VLSI Devices
Lecture 26

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Assumptions for double-gate

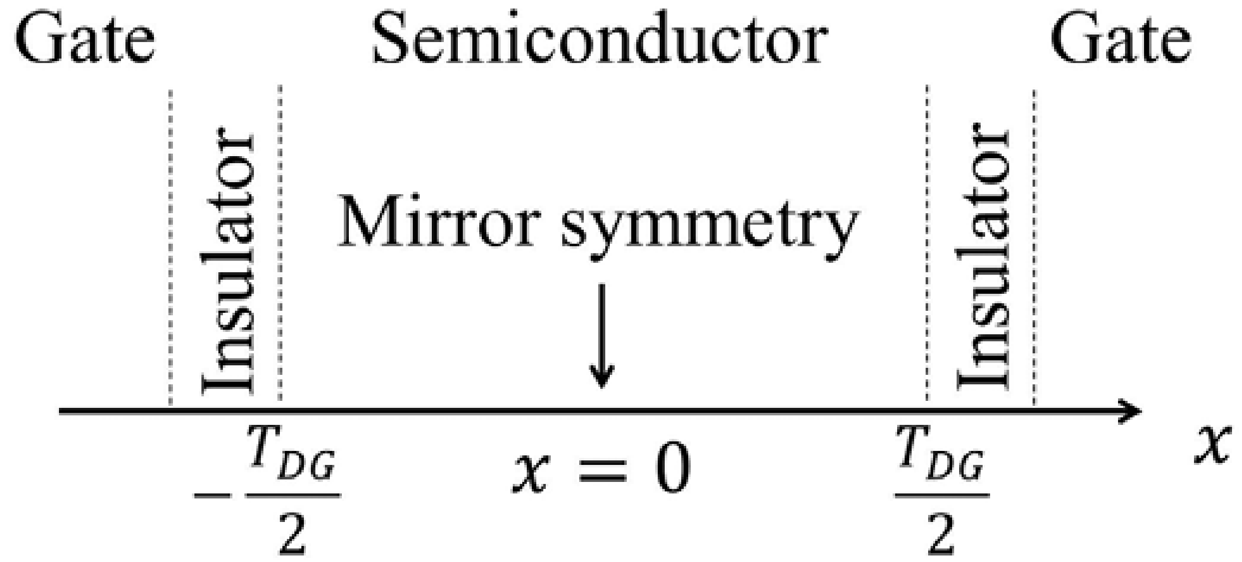
- No substrate doping
  - Fully-depleted channel ($p \approx 0$)
  - Then, the Poisson equation simply reads:

$$\frac{d^2\phi}{dx^2} = \frac{q}{\epsilon_{si}} n_i \exp\left(\frac{q}{k_B T}(\phi - V)\right)$$

It is NOT referenced to the substrate.

Taur, Eq. (10.5)

  - Constant V. For a while, $V = 0$.



Integrate it once.

- Multiply a weighting factor, $\frac{d\phi}{dx}$
  - Rearrange it yields $\frac{1}{2}\frac{d}{dx}\left(\left(\frac{d\phi}{dx}\right)^2\right) = \frac{d\phi}{dx}\frac{q}{\epsilon_{si}}n_i \exp\left(\frac{q\phi}{k_B T}\right)$.
  - After integration from 0 to x, we have $\frac{1}{2}\left(\frac{d\phi}{dx}\right)^2 = \frac{k_B T}{\epsilon_{si}}n_i \exp\left(\frac{q\phi}{k_B T}\right) - \frac{k_B T}{\epsilon_{si}}n_i \exp\left(\frac{q\phi_0}{k_B T}\right)$. $\phi(0)$
  - Therefore, (for a positive x)

$$\frac{d\phi}{dx} = \sqrt{\frac{2k_B T n_i}{\epsilon_{si}}\left[\exp\left(\frac{q\phi}{k_B T}\right) - \exp\left(\frac{q\phi_0}{k_B T}\right)\right]}$$

Surface field

- We need the surface electric field to solve the MOS equation.
  - It is found as

$$\left.\frac{d\phi}{dx}\right|_{x=\frac{T_{DG}}{2}} = \sqrt{\frac{2k_B T n_i}{\epsilon_{si}}\left[\exp\left(\frac{q\phi_s}{k_B T}\right) - \exp\left(\frac{q\phi_0}{k_B T}\right)\right]}$$

$$\phi\left(\frac{T_{DG}}{2}\right)$$

  - In the planar MOS, the surface field is a function of $\phi_s - \phi_\infty$. Now, it is a function of ϕ_s and ϕ_0.

Integrate it twice.

