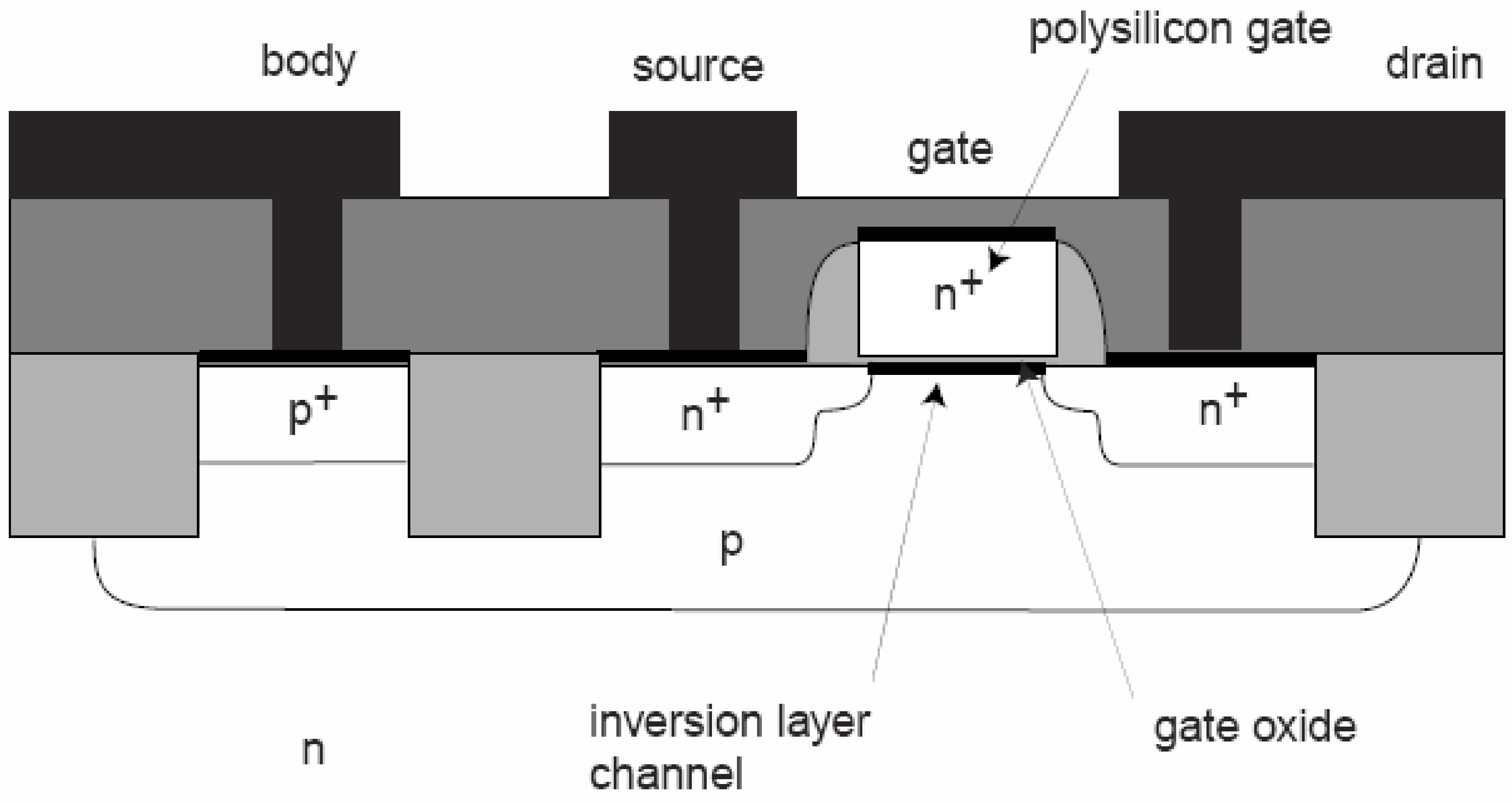
10

Metal Oxide Semiconductor Field Effect Transistors (MOSFETs)

December 2025

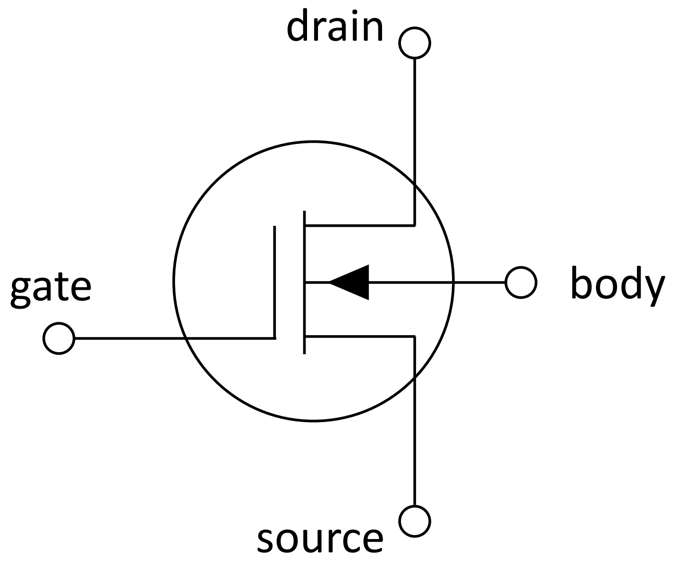
MOSFETs


body
source
polysilicon gate
drain
gate
n^+
p^+
n^+
n^+
p
n
inversion layer
channel
gate oxide

