Total Ionizing Dose and Single Event Effects in Strained Si Technologies

Hyunwoo Park¹, Daniel J. Cummings¹, Rajan Arora³, Jonathan A. Pellish⁴, Robert A. Reed², Ronald D. Schrimpf², Dale McMorrow⁵, Sarah Armstrong Nation²,Daniel M. Fleetwood²,⁷, Toshikazu Nishida¹, Mark E. Law¹ and Scott E. Thompson¹

¹ Electrical and Computer Engineering, University of Florida
² Department of Electrical Engineering & Computer Science, Vanderbilt University
³ School of Electrical & Computer Engineering, Georgia Institute of Technology
⁴ NASA Goddard Space Flight Center, Code 561.4
⁵ Naval Research Laboratory
⁶ Department of Material Science and Engineering, University of Florida
⁷ Department of Physics & Astronomy, Vanderbilt University
Outline

• Introduction

• Project Focus
  1. Total Ionizing Dose (TID) Effects on Strained HfO₂-based nMOSFETs
  2. Laser-Induced Current Transients in Strained-Si Diodes
  3. Laser-Induced Current Transients in Strained-Si MOSFETs

• Summary

• Publication
Uniaxial Stress in Si MOSFETs

- Uniaxial strained Si technology is successfully implemented beyond 90 nm logic device.
- It is widely used in commercial electronics market.
Mechanical Stress Alters Mobility Significantly

Electron Mobility Enhancement

Hole Mobility Enhancement

In modern devices, the strained-Si technology is implemented to boost transistor performance.
- Mechanical stress enhances electron and hole mobility significantly (Performance Booster).

Suthram, 2008
Researchers are interested in reducing the cost of chips using commercial technology. It is very important to understand reliability of strained Si under radiation.
Main Contributions

• The first systematic study about the effect of uniaxial-strained silicon technology under radiation.

1. Total Ionizing Dose (TID) Effects on Strained HfO$_2$-based nMOSFETs
   => Uniaxial stress lower hole trap energy level in HfO$_2$ and SiOx
   => Uniaxial stress decrease radiation-induced threshold voltage shift
   => Mobility enhancement under uniaxial stress is not lost after irradiation

2. Laser-Induced Current Transients in Strained-Si Diodes
   => Uniaxial stress alters electron mobility along <001> direction
   => Uniaxial stress changes shape of single event transients in large N+/P diodes

3. Laser-Induced Current Transients in Strained-Si MOSFETs
   => Impact of uniaxial stress on single event transients in submicron MOSFETs
External Mechanical Stress

A four point bending jig is used to apply mechanical stress to devices.

\[ \sigma = \frac{Eyt}{2a \left( \frac{L}{2} - \frac{2a}{3} \right)} \]
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TID Experiment on Strained MOSFET

<table>
<thead>
<tr>
<th>TiN</th>
<th>7.5nm</th>
</tr>
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<tbody>
<tr>
<td>HfO₂</td>
<td>1nm</td>
</tr>
<tr>
<td>SiOₓ</td>
<td></td>
</tr>
<tr>
<td>p-Si</td>
<td></td>
</tr>
</tbody>
</table>

10 keV X-ray
Dose Rate : 31.5 krad (SiO₂)/min

\[ V_G = -2 \text{ V} \]
\[ V_S = 0 \text{ V} \]
\[ V_D = 0 \text{ V} \]
\[ V_B = 0 \text{ V} \]
## TID Experiment Matrix

<table>
<thead>
<tr>
<th>Radiation Dose</th>
<th>Mechanical Stress</th>
<th>Compressive 200MPa</th>
<th>0MPa</th>
<th>Tensile 100MPa</th>
<th>Tensile 200MPa</th>
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</thead>
<tbody>
<tr>
<td>Pre-rad (0 Mrad)</td>
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<td>✓</td>
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<td>✓</td>
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<tr>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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<tr>
<td>1 Mrad</td>
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<td>✓</td>
<td>✓</td>
<td>✓</td>
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</tr>
<tr>
<td>5 Mrad</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
$I_D - V_{GS}$ under Tensile (200 MPa)

- Positive charge trapping in HfO$_2$/SiO$_x$ dielectrics is dominant.
$V_t$ Shift vs. Mechanical Stress

- Both stress reduce threshold voltage shifts.
Uniaxial Stress on Hole Trap Energy Level

Hole Poole-Frenkel Emission Conduction

\[ E_T(\sigma) \]

- Both stresses lower hole trap activation level in dielectrics.

