Characterization and modeling of displacement damage in CMOS SPAD sensors

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Online conference

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Outline

- Introduction and motivation
- Measurements
- Models
- Discussion and future work

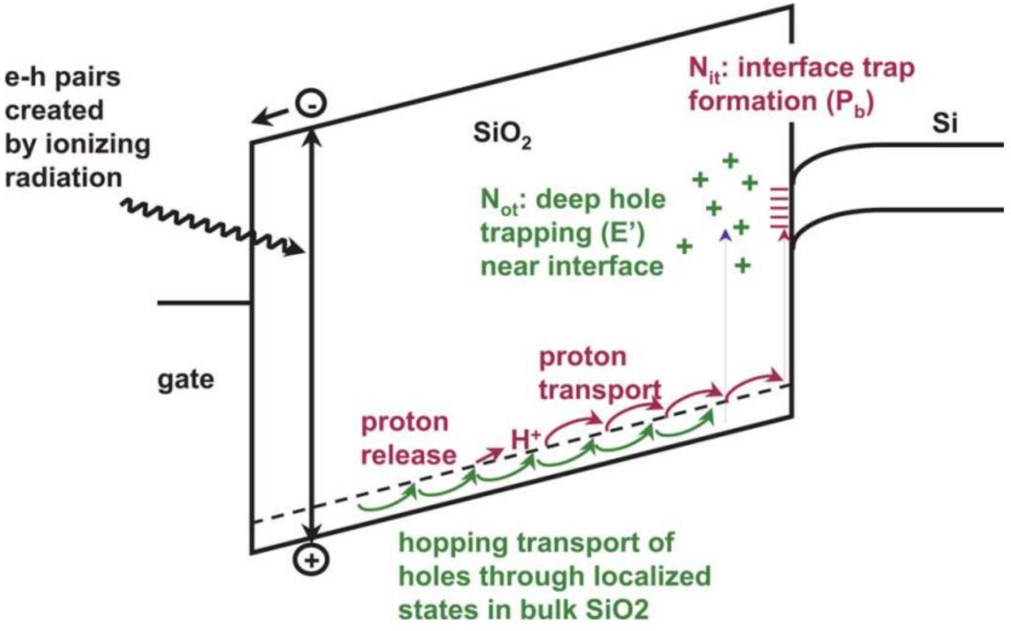
Motivation

Applications of SPADs/SiPMs in radiation environment:

- Space (LIDAR, astro-particles detection)
- High Energy Physics (calorimeters)
- Medical: Proton – Hadron therapy centers (e.g. inline monitor of treatment)

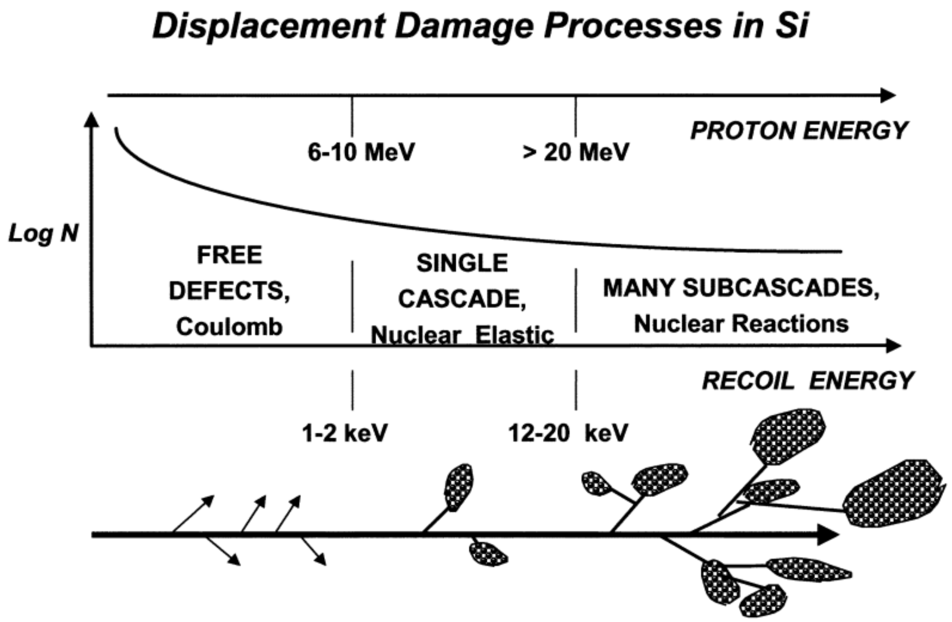
Radiation effects on detectors: Ionizing and Non-Ionizing

Ionizing radiation damage:
mainly oxide charge build-up and Si/SiO_2 interface traps (surface generation)



J.R. Schwank, et al., IEEE Tran. Nucl. Sci., 55, 4, 2008

Non-ionizing radiation damage:
displacement of atoms in the lattice - point defects and clusters

