Computational Microelectronics L5

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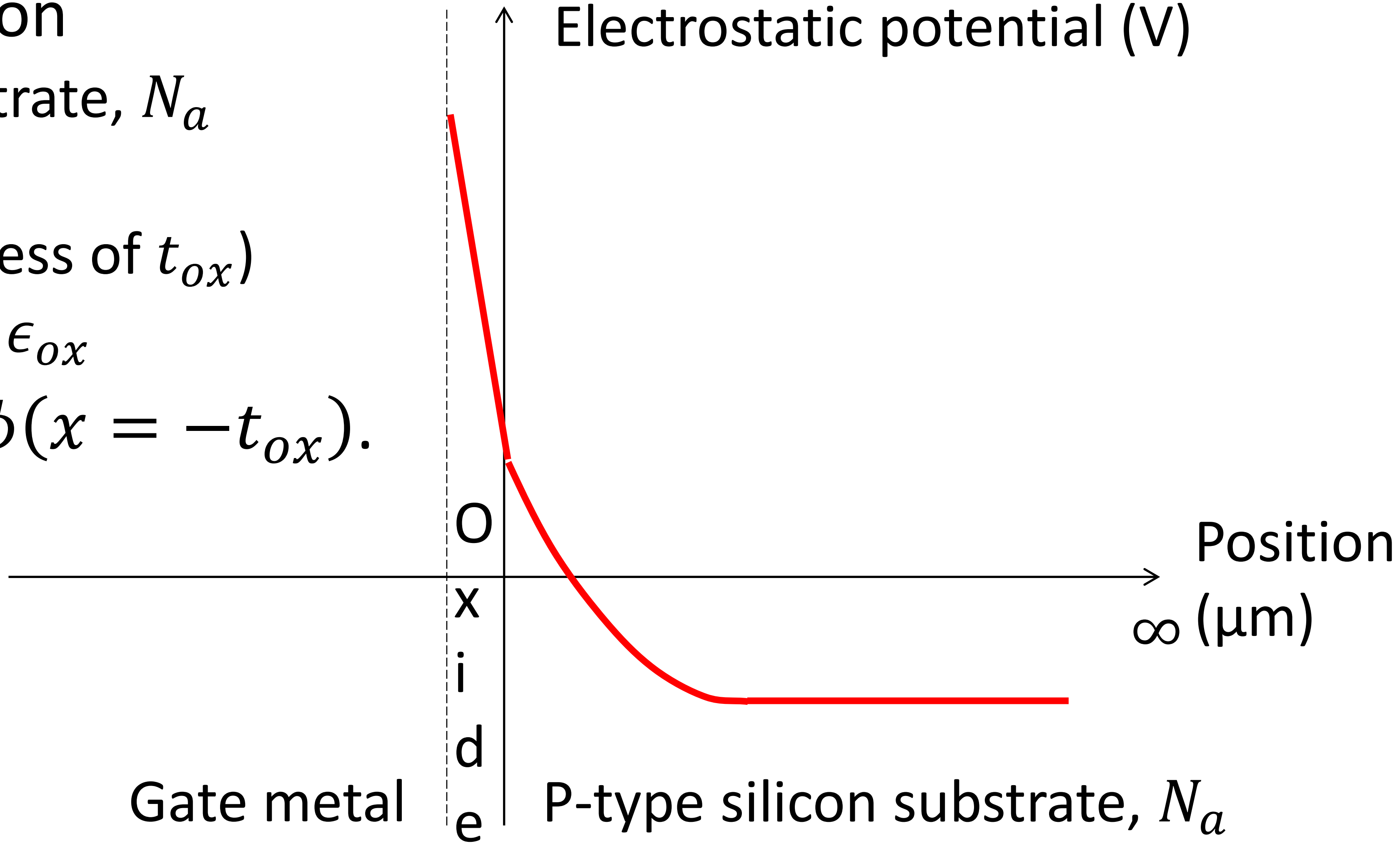
Compact charge model

MOS capacitor (with oxide layer)

- Problem specification
  - P-type silicon substrate, N_a
  - Interface at $x = 0$
  - Oxide layer (thickness of t_{ox})
  - Oxide permittivity, ϵ_{ox}
- We want to know $\phi(x = -t_{ox})$.



