III-V FET Channel Designs for High Current Densities and Thin Inversion Layers

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Art Gossard (UCSB), John Albrecht (DARPA)
Thin, high current density III-V FET channels

*InGaAs, InAs FETs*

THz & VLSI need **high current**

*low m* → **high velocities**

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**FET scaling for speed requires increased charge density**

*low m* → **low charge density**

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**Density of states bottleneck**  (Solomon & Laux IEDM 2001)

→ *For < 0.6 nm EOT, silicon beats III-Vs*

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**Open the bottle!**

*low transport mass → high v_{carrier}*

*multiple valleys or anistropic valleys → high DOS*

Use the L valleys.
Simple FET Scaling

Goal: double transistor bandwidth when used in any circuit
→ reduce 2:1 all capacitances and all transport delays
→ keep constant all resistances, voltages, currents

gate-source, gate-drain fringing capacitances:
0.15-0.25 fF/µm

\[
g_{m}/W_g \sim \nu \cdot \left(\frac{C_{gs}}{L_g W_g}\right)
\]

\[
C_{gs}/W_g = \left(\frac{C_{gs}}{W_g L_g}\right) \cdot L_g
\]

To double speed, we must double \((g_{m}/W_g)\), \((I_D/W_g)\), \((C_{gs}/L_g W_g)\), \(n_s\)
FET Scaling Laws

Changes required to double device / circuit bandwidth.

laws in constant-voltage limit:

<table>
<thead>
<tr>
<th>FET parameter</th>
<th>change</th>
</tr>
</thead>
<tbody>
<tr>
<td>gate length</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>current density (mA/μm), $g_m$ (mS/μm)</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>channel 2DEG electron density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>electron mass in transport direction</td>
<td>constant</td>
</tr>
<tr>
<td>gate-channel capacitance density</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>dielectric equivalent thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>channel thickness</td>
<td>decrease 2:1</td>
</tr>
<tr>
<td>channel density of states</td>
<td>increase 2:1</td>
</tr>
<tr>
<td>source &amp; drain contact resistivities</td>
<td>decrease 4:1</td>
</tr>
</tbody>
</table>

Current densities should double
Charge densities must double
Semiconductor Capacitances Must Also Scale

\[ (V_{gs} - V_{th}) \]

\[ c_{ox} \]

\[ c_{\text{depth}} = \varepsilon / T_{\text{inversion}} \]

\[ (E_f - E_{\text{well}}) / q \]

\[ c_{dos} = q^2 g m^* / 2 \pi \hbar^2 \]

channel charge \( = q n_s = c_{dos} (V_f - V_{\text{well}}) = q (E_f - E_{\text{well}}) \cdot (gm^* / 2\pi\hbar^2) \)

Inversion thickness & density of states must also both scale.
Calculating Current: Ballistic Limit

Channel Fermi voltage = voltage applied to $c_{dos}$

$$E_f = qV_f = m^*v_f^2 / 2$$

mean electron velocity $= \overline{v} = (4/3\pi)v_f$

Channel charge: $\rho_s = c_{dos}(V_f - V_c) = \frac{c_{dos}c_{equiv}}{c_{equiv} + c_{dos}}(V_{gs} - V_{th})$

$$c_{dos} = q^2gm^*/2\hbar^2 = c_{dos,o} \cdot g \cdot (m^*/m_o), \text{ where } g \text{ is the # of band minima}$$

$$\Rightarrow J = \left(84 \frac{mA}{\mu m}\right) \frac{g \cdot (m^*/m_o)^{1/2}}{\left(1 + (c_{dos,o} / c_{ox}) \cdot g \cdot (m^*/m_o)\right)^{3/2}} \left(\frac{V_{gs} - V_{th}}{1 \text{ V}}\right)^{3/2}$$

Do we get highest current with high or low mass?
InGaAs MOSFETs: superior $I_d$ to Si at large EOT.

InGaAs MOSFETs: inferior $I_d$ to Si at small EOT.

