Mobility Enhancement of 2DHG in an In$_{0.24}$Ga$_{0.76}$As Quantum Well by $<110>$ Uniaxial Strain

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05.25.2011
Motivation

- Improve p-channel InGaAs FETs for III-V CMOS
- Enhance $\mu$: biaxial strain + uniaxial strain

**Demonstrated:**
High-performance InGaAs nFET

**Wanted:**
High-performance InGaAs pFET

$\pi = -\frac{1}{\mu_0} \frac{\partial \mu}{\partial \sigma}$

$\pi_{L_{<110}}$ (with $\sigma_{bi}) > \pi_{L_{<110}}$ (without $\sigma_{bi}$)

Jesus del Alamo, IEDM 2007, short course
Leonardo Gomez, EDL, 2010
Experimental structure

- Biaxially strained p-channel In$_{0.24}$Ga$_{0.76}$As QW:
  - Channel strain: 1.7% biaxial compressive

- Typical output characteristics of fabricated QW-FET:

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ΔV_{GS} = 0.2 V  \quad V_{GS} = -0.4 V  
L_g = 2 \mu m
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![Diagram showing the structure and output characteristics of the QW-FET.](image)
Experiment approach

• Apply uniaxial stress to GaAs chips
• Measure response of ungated Hall bars
  – High $I_G$ prevents accurate C-V to extract $C_G$ and $p_s$

• Mechanism to bend GaAs chips
• Can apply tensile or compressive stress
• Supporting mechanism and connections
• Stress and Hall bar orientations
Sheet hole density change

Compressive $\leftrightarrow$ Tensile

$\Delta p_s/p_{s0}$ (%) vs Stress (MPa)

- $\sigma_{\perp}[110]$
  - Rate: $0.043\%$ per MPa
- $\sigma_{\parallel}[-110]$
  - Rate: $0.018\%$ per MPa
- Channel along [-110]

$\Delta p_s/p_{s0}$ (%) vs Stress (MPa)

- $\sigma_{\parallel}[110]$
  - Rate: $-0.036\%$ per MPa
- $\sigma_{\perp}[-110]$
  - Rate: $0.010\%$ per MPa
- Channel along [110]

Solid lines: linear fittings to data
Dashed lines: 1D SP simulation with piezoelectric effect

- Almost identical patterns in $\Delta p_s$ for Hall bars along [110] and [-110]
  - $\Delta p_s$ determined by piezoelectric effect
  - Similar to our previous p-channel GaAs study. (L. Xia, to be published on TED)
Hole mobility change

- General trends of $\mu_h$:
  - Dominant factor: relative orientation of stress and transport direction
  - Similar in Si and Ge
Sensitivities of $\mu_h$ to $\sigma_{<110>}$

- Preferred configuration: Compressive $\sigma$ parallel to [-110] channel
- Questions:
  - Why $\pi_{//}$ different from $\pi_{\perp}$?
  - Why $|\pi_{//,[-110]}| \neq |\pi_{//,[110]}|$, and $|\pi_{\perp,[-110]}| \neq |\pi_{\perp,[110]}|$?
Anisotropy between $\pi_{//}$ and $\pi_{\perp}$

- Dominated by in-plane VB dispersion anisotropy
  - Simulation: 2D in-plane dispersion relation in QW by $k.p$ method

No uniaxial stress

With uniaxial [-110] compressive stress

- Change of VB $(m^*)_{//}$ or $\perp$ to $\sigma$ are different $\rightarrow \pi_{//}$ and $\pi_{\perp}$ different
  - Sign – opposite for $\Delta m^*_{//}$ and $\Delta m^*_{\perp}$
  - Magnitude – different (will show quantitatively later)
  - Similar in Si or Ge (S. Thompson, IEDM, 2004; O. Weber, IEDM, 2007)
Different $\pi$ along the two $<110>$ directions

• Counterintuitive:
  – $\Delta m^*_{//}$ (or $\Delta m^*_{\perp}$) should be the same for $\sigma_{[-110]}$ and $\sigma_{[110]}$

• 1st effect: $p_s$ change due to piezoelectric effect ($p_s \uparrow \rightarrow \mu_h \downarrow$)
  – Partly explains $\pi_{\perp,-110}$ and $\pi_{\perp,110}$ difference
  – May have decreased $\pi_{//,-110}$ and increased $\pi_{//,110}$

• 2nd effect: polarization-field-induced quantization change

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al$<em>{0.42}$Ga$</em>{0.58}$As</td>
<td>21 nm</td>
</tr>
<tr>
<td>In$<em>{0.24}$Ga$</em>{0.76}$As</td>
<td>9 nm</td>
</tr>
<tr>
<td>Al$<em>{0.33}$Ga$</em>{0.67}$As</td>
<td>80 nm</td>
</tr>
<tr>
<td>GaAs buffer</td>
<td>70 nm</td>
</tr>
<tr>
<td>S.I. GaAs Substrate</td>
<td></td>
</tr>
</tbody>
</table>

Black: [110] -112 MPa
Red: [-110] -112 MPa

$\phi^2$(a.u.) vs. z along growth axis (nm)
Comparison between experiments and simulations

- Extract average conductivity $m^*$ by approximations:
  $m_i^*(E) = \frac{\hbar^2 k^2}{2(E - E_v)}$
  $m^* = \frac{\sum_i \int_{E_{mi}}^\infty m_i^*(E)f(E)g_i(E)dE}{\sum_i \int_{E_{mi}}^\infty f(E)g_i(E)dE}$

- Other sources of anisotropy:
  - Anisotropic scattering (e.g. polar optical phonon scattering) $\tau_\parallel \neq \tau_\perp$ when $m^*_\parallel \neq m^*_\perp$ (J. J. Harris, J. Phys. Chem. Solids, 1973)
Comparison with other materials

- Uniaxial strain is a viable path to enhance p-channel III-V FET performance
- Superposition of uniaxial strain on top of biaxial strain → large improvement in $\mu$

$|\pi| = \left| \frac{1}{\mu_0} \frac{\partial \mu}{\partial \sigma} \right|$  

Measured from 2DHG or inversion layers

$p_s = 6-8 \times 10^{11} \text{ cm}^{-2}$  
For Ge, $p_s = 2 \times 10^{12} \text{ cm}^{-2}$

[2] L. Xia, to be published on TED