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NANOSENSORS
Centre for Energy Research
Institute of Technical Physics and Materials Science

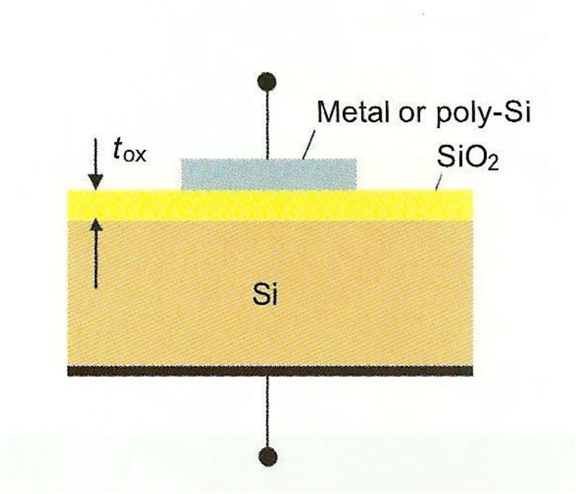
ADVANCED SEMICONDUCTOR DEVICES

04_MOS Capacitor

MŰEGYETEM 1782

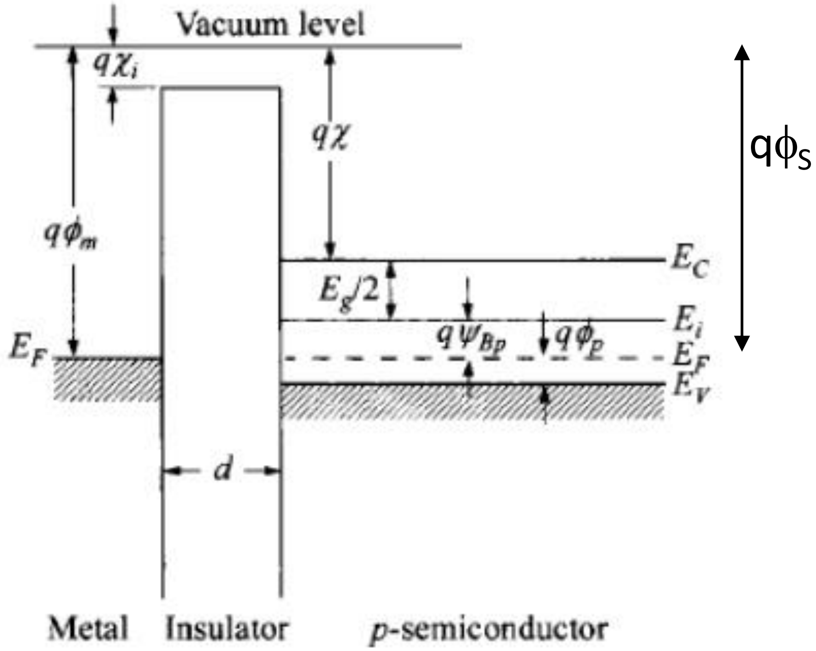
March 11th, 2020

MOS (or metal-insulator-semiconductor, MIS) capacitancor



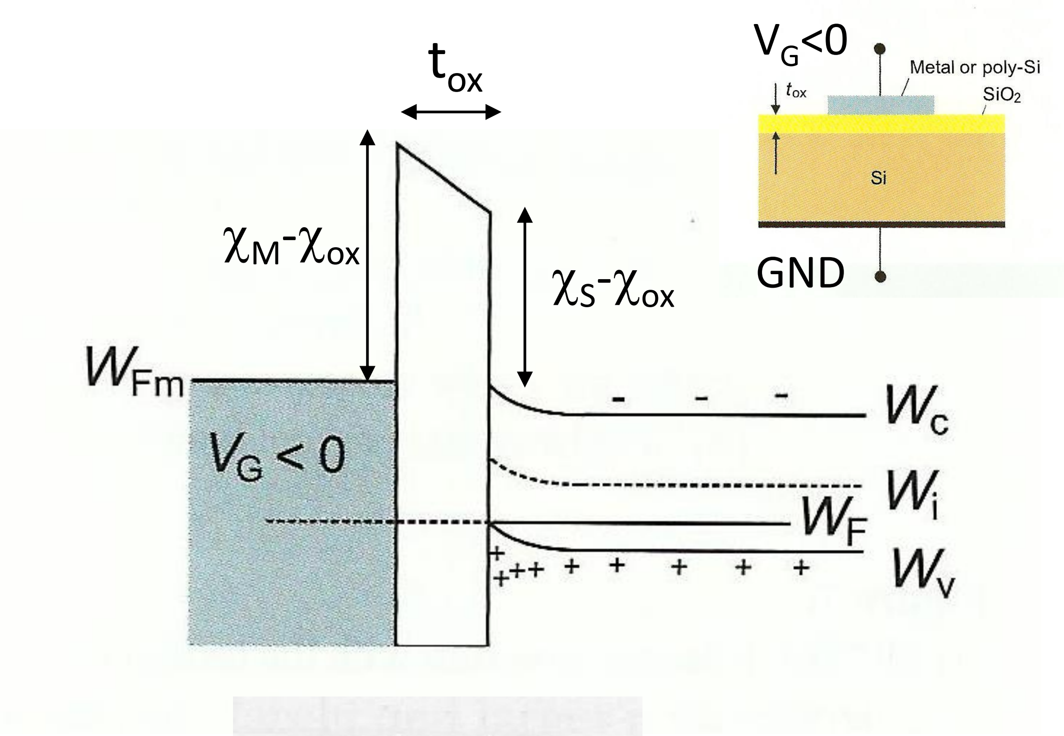
Idealizations:

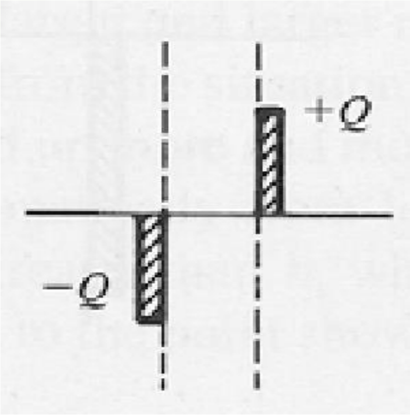
- Charges from the semiconductor and metal with equal but opposite sign; no interface trap, oxide charge etc. (net charge=0)
- No current transport through the insulator
- For the sake of simplicity: $\phi_{MS}=\phi_M-\phi_M=0$ (no band bending upon contacting: flat Band)



- χ: electron affinity (material parameter)
- ϕ: work-function (depends on χ and doping)
- $W_C(E_C)$: conduction band edge
- $W_V(E_V)$: valence band edge
- Eg: bandgap
- $W_F(E_F)$: Fermi level
- E_i: intrinsic Fermi level in the semiconductor