Solomon / Laux Density-of-States-Bottleneck → III-V loses to Si.
Transit delay versus mass, # valleys, and EOT

\[ \tau_{ch} = \frac{Q_{ch}}{I_D} = K_2 \cdot \left( \frac{L_g}{2.52 \cdot 10^7 \text{ cm/s}} \right) \cdot \left( \frac{1 \text{ Volt}}{V_{gs} - V_{th}} \right)^{1/2} \]

where \( K_2 = \left( \frac{m^*}{m_0} \right)^{1/2} \cdot \left( 1 + \frac{c_{dos,o}}{c_{eq}} \cdot g \cdot \frac{m^*}{m_0} \right)^{1/2} \)

Low \( m^* \) gives lowest transit time, lowest \( C_{gs} \) at any EOT.

EOT includes wavefunction depth term (mean wavefunction depth*\( \varepsilon_{\text{SiO}_2} / \varepsilon_{\text{semiconductor}} \))
Low effective mass also impairs vertical scaling

Shallow electron distribution needed for high $I_d$, high $g_m / G_{ds}$ ratio, low drain-induced barrier lowering.

Energy of $L^{th}$ well state $\propto L^2 / m^* T_{well}^2$.

For thin wells,
  only 1st state can be populated.
For very thin wells,
  1st state approaches L-valley.

Only one vertical state in well.
Minimum ~ 3 nm well thickness.
$\rightarrow$ Hard to scale below 10-16 nm $L_g$. 
III-V Band Properties, normal \{100\} Wafer

\[
\begin{array}{c}
\Gamma \\
\begin{array}{c}
\begin{array}{c}
\text{material} \\
\text{substrate}
\end{array} \\
\begin{array}{c}
\text{In}_{0.5}\text{Ga}_{0.5}\text{As} \\
\text{InP}
\end{array} \\
\begin{array}{c}
\text{InAs} \\
\text{InP}
\end{array} \\
\begin{array}{c}
\text{GaAs} \\
\text{GaAs}
\end{array} \\
\begin{array}{c}
\text{Si} \\
\text{Si}
\end{array}
\end{array}
\begin{array}{c}
\text{\(m^* / m_o\)} \\
0.045 \\
0.026 \\
0.067 \\
---
\end{array}
\end{array}
\begin{array}{c}
\text{\(\Gamma\) valley} \\
\begin{array}{c}
\begin{array}{c}
\text{\(m_t / m_o\)} \\
1.29 \\
1.13 \\
1.30 \\
0.92
\end{array} \\
\begin{array}{c}
\begin{array}{c}
\text{\(E_x - E_\Gamma\)} \\
0.83 \text{ eV} \\
0.87 \text{ eV} \\
0.47 \text{ eV} \\
0.92 \text{ (negative)}
\end{array}
\end{array}
\end{array}
\end{array}
\begin{array}{c}
\text{\(X\) valley} \\
\begin{array}{c}
\begin{array}{c}
\text{\(m_t / m_o\)} \\
1.29 \\
1.13 \\
1.30 \\
0.92
\end{array} \\
\begin{array}{c}
\begin{array}{c}
\text{\(E_x - E_\Gamma\)} \\
0.83 \text{ eV} \\
0.87 \text{ eV} \\
0.47 \text{ eV} \\
0.92 \text{ (negative)}
\end{array}
\end{array}
\end{array}
\end{array}
\begin{array}{c}
\text{\(L\) valley} \\
\begin{array}{c}
\begin{array}{c}
\text{\(m_t / m_o\)} \\
1.23 \\
0.65 \\
1.90
\end{array} \\
\begin{array}{c}
\begin{array}{c}
\text{\(E_L - E_\Gamma\)} \\
0.47 \text{ eV} \\
0.57 \text{ eV} \\
0.28 \text{ eV}
\end{array}
\end{array}
\end{array}
\end{array}
\end{array}
\]

