EE-612:
Lecture 25:
SOI Electrostatics

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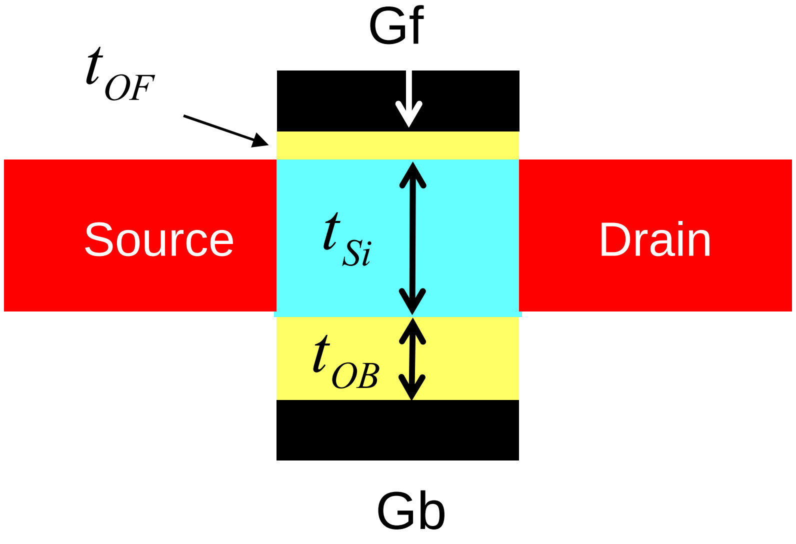
outline

1. Introduction
2. General solution
3. V_{TF} vs. V_{GB}
4. Subthreshold slope
5. Double gate (DG) SOI
6. Recap
7. Discussion
8. Summary

SOI MOSFETs

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



back gate - substrate

Goal: To understand the effect of the top and back gates on MOSFET operation

band diagram: PD SOI

- Maximum depletion width for bulk Si:

$$W_{DM} = \sqrt{\frac{4\varepsilon_{Si}\psi_B}{qN_A}} \qquad \psi_B = \frac{k_B T}{q}\ln\left(\frac{N_A}{n_i}\right)$$

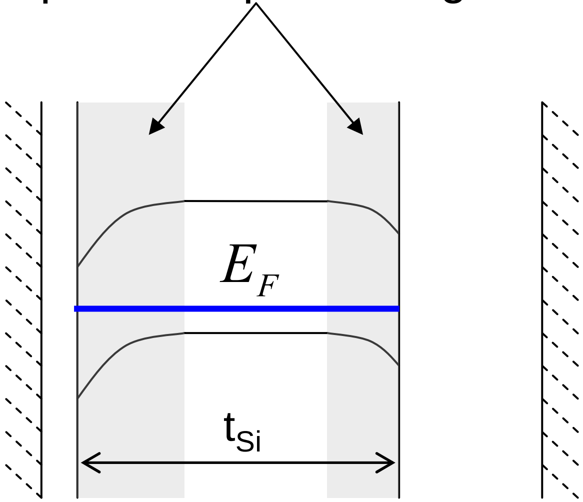
- Partially depleted (PD) SOI:

$$t_{Si} > 2W_{DM}$$

- Front and back gates are decoupled electrostatically: ψ_{SF} independent of ψ_{SB}

- Device operation similar to a bulk MOSFET

separate depletion regions



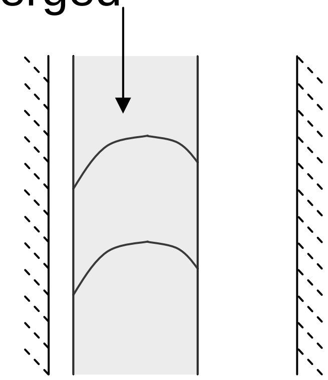
partially depleted SOI film

band diagram: FD SOI

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

- Front and back gates are electrostatically coupled: ψ_{SF} is a function of ψ_{SB}

- Back gate bias plays important role in device operation


Depletion regions merged

fully depleted
SOI film

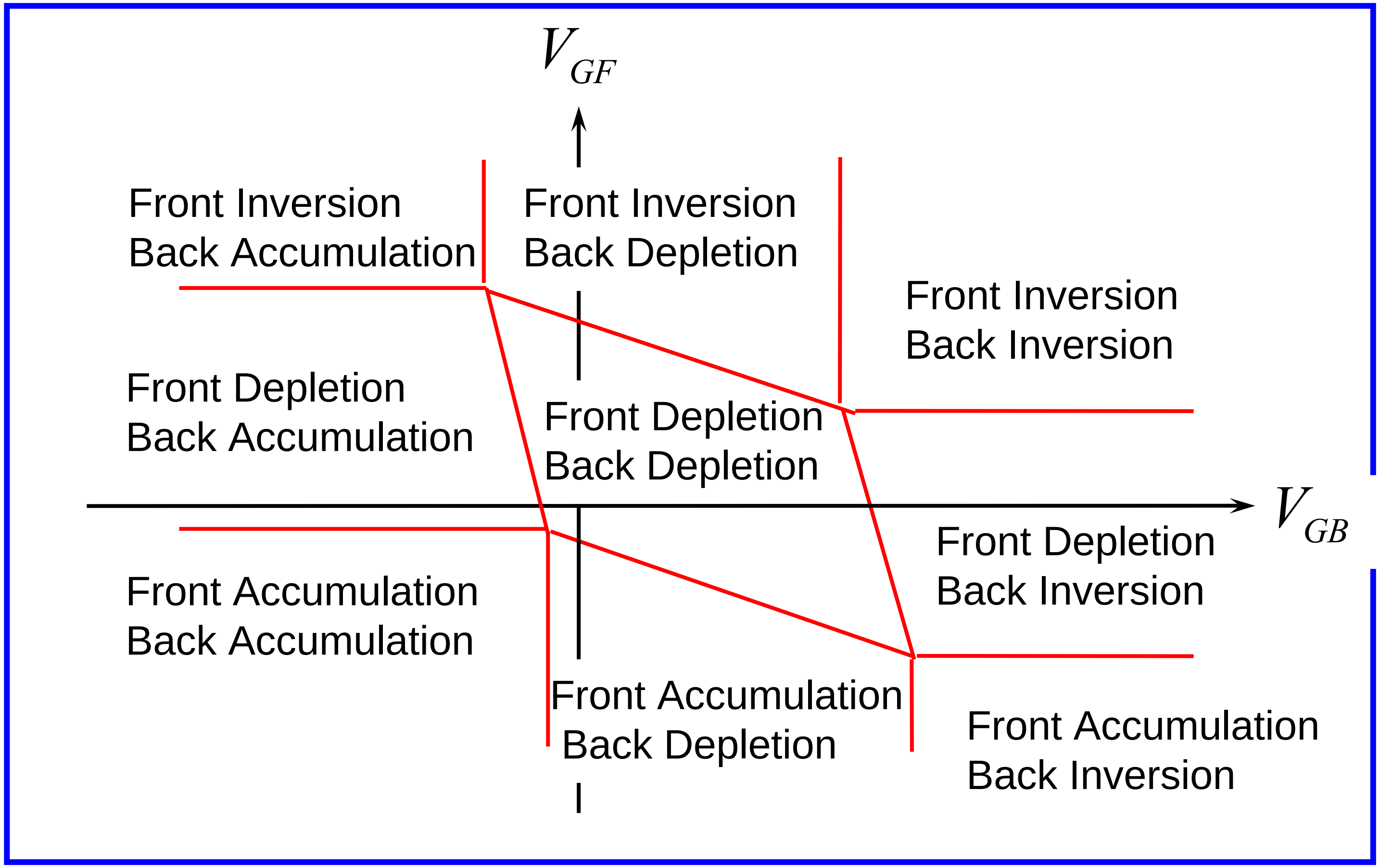
- The rest of this lecture will focus on fully depleted SOI

FD SOI nMOSFET operating regions

Nine operating regions:

Front gate:	**Back gate**:
depleted	depleted
inverted	inverted
accumulated	accumulated

FD SOI nMOSFET operating regions



Front Inversion
Back Accumulation

Front Inversion
Back Depletion

Front Inversion
Back Inversion

Front Depletion
Back Accumulation

Front Depletion
Back Depletion

Front Depletion
Back Inversion

Front Accumulation
Back Accumulation

Front Accumulation
Back Depletion

Front Accumulation
Back Inversion

Key references for SOI 1D Electrostatics

H.-K Lim and J.G. Fossum, “Threshold Voltage of Thin-Film Silicon-on-Insulator (SOI) MOSFETs,” *IEEE Trans. Electron Devices*, **30**, 1244-1251, 1983.

V.P. Trivedi, J.G. Fossum, and W. Zhang, “Threshold Voltage in Nonclassical CMOS Devices with Undoped Ultra-Thin Bodies,” *IEEE Trans. Electron Devices*, 2006**.**

