Simulation of Enhanced Hole Ballistic Velocity in Asymmetrically Strained Germanium Nanowire Trigate p-MOSFETs

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High Hole Mobility in Strained Ge

- **Strain-induced** high hole mobility and ballistic velocity can be used to increase current drive and decrease power consumption of p-FETs.
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**High Hole Mobility in Strained Ge**

- **Strain-induced** high hole mobility and ballistic velocity can be used to increase current drive and decrease power consumption of p-FETs.

- This work explains mobility results through QM simulations and extends analysis to ballistic velocity.

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**Graphical Data**

- Experimental Data
  - NW (w=49 nm) Chern, IEDM 2012
  - NW (w=40 nm) Ikeda, VLSI 2013
  - QWFET (biaxial strain) Pillarisetty, IEDM 2010
  - Planar (biaxial strain) Chern, IEDM 2012

**Symbols**

- HfO$_2$
- S
- G
- D

**Equation**

\[ \mu_{\text{eff}} (\text{cm}^2/\text{Vs}) \]

**Axes**

- \( N_{\text{inv}} \, (10^{12} \text{ cm}^{-2}) \)
- Silicon Hole Universal

James T. Teherani, MIT
Mobility, Current, and Ballistic Velocity

Long-channel device (drift-diffusion):

\[
I_{D,\text{sat}} = \frac{C_{ox}W}{2L} \mu (V_{GS} - V_{th})^2 \quad \mu = \frac{q\tau}{m^*}
\]
Mobility, Current, and Ballistic Velocity

Long-channel device (drift-diffusion):

\[ I_{D,\text{sat}} = \frac{C_{ox} W}{2L} \mu (V_{GS} - V_{th})^2 \]

\[ \mu = \frac{q \tau}{m^*} \]

Short-channel device (ballistic transport):

\[ I_{D,\text{sat}} = C_{ox} W (V_{GS} - V_{th}) \cdot \left( \frac{1 - r_c}{1 + r_c} \right) \nu_\theta \]

\[ \nu_\theta = \sqrt{\frac{2kT}{\pi m^*}} \]

Lundstrom, EDL 1997
1) s-GOI Substrate

- Biaxial Compression
- Begin with biaxially strained Ge on insulator

2) Electron Beam Patterning

- Lateral Relaxation
- Nanowire patterning creates free surfaces → lateral strain relaxation

3) Dielectric Deposition

- Final strain is asymmetric
  - Neither biaxial nor uniaxial

4) Final Device Structure

W. Chern et al., IEDM 2012
Asymmetric Strain (1/2)

(a) Source, Gate, Drain

(b) WN gate metal

(c) strained-Si

[110] [110]

HfO₂

5 nm

10 nm

10 nm
Asymmetric Strain (2/2)

(a) 

(b) WN gate metal

(strained-Si) 5 nm

(strained-Ge) 10 nm

HfO₂

(c)

εₓₓ

εᵧᵧ

εᵣᵣ

Si 1.7%

Ge -2.4%

Source

Drain

x

[110]

y

[001]

z

[110]
Measured & Simulated Strain

- Measured strain from Ge-Ge Raman peak shift
- Simulated strain from elastic energy minimization (nextnano3)

W. Chern et al., IEDM 2012
Xia, Univ. British Columbia
• Strain shifts the valence band through deformation potentials
  • 150 meV energy shift due to lateral strain relaxation near sidewalls
• Holes cluster near side gate due to
  • Strain relaxation near sidewall $\rightarrow$ valence band shift
  • Favorable gate electrostatics
• Few carriers near top gate, Si acts as dielectric due to large valence band offset with Ge
Quantum Mechanical Simulation Details

- Performed 2D numerical simulations using \textit{nextnano3} assuming infinite nanowire length
- Solved Schrödinger-Poisson equation using 6x6 $k\cdot p$ quantization method
Inverse Effective Mass Calculation

- Solved Schrödinger-Poisson for 80 eigenstates
- Strain mixes heavy-hole and light-hole valence bands
  - Small $m^*$ for small $|k_z|$ (light-hole characteristics)
  - Large $m^*$ for large $|k_z|$ (heavy-hole characteristics)

\[ \nu = \frac{\partial E}{\partial \hbar k} \]
\[ \frac{1}{m(k)} = \frac{\nu}{\hbar k} \]

\[ V_{FB} - 0.5 \text{ V} \Rightarrow N_{inv} = 3 \times 10^{12} \text{ cm}^{-2} \]
Inverse Effective Mass (1/2)

\[ \mu = \frac{q \tau}{m^*} \]

\[
\frac{1}{m_z}(x, y) = \frac{\sum_{i,k} \left( \frac{1}{m_z} \right)_{i,k} f(i, k) \cdot \Psi_{i,k}^2(x, y)}{\sum_{i,k} f(i, k) \cdot \Psi_{i,k}^2(x, y)}
\]
Inverse Effective Mass (2/2)

Inverse effective mass

- Peaks near the sidewalls
  - Same location as hole density peak
- Dips in center of device where higher $k_z$ states are occupied

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Inverse Effective Mass

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Inverse effective mass
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\mu = \frac{q \tau}{m^*}
\]

\( N_{inv} = 3 \times 10^{12} \text{ cm}^{-2} \)
To understand nanowire results, we performed a simulation experiment in which we changed strain in planar structures.
Impact of Strain on $E$-$k$ Dispersion (1/3)

Biaxial Compression

Strained Ge

$\langle 110 \rangle$

$\epsilon_{zz}$ (transport direction)

$\langle 110 \rangle$

$\epsilon_{xx}$
Impact of Strain on $E$-$k$ Dispersion (2/3)

