Radiation Effects on Electronic Components

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Corporate Profile

**Mission:** Improve our nation’s ability to defend itself from domestic and foreign threats by pioneering reliable solutions for counterfeit detection.

Clients include:
DHS, NIH, NSF, NASA, DOE, ONR, DARPA, Navy, defense and aerospace contractors
Our work at Fermi National Accelerator Laboratory – Fermilab
Not all radiation is equal

### Comparison of Radiation Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Alpha (α)</th>
<th>Proton (p)</th>
<th>Beta (β) or Electron (e)</th>
<th>Photon (γ or X ray)</th>
<th>Neutron (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>$\frac{4}{2}\alpha$ or He$^{2+}$</td>
<td>$\frac{1}{1}p$ or H$^{1+}$</td>
<td>$\frac{0}{-1}e$ or β</td>
<td>$\frac{0}{0}\gamma$</td>
<td>$\frac{1}{0}n$</td>
</tr>
<tr>
<td>Charge</td>
<td>+2</td>
<td>+1</td>
<td>-1</td>
<td>neutral</td>
<td>neutral</td>
</tr>
<tr>
<td>Ionization</td>
<td>Direct</td>
<td>Direct</td>
<td>Direct</td>
<td>Indirect</td>
<td>Indirect</td>
</tr>
<tr>
<td>Mass (amu)</td>
<td>4.001506</td>
<td>1.007276</td>
<td>0.00054858</td>
<td>—</td>
<td>1.008665</td>
</tr>
<tr>
<td>Velocity (cm/sec)</td>
<td>$6.944\times10^8$</td>
<td>$1.38\times10^9$</td>
<td>$2.82\times10^{10}$</td>
<td>$c=2.998\times10^{10}$</td>
<td>$1.38\times10^9$</td>
</tr>
<tr>
<td>Speed of Light</td>
<td>2.3%</td>
<td>4.6%</td>
<td>94.1%</td>
<td>100%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Range in Air</td>
<td>0.56 cm</td>
<td>1.81 cm</td>
<td>319 cm</td>
<td>82,000 cm*</td>
<td>39,250 cm*</td>
</tr>
</tbody>
</table>

*range based on a 99.9% reduction*

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**Alpha particle:**
- easily stopped
- least penetrating

**Beta particle:**
- very much smaller
- more penetrating

**Gamma ray and X-ray:**
- pure energy with no mass
- most penetrating

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K. E. Holbert, Radiation Effects Damage

www.CreativeElectron.com
What kind of ionizing radiation semiconductors are most frequently subject to?

• **Electromagnetic:**
  – X-rays
  – Gamma rays

• **Subatomic particles:**
  – Protons
  – Neutrons
  – Electrons
  – Pions
  – Muons
What are the sources of exposure for semiconductors?

• **Background**
  – Terrestrial: dependent on location.
  – Cosmic: dependent on altitude.

• **Man made**
  – Inspection on airports, ports, post offices, and delivery companies.
  – Inspection for quality assurance, failure analysis, and counterfeit detection.
What are the factors that increase the probability of component damage?

- **Radiation type:** Larger particles have higher probability of damage due to their cross section. Electromagnetic radiation such as gamma or x-rays need a huge amount of energy to cause bulk damage on silicon.

- **Energy:** The energy will be one of the main factors that will define the probability of interaction with matter.

- **Radiation flux:** Higher fluxes will increase the probability of damaged if the minimum energy threshold is reached.

- **Exposure time:** The time of exposure combine with the three factors above will define the total dose that the part is submitted.
What kind of damage radiation can cause on semiconductors?

• **Bulk damage**: Occurs when the energy transferred to the silicon atom is sufficient to remove it from the crystal lattice. This damage is permanent. The great majority of currently available X-ray inspection systems simply don’t have enough energy to cause this kind of damage.

• **Surface damage**: The passage of ionizing radiation in the silicon oxide on semiconductors causes the built up of trapped charge in the oxide layers of the semiconductor. With time, or high flux, the e-h pairs created in the oxide either recombine or move towards the SiO₂-Si interface, altering the characteristics of the semiconductor.

• **Single event upset**: Is a change of logical state caused by passage of radiation. This does not cause permanent damage on the semiconductor. It has potential to alter microcode or configware resident on certain devices such as FPGA’s and memory circuits.
When cosmic rays enter the Earth's atmosphere they collide with molecules, mainly oxygen and nitrogen, to produce a cascade of billions of lighter particles, a so-called air shower.

An average of 0.6 mrem per hour at cruise altitude.
Radiation type: Neutrons, protons, pions, muons, and gamma.
Any kind of cargo (including electronic parts) can go under mandatory x-ray inspection in ports of entry and airports.

It is not unusual to have electronic components being inspected with x-ray machines several times when moving from one country to another.

Port and airport x-ray machines are not designed to limit the amount of radiation cargo is exposed to.

- Exposure due to this systems can easily accumulate to several hundreds of milirems.
Example – Component travelling from Asia to USA

Cargo 160kV

Port of exit/entry
1MeV~6MeV

Flight ~10mRem

Counterfeit detection ~ 50mRem
• Typically X-ray systems deployed for counterfeit detection and quality control are in the range of 80kV to 120kV.

