RAP 2019

International Conference on Radiation Applications

September 16-19 2019, Belgrade

Radiation Induced Defects in CMOS SPADs Sensors

(M. Campajola, F. Di Capua, D. Fiore, C. Nappi, E. Sarnelli)

Marcello Campajola (University of Naples 'Federico II' and INFN)

marcello.campajola@na.infn.it

Università degli Studi di Napoli Federico II

INFN Istituto Nazionale di Fisica Nucleare

Single-Photon Avalanche Diodes

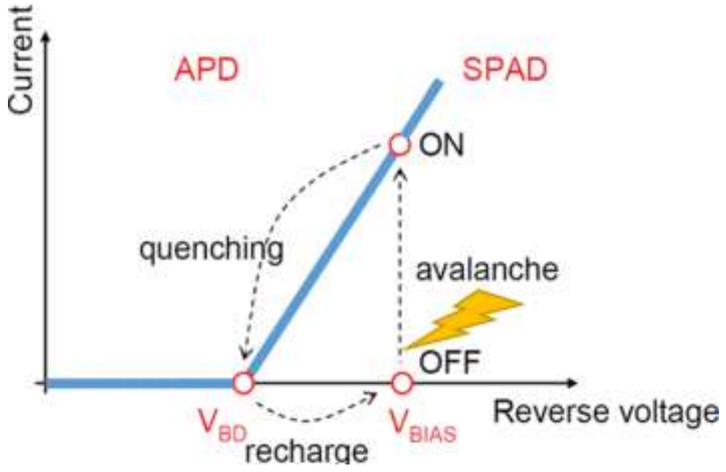
➢ **Working principle**

- Single-Photon Avalanche Diode (SPAD) is a photodiode biased above the breakdown voltage.
  - When a single photon hit the sensitive area, it can trigger a self-sustaining avalanche;
  - A quenching circuit stops the avalanche decreasing bias voltage;
  - SPAD is again able to detect a new photon;

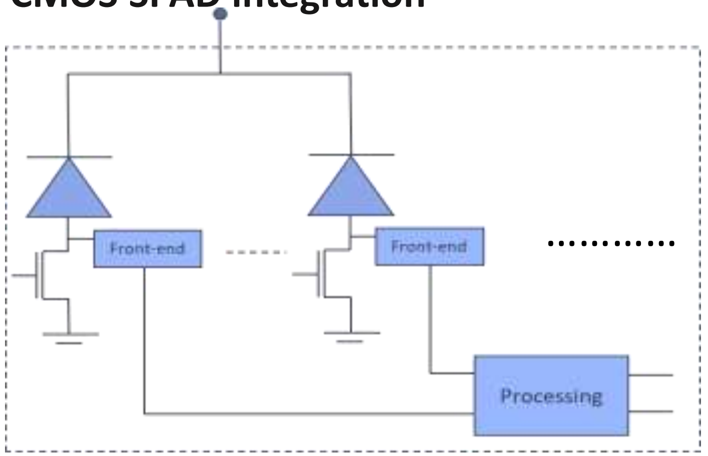
- SPAD have sensitivity at the single-photon level with no need for amplification.

- SPAD implemented in CMOS technology:
  - High time resolution;
  - High spatial resolution;
  - Post-processing circuits integrated on chip;

SPAD working principle



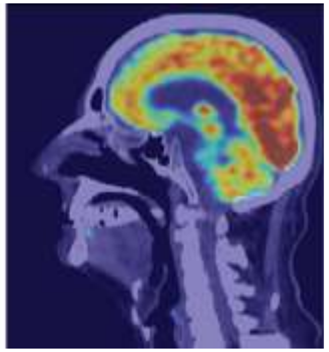
CMOS SPAD integration



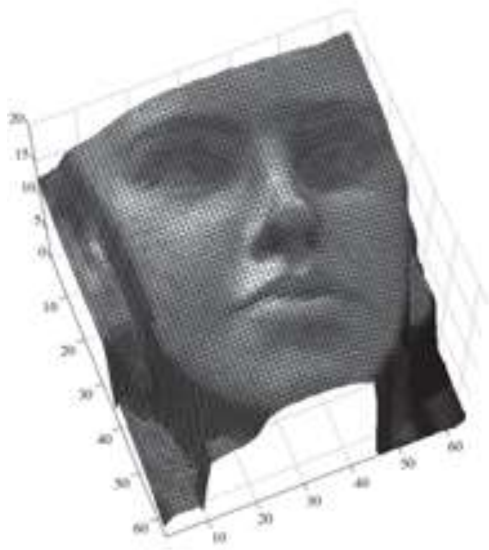
Single-Photon Avalanche Diod

➢ **Applications**

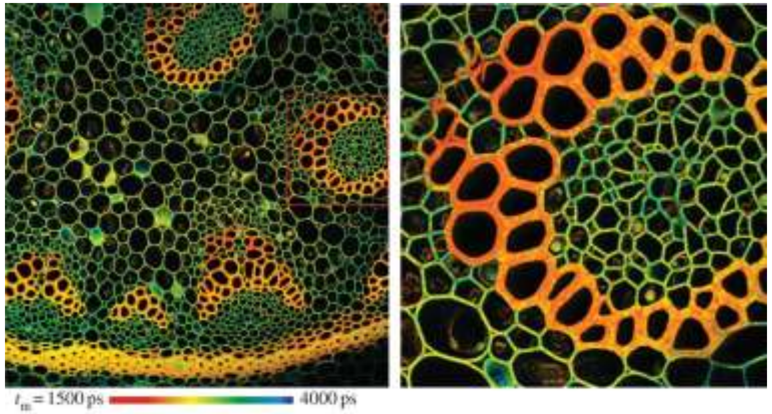
- Several possible applications (HEP, PET, Spectroscopy, LIDAR etc.)
- Many of them require the detector to be utilized in radiation environment;
- Fundamental to understand the radiation induced effects on CMOS SPADs.