Intrinsic Fermi level at gate

- Let us assume that V_G = 0 V.
  - For the gate metal, the workfunction (Φ_m) is known. The workfunction is the energy difference between the vacuum level and the Fermi level.
  - Therefore, when the workfunction is 4.3 eV, the vacuum level is located at 4.3 eV, because the Fermi level is the energy reference.
  - Moreover, the energy difference between the vacuum level and the intrinsic Fermi level of silicon is given. (About 4.63 eV)
  - Then, the intrinsic Fermi level <u>of silicon (not of oxide)</u> is located at -0.33 eV.

$$E_i = \Phi_m - \chi - (E_c - E_i)$$

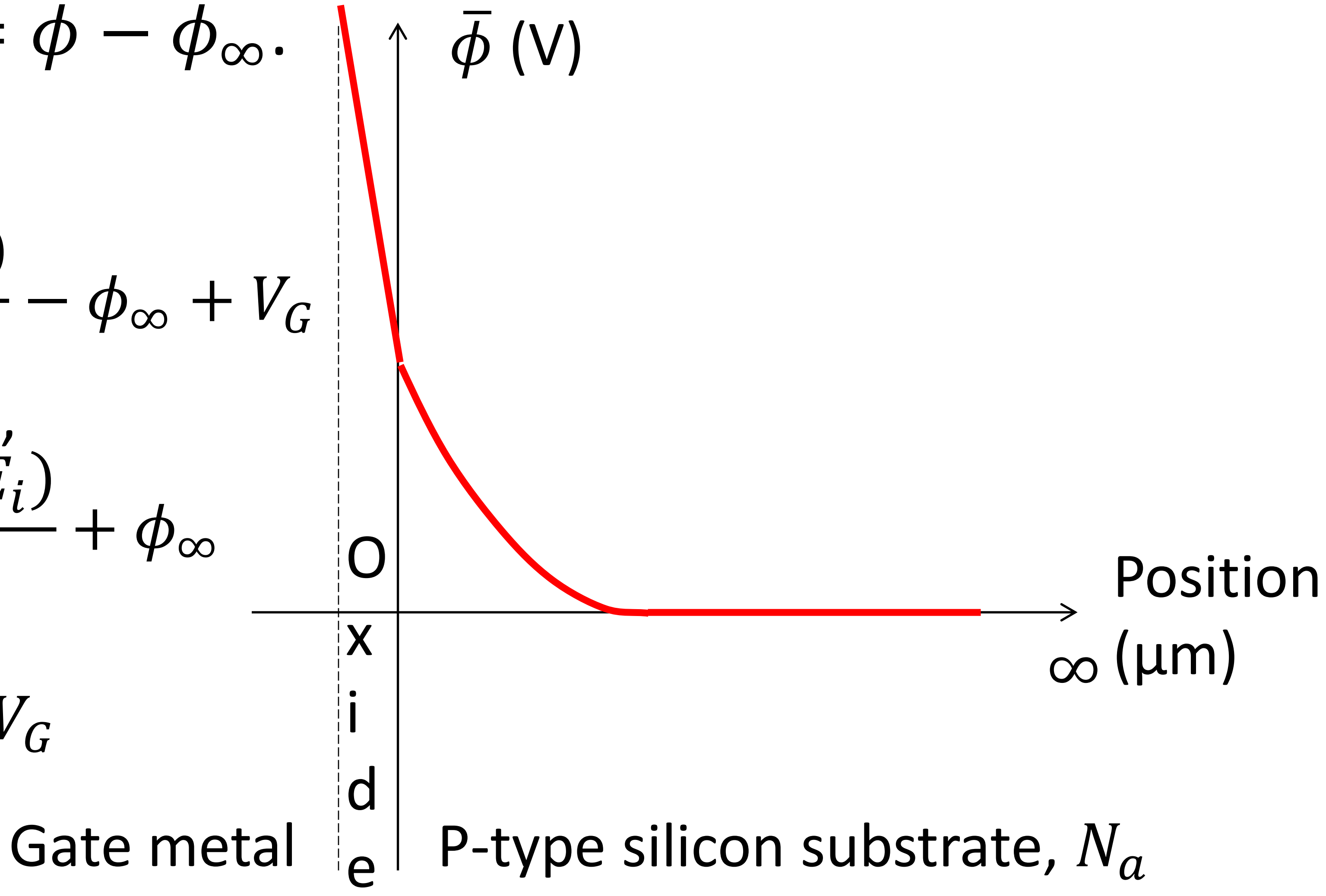
Electron affinity

Electrostatic potential at gate

- From the intrinsic Fermi level (of silicon),
  - We can calculate the electrostatic potential as
$$-q\phi = E_i$$
  - Simply speaking, we know $\phi(x = -t_{ox})$,
$$\phi(x = -t_{ox}) = -\frac{\Phi_m - \chi - (E_c - E_i)}{q}$$
  - For a general V_G,
$$\phi(x = -t_{ox}) = -\frac{\Phi_m - \chi - (E_c - E_i)}{q} + V_G$$

Flatband voltage, V_{fb}

- We are working on $\bar{\phi} = \phi - \phi_\infty$.
  - Then,
    $$\bar{\phi}(x = -t_{ox}) = -\frac{\Phi_m - \chi - (E_c - E_i)}{q} - \phi_\infty + V_G$$
  - When $\bar{\phi}(x = -t_{ox})$ = 0,
    $$V_{fb} = \frac{\Phi_m - \chi - (E_c - E_i)}{q} + \phi_\infty$$
  - Therefore,
    $$\bar{\phi}(x = -t_{ox}) = -V_{fb} + V_G$$



