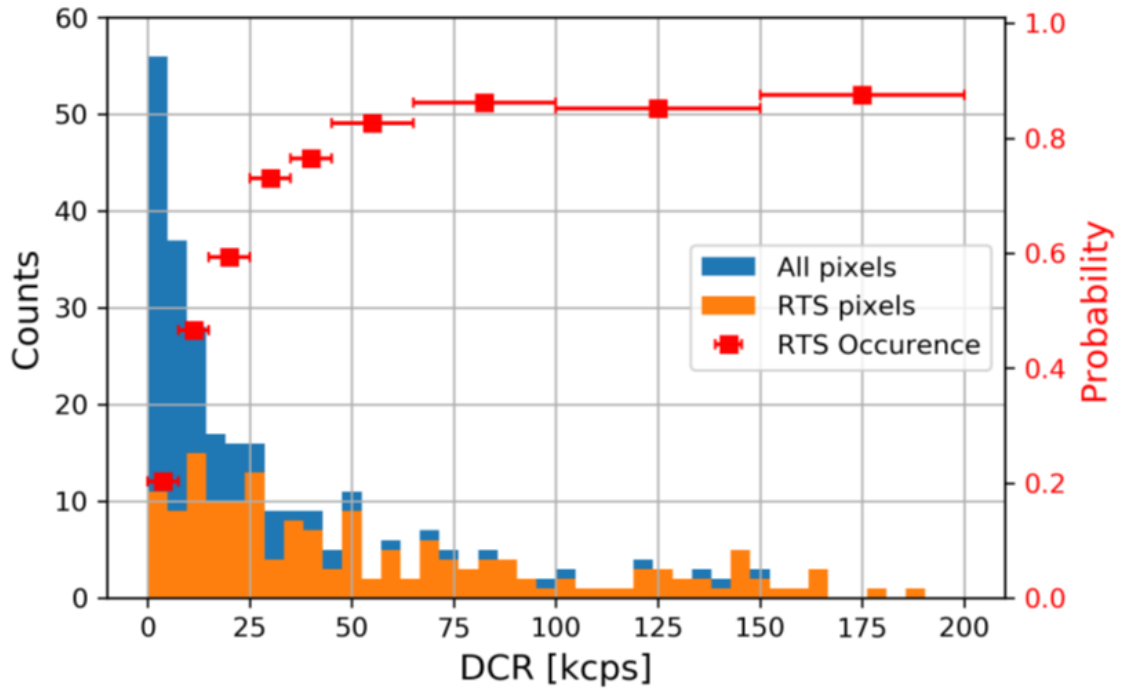


Random Telegraph Signal Noise

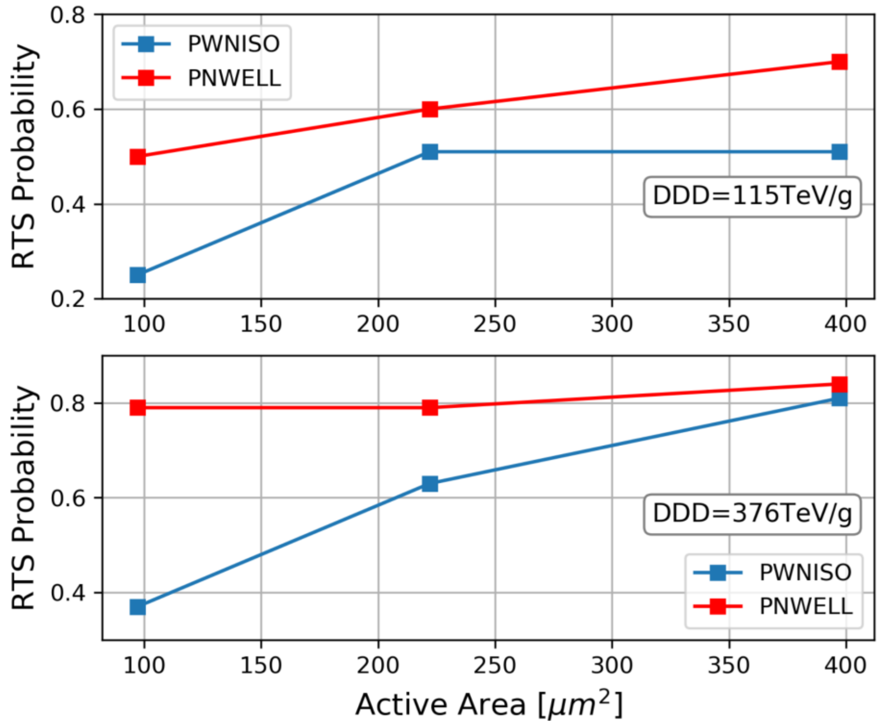
RTS occurrence probability studied for different SPAD layouts:

