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SOI MOSFETs

- Two separate gates
- Upper oxide thermal
- Lower gate oxide is the BOX (e.g. produced by SIMOX)
- Typically $t_{OF} \ll t_{OB}$

**Goal:** To understand the effect of the top and back gates on MOSFET operation
band diagram: PD SOI

- Maximum depletion width for bulk Si:
  \[ W_{DM} = \sqrt{\frac{4\varepsilon_{Si}\psi_B}{qN_A}} \]
  \[ \psi_B = \frac{k_B T}{q} \ln\left(\frac{N_A}{n_i}\right) \]

- Partially depleted (PD) SOI:
  \[ t_{Si} > 2W_{DM} \]

- Front and back gates are decoupled electrostatically: \( \psi_{SF} \) independent of \( \psi_{SB} \)

- Device operation similar to a bulk MOSFET
band diagram: FD SOI

- Fully depleted (FD) SOI: \( t_{Si} < W_{DM} \)

- Front and back gates are electrostatically coupled: \( \psi_{SF} \) is a function of \( \psi_{SB} \)

- Back gate bias plays important role in device operation

- The rest of this lecture will focus on fully depleted SOI
**FD SOI nMOSFET operating regions**

Nine operating regions:

<table>
<thead>
<tr>
<th>Front gate:</th>
<th>Back gate:</th>
</tr>
</thead>
<tbody>
<tr>
<td>depleted</td>
<td>depleted</td>
</tr>
<tr>
<td>inverted</td>
<td>inverted</td>
</tr>
<tr>
<td>accumulated</td>
<td>accumulated</td>
</tr>
</tbody>
</table>
FD SOI nMOSFET operating regions

\[ V_{GF} \]

- Front Inversion
- Back Accumulation
- Front Depletion
- Back Accumulation
- Front Accumulation
- Back Accumulation
- Front Inversion
- Back Depletion
- Front Inversion
- Back Depletion
- Front Depletion
- Back Depletion
- Front Accumulation
- Back Depletion
- Front Accumulation
- Back Depletion
- Front Inversion
- Back Inversion
- Front Inversion
- Back Inversion
- Front Inversion
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Key references for SOI 1D Electrostatics


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FD SOI band diagram

\[ \rho(x) = -qN_A \]
objectives

for bulk MOSFETS, we know:

\[ V'_G = \psi_S - Q_S / C_{ox} \]

for FDSOI MOSFETS, determine:

\[ \psi_{SF} = f(V_{GF}, V_{GB}) \]
\[ \psi_{SB} = f(V_{GF}, V_{GB}) \]
**electric field in SOI**

**Delta-depletion Approximation:** Assume that any mobile charge is at the Si surface in a delta function.

**Apply Gauss’ Law to FD bulk:**

\[
\frac{dE}{dx} = \frac{-qN_A}{\varepsilon_{Si}}
\]

\[
E(t_{Si}) - E(0^+) = \int_{E(0^+)}^{E(t_{Si})} dE = \frac{-qN_A}{\varepsilon_{Si}} \int_{0^+}^{t_{Si}} dx
\]

\[
E(t_{Si}^-) - E(0^+) = -qN_A t_{Si} / \varepsilon_{Si}
\]
electric field in SOI (ii)

from:

$$E(t_{Si}^-) - E(0^+) = -qN_At_{Si} / \varepsilon_{Si}$$

we get:

$$E(0^+) = E(t_{Si}^-) + qN_At_{Si} / \varepsilon_{Si} \quad \text{(1)}$$

also:

$$\Delta \psi = \psi_{SF} - \psi_{SB} = \frac{1}{2} \left[ E(0^+) + E(t_{Si}^-) \right] t_{Si}$$

from which, we obtain:

$$E(0^+) = 2\left( \psi_{SF} - \psi_{SB} \right) / t_{Si} - E(t_{Si}^-) \quad \text{(2)}$$
electric field in SOI (iii)

solve (1) and (2) for:

\[ E(0^+) = \left( \frac{\psi_{SF} - \psi_{SB}}{t_{Si}} \right) + \frac{qN_A t_{Si}}{2 \epsilon_{Si}} \]  
\[
(3)
\]

\[ E(t_{Si}^-) = \left( \frac{\psi_{SF} - \psi_{SB}}{t_{Si}} \right) - \frac{qN_A t_{Si}}{2 \epsilon_{Si}} \]  
\[
(4)
\]

we can also relate:

\[ E(0^+) \text{ to } V_{GF} \]

\[ E(t_{Si}^-) \text{ to } V_{GB} \]
effect of front and back gate voltages

The field in the front gate oxide is:

\[ E_{OF} = \left( V_{GF}' - \psi_{SF} \right) / t_{OF}, \quad \text{where} \quad V_{GF}' = V_{GF} - \phi_{msf} \]