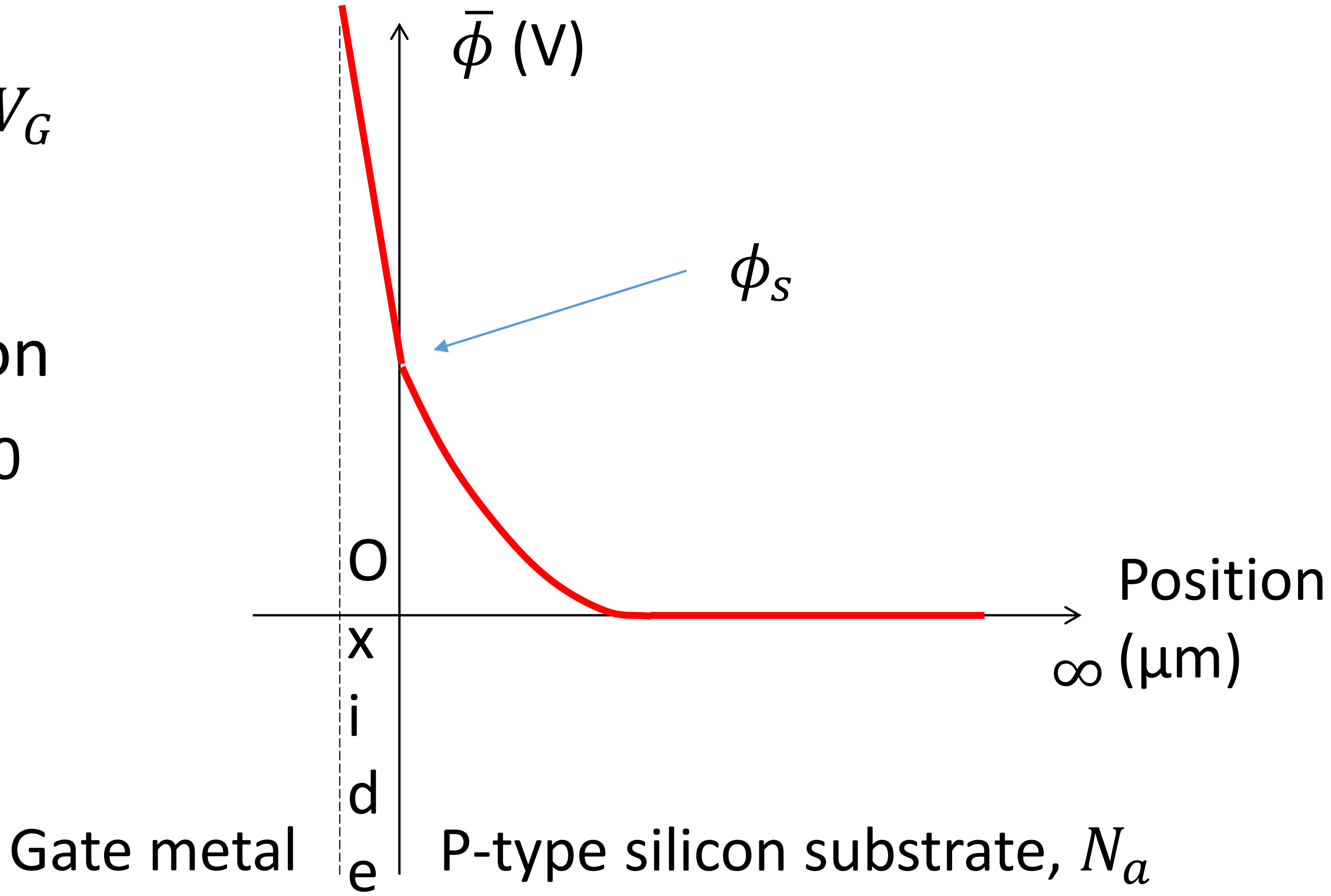
Values of $\bar{\phi}$

- Now we know that

$$\bar{\phi}(x = -t_{ox}) = -V_{fb} + V_G$$
$$\bar{\phi}(x = 0) = \phi_s$$
$$\bar{\phi}(x = \infty) = 0$$

- Ready to get the solution
  - Condition for $\frac{d\phi}{dx}$ at x = 0

$$\epsilon_{ox} \left.\frac{d\phi}{dx}\right|_{0^-} = \epsilon_{si} \left.\frac{d\phi}{dx}\right|_{0^+}$$



Equation to be solved

- When $\phi_s > 0$,
  - Left-hand-side

$$\epsilon_{ox}\frac{\phi_s - \left(-V_{fb} + V_G\right)}{t_{ox}}$$

  - Right-hand-side

$$Q_s = -\sqrt{\begin{array}{l} 2\epsilon_{si} k_B T n_{int} \\ \times \left[\begin{array}{l} \exp\left(-\dfrac{q\phi_\infty}{k_B T}\right)\left\{\exp\left(-\dfrac{q\phi_s}{k_B T}\right) - 1 + \dfrac{q\phi_s}{k_B T}\right\} \\ + \exp\left(\dfrac{q\phi_\infty}{k_B T}\right)\left\{\exp\left(\dfrac{q\phi_s}{k_B T}\right) - 1 - \dfrac{q\phi_s}{k_B T}\right\} \end{array} \right] \end{array}}$$

MOS equation

- With $\epsilon_{si} \left.\frac{d\phi}{dx}\right|_{0^+} = Q_S$,
  - The equation is simply written as

$$\epsilon_{ox} \frac{\phi_s - \left(-V_{fb} + V_G\right)}{t_{ox}} = Q_s$$

  - With $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$,

$$\phi_s - \left(-V_{fb} + V_G\right) = \frac{Q_s}{C_{ox}}$$

$$V_G - V_{fb} = -\frac{Q_s}{C_{ox}} + \phi_s$$

(Of course, Q_s is a nonlinear function of ϕ_s.)

Newton method

- It is straightforward to implement the Newton method.
  - The equation for ϕ_s is

$$-\frac{Q_s}{C_{ox}} + \phi_s - V_G + V_{fb} = 0$$

  - The derivative is

$$-\frac{1}{C_{ox}}\frac{dQ_s}{d\phi_s} + 1$$

(Of course, we know how to calculate $\frac{dQ_s}{d\phi_s}$.)

