Reliability and Modeling in Harsh Environments for Space Applications

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Outline

- Harsh Environments

- Radiation Effects on Electronics
  - Physics-based modeling and characterization
  - Ionizing and Non-ionizing Radiations
  - Radiation Environment Close to Earth
  - Radiation Effects on MOSFETs

- Low Temperature (Cryogenic) Electronics
  - Physics-based modeling and characterization
  - Compact models
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  ● Compact models
Extreme Harsh Environments [1]

Radiative stresses
• Cosmic rays and Van Allen belts

Temperature

Mechanical stresses
• Vibration, Shock, and pressure

Chemical
• Saltwater, Moisture, Noxious gases


Images: NASA
Extreme Harsh Environments [2]

**Earth Orbiter**

- TID: 0.1 - 0.3 krad
- LEO: 1 - 3 yrs (500 - 1500 cycles)
- Lifetime: ~1 hr (on surface)

**Venus**

- TID: ~7 krad
- Lifetime: ~1 hr (on surface)

**Mars Rover**

- TID: 0.1 - 0.3 krad
- LEO: 1 - 3 yrs (500 - 1500 cycles)
- Lifetime: 90 days

**Europa**

- TID: ~7 Mrad
- Lifetime: min/hrs (on surface)
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Non-ionizing and Ionizing Radiations

Non-ionizing is electromagnetic radiation that does not carry enough energy per quantum (photon energy) to ionize atoms or molecules.

Ionizing radiation is radiation that carries enough energy to liberate electrons from atoms or molecules made up of energetic subatomic particles, ions or atoms moving at high speeds, and electromagnetic waves.
Radiation Effects on MOSFETs

Radiation Effects:
- **Total Ionizing Dose (TID)**
  - long term failure
  - time dependent,
- **Single Event Effects (SEE)**
  - an instantaneous failure,
  - described by a mean time,
  - Soft and hard errors
- Can **partially** mitigate with shielding

Image for ATLAS from CERN: Higher level of total ionizing dose (1 Grad for the innermost components)

\[1 \text{Grad} = 1 \times 10^7 \text{Gy} = 1 \times 10^7 \text{J/kg}\]
Total Ionizing radiation effects on MOSFETs

- Mobility Degradation
- Subthreshold Swing Degradation
- Shift in threshold Voltage
- Leakage Current

Effects of $Q_{ot}$ and $Q_{it}$ in all oxides

Farzan Jazaeri et al., "Charge-Based Modeling of Radiation Damage in Symmetric Double-Gate MOSFETs," IEEE Journal of the Electron Devices Society, 2018
Total Ionizing radiation effects on MOSFETs

Pre-irradiation

Drain Current (Log)

Gate Voltage

Post-irradiation

Pre-irradiation

Effects of $Q_{ot}$ and $Q_{it}$ in all oxides

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Effects of $Q_{ot}$ and $Q_{qt}$ in all oxides

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Ionizing radiation effects on 28nm MOSFETs

Ionizing radiation effects on 28nm MOSFETs

Ionizing radiation effects on FinFETs

Analytical model (lines) and TCAD simulations (markers)

Farzan Jazaeri et al., "Charge-Based Modeling of Radiation Damage in Symmetric Double-Gate MOSFETs," IEEE Journal of the Electron Devices Society, 2018
Ionizing radiation effects on FinFETs

Uniform distribution of interface trap density (lines) and TCAD simulations (markers)

Farzan Jazaeri et al., "Charge-Based Modeling of Radiation Damage in Symmetric Double-Gate MOSFETs," IEEE Journal of the Electron Devices Society, 2018
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- **Harsh Environments**
- **Radiation Effects on Electronics**
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  - Radiation Environment Close to Earth
  - Radiation Effects on MOSFETs
- **Low Temperature (Cryogenic) Electronics**
  - Physics-based modeling and characterization
  - Compact models
Cryogenic MOS transistor models are essential to assess speed-power-noise trade-offs during design of cryogenic qubit control circuits.

- Cryo-characterization
- Physics-based Cryo-MOS model
- Compact models (EKV, BSIM6, UTSoI)
- Quantify cryogenic impact on circuit design Figure of-Merit
# 28 nm Bulk CMOS Characterization

## Measured devices and Sample chip

<table>
<thead>
<tr>
<th>Type</th>
<th>W/L</th>
<th>T [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>nMOS</td>
<td>3 μm / 1 μm</td>
<td>4.2, 300</td>
</tr>
<tr>
<td>pMOS</td>
<td>3 μm / 1 μm</td>
<td>4.2, 77, 300</td>
</tr>
<tr>
<td>nMOS</td>
<td>1 μm / 90 nm</td>
<td>4.2, 77, 300</td>
</tr>
<tr>
<td>nMOS</td>
<td>3 μm / 28 nm</td>
<td>4.2, 300</td>
</tr>
<tr>
<td>nMOS</td>
<td>300 nm / 28 nm</td>
<td>4.2, 77, 300</td>
</tr>
</tbody>
</table>