Taking the inversion charge into account:

\[ \varepsilon_{ox} E_{OF} = \varepsilon_{Si} E(0^+) - Q_{IF} \]

\[ E(0^+) = \frac{\varepsilon_{ox}}{\varepsilon_{Si}} E_{OF} + \frac{Q_{IF}}{\varepsilon_{Si}} \]

\[ E(0^+) = \frac{\varepsilon_{ox}}{\varepsilon_{Si}} \frac{(V_{GF}' - \psi_{SF})}{t_{OF}} + \frac{Q_{IF}}{\varepsilon_{Si}} \quad (5) \]
effect of front and back gate voltages (ii)

after a similar analysis for the back gate:

\[ E(0^+) = \frac{\varepsilon_{ox}}{\varepsilon_{Si}} \left( V_{GF}' - \psi_{SF} \right) + \frac{Q_{IF}}{\varepsilon_{Si}} \]  \hspace{1cm} (5)

\[ E(t_{Si}^-) = \frac{\varepsilon_{ox}}{\varepsilon_{Si}} \left( \psi_{SB} - V_{GB}' \right) - \frac{Q_{IB}}{\varepsilon_{Si}} \]  \hspace{1cm} (6)

\[ E(0^+) = \left( \frac{\psi_{SF} - \psi_{SB}}{t_{Si}} \right) + \frac{qN_A t_{Si}}{2 \varepsilon_{Si}} \]  \hspace{1cm} (3)

\[ E(t_{Si}^-) = \left( \frac{\psi_{SF} - \psi_{SB}}{t_{Si}} \right) - \frac{qN_A t_{Si}}{2 \varepsilon_{Si}} \]  \hspace{1cm} (4)
general solution

\[ V_{GF} = \phi_{msf} + \psi_{SF} - \frac{Q_{IF} + Q_{B}/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times (\psi_{SF} - \psi_{SB}) \]  

(7)

\[ V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_{B}/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times (\psi_{SB} - \psi_{SF}) \]  

(8)

\[ C_{Si} \equiv \frac{\varepsilon_{Si}}{t_{Si}} \quad Q_{B} \equiv -qN_{A}t_{Si} \]

extra volt drop across oxide due to different surface potentials

compare to: \[ V'_{G} = \psi_{S} - Q_{S}/C_{ox} \]
extra term due to different surface potentials

For bulk silicon MOS structure, the gate voltage is given by:

\[
V_G = \psi_S - \left( Q_B + Q_I \right) / C_{ox}
\]

Comparing with the bulk, the DGSOI gate voltage has an extra term that accounts for the voltage drop across oxide due to different surface potentials.

\[
E_{Si} = (\psi_{SF} - \psi_{SB}) / t_{Si}
\]

\[
\varepsilon_{of} E_{OF} = \varepsilon_{Si} E_{Si} \quad \varepsilon_{of} E_{OF} = \varepsilon_{Si} (\psi_{SF} - \psi_{SB}) / t_{Si}
\]

\[
\Delta V_{OX} = t_{OF} E_{OF} = \frac{C_{Si}}{C_{OF}} (\psi_{SF} - \psi_{SB})
\]
front and back coupled electrostatics

for a fixed $V_{GF}$, increasing $V_{GB}$ increases $\psi_{SF}$ (lowers $V_{TF}$)

**eqn. (7)**

**eqn. (8)**
outline

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$V_{TF}$ vs. $V_{GB}$
Raising $V_{GB}$ increases $\psi_{SF}$, so the front gate threshold voltage $V_{TF}$ should decrease.

$$V_{GF} = \phi_{msf} + \psi_{SF} - \frac{Q_{IF} + Q_{B}/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times (\psi_{SF} - \psi_{SB})$$

At threshold, $Q_{IF} = Q_{B}/2$ and $\psi_{SF} = 2\psi_{B}$

$$V_{TF} = \phi_{msf} + 2\psi_{B} - \frac{Q_{B}}{2C_{OF}} + \frac{C_{Si}}{C_{OF}}(2\psi_{B} - \psi_{SB})$$