An example

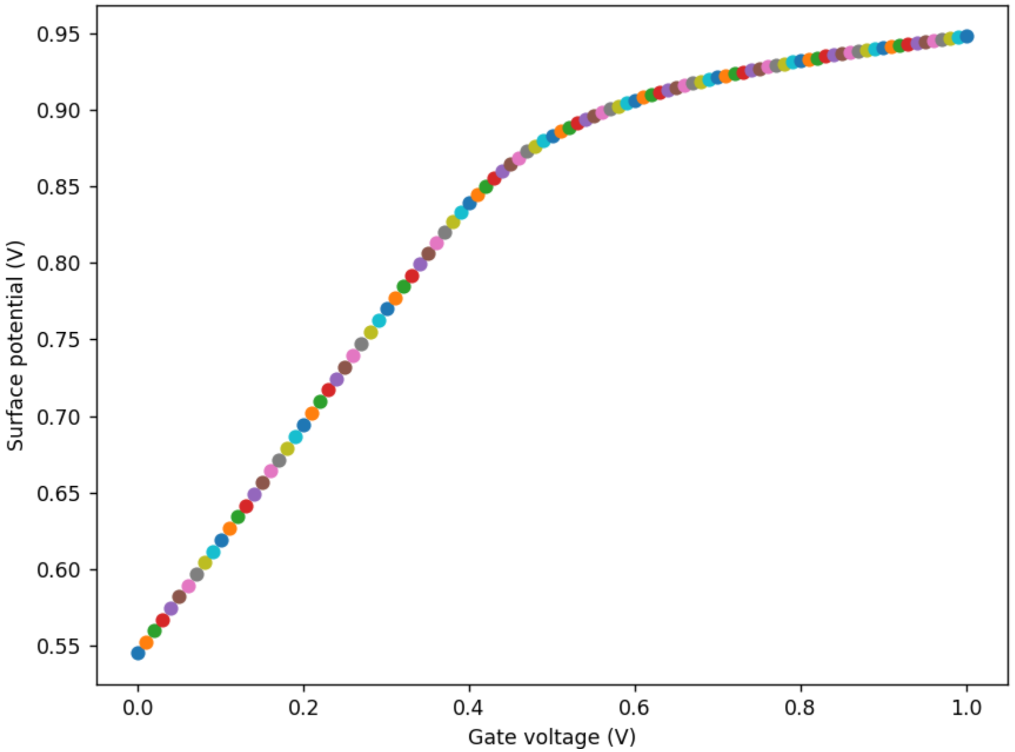
- Let us calculate ϕ_s. For example, 1.0 V?
  - Assume that Φ_m is 4.10 eV and χ is 4.05 eV.
  - Also, N_C at 300 K is 2.85665X10^{19} cm^{-3} and n_{int} at 300 K is 1.075X10^{10} cm^{-3}. Therefore, $E_C - E_i$ is 0.561 eV.
  - Assume that the p-type doping concentration is 10^{17} cm^{-3}. Then, the flatband voltage, V_{fb}, is about -0.92481 V. When V_G is 1.0 V, $\bar{\phi}$ at gate is 1.92481 V.
  - The oxide thickness is 10 nm.
  - Then, ϕ_s is about 0.948 V.

```
1.0 0.9479459310308174 0.0006777834886385816
1.0 0.9479408314730758 -5.099557741512596e-06
1.0 0.947940831181903 -2.911728105350234e-10
```

- How about V_G = 1.1 V?
  - Even in this case, ϕ_s is about 0.954 V. (Only slightly increased)

Homework#5

- Due: AM08:00, October 8
- Problem#1
  - Consider a MOS capacitor with N_a = 10^{17} cm^{-3} and t_{ox} = 10 nm. The metal workfunction is 4.10 eV. Draw ϕ_s as a function of V_G.



Thank you for your attention!