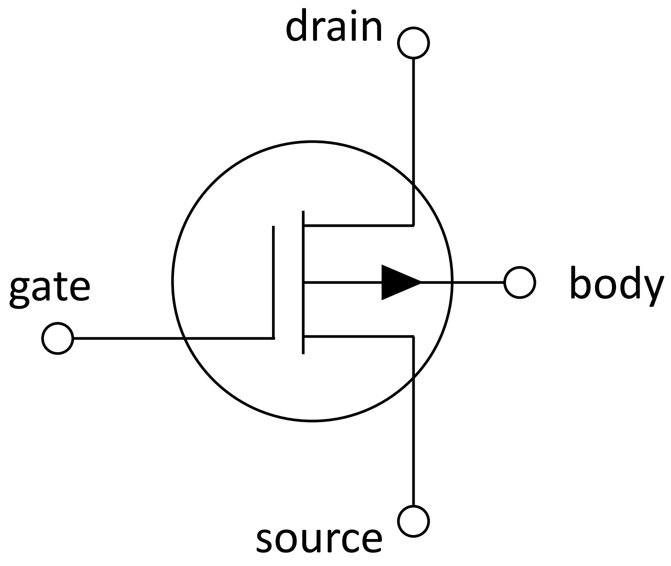
MOSFETs

functions as a switch~ 1 billion /chip

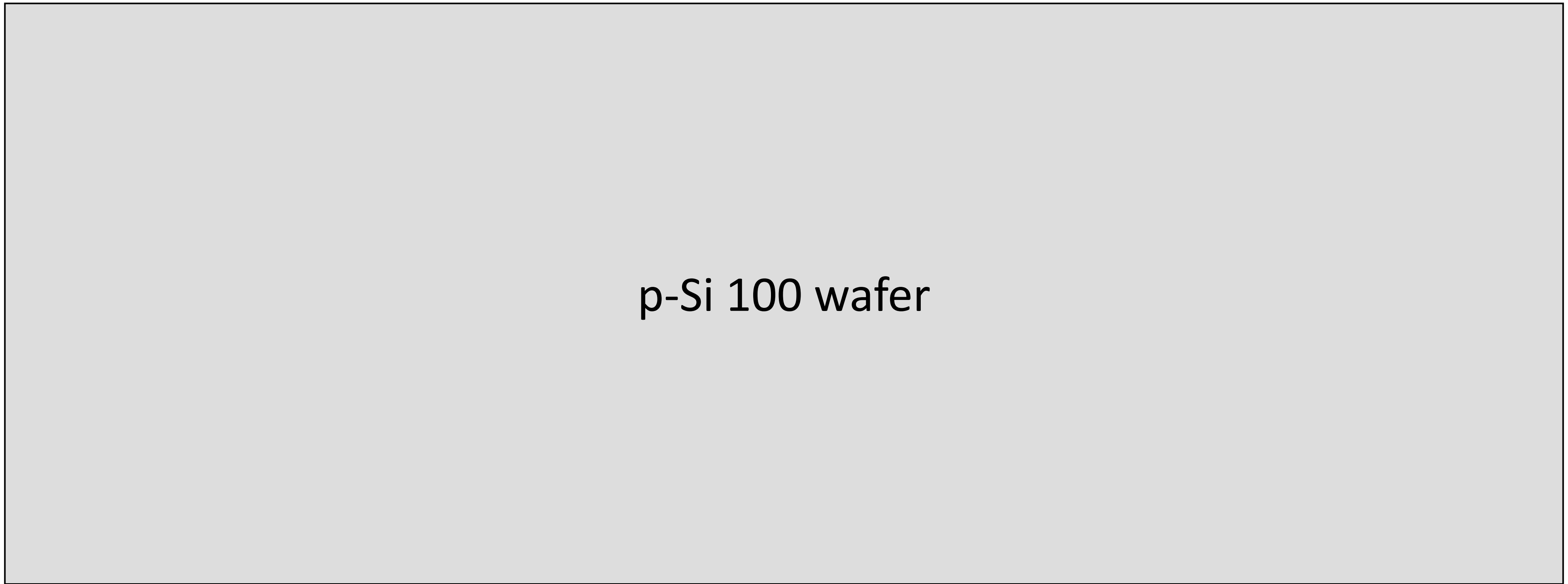
n - channel



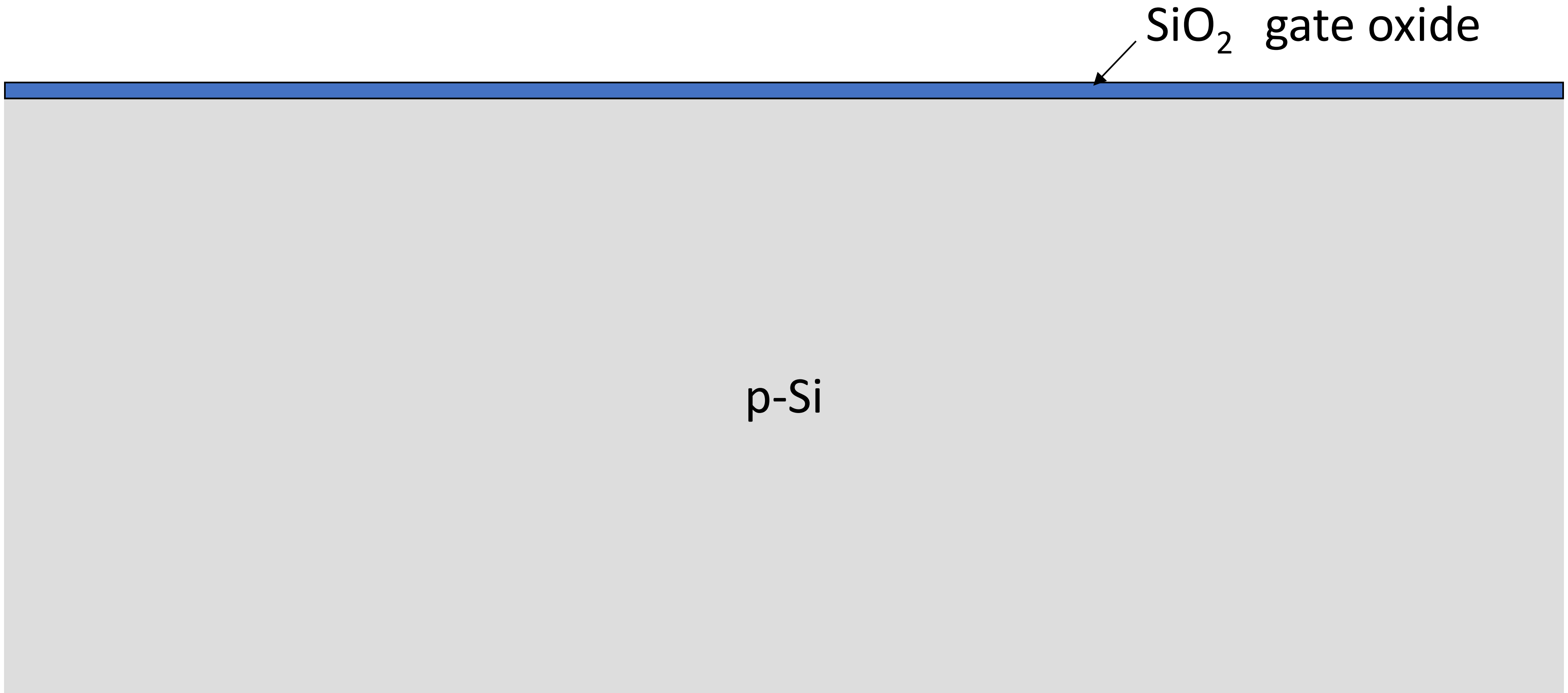
p - channel



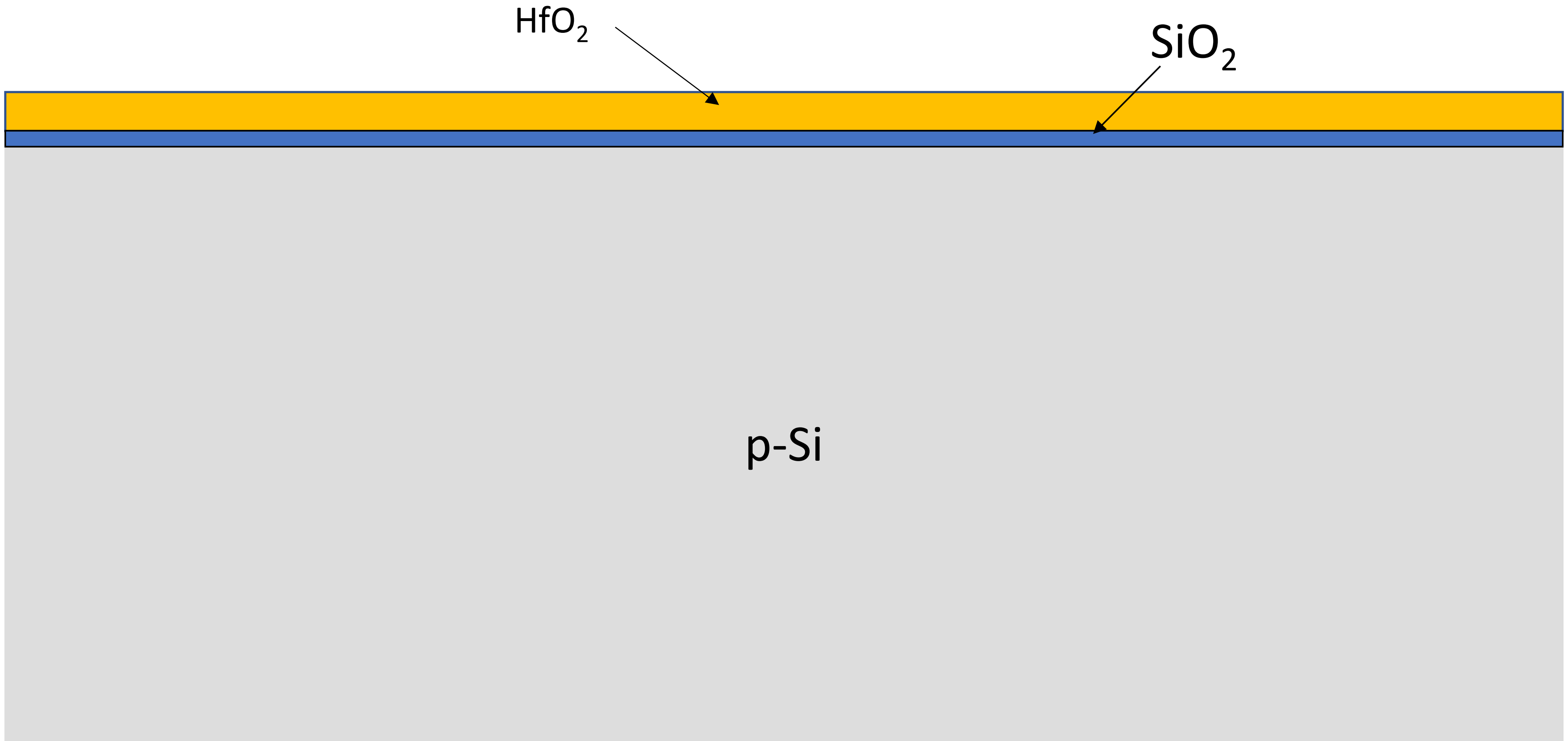
Self-aligned fabrication

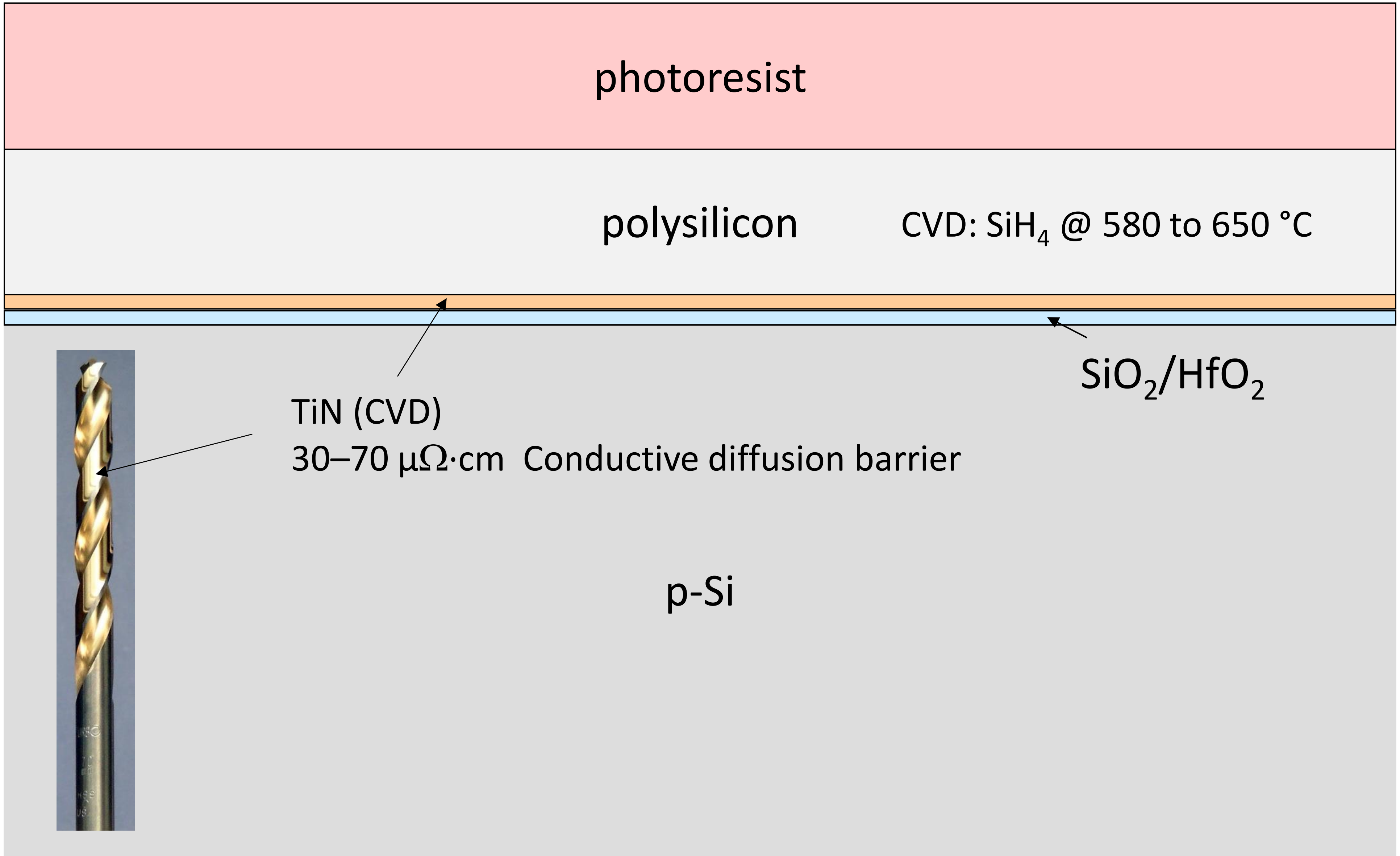


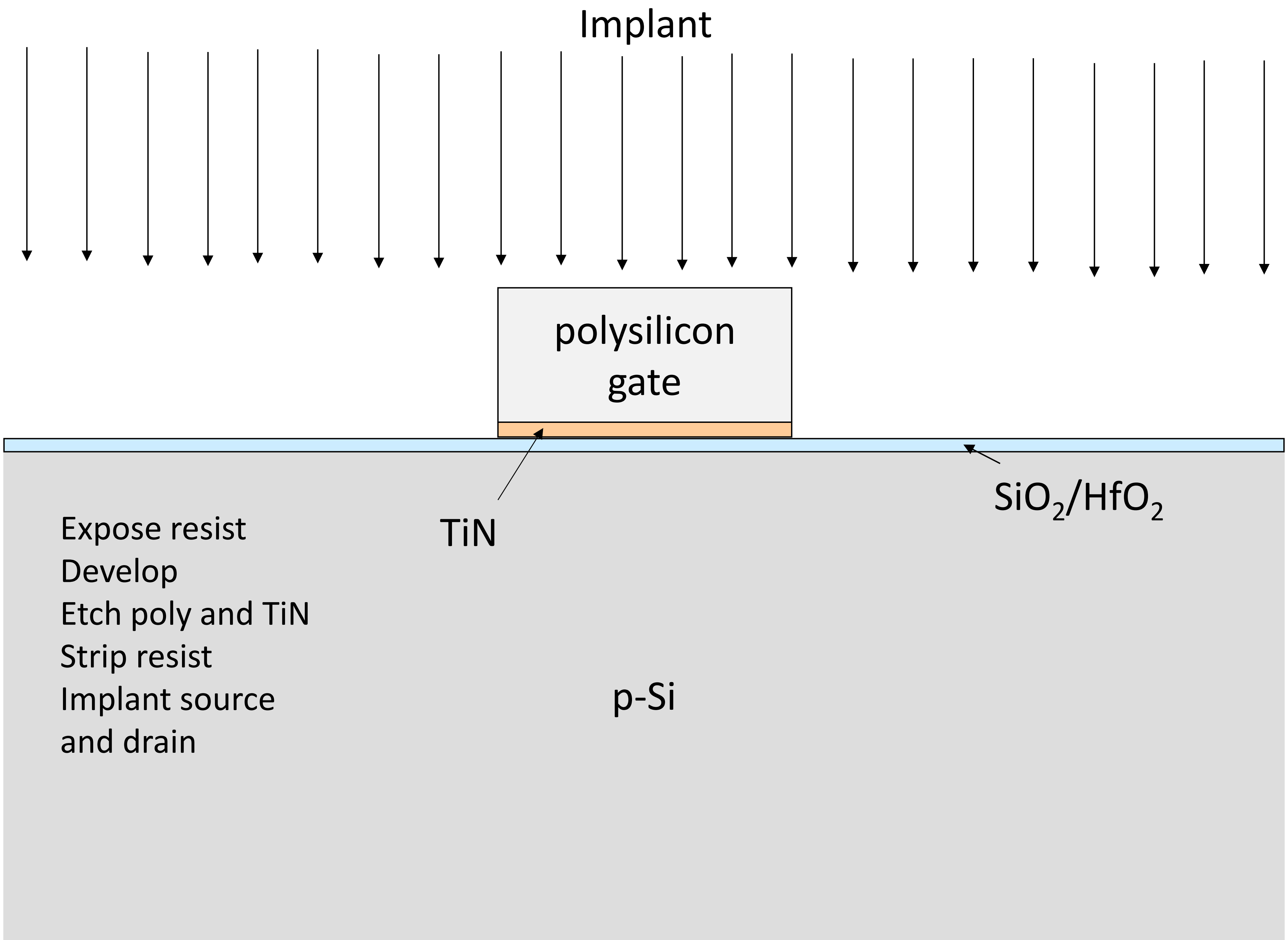
Dry oxidation



gate oxide

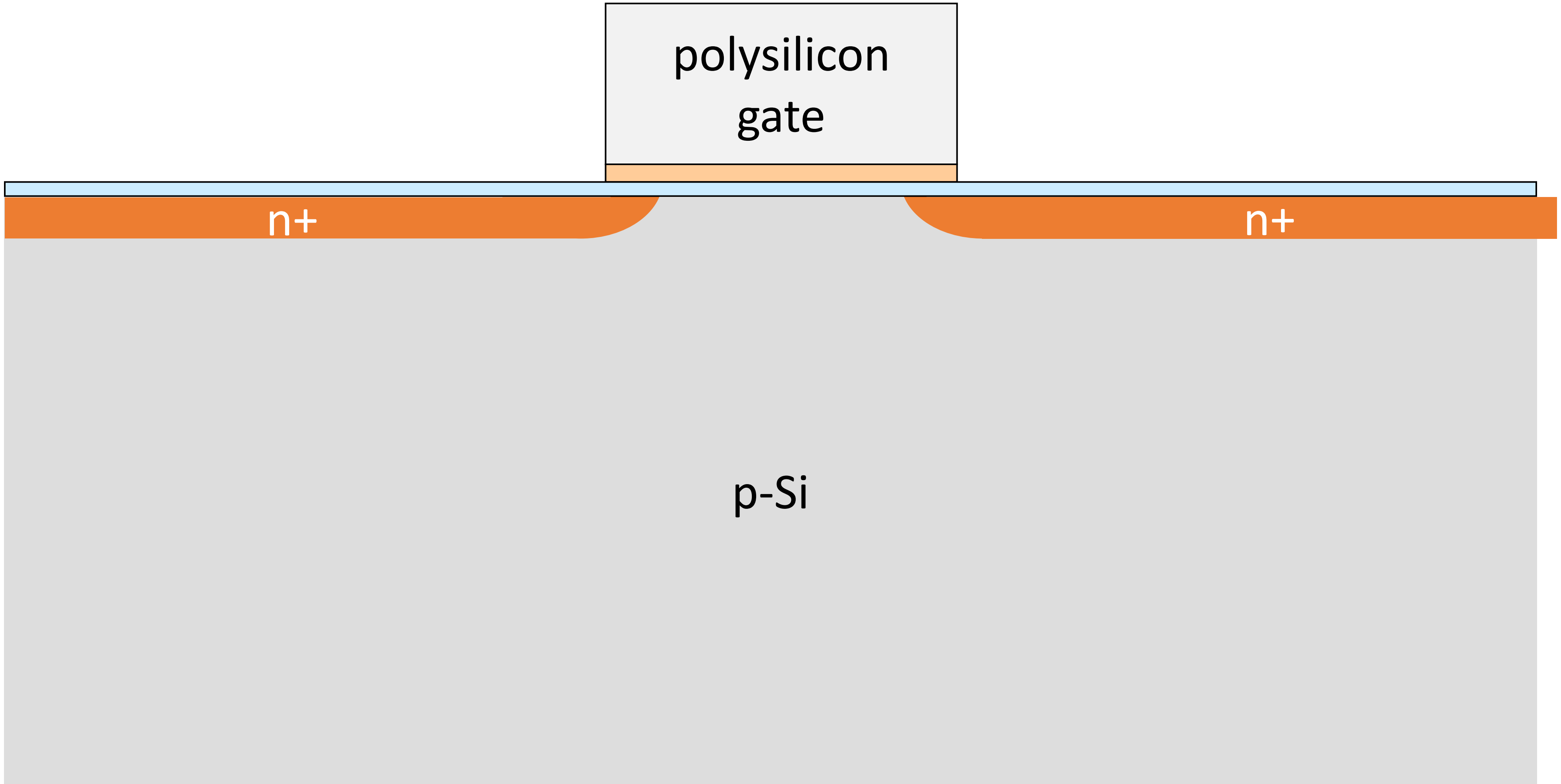



photoresist
polysilicon
CVD: SiH_4 @ 580 to 650 °C
TiN (CVD)
30–70 μΩ·cm Conductive diffusion barrier
SiO_2/HfO_2
p-Si



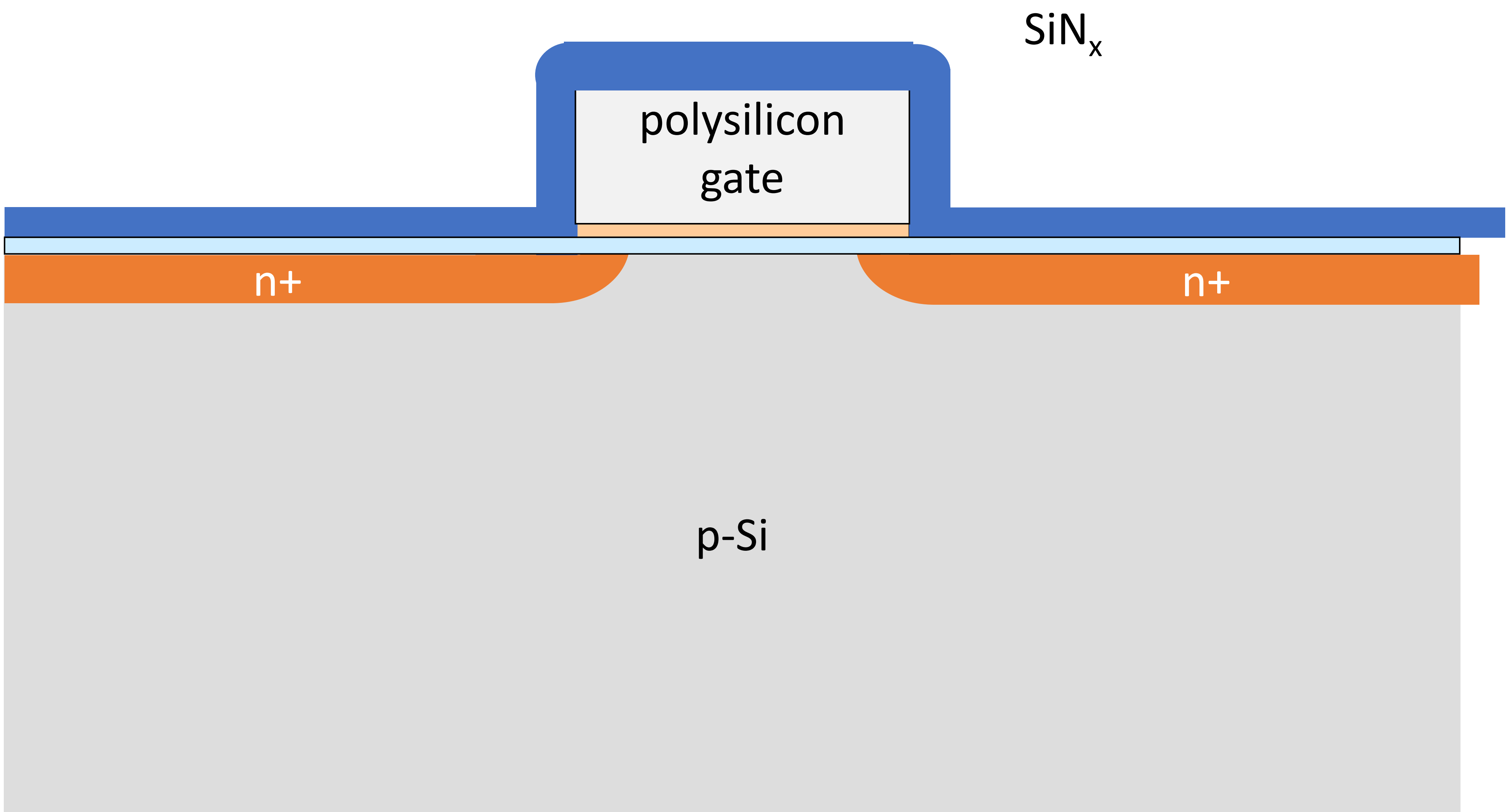
Implant
polysilicon
gate
TiN
SiO_2/HfO_2
Expose resist
Develop
Etch poly and TiN
Strip resist
Implant source
and drain
p-Si

