Total Ionizing Dose

Mechanisms and Effects

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Course Outline

• Definitions – Basic mechanisms
• TID effects in MOS devices
• TID effects in Bipolar components
• TID and Deep Submicron technologies
Near Earth TID environment

- For LEO orbits TID mainly due to trapped protons (SAA)
- For GEO missions, TID primarily caused by electrons and Bremsstrahlung.
- Electrons have low penetration depth therefore easier to shield
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Introduction - Definitions

- Ionization: process of adding or removing electrons (or other charged particles) from atoms.
- The creation of electron-holes pair in the material cause long term effects in the oxide (charge trapping).
- Consequence: alteration of the electrical characteristics of electronic devices.
Basic concepts - Units

• Absorbed dose: energy absorbed locally per unit mass due to ionization. The **gray** is the SI unit for absorbed dose, however, traditionally the **rad** (Radiation Absorbed Dose) is still used.
  – 1gray = 1J/kg (SI unit)
  – 1gray = 100rads

• The dose shall always be referred to the absorbing material. Common target materials are Si, SiO₂, GaAs.

• Equivalent Dose $H_T$: also a measure of transferred energy but weighted by a factor $W_R$ related to type and energy of particle, $H_T = W_R$. Expressed in Sievert (Sv). It gives a better measure of damage to tissue.

• Effective dose $E = W_T \cdot H_T$. The equivalent dose of each tissue is multiplied by an appropriate tissue weighting factor $W_T$ for that tissue (thyroid, skin, gonad…) and all the products are summed. It gives a measure of risk.
Definitions

1 rad = 100 erg / gram

# electron-hole pairs \((\text{SiO}_2)\) ~ \(8.1 \times 10^{12} / \text{cm}^3 / \text{rad}\)

Energy Unit Conversion of rad

\[
\frac{\text{# pairs}}{\text{rad} \cdot \text{cm}^3} = \left[ \left( \frac{100 \text{ ergs}}{\text{gram}} \right) \left( \frac{10^{-7} \text{ J}}{\text{erg}} \right) \left( \frac{\text{eV}}{1.6 \times 10^{-19} \text{ J}} \right) \right] \cdot (2.2 \text{ g} / \text{cm}^3)
\]

17 +/- 1 eV

(electron-hole pair creation energy in \(\text{SiO}_2\))
Recombination and yield

- Depends on radiation source and field oxide
Deposited dose: cumulative effect

- Electron and proton exposure result in cumulative effects. Main effects:
  - Oxide charge trapping = holes trapped in SiO2. Induces $V_{th}$ shift, noise, leakage (fast creation, temperature dependent)
  - Creation of interface states at SiO2-Si interface due to chemical bonding changes at interface. Induces $V_{th}$ shift, mobility, leakage (slow creation, less temperature dependent)

The electrical performance is degraded.

Note 1: bias, temperature and time dependence effects

Note 2: Galactic Cosmic Rays also deposit ionizing dose but their contribution to the total deposited dose is negligible as GCR fluxes are very low.
Basic mechanisms

1) Generation of e-/h pairs (17eV/pair in SiO₂). The density of e-/h pairs created depends on target material.
2) Prompt recombination (depends on radiation source and electric field)
3) Transport of free carrier remaining in the oxide
4) Formation of trapped charge via hole trapping in defect precursor sites OR formation of interface traps via reaction with hydrogen in SiO₂
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TID effects in MOS Devices (1)

Charge trapping in SiO₂ and at Si/SiO₂ interface.

1. Oxide Trapping ($N_{ot}$)
2. Interface Trapping ($N_{it}$)

- Dominated by point defects

$$V_{th} = V_{th}' + \phi_{MS} - Q_F \frac{C_o}{C_F} - Q_M \frac{C_o}{C_M} - \frac{N_{it} \cdot e \cdot (2 \phi_f)}{C_{ox}} \pm \frac{4qN_B}{K_s} \frac{\varepsilon}{\varepsilon_0} \pm \phi_F$$

After Space Radiation Effects on Microelectronics course from JPL, J.F. Conley
TID effects in MOS Devices (2)

Hole Trapping - $N_{OT}$

Oxygen Vacancy $E'$ Precursor

Interface Trap Formation - $N_{IT}$

$P_b$ Precursor

Radiation Damage Participants

$E'$, $P_b$, $P_b$ H, $E'H$, $H^+$, $H^0$, $H_2$, $h^+$

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Field oxide leakage

- Field oxides thick and poorly controlled.
- Dominant failure mechanism for commercial processes.
- Geometry is critical.