Measured devices (28 nm Bulk CMOS Process)  

Sample chip

Transfer characteristics

W/L = 300 nm / 28 nm

$V_{DB} = 0.9 \, V$

nMOS

Transfer characteristics

28 nm Bulk CMOS Characterization

Transfer characteristics

- $W/L = 300 \text{ nm} / 28 \text{ nm}$
- $V_{DB} = 0.9 \text{ V}$
- nMOS
- $T (K)$: 300, 77, 4.2

Parameter Extraction: Subthreshold Swing

\[ SS(mV/dec) = \frac{KT}{q} \times \ln(10) \times n \]

\[ n = (1 + \frac{C_d}{C_{ox}}) \]

- \( C_d \) = depletion layer capacitance
- \( C_{ox} \) = gate-oxide capacitance
- \( \frac{KT}{q} \) = Thermal Voltage

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Parameter Extraction: Subthreshold Swing

Subthreshold swing

- $\Delta SS_{\text{long}} \approx 10 \text{ mV/dec at 4.2 K and 300 K}$

$$SS (mV/dec) = \frac{KT}{q} \times \ln(10) \times n$$

$$n = (1 + \frac{C_d}{C_{ox}})$$

$c_d$ = depletion layer capacitance

$C_{ox}$ = gate-oxide capacitance

$\frac{kT}{q}$ = Thermal Voltage
Parameter Extraction: Subthreshold Swing

\[ SS(\text{mV/dec}) = \frac{KT}{q} \times \ln(10) \times n \]
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Subthreshold swing

- \( \Delta SS_{\text{long}} \approx 10 \text{ mV/dec at 4.2 K and 300 K} \)
Parameter Extraction: Subthreshold Swing

Subthreshold swing

- $\Delta S_{\text{long}} \approx 10 \text{ mV/dec at } 4.2 \text{ K and } 300 \text{ K}$
- $\Delta S_{\text{short}} \approx 30 \text{ mV/dec at } 4.2 \text{ K and } 300 \text{ K}$
- Short channel effects ($\approx 20 \text{ mV/dec}$) $T$-independent

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Cryogenic Physics-based Modeling

Important phenomena

- Incomplete ionization, $N \downarrow A \uparrow - (T)$
- Hot-carrier effects
- Decreased phonon scattering
- Dominant impurity / surface roughness scattering
- Quantum confinement
- Interface charge trapping, $D \downarrow it$

will affect the

- Subthreshold swing
- On-state current, leakage current
- Threshold voltage
- Mobility

Fermi–Dirac and Boltzmann statistics $(T)$
Intrinsic carrier concentration $n \downarrow i (T)$
Band gap widening, $E \downarrow g (T)$
Velocity saturation, $\Delta \varphi_{ms}$, Thermal voltage $(T)$

Physics-based Modeling: Model Overview

\[ \frac{d^2 \Psi(y)}{dy^2} = - \frac{q}{\varepsilon_{si}} \left( - n_p - N_A^-(T) + p_p \right) \]

**BCs:**
- Continuity of dielectric displacement vectors
  \[ \varepsilon_{si} E_s - \varepsilon_{ox} E_{ox} = Q_{it} \]
- Bulk charge neutrality

\[ \int_{E_{c}}^{E_{top}} g_c(E) f_c(E) dE - \int_{E_{bottom}}^{E_{v}} g_v(E) f_h(E) dE + \frac{N_A}{1 + g_A e^{E_A - E_F/kT}} = 0 \]

- Mobile charge: \[ Q_m = -\varepsilon_{si} E_s - Q_f \]
- Current (linear regime): \[ I = \frac{W}{L} \mu Q_m V_{DS} \]
- Maxwell-Boltzmann validity??

Interface charge traps
Reduced phonon scattering
Mobility reduction \( f(V_G) \)
Incomplete ionization
Physics-based Modeling

Wide & Long channel: 3 µm / 1 µm
\( V_{DB} = 0.9 \) V

\[
\frac{\partial V_{GB}}{\partial \psi_s} = 1 + \frac{\sqrt{2qN_A e_{si}}}{C_{ox}} \frac{1}{2\sqrt{\psi_s - \psi_b}} + \frac{qN_{it}}{C_{ox}} \frac{1}{U_T} \frac{1}{(1 + g_t)^2}
\]

\[
SS = n_0 U_T \ln 10 + \frac{qN_{it}}{C_{ox}} \frac{g_t}{(1 + g_t)^2} \ln 10
\]
Compact Modeling: BSIM6