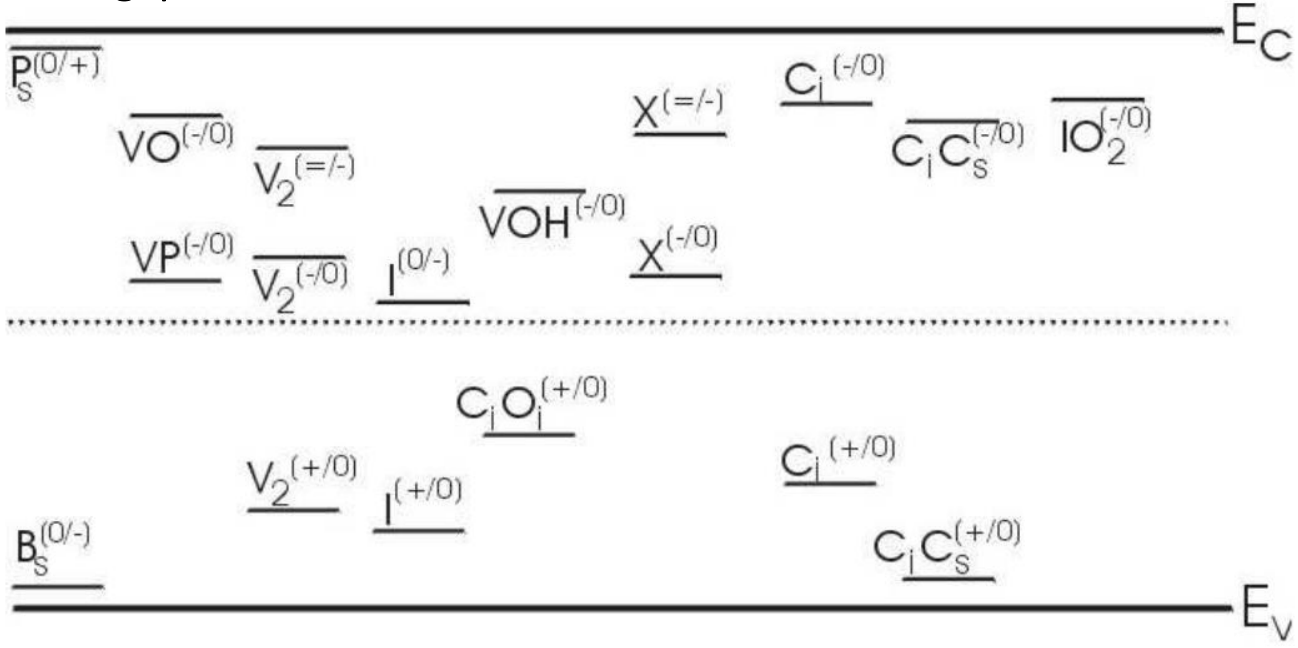


J.R. Srour, et al., IEEE Tran. Nucl. Sci., 50, 3, 2003

Radiation effects on SPADs: non-ionizing radiation

Deep band gap trap levels: enhance generation – recombination processes

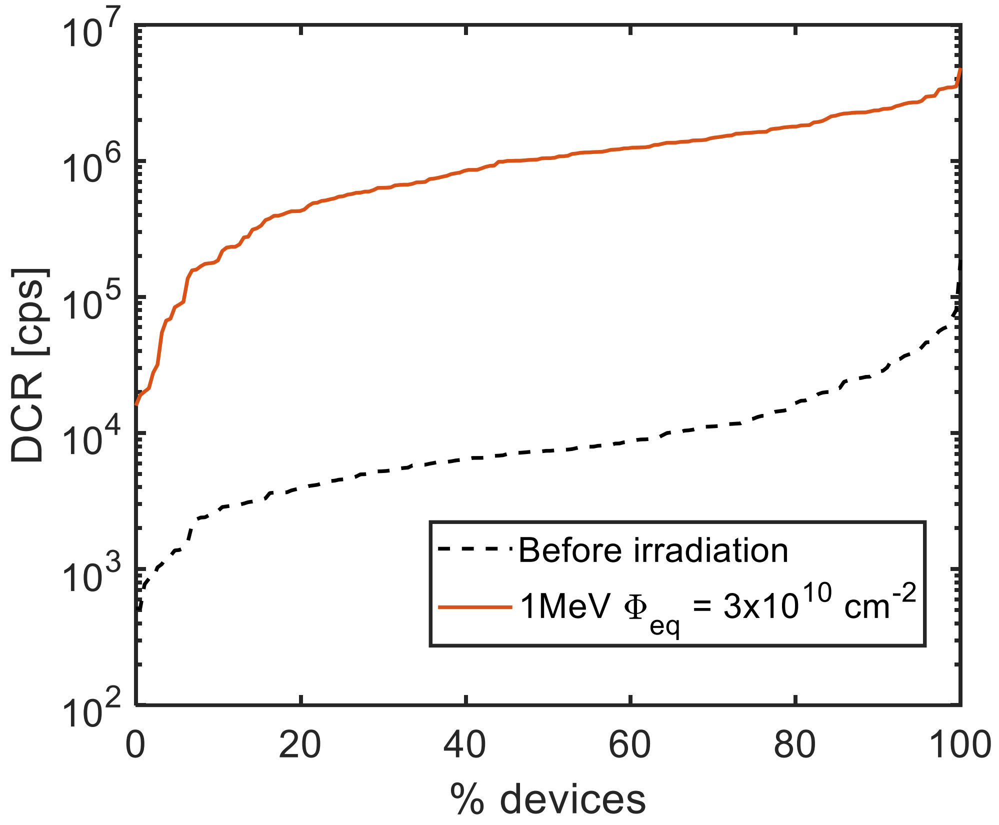
Band gap defect states

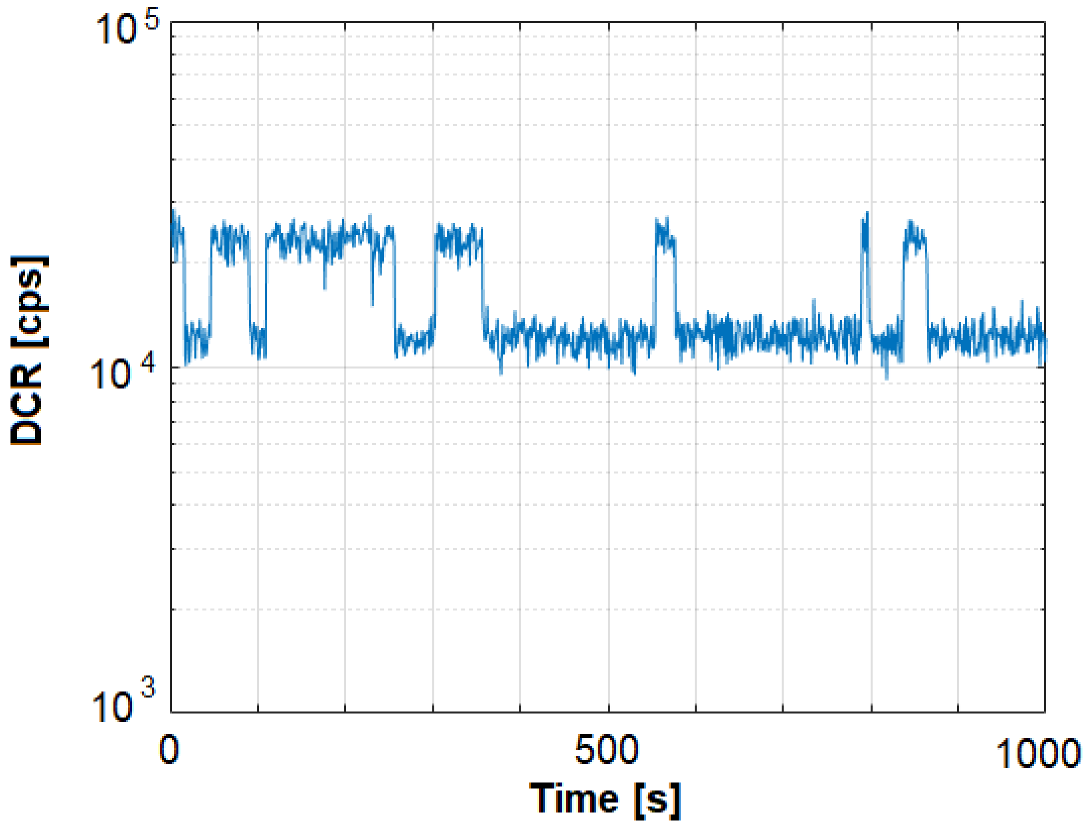


J. Stahl, PhD thesis, University of Hamburg, 2004

Radiation effects on SPADs: non-ionizing radiation

Effect on SPADs: increase of **DCR** and **Random Telegraph Signal** noise





Non-Ionizing energy loss scaling

- Protons and neutrons: damage proportional to particle fluence Φ (particles/cm^2)

- Displacement Damage Dose (DDD)

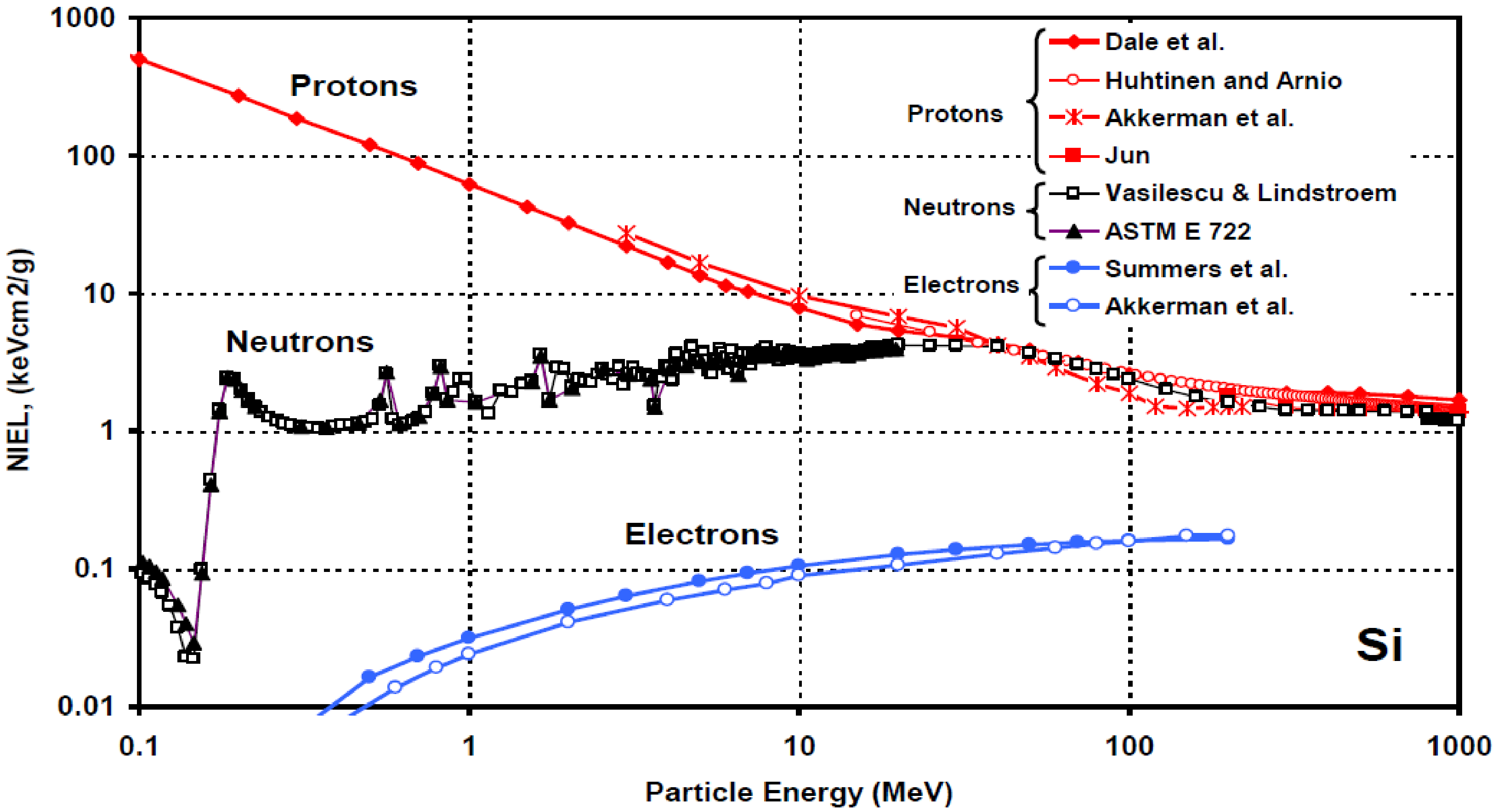
$$\boldsymbol{DDD} = NIEL\,\Phi$$

NIEL: proportionality coefficient, dependent on particle type and energy

- **NIEL scaling hypothesis**: the effect of DDD on device characteristics (e.g. dark current) is proportional to the energy released

NIEL scaling

In HEP community the 1MeV neutron equivalent fluence (1MeV Φ_{eq}) is typically used to quantify DDD



