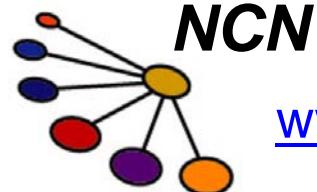


EE-612:

Lecture 30:

UTB SOI Electrostatics

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West Lafayette, IN USA
Fall 2006



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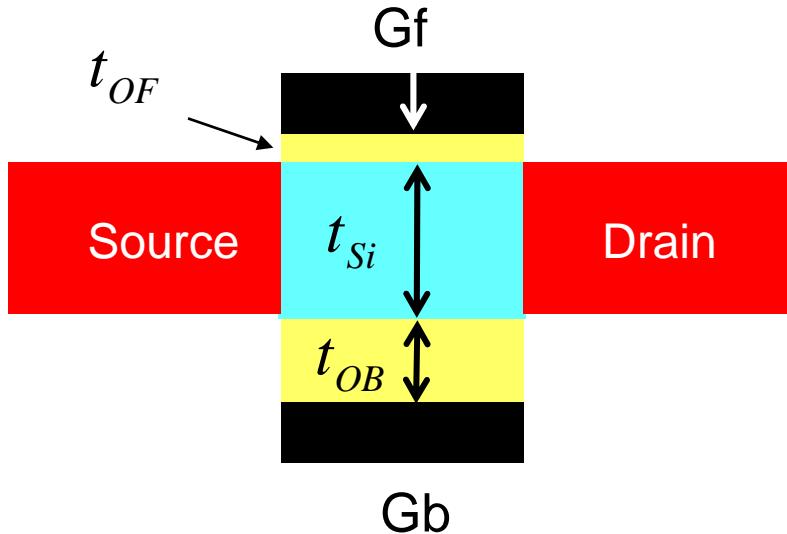
Lundstrom EE-612 F06

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outline

1. Review
2. Ultra-thin-bodies
3. Subthreshold
4. Threshold voltage
5. ‘Exact’ solution
6. Quantum effects

review: SOI MOSFET general solution

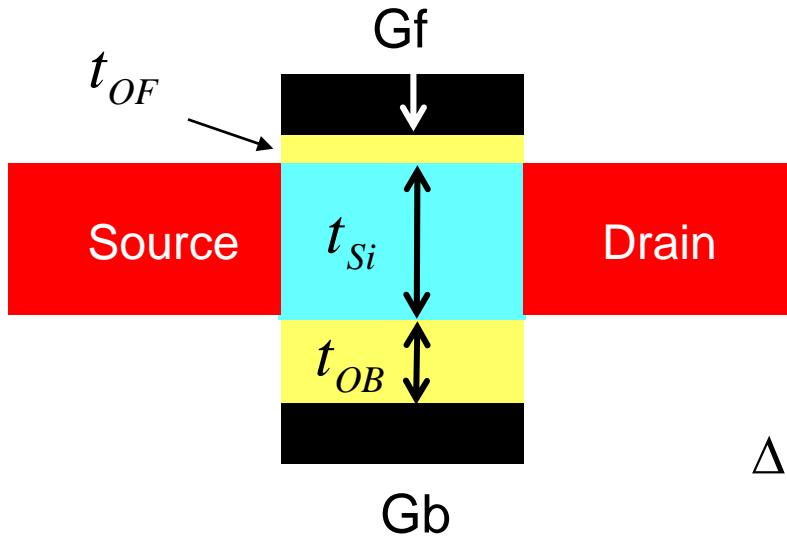


back gate - substrate

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

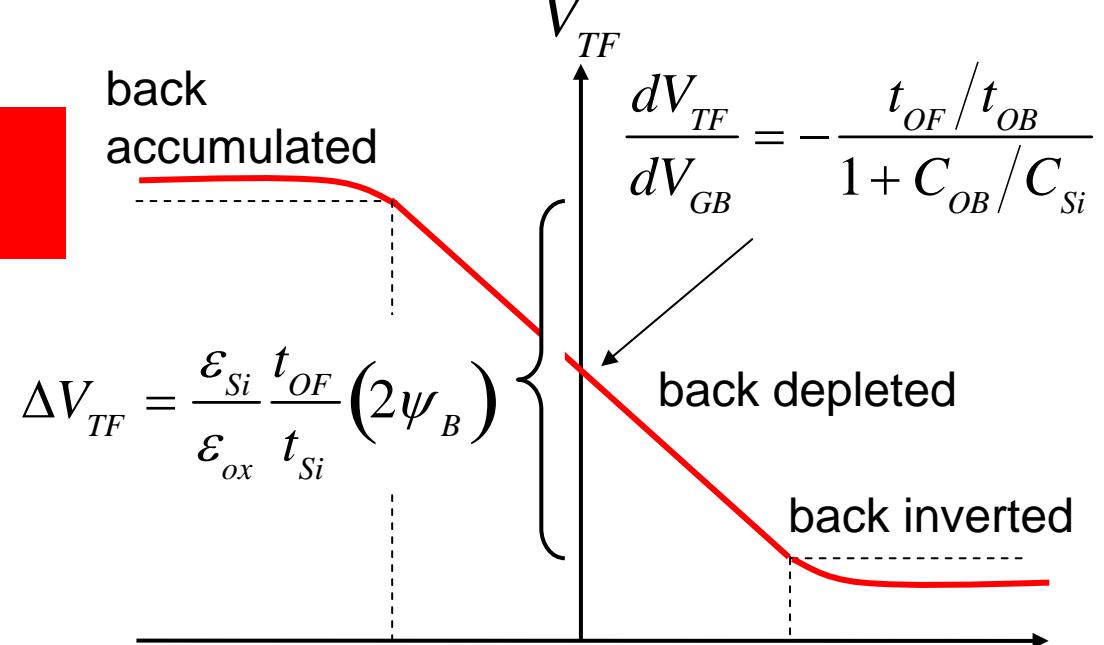
$$V_{GB} = \phi_{msb} + \psi_{SB} - \frac{Q_{IB} + Q_B/2}{C_{OB}} + \frac{C_{Si}}{C_{OB}} \times (\psi_{SB} - \psi_{SF}) \quad (8)$$