Positron Emission Tomography (PET)



3D-Reconstruction using Time of Flight (TOF) system, LIDAR



Fluorescence Lifetime Imaging Microscopy (FLIM)

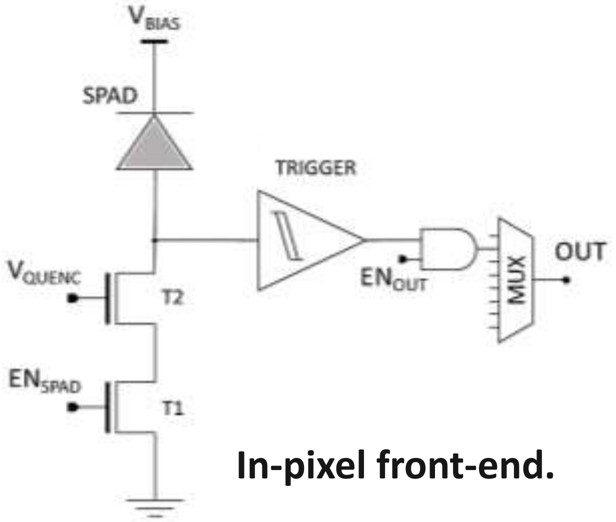
High Energy Physics Experiments

Tested Devices

➢ Test chip Architecture

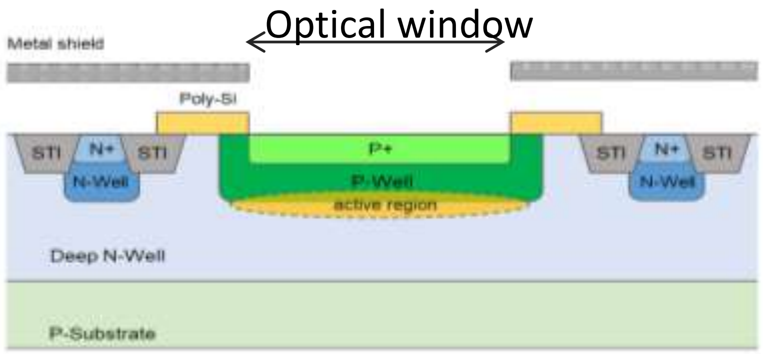
“Low-noise Single Photon Avalanche Diodes in 0.15 µm CMOS Technology”, L. Pancheri, D. Stoppa.

- Devices designed by Fondazione Bruno Kessler (FBK), Italy.
- SPADs implemented in a 150-nm CMOS process (LFoundry).
- Two junction layouts;
- Each SPADs is implemented with front-end electronics:
  - A trigger digitalize the pulse;
  - MUX select one pixel at the time;

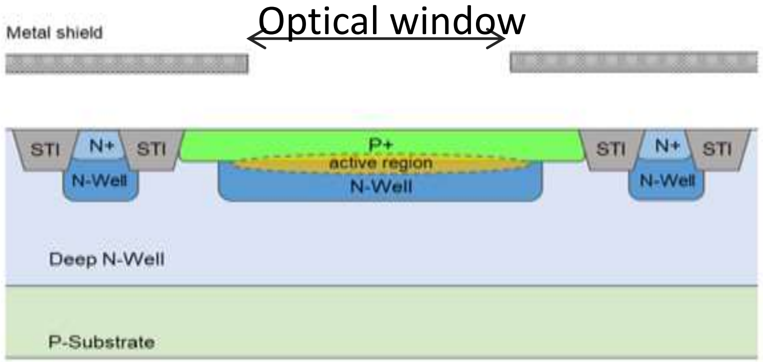


In-pixel front-end.

PWNISO layout.



PNWELL layout.