C. Poivey, ESA - CERN SCC Workshop, CERN, May 9 10, 2017

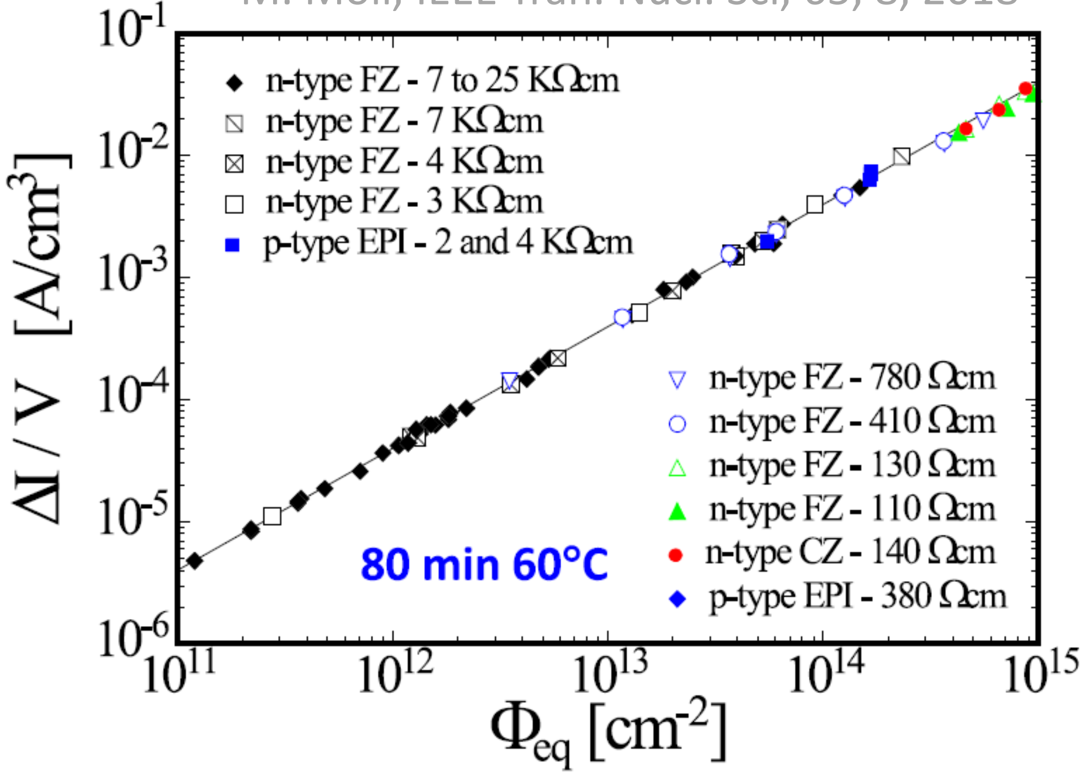
Displacement damage on silicon PIN detectors

- Irradiation on detectors obtained with different types of substrates
- Increase in volume dark current independent on type and doping of substrates:

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

- Coefficient $\boldsymbol{\alpha}$ **= 3.99e-17 A/cm** at T = 20°C after annealing 80min @ 60°C

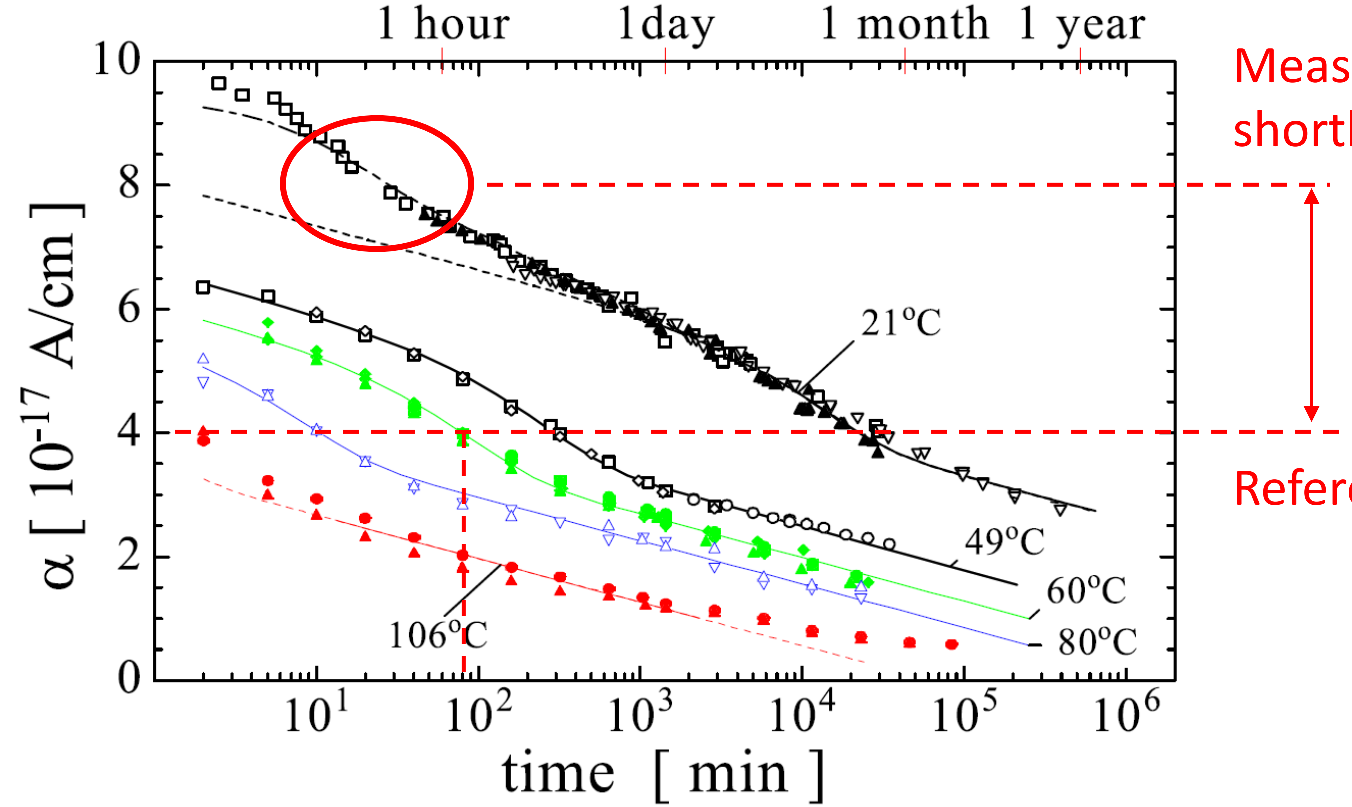
M. Moll, IEEE Tran. Nucl. Sci, 65, 8, 2018



Displacement damage on PIN detectors – effect of annealing

Annealing: rearrangement of defects. Accelerated with high T

M. Moll, IEEE Tran. Nucl. Sci, 65, 8, 2018



Measurements acquired shortly after irradiation (few mins to few hours)

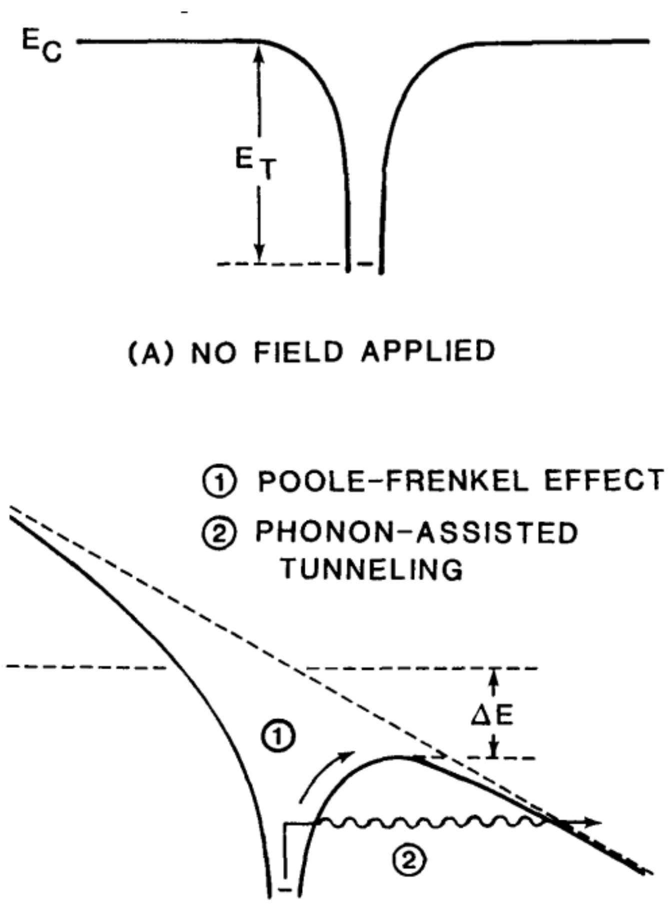
~ Factor 2

Reference annealing 80min 60°C

Displacement Damage in SPADs – physical effects

SPAD vs. PIN detector - additional factors:

- Breakdown (triggering) probability
- Poole-Frenkel effect
- Trap-Assisted Tunneling
- Small active volume:
  statistical distribution of DCR
- Multi-level DCR: Random Telegraph Signal



