Space Radiation Effects on Single Photon Avalanche Diode (SPAD)

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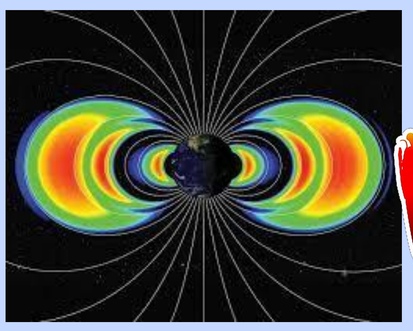
Space Radiation Environment

❑ Space is a radiation environment constantly emitting **particles (protons, electrons, neutrons, heavy ions) and photons (x-rays, γ-rays)**

❑ Sources of radiation during space missions
- **Solar events :** coronal mass ejections (CME) and solar winds
- **Trapped particles due to earth magnetic field (Van-Allen radiation belts)**
- **Galactic cosmic rays:** radiations coming from outside the solar system

Solar events: CME

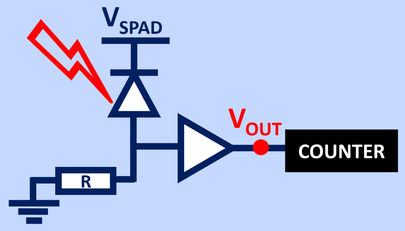


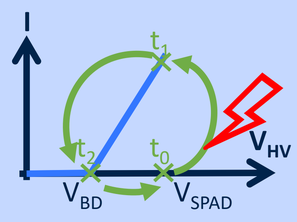
Van-Allen radiation belts

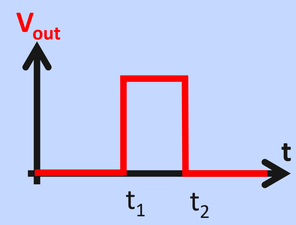
VS

Single Photon Avalanche Diode

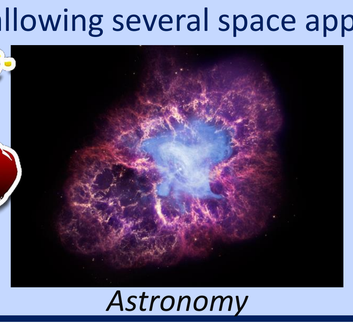
❑ **Single Photon Avalanche Diode (SPAD)**: photodiode biased above the breakdown voltage ➔ **a generated photoelectron will trigger an avalanche of electrons**







❑ SPADs have high sensitivity to light and high timing resolution performances, allowing several space applications:



Astronomy

Space rendezvous

LiDAR

SPAD Main Characteristics

❑ **Photon Detection Efficiency (PDE)**

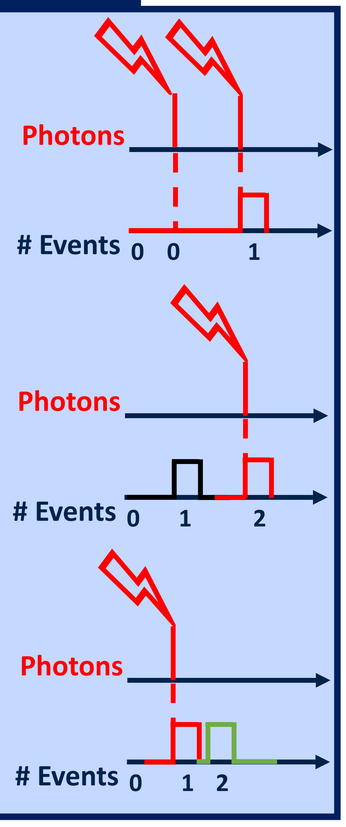
Probability for a photon to trigger an electronic avalanche

❑ **Dark Count Rate (DCR)**

Output pulse rate of SPADs in dark conditions

❑ **Afterpulsing**

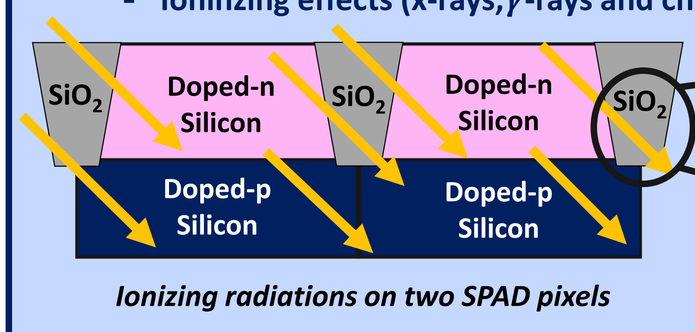
Output pulse due to the release of a trapped electron from a previous avalanche



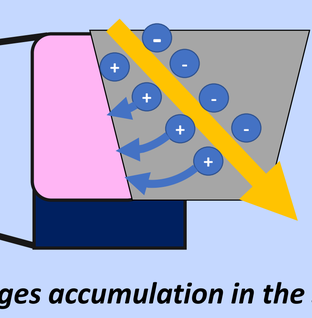
Radiation Effects on SPAD performances

❑ Space radiations can interact in two ways with SPADs:

- **Ioninzing effects (x-rays,γ-rays and charged particles)**



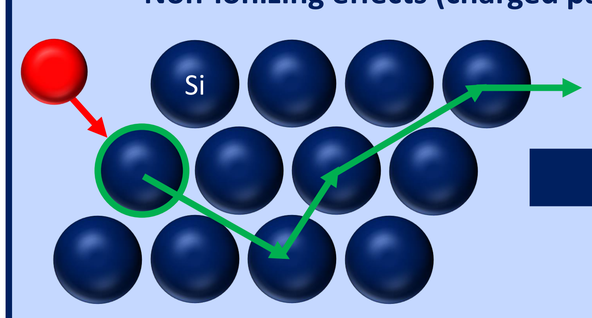
Ionizing radiations on two SPAD pixels



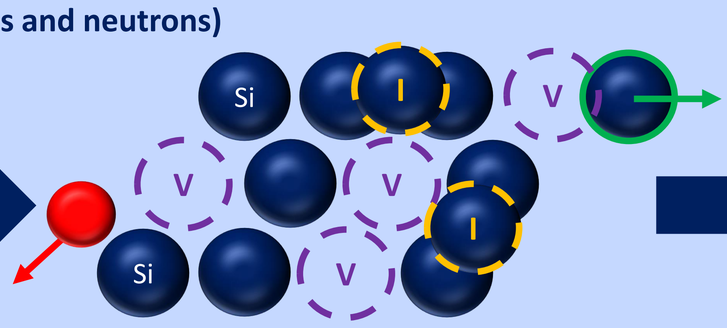
Charges accumulation in the SiO_2

DCR increase

- **Non-ionizing effects (charged particles and neutrons)**



Incident particle colliding with the atomic structure of the SPAD



Creation of vacancies (V) and interstitial atoms (I) due to collisions with the primary knock-on atom

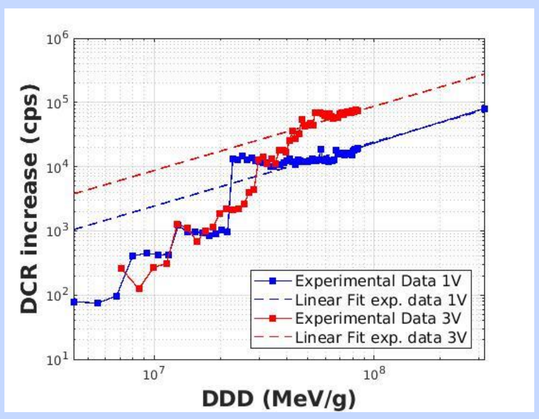
DCR increase

Afterpulsing increase

First Results: Proton Irradiations

❑ Proton irradiations performed on SPAD arrays (proton energy : 62 MeV)

- **Mean DCR increase versus the energy deposited by protons per unit mass, the DDD (Displacement Damage Dose)**



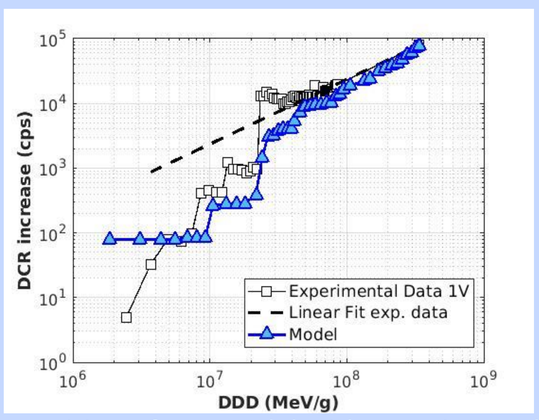
Mean DCR increase vs DDD measured for two SPAD voltages

➔ **High DDD points fit well with the linear fit**

➔ **Discrepancies with linear fit for low DDD points due to particle collision statistics**

➔ **The higher the voltage across SPADs, the higher the DCR degradation with DDD**

- **Set up of a model able to forecast the linear degradation of DCR**

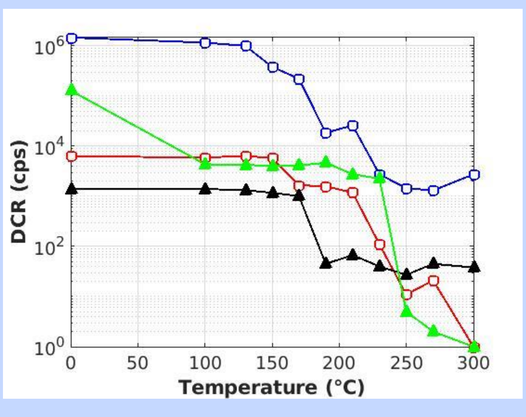


Superposition of our model with experimental data

Damage energy deposition at atomic level and high electric fields effects are considered in the model computations

➔ **Very good fit of the model with experimental data**

- **"Healing" of SPADs by performing annealing (= heat SPADs for tens of minutes)**



DCR variation for 4 SPADs after several annealing temperatures

The shape and the speed of the recovery depend only on the type of defect created (silicon vacancy, divacancies, big or small clusters of defects ,…)

➔ **Annealing study highlights the variety of defects due to proton irradiations**

Conclusions

- **DCR degradation was studied after proton irradiations on SPAD arrays**
- **Model based on SPAD electric field structure and physics of particle collisions was tested and fits well with experimental data**
- **Defect varieties underlined with annealing studies**

Perspectives

- **Improve the model by considering afterpulsing degradation and thermal effects**
- **Perform irradiations with other radiations such as:**
  - ➔ **Electrons**
  - ➔ **γ-rays**