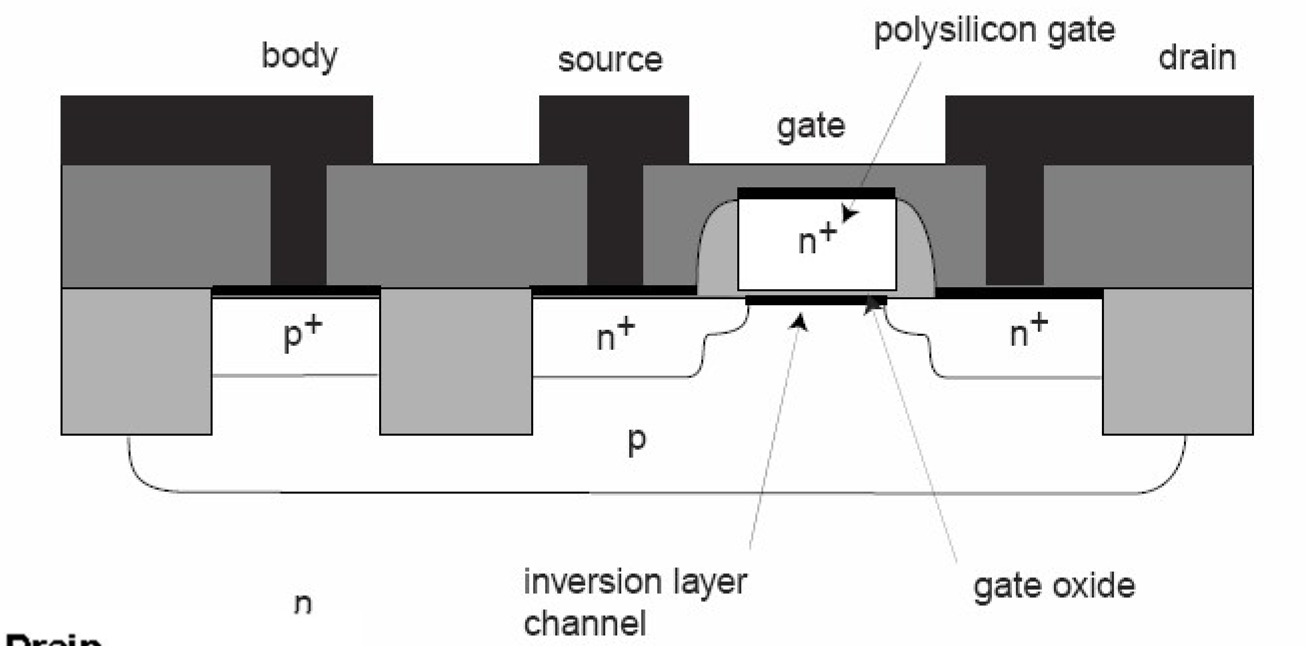
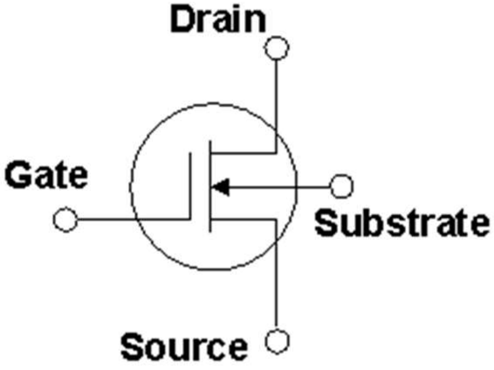
MOSFETs