$V_{TF}$ is a function of $\psi_{SB}$, and hence can be varied using back gate bias ($V_{GB}$)
1) back inverted

\[ V_{TF} = \phi_{msf} + 2\psi_B - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} \left( 2\psi_B - \psi_{SB} \right) \]

Back side inversion:

\[ \psi_{SB} = 2\psi_B \]

\[ V_{TF} \text{ (back inv)} = \phi_{msf} + 2\psi_B - \frac{Q_B}{2C_{OF}} \]

Current flows even when \( V_{GF} < V_{TF} \) because the back surface is inverted. Since the device doesn’t turn off, this mode of operation is not useful.
2) back accumulated

\[ V_{TF} = \phi_{msf} + 2\psi_B - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} (2\psi_B - \psi_{SB}) \]

Back accumulation:

\[ \psi_{SB} \approx 0 \]

\[ V_{TF} (\text{back acc}) = \phi_{msf} + 2\psi_B - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} (2\psi_B) \]

Net \( V_{TF} \) shift:

\[ \Delta V_{TF} = V_{TF} (\text{back acc}) - V_{TF} (\text{back inv}) \]

\[ = \frac{C_{Si}}{C_{OF}} (2\psi_B) = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \frac{t_{OF}}{t_{Si}} (2\psi_B) \]
3) back depleted

\[ V_{GF} = \phi_{msf} + \psi_{SF} - \frac{Q_{IF} + Q_B/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times (\psi_{SF} - \psi_{SB}) \]  \hspace{1cm} (7)

\[ V_{TF} = \phi_{msf} + 2\psi_{SB} - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} \times (2\psi_B - \psi_{SB}) \]  \hspace{1cm} (9)

We need to relate \( \psi_{SB} \) to \( V_{GB} \) …
3) back depleted (ii)

\[ V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_{B}/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times (\psi_{SB} - \psi_{SF}) \]  \hspace{1cm} (8)

at front threshold:

\[ V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{B}}{2C_{OB}} + \frac{C_{Si}}{C_{OB}} \times (\psi_{SB} - 2\psi_{B}) \]  \hspace{1cm} (10)

at the start of back accumulation (\(\psi_{SB} = 0\)):

\[ V_{GB}^{(acc)} = \phi_{msb} - \frac{Q_{B}}{2C_{OB}} - \frac{C_{Si}}{C_{OB}} 2\psi_{B} \]  \hspace{1cm} (11)
3) back depleted (iii)

The back surface is depleted when $V_{GB} > V_{GB}(acc)$

From (10) and (11):

$$V_{GB} - V_{GB}(acc) = \left(1 + \frac{C_{Si}}{C_{OB}}\right)\psi_{SB}$$

$$\psi_{SB} = \frac{C_{ob}}{C_{OB} + C_{Si}} \left[ V_{GB} - V_{GB}(acc) \right] \quad (12)$$
3) Back depleted (iv)

Recap:

\[ V_{TF} = \phi_{msf} + 2\psi_{SB} - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} \times \left( 2\psi_B - \psi_{SB} \right) \]  \hspace{1cm} (9)

\[ \psi_{SB} = \frac{C_{ob}}{C_{OB} + C_{Si}} \left[ V_{GB} - V_{GB} \left( \text{acc} \right) \right] \]  \hspace{1cm} (12)

\[ V_{TF} = \phi_{msf} + 2\psi_B - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} 2\psi_B - \frac{C_{Si} C_{OB}}{C_{OF} \left( C_{OB} + C_{Si} \right)} \left[ V_{GB} - V_{GB} \left( \text{acc} \right) \right] \]

\[ \frac{dV_{TF}}{dV_{GB}} = - \frac{C_{Si} C_{OB}}{C_{OF} \left( C_{OB} + C_{Si} \right)} = - \left( \frac{t_{OF}}{t_{OB}} \right) \frac{1}{\left( 1 + C_{OB} / C_{Si} \right)} \]
$\Delta V_{TF} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \frac{t_{OF}}{t_{Si}} (2\psi_B)$

\[
\frac{dV_{TF}}{dV_{GB}} = -\frac{t_{OF}/t_{OB}}{1 + C_{OB}/C_{Si}}
\]
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subthreshold swing (bulk MOSFET review)