review: SOI MOSFETs key results



back gate - substrate

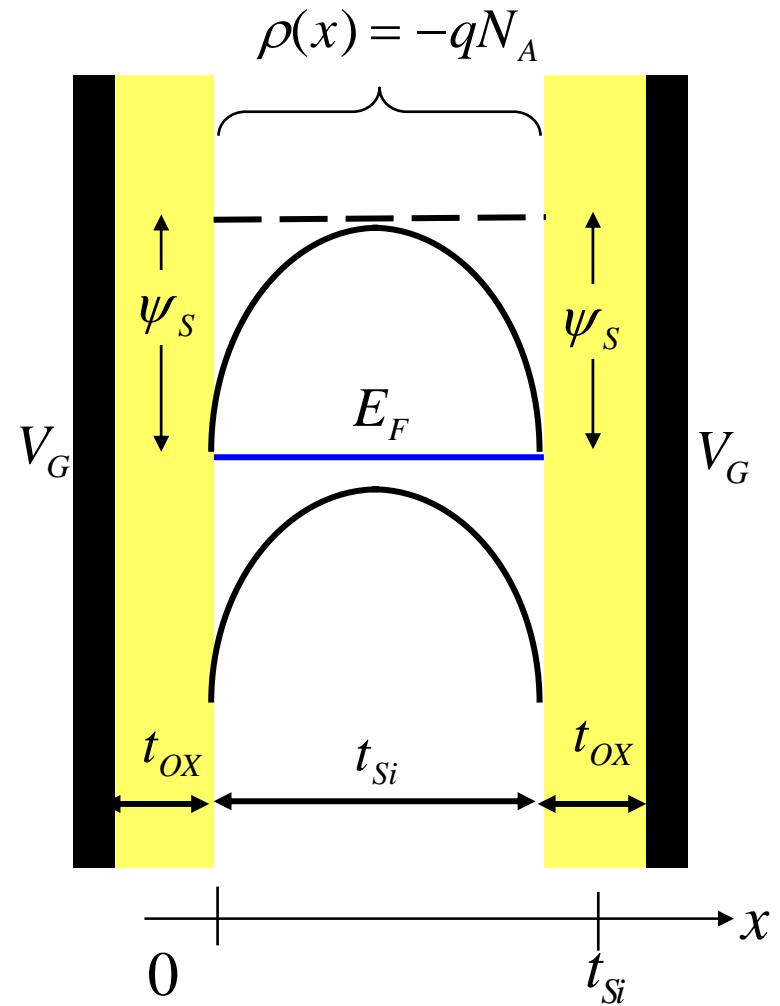
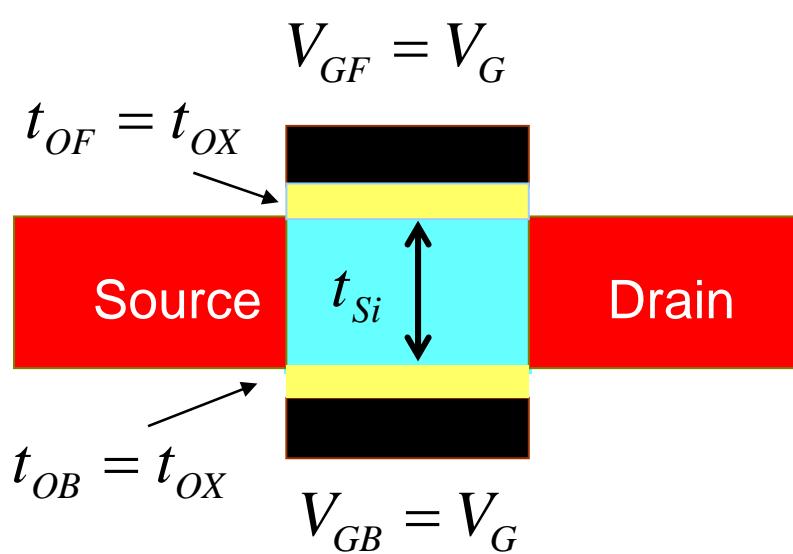
$$S = 2.3m(k_B T/q)$$



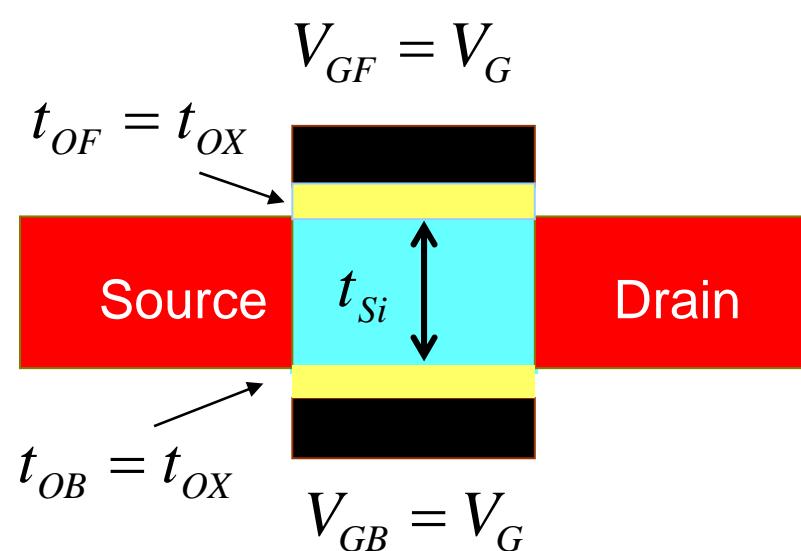
$$m = 1 + \frac{C_D(\text{eff})}{C_{OF}}$$

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

symmetrical double gate (SDG)



symmetrical double gate: key results



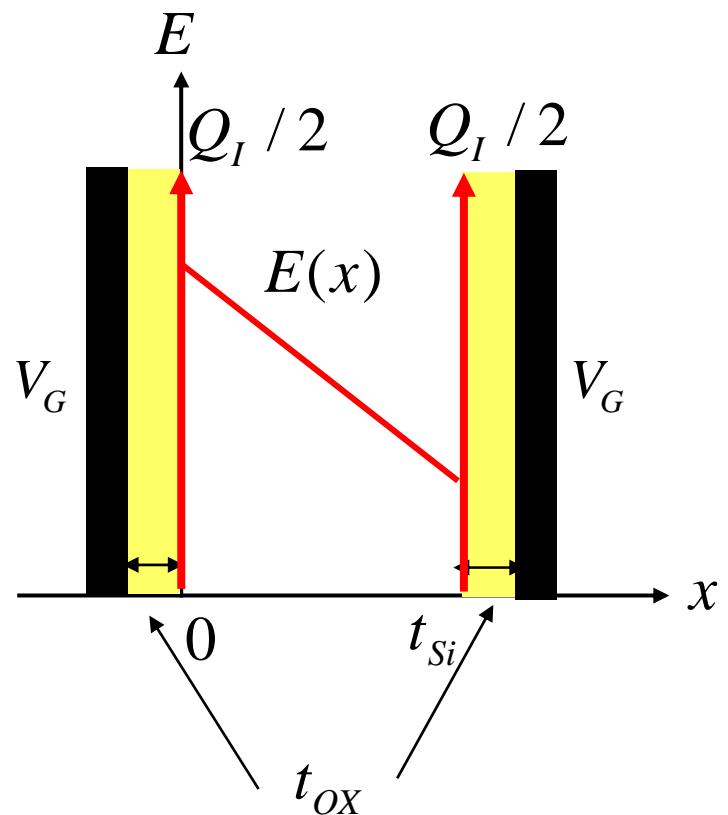
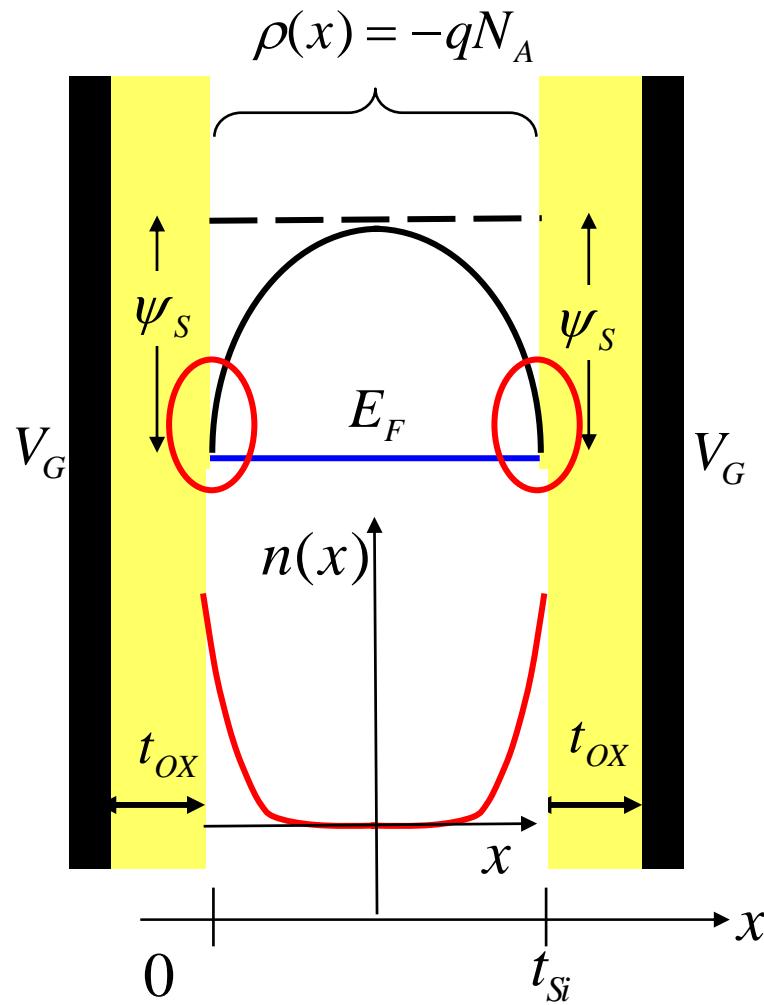
$$V_G = \phi_{ms} + \psi_s - \frac{Q_I + Q_B}{2C_{ox}}$$