Metal Oxide Semiconductor Field Effect Transistor

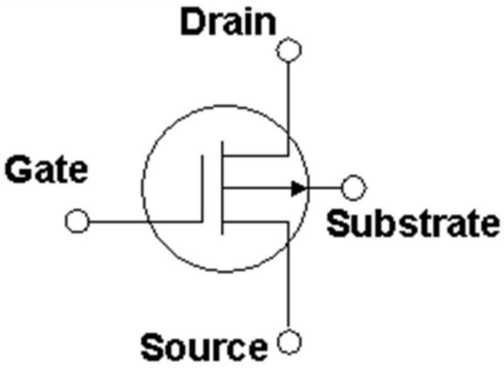
MOSFETs





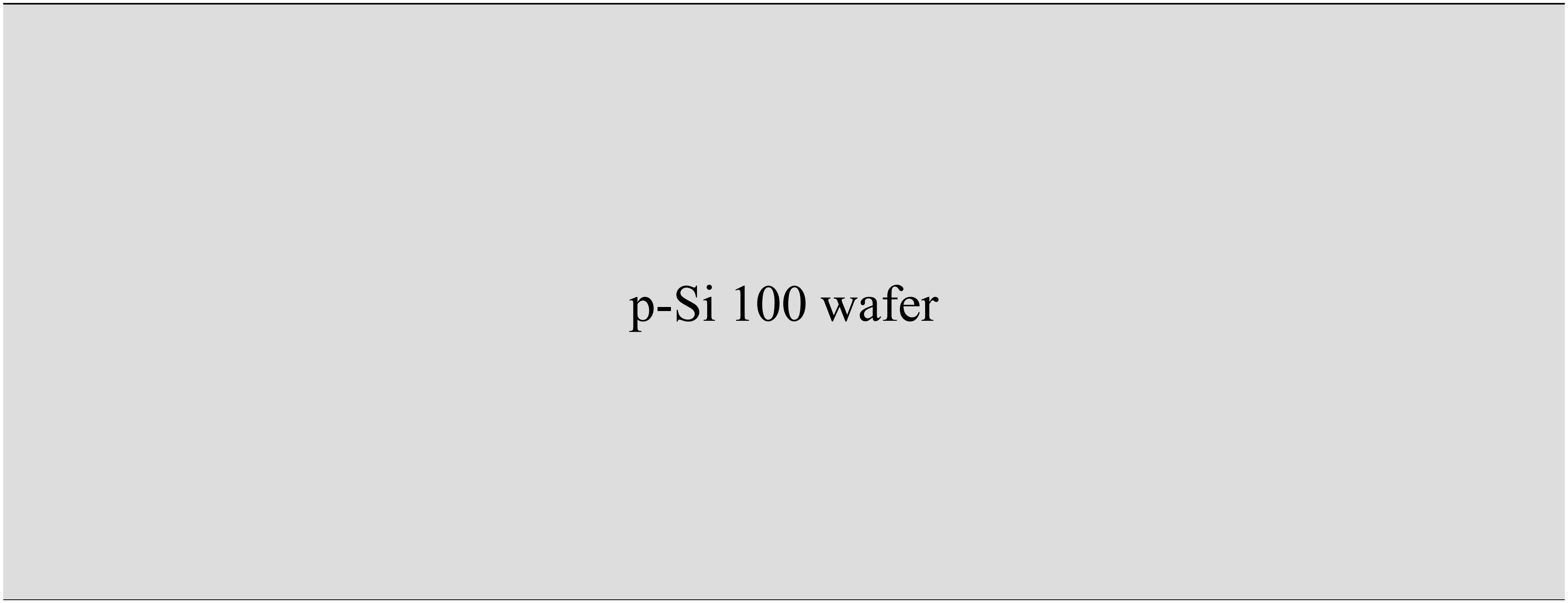
n - channel

functions as a switch
~ 1 billion /chip

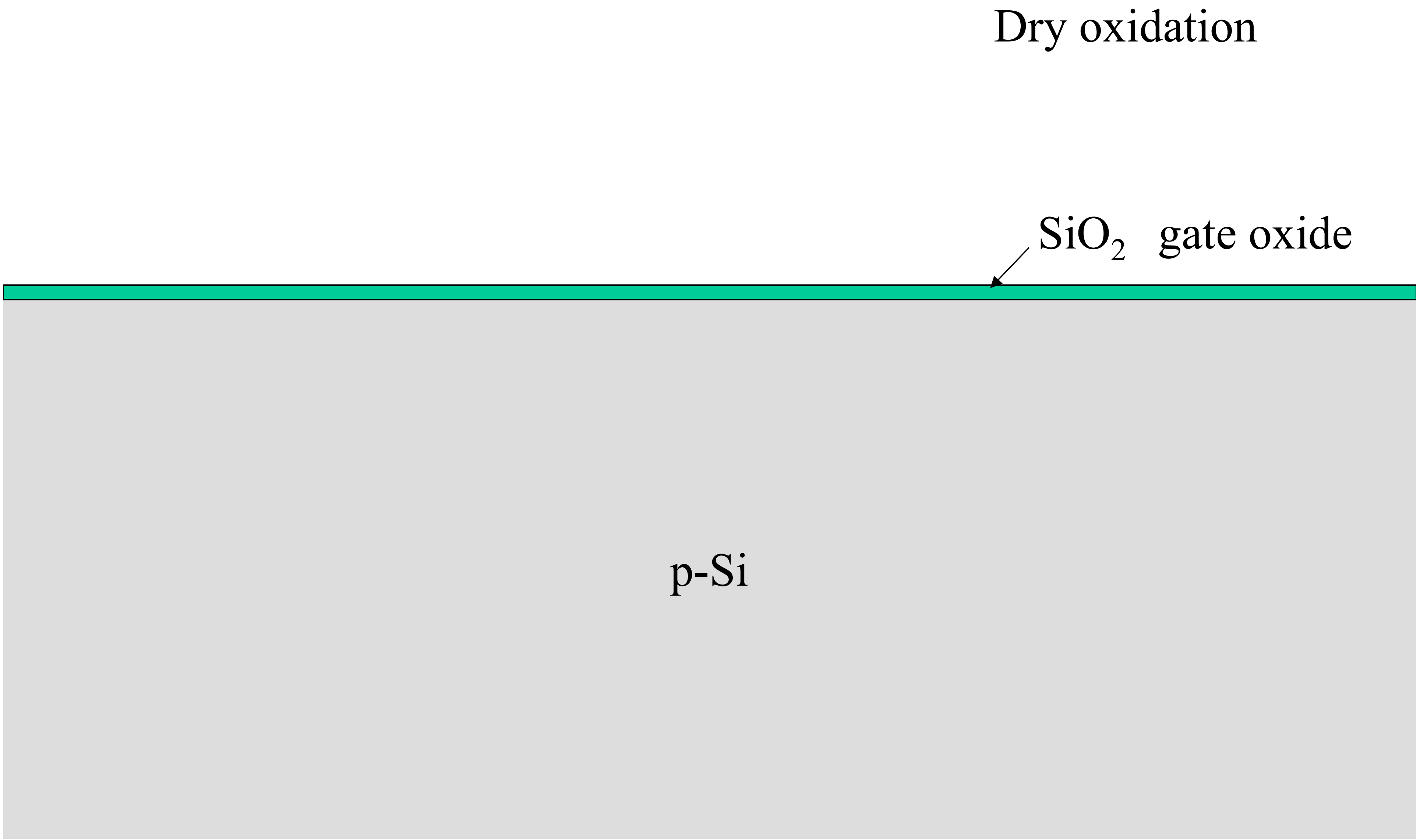


p - channel

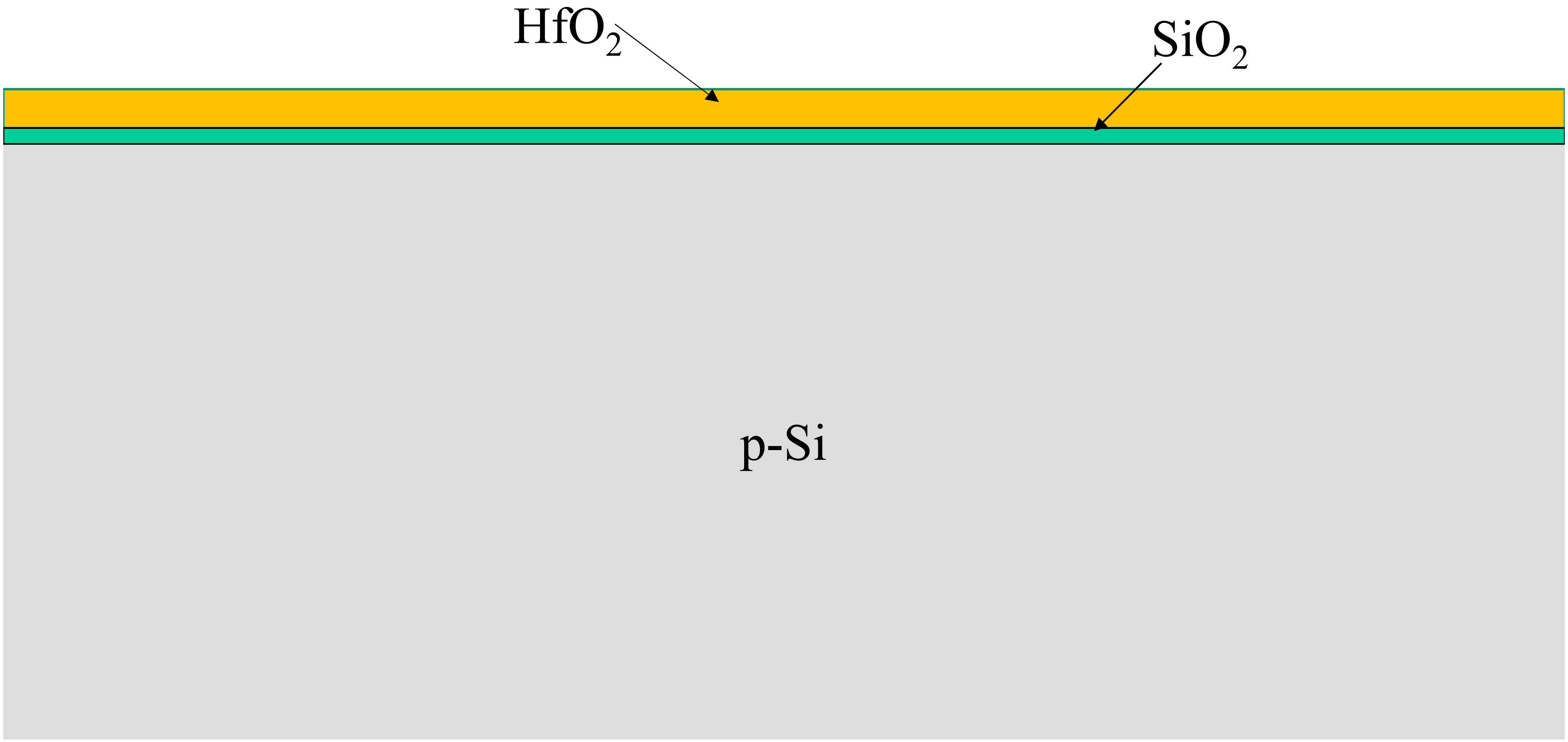
Self-aligned fabrication



p-Si 100 wafer


Dry oxidation
SiO_2 gate oxide
p-Si

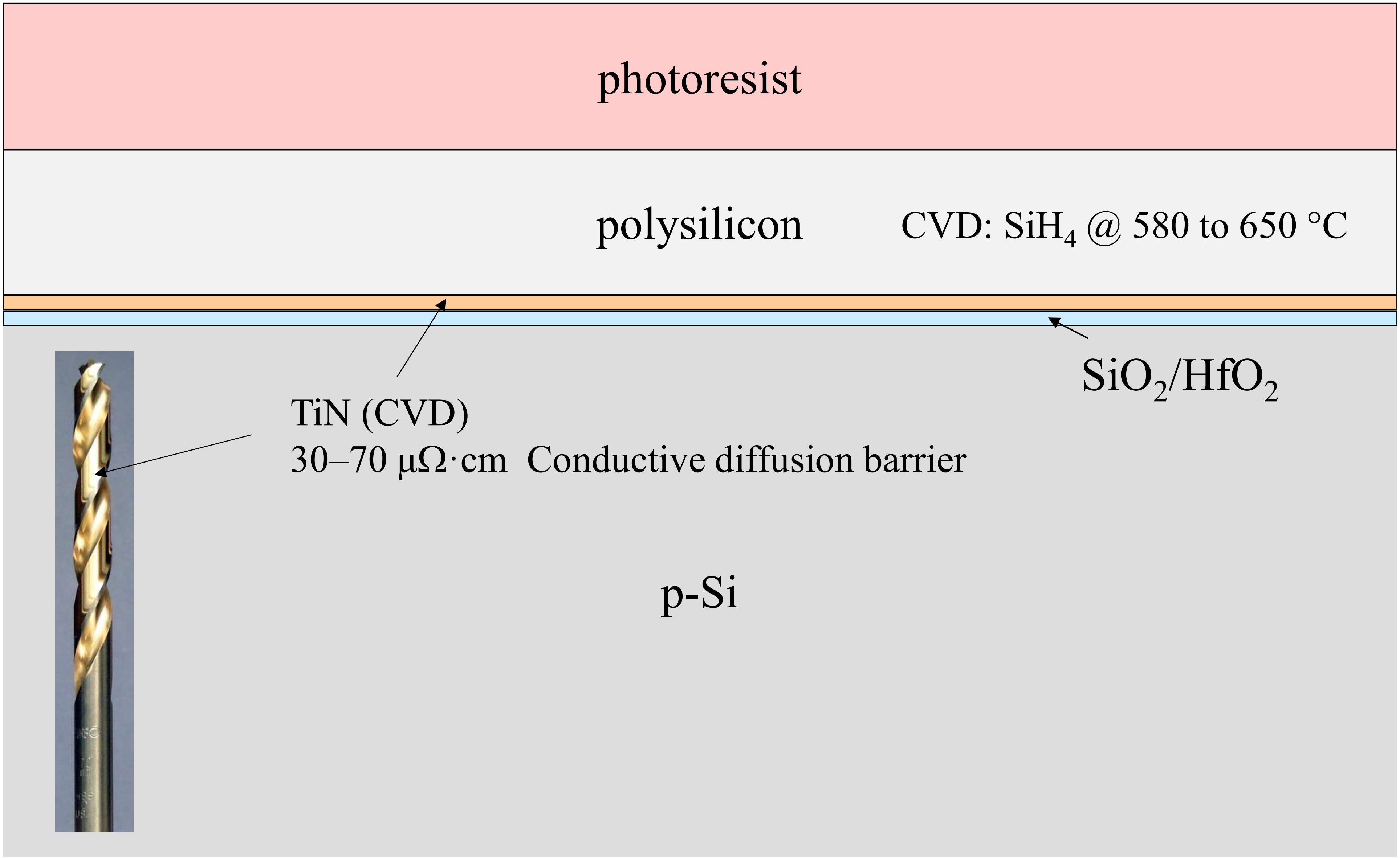
gate oxide



HfO_2

SiO_2

p-Si



photoresist

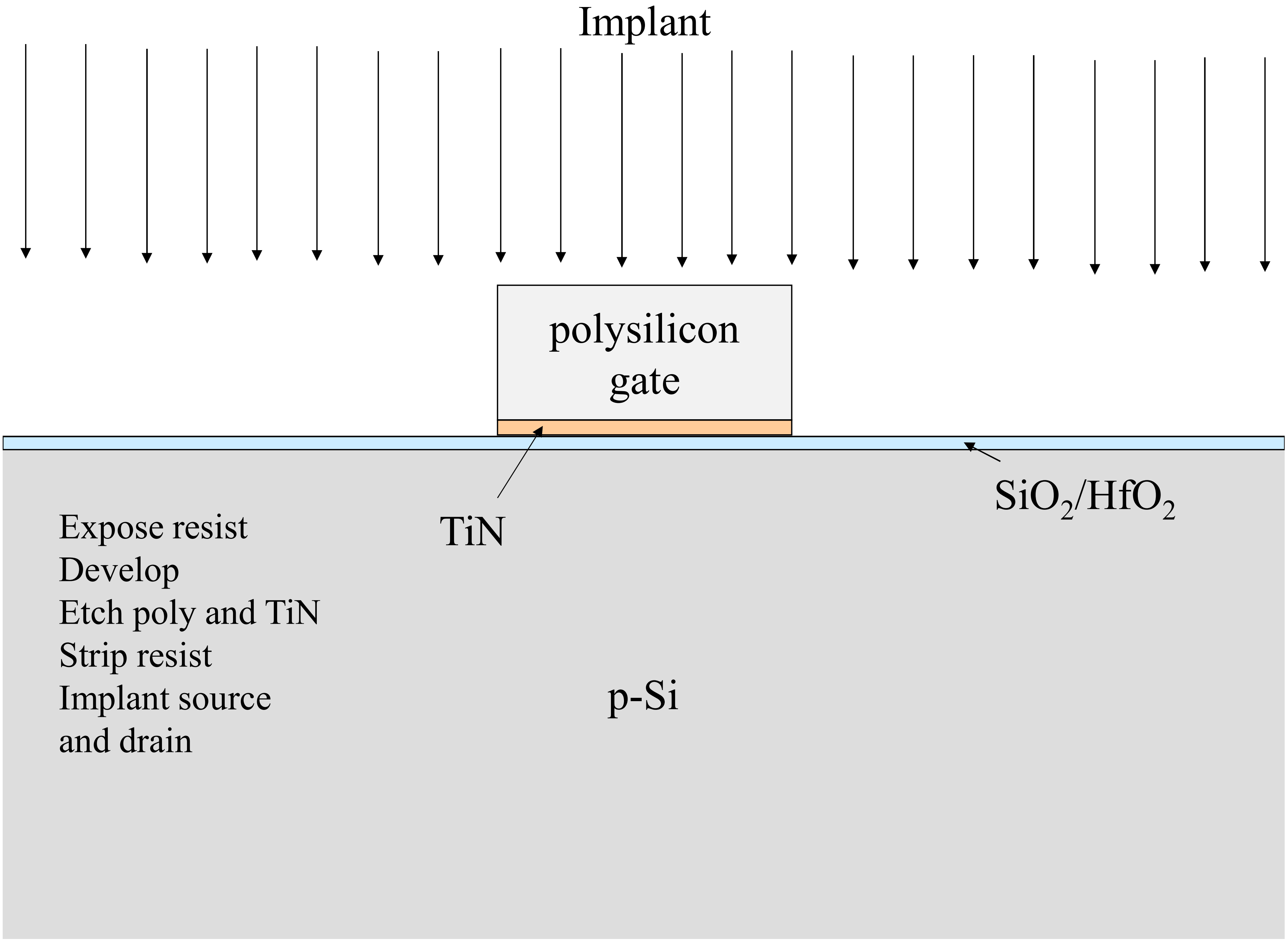
polysilicon