- Introduce $y \equiv \exp\left(-\frac{q(\phi-\phi_0)}{2k_BT}\right)$.
  - It is noted that $0 < y \leq 1$, when $\phi \geq \phi_0$. At $x = 0$, $y = 1$.
  - Rearrange it yields $\frac{dy}{dx} = -\exp\left(\frac{q\phi_0}{2k_BT}\right)\sqrt{\frac{q^2 n_i}{2\epsilon_{si}k_BT}(1-y^2)}$.
  - After integration from 0 to x,

$$\arcsin y - \frac{\pi}{2} = -\sqrt{\frac{q^2 n_i}{2\epsilon_{si}k_BT}}\exp\left(\frac{q\phi_0}{2k_BT}\right)x$$

  - Therefore,

$$y = \cos\left(\sqrt{\frac{q^2 n_i}{2\epsilon_{si}k_BT}}\exp\left(\frac{q\phi_0}{2k_BT}\right)x\right)$$

Solution

- Remember that $y \equiv \exp\left(-\frac{q(\phi-\phi_0)}{2k_BT}\right)$.

$$\frac{q(\phi-\phi_0)}{2k_BT} = -\log\left[\cos\left(\sqrt{\frac{q^2 n_i}{2\epsilon_{si}k_BT}}\exp\left(\frac{q\phi_0}{2k_BT}\right)x\right)\right]$$

– At $x = \frac{T_{DG}}{2}$,

$$\frac{q(\phi_s-\phi_0)}{2k_BT} = -\log\left[\cos\left(\sqrt{\frac{q^2 n_i}{2\epsilon_{si}k_BT}}\exp\left(\frac{q\phi_0}{2k_BT}\right)\frac{T_{DG}}{2}\right)\right]$$

– It provides us another equation for ϕ_s and ϕ_0.

Remarks

- It is great to have an analytic expression!
  - However, in general, it is difficult to find an analytic expression...
  - Various multi-gate cross-sections
  - *Should we make models for them?*

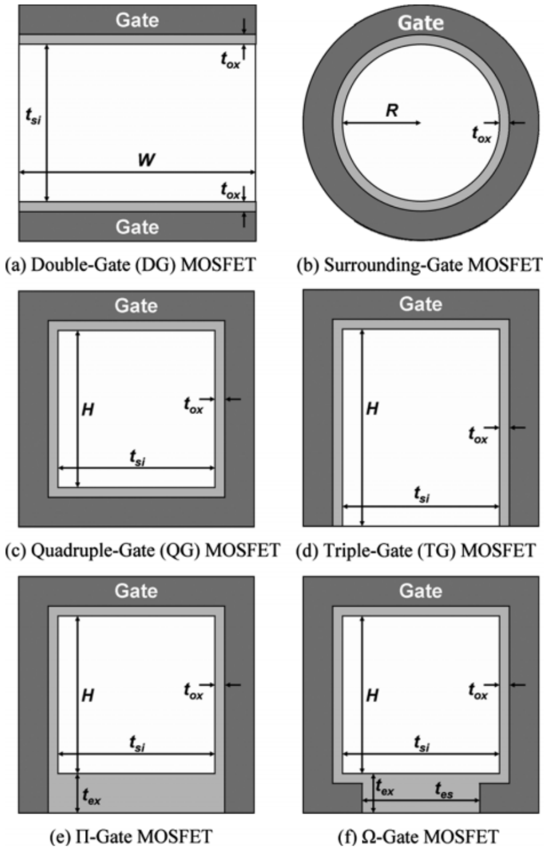


Fig. 13. Schematic diagrams of MG MOSFET cross-sections perpendicular to the channel direction.

Multi-gate MOSFET cross-sections
(Song et al, IEEE TCAS-I, 2009)

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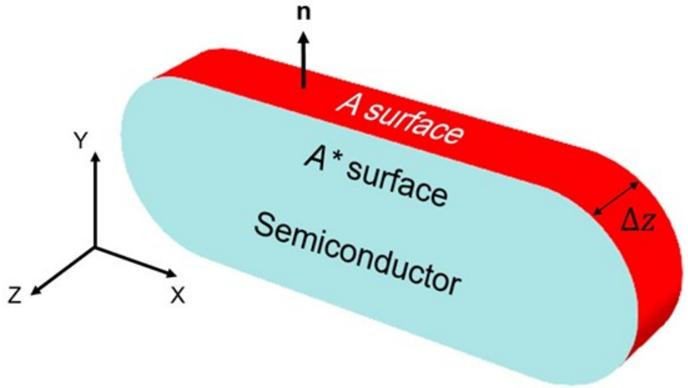
Common procedure

Derivation of a Universal Charge Model for Multigate MOS Structures With Arbitrary Cross Sections

Kwang-Woon Lee, *Graduate Student Member, IEEE*, and Sung-Min Hong, *Member, IEEE*

- Multiply a weighting factor (the electric field) to the Poisson equation.
  - For an arbitrary cross-section, we can find an appropriate weighting factor.



  - Then, integrate it. We can derive an approximate relation. For example,

$$\langle \phi \rangle_s \approx V_T \log\left(\frac{\frac{1}{2}\tilde{Q}_t^2 - \frac{\Psi P}{A^*}\tilde{Q}_d\left(\alpha_e \tilde{Q}_e + \alpha_d \tilde{Q}_d\right)}{q\epsilon V_T n_{\text{int}}\left(1 - \beta \exp\left(\Psi \frac{\left(\alpha_e \tilde{Q}_e + \alpha_d \tilde{Q}_d\right)}{\epsilon V_T}\right)\right)} \right)$$

  - Solve the MOS equation for the integrated electron charge.

Thank you!