Y.S. Choi and H. Park et al. APL 2008

Y.S. Choi and H. Park et al. JAP 2009
- Benefit of Strained Si is not lost after a total dose of 5 Mrad (SiO$_2$)
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- How does uniaxial stress change current transients in diodes (source/drain)?

\(I_{\text{max}}\): peak current, \(Q\): charge collection
Laser-Induced Current Transients Measurement

-We can observe changes of current transient pulses under mechanical stresses
Laser-Induced Current Transients

- Peak current: 
  ~11% at 400 MPa

Collected charges:
~14% at 400 MPa

- Tensile (Compressive) stress decrease (increase) peak current and collected charges.
Stress Dependence of Current

- $N_{1p} (\sigma)$ is related to bandgap narrowing under mechanical stress.
- Mechanical stress alters electron mobility along $<001>$ direction.
Strain Effect on E-H Pair Generation

Absorption coefficient

\[ \frac{\Delta \alpha}{\alpha} = \frac{\Delta E_g(\sigma)}{h\nu - E_g} \ll 1, \quad h\nu > E_g \]

The number of generated e-h pairs

\[ N_{1p}(z) = \frac{\alpha}{h\omega} \exp(-\alpha z) \int_{-\infty}^{\infty} I_0(z, t) dt \]

\[ \Delta E_g \approx 30 \text{ meV} \text{ at } 1 \text{ GPa of uniaxial tensile stress} \]

- Change in \( N_{1p} \) is less than 3\% for 1 GPa of uniaxial tensile stress
Strain Effect on Electron Mobility

Under Tensile Stress:

For 1 GPa of uniaxial tensile stress,
- electron mobility changes ~53% and number of e-h pairs < 3%
→ Electron mobility change dominates current transient change under stress

\[
I_n(\sigma) \propto N_{1p}(\sigma) \mu_{n\parallel}(\sigma)
\]

\[
\mu < \frac{1}{m}
\]
Experiment vs. 2-D Simulation results

- 2D simulation results have good agreement with experimental ones.

* FLOODS : Florida Object Oriented Device Simulator
$I_{\text{max}}$ under Uniaxial Stress

- $\sim$ 23% reduction of peak current under 1GPa of uniaxial tensile stress
Charge Collection until 10 ns

- ~21% reduction of collected charges under 1GPa of uniaxial tensile stress
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Motivation

- Vertical transport
- Vertical/Horizontal transport

< Large Diodes >
- Vertical transport

1D

V > 0

< Deep Submicron Devices>
- Vertical/Horizontal transport

2D or 3D

Musseau, 2000

DasGupta, 2007
Goal:

- Investigate impact of uniaxial stress on laser-induced current transients in MOSFETs experimentally and theoretically.

- Suggest how to mitigate single event effects in highly-scaled MOSFETs using uniaxial stress.
Laser-induced Current Transients Set up for “Large” diodes

- Current transients in diodes are measured using high-speed probe station.
- A four point bending jig and high speed probes will be modified.
Diodes vs. Transistors

< Diodes >

< Transistors >

One RF(GSG) probe is used!

How can we solve this?
New Mechanical Jig and Probes

Adjustable (up to 4000 µm)

~1000 µm

Pitch : 100 µm
Data to be collected

Control parameter:
Stress, Width, Length,
Applied Voltage to Drain

(Compressive) (Tensile)

1. Peak current
2. Collected Charges
3. Pulse width

- The trend of peak current and collected charge under MOSFET will be compared with that of diodes case (Fall 2010 and Spring 2011).
- It is also compared with FLOODS simulation.
Summary

- Uniaxial mechanical stresses reduces charge trapping in HfO\(_2\)-based nMOSFET due to lowering hole trap energy level in HfO\(_2\)/SiO\(_x\) dielectrics.
- Electron mobility enhancement remains under mechanical stress after irradiation.
- Uniaxial stress alter current transients due to vertical electron mobility change in large N+/P diodes.
- 2D simulation can predict current transient under high (~1GPa) uniaxial stress.
- The first experimental study of stress effects on current transients in MOSFETs is proposed.


