Electron-induced SEEs in SDRAMs and dosimetry of a pulsed electron beam

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RADSAGA Final Conference and Industrial event

Daniel Söderström, RADSAGA ESR 2, Work Package #1

RADiation and Reliability Challenges for Electronics used in Space, Aviation, Ground and Accelerators (RADSAGA) is a project funded by the European Commission under the Horizon2020 Framework Program under the Grant Agreement 721624.
RADSAGA began in Mars 2017 and will run for 5 years.
Presentation outline

- ESR 2 project
- Electron-induced stuck bits in SDRAMs
  - Irradiation facilities
  - Electron-induced SEE
  - Jovian environment
- Optical fiber-based dosimetry
  - Response to a pulsed electron beam
  - Emission spectra
  - Dose rate dependence
Project of ESR 2

- Based in the University of Jyväskylä, Department of Physics, RADEF
- Project surrounding electron environments
  - Electron radiation effects studied in SDRAMs
  - Dosimetry using optical fiber-based systems
- Co-supervised from and collaboration work with
  - Laboratoire Hubert Curien, Saint Etienne
  - LIRMM, Montpellier
Electron irradiation of SDRAMs

- Motivated by the JUICE mission
- A mission candidate component tested

Hard energy spectrum in the Jovian electron environment

Data from JUICE environment specification, European Space Agency (ESA)/ESTEC, Revision 5 Issue 5, Feb. 2017, reference JS-14-09.
Test facilities: VESPER at CERN

- Electron energy: 60 – 200 MeV

<table>
<thead>
<tr>
<th>VESPER beam parameters</th>
<th>Pulse frequency</th>
<th>Pulse length</th>
<th>Bunch frequency</th>
<th>Beam dosimetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 Hz</td>
<td>100 bunches</td>
<td>3 GHz</td>
<td></td>
<td>Beam current measured by a beam current transformer, beam spot shape from a scintillating screen</td>
</tr>
</tbody>
</table>

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Test facilities, Clinac at RADEF

- **Electrons**: 6 – 20 MeV
- **Photons**: Bremsstrahlung

<table>
<thead>
<tr>
<th>RADEF beam parameters</th>
<th>Pulse frequency</th>
<th>Pulse length</th>
<th>Beam dosimetry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt; 200 Hz</td>
<td>5 µs</td>
<td>In-beam ionization chambers, calibrated against absolute dosimeters in water.</td>
</tr>
</tbody>
</table>

Figure source: *Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment*, Söderström et al., IEEE TNS, Early access, 10.1109/TNS.2021.3068186, 2021.

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Tested components

- **512 Mb ISSI SDRAMs**
  - IS42S86400B most tested and most sensitive

<table>
<thead>
<tr>
<th>Memory</th>
<th>Node size</th>
<th>Irradiation field</th>
<th>Irradiation energies</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS42S86400B</td>
<td>110 nm</td>
<td>Electrons</td>
<td>6 – 200 MeV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Photons</td>
<td>6 MV</td>
</tr>
<tr>
<td>IS42S16320D</td>
<td>72 nm</td>
<td>Electrons</td>
<td>200 MeV</td>
</tr>
<tr>
<td>IS42S16320F</td>
<td>63 nm</td>
<td>Electrons</td>
<td>200 MeV</td>
</tr>
</tbody>
</table>
SEE induced by high-energy electrons

Stuck bits and bit-flips

- Sample IS42S86400B
- Stuck bits as a function of 123 MeV electron fluence.
- Similar look for bit-flips
- Linear part from SEE
- Power law increase from cumulative effects

Figure source: *Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment*, Söderström et al, IEEE TNS, Early access, 10.1109/TNS.2021.3068186, 2021.
Low-energy electron irradiation

- No SEE observed, only cumulative effects

- Dose in krad(Si) for electrons, and krad(H₂O) for photons

Figure source: Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment, Söderström et al, IEEE TNS, Early access, 10.1109/TNS.2021.3068186, 2021.
Similar values for stuck bits and bit-flips

