Random Telegraph Signals in CCDs and APS
(contract 17928/04/NL/PA)

Final Presentation

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Now at Supaero, Toulouse
Introduction

• What is RTS?
• Devices tested
• Irradiations
• Data analysis
• Results
• Conclusions (preliminary)
What is RTS?

- Random telegraph signals (RTS) are seen in many electronic components
  - Occur when a defect can exist in two or more metastable states and switches between them at random time intervals

- Can occur in MOSFETS (conductance fluctuations), memories (leakage current), IR detectors (dark current)
- & dark current in proton irradiated CCD and APS imagers
TH7890M CCD (e2v Grenoble)
- 512 x 512, 17 um x 17 um pixels
- frame transfer
- MPP

CCD57-10 (e2v technologies)
- 512 x 512, 13 um x 13 um pixels
- frame transfer
- AIMO

STAR250 (Cypress Semiconductor)
- 512 x 512, 25 um x 25 um pixels
- CMOS APS
- On-chip 10-bit ADC

STAR1000 (Cypress Semiconductor)
- 1024 x 1024, 15 um x 15 um pixels
- CMOS APS
- On-chip 10-bit ADC
Gaia AF device for alpha particle CTE damage

- Full frame CCD
- 4500 (vertical) x 1966 (horizontal) pixel
- n-buried channel.
- 4-phase parallel electrodes
- pixel width 30 µm and height 10 µm
- 2-phase readout register with single output
- Supplementary buried channel (SBC)
  - down each column of image area
  - small volume for charge packets < ~ 1000 e
- Back illuminated devices are thinned (to 16 µm),
- Front illuminated device for this study
Irradiations

CCD57-10

<table>
<thead>
<tr>
<th>9 MeV</th>
<th>1.5 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>0.3</td>
<td>1</td>
</tr>
</tbody>
</table>

# 8383-14-22

Star1000

<table>
<thead>
<tr>
<th>9 MeV</th>
<th>1.5 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
</tr>
</tbody>
</table>

# 8383-14-09

PSI 10 & 60 MeV

Harwell 9.0 & 1.5 MeV

Fluences x1E9 10 MeV equiv. p/cm²

TH7890M & STAR250, Harwell, 9.5 MeV protons October 2002

~ 5 10⁸ 1.7 10¹⁰ and 1.7 10¹¹ p/cm² 10 MeV equivalent p/cm²

Louvain-La-Neuve 23/24 January 2007

8th ESA D/TEC QCA Days
CCD57-10 Irradiations

PSI
10 MeV Irradiation (degraded)
2.0 E9 10 MeV equivalent p/cm²

Ebis Iotron
9.0 MeV Irradiation
2.0 E9 p/cm²
5.0 E8 p/cm²

-1°C, 12s Integration Time

Not Irradiated
10 MeV
1.0 10⁹ p/cm²
60 MeV
2.2 10⁹ p/cm²

9.0 MeV
1.0 10⁹ p/cm²
0.3 10⁹ p/cm²

9.0 MeV
0.3 10⁹ p/cm²
1.5 MeV
1.0 10⁹ p/cm²

10 MeV
1.0 10⁹ p/cm²
Not Irradiated

Irradiated at PSI, Switzerland

Irradiated at Ebis Iotron, Harwell
RTS Data Collection

- Each device: data collected for selected pixels at several temps
- # of pixels selected in each image ~ 1000 - 2000
- Number of images ~ 20000 to ~ 30000
  - typical for TH7890M & STAR250  typical for CCD57 & STAR1000
- Integration time (hence time between each image) increased for lower operating temperatures
  - varied between 2 and 60s (minimum time between images = 6s)
  - so typical runs (30000 images) took 2-14 days.
- For each pixel the average & RMS values were calculated.
  - RTS pixels identified by anomalously high RMS value
- Occurrence probabilities: pixels selected at random
- Activation energies: brightest pixels
  - Analysis done for 30-50 pixels in each fluence region on each device for typically 4 temperatures in the range –4°C to 18°C
  - ~ 2500 analyses of 30000 data points
  - so > 75 million data points!
Data Analysis (1)

<table>
<thead>
<tr>
<th>Levels</th>
<th>Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>5211</td>
<td>1223</td>
</tr>
<tr>
<td>6433</td>
<td></td>
</tr>
<tr>
<td>17140</td>
<td></td>
</tr>
<tr>
<td>19203</td>
<td></td>
</tr>
<tr>
<td>30574</td>
<td></td>
</tr>
<tr>
<td>4923</td>
<td></td>
</tr>
<tr>
<td>5960</td>
<td></td>
</tr>
</tbody>
</table>

