Radiation induced degradation in a 150-nm CMOS SPADs device

(M. Campajola, F. Di Capua, D. Fiore, L. Gasperini, E. Sarnelli)

Marcello Campajola (University of Naples ‘Federico II’ and INFN)
marcello.campajola@na.infn.it
Single-Photon Avalanche Diodes

- Single-Photon Avalanche Diodes (SPADs) are photodiode biased above the breakdown voltage.
- SPADs have sensitivity at the single-photon level with no need for amplification.
- First implementation of SPAD in CMOS technological process has been achieved in 2003, since then many improvements have been obtained.

**CMOS SPADs**
- Excellent timing resolution; 😊
- Position sensitive device; 😊
- Addressing the output of a single SPAD pixel; 😊
- Post-processing circuits integrated on chip; 😊
- High DCR wrt custom processes; 😞
Single-Photon Avalanche Diodes

- Several possible applications (HEP tracker, PET, Spectroscopy, LIDAR, 3D camera, space communication, etc.).

- Many of them require the detector to be utilized in radiation environment; It is fundamental to understand the radiation induced effects on CMOS SPADs.

- A critical issue is related to the Dark Count Rate (DCR). It is due to:
  - Fabrication process: impurities and crystal defects;
  - Radiation environments effects:
    - Displacement Damage: it is the result of energetic particles displacing atoms from their lattice structure;
      As a consequence of DD, new energy level are introduced in the mid-gap. Mid-gap levels lead to an increased rate of dark count rate according several mechanisms;

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Devices Under Test

- Devices designed by Fondazione Bruno Kessler (FBK), Italy.
- SPADs implemented in a 150-nm CMOS process (LFoundry).
- Two junction layouts;
- Several dimensions (5, 10, 15, 20 µm);
- Each SPADs is implemented with its front-end electronics:
  - A trigger to digitalize the pulse;
  - MUX to select one pixel at the time;

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

In-pixel front-end.
Irradiation Test

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
DCR Induced Degradation

- 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 significant changes in the breakdown voltage.

Mean DCR increase as a function of the dose

\[ y = b \times \]
\[ b = (685 \pm 52) \text{ cps/TeV g} \]

DCR distribution after irradiation steps

“Proton induced dark count rate degradation in 150-nm CMOS single-photon avalanche diodes”, M. Campajola et al.
Defects induced by protons may be produced relatively close together and form a local region of disorder (defect cluster or disordered region).

Electrons with energy less than about 2 MeV, produce relatively isolated defects (point-like defects).

**Mean DCR increase as a function of the dose**

\[ y = a + b \times x \]

- \( a = (1365 \pm 23) \text{ cps} \)
- \( b = (25 \pm 3) \text{ cps/TeV g} \)

**DCR distribution after irradiation steps**

- Green: pre-irradiation
- Orange: 155 TeV/g
- Red: 309 TeV/g
After proton irradiation discrete fluctuation between two or more levels have been observed;
This phenomenon is known as Random Telegraph Signal Noise;
Its occurrence increases with the DDD.


DCR Induced Degradation

Random Telegraph Signal Noise

- After proton irradiation discrete fluctuation between two or more levels have been observed;
- This phenomenon is known as Random Telegraph Signal Noise;
- Its occurrence increases with the DDD.

DCR vs observation time

DCR distribution

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Random Telegraph Noise

- In photon devices RTS is due to Displacement Damage Dose effects. Induced defects introduced by proton irradiation can exist 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: RTS.
- 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.

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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.

- 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.
Random Telegraph Noise

- 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

- 40 °C
- 30 °C
- 15 °C
- 5 °C

### RTS time constant vs. Temperature

\[
\frac{1}{\tau} = C \exp\left(\frac{-E_{\text{act}}}{K T}\right)
\]

<table>
<thead>
<tr>
<th>Equation</th>
<th>1/kT (1/eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T down PN</td>
<td>39, 37, 35, 33</td>
</tr>
<tr>
<td>T down PWNISO</td>
<td>39, 37, 35, 33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time constants</th>
<th>a</th>
<th>b</th>
</tr>
</thead>
<tbody>
<tr>
<td>T down PN</td>
<td>-29.94712</td>
<td>0.03097</td>
</tr>
<tr>
<td>T down PWNISO</td>
<td>-32.8866</td>
<td>1.66019</td>
</tr>
</tbody>
</table>

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DCR of irradiated SPAD has been measured after different 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.
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.

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

**IPRD19** Radiation induced degradation in a 150-nm CMOS SPADs device (M. Campajola)
High DCR level require some efficient mitigation method to allow SPADs operation.

Many possibility: thermal annealing, cooling, hot pixel masking, coincidence (adjacent pixels or vertical coincidence)

\[ E_a \sim 0.4 \text{ eV} \]
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. Requires further study.
- Long term 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.
- We investigated cooling and annealing, as possible methods of mitigation.
Contact:

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### Proton irradiation test summary.