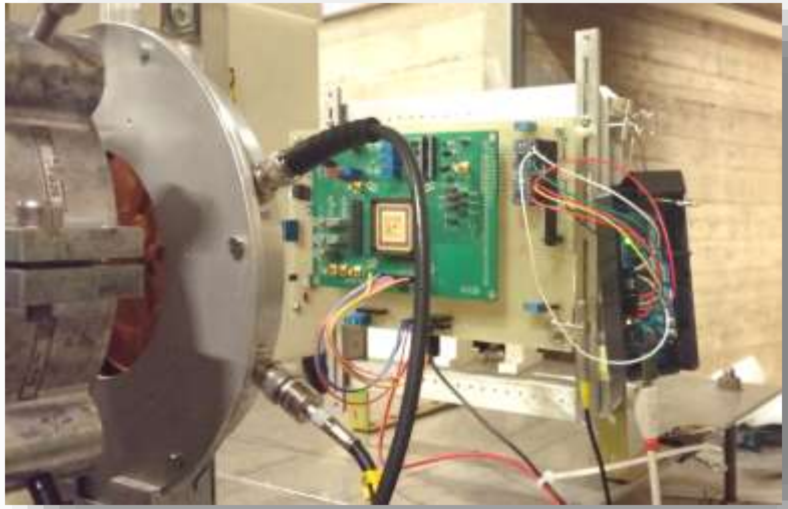


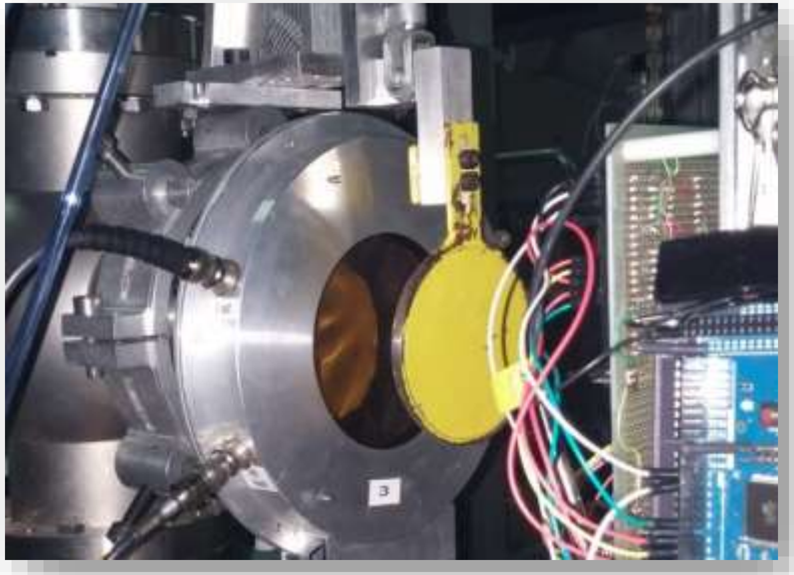
Irradiation Test

- **Proton irradiation**

- Test performed at INFN-LNS in Catania (Italy) using:
  - Tandem accelerator: 20 MeV proton beam;
  - Cyclotron line: 60 MeV proton beam;
- Beam current monitored using an ionization chamber;
- Beam profile on DUT checked by using radio-chromic film.
- Fluences from ~10^{10} to 10^{11} p/cm^2
- Displacement Damage Dose (DDD) up to 600 TeV/g.
- We focused on the irradiation effects on the Dark Count Rate (DCR), i.e., the rate of spurious events not triggered by photons.

Test at Tandem Accelerator line





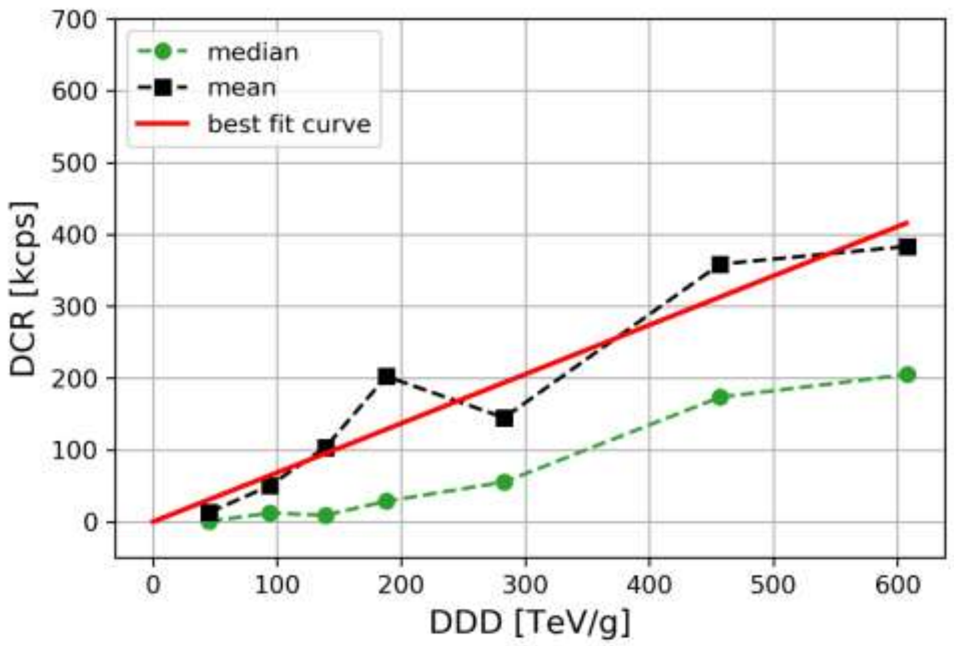
Radiation damage

➢ **DCR measurements**

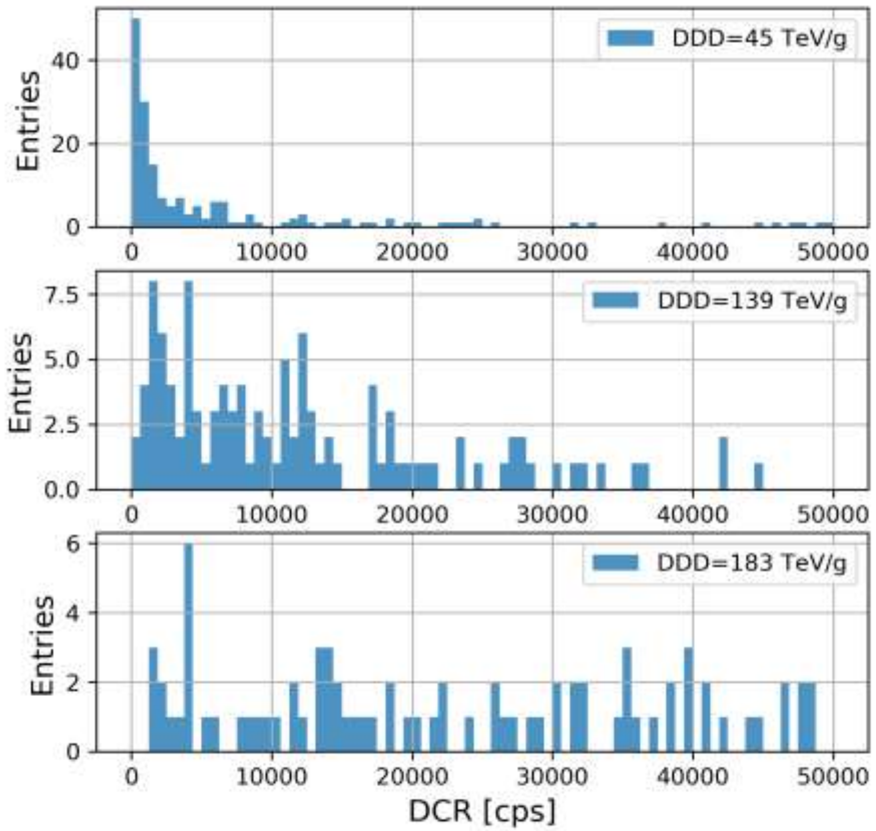
"Proton induced dark count rate degradation in 150-nm CMOS single-photon avalanche diodes", M. Campajola et al.