L-valley transverse masses are comparable to \(\Gamma\) valleys.
Consider instead: valleys in \{111\} Wafer

![Diagram showing valleys in \{111\} Wafer]

<table>
<thead>
<tr>
<th>Material</th>
<th>Substrate</th>
<th>(m^*/m_o)</th>
<th>(m_t/m_o)</th>
<th>(m_t/m_o)</th>
<th>(E_x - E_G)</th>
<th>(E_L - E_G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{In}<em>{0.5}\text{Ga}</em>{0.5}\text{As})</td>
<td>InP</td>
<td>0.045</td>
<td>1.29</td>
<td>0.19</td>
<td>0.83 eV</td>
<td></td>
</tr>
<tr>
<td>InAs</td>
<td>InP</td>
<td>0.026</td>
<td>1.13</td>
<td>0.16</td>
<td>0.87 eV</td>
<td></td>
</tr>
<tr>
<td>GaAs</td>
<td>GaAs</td>
<td>0.067</td>
<td>1.30</td>
<td>0.22</td>
<td>0.47 eV</td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>Si</td>
<td>---</td>
<td>0.92</td>
<td>0.19</td>
<td>(negative)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.90</td>
</tr>
</tbody>
</table>

Orientation: one L valley has high vertical mass

X valleys & three L valleys have moderate vertical mass
Valley in \{111\} wafer: with quantization in thin wells

Selects L[111] valley; low transverse mass
### $\{111\}$ Γ-L FET: Candidate Channel Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>$m^*/m_o$</th>
<th>$m_l/m_o$</th>
<th>$m_t/m_o$</th>
<th>$E_L - E_\Gamma$</th>
<th>Well thickness for Γ–L alignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{In}<em>{0.5}\text{Ga}</em>{0.5}\text{As}$</td>
<td>0.045</td>
<td>1.23</td>
<td>0.062</td>
<td>0.47 eV</td>
<td>1 nm (?)</td>
</tr>
<tr>
<td>$\text{GaAs}$</td>
<td>0.067</td>
<td>1.90</td>
<td>0.075</td>
<td>0.28 eV</td>
<td>2 nm</td>
</tr>
<tr>
<td>$\text{GaSb}$</td>
<td>0.039</td>
<td>1.30</td>
<td>0.10</td>
<td>0.07 eV</td>
<td>4 nm</td>
</tr>
<tr>
<td>$\text{Ge}$</td>
<td>0.039</td>
<td>1.58</td>
<td>0.08</td>
<td></td>
<td>- - -</td>
</tr>
</tbody>
</table>

* $E_L - E_\Gamma$ is the energy difference between the L valley and the Γ valley, indicating the alignment of the conduction bands at the $\Gamma$ and L points of the Brillouin zone.

For a negative value of $E_L - E_\Gamma$, the conduction bands are aligned at the $\Gamma$ and L points, which is desirable for FET performance.
Standard III-V FET: $\Gamma$ valley in [100] orientation

3 nm GaAs well
AlSb barriers

$\Gamma = 0$ eV
$L = 177$ meV
$X[100] = 264$ meV
$X[010] = 337$ meV
1st Approach: Use both $\Gamma$ and L valleys in [111]

2.3 nm GaAs well
AlSb barriers
[111] orientation

$\Gamma = 41$ meV
$L_{[11\bar{1}]} \,(1) = 0$ meV
$L_{[11\bar{1}]} \,(2) = 84$ meV
$L_{[11\bar{1}]} \,\text{etc.} = 175$ meV
$X = 288$ meV
Combined $\Gamma$-L wells in \{111\} orientation vs. Si

\[
J = K_1 \cdot \left(\frac{84 \text{ mA}}{\mu\text{m}}\right) \cdot \left(\frac{V_{gs} - V_{th}}{1 \text{ V}}\right)^{3/2}, \quad \text{where} \quad K_1 = \frac{g \cdot (m^*/m_o)^{1/2}}{\left(1 + (c_{dos,o} / c_{equiv}) \cdot g \cdot (m^*/m_o)^{1/2}\right)}/(1 + (c_{dos,o} / c_{equiv}) \cdot g \cdot (m^*/m_o)^{3/2})
\]

EOT includes the wavefunction depth term (mean wavefunction depth $\times \varepsilon_{SiO_2} / \varepsilon_{\text{semiconductor}}$).

