Laser-Induced Current Transients in Strained-Si Diodes

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• Laser-induced current transients in diodes under mechanical stress
  - <110> uniaxial stress : Experiment and Simulation Results
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• Conclusion and future work
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Single Event Effect in MOSFET

- Single Event Effect (transient pulse) occurs in MOSFET
  - Single Event Transient (SET) and Single Event Upset (SEU)
- Modern devices are sensitive to these effects.
Mechanical Stress Alters Mobility Significantly

In modern devices, the strained-Si technology is implemented to boost transistor performance.
- Mechanical stress enhances electron and hole mobility significantly (Performance Booster).
- What if we put this technologies in radiation environment?
Current Transients under Different Type of Stress

- How does different type of stress change current transient in diodes? ($I_{max}$: peak current, $Q$: charge collection)
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Laser-Induced Current Transient Measurement System

- We can observe changes of current transient pulses under mechanical stresses.
  It is possible to apply different tensile or compressive stress using mechanical bending jig.
Laser-induced Current Transients (Experiment)

Peak current:
~11% at 400 MPa

Collected charges:
~14% at 400 MPa

- Tensile (Compressive) stress decrease (increase) peak current and collected charges.
- $N_{1p}(\sigma)$ is related to bandgap narrowing under mechanical stress.
- Mechanical stress alters electron mobility along $<001>$ direction.
Strain Effect on Electron-hole Pair Generation (Bandgap Narrowing)

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

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

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

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

Under Tensile Stress:

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

For 1 GPa of uniaxial tensile stress,
- electron mobility changes \(~53\%\) and Number of e-h pairs \(< 3\%\)

\[ \mu < \frac{1}{m} \]

\[ \mu_{\perp} \text{ (Decrease)} \quad < 001> \]

\[ \mu_{\parallel} \text{ (Increase)} \quad < 110> \]

Mohta, 2005

→ Electron mobility change dominates current transient change under stress
Diode Structure through TEM and EDS

- Cu (280 nm)
- SiO$_2$ (720 nm)
- SiO$_2$ (STI) (310 nm)
- n$^+$ (~100 nm)
- NiSi (20 nm)
- P-well (~1.5 µm)
- SiO$_2$
- NiSi

Spectrum 5

Full Scale 278 cts  Cursor: 0.000 keV

Full Scale 262 cts  Cursor: 0.113 keV (0 cts)
Deposition of Pulse Laser into $n^+p$ diode

- Some of pulse laser energy are reflected and absorbed in layers on top of a diode.
Current Transients according to Pulse Laser Energy

- The discrepancy between simulated energy and measured energy is shown.

Measured Pulse Laser Energy = 218 pJ
Laser Pulse Energy into Si

\[ I_{Si} = I_{\text{initial}} \times (\text{transmission due to Cu/SiO}_2) \times (\text{transmission in SiO}_2) \times (\text{transmission in NiSi}) \]
\[ = I_{\text{initial}} \times (0.57) \times (0.80) \times (0.51 \times 0.23) \]
\[ = 0.056 I_{\text{initial}} \]

Intensity \((I) \propto \) Power \((P) \propto \) Laser Pulse Energy \((E)\)

Measured Laser Pulse Energy = 216 pJ

Pulse Laser Energy deposited in Si = \((216 \text{ pJ}) \times (0.054)\)

= 12 pJ

Melinger, 1994
Amiotti, 1990

If we consider uncertainty of every layer characteristics, \(E = 10 \sim 25 \text{ pJ}\)

Especially, consider the optical characteristics nickel silicide (NiSi, NiSi\(_2\), Ni\(_2\)Si)

2D Simulation value => 13.5 pJ (It is very close to calculated values above)
*Note: Carriers move along z-direction dominantly.