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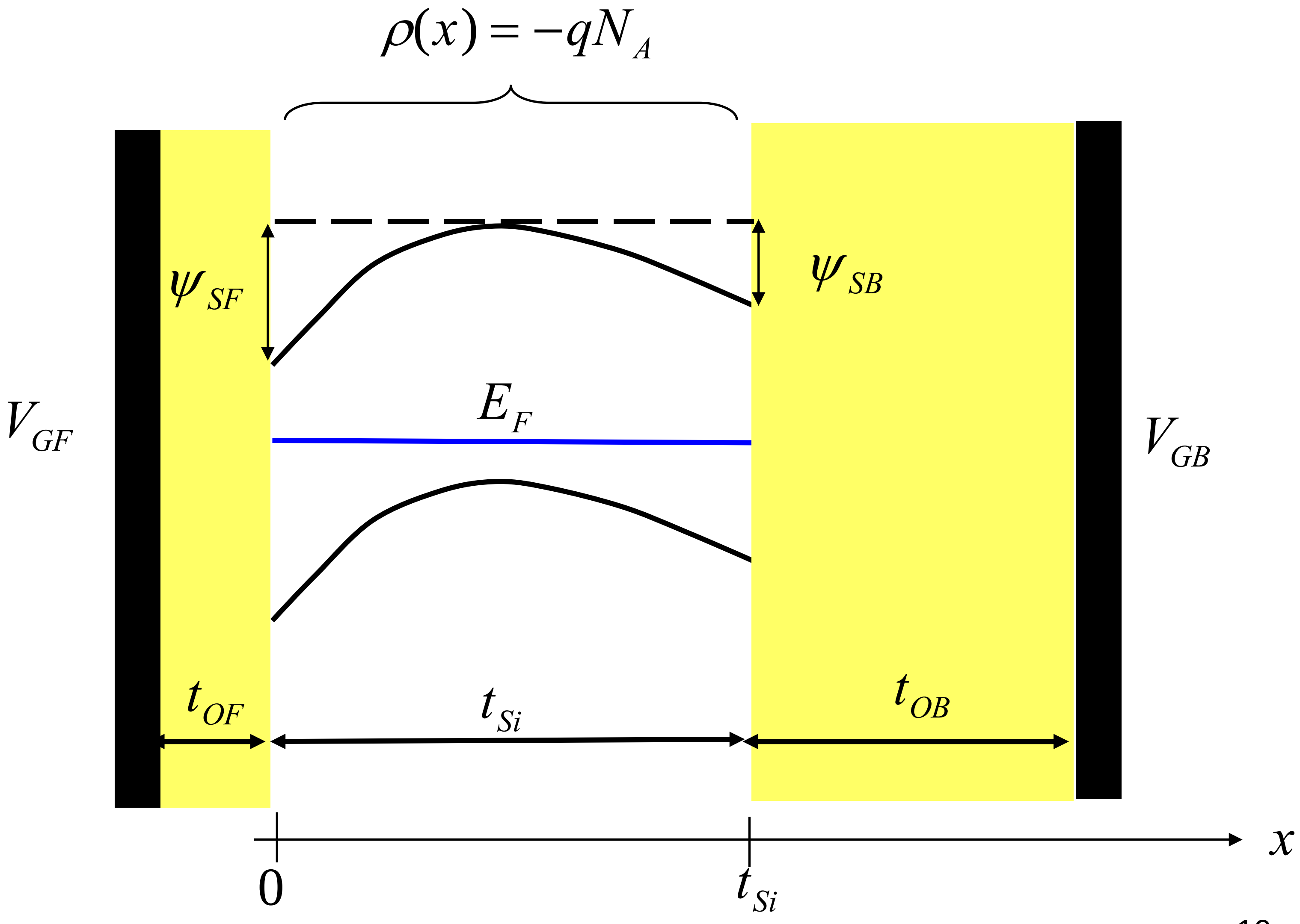
FD SOI band diagram



objectives

for bulk MOSFETS, we know:

$$V_G' = \psi_S - Q_S / C_{ox}$$

for FDSOI MOSFETS, determine:

$$\psi_{SF} = f\left(V_{GF}, V_{GB}\right)$$

$$\psi_{SB} = f\left(V_{GF}, V_{GB}\right)$$

electric field in SOI

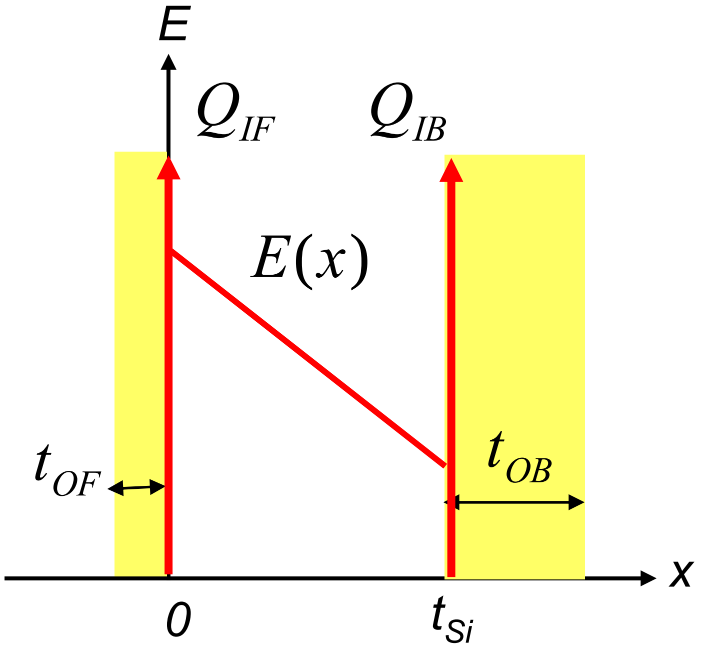
Delta-depletion Approximation: Assume that any mobile charge is at the Si surface in a delta function

Apply Gauss' Law to FD **bulk**:

$$\frac{dE}{dx} = \frac{-qN_A}{\varepsilon_{Si}}$$

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

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



electric field in SOI (ii)

from:

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

we get:

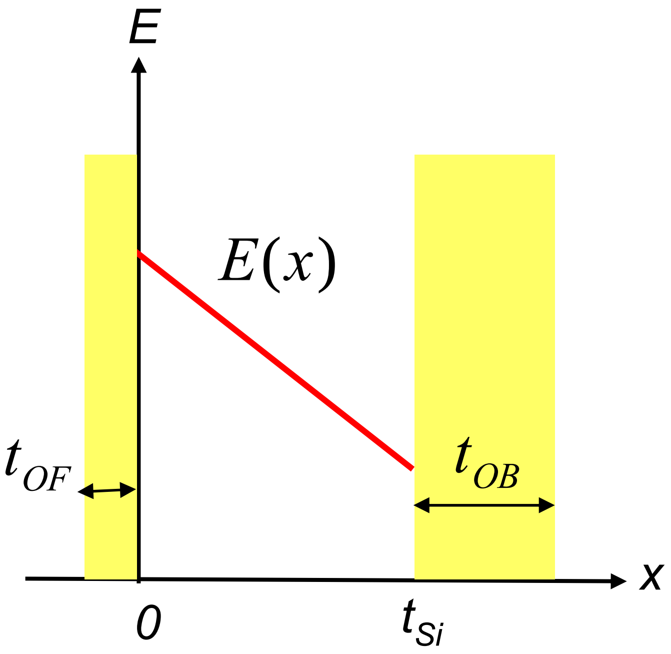
$$E(0^{+}) = E(t_{Si}^{-}) + qN_A t_{Si} / \varepsilon_{Si} \qquad (1)$$

also:

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

from which, we obtain:

$$E(0^{+}) = 2\left(\psi_{SF} - \psi_{SB}\right)/ t_{Si} - E(t_{Si}^{-}) \qquad (2)$$

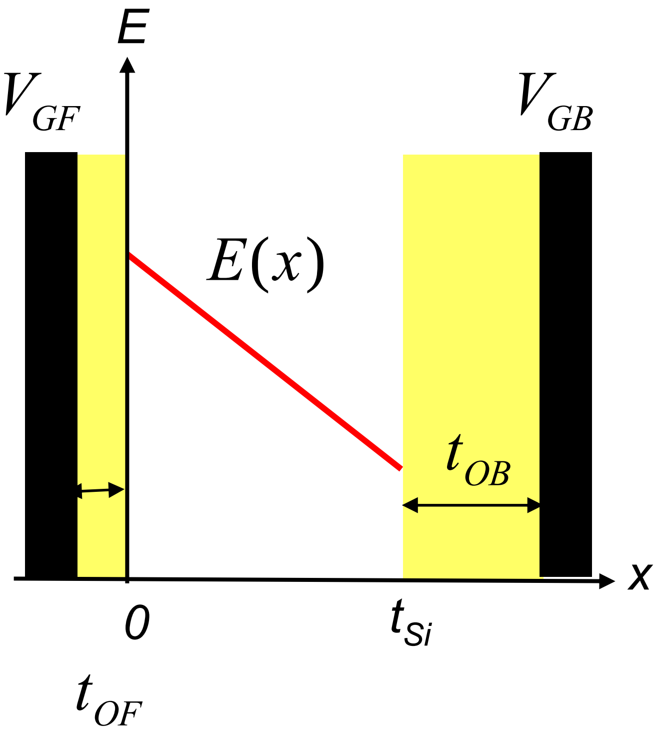


electric field in SOI (iii)

solve (1) and (2) for:

$$E(0^+) = \left(\frac{\psi_{SF} - \psi_{SB}}{t_{Si}}\right) + \frac{qN_A t_{Si}}{2\varepsilon_{Si}} \qquad (3)$$

$$E(t_{Si}^-) = \left(\frac{\psi_{SF} - \psi_{SB}}{t_{Si}}\right) - \frac{qN_A t_{Si}}{2\varepsilon_{Si}} \qquad (4)$$



we can also relate:

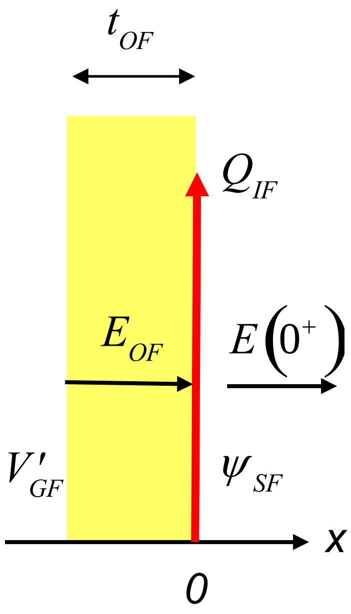
$E(0^+)$ to V_{GF}

$E(t_{Si}^-)$ 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:

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

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

$$E(0^+) = \frac{\varepsilon_{ox}}{\varepsilon_{Si}}\frac{(V'_{GF} - \psi_{SF})}{t_{OF}} + \frac{Q_{IF}}{\varepsilon_{Si}} \qquad (5)$$

effect of front and back gate voltages (ii)

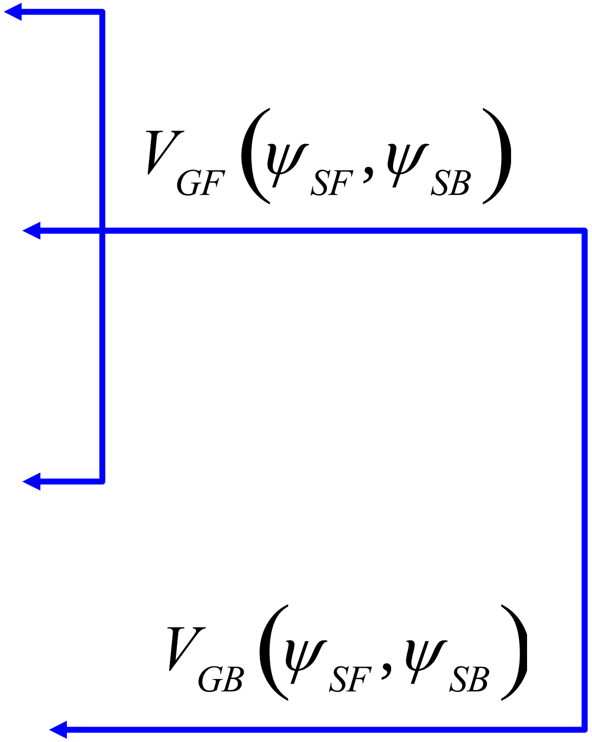
after a similar analysis for the back gate:

$$E(0^+) = \frac{\varepsilon_{ox}}{\varepsilon_{Si}}\frac{(V'_{GF} - \psi_{SF})}{t_{OF}} + \frac{Q_{IF}}{\varepsilon_{Si}} \qquad (5)$$

$$E(t_{Si}^-) = \frac{\varepsilon_{ox}}{\varepsilon_{Si}}\frac{(\psi_{SB} - V'_{GB})}{t_{OB}} - \frac{Q_{IB}}{\varepsilon_{Si}} \qquad (6)$$

$$E(0^+) = \left(\frac{\psi_{SF} - \psi_{SB}}{t_{Si}}\right) + \frac{qN_A t_{Si}}{2\varepsilon_{Si}} \qquad (3)$$

$$E(t_{Si}^-) = \left(\frac{\psi_{SF} - \psi_{SB}}{t_{Si}}\right) - \frac{qN_A t_{Si}}{2\varepsilon_{Si}} \qquad (4)$$