Self-aligned fabrication



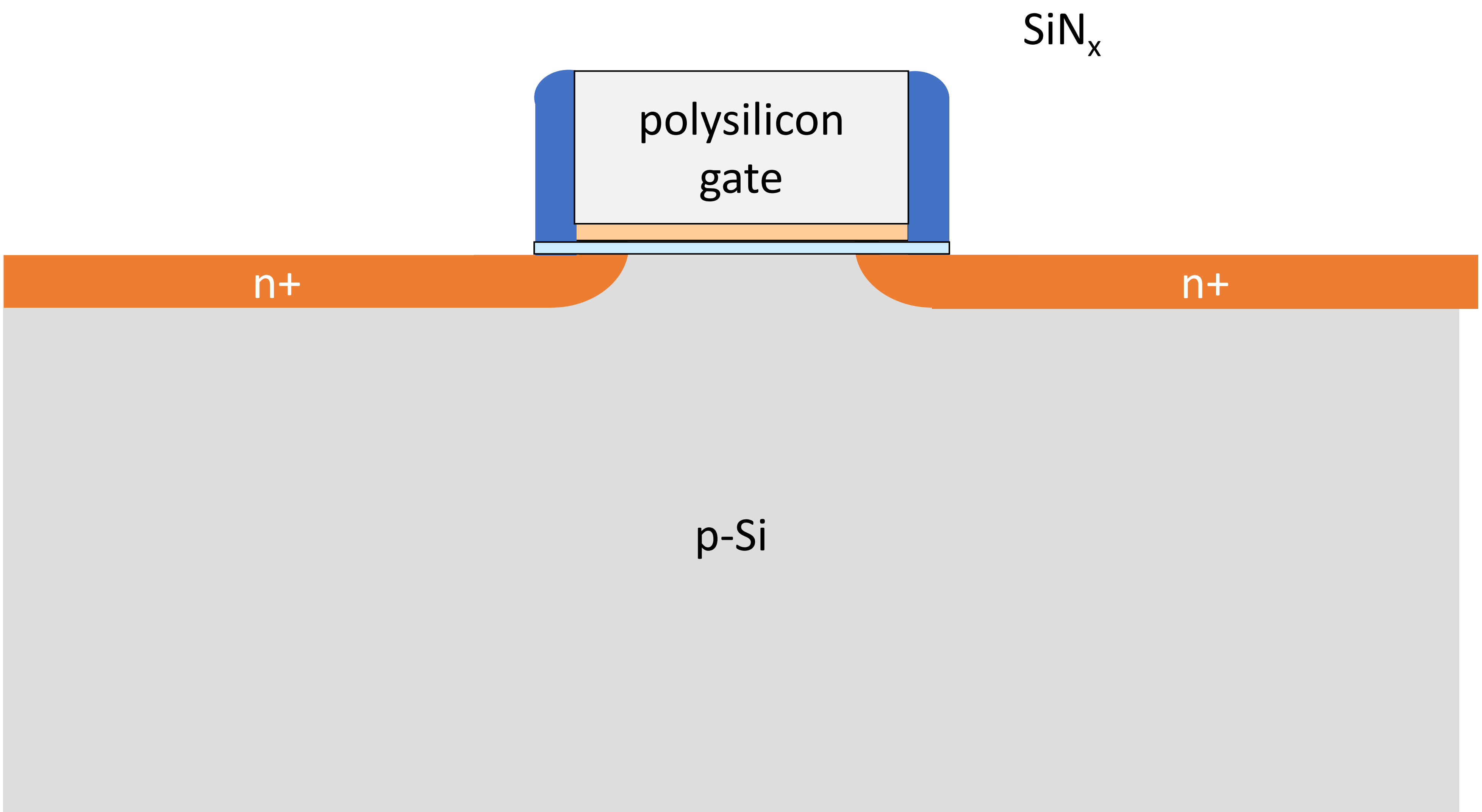
Spacer

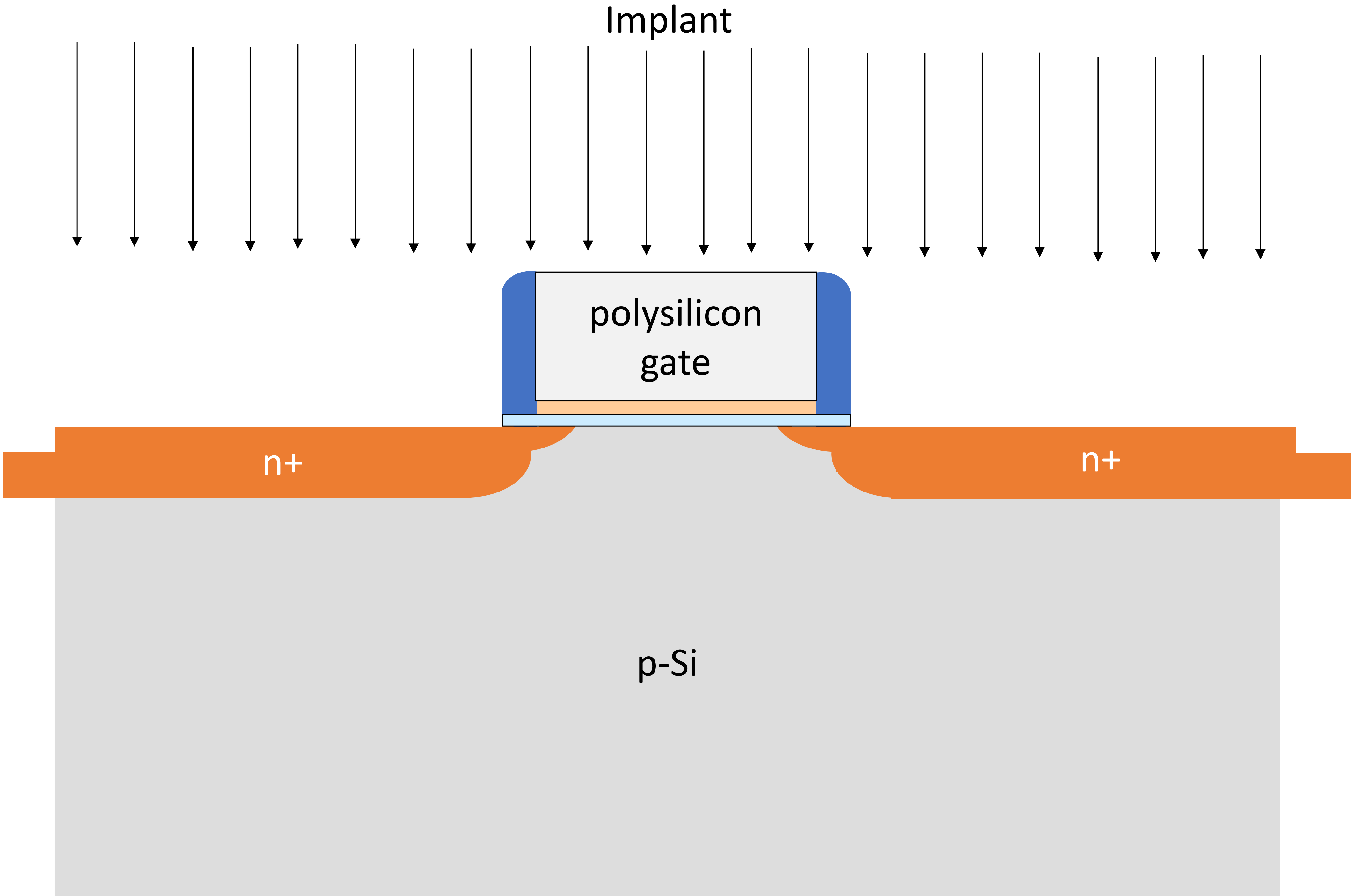
PECVD SiN_x



Spacer

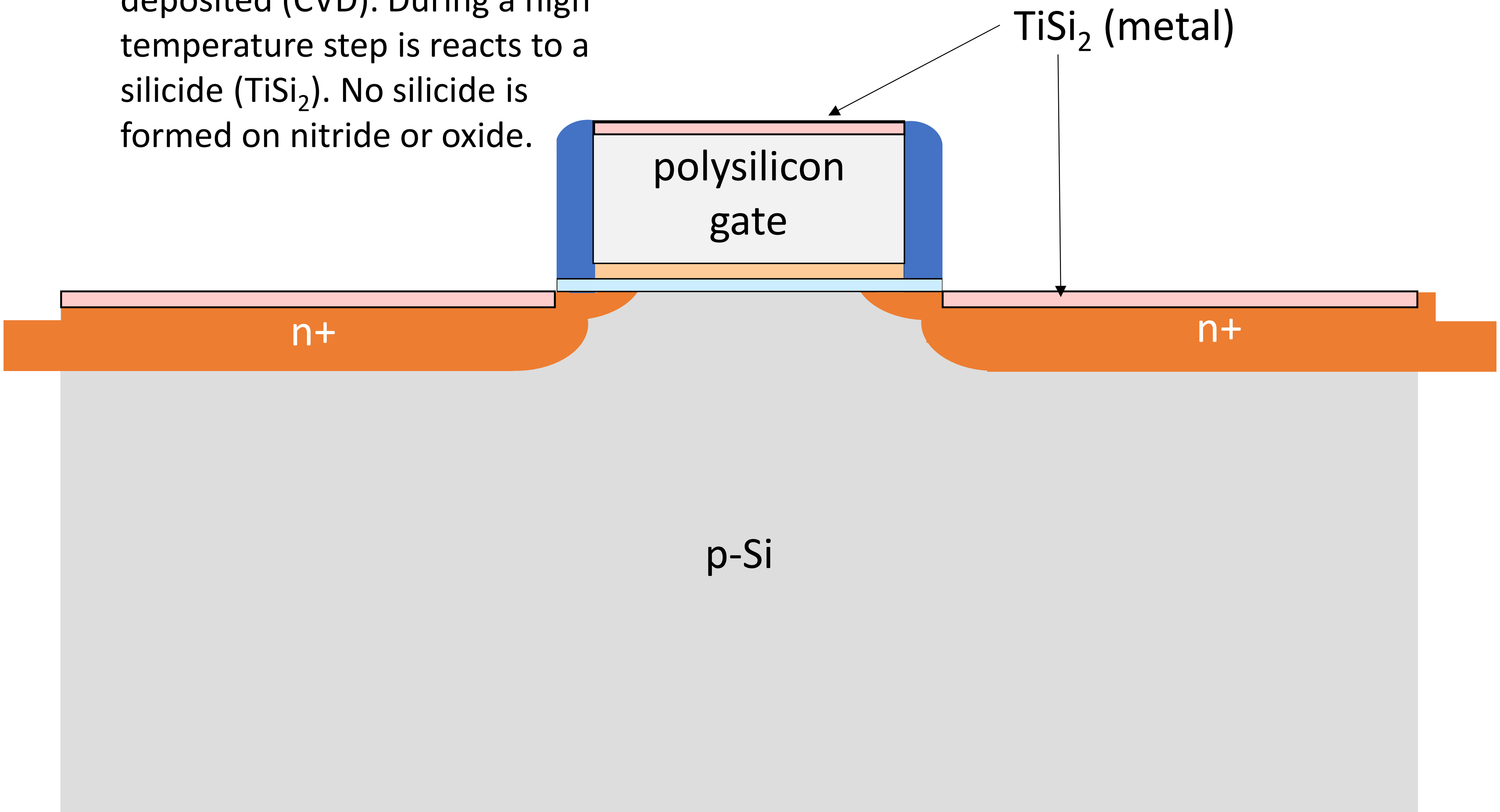
Etch back to leave only sidewalls




Implant
polysilicon gate
n+
n+
p-Si

Salicide (Self-aligned silicide)

Transition metal (Ti, Co,W) is deposited (CVD). During a high temperature step is reacts to a silicide ($TiSi_2$). No silicide is formed on nitride or oxide.



CMOS Complementary Metal Oxide Semiconductor

NMOS is n-channel so it should be in a p-well

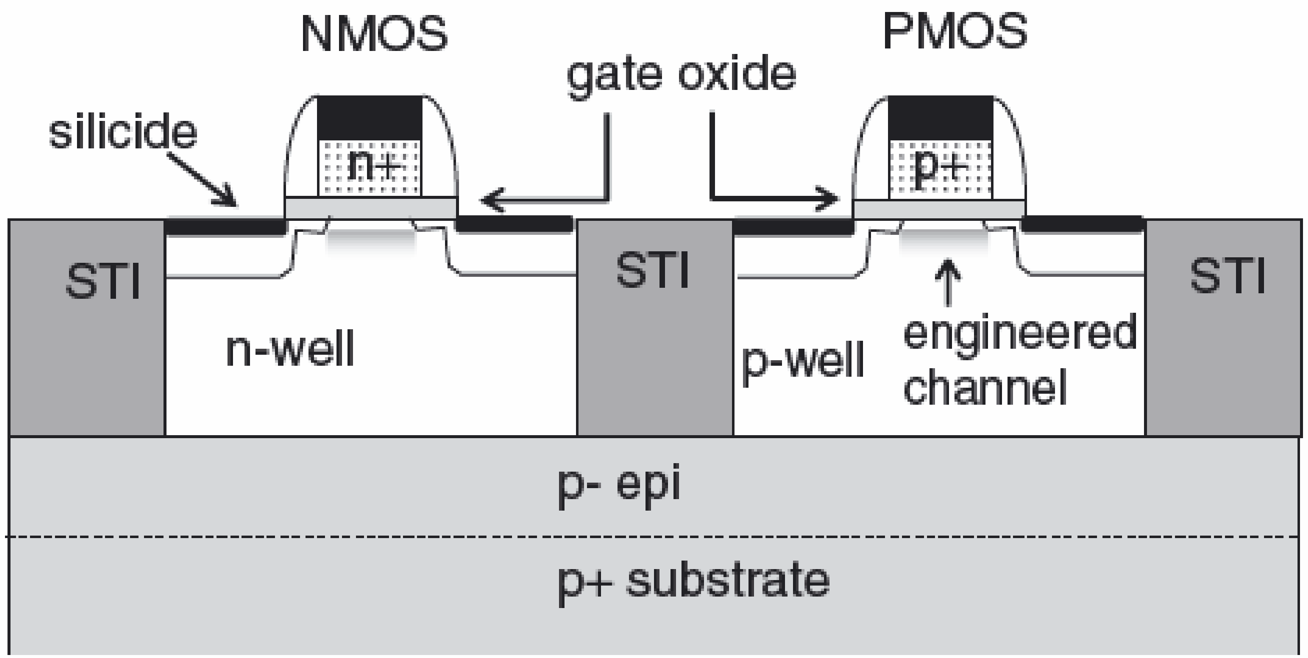
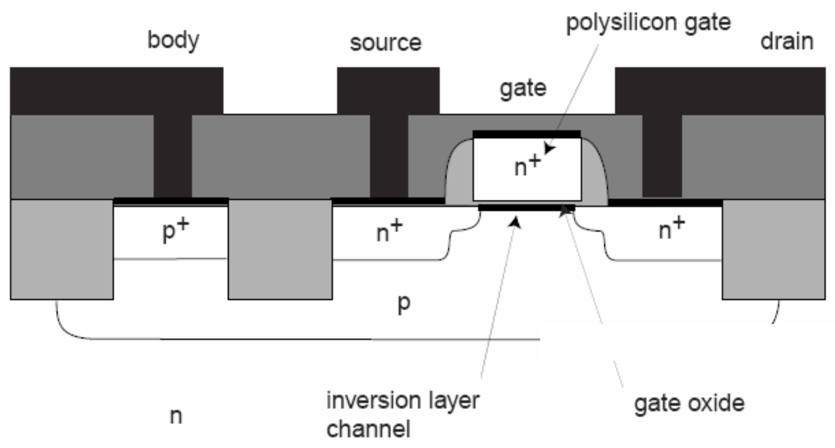
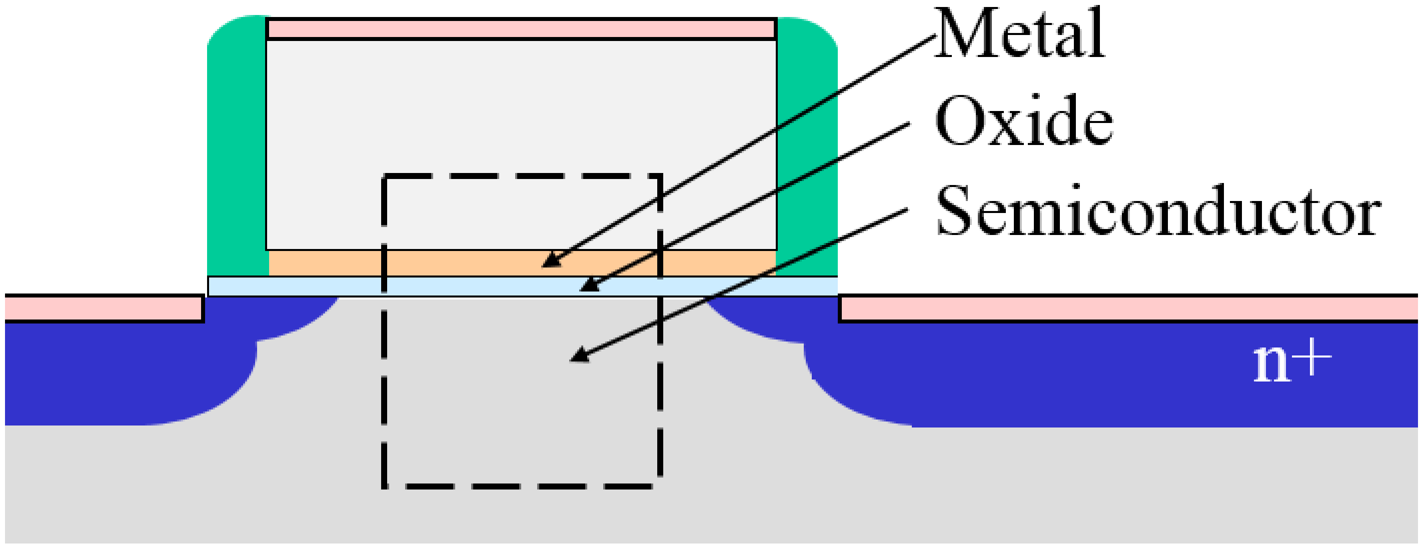


Figure 26.11 Deep submicron CMOS: 200 nm gate length, 5 nm gate oxide, 70 nm junction depth; n^+ poly for NMOS and p^+ poly for PMOS. Shallow trench isolation on epitaxial n^+/p^+ wafer