CVD: SiH_4 @ 580 to 650 °C

TiN (CVD)
30–70 μΩ·cm Conductive diffusion barrier

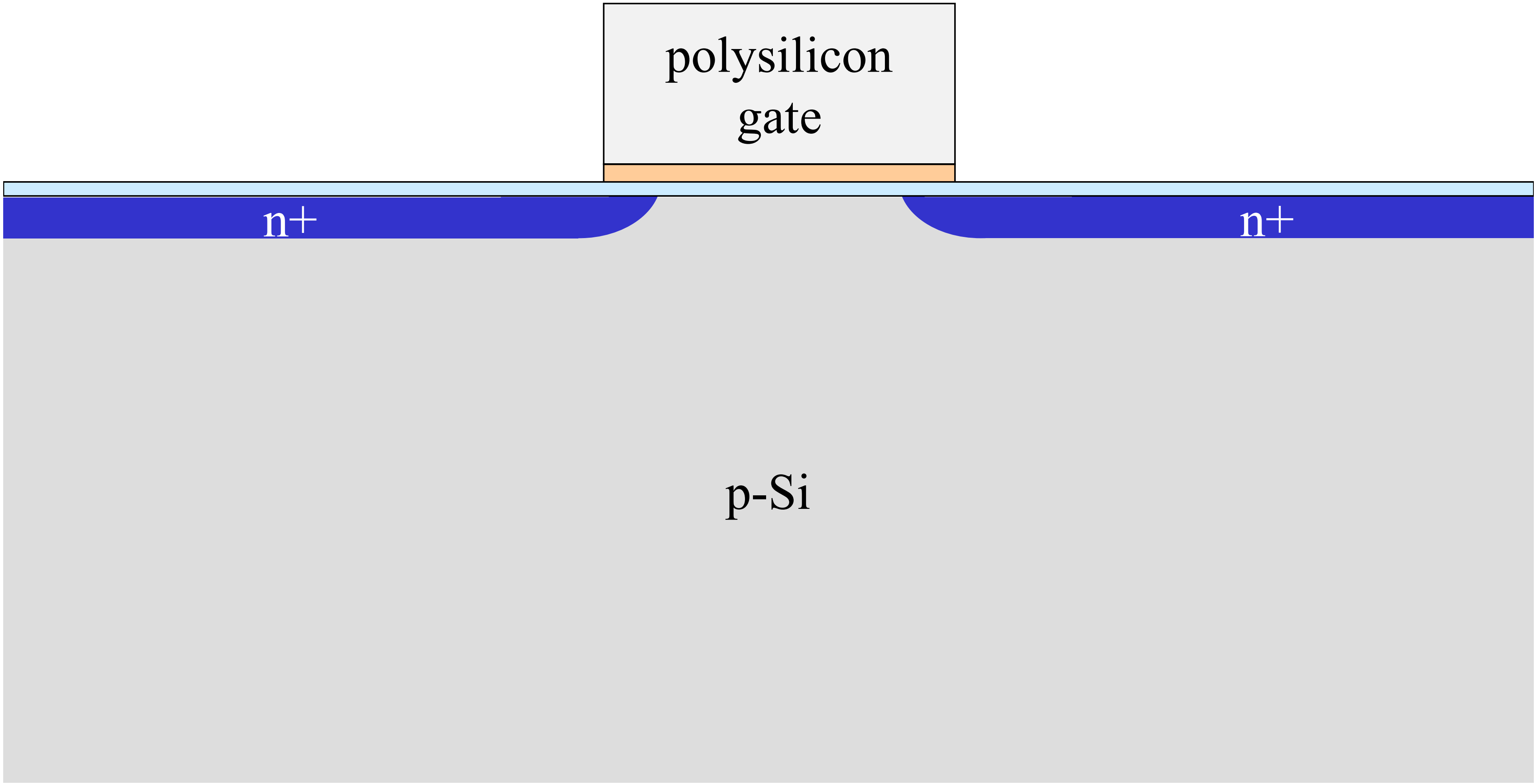
SiO_2/HfO_2

p-Si

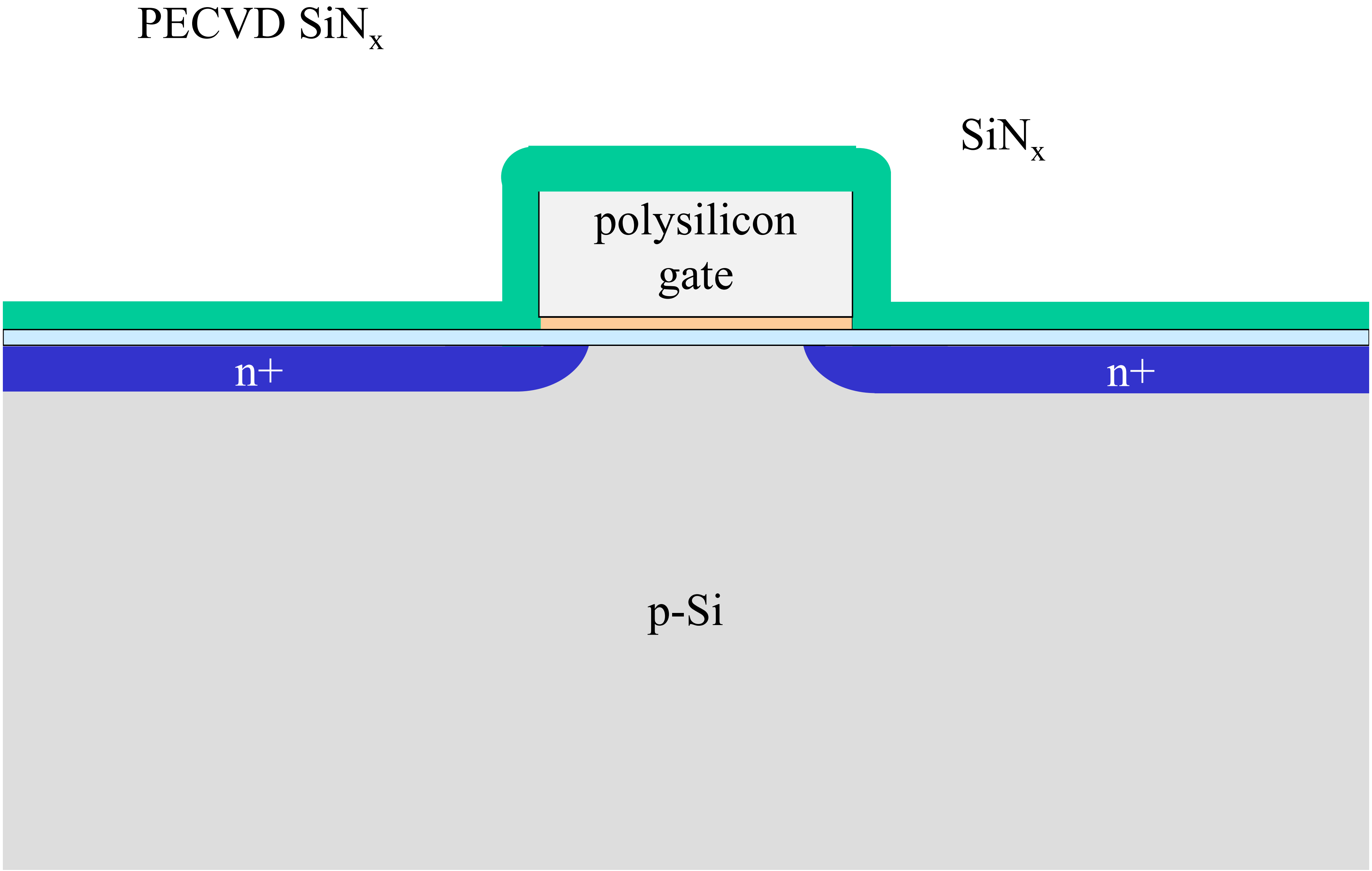


Expose resist
Develop
Etch poly and TiN
Strip resist
Implant source and drain

Self-aligned fabrication

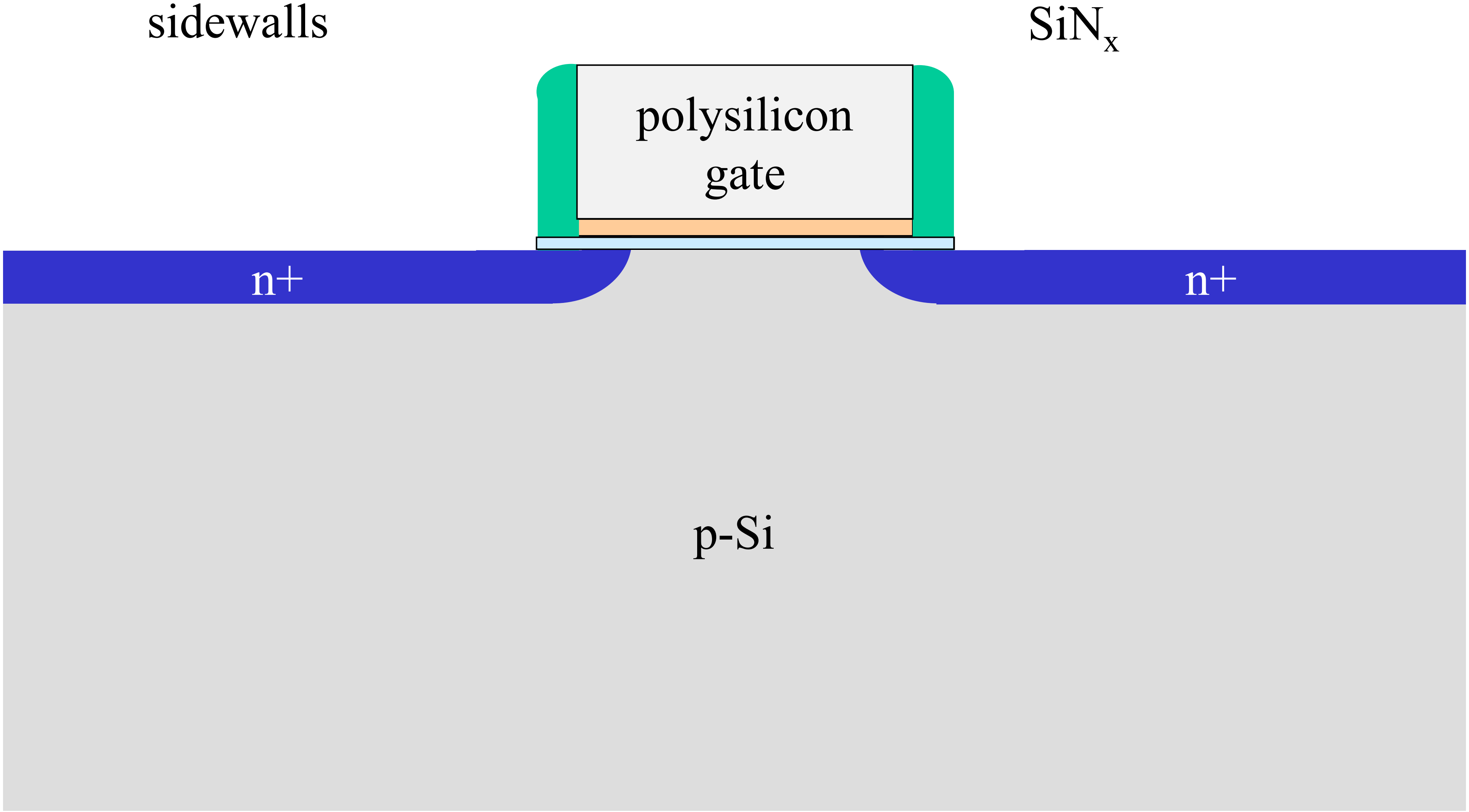


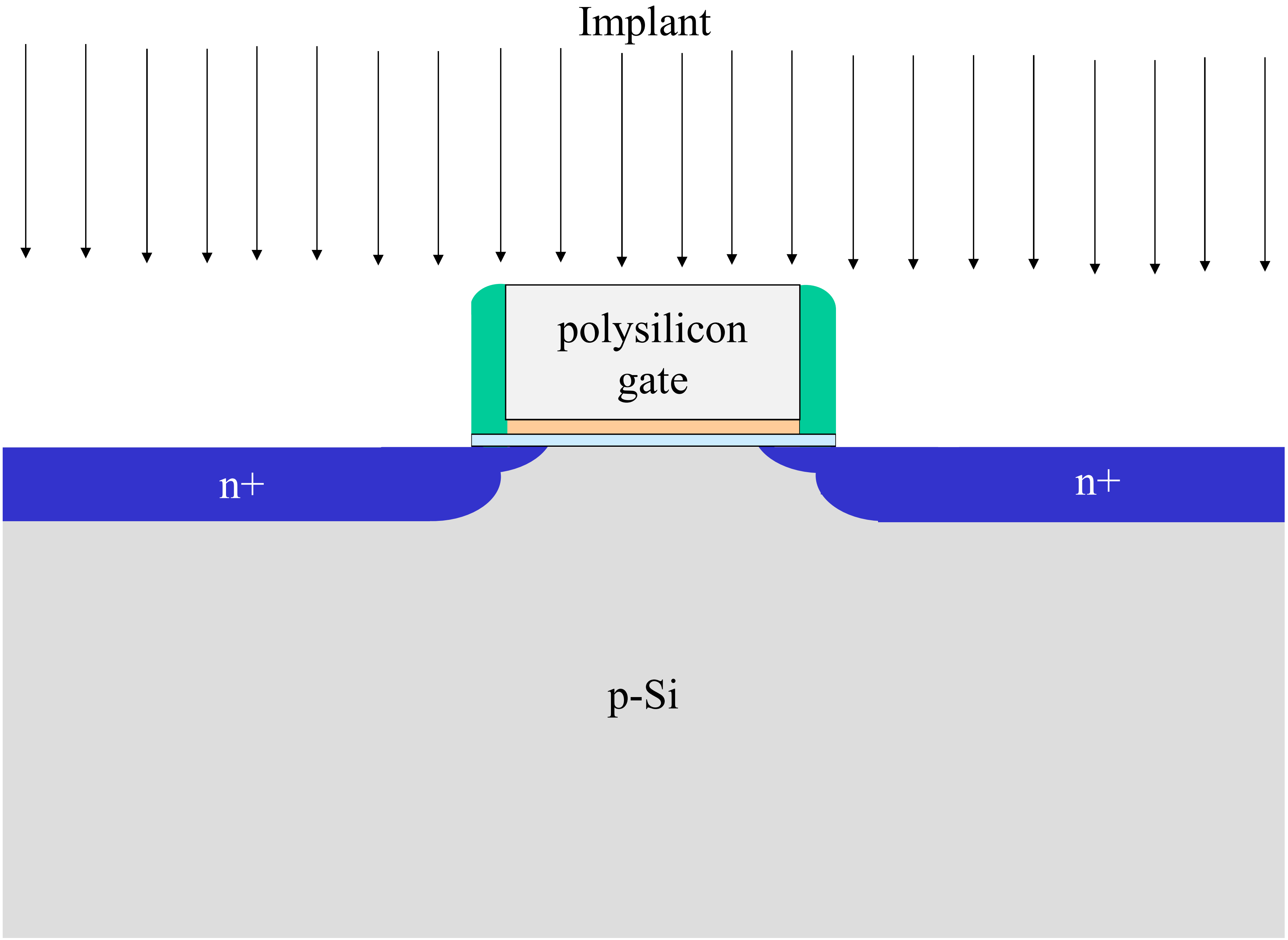
Spacer



Spacer

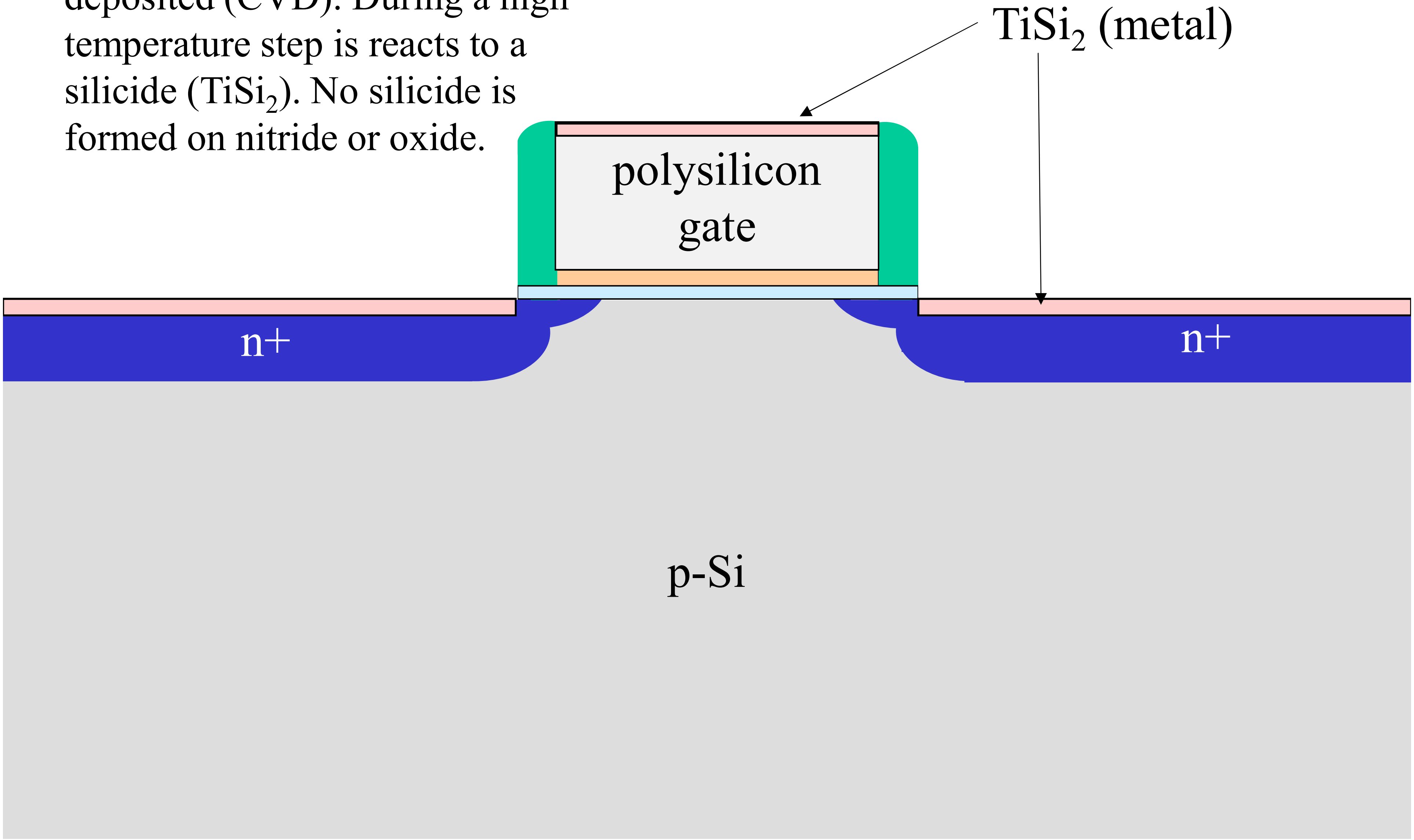
Etch back to
leave only
sidewalls




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.



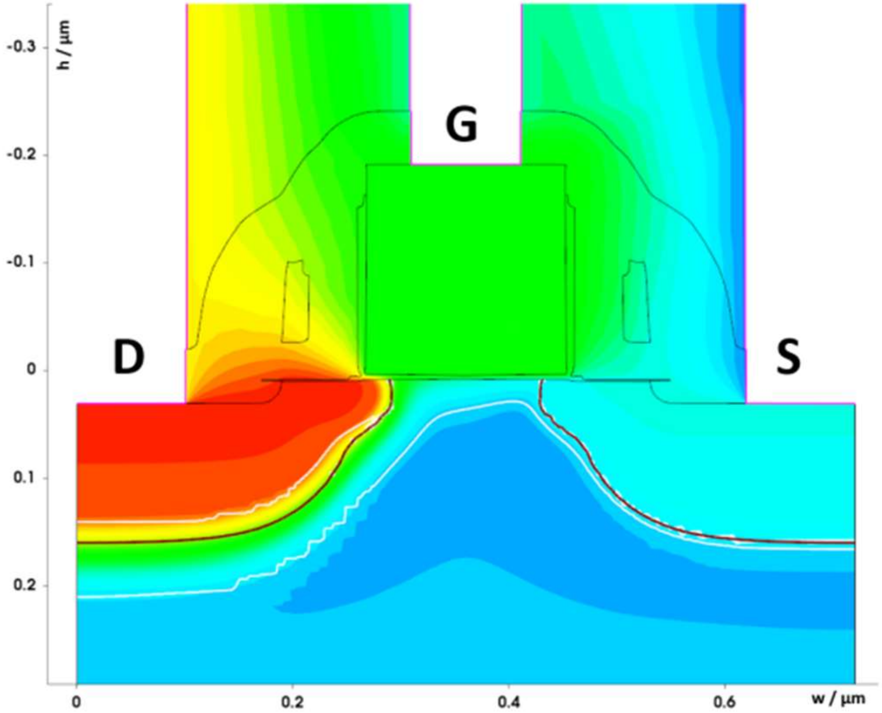