J.R. Srour, R.A. Hartmann,
IEEE Tran. Electron Dev., 36, 6, 1989

Outline – characterization and modeling activities

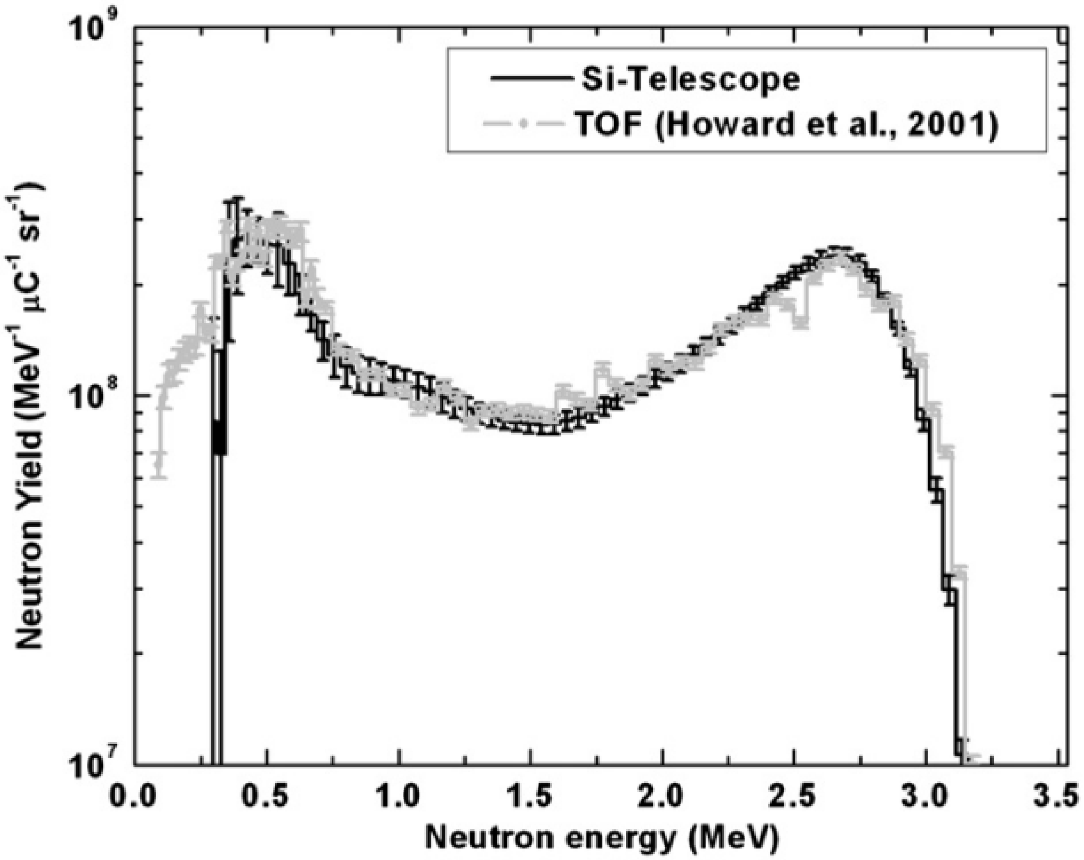
- Starting point: SPAD array with well-known (and modeled) detectors
- Measurements with **neutrons** at different fluences from 10^9 to 10^{11} 1MeV n_{eq}/cm^2
- **DCR distribution** can be predicted considering the **statistics of energy deposition** in the detector volume
- Last step: establish a **quantitative link** between the average increase of **SPAD DCR** and **previous results on dark current** obtained on PIN radiation detectors.

Experimental data acquisition

- 24 x 8 pixel arrays x 2 SPAD types
- Large SPADs with 45µm x 43µm active area

- **Neutron irradiation** at Legnaro National Laboratories, INFN, Italy
- Measurements at T=25°C, Vex = 2V
- DCR mapped after each irradiation step (annealing time: minutes – hours)

Energy spectrum of neutrons used in radiation damage studies

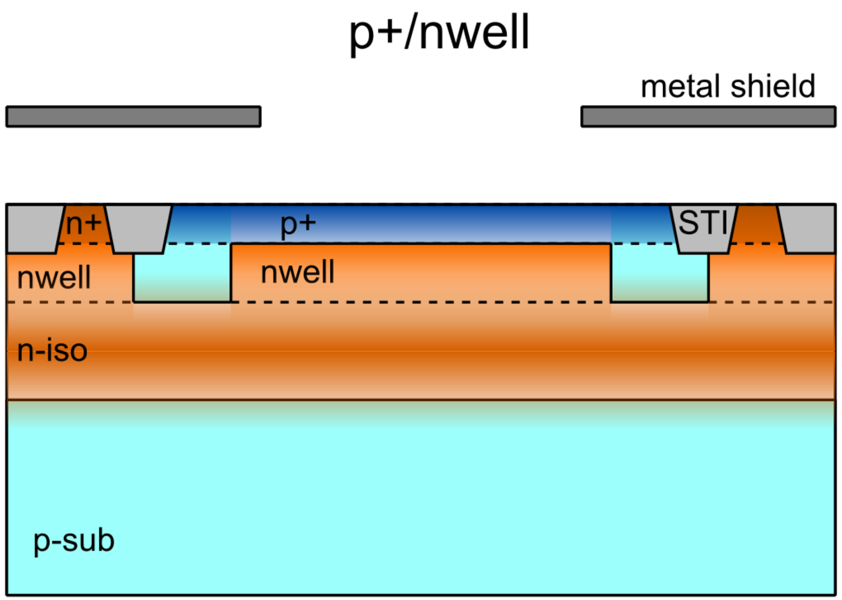


S. Agosteo, et al., Applied Radiation and Isotopes, 69(12):1664–1667, 2011.

Experimental data acquisition: SPAD types

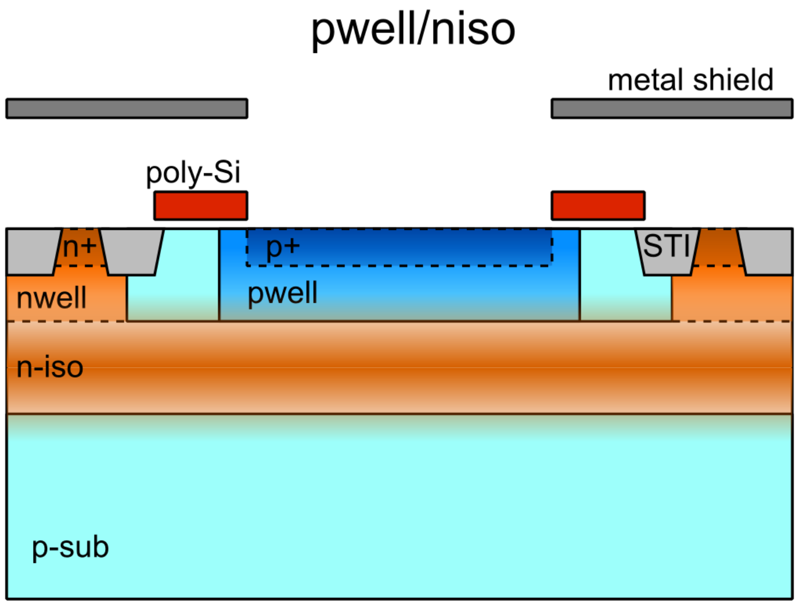
Type 1:

- Shallow step junction
- $V_B = 18V$
- Space-charge region width @ $V_B = 0.6\mu m$