subthreshold current: \[ I_D \sim e^{q\psi_S/k_BT} \]
\[ \ln I_D = q\psi_S / k_BT \]
\[ 2.303\log I_D = q\psi_S / k_BT \]

subthreshold slope: \[ \frac{\partial \log I_D}{\partial V_{GS}} = \frac{1}{2.3(k_BT/q) \partial V_{GS}} = S^{-1} \]

subthreshold swing: \[ S = 2.3(k_BT/q)^{-1} \left( \frac{\partial \psi_S}{\partial V_{GS}} \right)^{-1} = 2.3m(k_BT/q) \]
\[ m = \left( \frac{\partial \psi_S}{\partial V_{GS}} \right)^{-1} \]
subthreshold swing (SOI MOSFET)

subthreshold current: \[ I_D \sim e^{q\psi_{SF}/k_BT} \]

subthreshold swing: \[ S = 2.3(k_B T / q)\left(\frac{\partial \psi_{SF}}{\partial V_{GF}}\right)^{-1} = 2.3m(k_B T / q) \]

‘body effect parameter’: \[ m = \left(\frac{\partial \psi_{SF}}{\partial V_{GF}}\right)^{-1} \]
SOI subthreshold swing derivation

return to general solution:

\[ V_{GF} = \phi_{msf} + \psi_{SF} \frac{Q_{IF} + Q_B/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times (\psi_{SF} - \psi_{SB}) \]  

\[ V_{GB} = \phi_{msb} + \psi_{SB} \frac{Q_{IB} + Q_B/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times (\psi_{SB} - \psi_{SF}) \]  

compute \( dV_{GF} / d\psi_{SF} \) from (7)

assume \( Q_B \) is constant (FD)
SOI subthreshold swing derivation (ii)

\[
\frac{\partial V_{GF}}{\partial \psi_{SF}} = 1 + \frac{C_{Si}}{C_{OF}} \left( 1 - \frac{\partial \psi_{SB}}{\partial \psi_{SF}} \right) \tag{10}
\]

To get \( \frac{\partial \psi_{SB}}{\partial \psi_{SF}} \), differentiate (8) assuming \( V_{GB} \) is constant

\[
0 = \frac{\partial \psi_{SB}}{\partial \psi_{SF}} + \frac{C_{Si}}{C_{OB}} \left( \frac{\partial \psi_{SB}}{\partial \psi_{SF}} - 1 \right)
\]

\[
\frac{\partial \psi_{SB}}{\partial \psi_{SF}} = \frac{C_{Si}/C_{OB}}{1 + C_{Si}/C_{OB}} = \frac{C_{Si}}{C_{Si} + C_{OB}} \quad \text{insert in (10)}
\]
SOI subthreshold swing derivation (iii)

\[
\frac{dV_{GF}}{d\psi_{SF}} = m = 1 + \frac{C_{Si}C_{OB}}{C_{OF}(C_{Si} + C_{OB})}
\]

\[
m = 1 + \frac{C_D}{C_{ox}} \quad \text{bulk}
\]

\[
C_D(\text{eff}) = \frac{C_{Si}C_{OB}}{(C_{Si} + C_{OB})}
\]

\[
m = 1 + \frac{C_D(\text{eff})}{C_{OF}}
\]

if the bottom oxide is thick, \( C_{OB} \ll C_{Si}, C_{OF} \) \( m \to 1 \)
SOI summary

1) front and back gates are coupled electrostatically

2) front threshold voltage can be tuned by the back gate

3) for a thick BOX, the subthreshold swing is nearly ideal
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symmetrical double gate

\[ t_{OF} = t_{OX} \]

\[ t_{OB} = t_{OX} \]

\[ V_{GF} = V_G \]

\[ V_{GB} = V_G \]

\[ \rho(x) = -qN_A \]

\[ E_F \]

\[ \psi_S \]

\[ V_G \]