MOS: Accumulation





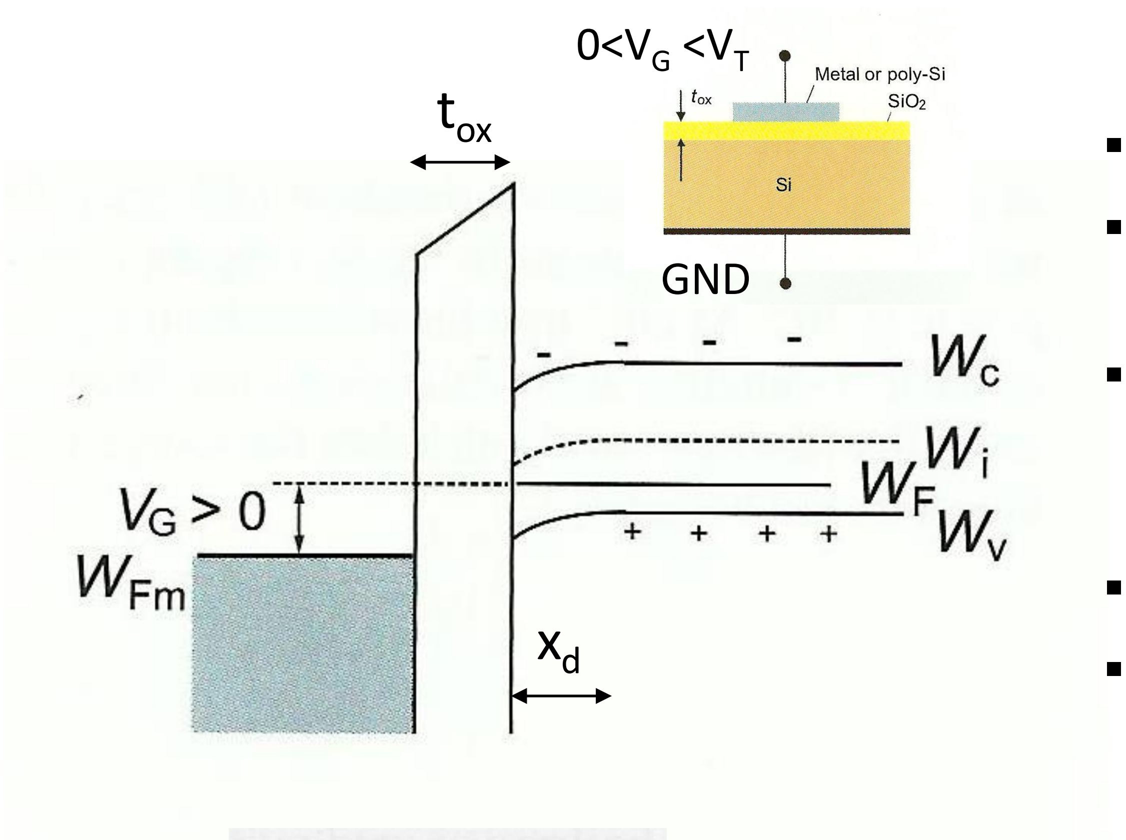
- Negative voltage pushes up the Fermi level in the metal (electron energy is shown: $\Delta W=-qV$)
- Band offsets do not change at oxide interfaces
- No charge in the oxide → straight slant
- Equilibrium: W_F is constant on both sides
- Electrons accumulate at the metal side
- Same amount of charge on both sides of the oxide: $Q_M=-Q_a$
- Surface becomes, more p-type: holes **accumulate**