- 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

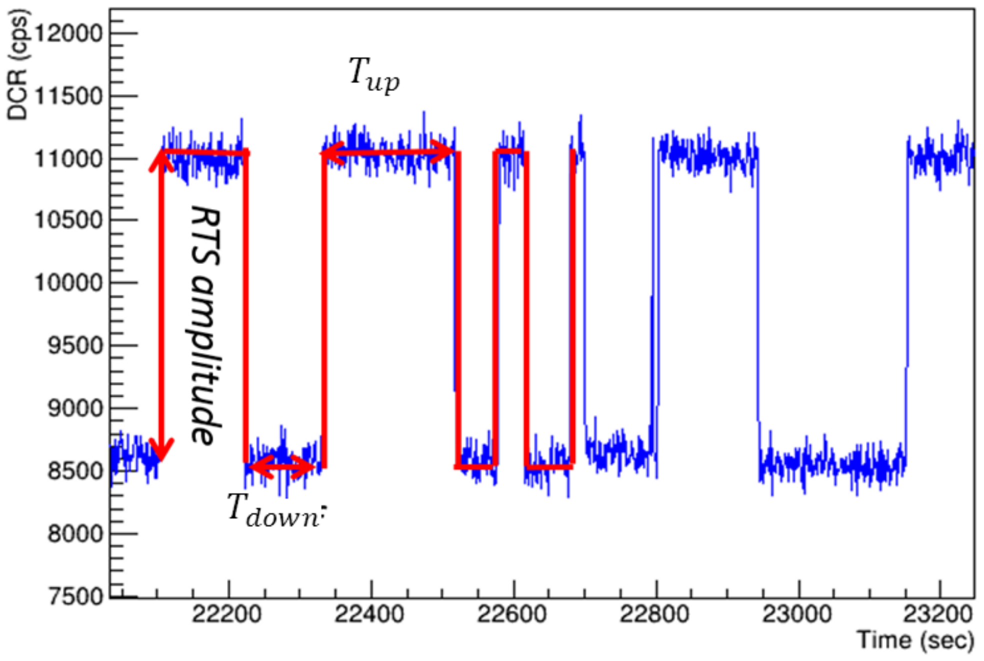


Random Telegraph Signal Noise

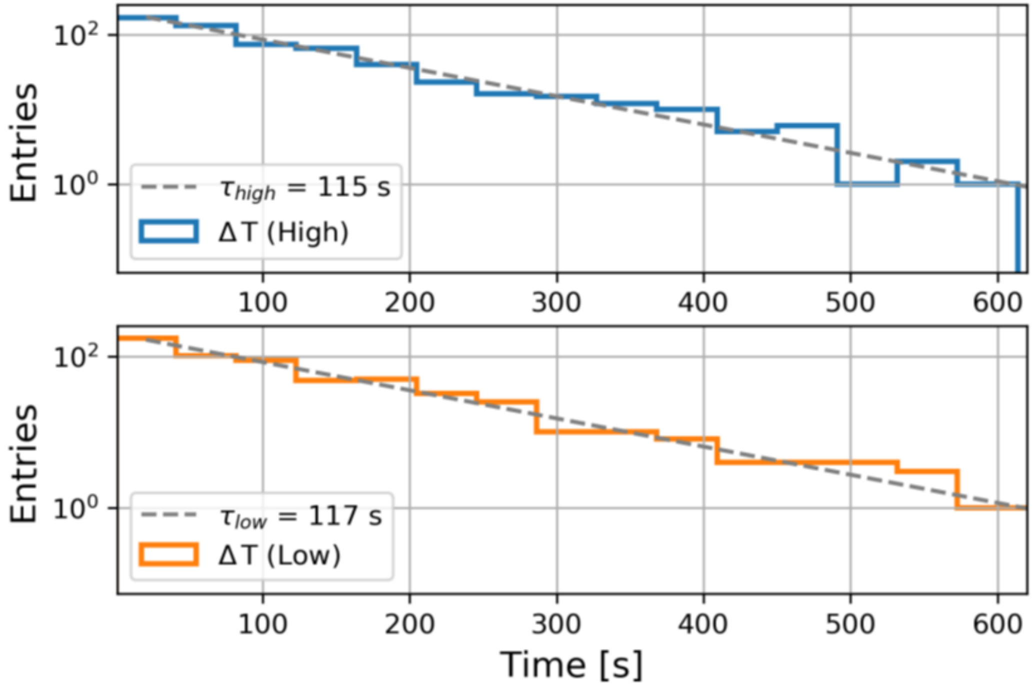
For the two-level case, **RTS behaviours analysed as a function of observation time**.