Combined ($\Gamma$-L) transport

- 2 nm GaAs $\Gamma/L$ well $\rightarrow g = 2, m^*/m_o = 0.07$
- 4 nm GaSb $\Gamma/L$ well $\rightarrow m_{\Gamma}^*/m_o = 0.039, m_{L,t}^*/m_o = 0.1$
2nd Approach: Use L valleys in Stacked Wells

Three 0.66 nm GaAs wells
0.66 nm AlSb barriers
[111] orientation

$L_{[111]}(1) = 0 \text{ meV}$
$L_{[111]}(2) = 61 \text{ meV}$
$L_{[111]}(3) = 99 \text{ meV}$

$\Gamma = 338 \text{ meV}$
$L_{[111]}$, etc $= 232 \text{ meV}$
$X = 284 \text{ meV}$
Increase in $C_{\text{dos}}$ with 2 and 3 wells
3 High Current Density (111) GaAs/AlSb Designs

(100) orientation

3 nm GaAs well AlSb barriers

Wavefunctions

Charge density, 1/cm³

position, nm

2.3 nm GaAs well AlSb barriers

N₅ (1/cm²)

position, nm

(111) orientation

Two 0.66 nm GaAs wells 0.66 nm AlSb barriers

Wavefunctions

Charge density, 1/cm³

position, nm

Three 0.66 nm GaAs wells 0.66 nm AlSb barriers

N₅ (1/cm²)

position, nm

(Vgs - Vth), V

(Vgs - Vth), V

(Vgs - Vth), V

(Vgs - Vth), V
Concerns

Nonparabolic bands reduce bound state energies

Failure of effective mass approximation: 1-2 nm wells

1-2 monolayer fluctuations in growth
  → scattering → collapse in mobility
Network for Computational Nanotechnology (NCN)

- AlSb-GaSb triple-QW
- QW extension ~1.2nm

- Non-primitive unit cell in lateral directions
- Therefore zone folding in $E(k)$

- Supervised by Profs. Gerhard Klimeck and Timothy Boykin
- Simulation software: OMEN3D by Hoon Ryu and Sunhee Lee
- TB parameters for AlSb and GaSb: Ganesh Hegde and Yachhua Tan
Band structure along [-1 1 0]

Effective masses:
E=1.587: m*=0.0875
E=1.589: m*=0.0624
E=1.600: m*=0.0902
E=1.601: m*=0.0650
E=1.607: m*=0.0937
E=1.608: m*=0.0663
E=1.872: m*=0.0972
E=1.874: m*=0.0706
E=1.877: m*=0.1448
E=1.878: m*=0.1122
E=1.877: m*=0.1066
E=1.878: m*=0.0767
E=1.882: m*=0.1053
E=1.883: m*=0.0756
E=1.940: m*=0.1395
E=1.940: m*=0.1154
E=1.964: m*=0.0853
E=1.965: m*=0.0751
1-D FET array = 2-D FET with high transverse mass

Weak coupling → narrow transverse-mode energy distribution → high density of states
3rd Approach: High Current Density L-Valley MQW FINFETs

valley energies $E_{\text{min},i} = qV_{\text{min},i} = \frac{h^2\pi^2}{2mW^2} t^2$

current $I = \sum_{i} \frac{gq^2}{\pi \hbar} (V_f - V_{\text{min},i})$

charge $Q_{ch} = \sum_{i} \frac{g_l}{\pi \hbar} \sqrt{2m^* q (V_f - V_{\text{min},i})}$

gate voltage $V_{gs} = V_f + Q_{ch} / C_{ox}$
4th Approach: \{110\} Orientation → Anisotropic Bands