$V_{GF}\left(\psi_{SF}, \psi_{SB}\right)$

$V_{GB}\left(\psi_{SF}, \psi_{SB}\right)$

general solution

$$\boxed{\begin{aligned} V_{GF} &= \phi_{msf} + \psi_{SF} - \frac{Q_{IF} + Q_B/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times \left(\psi_{SF} - \psi_{SB}\right) \qquad (7) \\ V_{GB} &= \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_B/2}{C_{OB}} + \underbrace{\frac{C_{Si}}{C_{OB}} \times \left(\psi_{SB} - \psi_{SF}\right)} \qquad (8) \end{aligned}}$$

$$C_{Si} \equiv \frac{\varepsilon_{Si}}{t_{Si}} \qquad Q_B \equiv -qN_A t_{Si}$$

extra volt drop across oxide due to different surface potentials

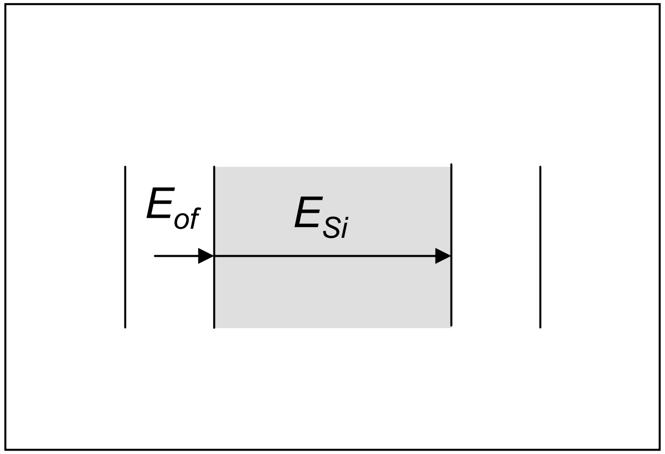
compare to: $V_G' = \psi_S - Q_S/C_{ox}$

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.

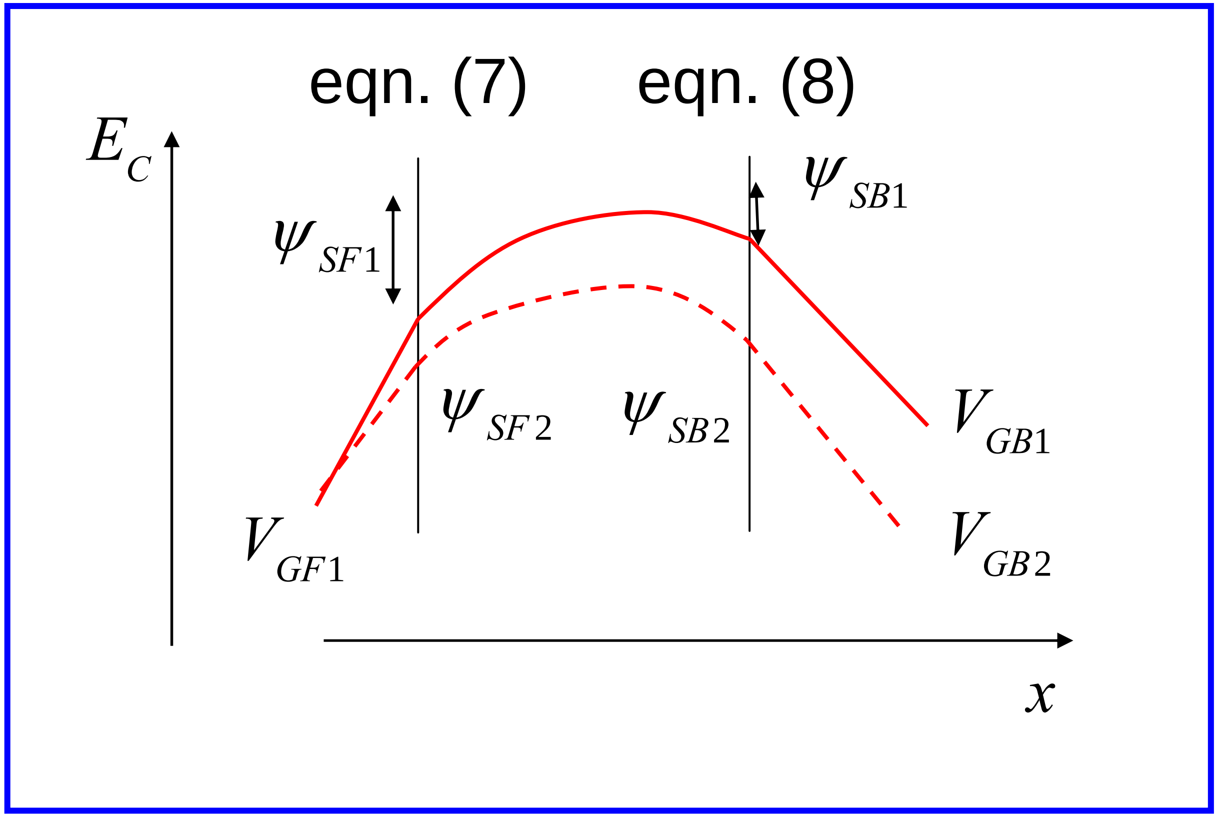


$$E_{Si} = (\psi_{SF} - \psi_{SB}) / t_{Si}$$

$$\varepsilon_{of} E_{OF} = \varepsilon_{Si} E_{Si} \;? \qquad \varepsilon_{of} E_{OF} = \varepsilon_{Si} (\psi_{SF} - \psi_{SB}) / t_{Si}$$

$$\Delta V_{OX} = t_{OF} E_{OF} = \frac{C_{Si}}{C_{OF}} (\psi_{SF} - \psi_{SB})$$

front and back coupled electrostatics



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

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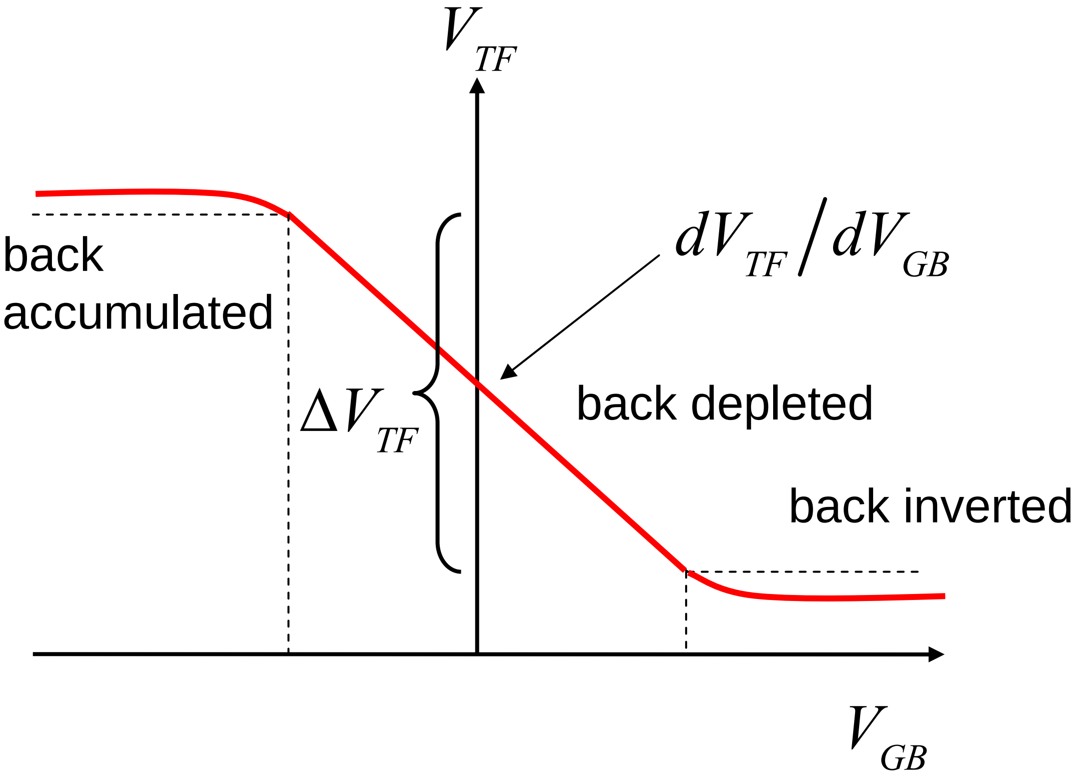
V_{TF} vs. V_{GB}


V_{TF}
back accumulated
dV_{TF}/dV_{GB}
ΔV_{TF}
back depleted
back inverted
V_{GB}

threshold voltage (V_{TF})

Raising V_{GB} increases ψ_{SF}, so the front gate threshold voltage V_{TF} should **decrease**.