<table>
<thead>
<tr>
<th>Weibull parameter</th>
<th>Stuck</th>
<th>Bit-flip</th>
</tr>
</thead>
<tbody>
<tr>
<td>A ($10^{-20}$ cm$^2$/bit)</td>
<td>1.41</td>
<td>1.20</td>
</tr>
<tr>
<td>$E_0$ (MeV)</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>W (MeV)</td>
<td>57.9</td>
<td>68.3</td>
</tr>
<tr>
<td>$s$</td>
<td>1.41</td>
<td>1.86</td>
</tr>
</tbody>
</table>
Projected electron SEE on board JUICE

<table>
<thead>
<tr>
<th>Fault</th>
<th>Errors without shielding</th>
<th>Errors with 15 mm Al shielding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stuck bits</td>
<td>4.2</td>
<td>0.86</td>
</tr>
<tr>
<td>Bit-flips</td>
<td>4.0</td>
<td>0.81</td>
</tr>
</tbody>
</table>

(Different fitting procedure than in Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment, Söderström et al, IEEE TNS, Early access, 10.1109/TNS.2021.3068186, 2021, but the results are similar.)
Fiber-based dosimetry in pulsed electron beams

- Samples are doped silica rods connected to a transport fiber
- Dopants: Ce, Cu, and Gd
Tests and setups

- Readout systems for different purposes
  - Photomultiplier tube (PMT) to oscilloscope
    - Analyze traces with many pulses
  - PMT to digitizer
    - Analyze the structure of individual pulses
  - Light signal to spectrometer
    - Analyze the optical emission spectra
Emission spectra

- Excited by 20-MeV electrons
- Peaks at
  - Gd: 314 nm
  - Ce: 494 nm
  - Cu: 543 nm
Accelerator parameters

- Non-standard operation of the accelerator

Normal dose rate tuning

Dose rate tuning here
Machine dose calibration

- Built-in ionization chambers diverted from linearity at larger electron pulses
- Data for tests of one minute duration, with increasing electron bunch sizes at a constant frequency
Fiber signal at different electron bunch sizes

- Pulse height as a function of bunch size

Ce-rod, 500 nm BP filter
- Fit $y = 2.40 \times x$
- 200 Hz pulse rate data
- 20 Hz pulse rate data

Gd-rod, no filter
- Fit $y = 0.54 \times x$
- 200 Hz pulse rate data
- 20 Hz pulse rate data
Fiber signal at different electron bunch sizes

- Pulse height with thin transport fiber (50 µm)

Small bunches are dominated by the noise.
Conclusion

- Electrons can cause stuck bits in SDRAMs as SEE
- Electron SEE is not a big problem for the tested device in the Jovian environment
- The doped silica rods have a linear response of luminescence vs electron bunch size (mrad – rad)
- Can be used to monitor pulsed radiation from a Clinac
Thank you for your attention

Thanks to all collaborators who have helped in experiments and analysis.
Backup slides
Rods in clinac beam

Sample in different configurations

Gd-rod 0.70 V PMT gain, Filter: none

Distance from beam data
Sample laying on cave floor
Sample behind accelerator

Gd-rod 0.70 V PMT gain, Filter: none

No shielding
Linear fit no shield
Lead over transport fiber
Linear fit shield over transport fibre
Lead over transport fibre and sample
Linear fit transport fiber and sample shielded
The PMT gain might affect linearity
Decay time plots

- Gd, Cu, and Ce samples
Collected pulses in oscilloscope

Ce sample

Cu sample

Gd sample

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Memory cell damage in different bit populations

- Comparison of three different populations:
  - Stuck bits (SEE)
  - Single bit-flips (SEE)
  - All bits

- Bits which were either stuck or had a bit-flip show reduced data retention capabilities compared to the global population

- The stuck bits generally fail at higher refresh frequencies than the flipped

- The stuck and flipped populations show signs of being damaged in a similar fashion during irradiation

- The mechanism behind both failure modes is likely one and the same, differing mainly in the severity of the event.

Figure: Fraction of the total number of words containing failing bits in different populations in the memory in a post-irradiation test, performed using different refresh frequencies in the memories. Data from four model B memories tested with different electron energies.

Figure source: Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment, Söderström et al, IEEE TNS, Early access, 10.1109/TNS.2021.3068186, 2021.
Annealing of irradiated samples

Figure source: Electron-Induced Upsets and Stuck Bits in SDRAMs in the Jovian Environment, Söderström et al, IEEE TNS, Early access, 10.1109/TNS.2021.3068186, 2021.