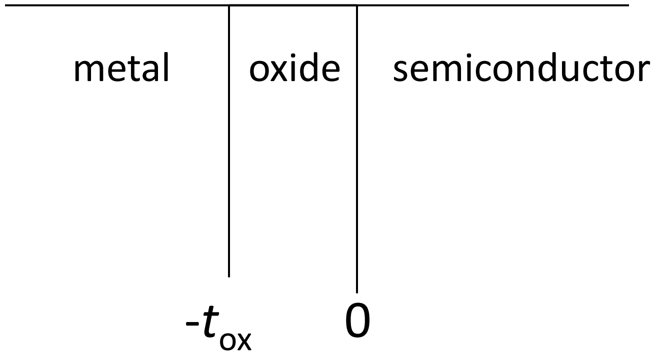
Source: Fransila

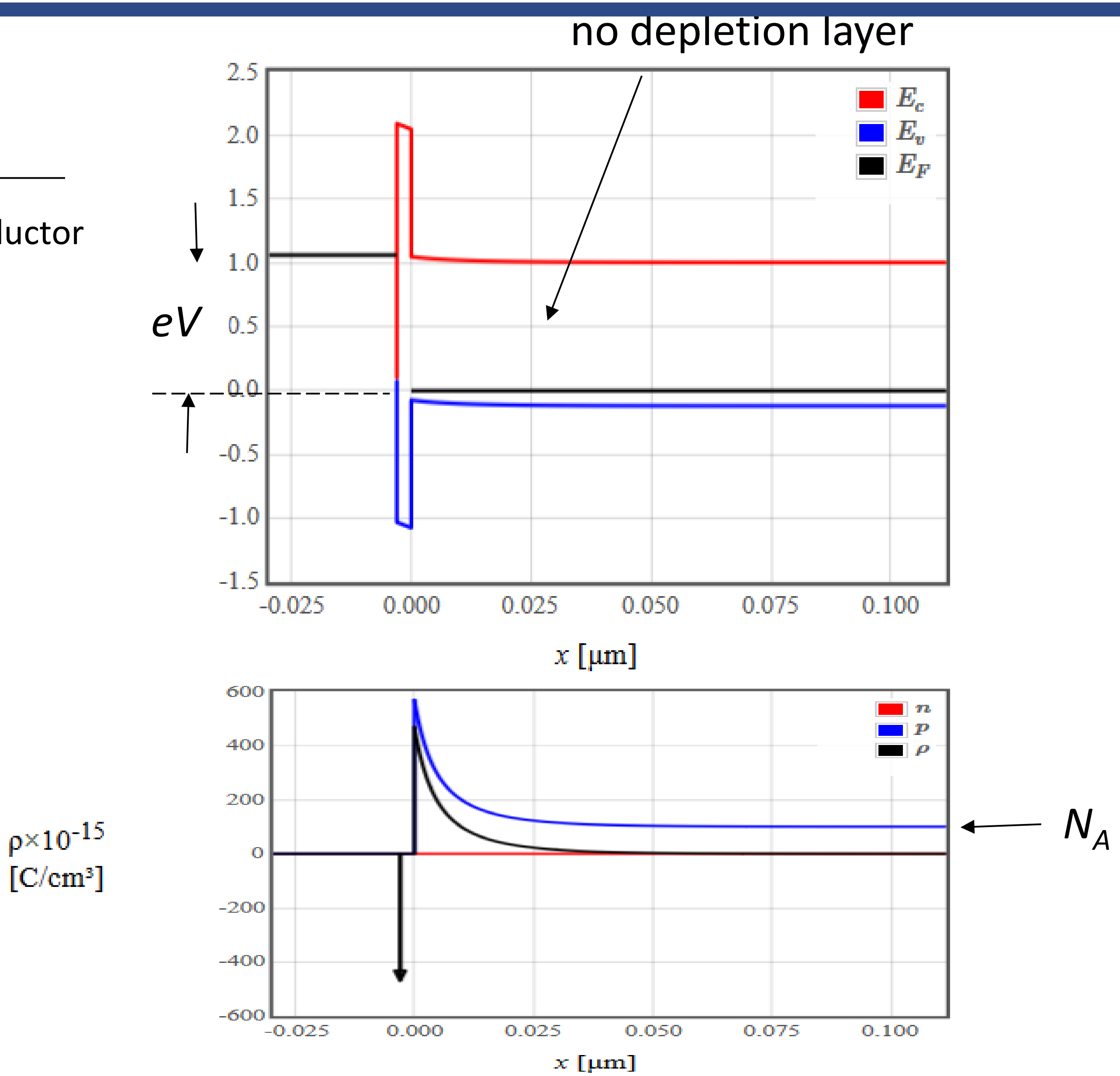
MOS capacitor



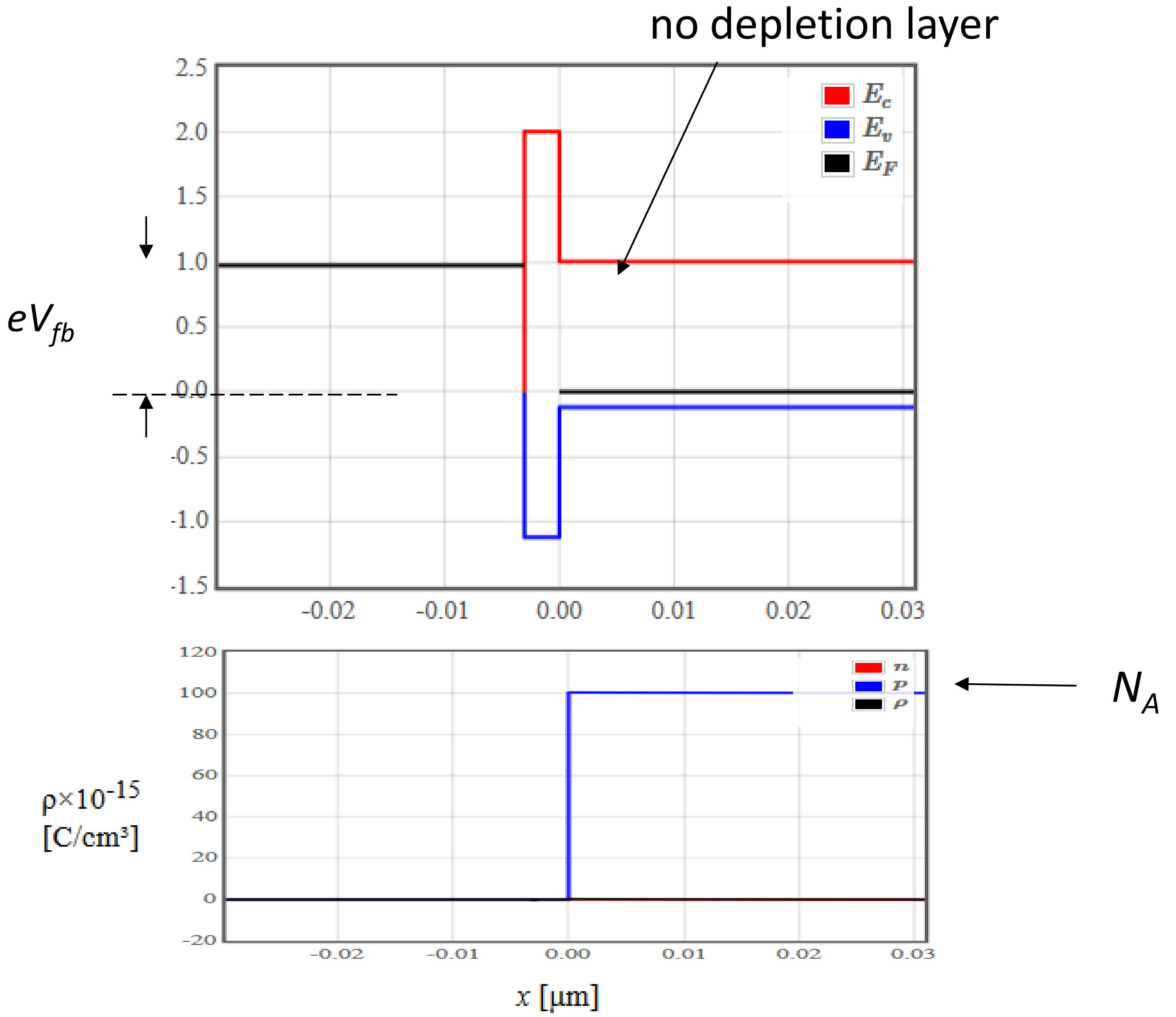


Accumulation



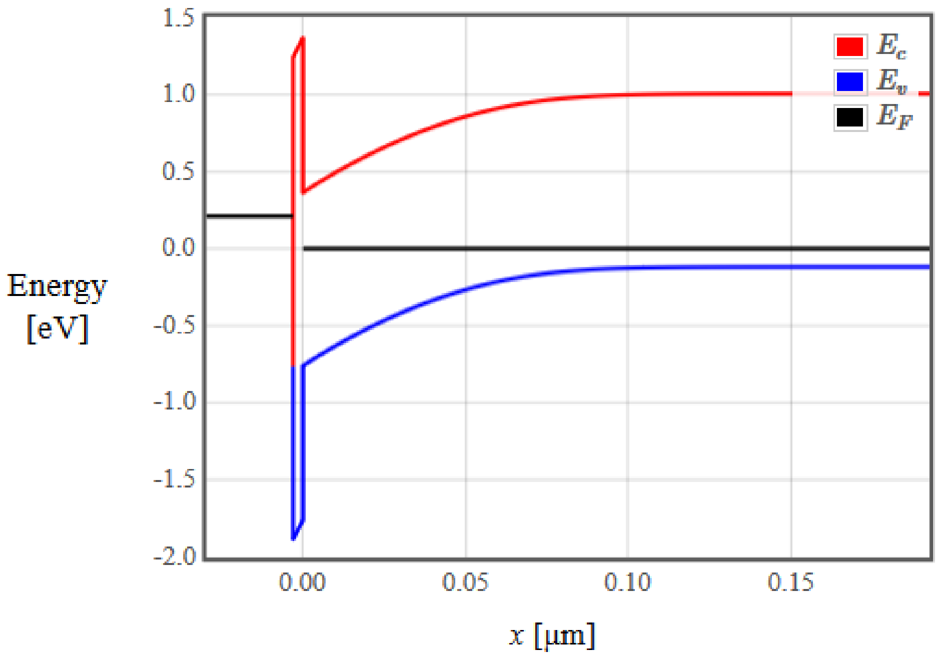


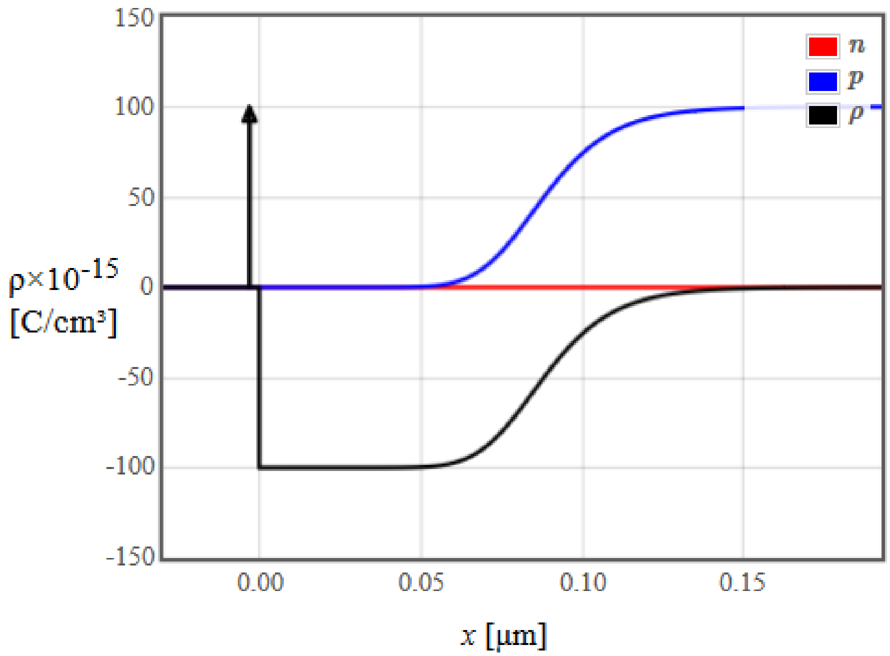
Flat band voltage



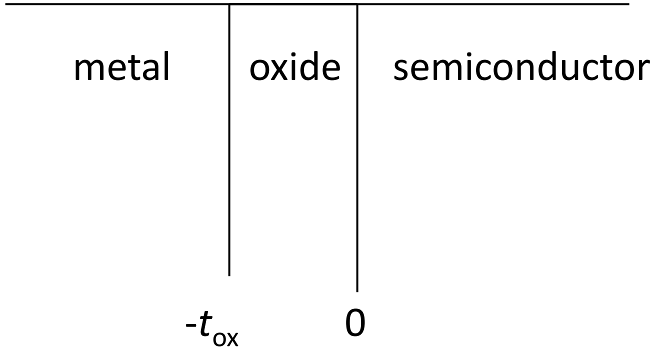
If $\phi_s = \phi_m$, the flatband voltage is the zero bias voltage

Depletion

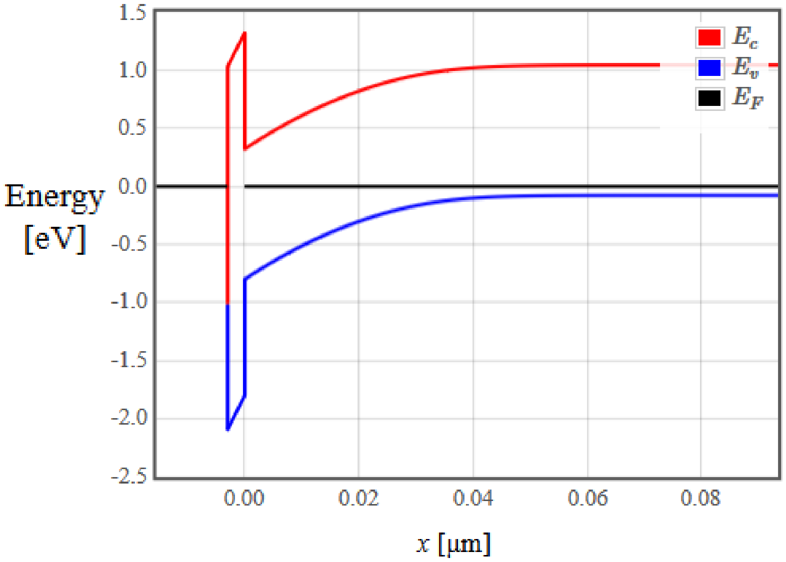

Energy [eV]
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
0.00
0.05
0.10
0.15
x [μm]
E_c
E_v
E_F