<table>
<thead>
<tr>
<th>Chip</th>
<th>Fluence [p/cm²]</th>
<th>Energy [MeV]</th>
<th>TID [krad]</th>
<th>DDD [TeV/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$6.7 \times 10^9$</td>
<td>16.4</td>
<td>2.3</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>$1.4 \times 10^{10}$</td>
<td>16.4</td>
<td>4.8</td>
<td>94</td>
</tr>
<tr>
<td>3</td>
<td>$2.0 \times 10^{10}$</td>
<td>16.4</td>
<td>7.1</td>
<td>139</td>
</tr>
<tr>
<td>4</td>
<td>$2.8 \times 10^{10}$</td>
<td>16.4</td>
<td>9.6</td>
<td>188</td>
</tr>
<tr>
<td>5</td>
<td>$4.1 \times 10^{10}$</td>
<td>16.4</td>
<td>14.5</td>
<td>283</td>
</tr>
<tr>
<td>6</td>
<td>$6.7 \times 10^{10}$</td>
<td>16.4</td>
<td>23.5</td>
<td>457</td>
</tr>
<tr>
<td>7</td>
<td>$9.1 \times 10^{10}$</td>
<td>21.1</td>
<td>30.5</td>
<td>608</td>
</tr>
</tbody>
</table>

### Electron irradiation test summary.

<table>
<thead>
<tr>
<th>Fluence (e/cm²)</th>
<th>Dose (krad)</th>
<th>DDD (TeV/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$6,92E+12$</td>
<td>202,2</td>
<td>308,8</td>
</tr>
<tr>
<td>$3,48E+12$</td>
<td>101,6</td>
<td>155,2</td>
</tr>
</tbody>
</table>
The expected radiation doses for several space environment case-studies have been investigated.

Low orbits can be considered safe enough for long lifetime space missions: only a slight DCR increase is expected. On the contrary, results showed a significant increase in DCR at a proton fluence corresponding to long-lifetime, high altitude missions.

This could be an issue for using SPADs in most of the applications in long life GEO mission, requiring the implementation of an efficient on-mission mitigation procedure.

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**DDD simulation**

**Expected ionizing and non-ionizing dose for different orbits, calculated for a 10-year mission lifetime and variable aluminum shielding.**

<table>
<thead>
<tr>
<th>Orbit Type</th>
<th>Mean Altitude [km]</th>
<th>Inclination [deg.]</th>
<th>Al Shield [mm]</th>
<th>TID [krad]</th>
<th>DDD [TeV/g]</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO-ISS</td>
<td>400</td>
<td>51.6°</td>
<td>2</td>
<td>3.7</td>
<td>19.6</td>
</tr>
<tr>
<td>LEO-FERMI</td>
<td>560</td>
<td>26°</td>
<td>2</td>
<td>3.0</td>
<td>64.3</td>
</tr>
<tr>
<td>MEO</td>
<td>20000</td>
<td>56.2°</td>
<td>3</td>
<td>2196</td>
<td>292</td>
</tr>
<tr>
<td>GEO</td>
<td>36000</td>
<td>0°</td>
<td>3</td>
<td>355</td>
<td>438</td>
</tr>
</tbody>
</table>

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DCR vs Active Area in electron irradiated SPAD

DDD = 309 TeV/g

DCR vs Active Area in proton irradiated SPAD

DDD = 139 TeV/g
Spare

Figure of merits

IPRD19  Radiation induced degradation in a 150-nm CMOS SPADs device (M. Campajola)
• Higher doping concentration in PN junction results in a more peaked electric field inside the junction.

<table>
<thead>
<tr>
<th>Layout</th>
<th>Analysed SPADs</th>
<th>RTS pixels</th>
<th>2 levels</th>
<th>3 levels</th>
<th>4 levels</th>
<th>≥5 levels</th>
<th>RTS fraction</th>
<th>DDD (TeV/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PN</td>
<td>118</td>
<td>65</td>
<td>18</td>
<td>10</td>
<td>10</td>
<td>27</td>
<td>55%</td>
<td>115</td>
</tr>
<tr>
<td>PN</td>
<td>124</td>
<td>80</td>
<td>31</td>
<td>11</td>
<td>5</td>
<td>33</td>
<td>65%</td>
<td>304</td>
</tr>
<tr>
<td>PN</td>
<td>139</td>
<td>118</td>
<td>17</td>
<td>11</td>
<td>8</td>
<td>82</td>
<td>85%</td>
<td>376</td>
</tr>
<tr>
<td>PWNISO</td>
<td>334</td>
<td>131</td>
<td>34</td>
<td>9</td>
<td>13</td>
<td>75</td>
<td>39%</td>
<td>115</td>
</tr>
<tr>
<td>PWNISO</td>
<td>334</td>
<td>190</td>
<td>51</td>
<td>19</td>
<td>16</td>
<td>104</td>
<td>57%</td>
<td>304</td>
</tr>
<tr>
<td>PWNISO</td>
<td>321</td>
<td>186</td>
<td>34</td>
<td>15</td>
<td>8</td>
<td>129</td>
<td>58%</td>
<td>376</td>
</tr>
</tbody>
</table>

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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:

\[ P_{\text{switch}}(t) = \frac{1}{\tau} \exp\left(-\frac{t}{\tau}\right) \]
Spare

- RTS amplitude increase with the overvoltage
Radiation induced degradation in a 150-nm CMOS SPADs device (M. Campajola)

"Low-noise Single Photon Avalanche Diodes in 0.15 μm CMOS Technology", L Pancheri, D Stoppa
Photon detection probability;

**Type 1: p+/nwell**

**Type 2: pwell/niso**

Figure of merits

**DCR vs. pixel index**

- DCR vs. pixel index graph showing the distribution of dark count rate (DCR) across different pixels.

**DCR Cumulative Distribution**

- Cumulative distribution of DCR with mean DCR = 1240 cps, median DCR = 840 cps, and $\frac{<\text{DCR}>}{\mu m^2} = 12.78$ Hz/\(\mu m^2\).

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