Figure 7: TCAD simulation of the potential distribution in a n-MOSFET @ $V_g = 0.85$ V, $V_d = 2.3$ V [2]

Alexander Schiffmann - Diplom thesis

CMOS Complementary Metal Oxide Semiconductor

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

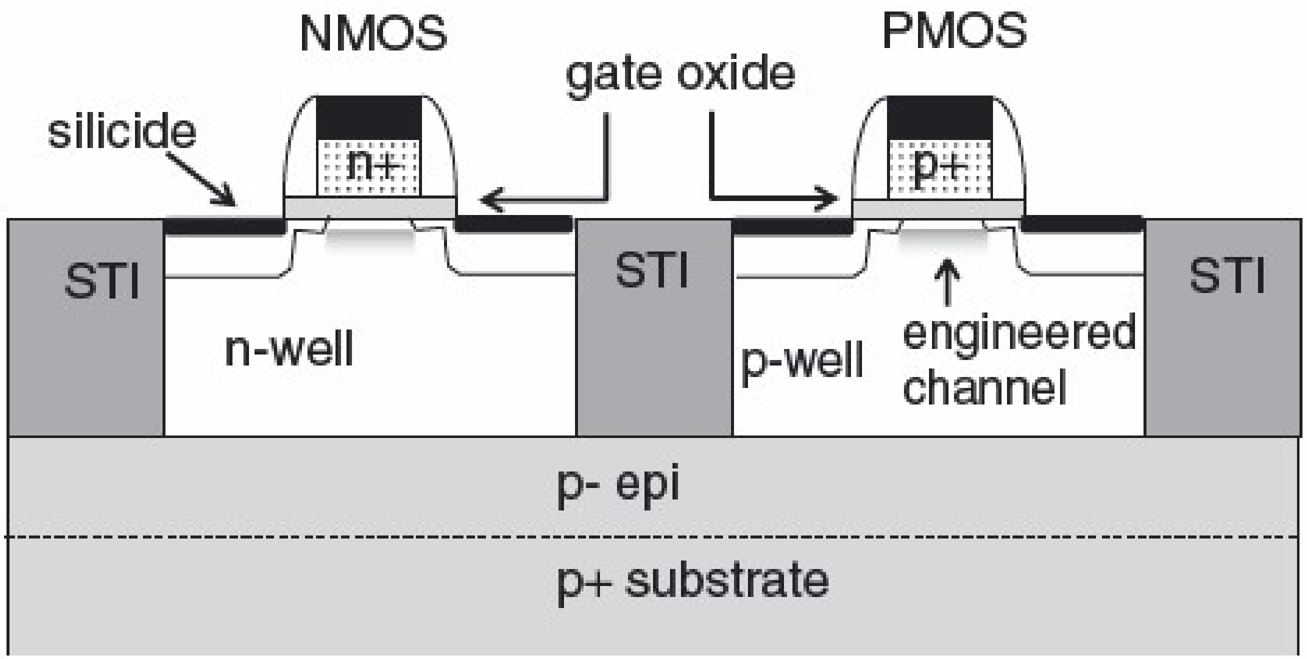
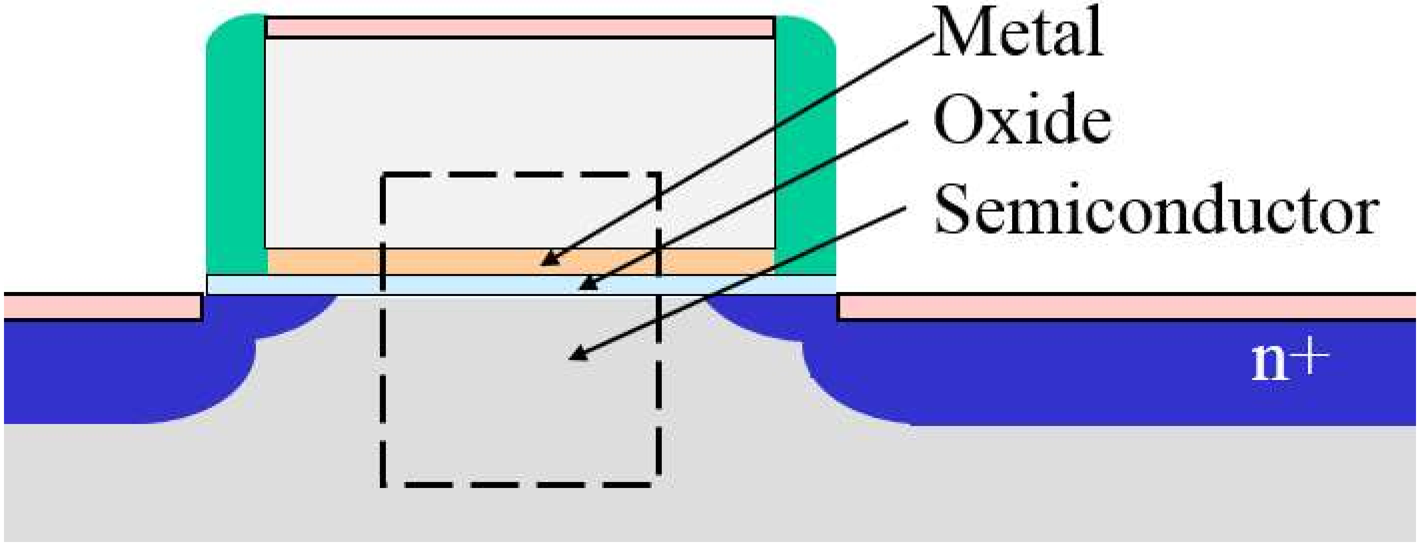


Figure 26.11 Deep submicron CMOS: 200 nm gate length, 5 nm gate oxide, 70 nm junction depth; n^+ poly for NMOS and p^+ poly for PMOS. Shallow trench isolation on epitaxial n^+/p^+ wafer