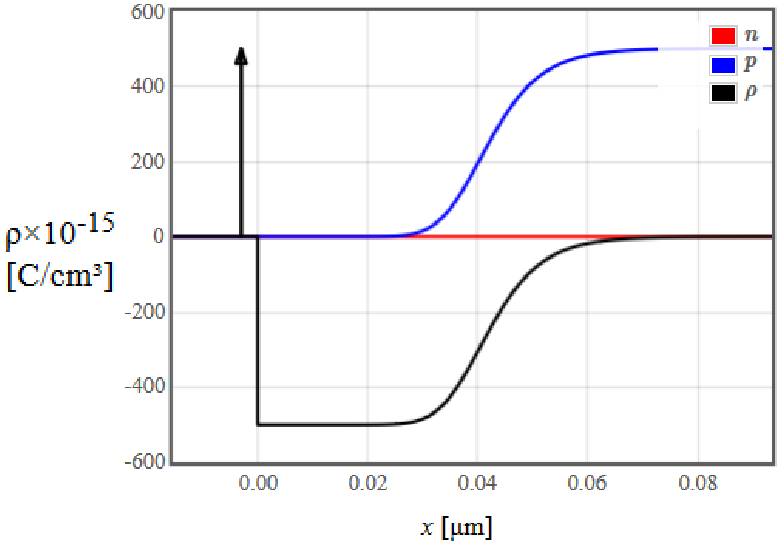

ρ×10-15 [C/cm³]
150
100
50
0
-50
-100
-150
0.00
0.05
0.10
0.15
x [μm]
n
p
ρ

Zero bias



$e\phi_m$
Al 4.1 eV
p+ poly 4.05 eV
n+ poly 5.05 eV



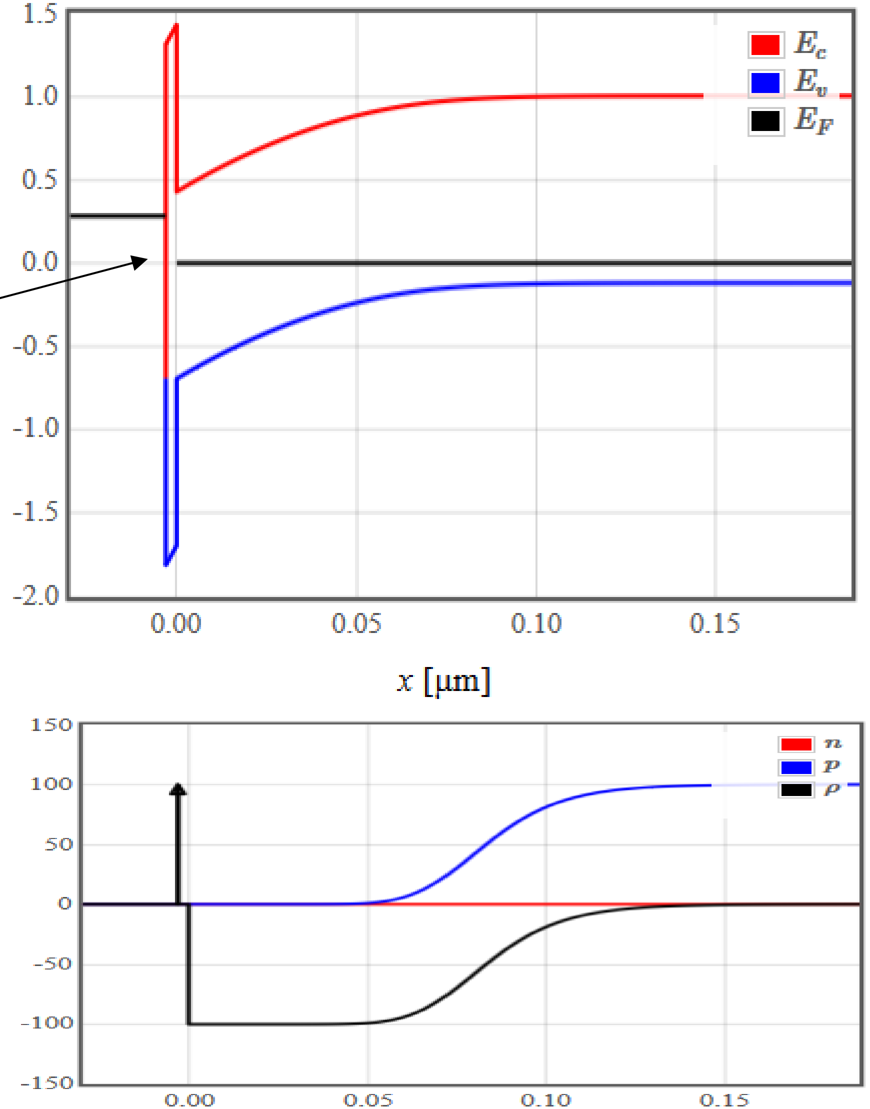


Can be in accumulation or depletion depending on workfunctions

Weak Inversion

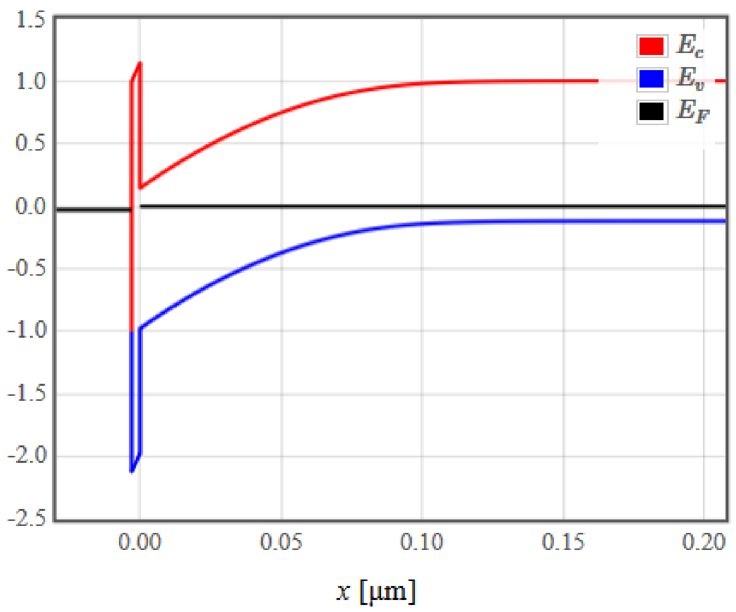
Majority carriers at x = 0 change from p to n

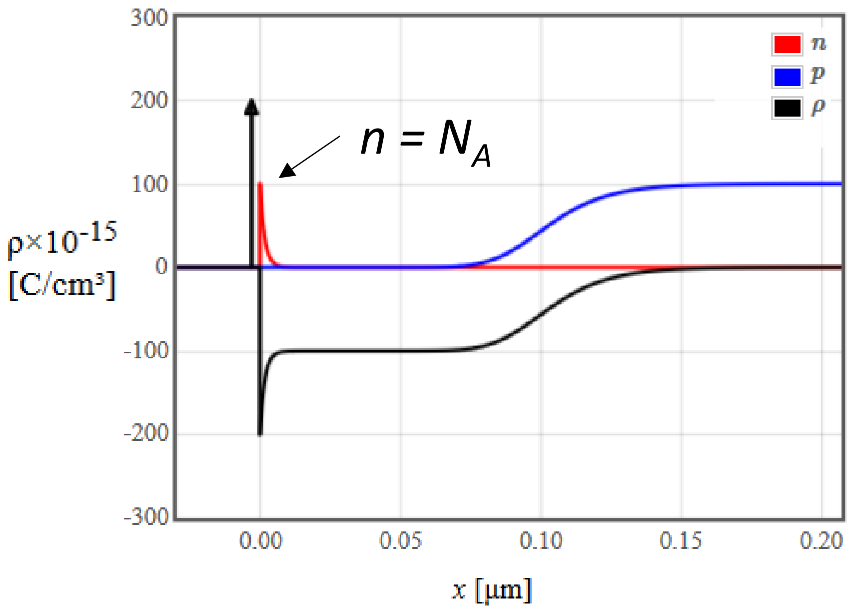
n > p
at the interface



$\rho \times 10^{-15}$
[C/cm³]