- High susceptibility to the DCR increase as a function of the dose: mean DCR increases up to two order of magnitude at maximum dose delivered;
- No significative changes in the breakdown voltage.

Mean DCR increase as a function of the dose



DCR distribution after irradiation steps



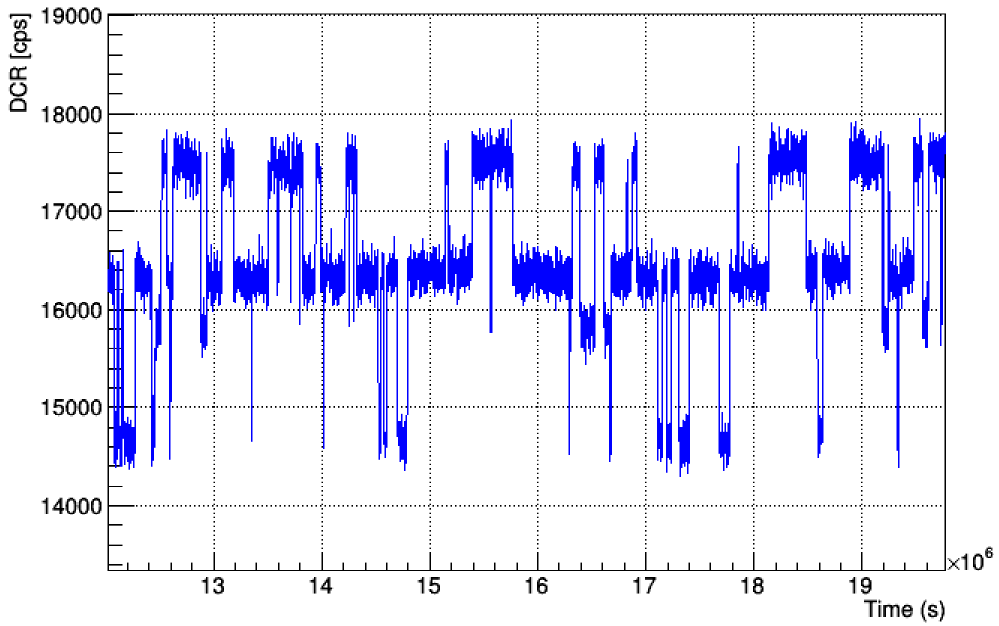
Radiation damage

➢ **Random Telegraph Noise**

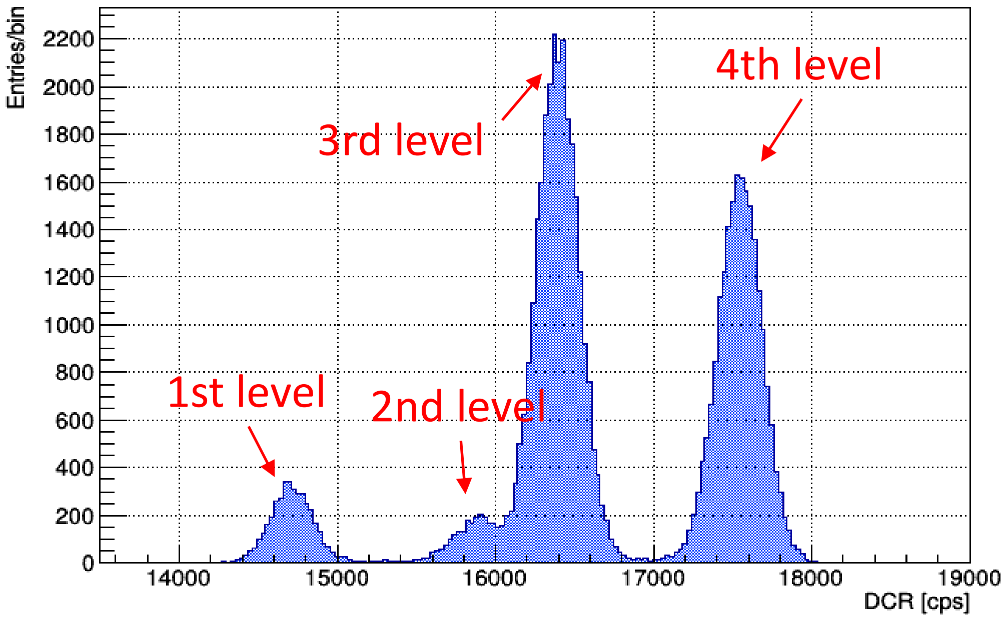
"Random Telegraph Signal in Proton Irradiated Single-Photon Avalanche Diodes", F. Di Capua et al.

- After irradiation discrete fluctuation between two or more levels (Random Telegraph Signal, RTS) have been observed;
- RTS observed in SPADs is correlated with bulk damage: not observed in Co60 irradiation; in proton irradiation more frequent with increasing of the DDD.