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

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

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

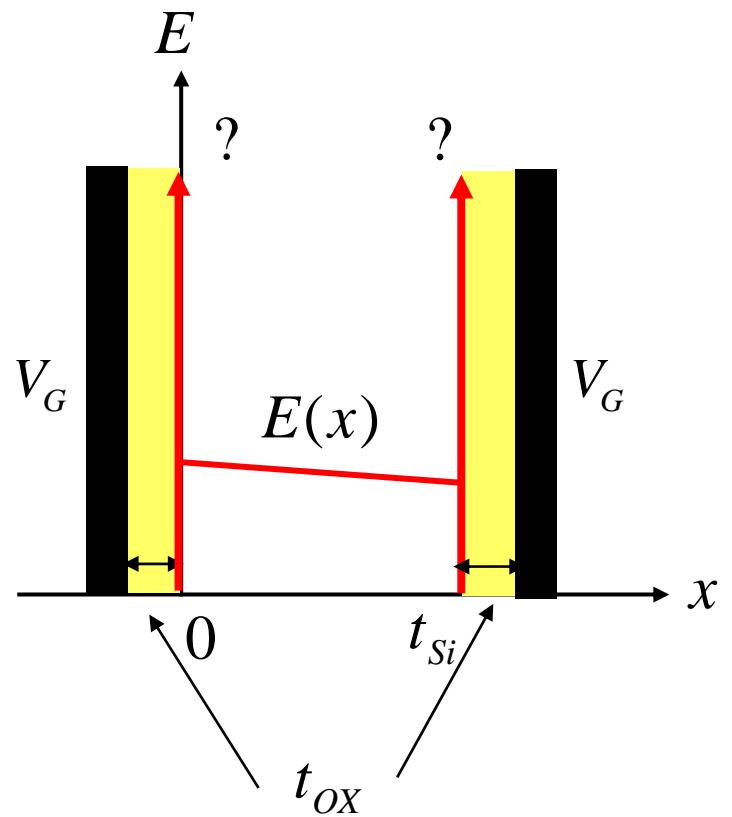
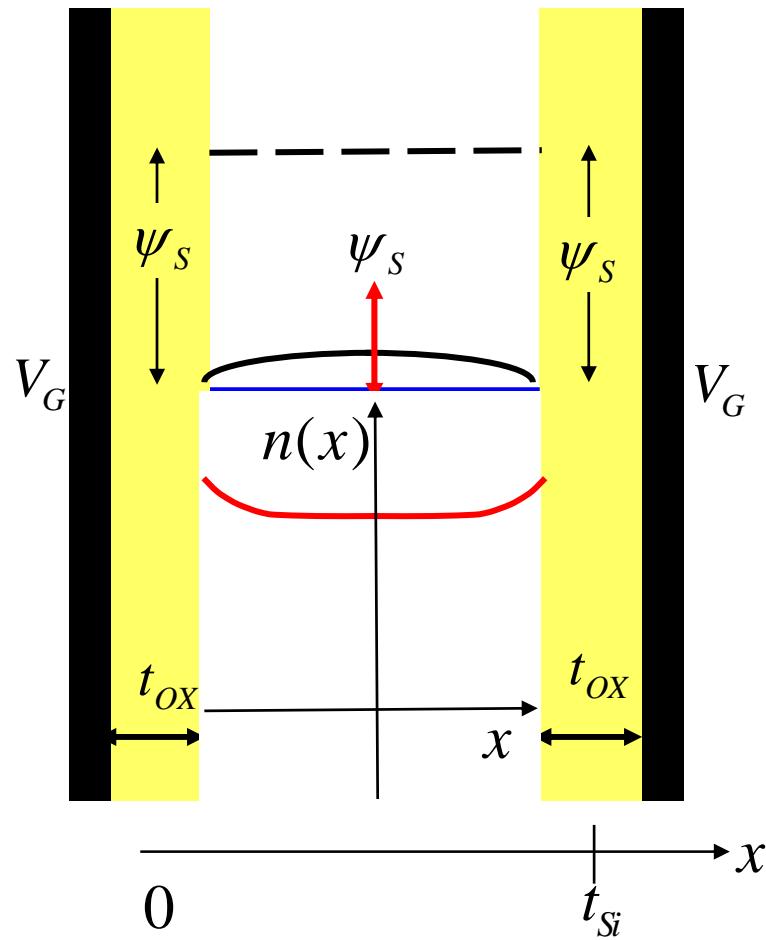
SDG and delta-depletion approximation



