Space Radiation Effects in Optoelectronics

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Outline

- Space Environments
- Light-emitting Diodes
- Laser Diodes
- Optical Detectors
- Optical Couplers
- Conclusions
Wavelengths of Interest

Three Fiber Optic Windows
- 850 nm, 1320 nm and 1550 nm
- Some interest in the visible spectrum as well (400 to 700 nm)
- Silicon detectors: limited to 1040 nm (bandgap edge)

Particles in Space Environments

Trapped Particles in the Van Allen Belts
- Electrons with energies up to several MeV
- Protons with a wide range of energies

Solar Particles (Coronal Mass Ejections)

Galactic Cosmic Rays
- Heavy particles
- Extremely high energies
Typical Proton Spectrum

The peak in the proton energy spectrum is typically between 20 and 50 MeV. Adding shielding causes the peak energy to increase.

Energy Dependence of Proton Damage in LEDs

Experimental GaAs LED results continue to decrease at energies above 50 MeV.

Proton Spectrum Corrected for NIEL Dependence

![Graph showing proton spectrum corrected for NIEL dependence with energy (MeV) on the x-axis and differential spectrum (particles/steradian) on the y-axis. The graph includes data for silicon, GaAs, and raw spectrum. An Earth Orbit 705 km 90° shield is also shown.]

Heavy Ion Distribution in Space

![Graph showing heavy ion distribution in space with LET (MeV·cm²/mg) on the x-axis and average daily flux (cm⁻²) on the y-axis. The graph includes data for deep space, 600 km, 98 deg, 600 km, 28 deg, and LET of Alpha Particles.]

Optical Emitters: Light Emitting Diodes and Laser Diodes

Simple process developed in 1960's
Highly efficient: 860 – 930 nm

An Amphoterically Doped LED

Temperature change during growth creates junction

Amphoteric dopants can be n- or p-type impurities (depends on temperature)
I-V Characteristics of an LED

![Graph showing I-V characteristics of an LED with a slope change when light output threshold is reached.]

A Double-Heterojunction LED

Complex fabrication process with many layers
Produced LEDs with fast response times

![Diagram of a double-heterojunction LED with layers labeled: n-electrode, n-GaAs, n-AlGaAs, AlGaAs guiding layer, Active layer (GaAs), p-AlGaAs guiding layer, p-GaAs, p-electrode.]
Degradation of LEDs after Proton Irradiation

$10^{10}$ 50 Mev p/cm² ~ 1.6 krad

Annealing of Amphoterically Doped LEDs after Proton Irradiation

Annealing does not occur until forward current is applied
Comparison of LED Annealing with Different Forward Currents

To first order, annealing depends on injected charge

Results shown for three different current conditions

Recovery of LED Damage in Galileo Tape Recorder

Tape recorder stopped working after 34th orbit around Jupiter
Caused by LED degradation in control circuitry
Operation was successfully restored after forward biasing the LED to anneal the damage

Absorption and Emission Processes for Lasers

Current back facet
Partially reflective front facet

$E_{c}$
$E_{v}$

Spontaneous emission
Absorption
Stimulated emission

Laser Diodes

Basic five-layer laser
Current is confined to narrow stripe

Metal
(AIGaAs (n))
GaAs (p)
(AIGaAs (p))
(AIGaAs (n))
GaAs (n)
Active Region
Oxide
(AIGaAs (n))
Proton Degradation of a Laser Diode

Semi-logarithmic Plot of Laser Degradation
Degradation of Various Types of Lasers

Annealing of Laser Damage

Annealing proceeds more rapidly when lasers operate above threshold
Photodiode Degradation

Many lasers contain internal diodes to monitor output power.

Optical Emitter Degradation: Summary

Amphoteronically doped LEDs are one of the most sensitive components that can be used in space. Often used in optocouplers.

<table>
<thead>
<tr>
<th>Device Type</th>
<th>Approximate Threshold for Degradation</th>
<th>Annealing Properties</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amphoteronically Doped LED</td>
<td>$5 \times 10^9$ p/cm²</td>
<td>Strong</td>
<td>Extremely sensitive to radiation damage</td>
</tr>
<tr>
<td>Heterojunction LED</td>
<td>$1 \times 10^{11}$ p/cm²</td>
<td>Very weak</td>
<td></td>
</tr>
<tr>
<td>Laser Diode</td>
<td>$1 \times 10^{12}$ p/cm²</td>
<td>Very Strong</td>
<td>Monitor diode degradation may be more significant</td>
</tr>
</tbody>
</table>
Optocouplers

Permanent damage effects are covered in the notes.

We will concentrate on transient effects during the presentation.

Usually dominated by charge collection in the large area photodiode.

Only important for optocouplers with high-gain amplifiers.

Optocouplers are heavily overdriven (on or off).

(a) Basic optocoupler

(b) Integrated amplifier
Transient Sensitivity of High-Speed Optocouplers

Charge sensitivity for an optocoupler with 20 ns response time is ~ 100 femtocoulombs!

Heavy-ion upset at LET values ~ 0.1 MeV-cm²/mg

Dependence of Optocoupler Cross Section on Angle During Proton Testing

Angular dependence is caused by direct ionization from protons in large diameter photodiode

Effective LET for direct ionization is ~ 0.007 MeV-cm²/mg
Two Mechanisms Contribute to the Angular Dependence of the Cross Section

Direct ionization LET is \( \sim 0.01 \text{ MeV-cm}^2/\text{mg} \)

Long path length provides significant total charge at extreme angles

Summary (displacement damage)

Optical Emitters
- Discussed operating principles
- Emphasized importance of proton displacement damage
  - Some types of optical emitters are severely degraded by protons with an effective total dose of 1-2 krad
  - Compared degradation of LEDs and lasers
  - Discussed injection-enhanced annealing

Optocoupler Displacement Damage
- Strongly affected by the type of LED used in the optocoupler
- Decrease in diffusion length of conventional photodetectors and phototransistors dominates damage for optocouplers with less sensitive LEDs
Summary (transient effects)

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<tr>
<td>- Very basic subsystem</td>
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<tr>
<td>- High-bandwidth optocouplers are extremely sensitive to SEU</td>
</tr>
<tr>
<td>- Dominated by charge collection in the phototransistors</td>
</tr>
</tbody>
</table>

Proton Upset Has Strong Angular Dependence
- Caused by direct ionization along the large track length
- Requires testing at different angles