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

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

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

V_{TF} is a function of ψ_{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:

$$\psi_{SB} = 2\psi_B$$

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

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

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

Back accumulation:

$$\psi_{SB} \approx 0$$

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

Net V_{TF} shift:

$$\Delta V_{TF} = V_{TF}\left(\text{back acc}\right) - V_{TF}\left(\text{back inv}\right)$$

$$= \frac{C_{Si}}{C_{OF}}\left(2\psi_B\right) = \frac{\varepsilon_{Si}}{\varepsilon_{ox}}\frac{t_{OF}}{t_{Si}}\left(2\psi_B\right)$$

3) back depleted

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

$$V_{TF} = \phi_{msf} + 2\psi_{SB} - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} \times \left(2\psi_B - \psi_{SB}\right) \qquad (9)$$

We need to relate ψ_{SB} to V_{GB} …

3) back depleted (ii)

$$V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_B/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times \left(\psi_{SB} - \psi_{SF}\right) \qquad (8)$$

at front threshold:

$$V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_B}{2C_{OB}} + \frac{C_{Si}}{C_{OB}} \times (\psi_{SB} - 2\psi_B) \qquad (10)$$

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

$$V_{GB}\left(\mathrm{acc}\right) = \phi_{msb} - \frac{Q_B}{2C_{OB}} - \frac{C_{Si}}{C_{OB}} 2\psi_B \qquad (11)$$

3) back depleted (iii)

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

From (10) and (11):

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

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

3) back depleted (iv)

recap:

$$V_{TF} = \phi_{msf} + 2\psi_{SB} - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}} \times \left(2\psi_B - \psi_{SB}\right) \qquad (9)$$

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

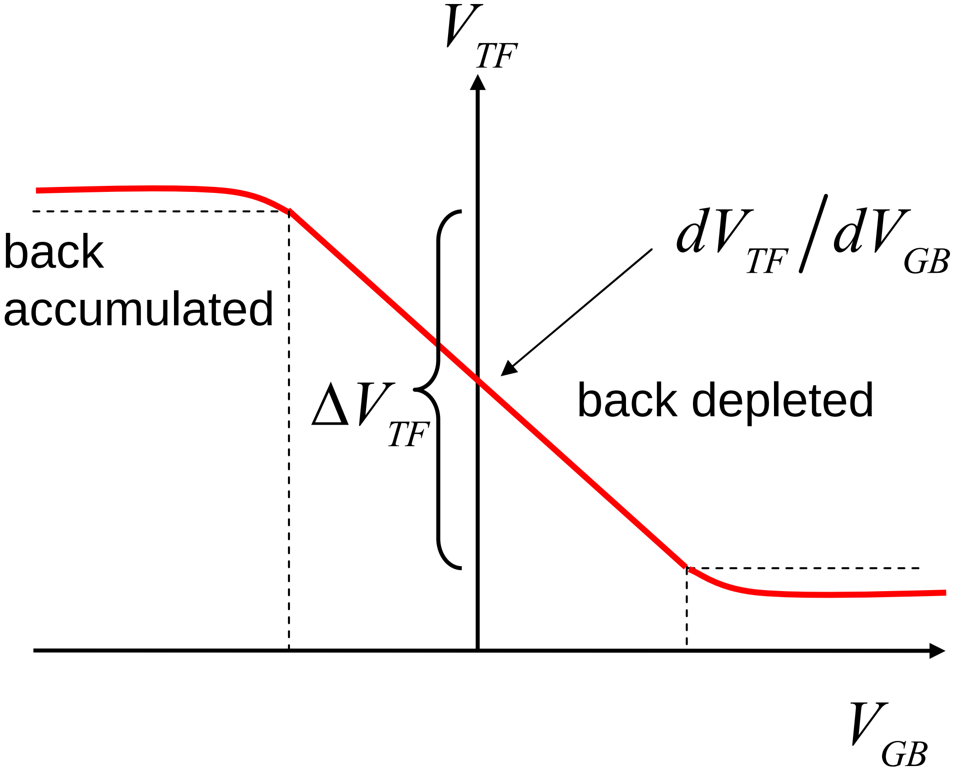
$$V_{TF} = \phi_{msf} + 2\psi_B - \frac{Q_B}{2C_{OF}} + \frac{C_{Si}}{C_{OF}}2\psi_B - \frac{C_{Si}C_{OB}}{C_{OF}\left(C_{OB} + C_{Si}\right)}\left[V_{GB} - V_{GB}(\text{acc})\right]$$

$$\frac{dV_{TF}}{dV_{GB}} = -\frac{C_{Si}C_{OB}}{C_{OF}\left(C_{OB} + C_{Si}\right)} = -\left(\frac{t_{OF}}{t_{OB}}\right)\frac{1}{\left(1 + C_{OB}/C_{Si}\right)}$$

V_T summary

$$\Delta V_{TF} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \frac{t_{OF}}{t_{Si}} \left(2\psi_B\right)$$

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



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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:

$$\frac{\partial \log I_D}{\partial V_{GS}} = \frac{1}{2.3(k_BT/q)} \frac{\partial \psi_S}{\partial V_{GS}} = S^{-1}$$

subthreshold swing:

$$S = 2.3(k_BT/q)\left(\frac{\partial \psi_S}{\partial V_{GS}}\right)^{-1} = 2.3m(k_BT/q)$$

$$m = \left(\partial \psi_S / \partial V_{GS}\right)^{-1}$$

subthreshold swing (SOI MOSFET)

subthreshold current: $I_D \sim e^{q\psi_{SF}/k_B T}$

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': $$m = \left(\partial \psi_{SF} / \partial V_{GF}\right)^{-1}$$

SOI subthreshold swing derivation

return to general solution:

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

$$V_{GB} = \phi_{msb} + \psi_{SB} - \frac{\cancel{Q_{IB}} + Q_B/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times \left(\psi_{SB} - \psi_{SF}\right) \qquad (8)$$

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

assume Q_B is constant (FD)

SOI subthreshold swing derivation (ii)

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

(☯)

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

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

$$\frac{\partial \psi_{SB}}{\partial \psi_{SF}} = \frac{C_{Si}/C_{OB}}{1 + C_{Si}/C_{OB}} = \frac{C_{Si}}{C_{Si} + C_{OB}}$$

insert in (☯)

SOI subthreshold swing derivation (iii)

$$\frac{dV_{GF}}{d\psi_{SF}} = m = 1 + \frac{C_{Si}C_{OB}}{C_{OF}\left(C_{Si} + C_{OB}\right)}$$

$$\left(m = 1 + \frac{C_D}{C_{ox}} \quad \text{bulk} \right)$$

$$C_D\left(\text{eff}\right) = \frac{C_{Si}C_{OB}}{\left(C_{Si} + C_{OB}\right)}$$

$$m = 1 + \frac{C_D\left(\text{eff}\right)}{C_{OF}}$$

if the bottom oxide is thick, $C_{OB} << C_{Si}, C_{OF}$ $\boxed{m \to 1}$

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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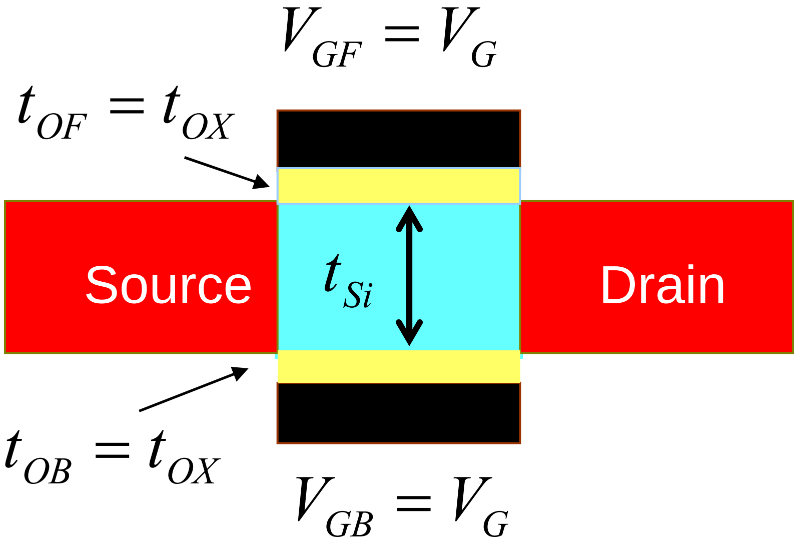
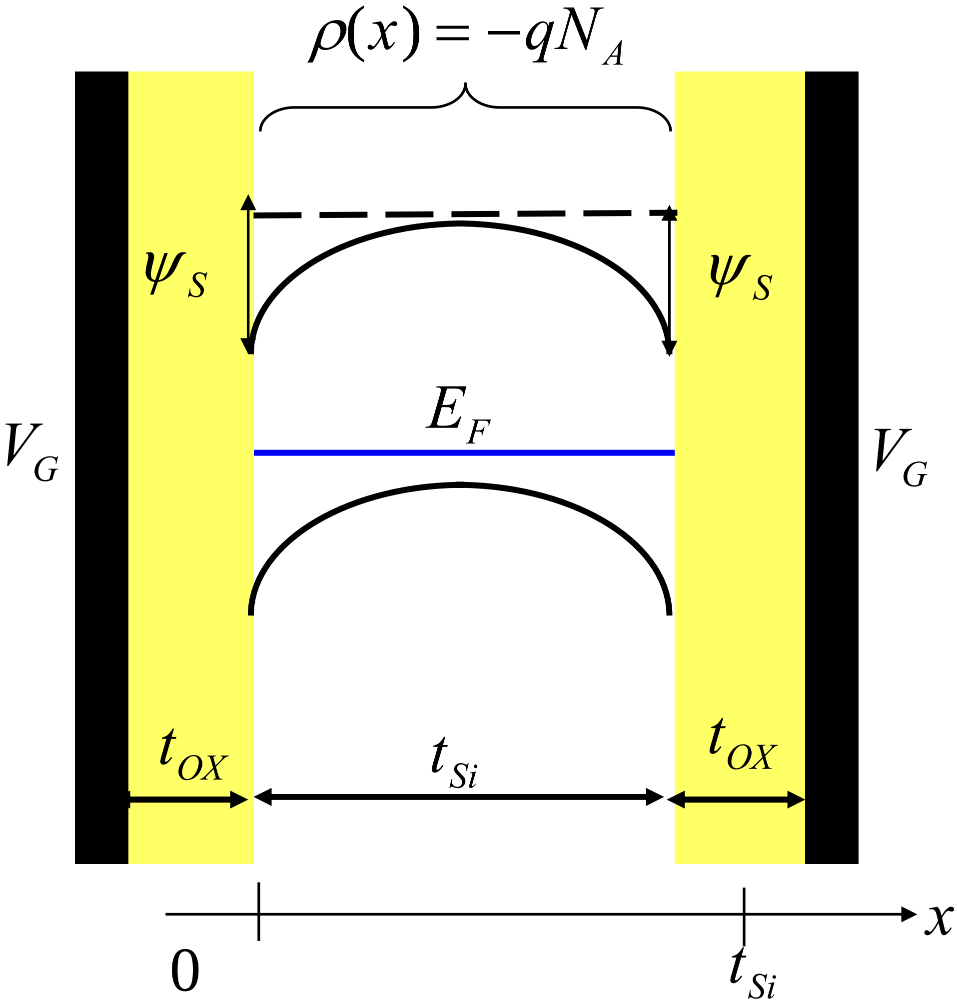
symmetrical double gate





DG electrostatics

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

$$V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_B/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times \left(\psi_{SB} - \psi_{SF}\right) \qquad (8)$$

for double gate SOI: $V_{GF} = V_{GB} \quad \psi_{SF} = \psi_{SB}$

$C_{OF} = C_{OB} = C_{ox} \quad Q_{IF} = Q_{IB} = Q_I/2$

then either (7) or (8) gives:

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

DG subthreshold swing

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

$$Q_I \approx 0$$

$$\frac{dV_G}{d\psi_S} = m = 1$$

(fully depleted, Q_B independent of ψ_S)

ideal subthreshold characteristics

DG above threshold

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

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

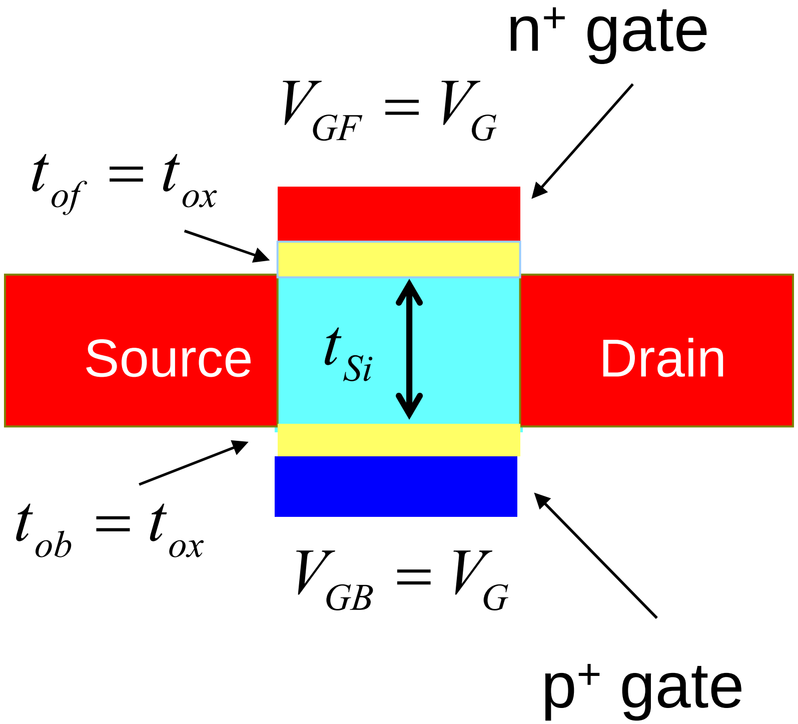
for $V_G > V_T$:

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

$$\boxed{Q_I = -2C_{ox}\left(V_G - V_T\right)}$$

twice as much charge ⇒ 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

$$Q_I = -2C_{ox}\left(V_G - V_T\right)$$

be modified?

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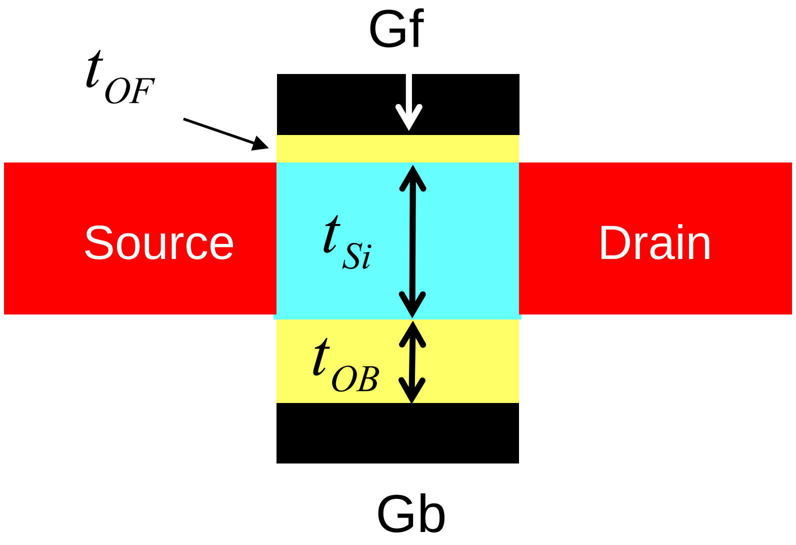
review: SOI MOSFET general solution



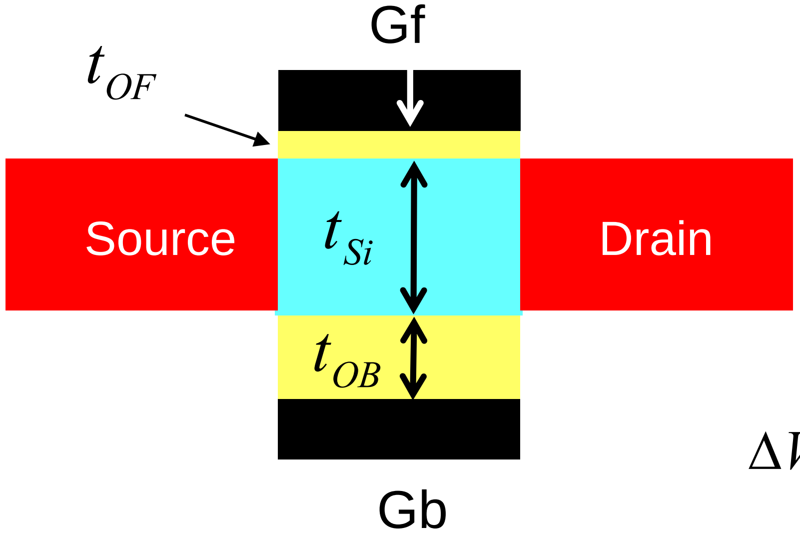
$$C_{Si} \equiv \frac{\varepsilon_{Si}}{t_{Si}} \qquad Q_B \equiv -qN_A t_{Si}$$

back gate - substrate

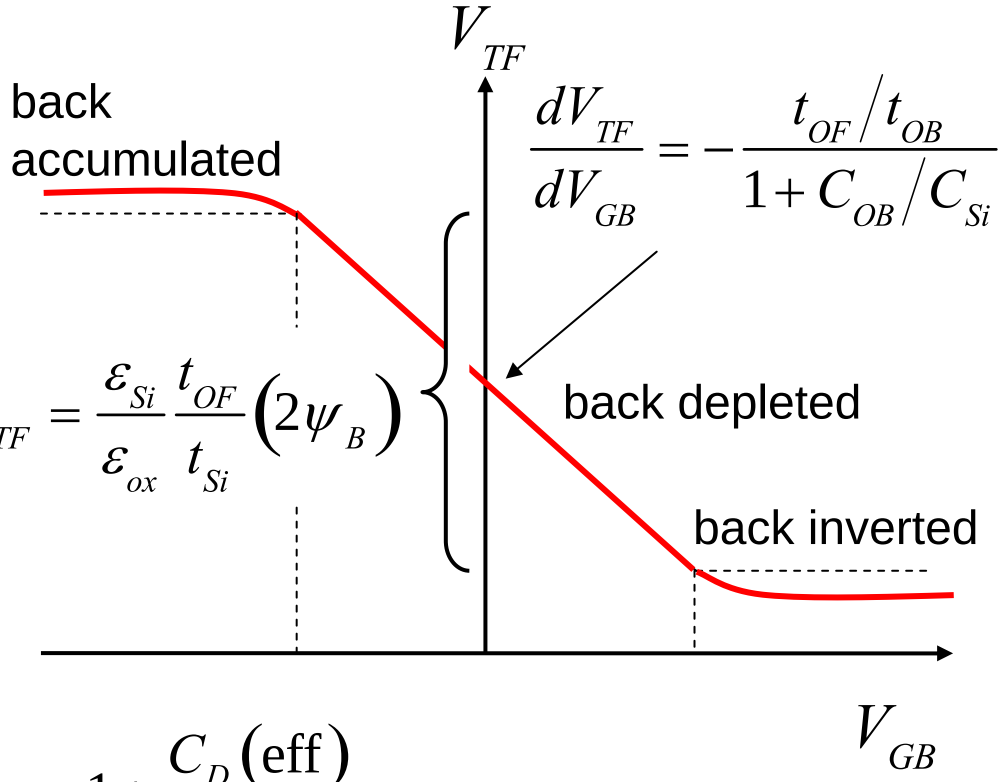
$$V_{GF} = \phi_{msf} + \psi_{SF} - \frac{Q_{IF} + Q_B/2}{C_{OF}} + \frac{C_{Si}}{C_{OF}} \times \left(\psi_{SF} - \psi_{SB}\right) \qquad (7)$$

$$V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_B/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times \left(\psi_{SB} - \psi_{SF}\right) \qquad (8)$$

review: SOI MOSFETs key results



back gate - substrate



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

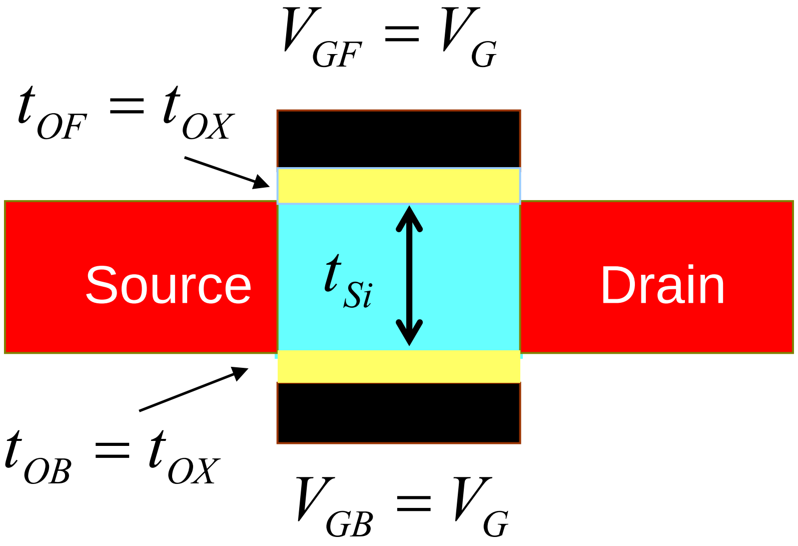
$$\Delta V_{TF} = \frac{\varepsilon_{Si}}{\varepsilon_{ox}} \frac{t_{OF}}{t_{Si}} \left(2\psi_B\right)$$