L\[111\], L\[1\overline{1}\overline{1}\]: moderate vertical mass → valleys populate
High in-plane mass perpendicular to transport → high density of states
Low in-plane mass parallel to transport → high carrier velocity

L\[1\overline{1}\overline{1}\], \[\overline{1}11\]: low vertical mass → depopulate
High in-plane mass parallel to transport → low carrier velocity

Challenge: only moderate energy separation between desired and undesired valleys.
Anisotropic bands, e.g. \{110\}

\[ J = K_1 \cdot \left( 84 \frac{\text{mA}}{\mu \text{m}} \right) \cdot \left( V_{gs} - V_{th} \right)^{3/2} \]

where \( K_1 = \frac{g \cdot (m_{\perp}^{1/2} / m_o^{1/2})}{\left(1 + (c_{d_\text{os,o}} / c_{\text{equiv}}) \cdot g \cdot (m_{\perp}^{1/2} m_\|^{1/2} / m_o)\right)^{3/2}} \)

**Transport in \{110\} oriented \( L \) valleys**

\[ c_{\text{equiv}} = \left( \frac{1}{\varepsilon_{ox}} + \frac{1}{\varepsilon_{\text{semi}}} \right)^{-1} = \frac{\varepsilon_{\text{SiO}_2}}{\varepsilon_{\text{EOT}}} \]

**GaAs and Ge \{110\} MOSFETs with \( L \)-valley transport**

GaAs: \( n = 2, m_t / m_o = 0.075, m_\| / m_o = 1.9 \quad \text{Ge: } n = 2, m_t / m_o = 0.081, m_\| / m_o = 1.58 \)
### THz FET scaling: with & without increased DOS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>50</th>
<th>35</th>
<th>25</th>
<th>18</th>
<th>13</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gate length</td>
<td>nm</td>
<td>50</td>
<td>35</td>
<td>25</td>
<td>18</td>
<td>13</td>
<td>9</td>
</tr>
<tr>
<td>Gate barrier EOT</td>
<td>nm</td>
<td>1.2</td>
<td>0.83</td>
<td>0.58</td>
<td>0.41</td>
<td>0.29</td>
<td>0.21</td>
</tr>
<tr>
<td>Well thickness</td>
<td>nm</td>
<td>8.0</td>
<td>5.7</td>
<td>4.0</td>
<td>2.8</td>
<td>2.0</td>
<td>1.4</td>
</tr>
<tr>
<td>S/D resistance</td>
<td>Ω·μm</td>
<td>210</td>
<td>150</td>
<td>100</td>
<td>74</td>
<td>53</td>
<td>37</td>
</tr>
<tr>
<td>Effective mass</td>
<td>*m₀</td>
<td>0.05</td>
<td>0.05</td>
<td>0.05</td>
<td>0.08</td>
<td>0.08</td>
<td>0.08</td>
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<tr>
<td># band minima</td>
<td></td>
<td>1</td>
<td>1.4</td>
<td>2</td>
<td>2.8</td>
<td>4</td>
<td>5.7</td>
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<tr>
<td>Canonical</td>
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<td>1</td>
<td>1.4</td>
<td>2</td>
<td>2.8</td>
<td>4</td>
<td>5.7</td>
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<tr>
<td>Fixed DOS</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Stepped #</td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>
Scaled FET performance: fixed vs. increasing DOS

Increased density of states needed for high drive current, fast logic @ 16, 11, 8 nm nodes
10 nm / 3 THz III-V FETs: Challenges & Solutions

To double the bandwidth:

- **Gate dielectric**: decrease EOT 2:1

- **S/D access regions**: decrease resistivity 2:1

- **Channel**: keep same velocity, but thin channel 2:1, increase density of states 2:1