DCR vs observation time on a single SPAD



DCR distribution on a single SPAD

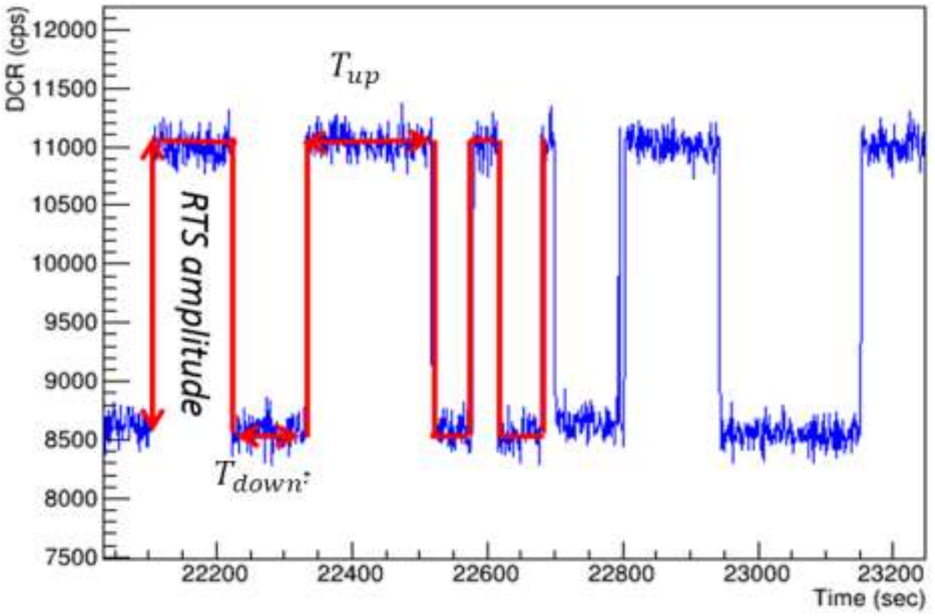


Radiation damage

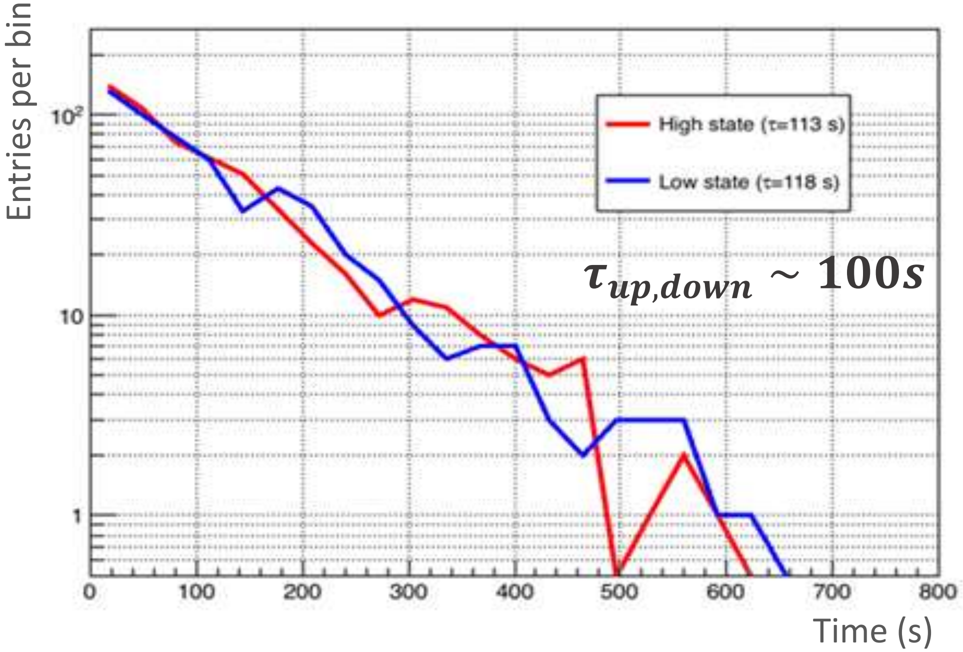
➢ **Random Telegraph Noise**

- RTS characterized by an amplitude, and 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 $P_{switch}(t) = \frac{1}{\tau}\exp(-t/\tau)$