**Diagram:**

- n+ SOURCE
- THIN GATE OXIDE
- GATE METAL
- LEAKAGE PATH
- n+ DRAIN
- GATE METAL
- CHANNEL REGION
- FIELD OXIDE
- LEAKAGE

**Graph:**

<table>
<thead>
<tr>
<th>$I_{DS}$ (A)</th>
<th>-10</th>
<th>-10^{-2}</th>
<th>-10^{-4}</th>
<th>-10^{-6}</th>
<th>-10^{-8}</th>
<th>-10^{-10}</th>
<th>-10^{-12}</th>
</tr>
</thead>
<tbody>
<tr>
<td>GATE VOLTAGE (V)</td>
<td>-5</td>
<td>-4</td>
<td>-3</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

10 krad (Si)

1 2 3 4 5

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Influence of hole traps and Interface traps on CV and IV curves

CV

\( t_{ox} = 48 \text{ nm} \)

GATE VOLTAGE (V) (a)

IV

THRESHOLD

500 krad

MIDGAP \((\Psi = \Phi_B)\)

GATE VOLTAGE (V) (b)
Influence of Interface and oxide trapped charges
Effects of bias

- Bias has a strong influence on the radiation response
- Powering down a device can sometimes improve radiation response
- A powered device is not always worst case
Annealing

- Tunnel annealing: spatial and logtime dependence
- Thermal annealing: Energy and temperature dependence

1) Electron Tunneling
2) Electron Thermal Emission

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Influence of oxide thickness

- Trapping drops off steeply in thin oxides but there are still problems:
  - Radiation induced leakage currents (RILC) in ultra thin oxides
- But thick oxides layers inherent to some technologies (power MOSFETs, silicon-on-insulator buried oxide...)

Space Radiation and its Effects on EEE Components

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Some test results

Motorola MTP50N06VL.
Ref. report ESA_QCA990903T_C
More test results: Example of TID degradation for 0.18 μm CMOS SRAM

- No degradation up to 90 krad(Si)
- Sufficient for most space applications:
  - 10 year GEO mission: 50 krad(Si)
  - 5 year LEO mission: 20 krad(Si)
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Bipolar linear devices

Structure of a bipolar transistor
Bipolar transistor: gain degradation

- Charged trapped at and near the interface above the base region can degrade gain and increase leakage.
Effects in Bipolar devices

The passivation oxide layer (protection) is thicker than in CMOS.

*Process similar to MOS devices: Charge trapping + Interface States*

\[ I_E = I_C + I_B \]

Main effects:
- Gain degradation (\( \beta \) or \( h_{FE} \))
- Leakage

Lower-quality oxide → Greater Damage
TID effects in bipolar devices

- Lot to lot variability:
  - More variability at lower dose rates
  - Manufacturing process determinant (impurities)
Enhanced Low Dose Rate Sensitivity (ELDRS). (1)

- Some bipolar based devices illustrate higher degradation when irradiated at lower dose rates.
- Most spacecraft are operated in Low Dose Rate Environment.

Main problem $\rightarrow$ Time & cost for testing

<table>
<thead>
<tr>
<th>Krad(Si)</th>
<th>2 Krad/h</th>
<th>360 rad/h</th>
<th>36 rad/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>5 hours</td>
<td>1.1 days</td>
<td>11.5 days</td>
</tr>
<tr>
<td>50</td>
<td>25 hours</td>
<td>5.7 days</td>
<td>57.8 days</td>
</tr>
<tr>
<td>100</td>
<td>50 hours</td>
<td>11.5 days</td>
<td>115.7 days</td>
</tr>
<tr>
<td>300</td>
<td>150 hours</td>
<td>34.7 days</td>
<td>347.2 days</td>
</tr>
</tbody>
</table>
Enhanced Low Dose Rate Sensitivity (ELDRS). (2)

- Evidence of dose rate dependency:

ELDRS in space

Input bias current vs total dose for NSC LM139 in a space experiment and for various ground tests at different dose rates.