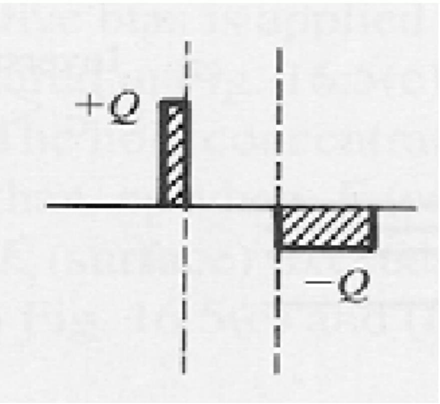
$$p = n_i e^{\frac{W_i - W_F}{kT}}$$

Nongenerate and W_i-W_F» kT
Boltzmann statistics

$$qV_G = W_{F,S} - W_{F,M}$$

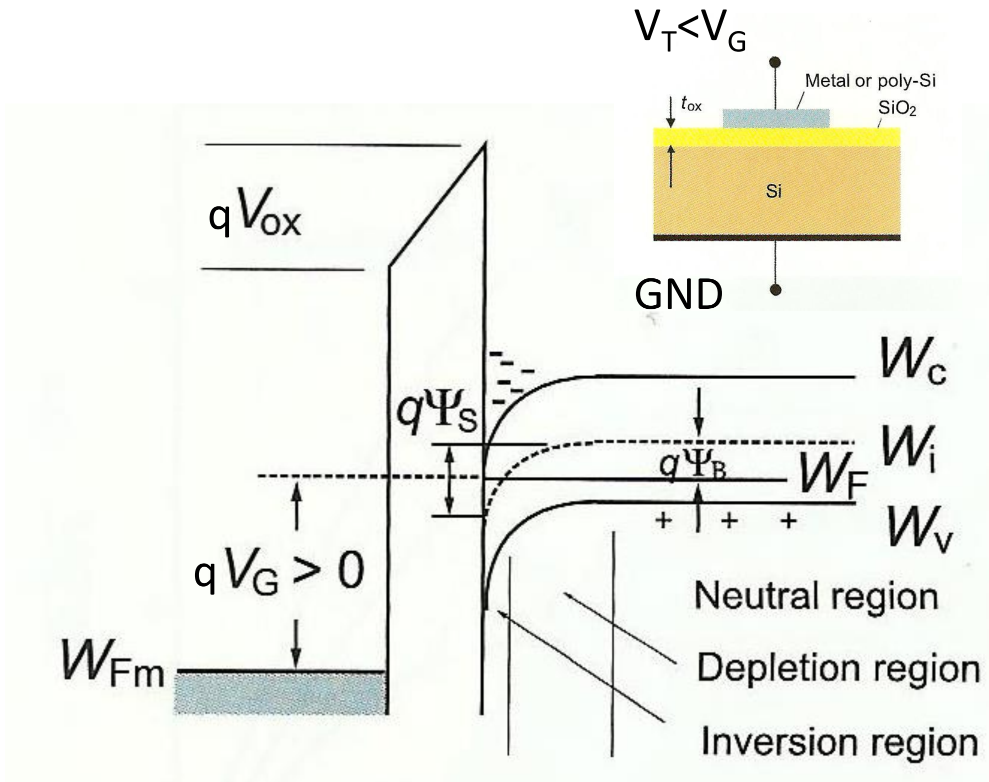
MOS: Depletion

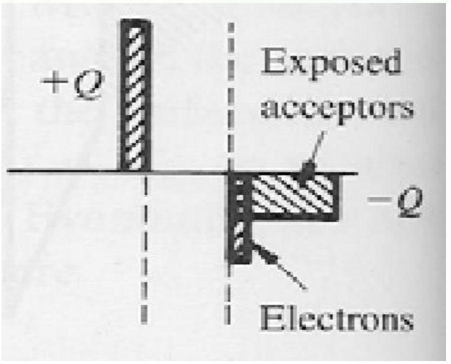




- Positive voltage pulls down the Fermi level in the metal
- Holes are repelled at the semiconductor side near to the surface leaving **ionized acceptors** behind → **depletion**
- Ions are not mobile and have a relatively low concentration → building up of a space charge region in a thickness of x_d
- Positive charges at the metal side $Q_M = -Q_d$
- What happens if we apply even higher V_G? More depletion? No.

MOS: Inversion





- Fermi level pulled down further in the metal → more positive charges at the metal/oxide interface
- W_F goes above W_i → $p = n_i e^{\frac{W_i - W_F}{kT}} < n_i$

  → n increases drastically according to the mass action law ($np = n_i^2$) → n>p in p-type semiconductor: **inversion** layer
- Ionized acceptors, hence depletion region remains
- $Q_m = -(Q_i + Q_d)$

- Where do the holes come from?