- The number of DCR switching in a fixed time interval follows a Poisson distribution for random switching events. As a consequence times between RTS transitions are exponentially distributed.

DCR vs observation time



Up/Down state life-time distribution

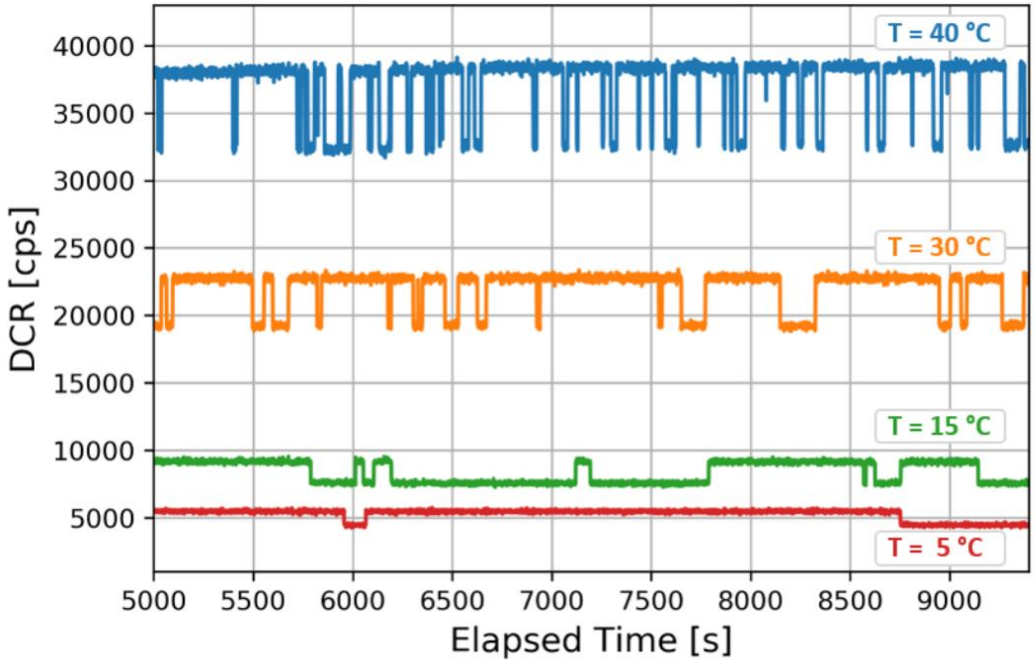


Random Telegraph Signal Noise

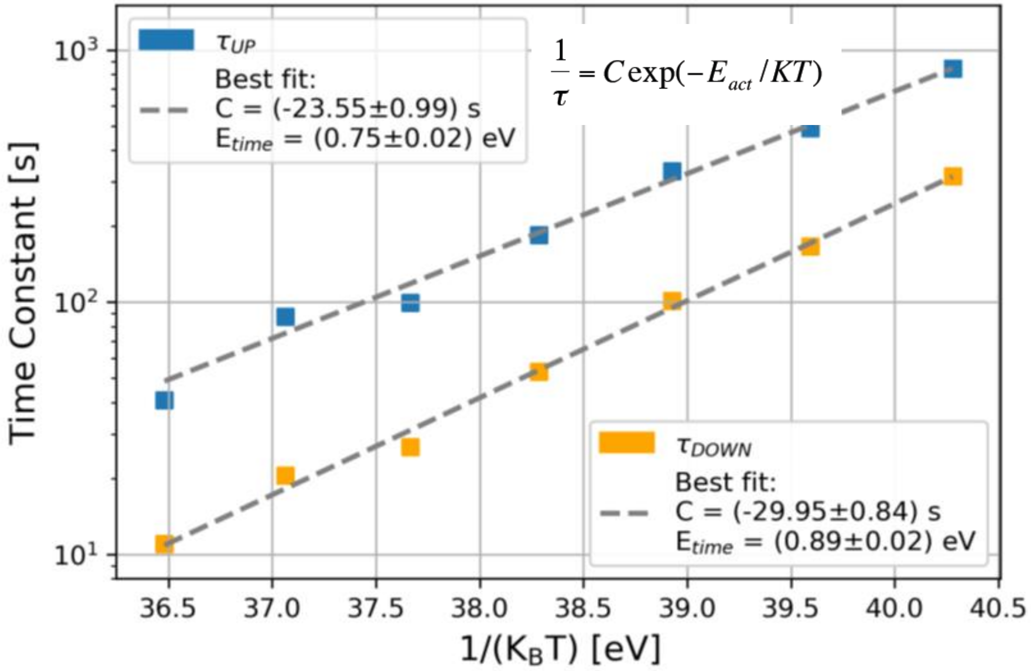
For the two-level case, **RTS behaviours analysed as a function of temperature**.