0 \quad t_{Si} \quad t_{OX} \quad t_{Si} \quad x
DG electrostatics

\[
V_{GF} = \phi_{msf} + \psi_{SF} - \frac{Q_{IF} + Q_B/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times (\psi_{SF} - \psi_{SB}) \tag{7}
\]

\[
V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_B/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times (\psi_{SB} - \psi_{SF}) \tag{8}
\]

for double gate SOI:

\[
V_{GF} = V_{GB} \quad \psi_{SF} = \psi_{SB} \quad C_{OF} = C_{OB} = C_{ox} \quad Q_{IF} = Q_{IB} = Q_{I}/2
\]

then either (7) or (8) gives:

\[
V_G = \phi_{ms} + \psi_S - \frac{Q_I + Q_B}{2C_{ox}}
\]
DG subthreshold swing

\[ V_G = \phi_{ms} + \psi_S - \frac{Q_I + Q_B}{2C_{ox}} \quad Q_I \approx 0 \]

\[ \frac{dV_G}{d\psi_S} = m = 1 \quad \text{(fully depleted, } Q_B \text{ independent of } \psi_S) \]

*ideal* subthreshold characteristics
DG above threshold

\[ V_G = \phi_{ms} + \psi_S - \frac{Q_B}{2C_{ox}} - \frac{Q_I}{2C_{ox}} \]

\[ V_T = \phi_{ms} + 2\psi_B - \frac{Q_B}{2C_{ox}} \]

for \( V_G > V_T \):

\[ V_G - V_T = -\frac{Q_I}{2C_{ox}} \]

\[ Q_I = -2C_{ox}(V_G - V_T) \]

twice as much charge \( \Rightarrow \) twice as much current
asymmetric gates

\[ V_{GF} = V_{GB} = V_g \]

\[ t_{OF} = t_{OB} = t_{OX} \]

\[ \phi_{msf} \neq \phi_{msb} \]

how should \( Q_I = -2C_{ox} (V_g - V_T) \) be modified?
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review: SOI MOSFET general solution

$$C_{Si} \equiv \frac{\varepsilon_{Si}}{t_{Si}} \quad Q_{B} \equiv -qN_{A}t_{Si}$$

back gate - substrate

$$V_{GF} = \phi_{msf} + \psi_{SF} - \frac{Q_{IF} + Q_{B}/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times \left(\psi_{SF} - \psi_{SB}\right) \quad (7)$$

$$V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_{B}/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times \left(\psi_{SB} - \psi_{SF}\right) \quad (8)$$
review: SOI MOSFETs key results

\[ \Delta V_{TF} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \frac{t_{OF}}{t_{Si}} (2\psi_B) \]

\[ \frac{dV_{TF}}{dV_{GB}} = -\frac{t_{OF}}{t_{OB}} \frac{1}{1 + \frac{C_{OB}}{C_{Si}}} \]

\[ m = 1 + \frac{C_D(\text{eff})}{C_{OF}} \]

\[ C_D(\text{eff}) = \frac{C_{Si}C_{OB}}{C_{Si} + C_{OB}} \]

\[ S = 2.3m \left( \frac{k_B T}{q} \right) \]
symmetrical double gate (SDG)

\[ V_{GF} = V_G \]
\[ V_{GB} = V_G \]
\[ t_{OF} = t_{OX} \]
\[ t_{OB} = t_{OX} \]
\[ \rho(x) = -qN_A \]

\[ V_G \]
\[ E_F \]
\[ t_{OX} \]
\[ t_{Si} \]
\[ t_{OX} \]
\[ \psi_S \]
\[ 0 \]
\[ t_{Si} \]
\[ x \]
symmetrical double gate: key results

\[ V_{GF} = V_G \]
\[ t_{OF} = t_{OX} \]
\[ t_{OB} = t_{OX} \]

\[ V_{GB} = V_G \]

\[ V_G = \phi_{ms} + \psi_S - \frac{Q_I + Q_B}{2C_{ox}} \]

\[ V_T = \phi_{ms} + 2\psi_B - \frac{Q_B}{2C_{ox}} \]

\[ Q_I = -2C_{ox}(V_G - V_T) \]

\[ S = 2.3\left(\frac{k_B T}{q}\right) \text{ (ideal)} \]
If $T_{Si}$ is very thin, then the device is called an ultra-thin-body SOI MOSFET
why UTB DG MOSFETs?