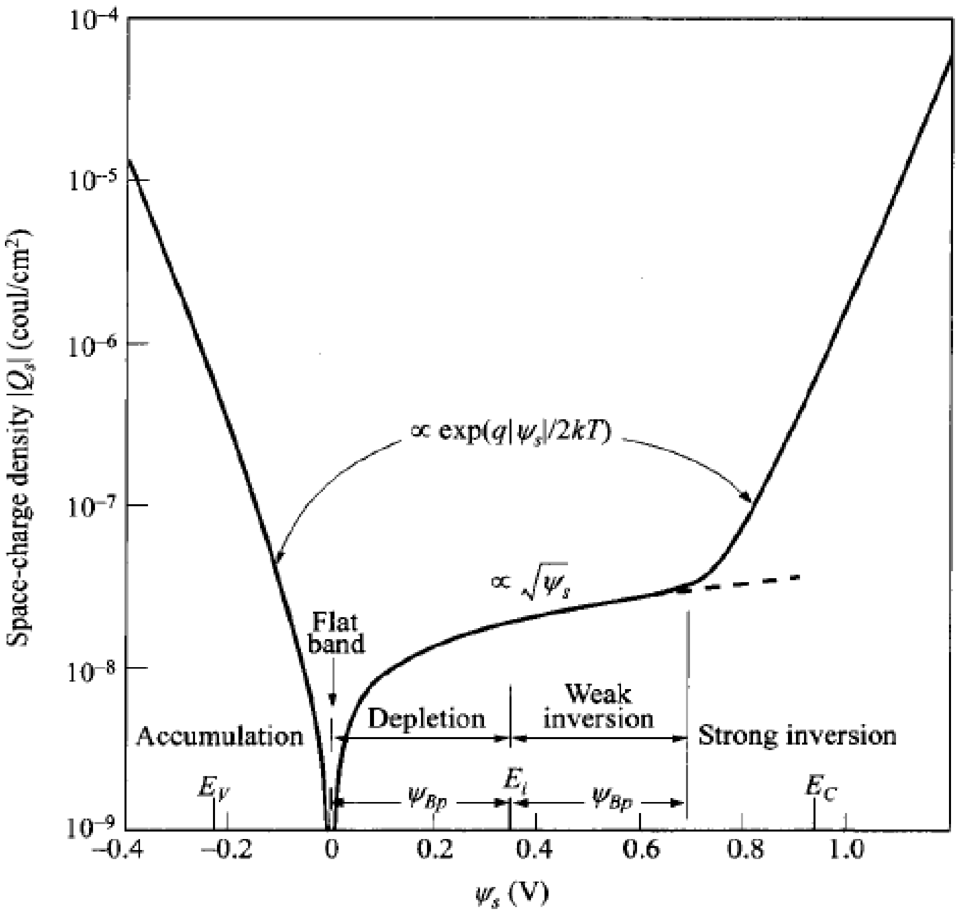
- From thermally generated electron-hole pairs will be (‚slow process', can be followed by CV measurement using AC signal)

- Strong inversion: $\psi_s > 2\,\psi_B$, where ψ_s is the surface potential; surface potential is the voltage between surface and bulk