BSIM6 Model Card Extraction at 4.2 K

\[ I_D [\text{A}] \]

\[ V_{\text{GB}} [\text{V}] \]

- \( W/L = 3 \, \mu\text{m} / 28 \, \text{nm} \)
- \( V_{\text{DB}} = 0.9 \, \text{V} \)

nMOS

4.2 K

Measurement

BSIM6 Model

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1. **Long-channel model** validated on **28-nm process at 4.2 K**
2. Simple expressions
3. Few parameters
4. capture physical effects
5. Fitting parameters

Compact Modeling: Simplified EKV

1. **Short-channel model** validated on 28-nm process at 4.2 K
2. Simple expressions
3. Few parameters
4. capture physical effects
5. Fitting parameters

Thank you for your attention!
References


References


## High Temperature Electronics

### Sources of Ionizing Radiation in Interplanetary Space

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Planet</th>
<th>Average distance from Sun (km)</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mercury</td>
<td>$5.7 \times 10^7$</td>
<td>+465 (side exposed to Sun); −184 (dark side)</td>
</tr>
<tr>
<td>2</td>
<td>Venus</td>
<td>$1.08 \times 10^8$</td>
<td>+460</td>
</tr>
<tr>
<td>3</td>
<td>Earth</td>
<td>$1.50 \times 10^8$</td>
<td>+7.2 varying from +70.7 (the deserts of Iran) to −89.2 (Antarctica)</td>
</tr>
<tr>
<td>4</td>
<td>Mars</td>
<td>$2.28 \times 10^8$</td>
<td>−55, ranging between as high as +20 at the equator during midday, to as low as −153 at the poles</td>
</tr>
<tr>
<td>5</td>
<td>Jupiter</td>
<td>$7.79 \times 10^8$</td>
<td>−145</td>
</tr>
<tr>
<td>6</td>
<td>Saturn</td>
<td>$1.43 \times 10^9$</td>
<td>−178</td>
</tr>
<tr>
<td>7</td>
<td>Uranus</td>
<td>$2.88 \times 10^9$</td>
<td>−216</td>
</tr>
<tr>
<td>8</td>
<td>Neptune</td>
<td>$4.50 \times 10^9$</td>
<td>−218</td>
</tr>
<tr>
<td>9</td>
<td>Pluto</td>
<td>$5.91 \times 10^9$</td>
<td>−233 to −223</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Hottest places</th>
<th>Temperature (°C)</th>
<th>Coldest places</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lut Desert in Iran</td>
<td>+70.7</td>
<td>Vostok Station, Antarctica</td>
<td>−89.2</td>
</tr>
<tr>
<td>2</td>
<td>Death Valley, California, North America</td>
<td>+56.7</td>
<td>Oymyakon, Russia</td>
<td>−71.2</td>
</tr>
<tr>
<td>3</td>
<td>Al’Aziziyah, Northwest Libya, Africa</td>
<td>+57.8</td>
<td>Verkhoyansk, Russia</td>
<td>−69.8</td>
</tr>
<tr>
<td>4</td>
<td>Ghudamis, Libya, Africa</td>
<td>+55</td>
<td>North Ice, Greenland Snag, Yukon, Canada</td>
<td>−66</td>
</tr>
<tr>
<td>5</td>
<td>Kebili, Tunisia, Africa</td>
<td>+55</td>
<td>Prospect Creek, Alaska, USA</td>
<td>−62</td>
</tr>
<tr>
<td>6</td>
<td>Timbuktu, Mali, West Africa</td>
<td>+54.5</td>
<td></td>
<td></td>
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</table>

Impact on Analog Figures-of-Merit: $G_m/I_D$

1. Simple model of current efficiency at 4.2 K validated on a 28-nm process
2. The $G_m/I_D$ -characteristic is the basis for additional analog metrics (noise, gain, linearity, ...), as well as transistor sizing and biasing.

\[
I_{\text{spec}} = I_{\text{spec,W}} \frac{W}{L} \quad \text{with} \quad I_{\text{spec,W}} = 2n \cdot \mu \cdot C_{\text{ox}} \cdot U_T^2 \quad \text{and} \quad U_T = \frac{kT}{q}
\]

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Compact Modeling: BSIM6

Cryo?
BSIM6's temperature scaling cannot catch SS at 4.2 K for 28 nm. For long channel T-scaling works.
Radiation Environment Close to Earth

**Van Allen belts:** Particles trapped in the Van Allen belts i.e. energetic charged particles, most of which originate from the solar wind (protons, electrons, and heavy ions).

**Cosmic rays:** Galactic cosmic ray particles and particles from solar events (mass ejections and solar flares).

Images Credit: NASA