DCR vs observation time



Time Up and Down Distributions



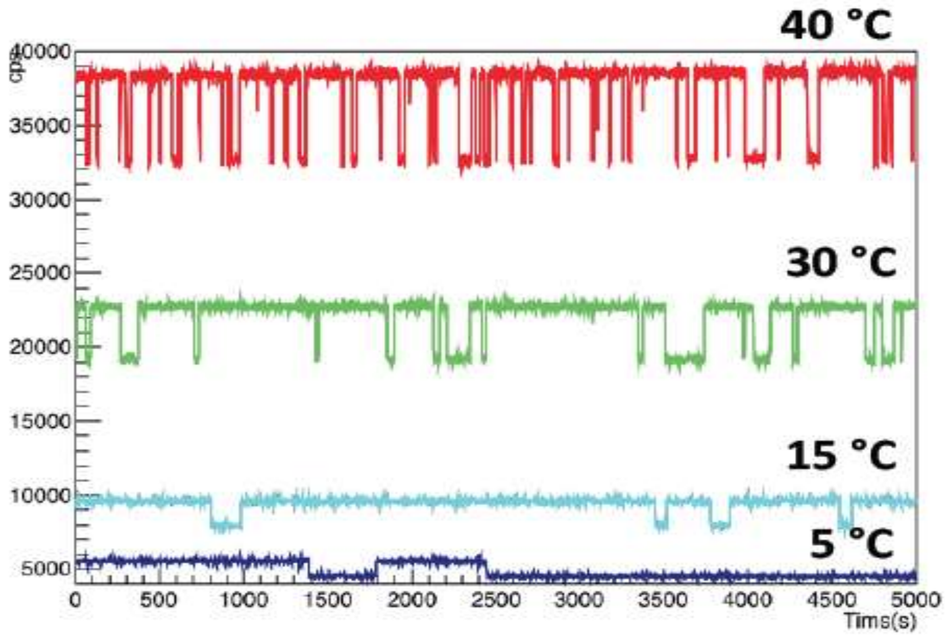
Radiation damage

➢ **Random Telegraph Noise**

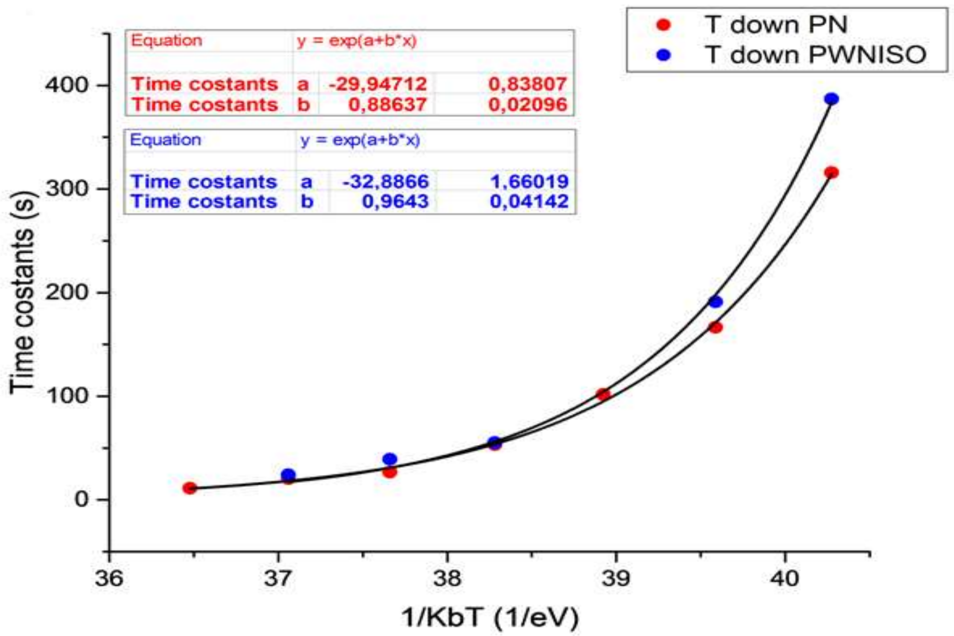
- RTS amplitude increases with temperature;
- Also the RTS switching probability increases with temperature: exponential dependence.

$$\frac{1}{\tau} = C\exp(-E_{act}/KT)$$

RTS as a function on Temperature



RTS time constant vs. Temperature



Radiation damage

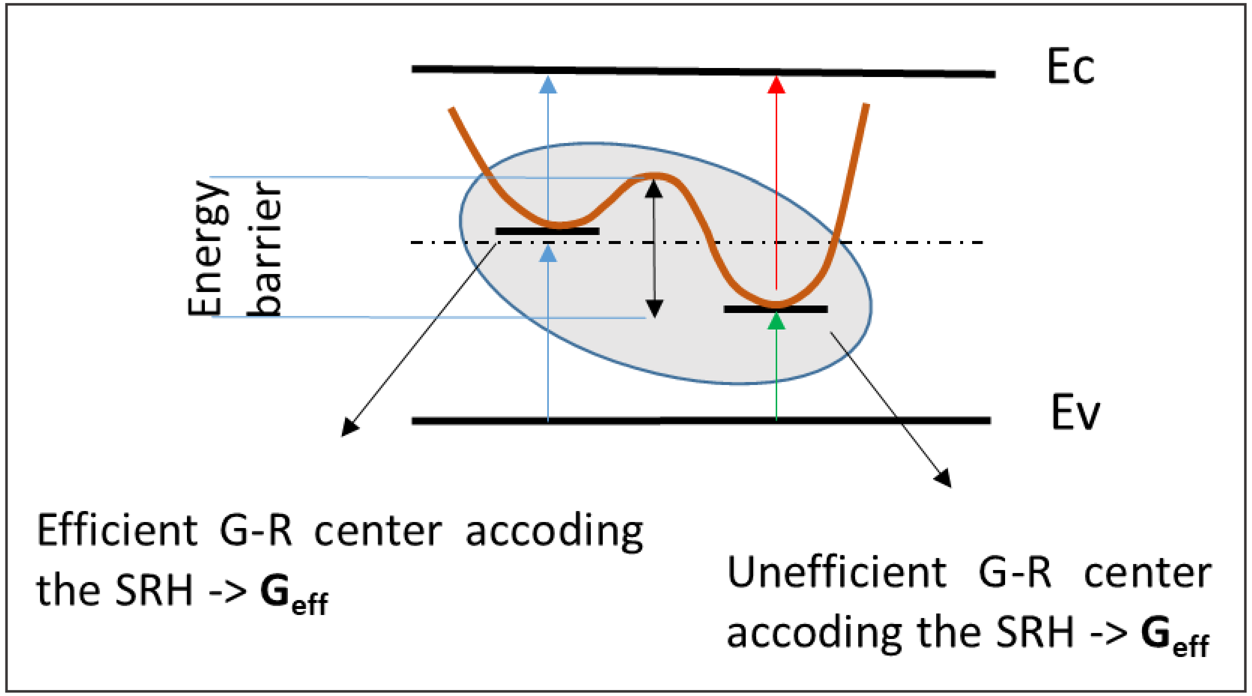
➢ **A possible explanation**

- Displacement damage is responsible of the creation of bulk defects that induce localized energy level near the middle of the bandgap. These act as efficient electrons and holes generation-recombination (G-R) centers, thus increasing the DCR generation.