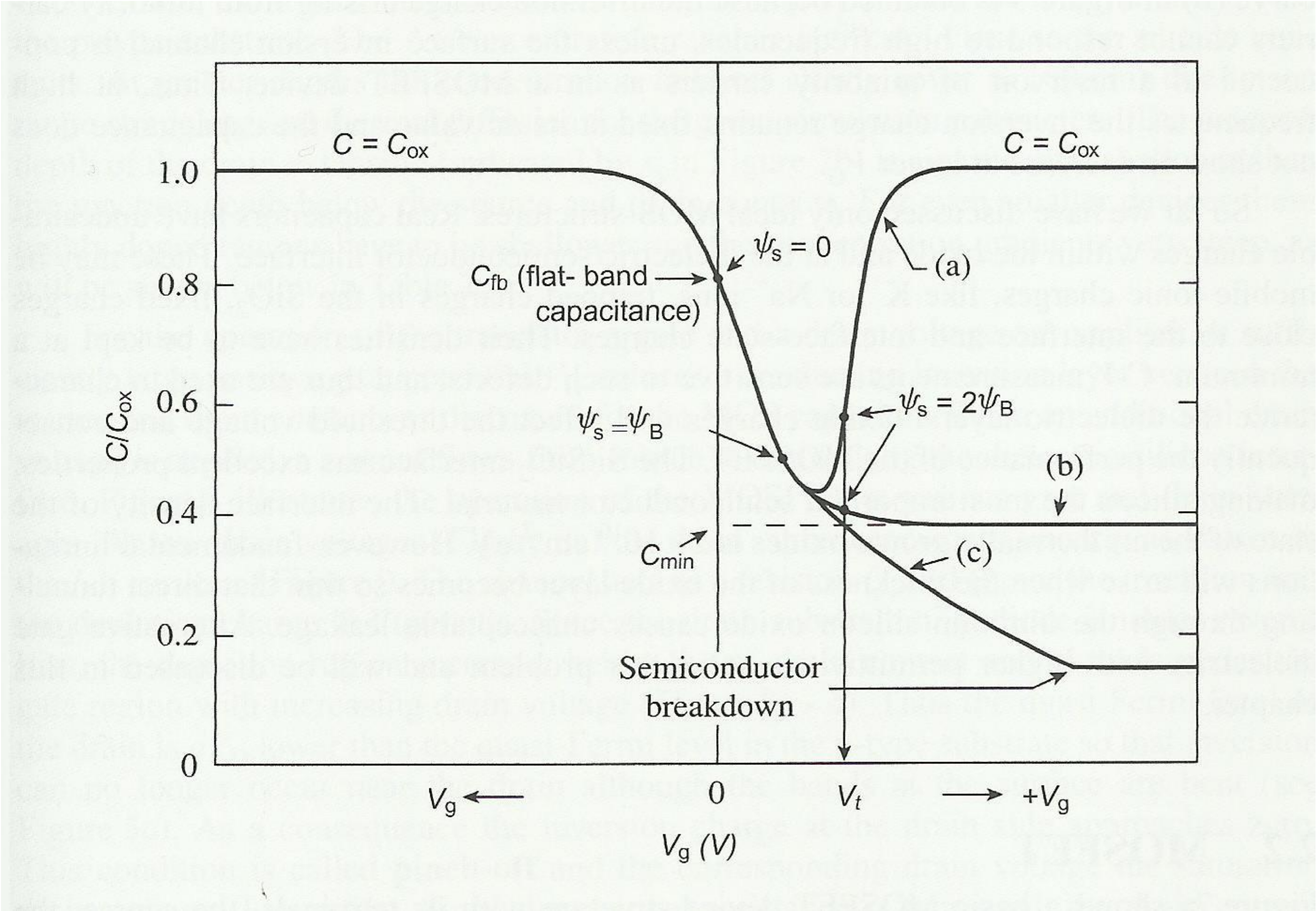
Space charge density vs surface potential

$\psi_s < 0$	Accumulation of holes (bands bending upward).
$\psi_s = 0$	Flat-band condition.
$\psi_{Bp} > \psi_s > 0$	Depletion of holes (bands bending downward).
$\psi_s = \psi_{Bp}$	Fermi-level at midgap, $E_F = E_i(0)$, $n_p(0) = p_p(0) = n_i$.
$2\psi_{Bp} > \psi_s > \psi_{Bp}$	Weak inversion [electron enhancement, $n_p(0) > p_p(0)$].
$\psi_s > 2\psi_{Bp}$	Strong inversion [$n_p(0) > p_{po}$ or N_A].