**Main Results**
- UpState Time(s): 18607
- Up/Down prob (%): 62.02%
- Transitions: 92

**Intermediate results**
- Levels drawing:
  - 5211
  - 6433
- Transitions: 5822
### Data Analysis (2)

<table>
<thead>
<tr>
<th>Temperature (deg)</th>
<th>-15</th>
<th>-7</th>
<th>-2</th>
<th>4</th>
<th>11</th>
<th>18</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>258.15</td>
<td>266.15</td>
<td>271.15</td>
<td>277.15</td>
<td>284.15</td>
<td>291.15</td>
</tr>
<tr>
<td>(-\frac{1}{kT}) (1/eV)</td>
<td>(-4.49E+01)</td>
<td>(-4.36E+01)</td>
<td>(-4.28E+01)</td>
<td>(-4.19E+01)</td>
<td>(-4.08E+01)</td>
<td>(-3.98E+01)</td>
</tr>
<tr>
<td>Nb of points</td>
<td>23370</td>
<td>30000</td>
<td>30000</td>
<td>30000</td>
<td>30000</td>
<td>30000</td>
</tr>
<tr>
<td>Gain (ADU/V)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Integration time (s)</td>
<td>60</td>
<td>30</td>
<td>20</td>
<td>12</td>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>Time interval (s)</td>
<td>60</td>
<td>30</td>
<td>20</td>
<td>12</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Experiment duration (s)</td>
<td>1402140</td>
<td>899970</td>
<td>599980</td>
<td>359988</td>
<td>179994</td>
<td>179994</td>
</tr>
<tr>
<td>Up/DownProb (%)</td>
<td>1.7%</td>
<td>1.4%</td>
<td>2.1%</td>
<td>3.2%</td>
<td>3.5%</td>
<td>3.6%</td>
</tr>
<tr>
<td>Transitions</td>
<td>34</td>
<td>72</td>
<td>110</td>
<td>192</td>
<td>220</td>
<td>500</td>
</tr>
<tr>
<td>Amplitude (ADU)</td>
<td>6060</td>
<td>5998</td>
<td>6091</td>
<td>5508</td>
<td>4745</td>
<td>2754</td>
</tr>
<tr>
<td>Amplitude/Tint (V/s)</td>
<td>101</td>
<td>199.933333</td>
<td>304.55</td>
<td>459</td>
<td>790.833333</td>
<td>1377</td>
</tr>
<tr>
<td>(\tau_{\text{high}})</td>
<td>0.3780279</td>
<td>0.09721898</td>
<td>0.063634242</td>
<td>0.03333222</td>
<td>0.01590856</td>
<td>0.00719976</td>
</tr>
<tr>
<td>(1/\tau_{\text{high}})</td>
<td>2.6453071</td>
<td>10.2860572</td>
<td>15.71480954</td>
<td>30.001</td>
<td>62.8592382</td>
<td>138.893519</td>
</tr>
<tr>
<td>(\tau_{\text{low}})</td>
<td>22.532756</td>
<td>6.84699398</td>
<td>2.96657778</td>
<td>1.00829972</td>
<td>0.43862174</td>
<td>0.19279357</td>
</tr>
<tr>
<td>(1/\tau_{\text{low}})</td>
<td>0.0443798</td>
<td>0.14604949</td>
<td>0.33709888</td>
<td>0.9917686</td>
<td>2.2798674</td>
<td>5.18689489</td>
</tr>
<tr>
<td>(\tau_{\text{high}}/\tau_{\text{low}})</td>
<td>0.0167768</td>
<td>0.01419878</td>
<td>0.02149878</td>
<td>0.03305785</td>
<td>0.03626943</td>
<td>0.0373444</td>
</tr>
<tr>
<td>Eact (eV)</td>
<td>0.7501691</td>
<td>3.339E+13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(C)</td>
<td>0.9537716</td>
<td>1.9352E+18</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplitude</td>
<td>0.5075846</td>
<td>4.2429E+11</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[
y = 8E+11e^{0.5076x}
\]

\[
y = 2E+17e^{0.8538x}
\]

\[
y = 1E+15e^{0.7502x}
\]
CCD57-10 Pre-rad RTS

![CCD57-10 Pre-rad RTS Graph](image)