Source: Fransila

MOS capacitor

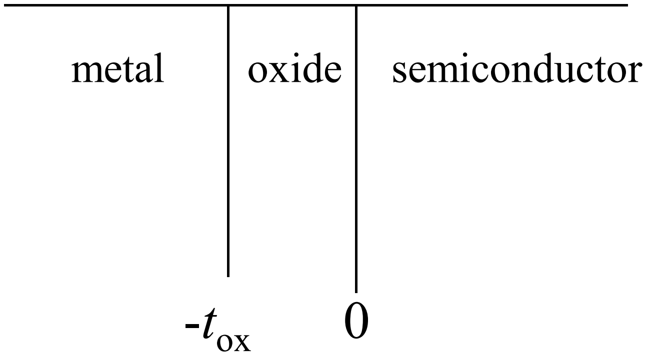


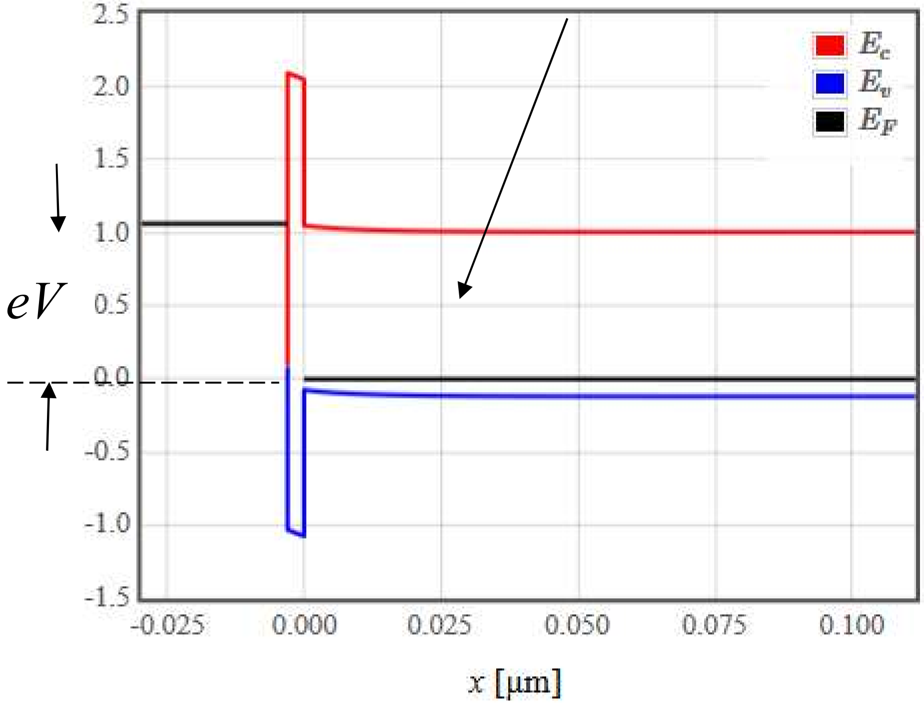
Metal

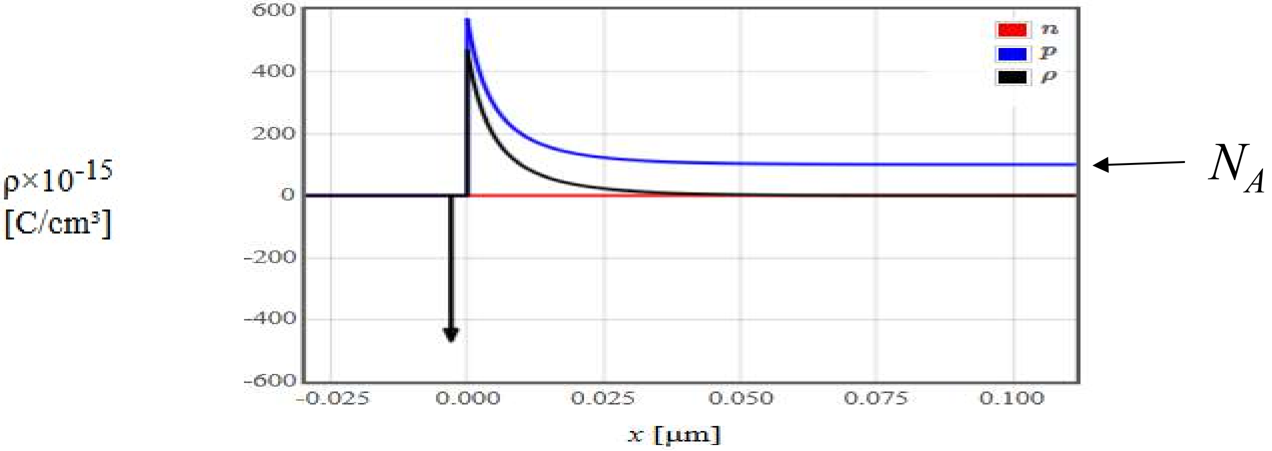
Oxide

Semiconductor

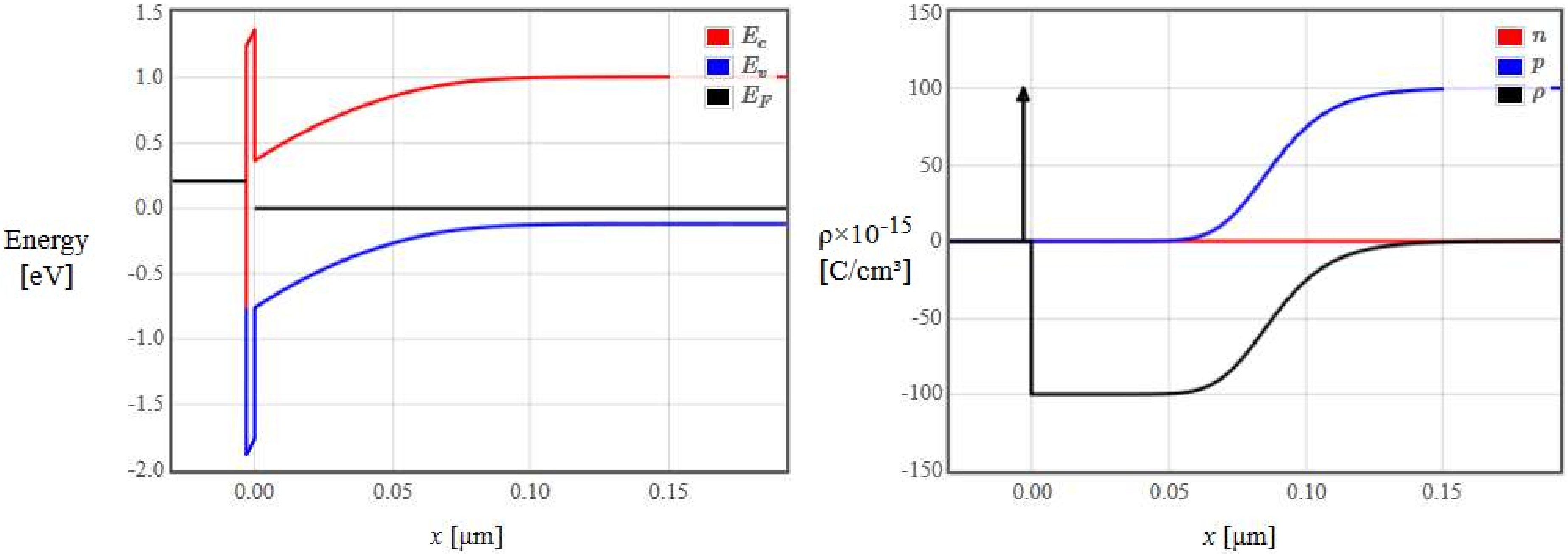
Accumulation



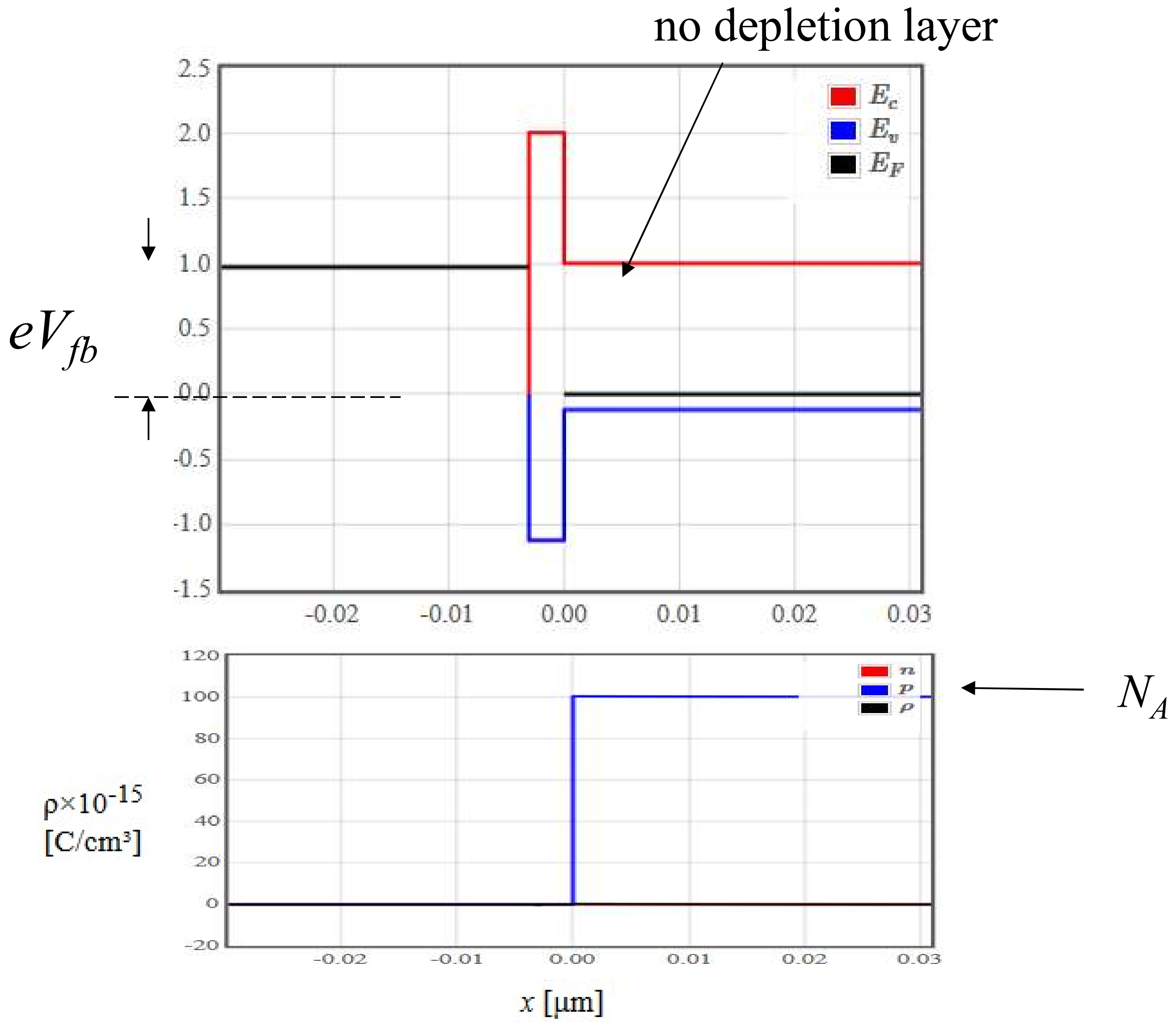

no depletion layer



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/cm^3]
150
100
50
0
-50
-100
-150
0.00
0.05
0.10
0.15
x [μm]
n
p
ρ