Threshold voltage

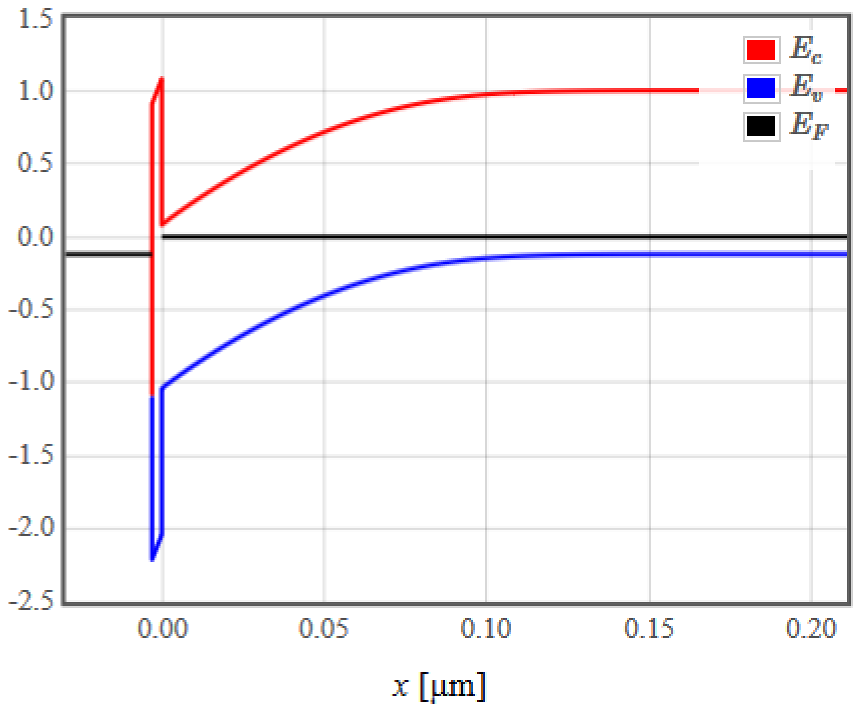


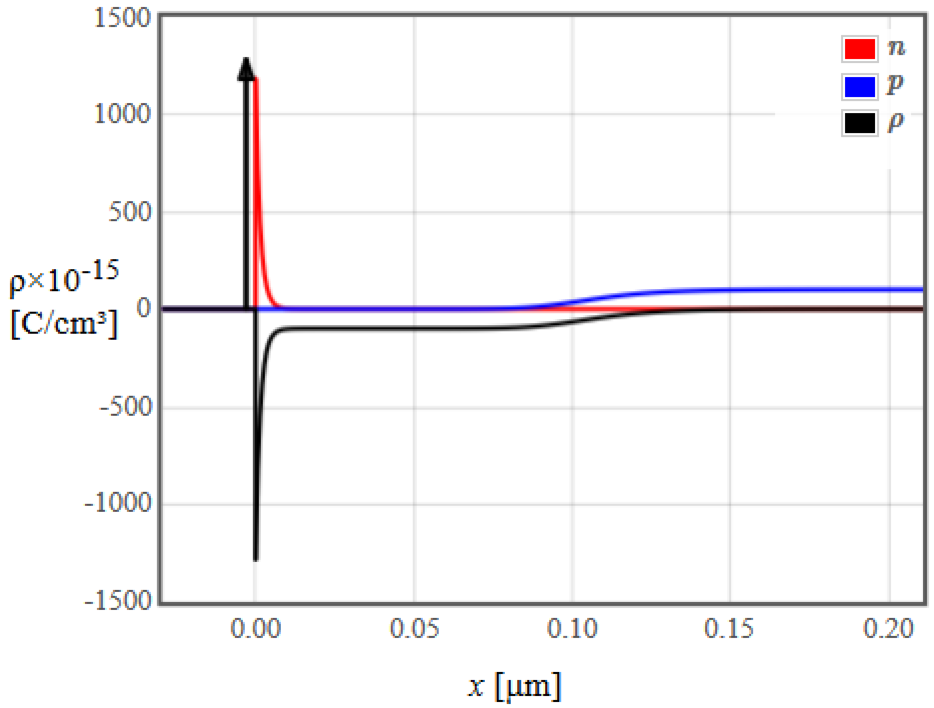


Strong inversion: $n = N_A$ at $x = 0$, the semiconductor-oxide interface

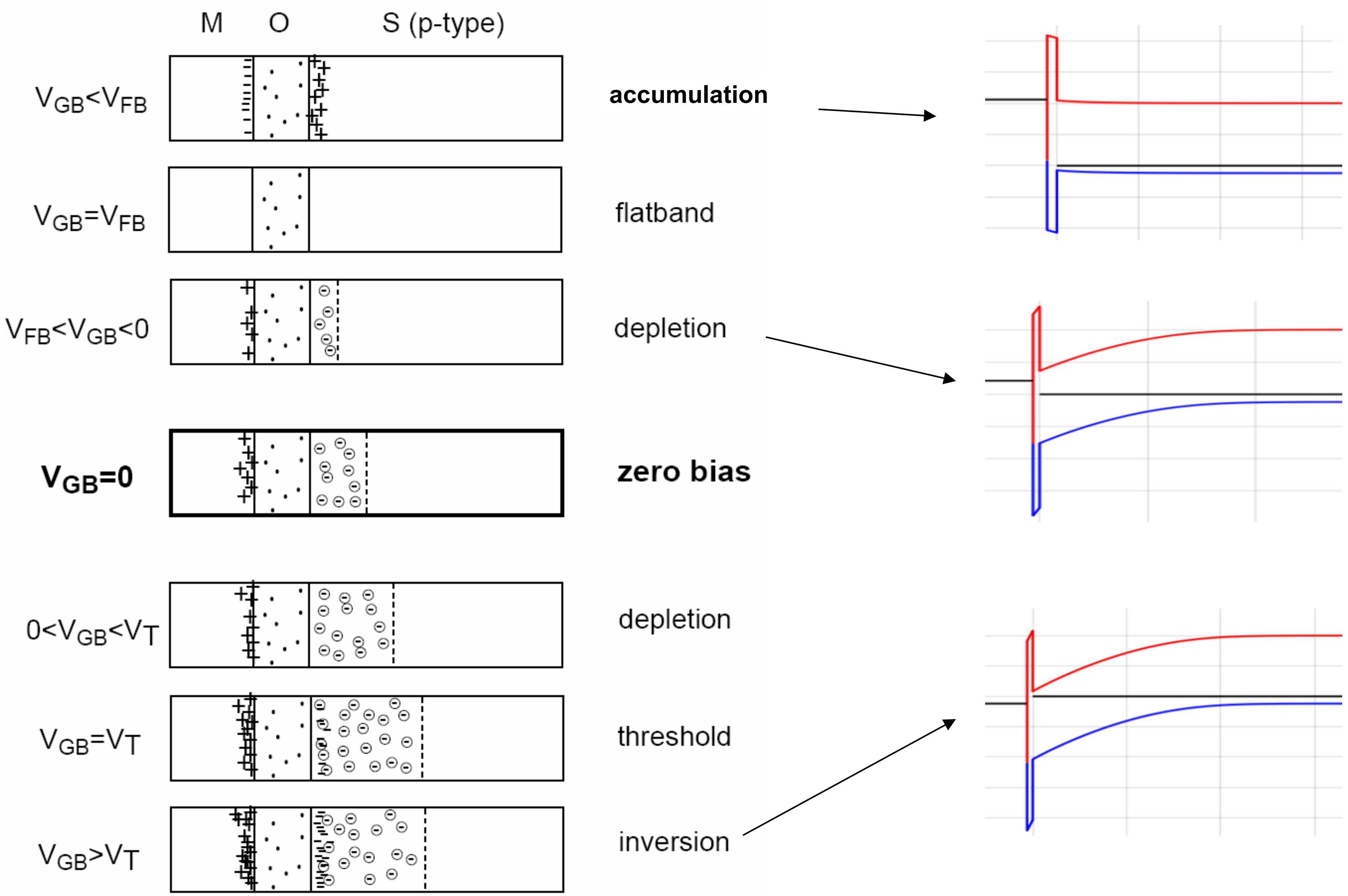
Inversion

$n > N_A$ at $x = 0$, the semiconductor-oxide interface

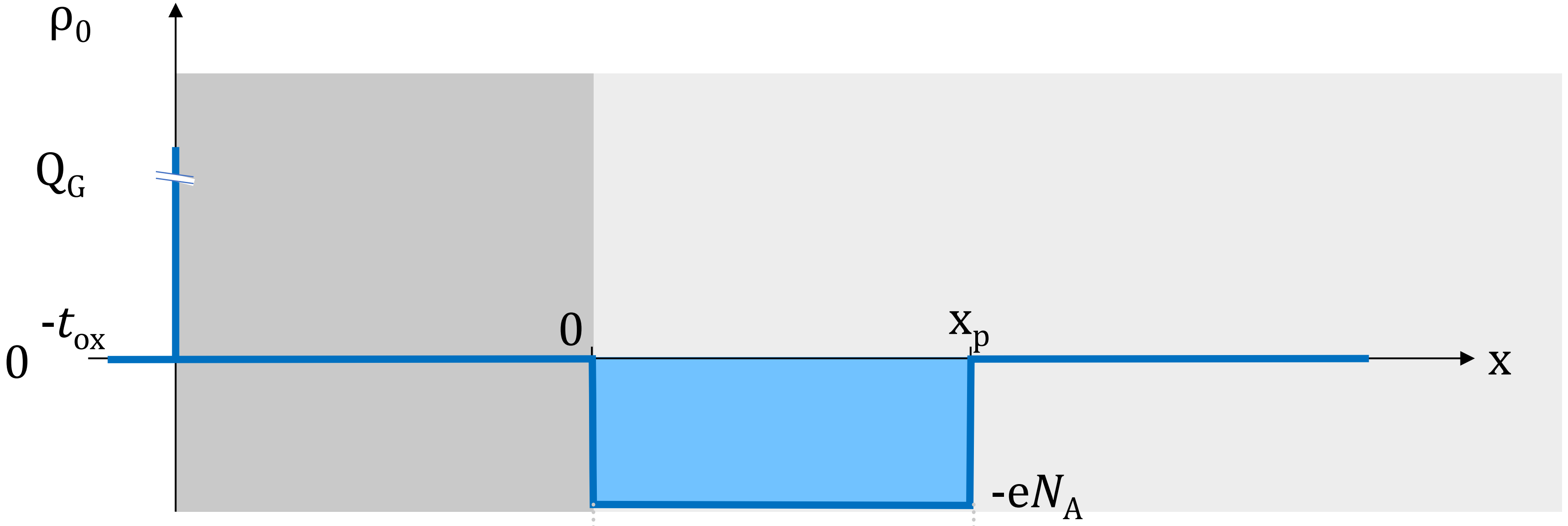




MOS capacitor



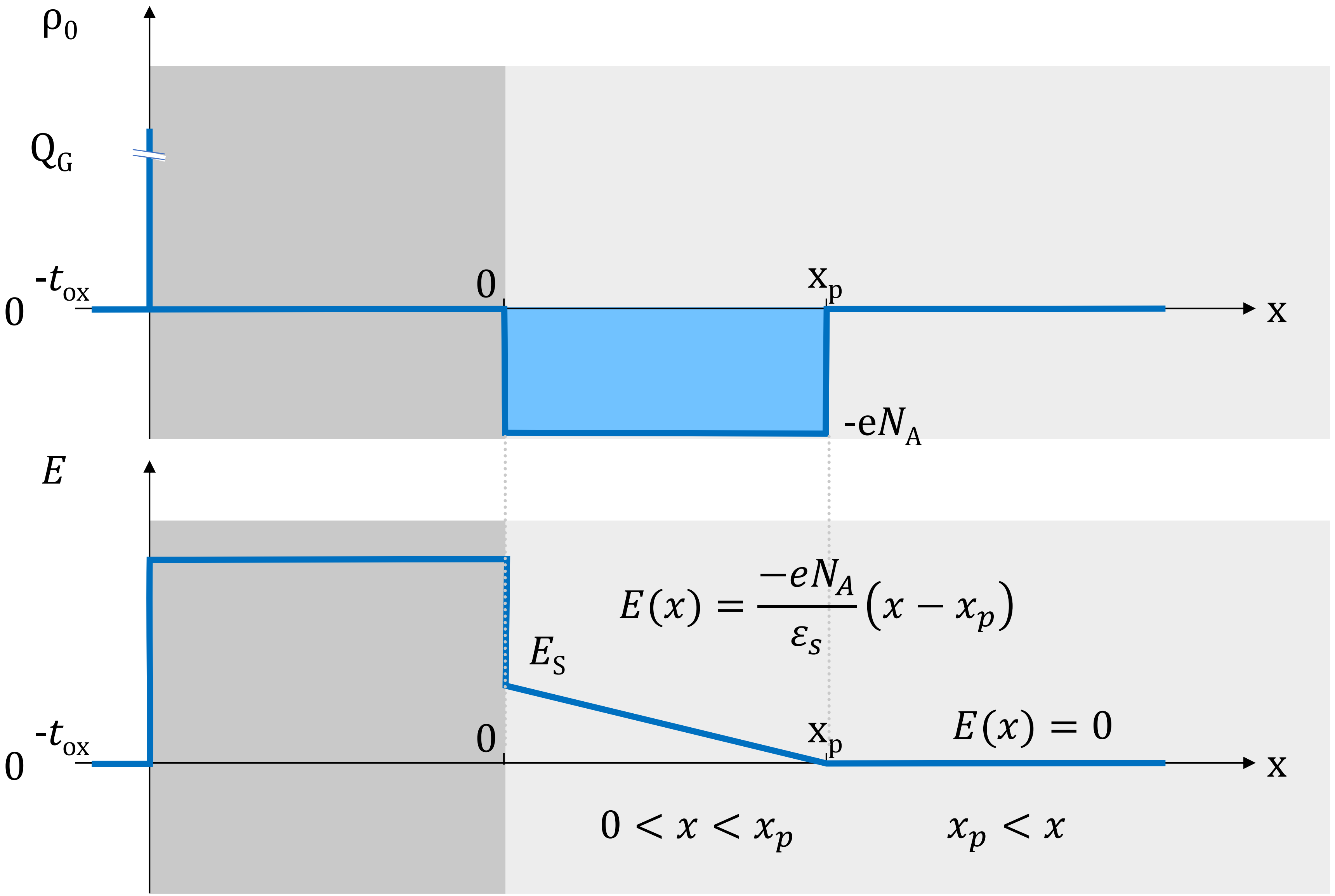
charge density (depletion)



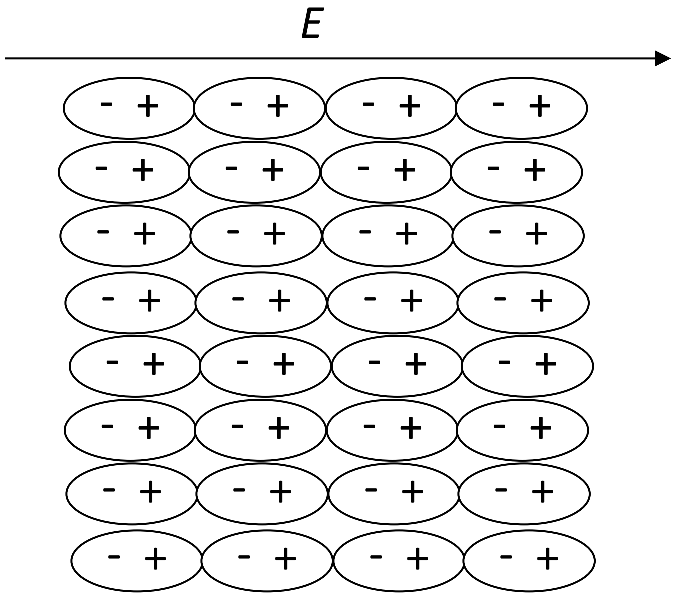
$-t_{ox} < x < 0$ $\quad$ $0 < x < x_p$ $\quad$ $x_p < x$

$\rho(x) = 0$ $\quad$ $\rho(x) = -eN_A$ $\quad$ $\rho(x) = 0$

electric field (depletion)



electric field (semiconductor oxide interface)

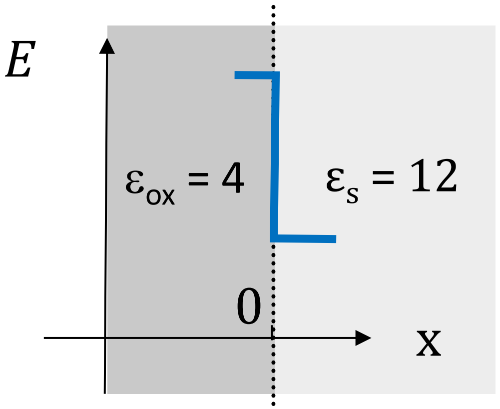


E is decreased by a factor of the dielectric constant

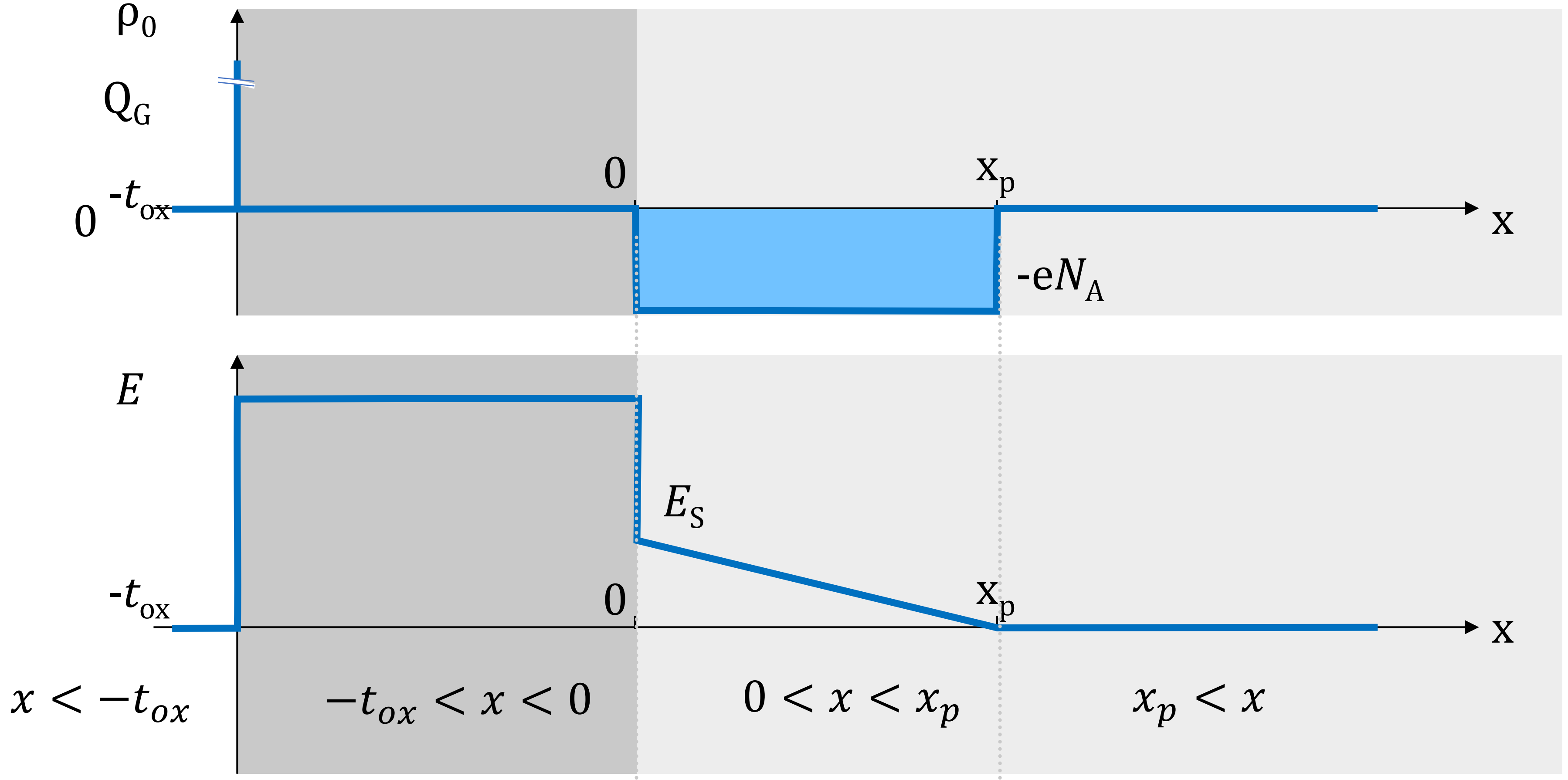
$$\epsilon_r = \frac{E_{\text{vacuum}}}{E_{\text{dielectric}}}$$

$$\epsilon_{\text{s}} E_{\text{s}} = \epsilon_{\text{ox}} E_{\text{ox}}$$

$$\frac{E_{\text{ox}}}{E_{\text{s}}} = \frac{\epsilon_{\text{s}}}{\epsilon_{\text{ox}}} \approx 3$$

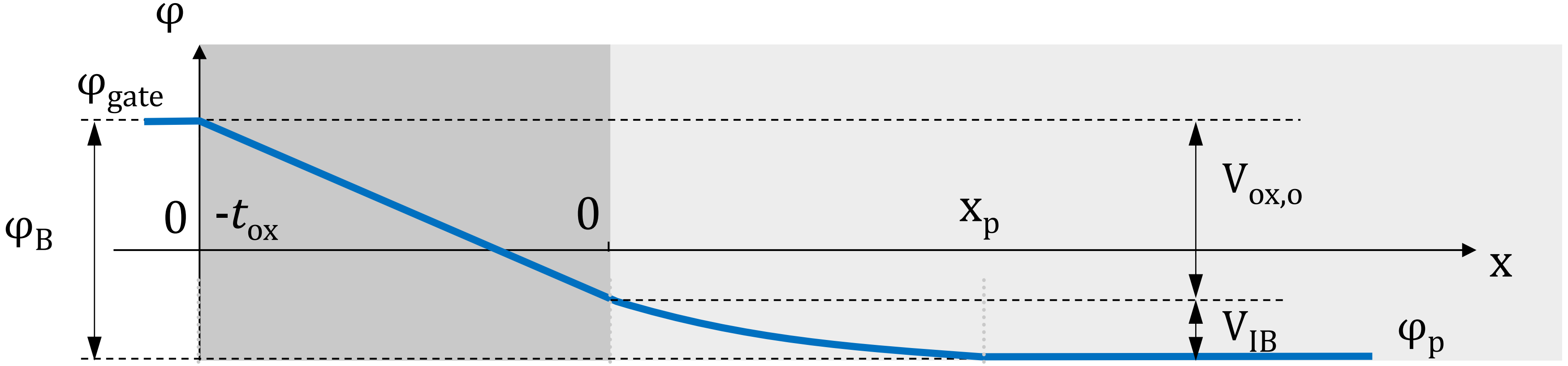


electric field (depletion)



$E(x)$:	0	$\frac{\varepsilon_S}{\varepsilon_{ox}} E(x = 0^+)$ $= \frac{eN_A x_p}{\varepsilon_{ox}}$	$\frac{-eN_A}{\varepsilon_S}(x - x_p)$	0

electrostatic potential (depletion)



	$x < -t_{ox}$	$-t_{ox} < x < 0$	$0 < x < x_p$	$x_p < x$
$\varphi(x)$:	φ_{gate}	$\varphi_p + \frac{eN_A x_p^2}{2\varepsilon_s} + \frac{eN_A x_p}{\varepsilon_{ox}}(-x)$	$\varphi_p + \frac{eN_A}{2\varepsilon_s}(x - x_p)^2$	φ_p

MOS Capacitor - Depletion approximation

$t_{ox} =$ 3 nm $\epsilon_{ox} =$ 4 $N_c(300) =$ 2.78E19 1/cm³ $T =$ 300 K

$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV $\epsilon_s =$ 12 $N_v(300) =$ 9.84E18 1/cm³ $N_A =$ 1E17 1/cm³

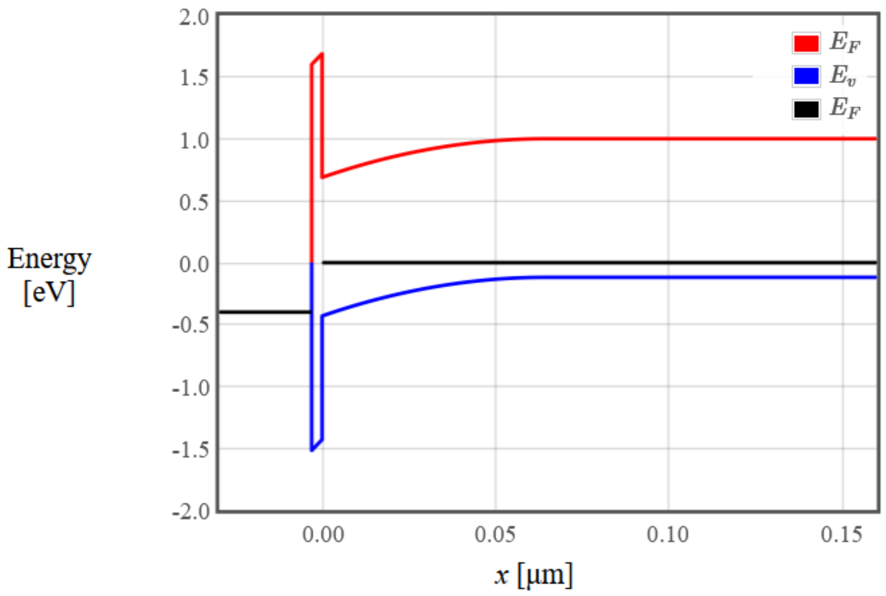
$V_g =$ 0 V

- +

Submit Si Ge GaAs $V_{fb} =$ -0.4

Flatband Depletion Threshold

Band diagram



$E_g = 1.12$ eV

$n_i = 6.41e{+}9$ 1/cm³

$x_p = 0.0644$ µm

$V_T = 0.601$ V

$V_{\text{ox}} = V_g - \phi(x=0) = 0.0874$ V

At the oxide/semiconductor interface

$n(x=0) = 7.33e{+}7$ 1/cm³

$\phi(x=0) = 0.313$ V

$E(0-) = 2.91e{+}7$ V/m

$E(0+) = 9.71e{+}6$ V/m

$n_{2d} = 19.5$ 1/cm²

MOS Capacitor - Solving the Poisson Equation

The app below solves the Poisson equation to determine the band bending, the charge distribution, and the electric field in a MOS capacitor with a p-type substrate.