- RTS amplitude has been found to increase with temperature; also the switching probability increases with temperature, following an exponential dependence.

RTS as a function on Temperature



RTS time constant vs. Temperature

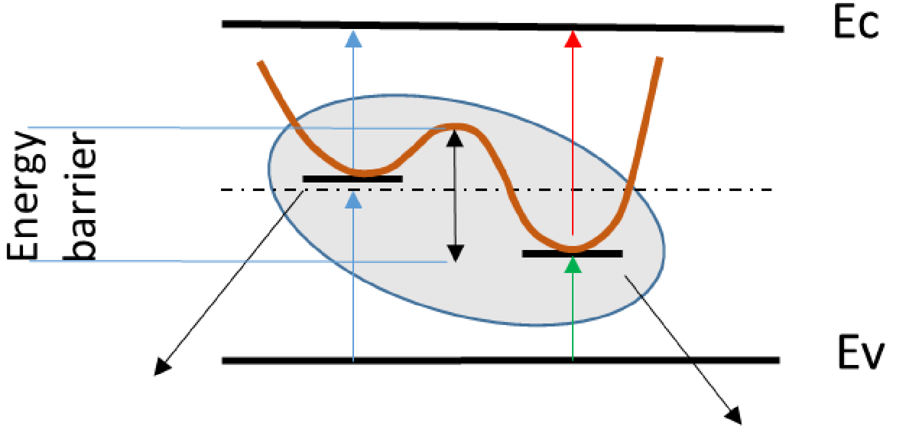


Random Telegraph Signal Noise

Defects introduced by proton irradiation can exist in two or more stable configurations.

- Metastable defects randomly change their configuration.
- As a consequence *e-h* generation rate change, resulting in the DCR level switching.
- 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 acoding the SRH -> $\mathbf{G_{eff}}$

Unefficient G-R center acoding the SRH -> $\mathbf{G_{eff}}$

Possible source:

- **Phosphorus-Vacancy (P-V) defects** have 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]

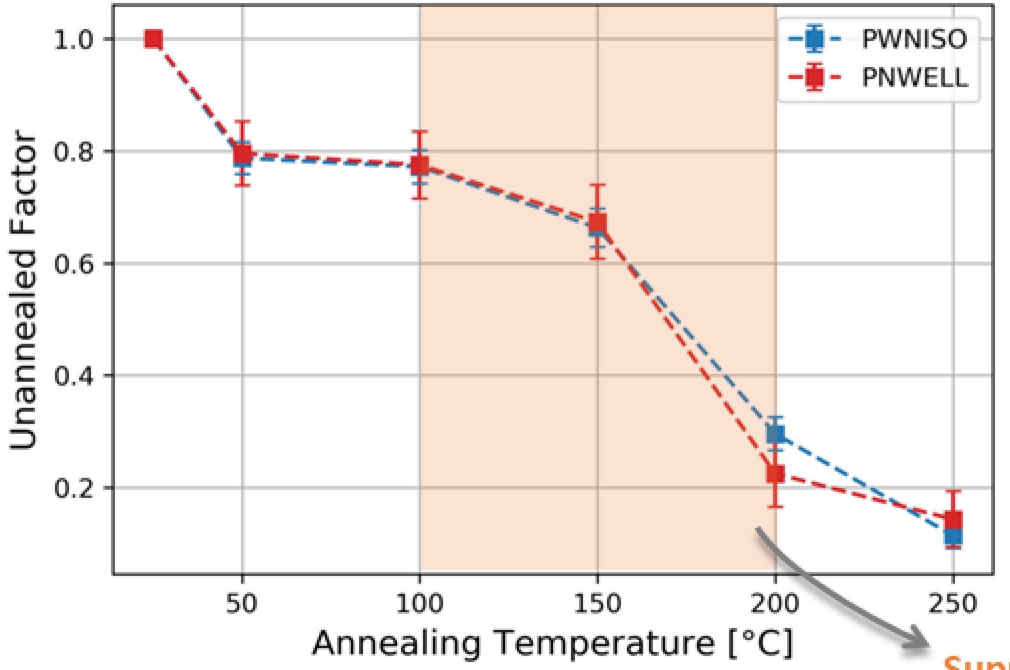
- The interaction of neutral **di-vacancies in cluster defects** can produce a reaction called “Inter-center transfer” which has the effect of increase the generation rate.