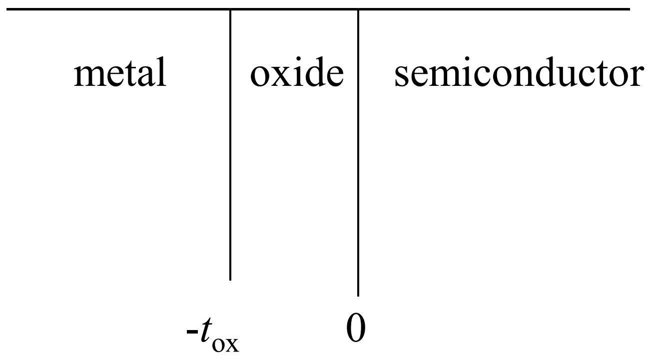
Flat band voltage



no depletion layer

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

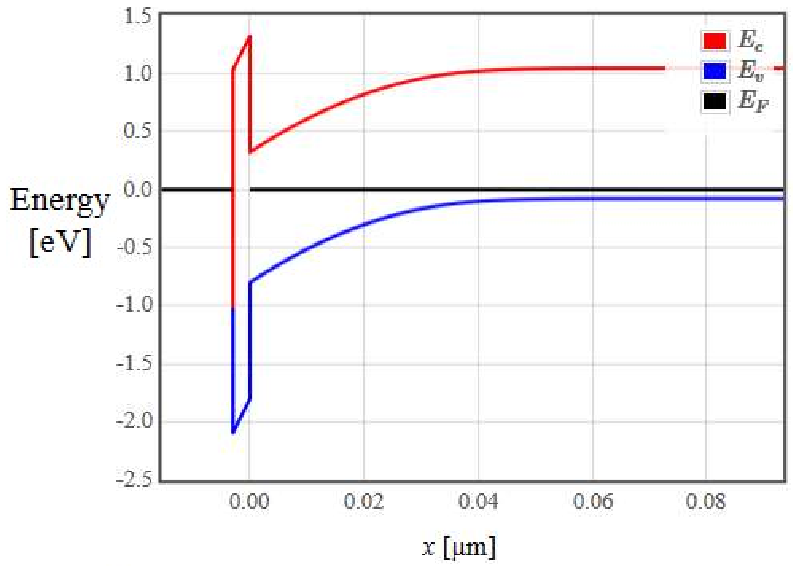
Zero bias

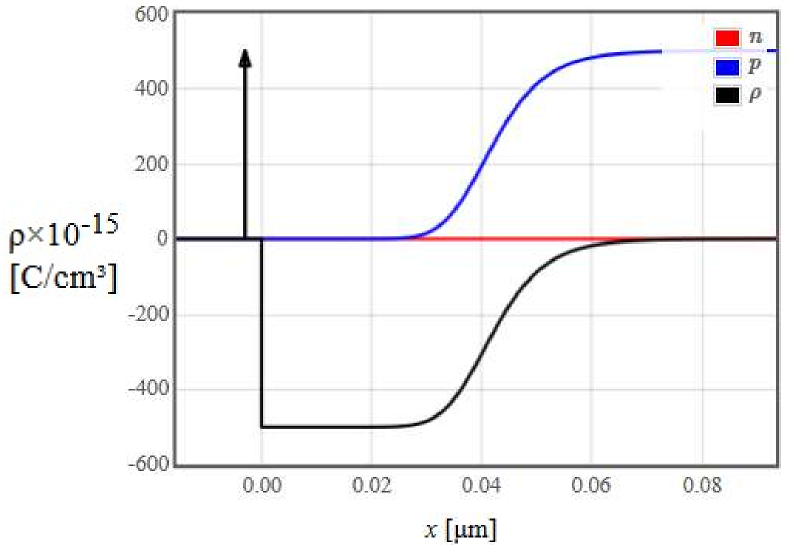


metal oxide semiconductor

$-t_{ox}$ 0

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

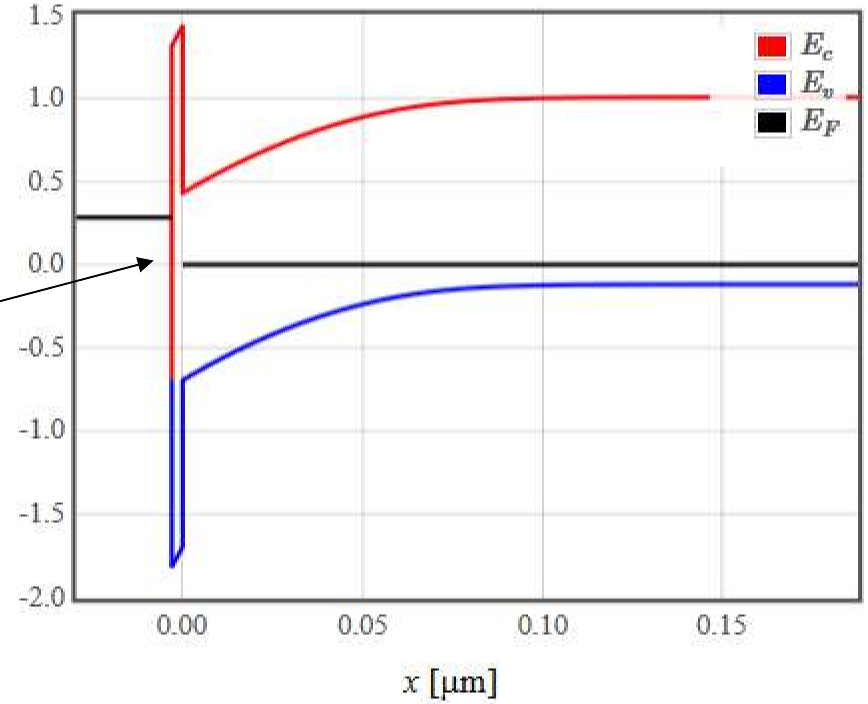




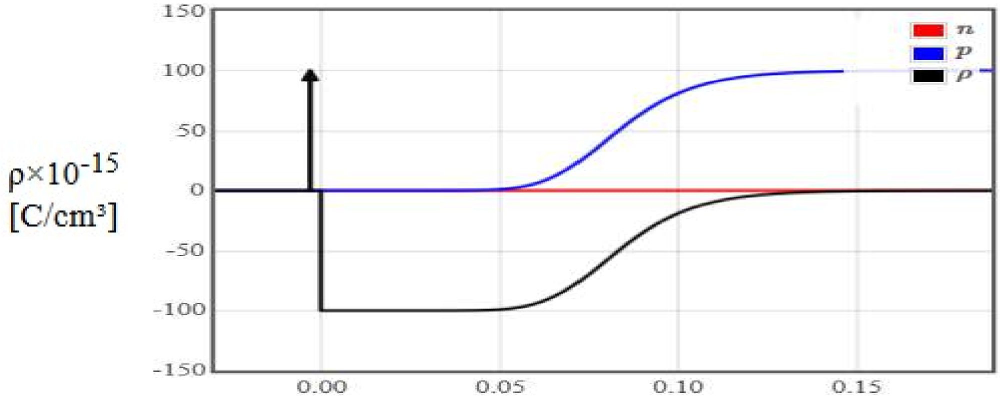
Can be in accumulation or depletion depending on workfunctions

Weak Inversion

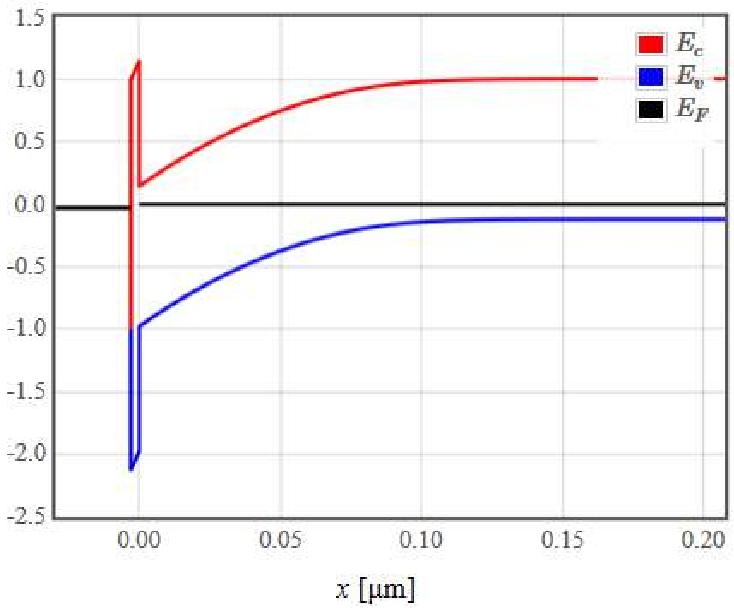
Majority carriers at $x = 0$ change from p to n