ϕ_m = 4.08 eV χ_s = 4.05 eV

t_{ox} = 3 nm ϵ_{ox} = 4 $N_c(300)$ = 2.78E19 1/cm³ T = 300 K

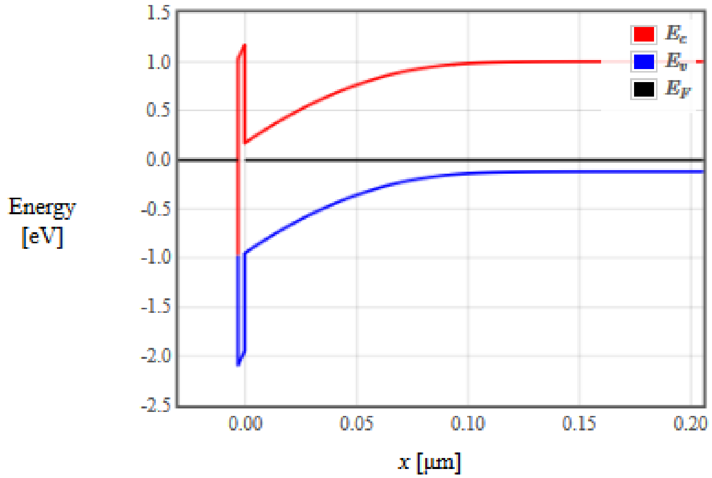
E_g = 1.166-4.73E-4*T*T/(T+636) eV ϵ_{semi} = 12 $N_v(300)$ = 9.84E18 1/cm³ N_A = 1E17 1/cm³

V = 0 V

- +

Submit Si Ge GaAs

Band diagram



E_g = 1.12 eV n_i = 6.40e+9 1/cm³

E_s = 1.57e+7 V/m V_s = 0.831 V

Q = -0.00167 C/m²

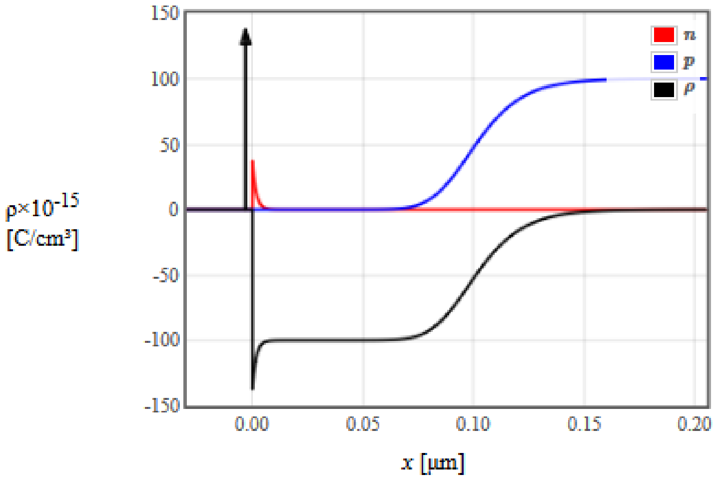
E_{ox} = 4.70e+7 V/m V_{shoot} = 0.0000221 V

ϕ_s = 5.05 eV $V_{fb} = \phi_m - \phi_s$ = -0.972 V

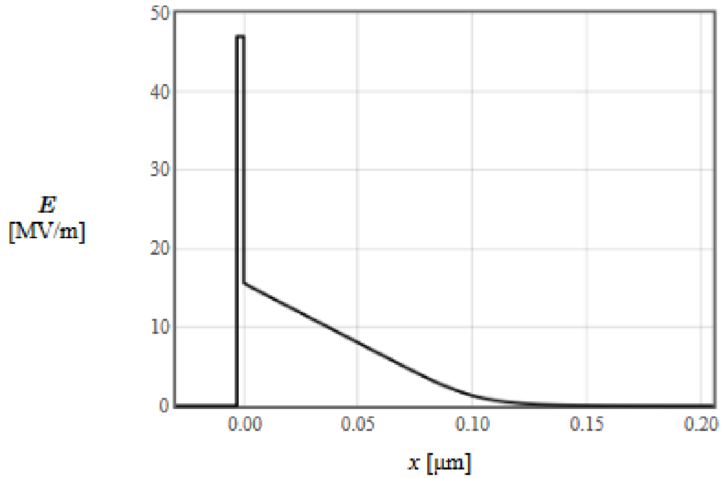
From the depletion approximation:

max(x_p) 0.107 µm V_T = 0.0292 V

Charge density



Electric field



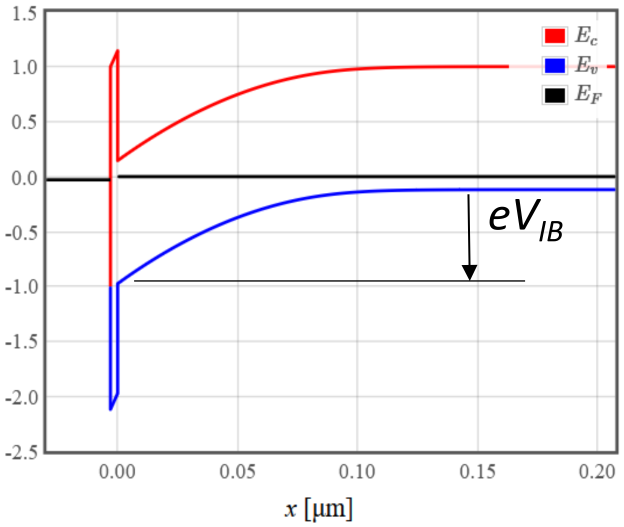
Band bending at inversion

$n = N_A$ at threshold

at the interface, $n = N_A$

$$N_A = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

$$E_F - E_c = k_B T \ln\left(\frac{N_A}{N_c}\right)$$



far on the p side

$$n = \frac{n_i^2}{N_A} = N_c \exp\left(\frac{E_F - E_c}{k_B T}\right)$$

$$E_F - E_c = k_B T \ln\left(\frac{n_i^2}{N_A N_c}\right)$$

V_{IB} is the voltage between the semiconductor-oxide interface and the body

$$eV_{IB} = k_B T \ln\left(\frac{N_A}{N_c}\right) - k_B T \ln\left(\frac{n_i^2}{N_A N_c}\right)$$

strong inversion

$n_s = N_A$ at the semiconductor-oxide interface

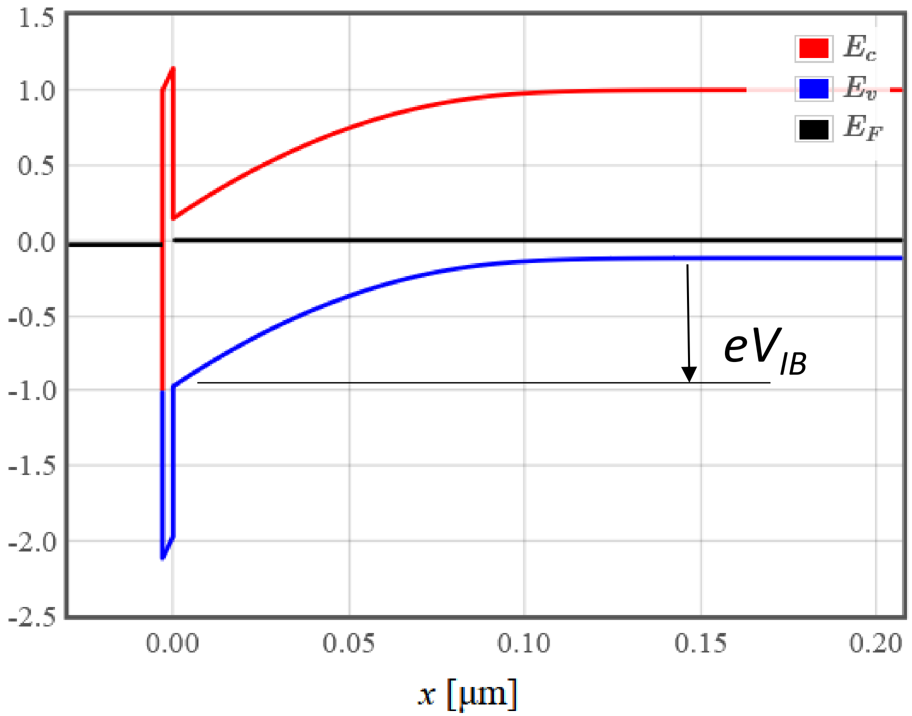
$$eV_{\text{IB}} = k_B T \ln \frac{N_A}{N_c} - k_B T \ln \frac{n_i^2}{N_A N_c}$$

$$\ln(a) - \ln(b) = \ln \frac{a}{b}$$

$$eV_{\text{IB}} = k_B T \ln \frac{N_A^2}{n_i^2}$$

$$\ln(a^2) = 2\ln(a)$$

$$eV_{\text{IB}} = 2k_B T \ln \frac{N_A}{n_i}$$



the depletion width remains constant in inversion

Depletion width in inversion

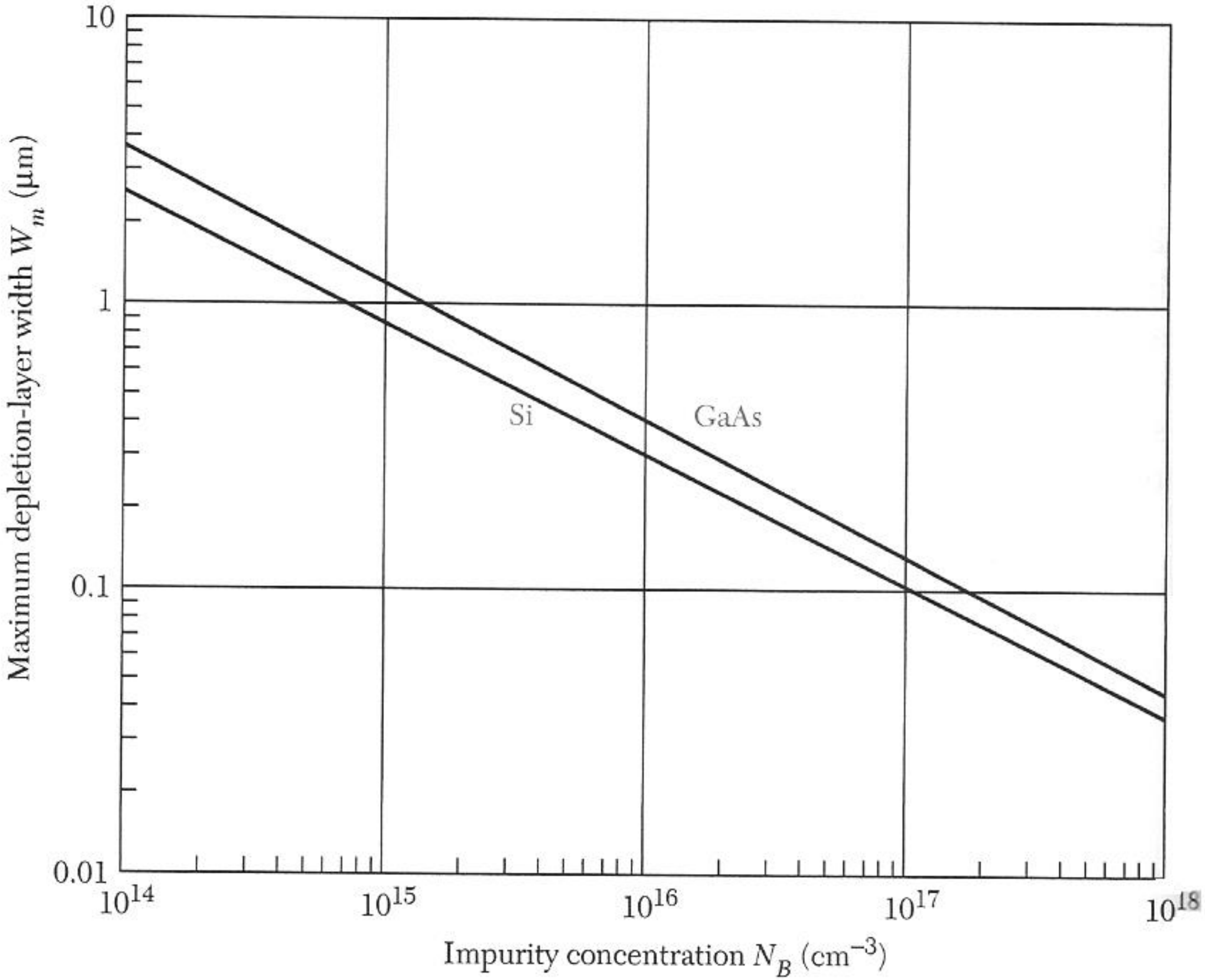
$$V_{IB} = \frac{eN_A x_p^2}{2\varepsilon}$$

$$eV_{IB} = 2k_B T \ln\left(\frac{N_A}{n_i}\right)$$

$$x_{p(\max)} = \sqrt{\frac{2\varepsilon V_{IB}}{eN_A}} = 2\sqrt{\frac{\varepsilon}{e^2 N_A} k_B T \ln\left(\frac{N_A}{n_i}\right)}$$

The **depletion width** remains **constant** in inversion

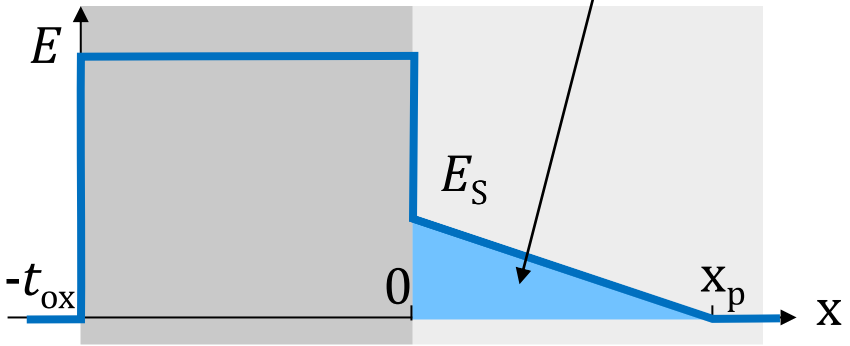
Depletion width



Electric field at semi-oxide interface at strong inversion

$$eV_{IB}(\text{strong inversion}) = 2k_BT\ln\left(\frac{N_A}{n_i}\right)$$

$V_{IB} = E_s x_p/2$ = area of the triangle



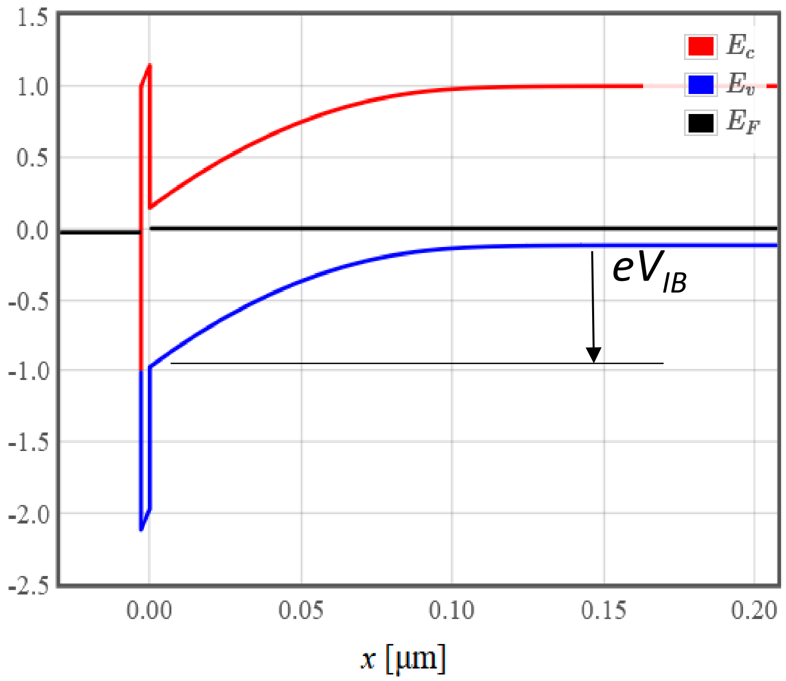
$$E_s = 2\frac{V_{IB}}{x_{p(\max)}} = \frac{2V_{IB}}{\sqrt{\frac{2\varepsilon V_{IB}}{eN_A}}} = 2\sqrt{\frac{N_A}{\varepsilon}k_BT\ln\left(\frac{N_A}{n_i}\right)}$$

$$E_{ox} = \frac{\varepsilon}{\varepsilon_{ox}}E_s = \frac{2\varepsilon}{\varepsilon_{ox}}2\sqrt{\frac{N_A}{\varepsilon}k_BT\ln\left(\frac{N_A}{n_i}\right)}$$