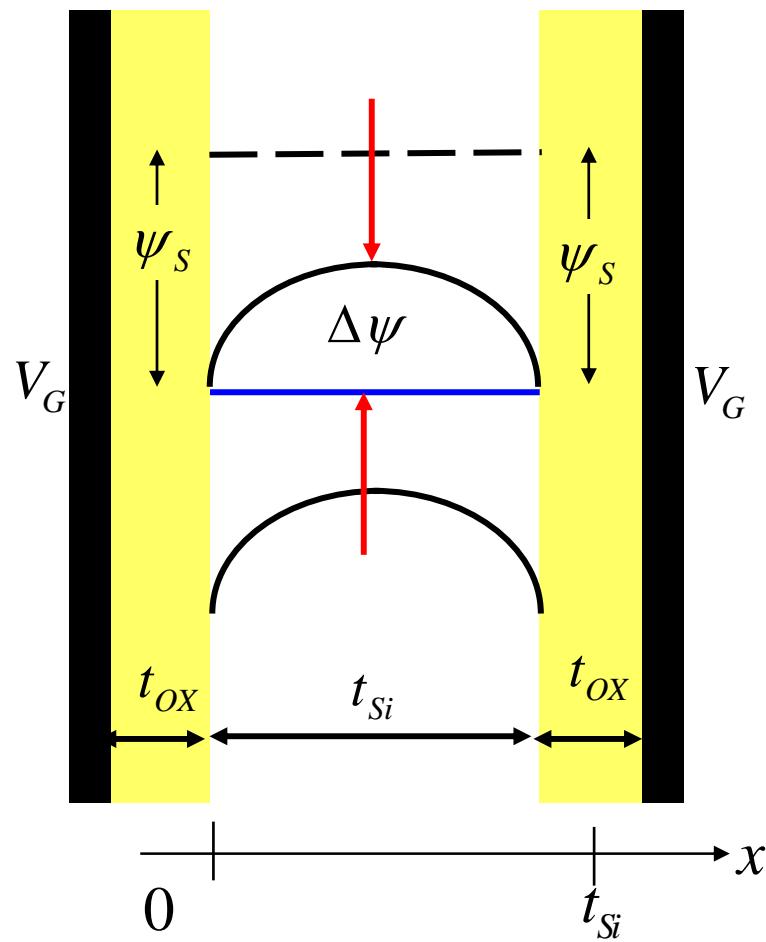
outline

1. Review
2. **Ultra-thin-bodies**
3. Weak Inversion
4. Threshold voltage
5. ‘Exact’ solution
6. Quantum effects

“volume inversion” in UTB SDG SOI



criterion for volume inversion



if

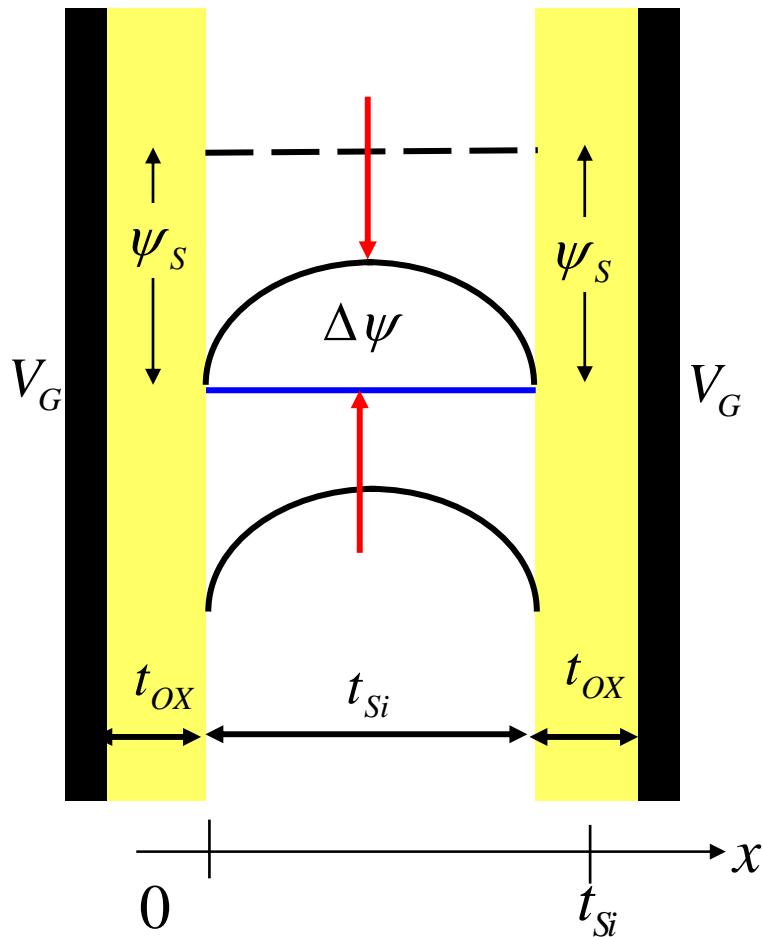
$$\Delta\psi \ll k_B T / q$$

then

$$n(x) \approx \text{constant}$$

$$\Delta\psi = \int_0^{t_{Si/2}} E(x) dx$$

definition of UTB



$$\frac{dE}{dx} = \frac{-qN_A}{\varepsilon_{Si}} \quad (\text{subthreshold})$$

$$E(0^+) = qN_A t_{Si} / 2\varepsilon_{Si}$$

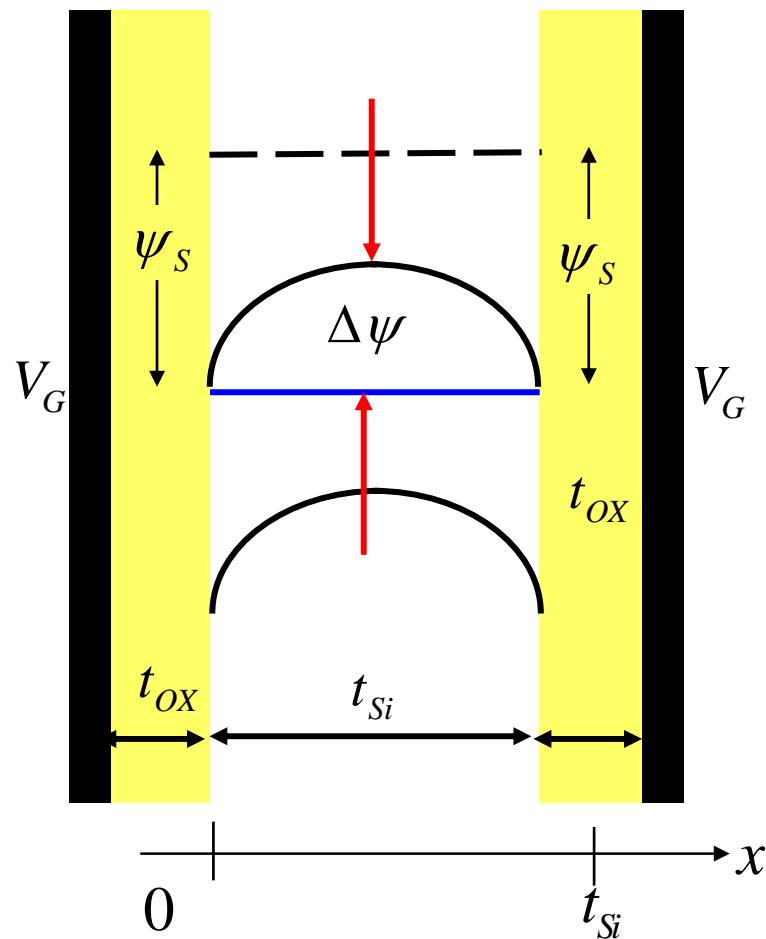
$$\Delta\psi = \frac{1}{2} E(0^+) \left(\frac{t_{Si}}{2} \right) = \frac{qN_A t_{Si}^2}{4\varepsilon_{Si}}$$

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

$$t_{Si} \ll \sqrt{\frac{8\varepsilon_{Si} k_B T}{q^2 N_A}} \quad t_{Si} \ll 2\sqrt{2} L_D$$

definition of UTB (ii)

$$t_{Si} \ll 2\sqrt{2}L_D \quad \psi(x) \approx \text{constant}$$



Note: above threshold, free carriers can screen electric fields, and inversion layers at the surfaces can appear

$N_A (\text{cm}^3)$	$L_D (\text{nm})$
10^{15}	130
10^{16}	40
10^{17}	13
10^{18}	4