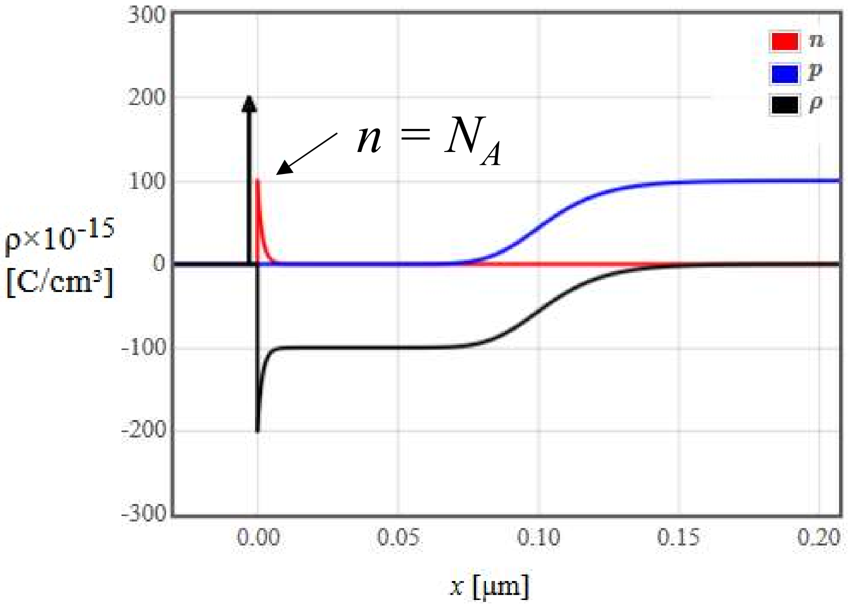


n > p
at the interface



Threshold voltage

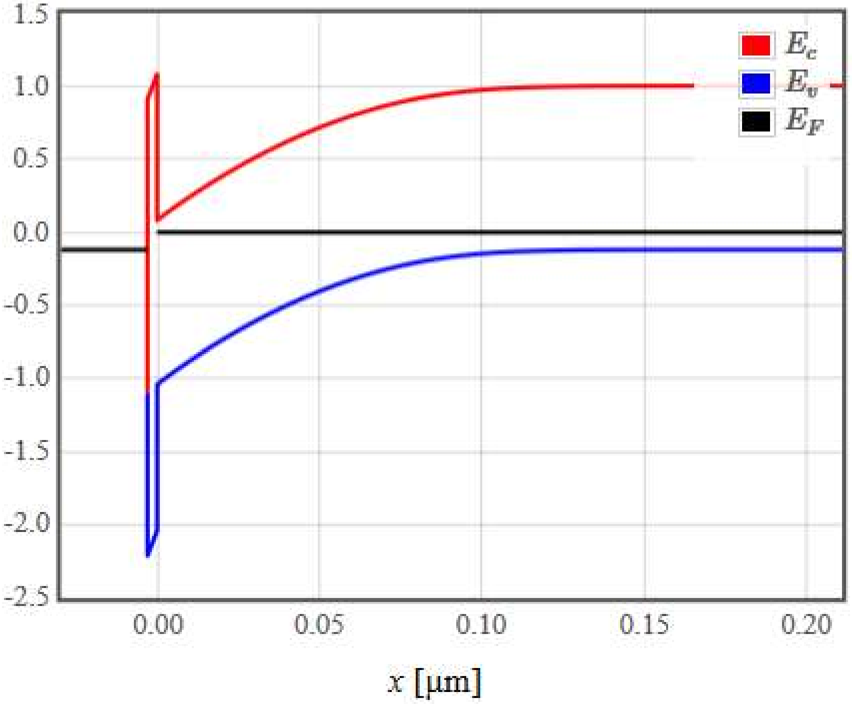


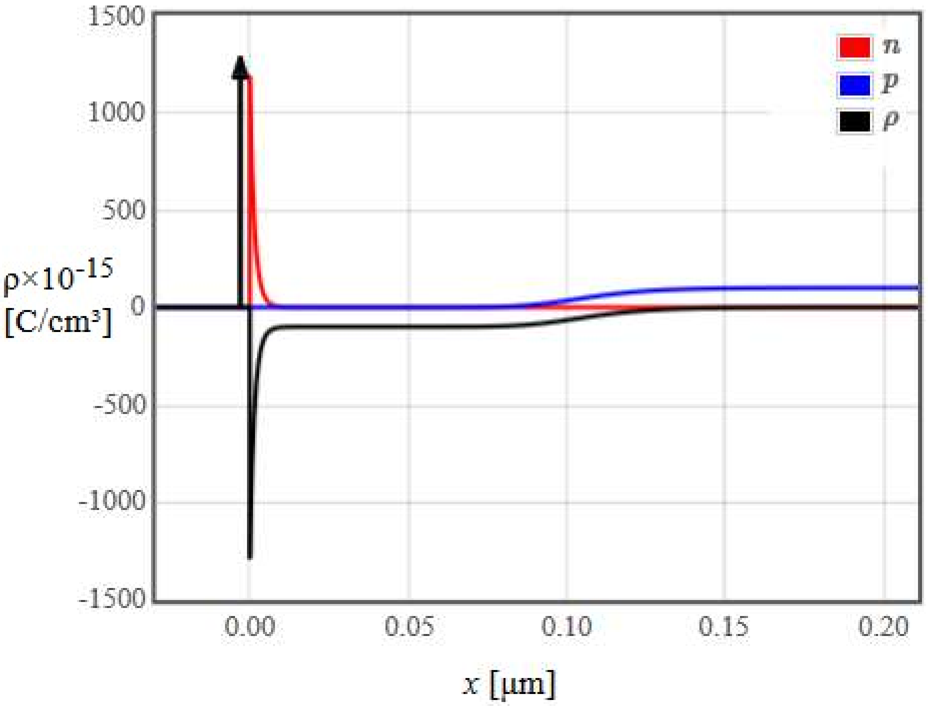


Strong inversion: $n = N_A$ at $x = 0$, the semiconductor-oxide interface

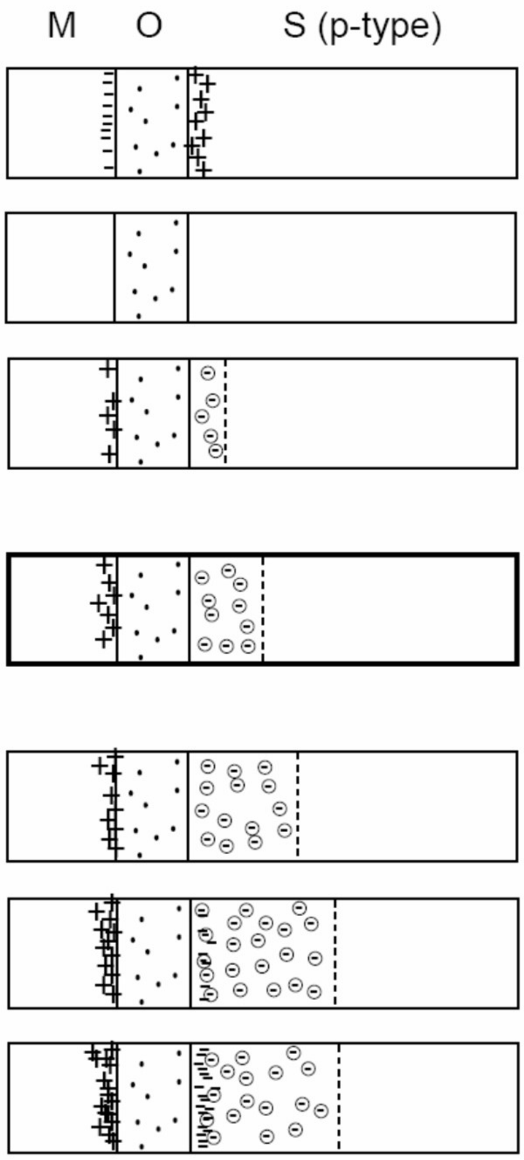
Inversion

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

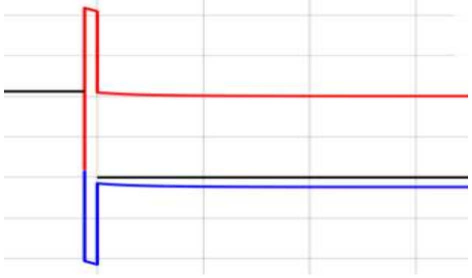




MOS capacitor

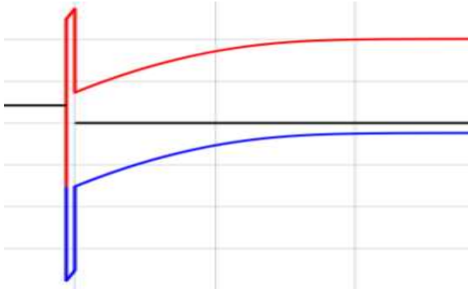


$V_{GB}<V_{FB}$ **accumulation**



$V_{GB}=V_{FB}$ flatband

$V_{FB}<V_{GB}<0$ depletion

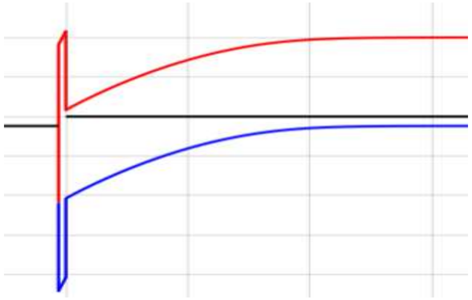


$\mathbf{V_{GB}=0}$ **zero bias**

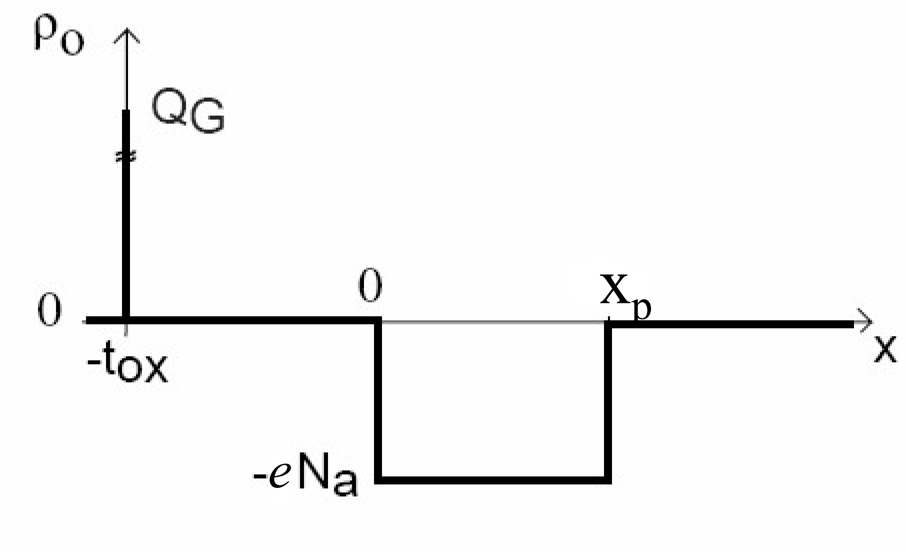
$0<V_{GB}<V_T$ depletion

$V_{GB}=V_T$ threshold

$V_{GB}>V_T$ inversion



charge density (depletion)

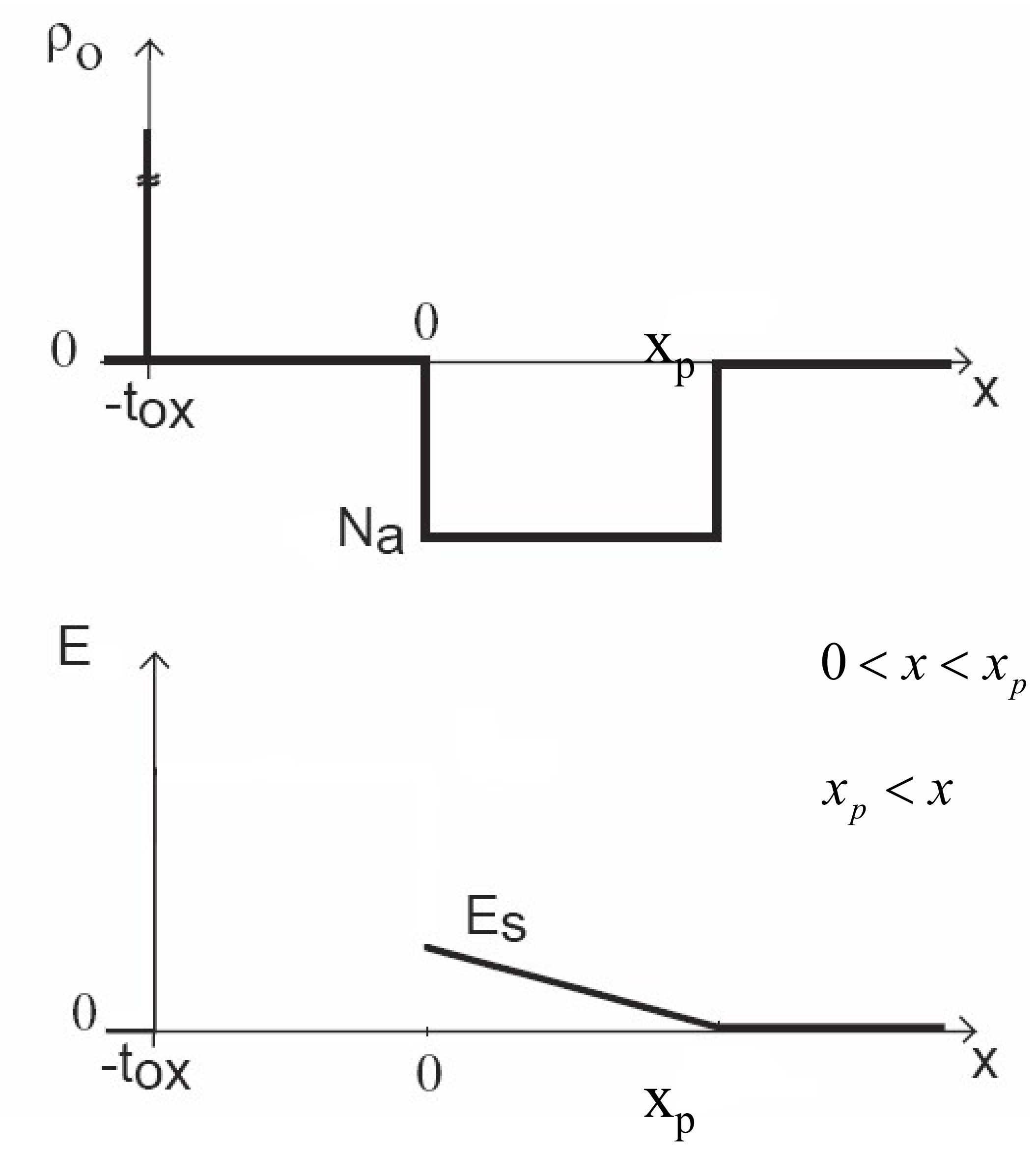


$$-t_{ox} < x < 0 \qquad \rho(x) = 0$$

$$0 < x < x_p \qquad \rho(x) = -eN_A$$

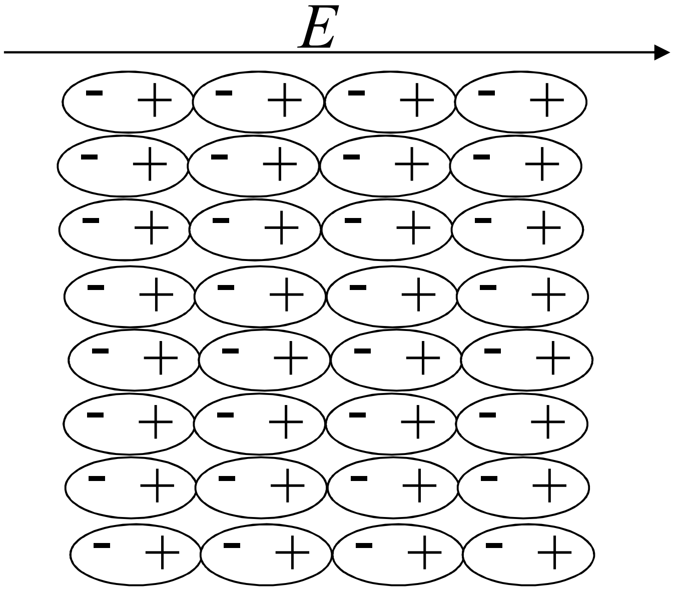
$$x_p < x \qquad \rho(x) = 0$$

electric field



$0 < x < x_p$	$E(x) = \frac{-eN_A}{\varepsilon_s}\left(x - x_p\right)$
$x_p < x$	$E(x) = 0$

electric field (depletion)