S/D regrowth

Wistey et al
Singisetti et al
Bandstructure of the [111] AISb/GaSb triple-QW

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Network for Computational Nanotechnology (NCN)
Electrical and Computer Engineering
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- Supervised by Profs. Gerhard Klimeck and Timothy Boykin
- Simulation software: OMEN3D by Hoon Ryu and Sunhee Lee
- TB parameters for AISb and GaSb: Ganesh Hegde and Yaohua Tan
MOSFET Scaling Laws

<table>
<thead>
<tr>
<th>parameter</th>
<th>law</th>
<th>parameter</th>
<th>law</th>
</tr>
</thead>
<tbody>
<tr>
<td>gate length $L_g$, source-drain contact lengths $L_{S/D}$ (nm)</td>
<td>$\gamma^{-1}$</td>
<td>gate-channel capacitance $C_{g-ch}$</td>
<td>$\gamma^{-1}$</td>
</tr>
<tr>
<td>$L_{S/D}$ (nm)</td>
<td></td>
<td>$=[1/C_{ox} + 1/C_{semi} + 1/C_{DOS}]^{-1}$ (fF)</td>
<td></td>
</tr>
<tr>
<td>gate width $W_g$ (nm)</td>
<td>$\gamma^{-1}$</td>
<td>transconductance $g_m \sim C_{g-ch} v_{injection} / L_g$ (mS)</td>
<td>$\gamma^0$</td>
</tr>
<tr>
<td>equivalent oxide thickness $T_{eq} = T_{ox} \varepsilon_{SiO_2} / \varepsilon_{oxide}$ (nm)</td>
<td>$\gamma^{-1}$</td>
<td>gate-source, gate-drain fringing capacitances $C_{gs,f} \propto \varepsilon W_g$, $C_{gd} \propto \varepsilon W_g$ (fF)</td>
<td>$\gamma^{-1}$</td>
</tr>
<tr>
<td>dielectric capacitance $C_{ox} = \varepsilon_{SiO_2} L_g W_g / T_{eq}$ (fF)</td>
<td>$\gamma^{-1}$</td>
<td>S/D access resistances $R_s$, $R_d$ ($\Omega$)</td>
<td>$\gamma^0$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S/D contact resistivity $R_s / W_g$, $R_d / W_g$ ($\Omega - \mu m$)</td>
<td>$\gamma^{-1}$</td>
</tr>
<tr>
<td>inversion thickness $T_{inv} \sim T_{well} / 2$ (nm)</td>
<td>$\gamma^{-1}$</td>
<td>S/D contact resistivity $\rho_c$ ($\Omega - \mu m^2$)</td>
<td>$\gamma^{-2}$</td>
</tr>
<tr>
<td>semiconductor capacitance $C_{semi} = \varepsilon_{semi} L_g W_g / T_{inv}$ (fF)</td>
<td>$\gamma^{-1}$</td>
<td>drain current $I_d \sim g_m (V_{gs} - V_{th})$ (mA)</td>
<td>$\gamma^0$</td>
</tr>
<tr>
<td>DOS capacitance $C_{DOS} = q^2 nm^* L_g W_g / 2\pi \hbar^2$ (fF)</td>
<td>$\gamma^{-1}$</td>
<td>drain current density (mA/$\mu m$)</td>
<td>$\gamma^1$</td>
</tr>
<tr>
<td>electron density $n_s$ (cm$^{-2}$)</td>
<td>$\gamma^1$</td>
<td>temperature rise (one device, K)</td>
<td>$\sim W_g^{-1}$</td>
</tr>
</tbody>
</table>
2 nm well: \( \Gamma \) and \( L(l) \) minima both populated.
\[ \Gamma: m^* / m_o = 0.067 \quad \text{L(l): } \quad m_{\text{lateral}}^* / m_o = 0.075 \]
Low \( m^* \) \( \rightarrow \) high carrier velocity
Two band minima \( \rightarrow \) doubles \( c_{\text{dos}} \)
2 nm well \( \rightarrow \) good electrostatics at \( \sim 5 - 7 \) nm \( L_g \).
GaSb well, AlSb barriers, on \{110\} GaSb