numerical (Schred) simulation

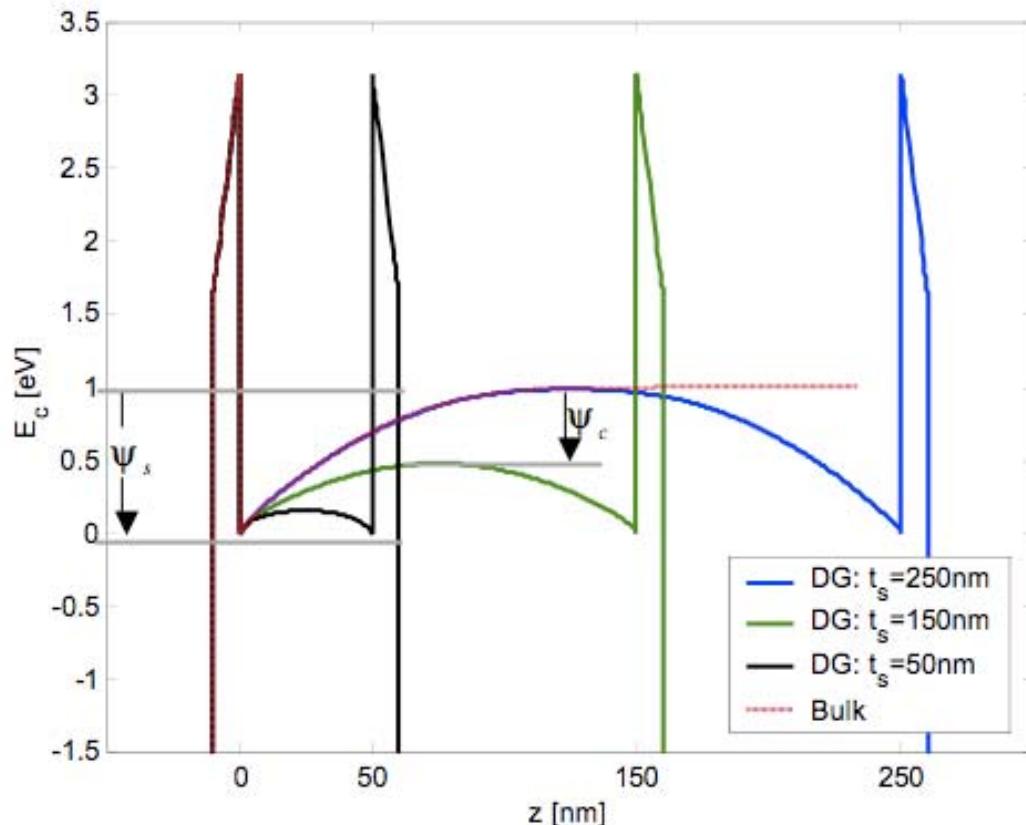
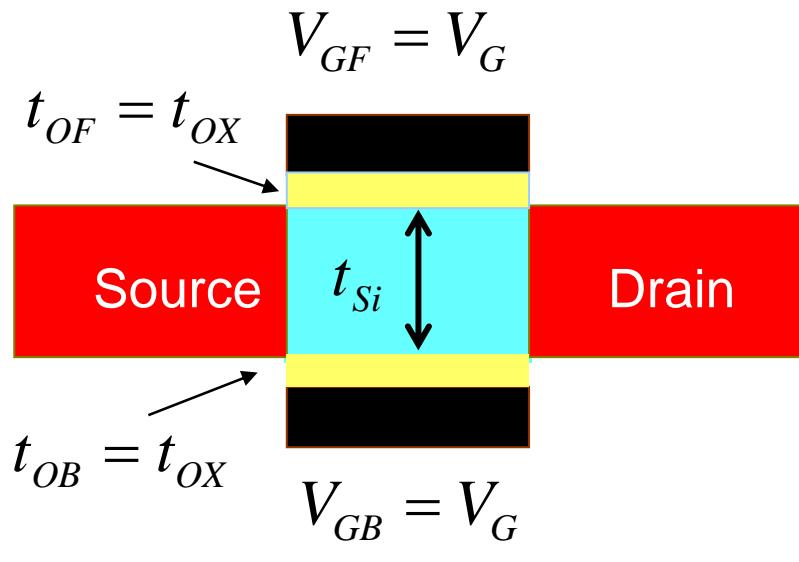


Fig. 14. Band-diagram of DGMOS capacitors of different body thickness at same V_G . Also shown the band diagram of bulk MOSC (red-dashed line). $t_{ox} = 10\text{nm}$, $N_A = 1.E17 \text{ cm}^{-3}$, $V_G = 1.5\text{V}$. Classical mode calculation.

doping in UTB MOSFETs



$$N_A = 10^{15} \text{ cm}^3$$

$$L = 100 \text{ nm}$$

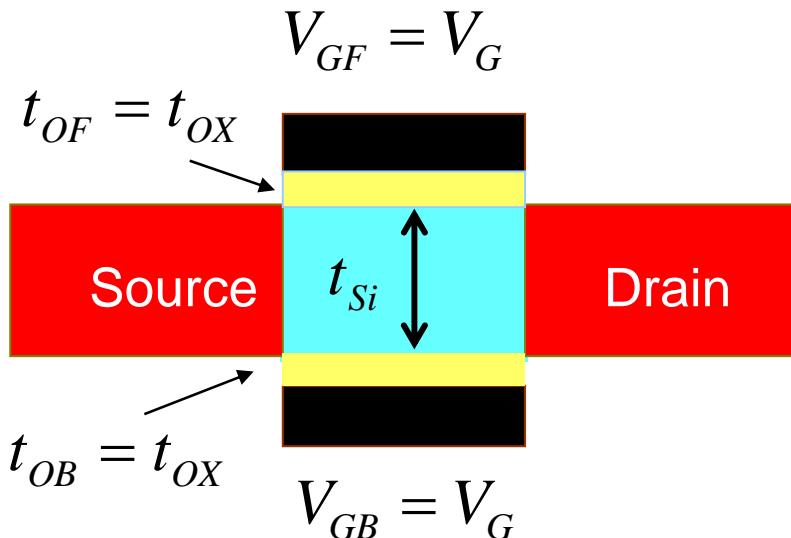
$$W = 1000 \text{ nm}$$

$$t_{Si} = 10 \text{ nm}$$

$$N = WL N_A = 1$$

assume intrinsic body!

why UTB DG MOSFETs?



- good 2D electrostatics
- 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

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 for strong inversion)

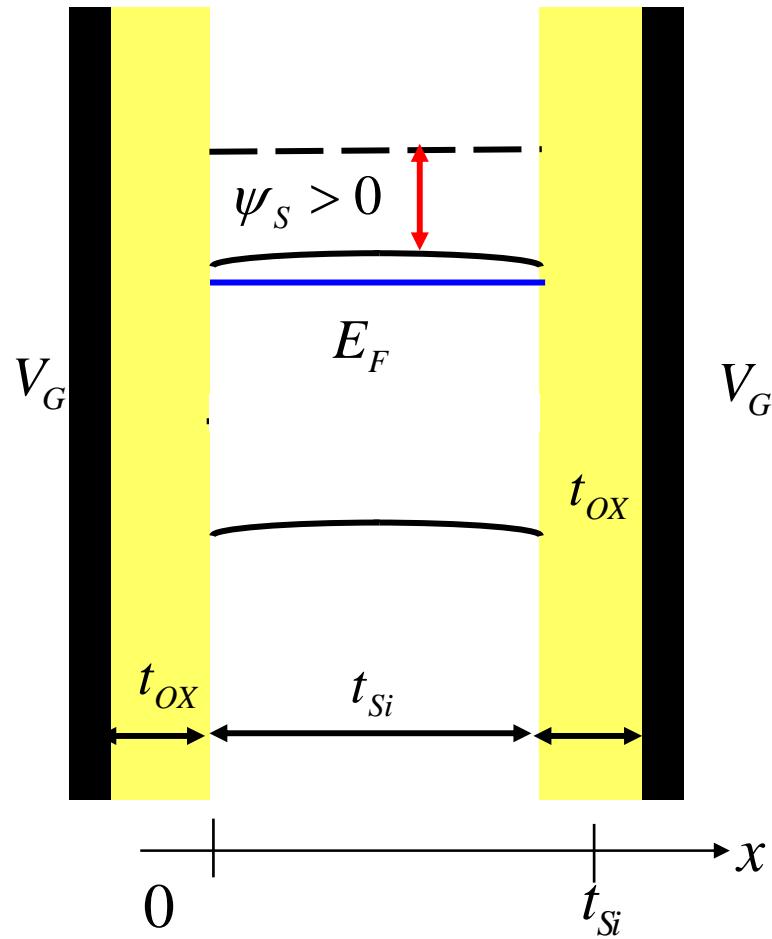
reference for DG SOI Electrostatics

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

outline

1. Review
2. Ultra-thin-bodies
- 3. Subthreshold**
4. Threshold voltage
5. ‘Exact’ solution
6. Quantum effects

the meaning of surface potential



$$V_{GS} = \phi_{ms} + \psi_S - \frac{Q_B + Q_N}{2C_{ox}}$$

$$Q_B = 0$$

$$Q_N = qn_i e^{q\psi_S/k_B T} t_{Si}$$

$$|Q_N| < \sim q10^{11} \text{ cm}^2$$

$$\frac{Q_N}{2C_{ox}} \ll \psi_S$$

subthreshold conduction

$$V_{GS} = \phi_{ms} + \psi_s$$

$$S = 2.3 \left(k_B T / q \right) \left(\frac{\partial \psi_s}{\partial V_{GS}} \right) = 60 \text{ mV/dec}$$

recall:

$$I_D = qW \left[\frac{n_i^2}{N_A} e^{q\psi_s/k_B T} \frac{k_B T / q}{E_S} \right] \left(\frac{k_B T / q\mu_{eff}}{L} \right) \left(1 - e^{-qV_{DS}/k_B T} \right) A$$

$$I_D = qW \left[n_i e^{q(V_{GS} - \phi_{ms})/k_B T} t_{Si} \right] \left(\frac{k_B T / q\mu_{eff}}{L} \right) \left(1 - e^{-qV_{DS}/k_B T} \right) A$$

outline

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threshold voltage

recall:

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

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

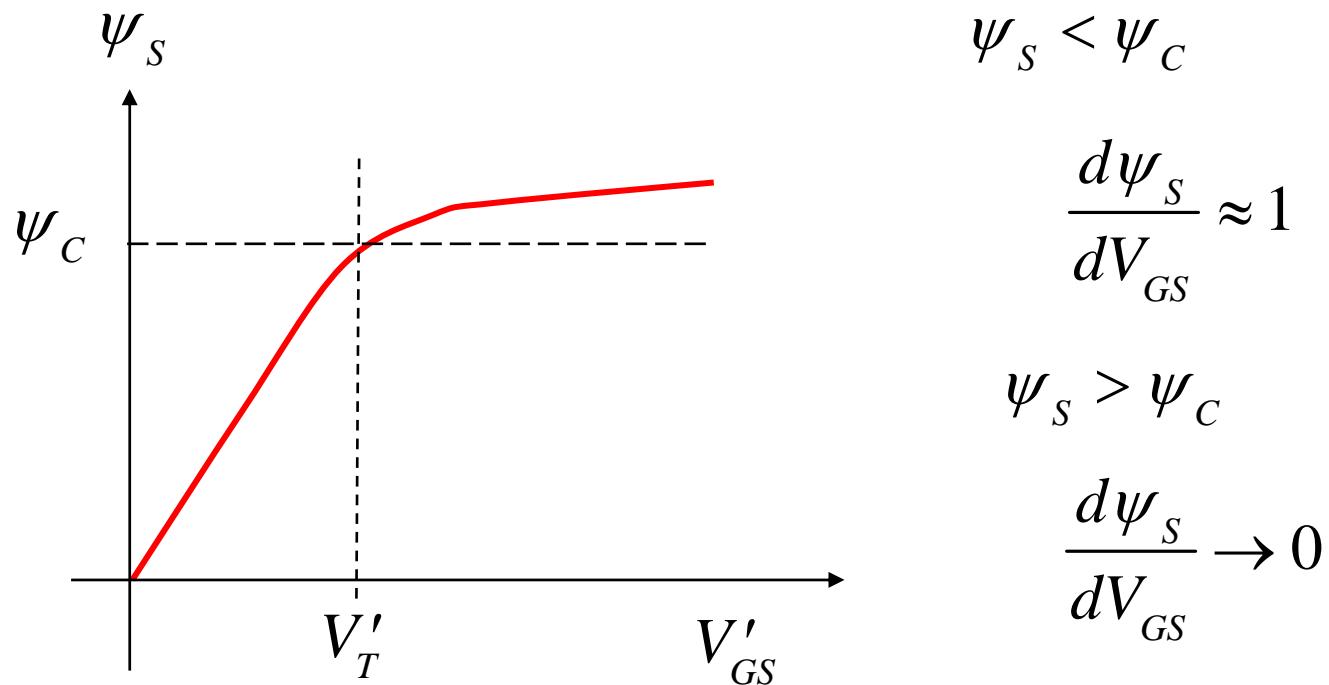
assume:

1) symmetrical, double gate: $V_G = V_{GF} = V_{GB}$
 $Q_{IF} = Q_{IB} = Q_I/2$

2) intrinsic body: $Q_B = 0$ $\psi_S = \psi_{SF} = \psi_{SB}$

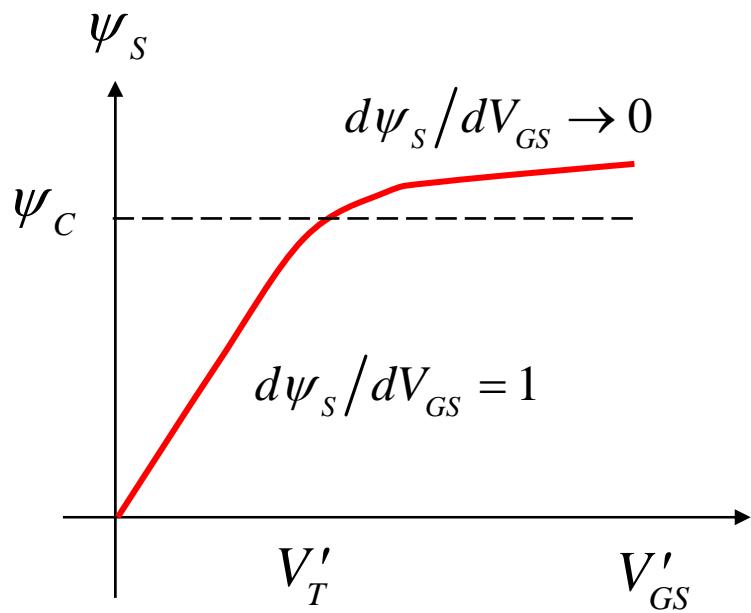
threshold voltage (ii)

$$V_G = \phi_{ms} + \psi_s \quad \text{how to specify } \psi_s? \quad \psi_s \neq 2\psi_B$$



threshold voltage (iii)

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:

$$d\psi_s/dV_{GS} \Big|_{\psi=\psi_c} = 1/2$$

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

above threshold

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

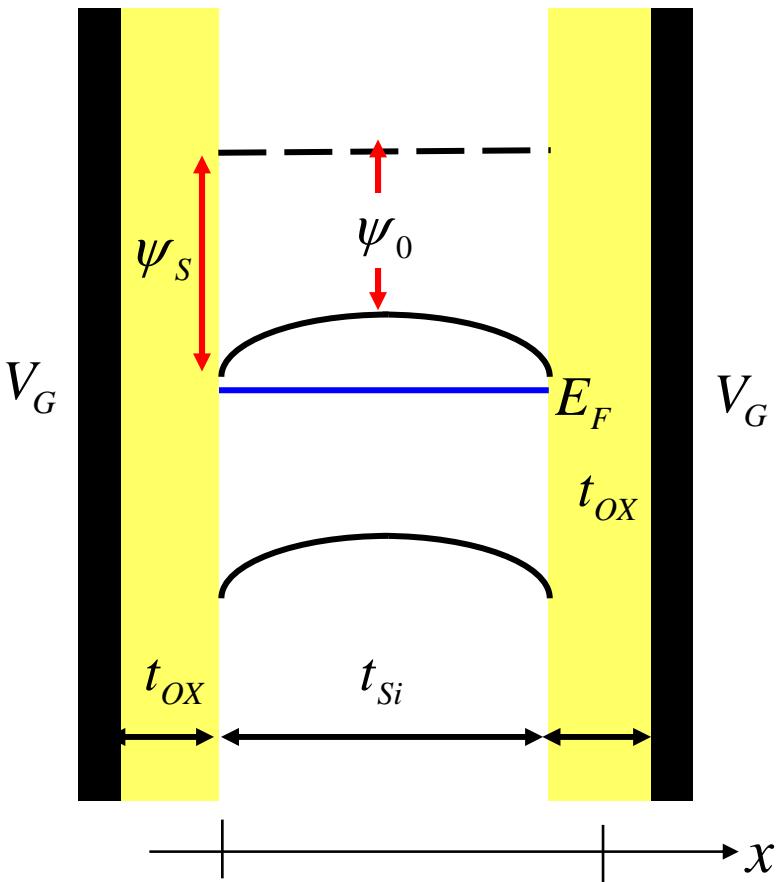
$$V_T = \phi_{ms} + \psi_c$$

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

outline

1. Review
2. Ultra-thin-bodies
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UTB electrostatics above threshold



1) below threshold:

-bands are flat

2) weak / moderate inversion:

-bands are nearly flat

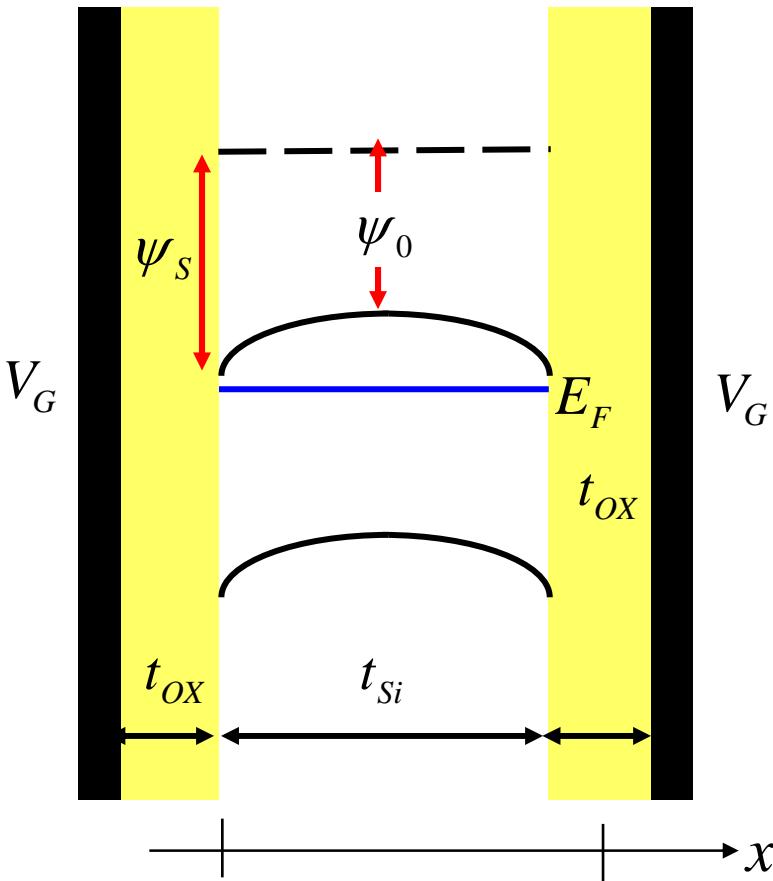
-volume inversion

3) strong inversion:

-strong band bending may develop

-volume inversion may be lost

'exact' UTB electrostatics



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

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

numerical (Schred) simulation

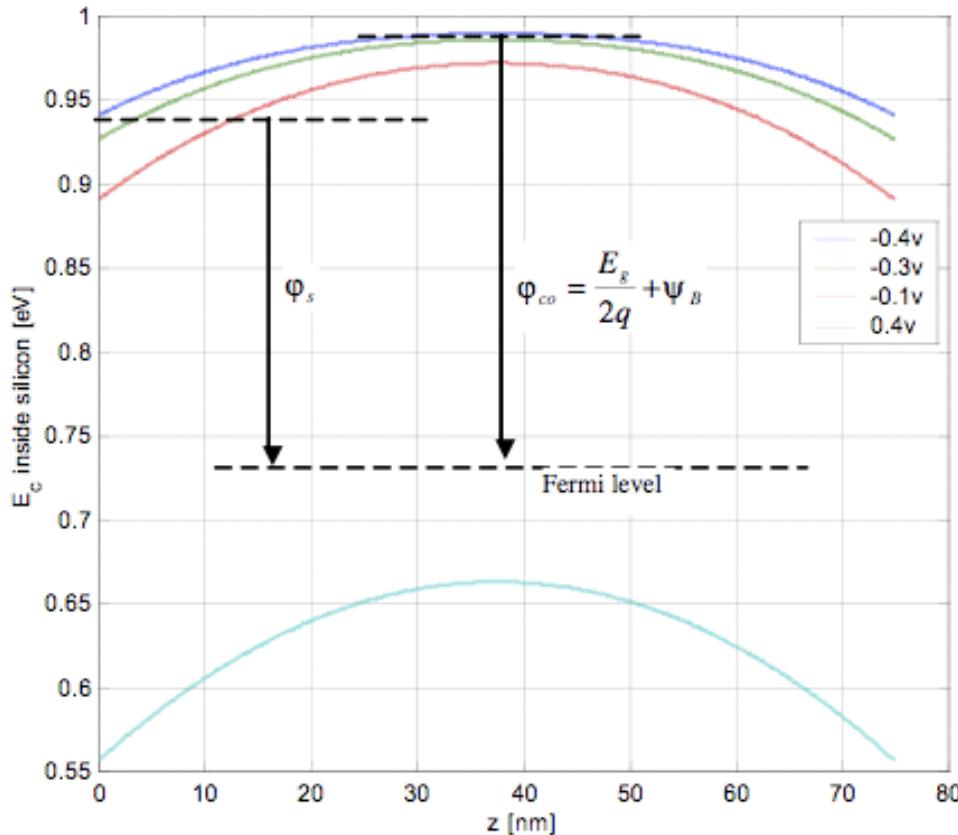


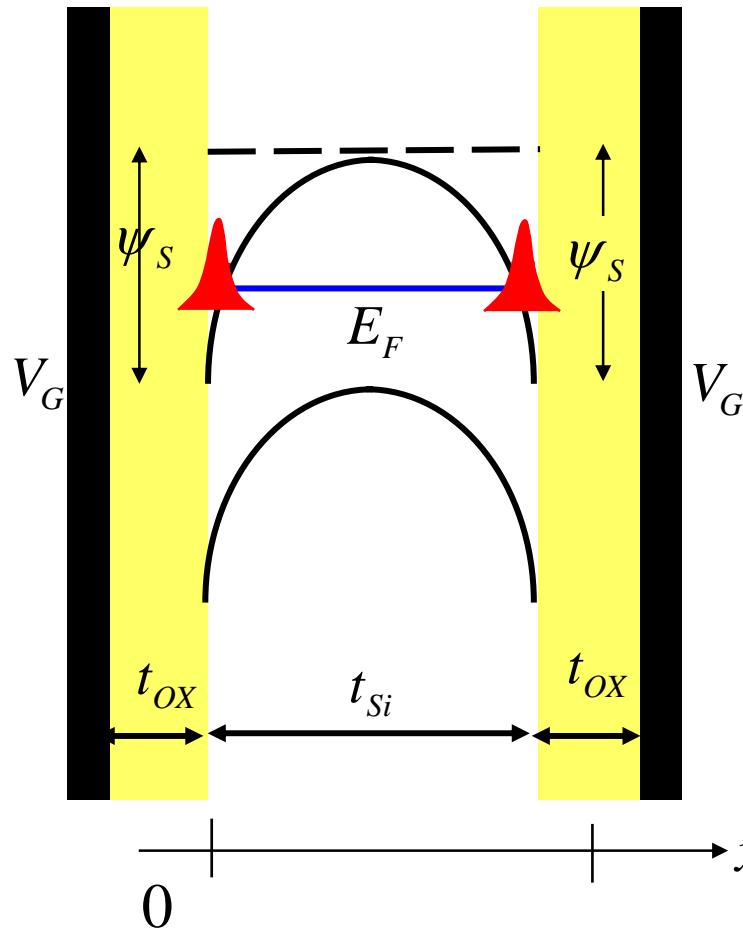
Fig. 17. Variation of band-diagram with applied bias. Top three curves show that only the band at the surface varies while band center does not vary much. The bottom curve shows a complete shift of along with the center of the conduction band.