- Defects introduced by proton irradiation can also exist in two or more stable configurations.
- when it changes configuration, the e-h pair generation rate will change, causing a jump in the level of DCR: RTS.

- It is possible that there is a potential barrier to switch from one configuration to another: for this reason the RTS switching frequency depends on the temperature.

Bi-stable complex defect schematization



Radiation damage

➢ **A possible explanation**

- Phosphorus-Vacancy (P-V) center defects can be generated in doped silicon devices. P-V center has a dipole structure. The P-V center could be formed at any of four Si-atoms around the P-atom.
- 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]

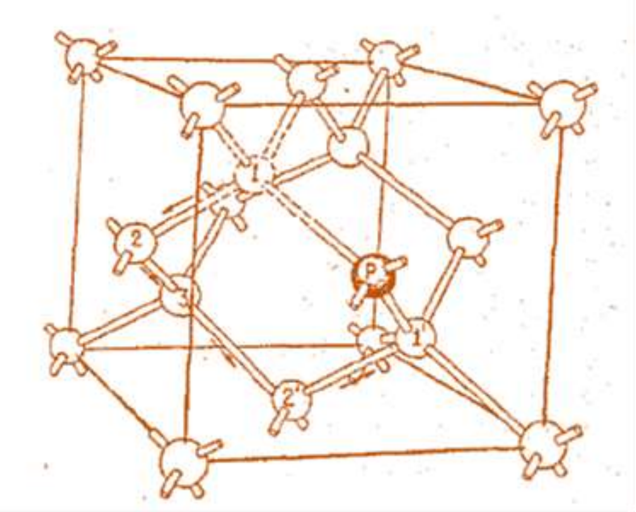


Figure from Watkins & Corbett (1964)

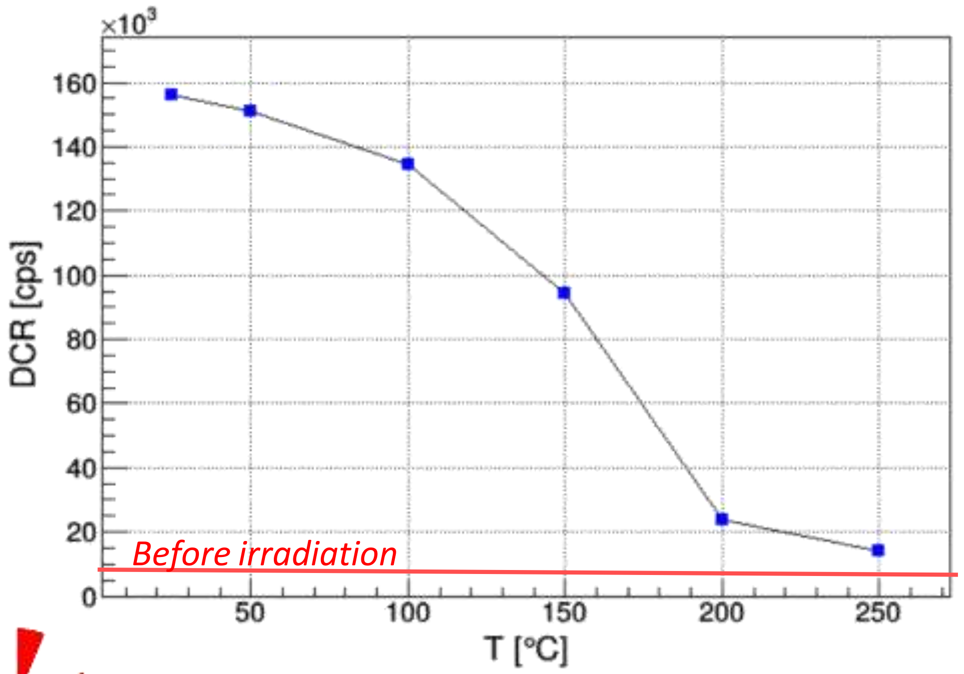
- Di-Vacancies cluster: these defects have three energy levels and four charge states (+,0,-,2-).
- The interaction of neutral divacancies (the most probable state) can produce a reaction called "Intercenter transfer" which has the effect to increase the generation rate.
- The movement of defects can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