Space charge density vs. Surface potential



Capacitance-voltage curve of MOS



Low frequency

High frequency

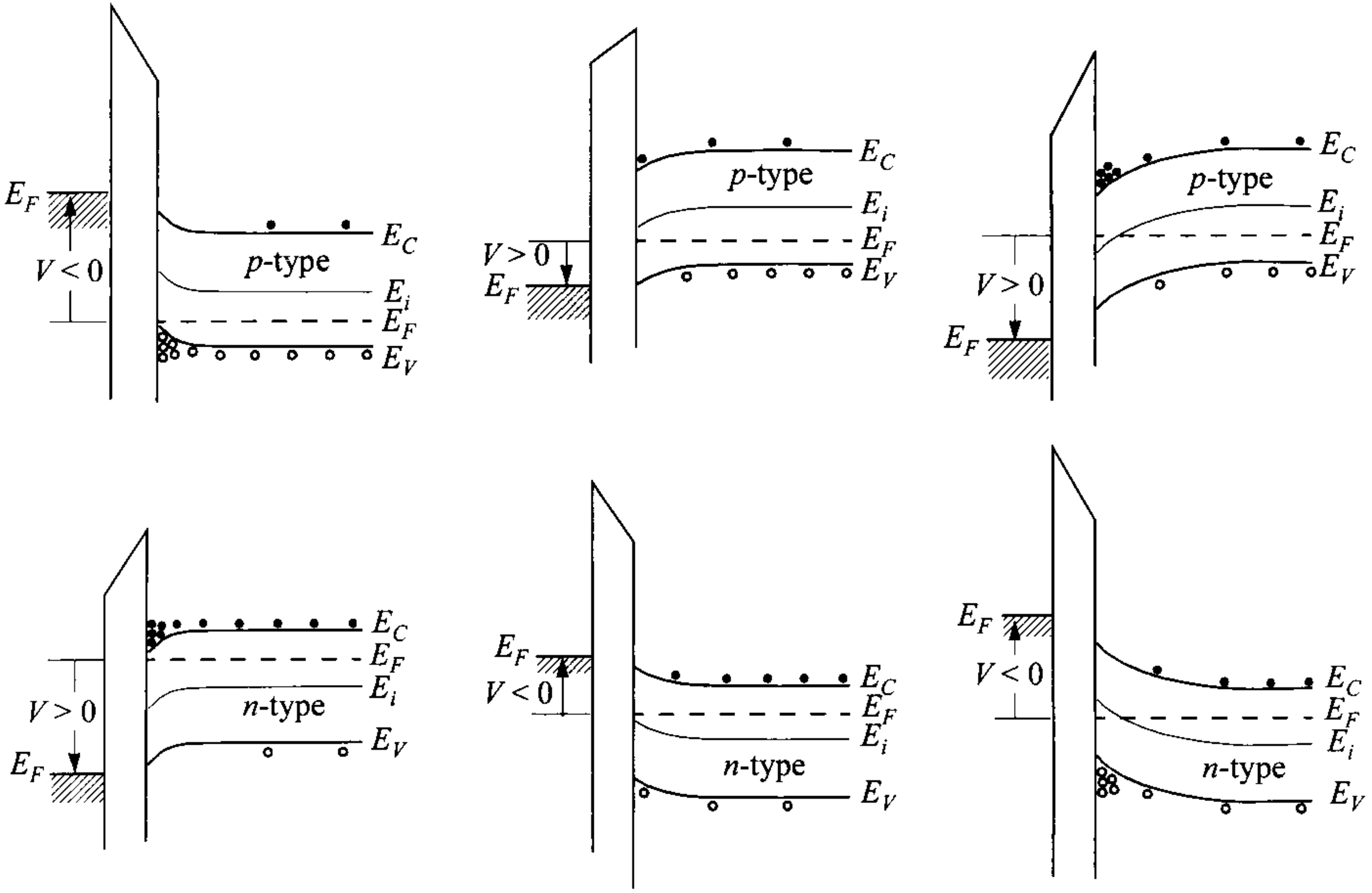
Deep depletion

MOS on p-type vs n-type semiconductor

Accumulation **Depletion** **Inversion**

p-type

n-type



Calculation of the threshold voltage

Assumption: before the onset of strong inversion Q_d»Q_i → the effect of the weak inversion layer is neglected

$$V_G = V_{ox} + \psi_s$$

$$V_{ox} = t_{ox}E_{ox} \qquad D_{ox} = D_S \rightarrow \varepsilon_{ox}E_{ox} = \varepsilon_{ox}E_{ox}$$