outline

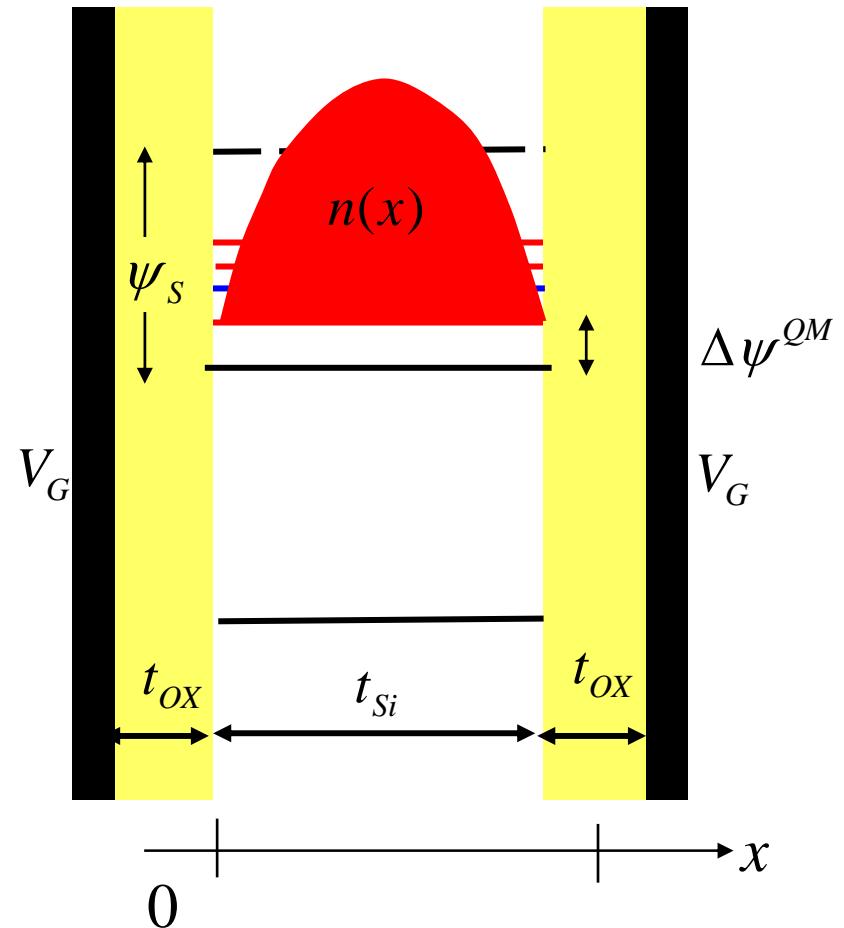
1. Review
2. Ultra-thin-bodies
3. Subthreshold
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6. **Quantum effects**

quantum confinement

FD (thick)



FD (UTB)



numerical (Schred) simulation

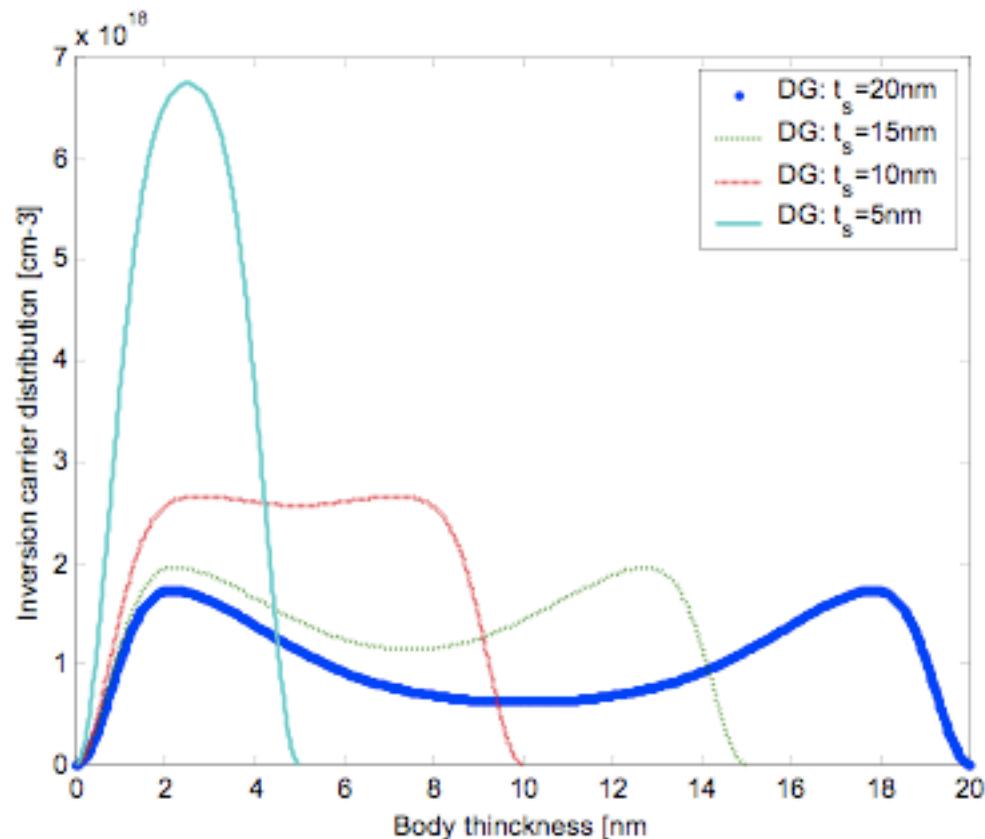


Fig. 20. Inversion carrier distribution inside the DGMOSC, for various body thickness, with $t_{\text{ox}}=10\text{nm}$, $N_a=1.\text{E}17\text{cm}^{-3}$, $V_G = 0.5V$.

numerical (Schred) simulation

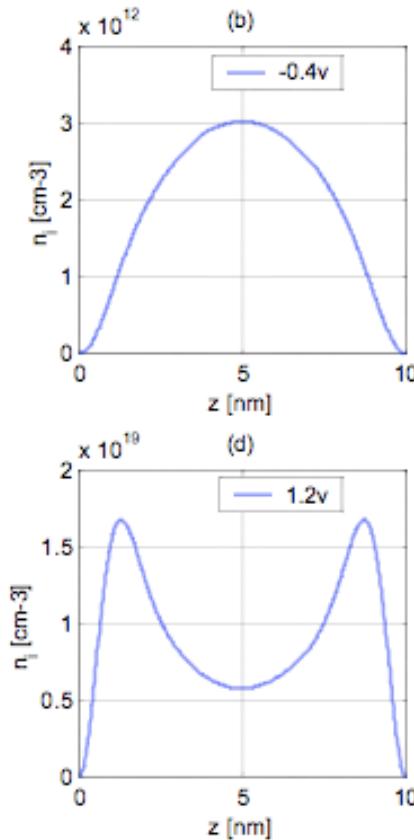


Fig. 22. Quantum calculation, $t_{ox}=5\text{nm}$, $t_{si}=10\text{nm}$, $N_A=1.e17\text{cm}^{-3}$. (a) variation of centroid with gate voltage, rest three are electron distribution inside silicon film at gate voltage: (b) -0.4v , (c) 0.1v , (d) 1.2v .

discussion

- 1) important when only a few subbands are occupied
ultra-ultra-thin body (5 nm or less)
- 2) increases V_T
- 3) lowers C_S
- 4) increases ΔV_T because of body thickness variations
- 5) lowers mobility because of increased surface roughness scattering

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