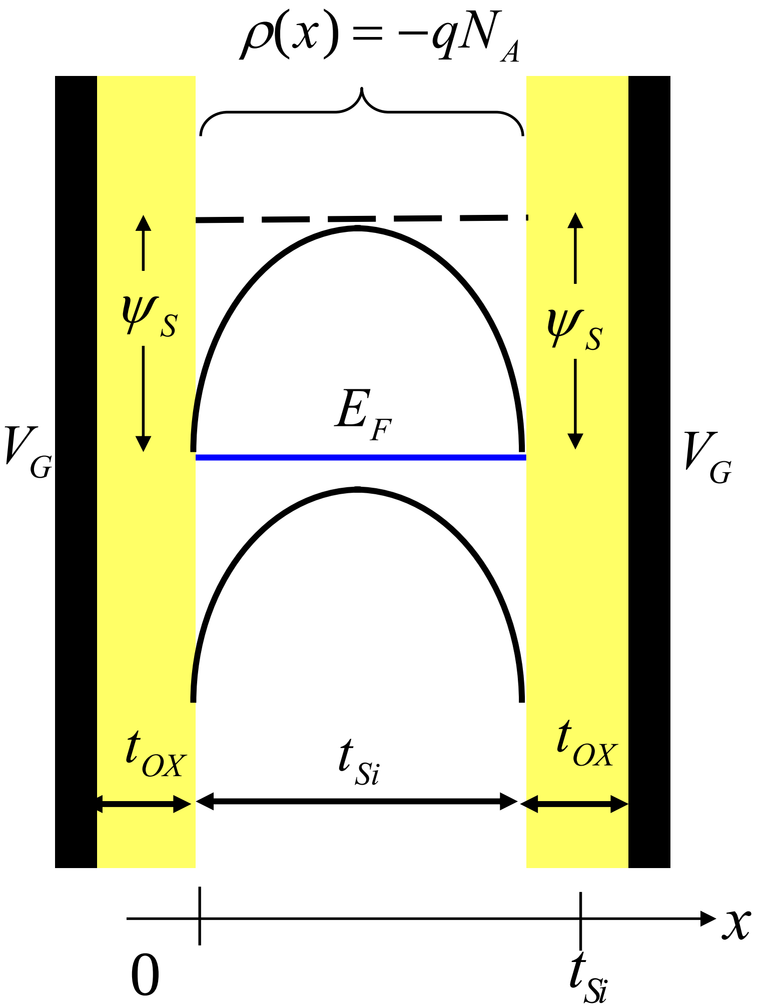
$$S = 2.3m\left(k_B T/q\right)$$

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

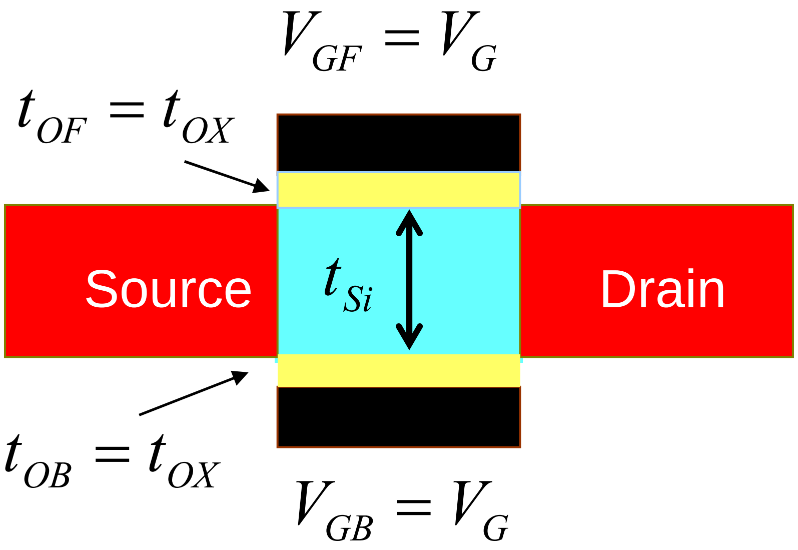
$$C_D(\text{eff}) = \frac{C_{Si}C_{OB}}{\left(C_{Si} + C_{OB}\right)}$$

symmetrical double gate (SDG)





symmetrical double gate: key results



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

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

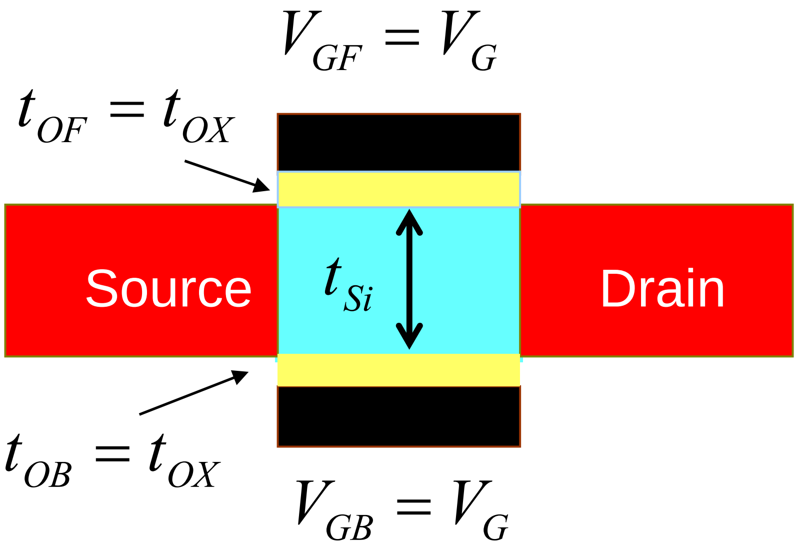
$$Q_I = -2C_{ox}\left(V_G - V_T\right)$$

$$S = 2.3\left(k_B T/q\right) \quad \text{(ideal)}$$

ultra-thin body (UTB) DG MOSFET

If T_{Si} is very thin, then the device is called an ultra-thin-body SOI MOSFET

why UTB DG MOSFETs?



- good 2D electrostatics

$$\Lambda_{DG\,SOI} \approx \sqrt{\varepsilon_{Si} t_{Si} t_{OX} / 2\varepsilon_{OX}} = \Lambda_{BULK} / \sqrt{2}$$

- 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

outline

1. Introduction
2. General solution
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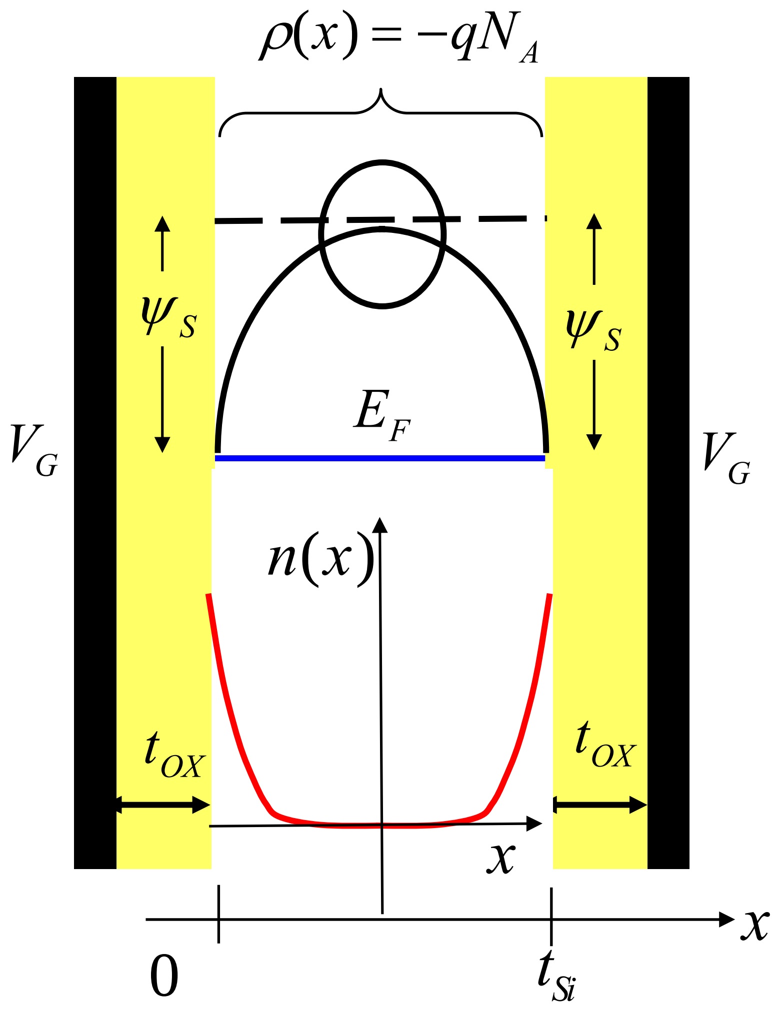
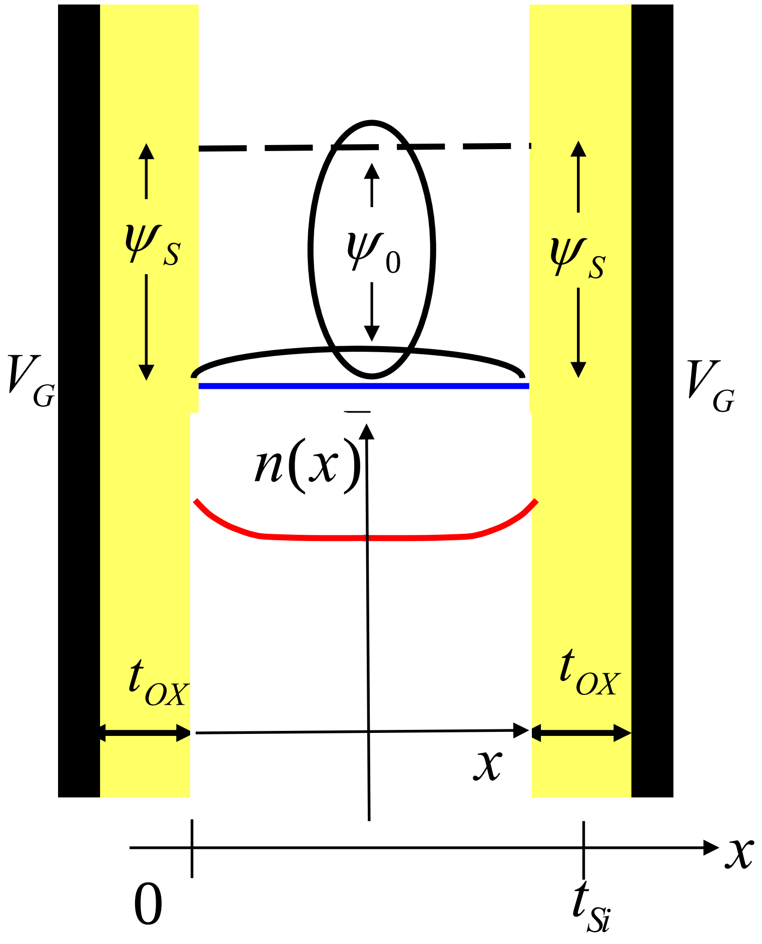
thick vs. thin body





definition of UTB

1) fully depleted

$$t_{Si} < W_{DM} \qquad \frac{dE}{dx} = \frac{-qN_A}{\varepsilon_{Si}}$$

2) little band bending across the body

$$\Delta\psi < k_B T / q$$

(requires a numerical solution in general)