Threshold voltage

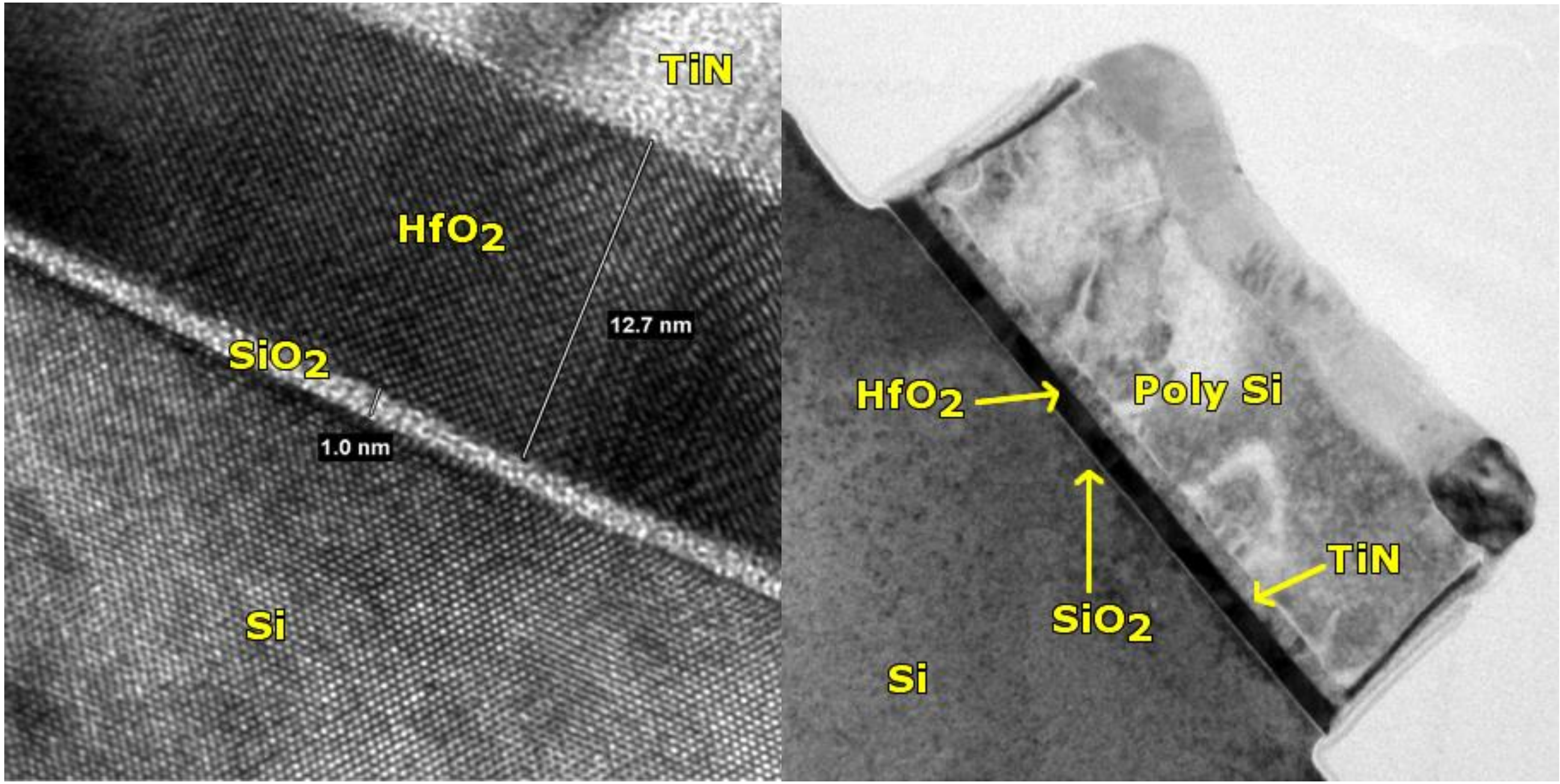
$$V_T = E_{ox}(\text{strong inversion})t_{ox} + V_{IB}(\text{strong inversion}) + V_{FB}$$

$$V_T = \underbrace{\frac{2\varepsilon t_{ox}}{\varepsilon_{ox}}\sqrt{\frac{N_A k_B T \ln\left(\frac{N_A}{n_i}\right)}{\varepsilon}}}_{\frac{\varepsilon t_{ox}}{\varepsilon_{ox}} E_{inversion}} + \underbrace{2\frac{k_B T}{e}\ln\left(\frac{N_A}{n_i}\right)}_{V_{IB}} + V_{FB}$$



Small V_T requires a small t_{ox} and a large ε_{ox}.

High-k dielectrics

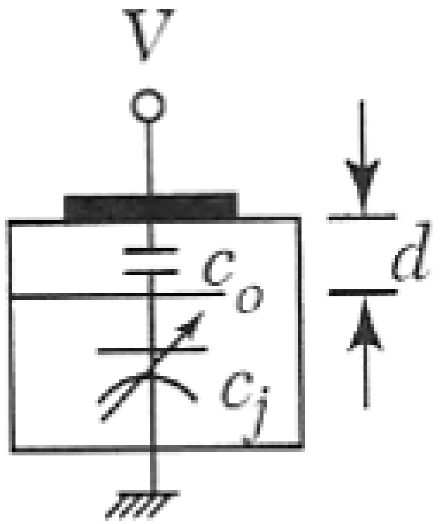


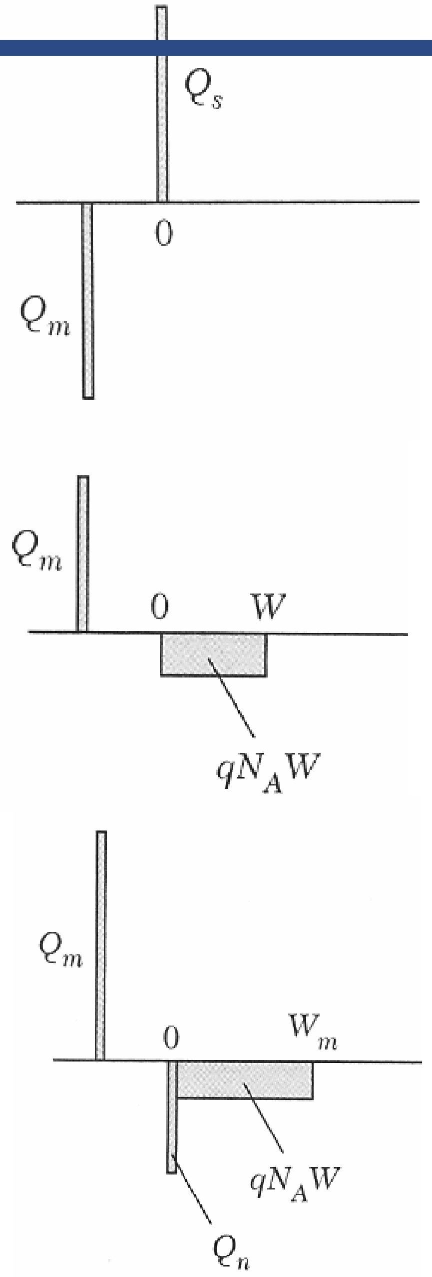
http://nano.boisestate.edu/research-areas/gate-oxide-studies/

MOS capacitance

$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \qquad C_j = \frac{\varepsilon}{x_p}$$

$$C = \left(\frac{1}{C_{ox}} + \frac{1}{C_j} \right)^{-1}$$





MOS Capacitor - Capacitance voltage

In capacitance-voltage profiling, the capacitance of a MOS capacitor is measured as a function of the bias voltage. The app below solves the Poisson equation to determine the charge-voltage and capacitance voltage characteristics of a MOS capacitor with a p-type substrate. This is the low-frequency result. At high frequencies, the charge at the oxide interface does not change fast enough and the characteristics take on another form.

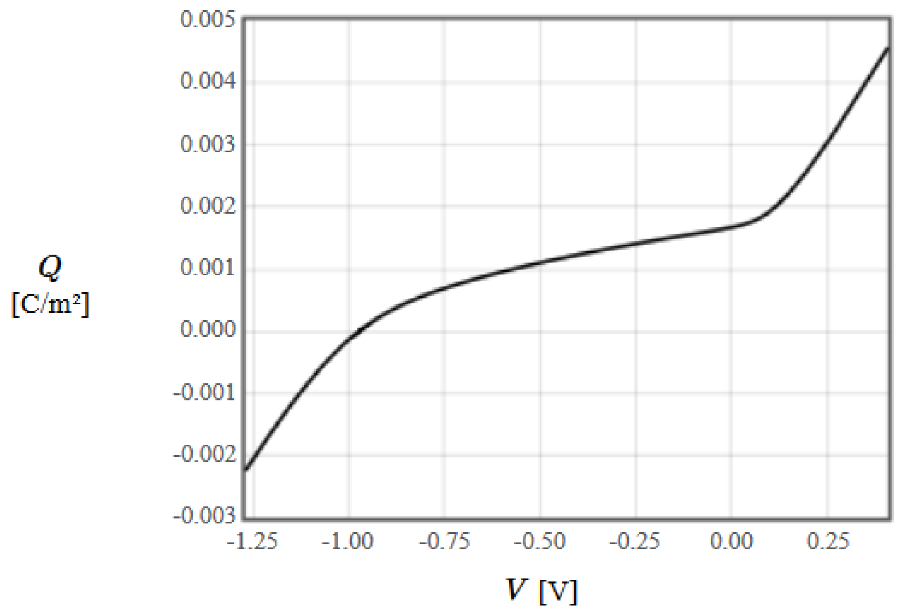
ϕ_m = 4.08 eV χ_s = 4.05 eV

t_{ox} = 3 nm ϵ_{ox} = 4 $N_c(300)$ = 2.78E19 1/cm³ T = 300 K

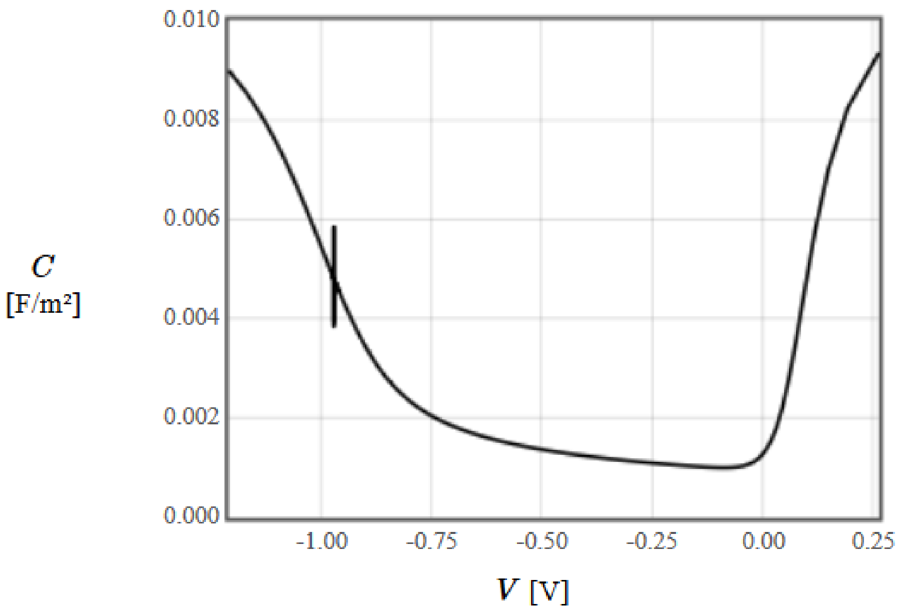
E_g = 1.166-4.73E-4*T*T/(T+636) eV ϵ_{semi} = 12 $N_v(300)$ = 9.84E18 1/cm³ N_A = 1E17 1/cm³

Submit Si Ge GaAs

Q - V



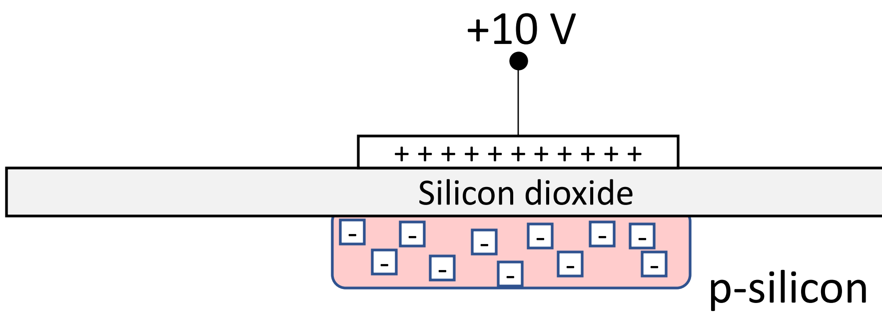
C - V



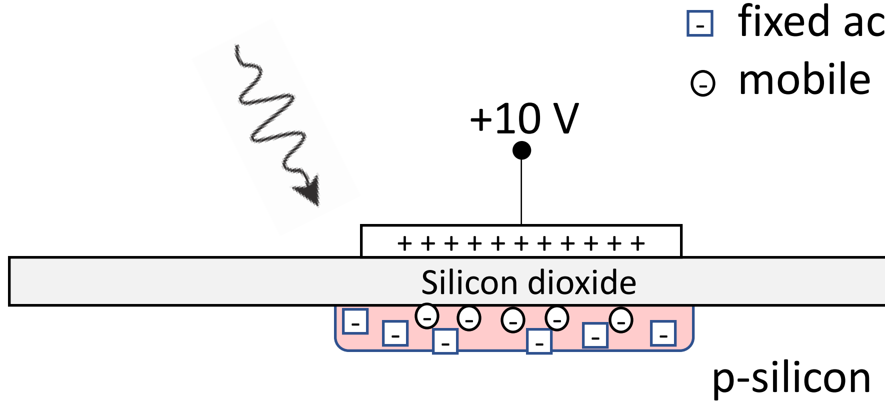
$E_g = 1.12$ eV $n_i = 6.40\text{e}+9$ 1/cm³ $\phi_s = 5.05$ eV $V_{fb} = \phi_m - \phi_s = -0.972$ V

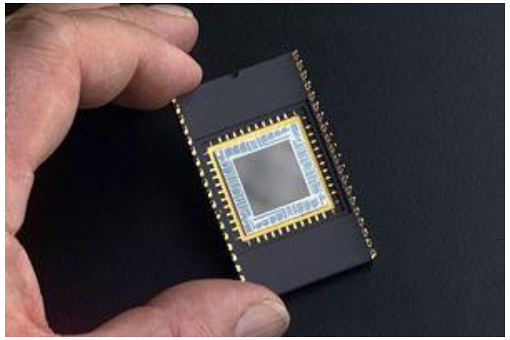
$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = 0.0118$ F/m² $V_T = 0.0292$ V

CCD devices

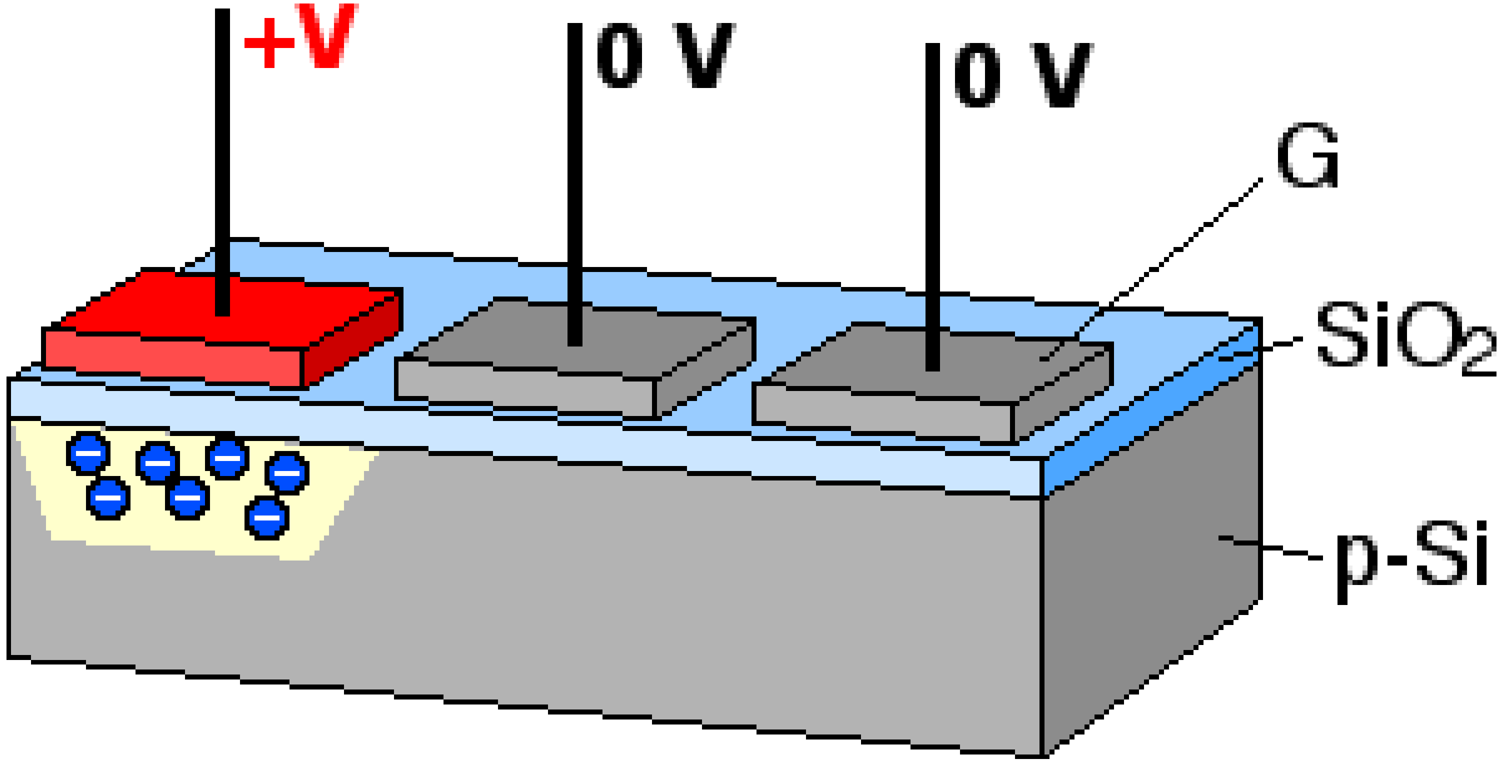


▫ fixed acceptors
⊝ mobile electrons





CCD devices



https://en.wikipedia.org/wiki/Charge-coupled_device#/media/File:CCD_charge_transfer_animation.gif