Electric displacement field is continuous over the interface

$$V_{ox} = t_{ox}\frac{\varepsilon_s}{\varepsilon_{ox}}E_s = t_{ox}\frac{\varepsilon_s}{\varepsilon_{ox}}\frac{qN_Ax_d}{\varepsilon_s} = \frac{qN_Ax_d}{C_{ox}}$$

$$E(x) = \frac{qN_D}{\epsilon_s}(x_d - x)$$

$$\psi(x) = -\int_{x_d}^{x}E(x)dx = \frac{qN_A}{2\varepsilon_s}(x_d - x)^2$$

$$\psi_s = \frac{qN_Ax_d^2}{2\varepsilon_s} \rightarrow x_d = \sqrt{\frac{2\varepsilon_s\psi_s}{qN_A}}$$

$$V_{ox} = \frac{qN_A}{C_{ox}}\sqrt{\frac{2\varepsilon_s\psi_s}{qN_A}} = \frac{\sqrt{2q\varepsilon_sN_A}}{C_{ox}}\sqrt{\psi_s} = \gamma\sqrt{\psi_s}$$

$$V_G = \psi_s + \gamma\sqrt{\psi_s}$$

Calculation of the threshold voltage

Onset of the strong inversion: $\psi_s = 2\,\psi_B$

$$\psi_B = \frac{W_i - W_F}{q}$$

$$p = n_i e^{\frac{W_i - W_F}{kT}} \rightarrow \psi_B = \frac{kT}{q} ln\left(\frac{p}{n_i}\right) \approx \frac{kT}{q} ln\left(\frac{N_A}{n_i}\right)$$

Threshold voltage (ideal): $V'_{T0} = 2\psi_B + \gamma\sqrt{2\psi_B}$

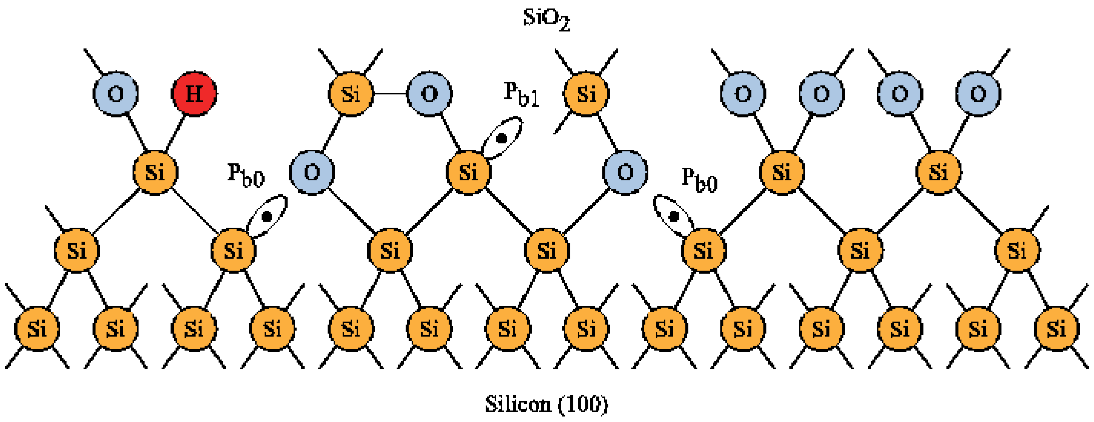
It shows how much gate voltage is need to make the surface as much n-type as the bulk is p-type.

Note, the original asssumptions: i) $\phi_{MS} = \phi_M - \phi_S = 0$ (flat band assumption), ii) no net charge

Non-ideal MOS: surface states and work function adjustment

$$V_{T0} = V_{FB} + 2\psi_B + \gamma\sqrt{2\psi_B}$$

where $$V_{FB} = \phi_{MS} - \frac{Q_{ss}}{C_{ox}} - \frac{Q_i}{C_{ox}}$$



- In practice $\phi_M \neq \phi_S$
- Q_{SS} : surface state charges
- Q_i: Threshold voltage adjustment charge, donor or acceptor (D·q)

In strong inversion $Q_i \gg Q_d \rightarrow$ $Q_i = C_{ox}(V_G - V_{T0})$, governs the MOSFET ON-state

Below that weak inversion; governs the MOSFET OFF-state (subthreshold behavior)