- Using analysis from experimental results such as piezoresistance coefficient and bandgap narrowing effect, we did 2-D FLOOD current transient simulation under stress.
Strain Model (Piezoresistance Effect)

\[
\begin{bmatrix}
\pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\
\pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\
\pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\
0 & 0 & 0 & \pi_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & \pi_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & \pi_{44}
\end{bmatrix}
\begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{yz} \\
\sigma_{zx} \\
\sigma_{xy}
\end{bmatrix}
=
\begin{bmatrix}
\Delta \rho_{xx} / \rho_{xx} \\
\Delta \rho_{yy} / \rho_{yy} \\
\Delta \rho_{zz} / \rho_{zz} \\
\Delta \rho_{yz} / \rho_{yz} \\
\Delta \rho_{zx} / \rho_{zx} \\
\Delta \rho_{xy} / \rho_{xy}
\end{bmatrix}
\begin{bmatrix}
-\Delta \mu_{xx} / \mu_{xx} \\
-\Delta \mu_{yy} / \mu_{yy} \\
-\Delta \mu_{zz} / \mu_{zz} \\
-\Delta \mu_{yz} / \mu_{yz} \\
-\Delta \mu_{zx} / \mu_{zx} \\
-\Delta \mu_{xy} / \mu_{xy}
\end{bmatrix}
\]

\[
\begin{bmatrix}
\rho_{xx} + \Delta \rho_{xx} \\
\Delta \rho_{xy} \\
\Delta \rho_{xz} \\
\rho_{xy} + \Delta \rho_{yy} \\
\rho_{xz} \\
\rho_{yz}
\end{bmatrix}
\begin{bmatrix}
J_{x}(0) \\
J_{y}(0) \\
J_{z}(0)
\end{bmatrix}
= 
\begin{bmatrix}
\mu_{xx} - \Delta \mu_{xx} & -\Delta \mu_{xy} & -\Delta \mu_{xz} \\
\mu_{xy} & \mu_{yy} - \Delta \mu_{yy} & -\Delta \mu_{yz} \\
-\Delta \mu_{yz} & \mu_{yz} & \mu_{zz} - \Delta \mu_{zz}
\end{bmatrix}
\begin{bmatrix}
J_{x}(0) \\
J_{y}(0) \\
J_{z}(0)
\end{bmatrix}
\]

Mason, 1957
Smith, 1954
2-D Piezoresistance Coefficients

[100] Orientation “Smith” Coefficients:

<table>
<thead>
<tr>
<th>Material</th>
<th>n-Si</th>
<th>p-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi_{11})</td>
<td>-102.2</td>
<td>6.6</td>
</tr>
<tr>
<td>(\pi_{12})</td>
<td>53.4</td>
<td>-1.1</td>
</tr>
<tr>
<td>(\pi_{44})</td>
<td>-13.6</td>
<td>138.1</td>
</tr>
</tbody>
</table>

Using directional cosine transformation

\[
\begin{bmatrix}
\pi_{ij}
\end{bmatrix} = \begin{bmatrix}
\pi_{11} & \pi_{12} & 0 \\
\pi_{12} & \pi_{11} & 0 \\
0 & 0 & \pi_{44}
\end{bmatrix}
\]

1 = [100]  
2 = [010]  
3 = 3' = [001]

\(2' = [110]\)  
\(1' = [110]\)

[110] Orientation Coefficients:

<table>
<thead>
<tr>
<th>Material</th>
<th>n-Si</th>
<th>p-Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi'_{11})</td>
<td>-31.2</td>
<td>71.8</td>
</tr>
<tr>
<td>(\pi'_{13})</td>
<td>53.4</td>
<td>-1.1</td>
</tr>
<tr>
<td>(\pi'_{33})</td>
<td>-102.2</td>
<td>6.6</td>
</tr>
<tr>
<td>(\pi'_{55})</td>
<td>-13.6</td>
<td>138.1</td>
</tr>
</tbody>
</table>

Using directional cosine transformation

\[
\begin{bmatrix}
\pi'_{ij}
\end{bmatrix} = \begin{bmatrix}
\pi'_{11} & \pi'_{13} & 0 \\
\pi'_{13} & \pi'_{33} & 0 \\
0 & 0 & \pi'_{55}
\end{bmatrix}
\]

\(3 = 3' = [001]\)

\(2 = [010]\)

\(1 = [100]\)

\(1' = [110]\)

Smith, 1954  
Kanda, 1982
-2D simulation results have good agreement with experimental ones.
Imax under Uniaxial Mechanical Stress

- ~23% reduction of peak current under 1GPa of uniaxial tensile stress

~23% decrease
Charge Collection until 10 ns

- ~22% reduction of collected charges under 1GPa of uniaxial tensile stress
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Strain Model (Piezoresistance Effect)

\[
\frac{\Delta \rho_{zz}}{\rho_{zz}} - \Delta \mu_{zz} / \mu_{zz} = \pi_{12} \sigma_{xx} + \pi_{12} \sigma_{yy} + \pi_{11} \sigma_{zz}
\]