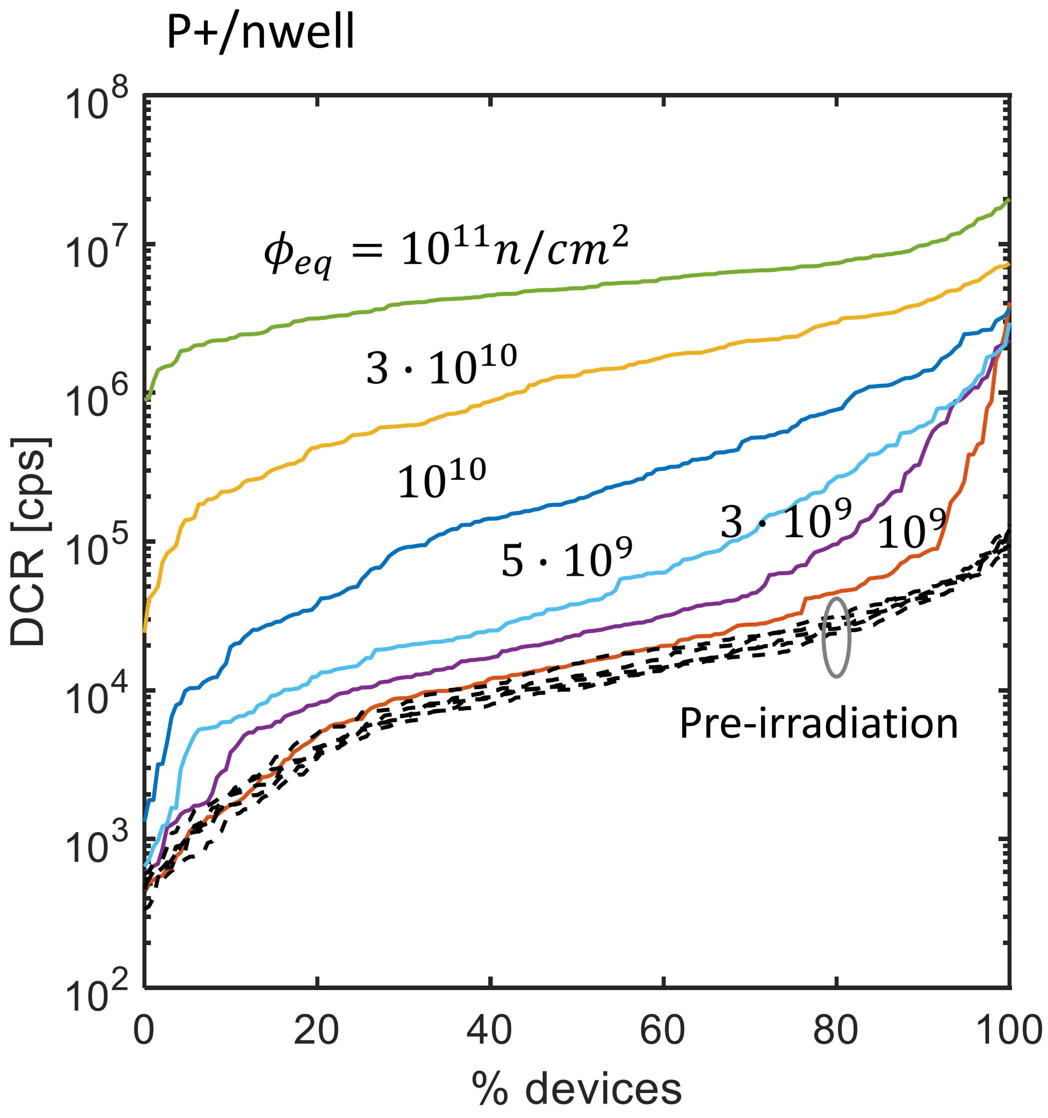


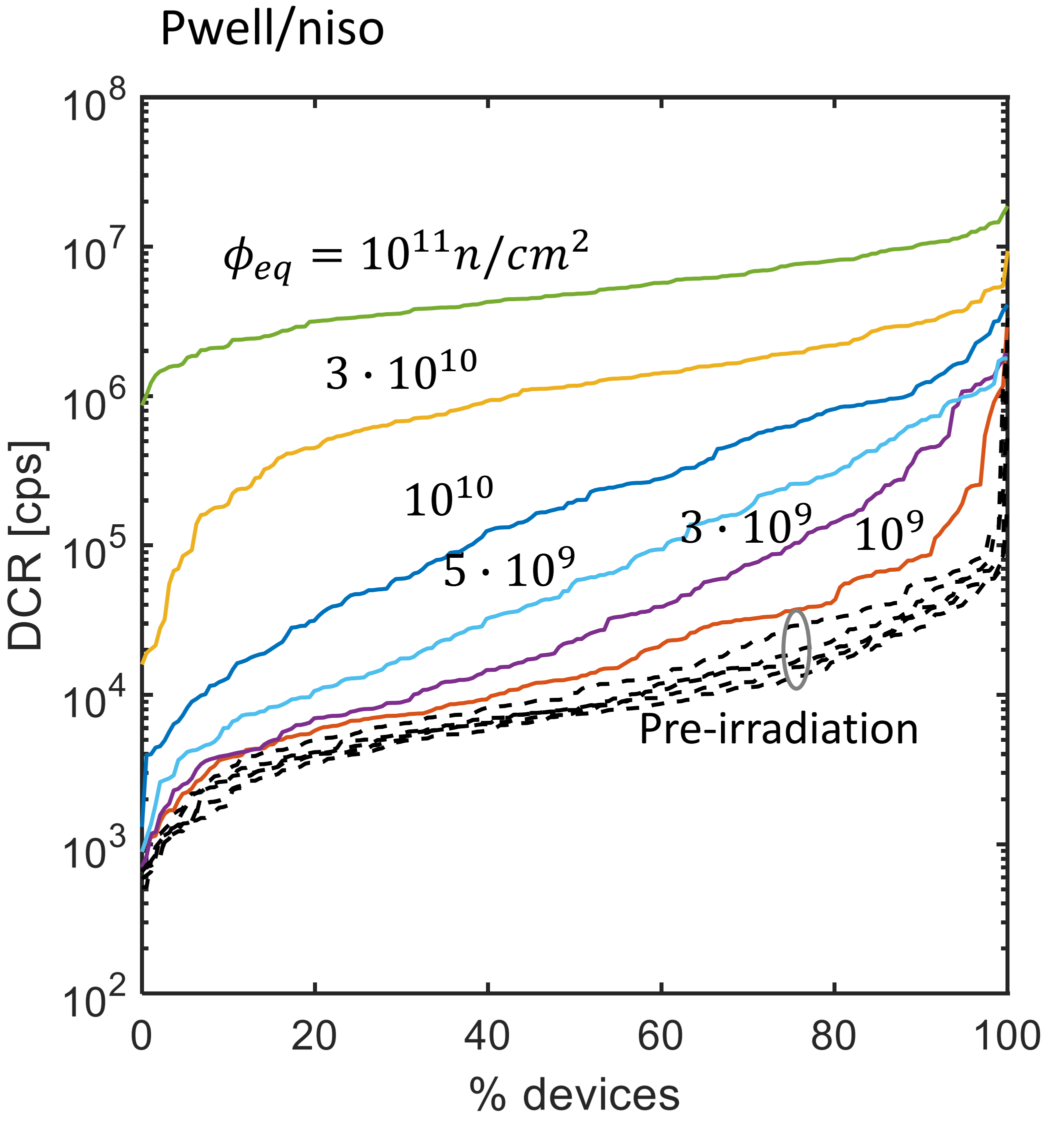
Type2:

- Deep graded junction
- $V_B = 22V$
- Space-charge region width @ $V_B = 0.7\mu m$



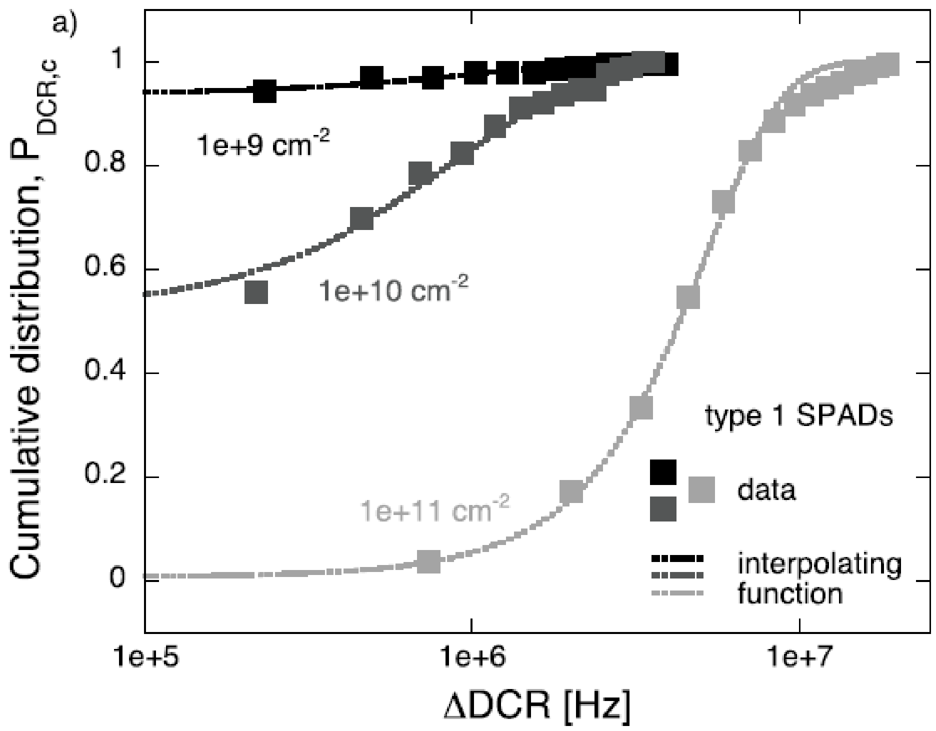
Summary of results – SPADs with 43µm x 45µm active area