Random Telegraph Signal Noise

We performed 1-hour **isochronal temperature annealing** with 50 °C steps between 50°C and 250°C.

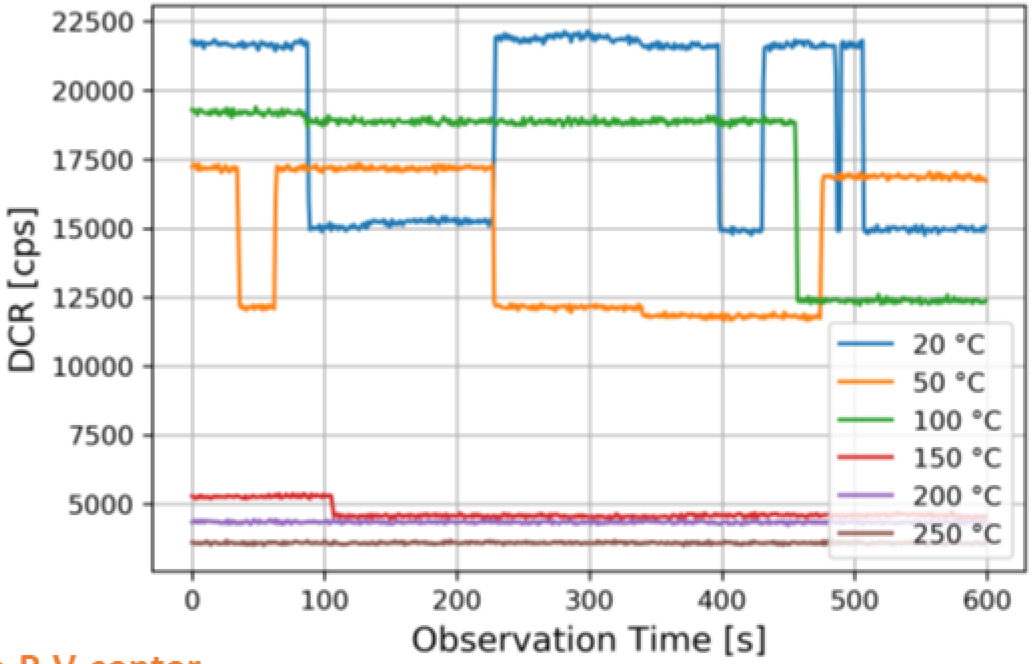
- After annealing the mean DCR recovered its initial value, while multi-level RTS transformed into lower level and less frequent RTS. **At the end of the procedure, only 15% of RTS pixels survives.**

Mean DCR vs annealing step



Supports the P-V center hypothesis

Evolution of DCR vs Time as a function of Annealing



Conclusion

We analysed the dark count behaviour of proton and electron irradiated CMOS SPADs.

- DCR has been found to depend heavily on proton-induced displacement damage.
- A less marked dependence was found in electron-irradiated devices.

- Long time measurements of DCRs also showed Random Telegraph Signal behaviour in the DCR level after proton irradiation.
- RTS characterization and annealing procedure indicate the P-V complex defect as a possible responsible for RTS.
- In future we will analyse SPAD with lower phosphorus doping and As-doping to further investigate the RTS origin

For reference:

"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.*

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