<table>
<thead>
<tr>
<th>Device</th>
<th>Number of RTS pixels</th>
<th>% of RTS pixels that are 2-level</th>
<th>% of RTS pixels that are multi-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>8383-14-09</td>
<td>136</td>
<td>51%</td>
<td>46%</td>
</tr>
<tr>
<td>8383-14-12</td>
<td>81</td>
<td>47%</td>
<td>41%</td>
</tr>
<tr>
<td>8383-14-22</td>
<td>163</td>
<td>79%</td>
<td>21%</td>
</tr>
</tbody>
</table>
Pre-rad RTS

![Graph depicting Dark Signal (ADU) vs Sample Number]
Pre-rad RTS

CCD57-10 #8383-14-22
Pre-irradiation

Activation Energy (eV)

Amplitude at 1°C (ADU/s)

CCD57-10 #8383-14-22
Pre-irradiation

Time Constant at 2°C (hours)

Activation Energy (eV)

Amplitude at 1°C (ADU/s)
Post-rad Ocurrence Probability

Random Pixels: ~ 50% of the RTS pixels were 2-level, regardless of fluence or proton energy

Displacement Damage Dose (Arbitrary Units)

Percentage of RTS Pixels

0% 5% 10% 15% 20% 25% 30% 35% 40%

6.4 \times 10^{-5} / 10 \text{ MeV proton / pixel}

#22 9 MeV
#22 1.5 MeV
#12 10 MeV
#12 60 MeV
#09 10 MeV
#09 9 MeV

Random Pixels: ~ 50% of the RTS pixels were 2-level, regardless of fluence or proton energy
RTS Probability for CCDs

![Graph showing RTS probability for different CCDs.](image)

- **CCD57-10**: 13 µm pixel
- **TH7890M**: 17 µm pixel
- **CCD02**: 22 µm pixel

RTS probability ~ $10^{-10}$ / $(10 \text{ MeV proton/cm}^2)$

No Annealing?
## CCD57-10 Bright Pixels

<table>
<thead>
<tr>
<th>Device</th>
<th>Number of RTS pixels</th>
<th>% of bright pixels that are RTS</th>
<th>% of RTS pixels that are 2-level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>8383-14-09 before anneal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 $10^9$ 9 MeV p/cm², Harwell</td>
<td>977</td>
<td>98 %</td>
<td>9 %</td>
</tr>
<tr>
<td>5 $10^8$ 9 MeV p/cm², Harwell</td>
<td>185</td>
<td>96 %</td>
<td>17 %</td>
</tr>
<tr>
<td>2 $10^9$ 9 MeV p/cm², PSI</td>
<td>828</td>
<td>97 %</td>
<td>12 %</td>
</tr>
<tr>
<td><strong>8383-14-09 after anneal</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 $10^9$ 9 MeV p/cm², Harwell</td>
<td>518</td>
<td>52 %</td>
<td>46 %</td>
</tr>
<tr>
<td>5 $10^8$ 9 MeV p/cm², Harwell</td>
<td>83</td>
<td>43 %</td>
<td>39 %</td>
</tr>
<tr>
<td>2 $10^9$ 9 MeV p/cm², PSI</td>
<td>471</td>
<td>55 %</td>
<td>48 %</td>
</tr>
<tr>
<td><strong>8383-14-12</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $10^9$ 10 MeV p/cm², PSI</td>
<td>957</td>
<td>96 %</td>
<td>11 %</td>
</tr>
<tr>
<td>2.2 $10^9$ 60 MeV p/cm², PSI</td>
<td>948</td>
<td>95 %</td>
<td>9 %</td>
</tr>
<tr>
<td><strong>8383-14-22</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $10^9$ 9 MeV p/cm², Harwell</td>
<td>454</td>
<td>91 %</td>
<td>17 %</td>
</tr>
<tr>
<td>3 $10^8$ 9 MeV p/cm², Harwell</td>
<td>408</td>
<td>82 %</td>
<td>35 %</td>
</tr>
<tr>
<td>3 $10^8$ 1.5 MeV p/cm², Harwell</td>
<td>456</td>
<td>91 %</td>
<td>18 %</td>
</tr>
<tr>
<td>1 $10^9$ 1.5 MeV p/cm², Harwell</td>
<td>457</td>
<td>91 %</td>
<td>12 %</td>
</tr>
</tbody>
</table>
CCD57-10 Bright Pixels

Graph showing the relationship between Activation Energy (eV) and Time Constant at 1°C and 2°C, with distinctions for different energy levels (10 MeV, 60 MeV) and temperature levels (THigh, TLow).
STAR1000 Pre-rad RTS

STAR1000 #1
18°C, 2s Integration Time

Sample Number

Dark signal (ADU)