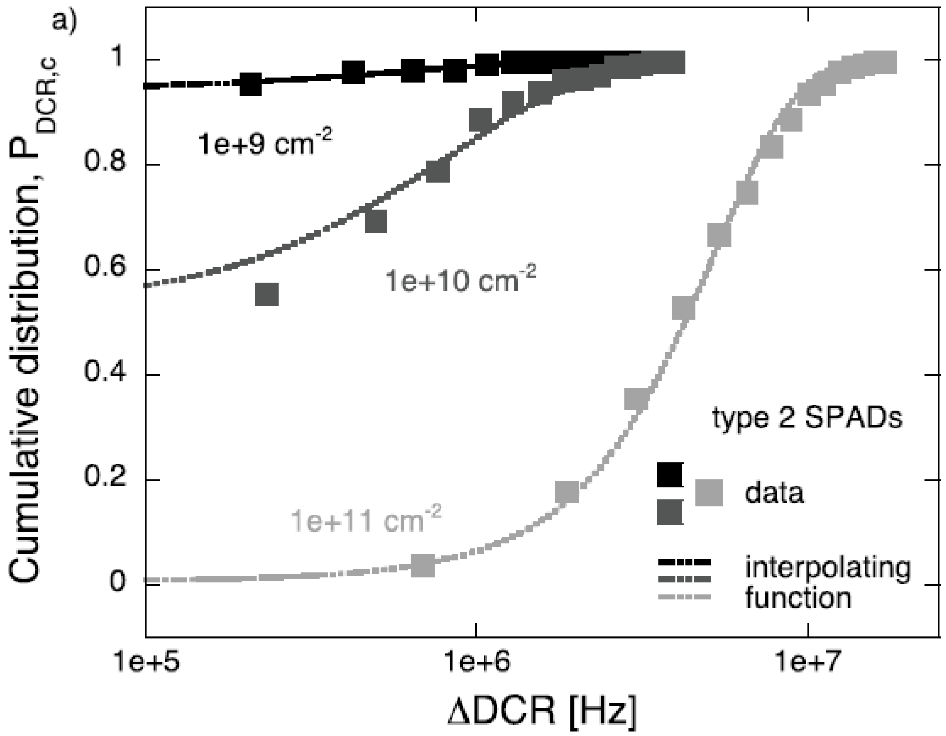




Modeling: DCR distribution

- Model based on the **statistics of energy deposition** in the SPAD volume
- DCR proportional to the non-ionizing energy deposited within the SPAD volume
- Good matching with experimentally measured DCR distributions





L. Ratti, et al., IEEE Tran. Electron Dev., 66 (12) 2019

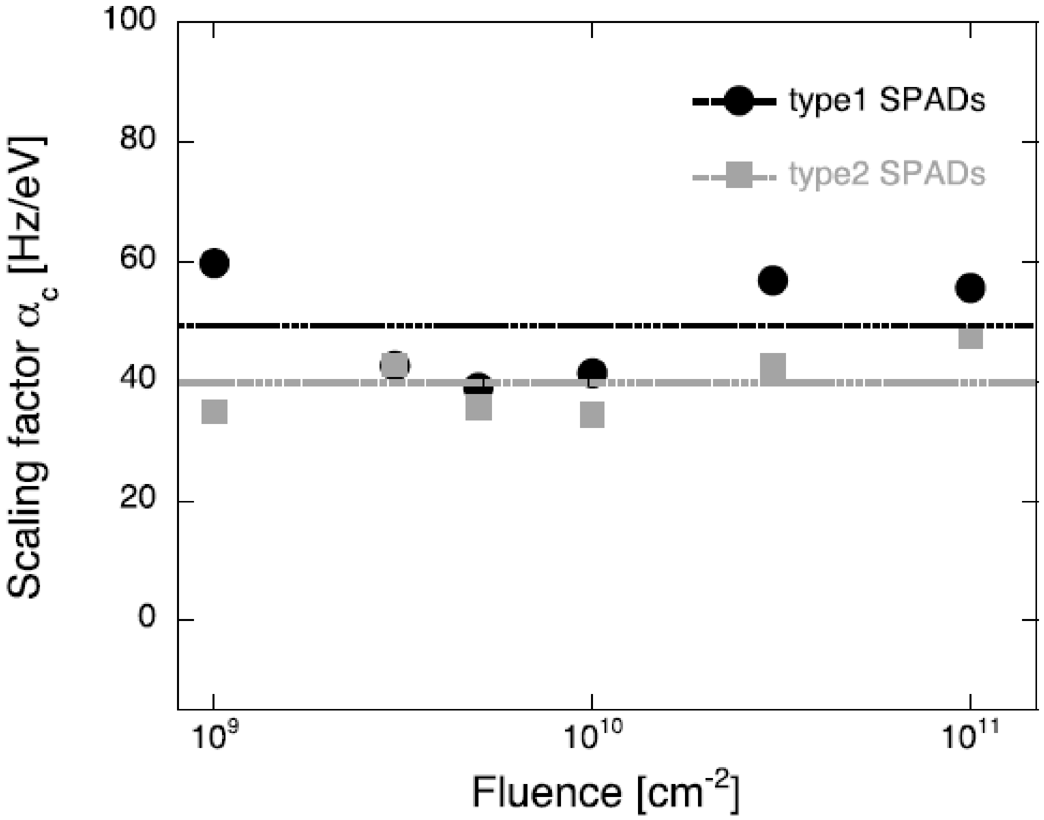
Interpretation: average DCR increase

Device-dependent scaling factor: obtained by fitting

Average DCR in p+/nwell SPADs (type 1) is systematically larger than in pwell/niso SPADs (type 2)

↓

Hypothesis: field enhancement effects stronger in Type 1 SPADs



L. Ratti, et al., IEEE Tran. Electron Dev., 66 (12) 2019

Simulation model

TCAD 1D model:

- Drift-diffusion
- Breakdown probability P_b with local impact ionization model: Van Overstraeten and De Man ionization coefficients
- Slotboom band gap narrowing
  [J. W. Slotboom and H. C. de Graaff, Solid-State Electron., 19 (10) 1976]
- Hurkx Trap-Assisted Tunneling (TAT)
  [G.A.M. Hurkx et al., IEEE Tran. Electron Dev., 39 (2) 1992]
- Poole-Frenkel effect

Simulation model

Radiation-generated trap model based on Perugia model

[M. Petasecca et al., IEEE Tran. Nucl. Sci., 53 (5) 2006]

3 trap levels:

1. Ec – 0.42eV, related to $VV^{(-/0)}$ defect
2. Ec – 0.46eV, related to $VVV^{(-/0)}$ defect
3. Ev + 0.36eV, related to C_iO_i complex

} Deep acceptors (items 1–2)

Defect cross sections slightly modified to match α coefficient [Moll] at low field and Room Temperature.