1) Uniaxial stress along the <110> direction
\[
\frac{\Delta \rho_{zz}}{\rho_{zz}} - \Delta \mu_{zz} / \mu_{zz} = \pi_{12} \sigma_{xx} / 2 + \pi_{12} \sigma_{yy} / 2 = \pi_{12} \sigma
\]

2) Uniaxial stress along the <100> direction
\[
\frac{\Delta \rho_{zz}}{\rho_{zz}} - \Delta \mu_{zz} / \mu_{zz} = \pi_{12} \sigma_{xx} = \pi_{12} \sigma
\]

3) Biaxial stress
\[
\frac{\Delta \rho_{zz}}{\rho_{zz}} - \Delta \mu_{zz} / \mu_{zz} = \pi_{12} \sigma_{xx} + \pi_{12} \sigma_{yy} = \pi_{12} (2\sigma)
\]

- Mobility along z <001>-direction change is dominant factor for current transients change.
- Biaxial tensile stress has the potential to decrease \(\mu_{n\perp}\) more than uniaxial stresses do.
- It is expected that peak current under biaxial tensile stress is reduced more.
Mobility Enhancement using $\pi$-coefficient

\[
\frac{\Delta \rho_{zz}}{\rho_{zz}(0)} = \frac{\rho_{zz}(\sigma) - \rho_{zz}(0)}{\rho_{zz}(0)} = \frac{1/ \mu_{zz}(\sigma) - 1/ \mu_{zz}(0)}{1/ \mu_{zz}(0)} = \frac{\mu_{zz}(0) - \mu_{zz}(\sigma)}{\mu_{zz}(\sigma)} = \pi \sigma
\]

Using power series in $-1 < \pi \sigma < 1$,

\[
\mu_{zz}(\sigma) = \frac{1}{1 + \pi \sigma} \mu_{zz}(0)
\]

Non-Linear

\[
= [1 - \pi \sigma + (\pi \sigma)^2 - (\pi \sigma)^3 + (\pi \sigma)^4 - (\pi \sigma)^5 + \cdots] \mu_{zz}(0)
\]

Linear

If $\pi \sigma$ is very small, \( \mu_{zz}(\sigma) = [1 - \pi \sigma] \times \mu_{zz}(0) \)

- We need to consider nonlinear effect in high stress and large piezocoefficient.
Linear vs. Nonlinear in Uniaxial Stress

\[ \frac{\mu(\sigma)}{\mu(0)} = \frac{1}{1 + \pi_{12} \sigma} \]

\[ \frac{\mu(\sigma)}{\mu(0)} = 1 - \pi_{12} \sigma \]

\( \pi_{12} = +22.4 \times 10^5 \text{ MPa} \)
Linear vs. Nonlinear in Biaxial Stress

- Biaxial stress shows significant non-linear mobility effect more than uniaxial stress does.

\[
\frac{\mu(\sigma)}{\mu(0)} = 1/(1 + 2\pi_{12} \sigma)
\]

\[
\pi_{12} = +22.4 \times 10^{-6}/\text{MPa}
\]
$I_{\text{max}}$ under $<110>$ Uniaxial Stress

![Graph showing Bandgap Narrowing](image)

\[ \frac{I(\sigma)}{I(0)} = \left[ \frac{N_{1p}(\sigma)}{N_{1p}(0)} \right] \left[ \frac{\mu(\sigma)}{\mu(0)} \right] \]
$I_{\text{max}}$ under Uniaxial vs. Biaxial Stress

- Biaxial stress reduces peak current ($I_{\text{max}}$) more than uniaxial stress does.
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Conclusions/2009 Goals

• Conclusions
  - Experimental results show uniaxial mechanical stress alter current transients due to electron mobility change under stress.
  - 2D simulation results have a good agreement with experiment results in low stress region.
  - Less peak current (~23% decrease at 1 GPa) and charge collection (~21% decrease until 10 ns) in uniaxial tensile stressed diodes are observed.
  - Tensile biaxial stress decreases peak current more than uniaxial stress does.

• Future work
  - Biaxial stress modeling into TCAD simulation
  - Optimum stress type to minimize SET and SEE
  - Hole (P+/n-well) SET modeling


Thank you!!

Q & A