numerical (Schred) simulation

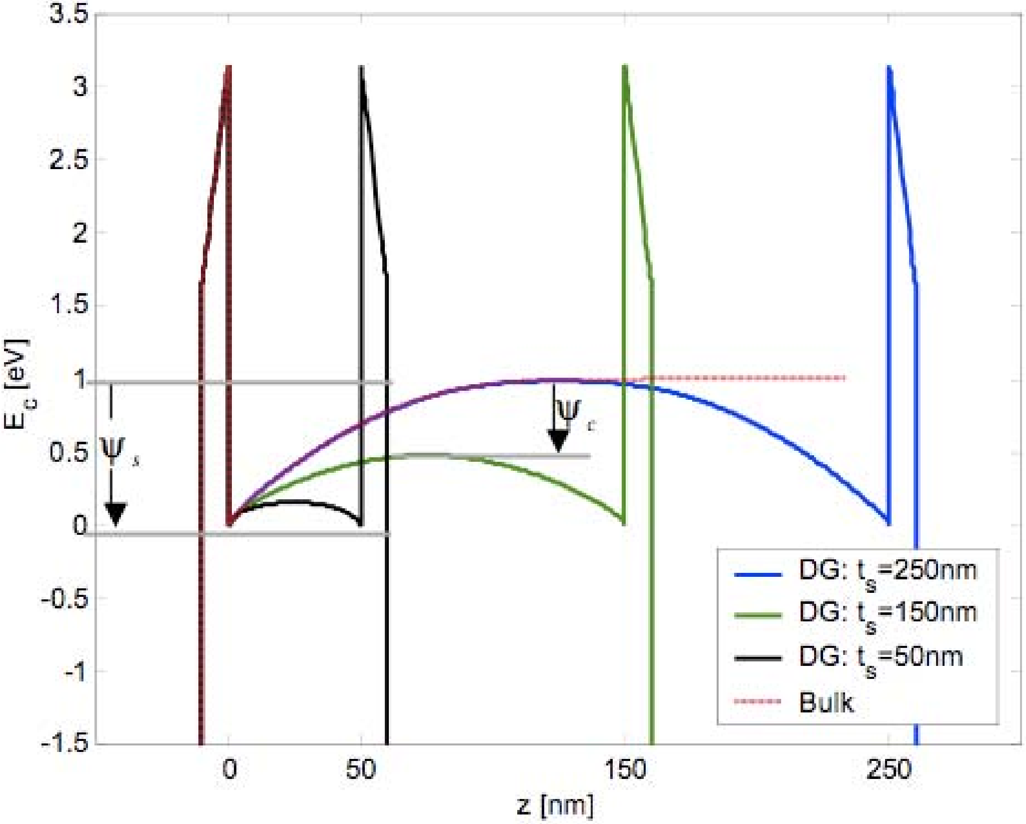


Fig. 14. Band-diagram of DGMOS capacitors of different body thickness at same V_G. Also shown the band diagram of bulk MOSC (red-dashed line). t_{ox} = 10nm, $N_A = 1.E17\ cm^{-3}$, $V_G = 1.5$v. Classical mode calculation.

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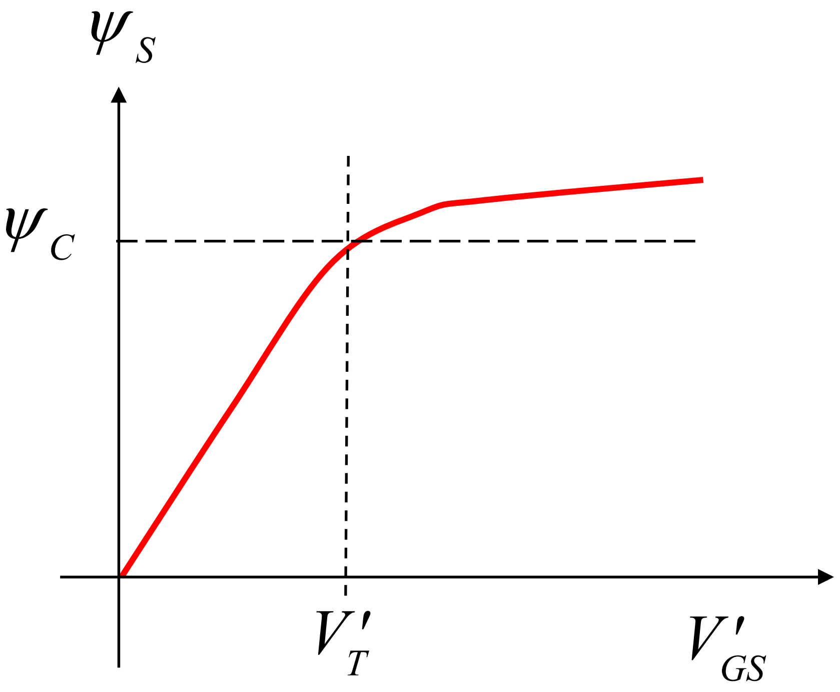
threshold voltage for an undoped body

$V_G = \phi_{ms} + \psi_S$ how to specify ψ_S? $\psi_S \neq 2\psi_B$



$\psi_S < \psi_C$

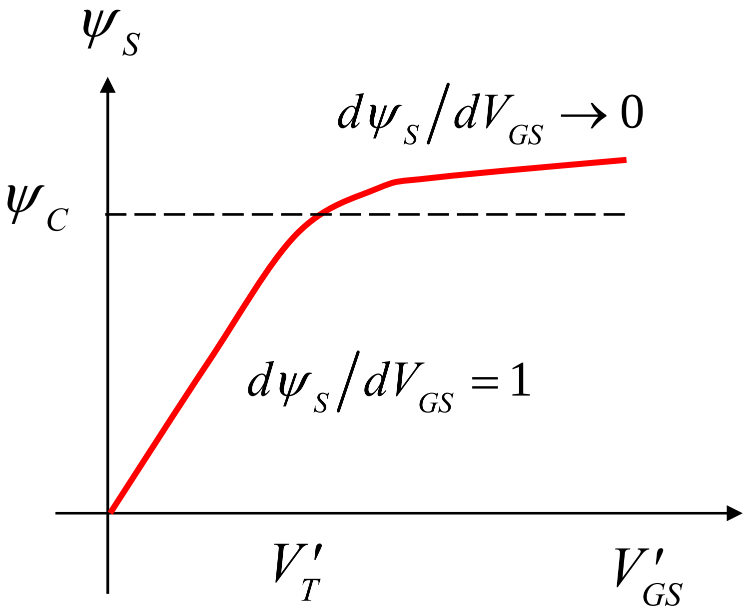
$$\frac{d\psi_S}{dV_{GS}} \approx 1$$

$\psi_S > \psi_C$

$$\frac{d\psi_S}{dV_{GS}} \to 0$$

threshold voltage (ii)

how to specify ψ_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:

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

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

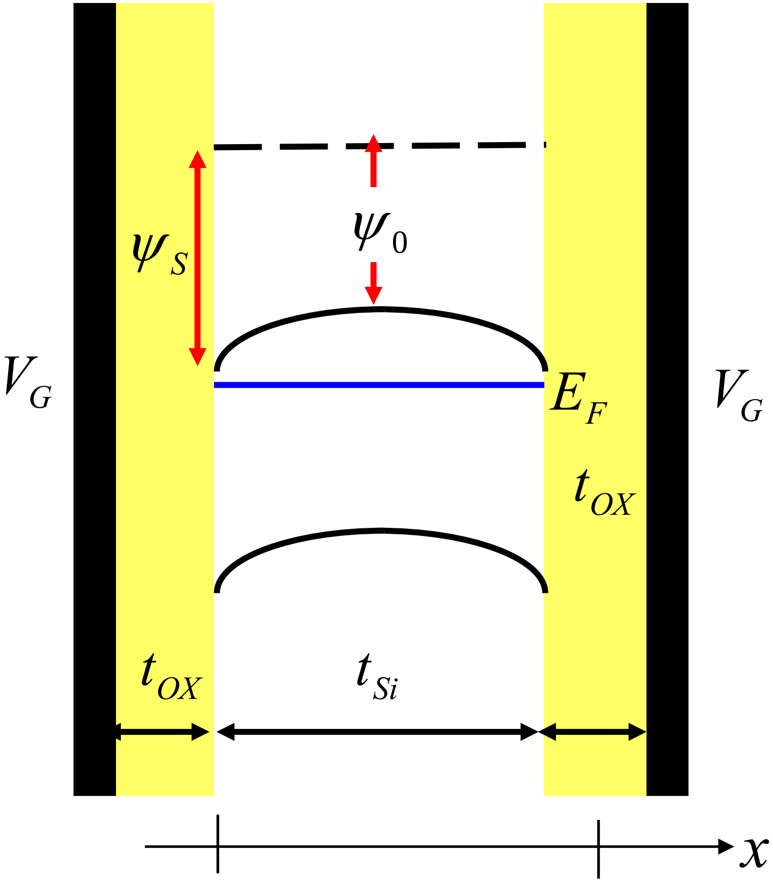
threshold voltage (iii)

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

$$V_T = \phi_{ms} + \psi_C$$

$$Q_I = -2C_{ox}\left(V_G - V_T\right)$$

UTB electrostatics above threshold



1) below threshold:

-bands are flat

2) weak / moderate inversion:

-bands are nearly flat

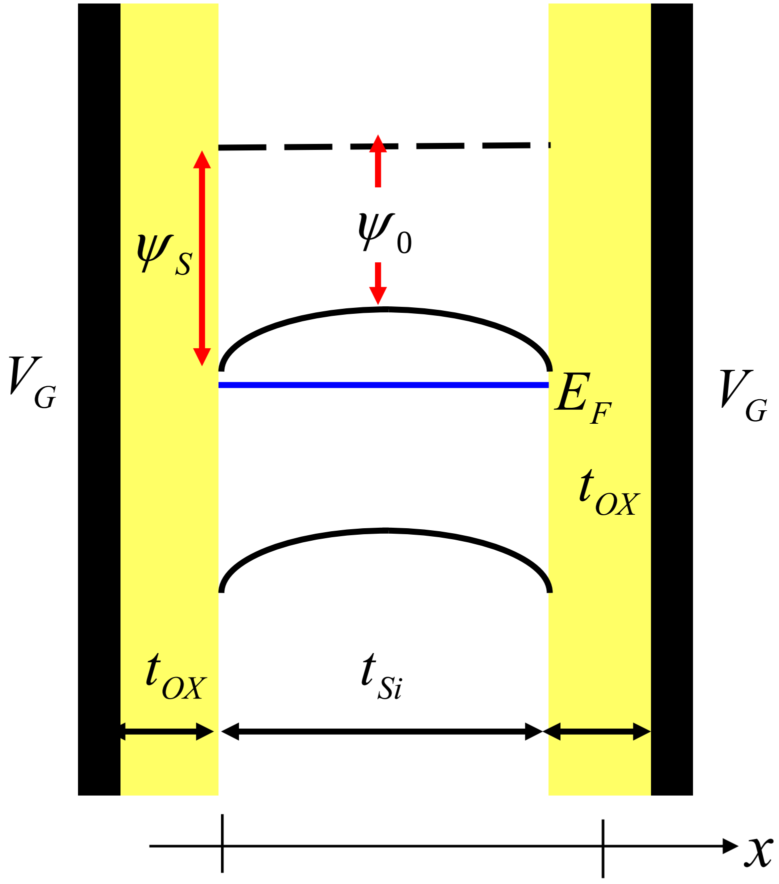
-volume inversion

3) strong inversion:

-strong band bending may develop

-volume inversion may be lost

‘exact’ UTB electrostatics



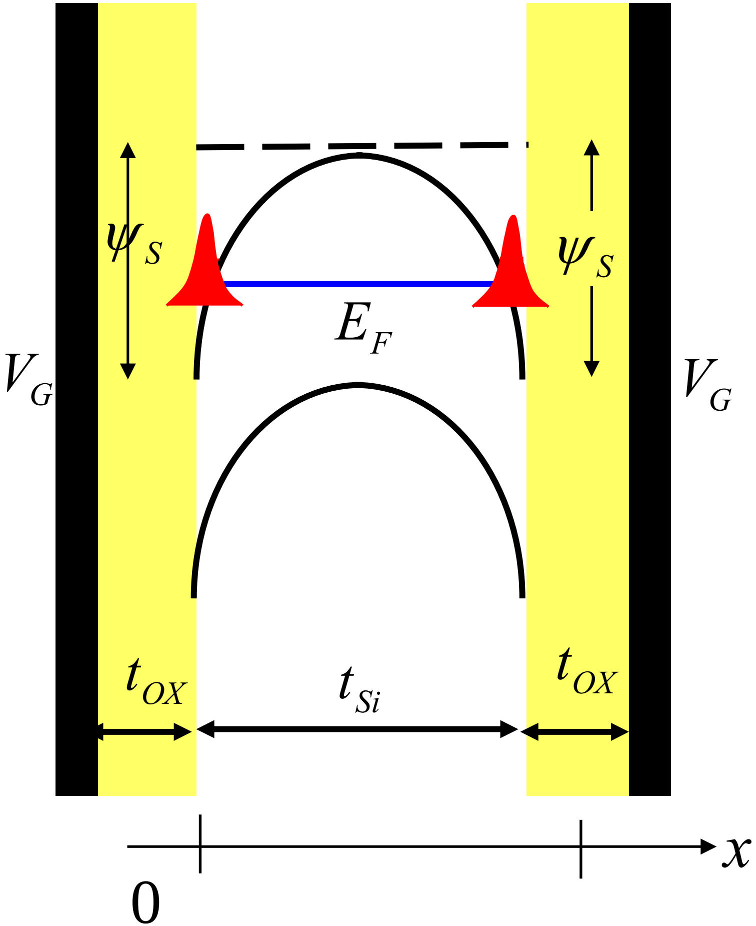
$$\frac{d^2\psi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_{Si}} = \frac{qn_i}{\varepsilon_{Si}} e^{q\psi(x)/k_BT}$$

can solve exactly, see:

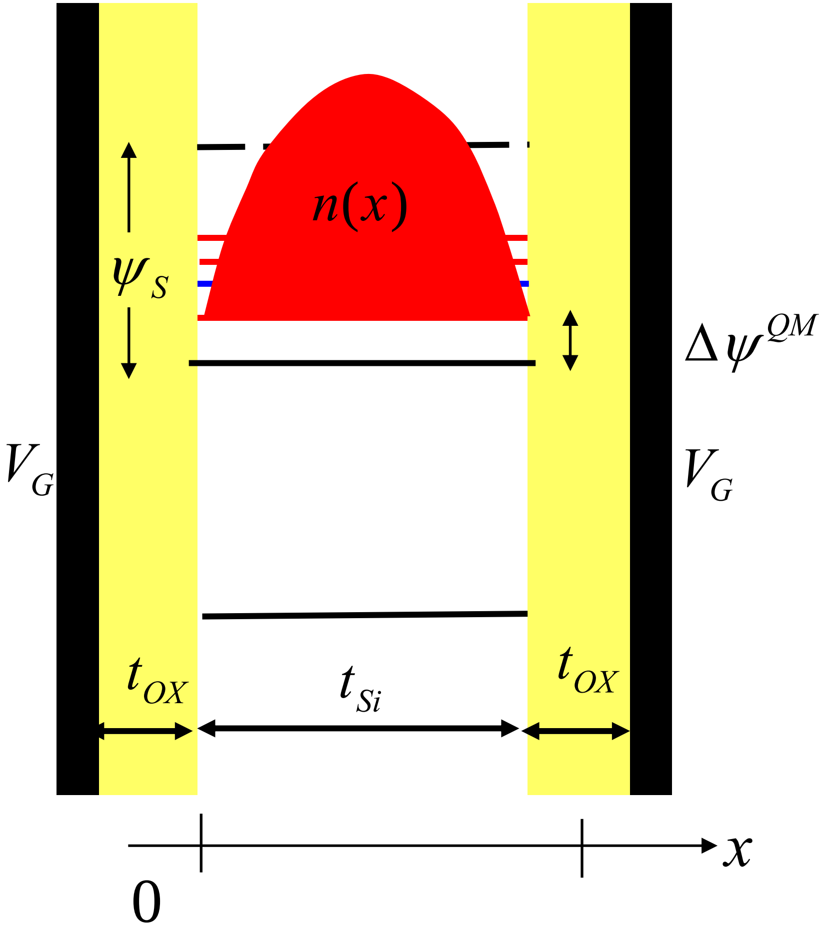
Y. Taur, “Analytic Solutions of Charge and Capacitance in Symmetric and Asymmetric Double-Gate MOSFETs, *IEEE Trans. Electron Dev*., **48**, 2861-2869, 2001

quantum confinement

FD (thick)



FD (UTB)



numerical (Schred) simulation

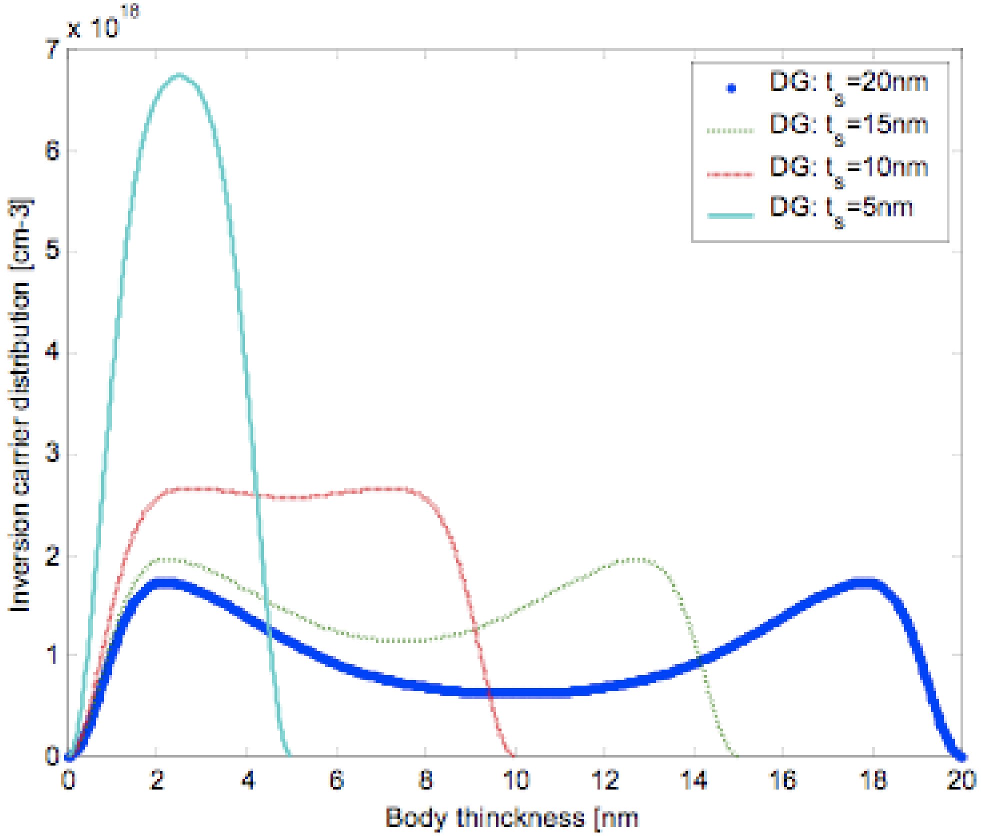


Fig. 20. Inversion carrier distribution inside the DGMOSC, for various body thickness, with t_{ox}=10nm, N_a=1.E17cm-3, V_G = 0.5v.

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numerical (Schred) simulation

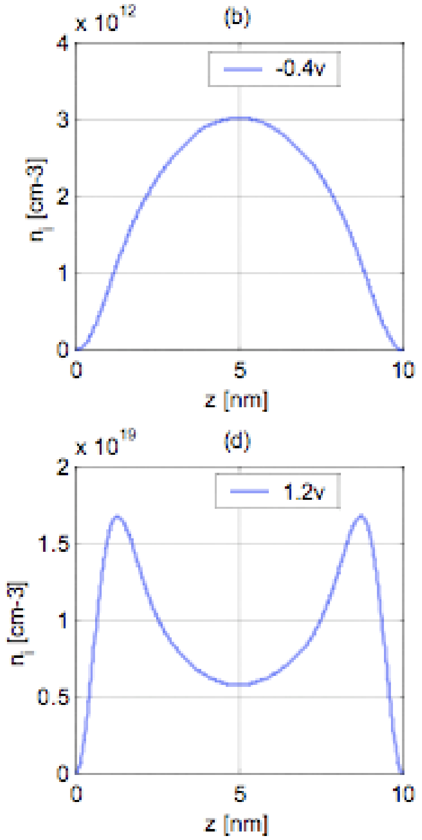

Fig. 22. Quantum calculation, t_{ox}=5nm, t_{si}=10nm, N_A=1.e17cm-3. (a) variation of centroid with gate voltage, rest three are electron distribution inside silicon film at gate voltage: (b) –0.4v, (c) 0.1v, (d) 1.2v.

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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 ΔV_T because of body thickness variations

5) lower mobility because of increased surface roughness scattering

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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