Some test results

Ib as a function of Dose, gamma, 0.8 rads/min
(LM139a date code 0121)

Dev. 1 biased at 20V, Dev. 2 biased at 12V

Ref. report ESA-QCA-RTR-LM139-00102
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Future DSM technologies

• MOSFETs with thin gate dielectrics are relatively insensitive to TID as:
  – Trapped hole density is approximately proportional to oxide thickness $X_{ox}$ (very simple model)
  – $Cox$ is inversely proportional to $X_{ox}$

• In very thin oxides (< 50Å), there is almost no hole trapping because of tunneling

$$\Delta V_{ot} = -\frac{Q_{ot}}{C_{ox}} \alpha X_{ox}^2$$

After Radiation Effects on Microelectronics, R. Schrimpf, SERESSA 2006
DSM technologies: Silicon-On-Insulator

SOI Advantages:
1. Total Isolation
2. SEU Immune
3. High Speed
4. Low Power
5. Latchup Eliminated

New SOI Total Dose Leakage Paths:
1. Back Channel Leakage
2. Sidewall Leakage

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Flash memories

Measurements made on unlidded unit with special probe

Samsung 128 Mb Flash memory

Range of failure levels for other units in ERASE or WRITE mode

Failed to erase
Other DSM technologies

- High-k dielectrics ($\text{HfO}_2$ for example instead of $\text{SiO}_2$)
- Advanced CMOS – LOCOS
- Gallium-Nitride based High Electron Mobility Transistors (HEMT)
- SiGe Heterojunction Bipolar Transistors
- Preliminary studies on DSM show TID hardness up to several Mrad but testing and analysis shall continue to justify these claims
## Summary: Technologies susceptible to TID effects

<table>
<thead>
<tr>
<th>Technology category</th>
<th>Sub categories</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOS</td>
<td>NMOS, PMOS, CMOS, CMOS/SOS/SOI</td>
<td>Threshold voltage shift, decrease in drive current, decrease in switching speed, increased leakage current</td>
</tr>
<tr>
<td>BJT</td>
<td></td>
<td>hFE degradation, particularly for low-current conditions</td>
</tr>
<tr>
<td>JFET</td>
<td></td>
<td>Enhanced source-drain leakage currents</td>
</tr>
<tr>
<td>Analogue microelectronics</td>
<td></td>
<td>Changes in offset voltage and offset current, changes in bias-current, gain degradation</td>
</tr>
<tr>
<td>Digital microelectronics</td>
<td></td>
<td>Enhanced transistor leakage, logic failure (1) reduced gain (BJT), or (2) threshold voltage shift and reduced switching speeds (CMOS)</td>
</tr>
<tr>
<td>CCDs</td>
<td></td>
<td>Increased dark currents, effects on MOS transistor elements (described above), some effects on CTE</td>
</tr>
<tr>
<td>APS</td>
<td></td>
<td>Changes to MOS-based circuitry of imager (as described above) – including changes in pixel amplifier gain</td>
</tr>
<tr>
<td>MEMS</td>
<td></td>
<td>Shift in response due to charge build-up in dielectric layers near to moving parts</td>
</tr>
<tr>
<td>Quartz resonant crystals</td>
<td></td>
<td>Frequency shifts</td>
</tr>
<tr>
<td>Optical materials</td>
<td>Cover glasses, fibre optics, optical components, coatings, instruments and scintillators</td>
<td>Increased absorption, variation in absorption spectrum (coloration)</td>
</tr>
<tr>
<td>Polymeric surfaces</td>
<td></td>
<td>Mechanical degradation, changes to dielectric properties</td>
</tr>
</tbody>
</table>

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**ECSS-E-10-12**
Conclusion

- TID predominantly affects the device oxide resulting in device parameter degradation
- Sensitivity to TID is strongly technology and manufacturing process dependent. Hence, a simplified model for accurate predictions of TID effects is not available
- ELDRS is an issue for all devices containing bipolar transistors
- Lot-non-uniformity is an issue for TID specifically with respect to ELDRS issue
- New DSM technologies seem quite TID tolerant (but there are other issues...)

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References

• IEEE NSREC Short courses.
• RADECS Short courses.
• ECSS-E-10-12.