• A good digital image can be achieved with an exposure time between 200 and 500ms.

• Considering a system that exposes its parts for 1.5s at 80kV as a benchmark. Each inspected part will receive on average 50mRem of total dose.
Automation is key to reduce exposure

- Each component exposed to radiation for only 1.5s
- Automated image acquisition
- No human interference to take image of each component
Aircrafts like the Boeing 737 usually fly at least 50,000 hours during their lifetime. That accounts for an average total dose of around 30,000 mRem due to background radiation.
Particles (protons, electrons) cause more damage to semiconductors than photons (x-ray).

X-ray inspection systems used for counterfeit detection don’t have enough energy (<120kV) to cause bulk damage to silicon.

Radiation type, power, distance, and time matters a lot.

Automated systems expose components to an average of 50mRem (0.050Rem).

Most components show failures starting at least few thousands of Rem, or millions of mRem.

Commercial airplanes are exposed to ~30,000mRem of background radiation that has more particles than what’s found in x-ray cabinet.

Wide safety margin to inspect components using x-rays.

Most radiation tolerance tests are done with particles, not photons.
Our background in the subject (1)

- **First look at the beam test results of the FPIX2 readout chip for the BTeV silicon pixel detector**
- **First prototype of a silicon microstrip detector with the data-driven readout chip FSSR2 for a tracking-based trigger system**
  Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment Volume 572, Issue 1, 1 March 2007, Pages 388-391
- **First prototype of a silicon microstrip detector with the data-driven readout chip FSSR2 for a tracking-based trigger system**
  Frontier Detectors for Frontier Physics - Proceedings of the 10th Pisa Meeting on Advanced Detectors
- **Radiation tolerance of prototype BTeV pixel detector readout chips**
- **CDF run IIb silicon vertex detector DAQ upgrade**
- **CDF run IIb silicon detector: the innermost layer**
- **CDF run IIb silicon: design and testing**
- **Pixel multichip module design for a high energy physics experiment**
- **Sensors for the CDF Run2b silicon detector**
- **Stave design and testing**
Our background in the subject (2)

- **The BTeV pixel detector system**
- **Single event upset rate of 140Mb/s pixel data serializer**
- **The BTeV pixel and microstrip detectors**
- **The BTeV pixel detector and trigger system**
- **Radiation tolerance of prototype BTeV pixel detector readout chips**
- **First bench-test results on irradiated BTeV hybrid silicon pixel detector prototypes**
- **The BTeV pixel and microstrip detectors**
  11th International Workshop on Vertex Detectors, Kona, Kailua, Hawaii, pp. 3-8, November 2002.
- **BTeV pixel system**
  International Workshop on Semiconductor Pixel Detectors for Particle Physics and X-rays, Carmel, California, September 9-12, 2002.
- **Overview of the BTeV pixel detector**
  International Workshop on Semiconductor Pixel Detectors for Particle Physics and X-rays, Carmel, California, September 9-12, 2002.
Our background in the subject (3)

- **Radiation tolerance of prototype BTeV pixel detector readout chips**

- **Silicon detector upgrades for the Tevatron run 2**
  31st International Conference on High energy Physics, Amsterdam, July 24-31, 2002.

- **Radiation tolerance of prototype BTeV pixel detector readout chips**

- **The BTeV pixel detector and trigger system**
  5th International Conference on Hyperons, Charm and Beauty Hadrons, Vancouver, Canada, 25-29 June 2002

- **The BTeV vertex trigger**
  8th International Conference on B-Physics at Hadron Machines, Santiago de Compostela, Galicia, Spain, June 17-21, 2002.

- **Development of a readout technique for the high data rate BTeV pixel detector at Fermilab**

- **The BTeV pixel detector system**

- **CDF for run IIb**

- **Development of a high density pixel multichip module at Fermilab**

- **Beam test of BTeV pixel detectors**

- **Development of a readout technique for the high data rate BTeV pixel detector at Fermilab**
Our background in the subject (4)

- **The BTeV pixel detector system**

- **Performance of prototype BTeV silicon pixel detectors in a high energy pion beam**

- **Beam test results of the BTeV silicon pixel detector**

- **Single event effects in the pixel readout chip for BTeV**

- **Radiation tolerance studies of BTeV pixel readout chip prototypes**

- **Development of the pixel detector module for the BTeV experiment at Fermilab**

- **Development of a high density pixel multichip module at Fermilab**

- **Overview of the BTeV pixel detector**

- **Single event effects in the pixel readout chip for BTeV**

- **Beam test results of the BTeV silicon pixel detector**
Our background in the subject (5)

- **The BTeV pixel detector and trigger system**

- **Beam test of BTeV pixel detector**

- **Beam test results of the BTeV silicon pixel detector**

- **Development of high data readout rate pixel module and detector hybridization at Fermilab**

- **Overview of the BTeV pixel detector**

- **Beam test results of the BTeV silicon pixel detector**

- **Development of high data readout rate pixel module and detector hybridization at Fermilab**

- **The BTeV pixel vertex detector**