STAR1000 #1
18°C, 2s Integration Time
1 ADU = 1.5e
STAR1000: Dark Signal Histograms

Count

Dark Signal at 18°C (e/pixel/s)

#2 $1.0 \times 10^{10}$ 1.5 MeV p/cm$^2$, Harwell
#2 $1.0 \times 10^{10}$ 9.0 MeV p/cm$^2$, Harwell
#1 $1.0 \times 10^{10}$ 10 MeV p/cm$^2$, PSI
#1 $2.2 \times 10^{10}$ 60 MeV p/cm$^2$, PSI
CCD57-10 # 8383-14-12
1.0 $10^9$ 10 MeV p/cm$^2$, PSI
## STAR1000 Occurrence Probabilities

<table>
<thead>
<tr>
<th>Device</th>
<th>Number of RTS pixels in block of 500 pixels</th>
<th>% of pixels that are RTS</th>
<th>Number of RTS pixels that are multi-level</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $10^{10}$ 10 MeV p/cm², PSI</td>
<td>17</td>
<td>3.4 %</td>
<td>3</td>
</tr>
<tr>
<td>2.2 $10^{10}$ 60 MeV p/cm², PSI</td>
<td>21</td>
<td>4.2 %</td>
<td>3</td>
</tr>
<tr>
<td>#2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $10^{10}$ 1.5 MeV p/cm², Harwell</td>
<td>11</td>
<td>2.2 %</td>
<td>1</td>
</tr>
<tr>
<td>2 $10^{8}$ 1.5 MeV p/cm², Harwell</td>
<td>5</td>
<td>1 %</td>
<td>0</td>
</tr>
<tr>
<td>1 $10^{10}$ 9 MeV p/cm², Harwell</td>
<td>8</td>
<td>1.6 %</td>
<td>3</td>
</tr>
<tr>
<td>2 $10^{8}$ 9 MeV p/cm², Harwell</td>
<td>4</td>
<td>0.8 %</td>
<td>0</td>
</tr>
</tbody>
</table>

### Random Pixels
STAR1000 Brightest Pixels

STAR1000 #1
$2 \times 10^9$ 1.5 MeV p/cm$^2$

Sample Number

Dark Signal (ADU)

STAR1000 #1
2 $\times 10^9$ 1.5 MeV p/cm$^2$
### STAR1000 Brightest Pixels

<table>
<thead>
<tr>
<th>Device</th>
<th>Number of RTS pixels</th>
<th>% of pixels that are RTS</th>
<th>% of RTS pixels that are 2-level</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>#1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $10^{10}$ 10 MeV p/cm², PSI</td>
<td>449</td>
<td>65 %</td>
<td>29 %</td>
</tr>
<tr>
<td>2.2 $10^{10}$ 60 MeV p/cm², PSI</td>
<td>722</td>
<td>72 %</td>
<td>31 %</td>
</tr>
<tr>
<td><strong>#2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 $10^{10}$ 1.5 MeV p/cm², Harwell</td>
<td>404</td>
<td>54 %</td>
<td>50 %</td>
</tr>
<tr>
<td>2 $10^9$ 1.5 MeV p/cm², Harwell</td>
<td>123</td>
<td>59 %</td>
<td>39 %</td>
</tr>
<tr>
<td>1 $10^{10}$ 9 MeV p/cm², Harwell</td>
<td>195</td>
<td>53 %</td>
<td>32 %</td>
</tr>
<tr>
<td>2 $10^9$ 9 MeV p/cm², Harwell</td>
<td>128</td>
<td>51 %</td>
<td>30 %</td>
</tr>
</tbody>
</table>
STAR1000 Brightest Pixels

Graphs showing activation energy vs. time constant at 4°C for PSI and Harwell irradiation, with data points for different energy levels (10 MeV, 1.5 MeV) and irradiation types (Thigh, Tlow).
Conclusions (Preliminary)

• RTS behaviour is very similar for all devices and proton energies (including pre-rad) – after NIEL scaling

• With (random) occurrence probabilities of a few % still get a lot of multi-level defects

• Most of the brightest pixels (~ 1000 per chip) are multi-level
  – Cannot be explained by several independent collision events in a pixel
    • Also found by Thierry Nuns at ONERA
  – Either single RTS defects that are multi-level, or
  – Several defects (each 2-level) created by a collision – clusters (so intrinsic defects)
    • Even at 1.5 MeV, where expect mostly point defects
Cluster Production

Beck et al. NSREC 2006
SRIM Simulation: 1.5 MeV

Depth vs. Y-Axis

Layer 1

0 A - Target Depth - 1000 A