- good 2D electrostatics

  \[
  \Lambda_{DG\,SOI} \approx \sqrt{\varepsilon_{Si} t_{Si} t_{OX}} \frac{1}{2 \varepsilon_{OX}} = \Lambda_{BULK} / \sqrt{2}
  \]

- undoped body
  
  (no random dopant fluctuations of \(V_T\))

- ideal subthreshold swing

issues:

  - \(V_T\) must be tuned with workfunctions
  - \(2\psi_B\) loses relevance
  - mobility degradation for very thin bodies
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thick vs. thin body

\[ \rho(x) = -qN_A \]

\[ n(x) \]

\[ E_F \]

\[ \psi_S \]

\[ V_G \]

\[ t_{OX} \]

\[ t_{Si} \]

\[ x \]
definition of UTB

1) fully depleted

\[ t_{Si} < W_{DM} \quad \frac{dE}{dx} = \frac{-qN_A}{\varepsilon_{Si}} \]

2) little band bending across the body

\[ \Delta \psi < k_B T / q \]

(requires a numerical solution in general)
numerical (Schred) simulation

Fig. 14. Band-diagram of DGMOS capacitors of different body thickness at same $V_G$. Also shown the band diagram of bulk MOSC (red-dashed line). $t_{ox} = 10$nm, $N_A = 1.1E17$ cm$^{-3}$, $V_G = 1.5$V. Classical mode calculation.

Sayed Hasan, Schred 2.1 Tutorial, April 28, 2003
threshold voltage for an undoped body

\[ V_G = \phi_{ms} + \psi_S \]

how to specify \( \psi_S \) ?

\[ \psi_S \neq 2\psi_B \]

\[ \psi_S < \psi_C \]

\[ \frac{d\psi_S}{dV_{GS}} \approx 1 \]

\[ \psi_S > \psi_C \]

\[ \frac{d\psi_S}{dV_{GS}} \to 0 \]
how to specify $\psi_C$?

1) according to Trivedi, Fossum, and Zhang:

$$n_i e^{q\psi_C/k_B T} t_{Si} \approx 10^{11} \text{ cm}^2$$

2) also could say:

$$\psi_C = E_G / 2q$$

3) another possibility:

$$d\psi_S / dV_{GS} \bigg|_{\psi = \psi_C} = 1/2$$

$$\psi_C = \left(k_B T / q\right) \ln \left(2C_{ox} k_B T / n_i t_{Si} q^2\right)$$
threshold voltage (iii)

\[ V_G = \phi_{ms} + \psi_S - \frac{Q_I}{2C_{ox}} \]

\[ V_T = \phi_{ms} + \psi_C \]

\[ Q_I = -2C_{ox} \left( V_G - V_T \right) \]
1) below threshold:
- *bands are flat*

2) weak / moderate inversion:
- *bands are nearly flat*
  - *volume inversion*

3) strong inversion:
- *strong band bending may develop*
  - *volume inversion may be lost*
‘exact’ UTB electrostatics

\[
\frac{d^2 \psi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_{Si}} = \frac{q n_i}{\varepsilon_{Si}} e^{q \psi(x)/k_B T}
\]

can solve exactly, see:

quantum confinement

FD (thick)

FD (UTB)

Lundstrom EE-612 F08
numerical (Schred) simulation

Fig. 20. Inversion carrier distribution inside the DGMOSC, for various body thickness, with $t_{ox}=10\text{nm}$, $N_a=1.1E17\text{cm}^{-3}$, $V_G = 0.5\text{v}$.

Sayed Hasan, Schred 2.1 Tutorial, April 28, 2003
numerical (Schred) simulation

Fig. 22. Quantum calculation, $t_{ox}=5\text{nm}$, $t_{sl}=10\text{nm}$, $N_A=1.e17\text{cm}^{-3}$. (a) variation of centroid with gate voltage, rest three are electron distribution inside silicon film at gate voltage: (b) $-0.4\text{v}$, (c) $0.1\text{v}$, (d) $1.2\text{v}$.

Sayed Hasan, Schred 2.1 Tutorial, April 28, 2003
quantum effects...

1) important when only a few subbands are occupied
   ultra-ultra-thin body (5 nm or less)

2) increase $V_T$

3) lower $C_S$

4) increase $\Delta V_T$ because of body thickness variations

5) lower mobility because of increased surface roughness
   scattering
1. Introduction
2. General solution
3. $V_{TF}$ vs. $V_{GB}$
4. Subthreshold slope
5. Double gate (DG) SOI
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SOI summary

1. SOI offers several advantages:
   - no latch-up
   - radiation hard
   - lower junction capacitance
   - good electrostatics (scaling, SS)
   - high drive current (DG)

2. But there are some trade-offs:
   - a more complex process
   - floating body effects
   - thermal issues