Lateral strain relaxation ($\epsilon_{xx}$)

- Significantly reduces $m^*$ in the transport direction

Biaxial Compression

\( \langle 110 \rangle \)

\( \epsilon_{zz} \) (transport direction)

\( \langle 110 \rangle \)

\( \epsilon_{xx} \)

\( \epsilon_{xx} \) lateral relaxation

-2.4%

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Lateral strain relaxation ($\varepsilon_{xx}$)
- Significantly reduces $m^*$ in the transport direction

Vertical strain relaxation ($\varepsilon_{yy}$)
- No effect

Impact of Strain on $E$-$k$ Dispersion (3/3)
Mass Decrease with $|\epsilon_{xx}|$ (1/3)

Average Inverse Effective Mass $\langle 1/m_z \rangle$ (in $m_0^{-1}$)

<table>
<thead>
<tr>
<th>(1/3)</th>
<th>20% lateral relaxation</th>
<th>40% lateral relaxation</th>
<th>60% lateral relaxation</th>
<th>80% lateral relaxation</th>
<th>100% lateral relaxation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>2.4% initial biaxial compressive strain</td>
<td>Planar $\langle 110\rangle$ Channel</td>
<td>(100) Surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>unstrained</td>
<td>1% uniaxial</td>
<td>unstrained</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td>unstrained</td>
<td>biaxial (0% lateral relaxation)</td>
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$\mu = \frac{q\tau}{m^*}$

$N_{inv} = 2.5 \times 10^{12}$ cm$^{-2}$

$\langle 1/m_z \rangle$ and $\nu_\theta$ significantly increase as $|\epsilon_{xx}|$ is reduced
Mass Decrease with $|\epsilon_{xx}|$ (2/3)

$N_{inv} = 2.5 \times 10^{12} \text{ cm}^{-2}$

$\langle 1/m_z \rangle$ and $\nu_\theta$ significantly increase as $|\epsilon_{xx}|$ is reduced

$\langle 1/m_z \rangle = \frac{2kT}{\mu} \frac{1}{\pi}$

Planar ⟨110⟩ Channel (100) Surface

2.4% initial biaxial compressive strain

(transport direction)

Average Inverse Effective Mass $\langle 1/m_z \rangle$ (in $m_0^{-1}$)
Mass Decrease with $|\epsilon_{xx}|$ (3/3)

\[ \langle (1/m_z) \rangle \text{ (in } m_0 \text{)} \]

- Planar \( \langle 110 \rangle \) Channel
- \( (100) \) Surface

- 2.4% initial biaxial compressive strain

\[ \epsilon_{xx} \]
(transport direction)

\[ \epsilon_{zz} \]

\[ \mu = \frac{q\tau}{m^*} \]

\[ \nu_\theta = \sqrt{2kT \langle (1/m_z) \rangle / \pi} \]

$N_{inv} = 2.5 \times 10^{12} \text{ cm}^{-2}$

\[ \langle (1/m_z) \rangle \text{ and } \nu_\theta \text{ significantly increase as } |\epsilon_{xx}| \text{ is reduced} \]
Lateral strain $|\epsilon_{xx}|$ decreases with decreasing NW width.
Increased Mobility for Narrow NWs (1/3)

\[ \langle \frac{1}{m_z} \rangle \] and \( \nu_\theta \) increase as \( w_{NW} \) decreases.

\[ \langle \frac{1}{m_z} \rangle \text{ increases by 1.6x} \]

- Ge, 2.4% biaxial comp.
- Si, 1% uniaxial comp.
- Ge NWs
- Si, unstrained

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Increased Mobility for Narrow NWs (2/3)

\[ (\langle 1/m_z \rangle) \text{ and } v_\theta \text{ increase as } w_{NW} \downarrow \]

W. Chern et al., IEDM 2012

\[ \mu_{\text{eff}} \text{ (cm}^2\text{/Vs)} \]

\[ N_{\text{inv}} \text{ (10}^{12} \text{ cm}^{-2}) \]

\[ \langle 1/m_z \rangle \text{ (in } m_0^{-1}) \]

\[ w_{NW} \text{ (nm)} \]

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Increased Velocity for Narrow NWs (3/3)

\[ \left\langle \frac{1}{m_z} \right\rangle \text{ and } v_\theta \text{ increase as } w_{NW} \downarrow \]
Drive Current Improvement

$$I_{D,sat} = C_{ox} W (V_{GS} - V_{th}) \cdot \left( \frac{1 - r_c}{1 + r_c} \right) v_{\theta}$$

$$I_{D,sat} = Q \cdot B v_{\theta}$$

- $v_{\theta}$ improvement of 2.8× with respect to unstrained Si
- $v_{\theta}$ improvement of 1.6× with respect to 1% uniaxial Si

- $B$ also improves as strain splits bands and reduces scattering
  - Reduced backscattering inferred from highly enhanced experimental s-Ge hole mobility

$\Rightarrow I_D$ improvement of at least 2× with respect to 1% uniaxial Si
Summary

• Asymmetric lateral strain in NW device structure
• Significant lateral relaxation for small nanowire widths
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Summary

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- Inverse effective mass peak near sidewalls
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- Significant decrease in $m^*$ with lateral strain relaxation

- $2.8\times$ increase in $\nu_\theta$ with respect to unstrained Si
- $1.6\times$ increase in $\nu_\theta$ with respect to 1% uniaxial Si
- $I_D$ increase of at least $2\times$ with respect to 1% uniaxial Si
Slides available at:
http://teherani.mit.edu/