$$DCR = A \int_{x_1}^{x_2} G(x)\, P_b(x) dx$$

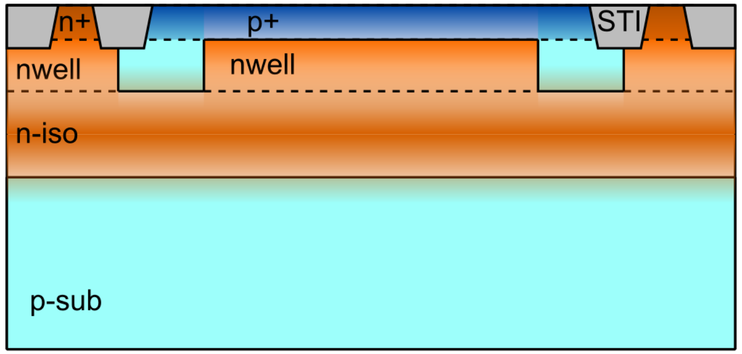
with $G(x)$: generation profile

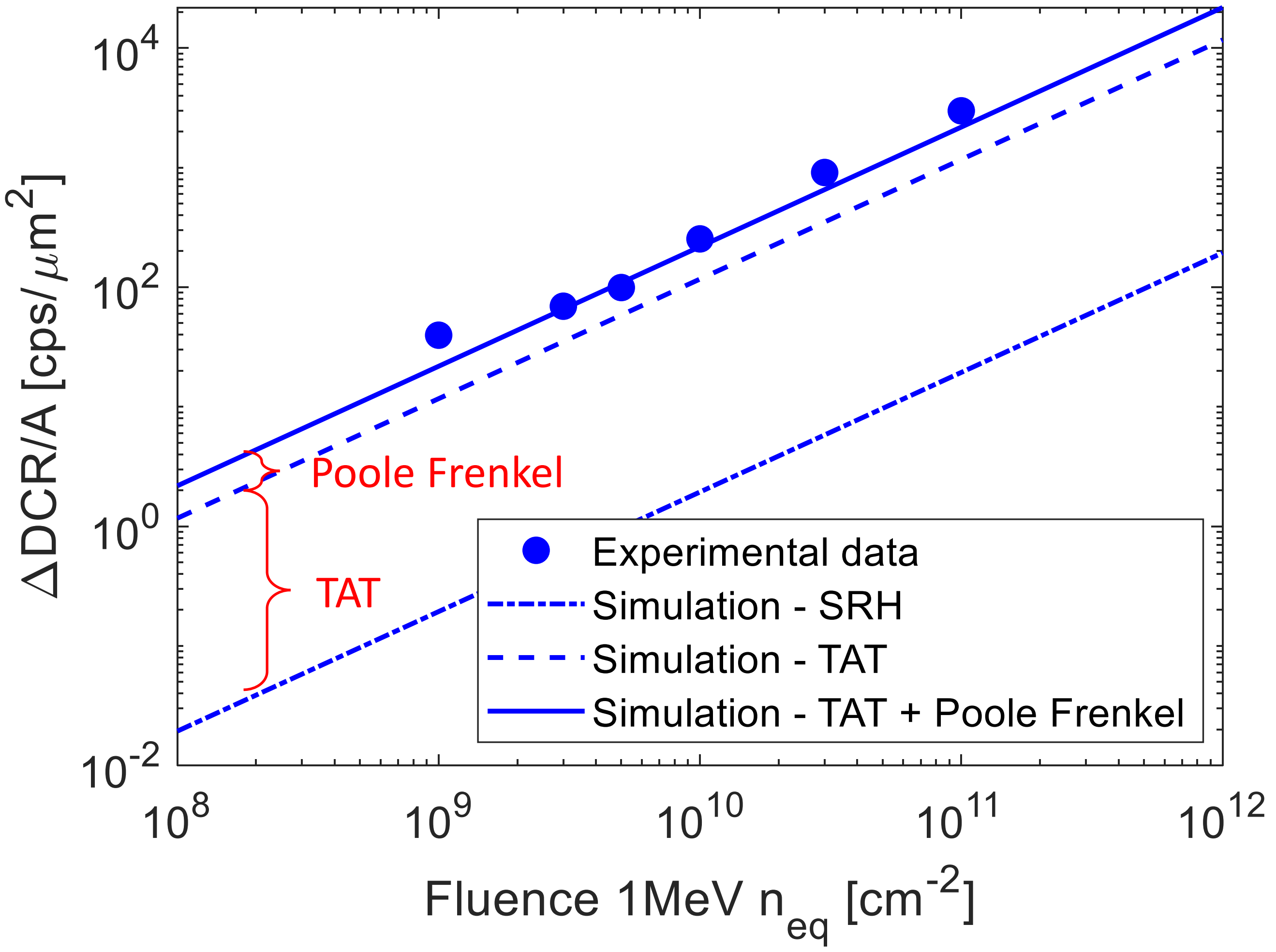
$P_b(x)$: joint e-h breakdown probability

Average DCR simulation: field-enhanced generation

p+/nwell SPADs:

2 orders of magnitude increase introducing field enhanced generation mechanisms

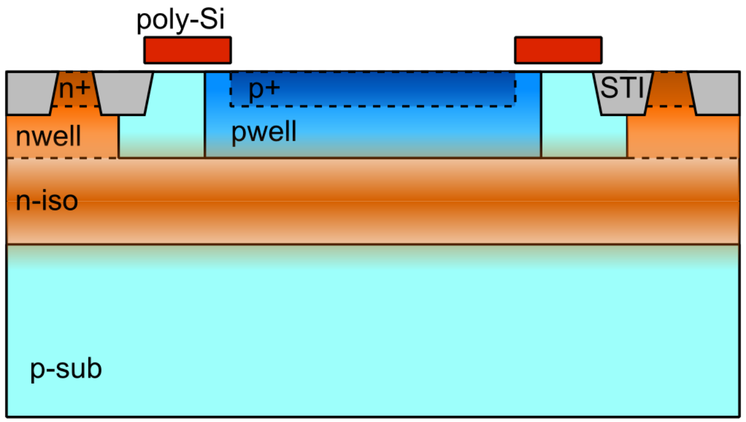


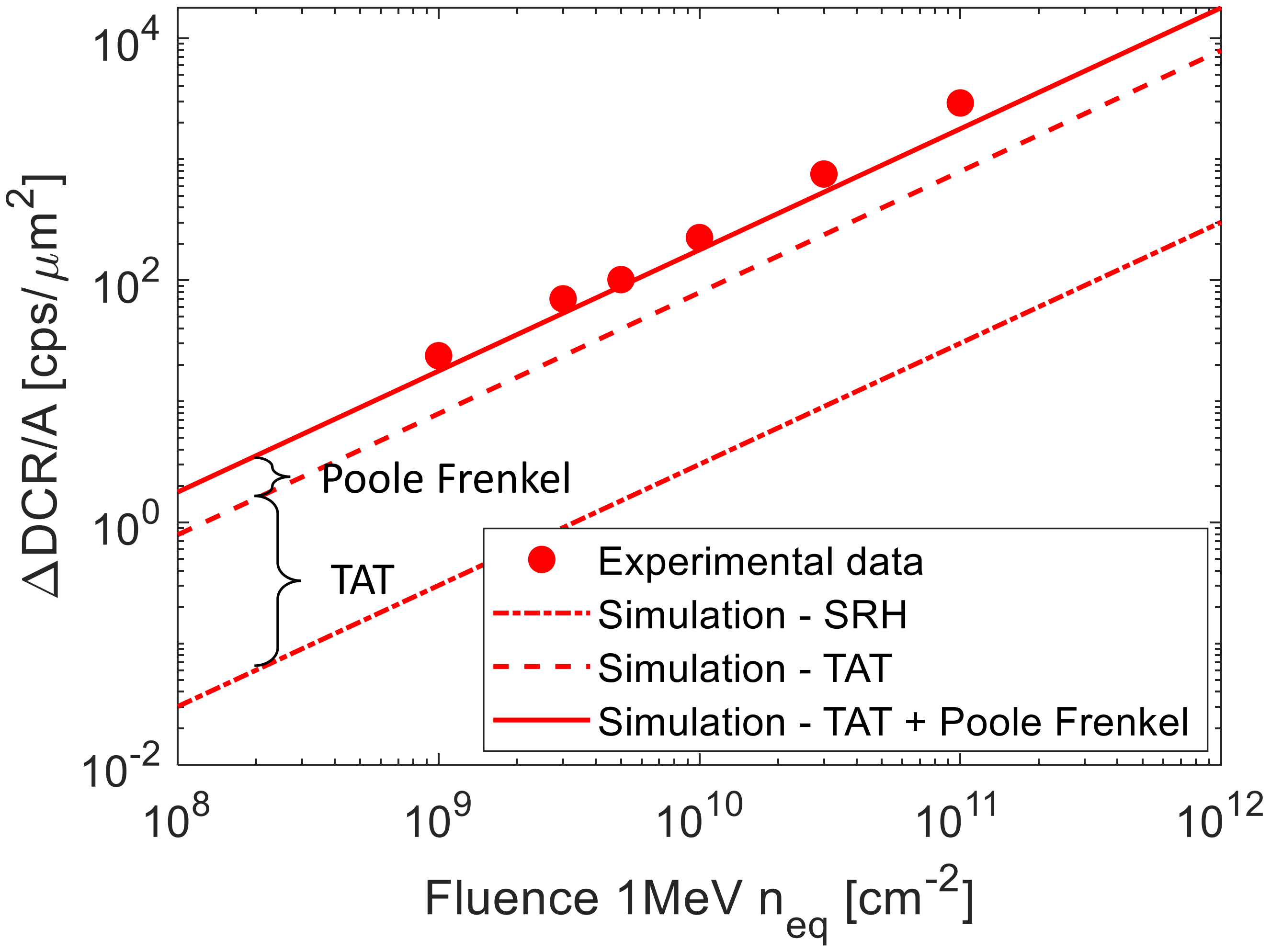


Average DCR simulation

pwell/niso SPADs:

Qualitatively similar increase, but slightly smaller enhancement

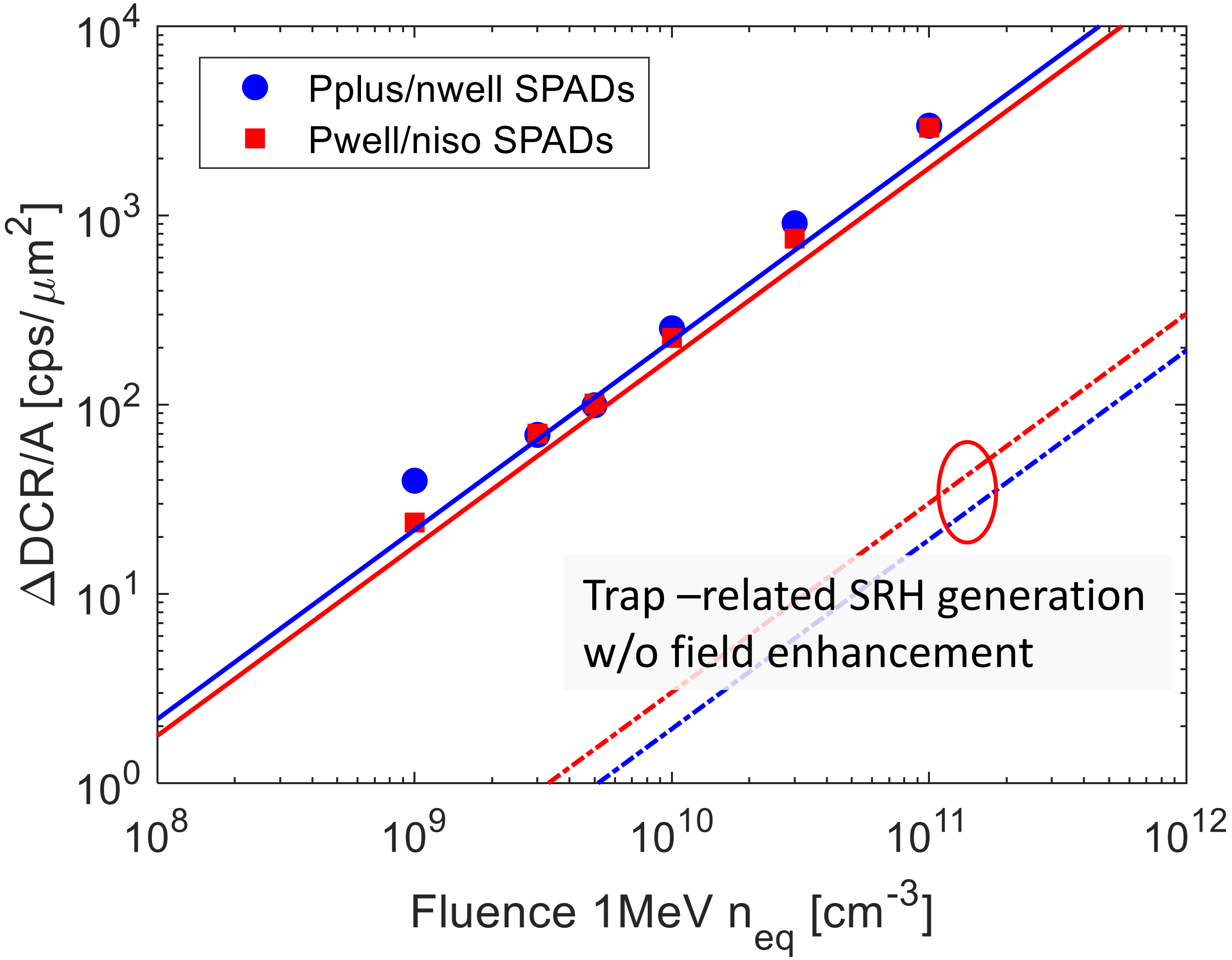




Average DCR simulation: SPAD comparison

Primary generation 50% larger in SPAD with graded junction

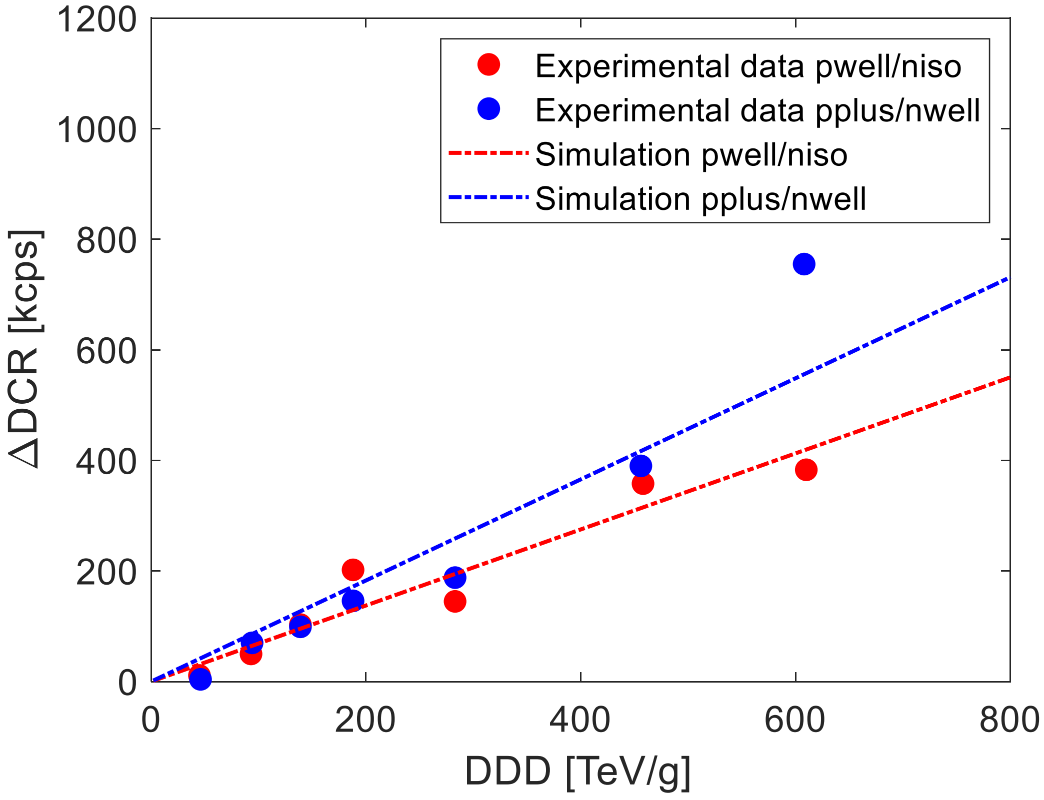
Peak electric field larger in SPAD with abrupt junction: larger field-enhanced generation (confirmed both by experiment and simulation)



Results and comparison with experimental data

Data obtained with SPADs arrays of the same type but:

- Smaller area (10µm x 10µm)
- Different fabrication run
- Different particle type: protons @ 16.4 MeV
- Different voltage (3.3V for both types)
- Different annealing (1week)



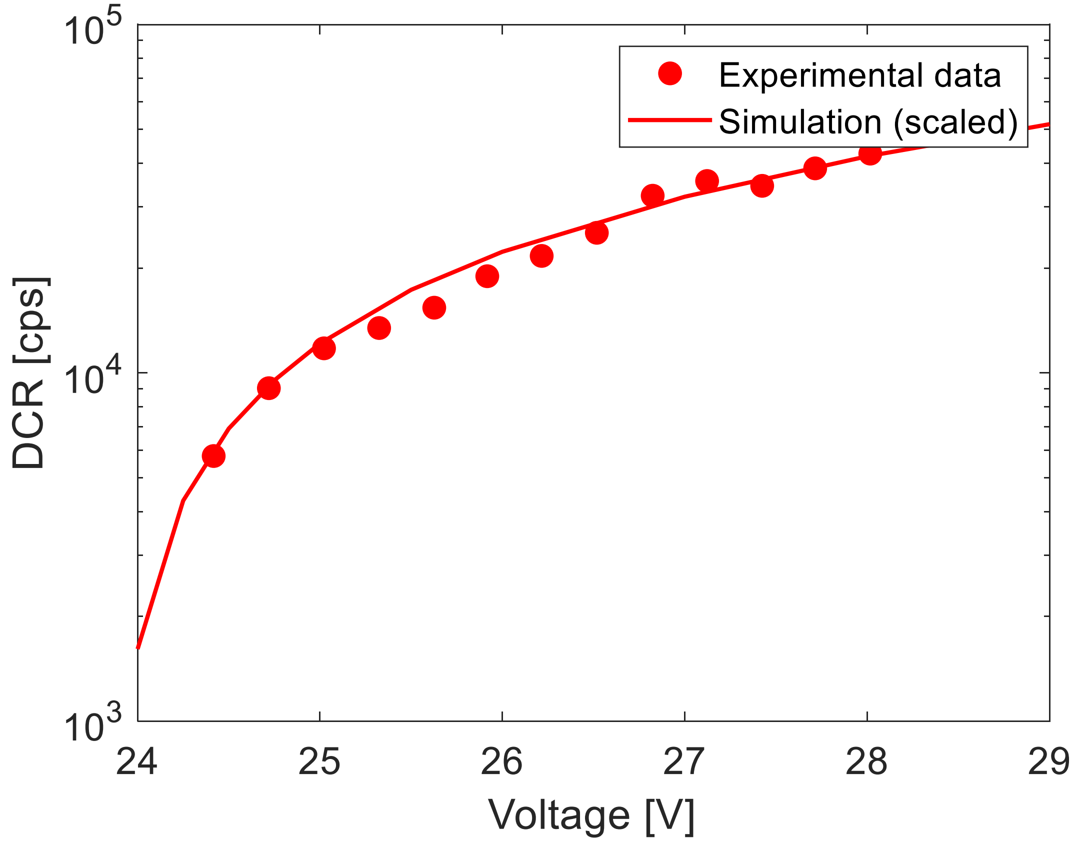
Experimental data from: M. Campajola, Nuclear Inst. Methods A 947 (2019) 162722

Results and comparison with experimental data - voltage

DCR – voltage curve on single pwell/niso SPAD with:

- 10µm x 10µm area
- Proton irradiation @ 60 MeV, fluence of $7.56 \cdot 10^{10}$ cm^{-2}
- Simulation scaled to match experimental data

Experimental trend is reproduced with good accuracy



Experimental data from M. Campajola, Proc. RADECS 2018.

Conclusion – future work

- **DCR distribution** can be modeled from the statistics of non-ionizing energy deposition
- **Average DCR** can be modeled with TCAD: trap levels + field enhanced generation mechanisms: TAT + Poole-Frenkel

- Improved **Temperature dependence** of DCR: more accurate definition of trap levels
- Apply model to SPADs fabricated in **different process technologies**: requires knowledge of doping profiles

Acknowledgments

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