Radiation damage

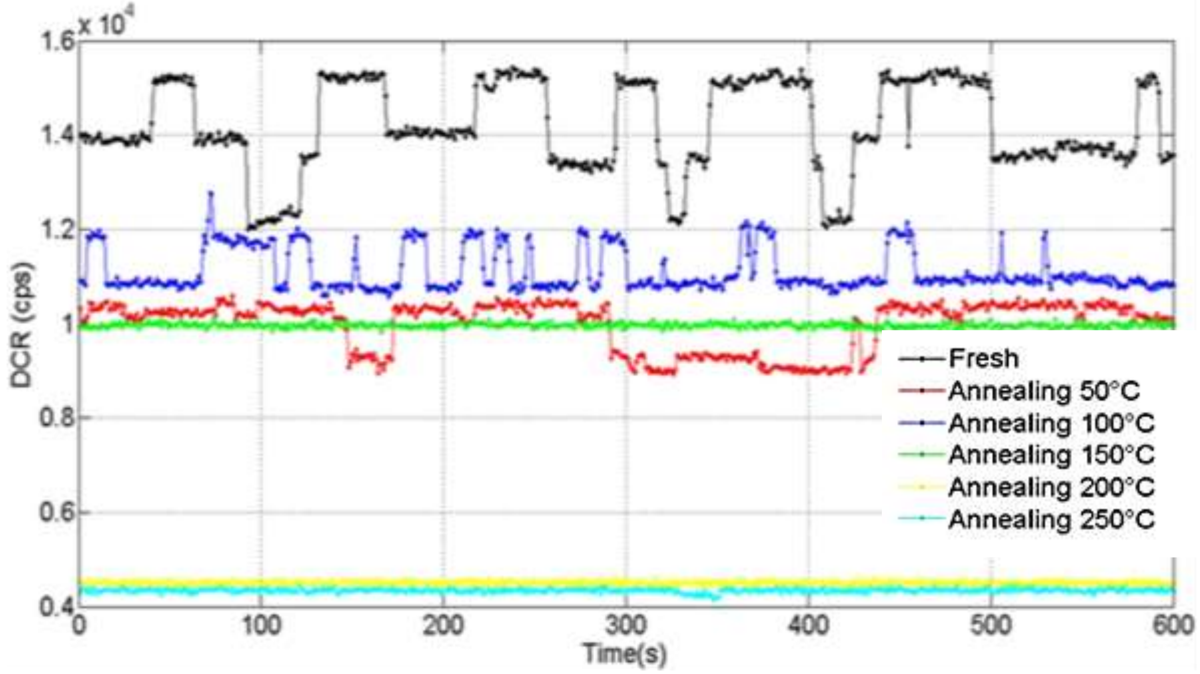
➢ **Annealing**

- Irradiated SPAD DCR has been studied after different annealing temperatures between di annealing 50°C and 250°C.
- After annealing the Mean DCR recovered its initial value, while multi-level RTS transformed into lower level RTS and into less frequent RTS before completely disappear.

Mean DCR as a function of Annealing



Evolution of DCR vs Time as a function of Annealing

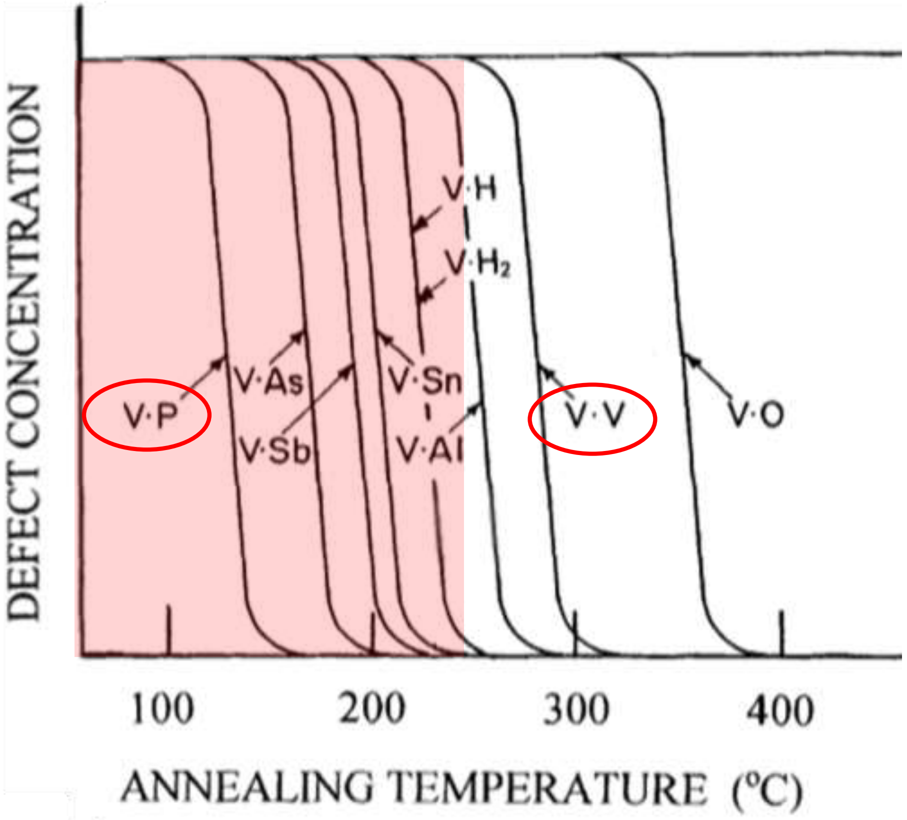


Radiation damage

➢ **Annealing**

- The annealing procedure is an useful tool to investigate the defects responsible for DCR and RTS
- Annealing should help in the understanding defects responsible for RTS due to the different kinematics of the defects:
    - P-V centers anneal at about 130°C
    - Di-Vacancies anneal at 270°C
- Our results suggest the PV complex defects as possible responsible for DCR increase and Random Telegraph Signal.

Schematic of vacancy-defect annealing [1].



[1] "Annealing of Proton-Induced Random Telegraph Signal in CCDs" , T. Nuns et al.

Conclusions

➢ ....

- We analysed the dark count behaviour of proton irradiated CMOS SPADs.
- DCR has been found to depend heavily on proton-induced displacement damage.
- Long term measurements of DCRs also reveal Random Telegraph Signal behaviour in the DCR level after proton irradiation.
- RTS time constants and amplitude have been investigated as a function of the temperature.
- RTS characterization and annealing procedure indicate the P-V complex defect as a possible responsible for RTS.
- In future we will analyze SPAD with lower phosphorus doping and As-doping to further investigate the RTS origin.

Contact:

Marcello Campajola (University of Naples ‘Federico II’ and INFN)

marcello.campajola@na.infn.it