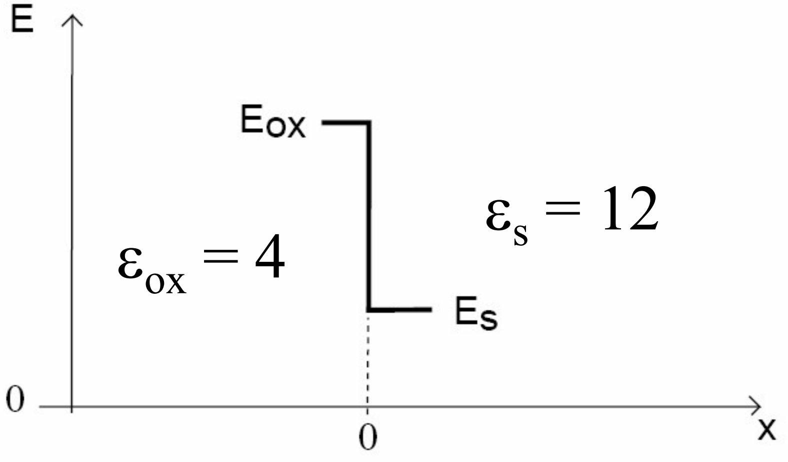


E is decreased by a factor of the dielectric constant

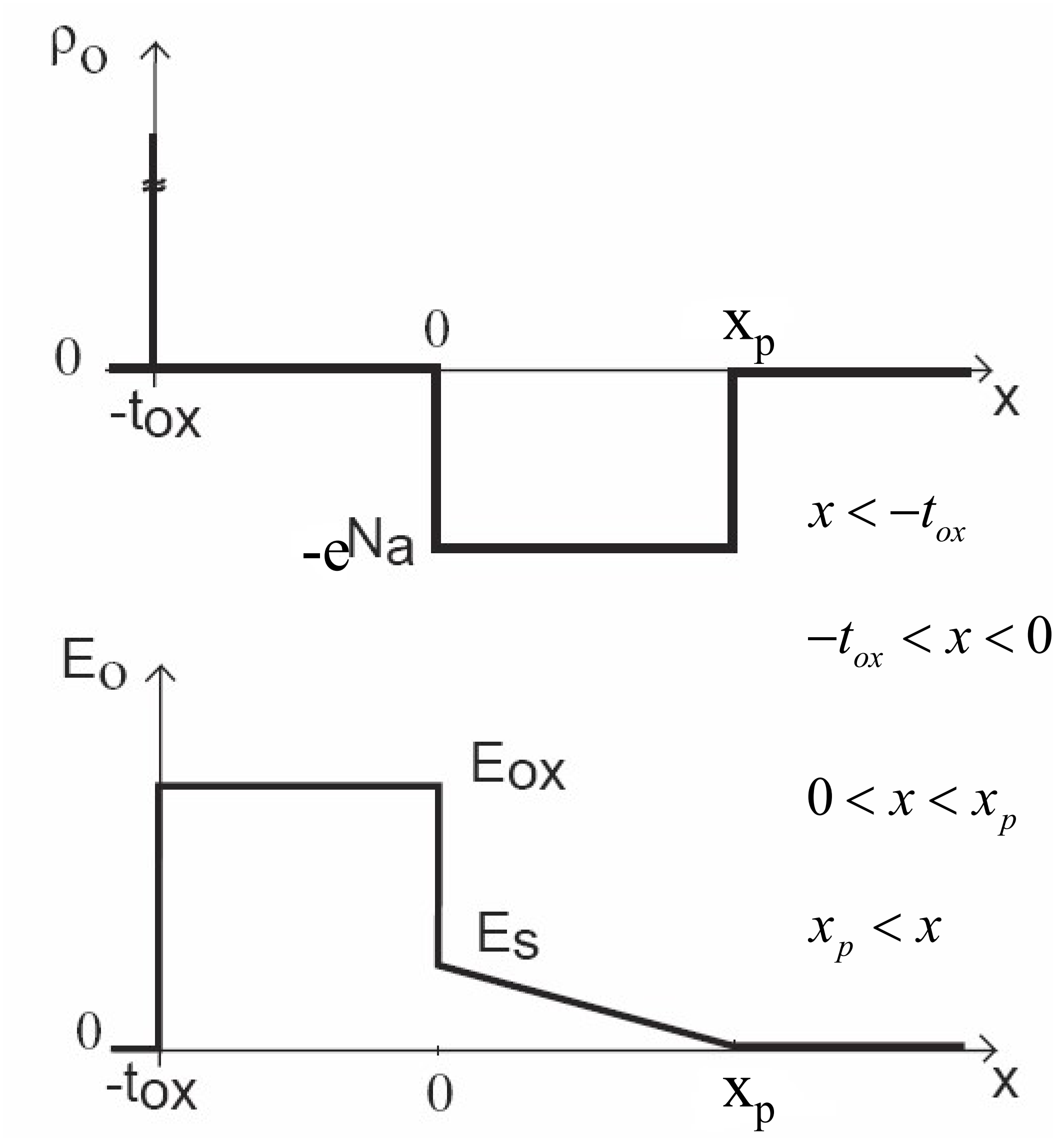
$$\varepsilon_r = \frac{E_{vacuum}}{E_{dielectric}}$$

$$\epsilon_{ox} E_{ox} = \epsilon_s E_s$$

$$\frac{E_{ox}}{E_s} = \frac{\epsilon_s}{\epsilon_{ox}} \simeq 3$$



electric field



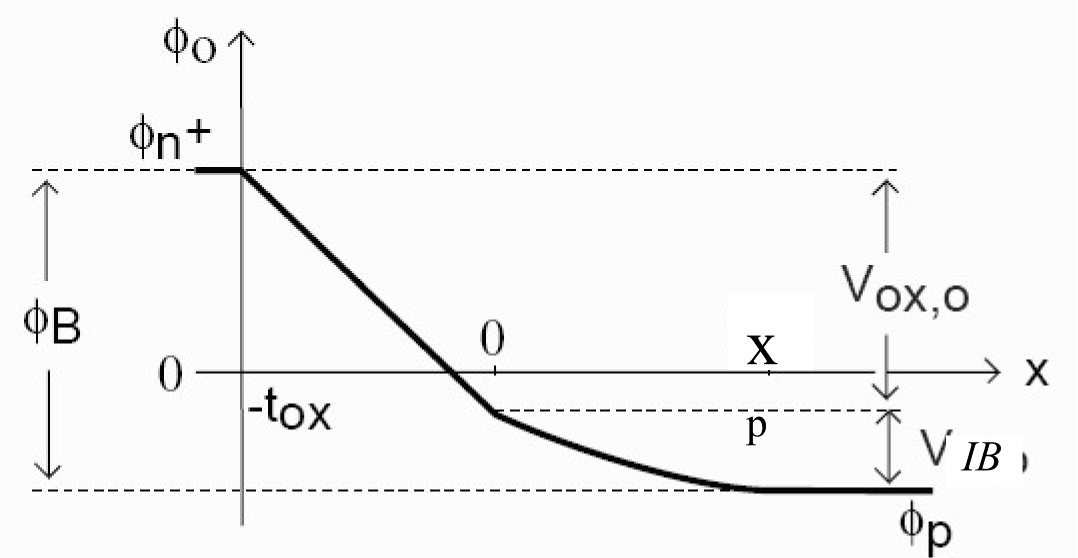
$$x < -t_{ox} \qquad E(x) = 0$$

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

$$0 < x < x_p \qquad E(x) = \frac{-eN_A}{\varepsilon_s}\left(x - x_p\right)$$

$$x_p < x \qquad E(x) = 0$$

electrostatic potential



$$x < -t_{ox} \qquad \phi(x) = \phi_{gate}$$

$$-t_{ox} < x < 0 \qquad \phi(x) = \phi_p + \frac{eN_A x_p^2}{2\varepsilon_s} + \frac{eN_A x_p}{\varepsilon_{ox}}(-x)$$

$$0 < x < x_p \qquad \phi(x) = \phi_p + \frac{eN_A}{2\varepsilon_s}\left(x - x_p\right)^2$$

$$x_p < x \qquad \phi(x) = \phi_p$$

(We still don't know x_p)

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

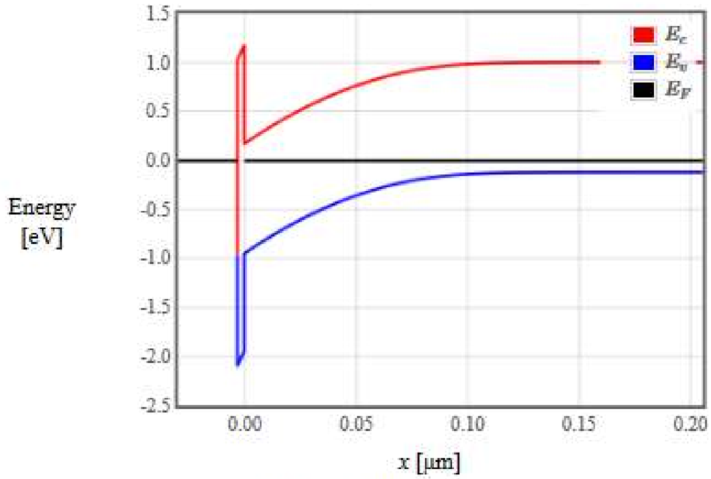
t_{ox} = 3 nm ϵ_{ox} = 4 $N_c(300)$ = 2.78E19 1/cm³ T = 300 K

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 $n_i = 6.40\text{e+}9$ 1/cm³

$E_s = 1.57\text{e+}7$ V/m $V_s = 0.831$ V

$Q = -0.00167$ C/m²

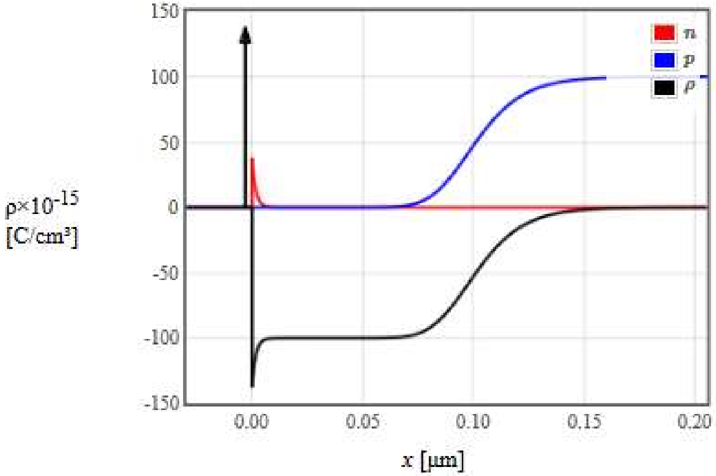
$E_{ox} = 4.70\text{e+}7$ V/m $V_{shoot} = 0.0000221$ V

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

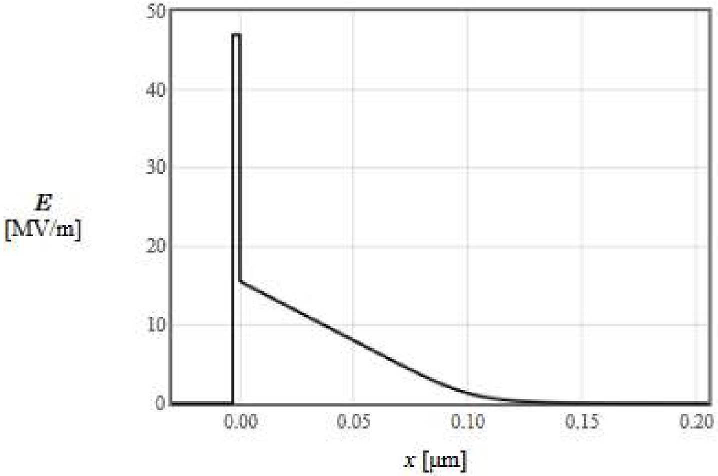
From the depletion approximation:

$\max(x_p)$ 0.107 µm $V_T = 0.0292$ V

Charge density



Electric field

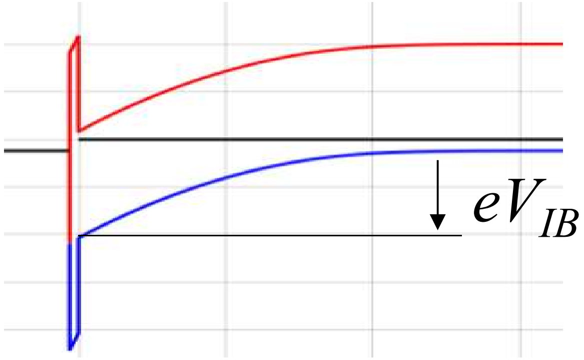


Band bending at inversion

$n = N_A$ at threshold

Far on the p side

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



At the interface, $n = N_A$

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

V_{IB} is the voltage between the interface and the body

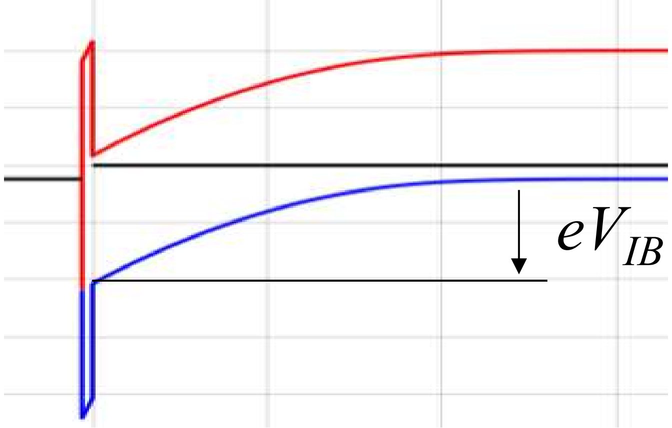
The voltage between the semiconductor-oxide interface and the body

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

Strong inversion

$n_s = N_A$ at the semiconductor-oxide interface

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



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

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

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

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

The depletion width remains constant in inversion.

Depletion width in inversion

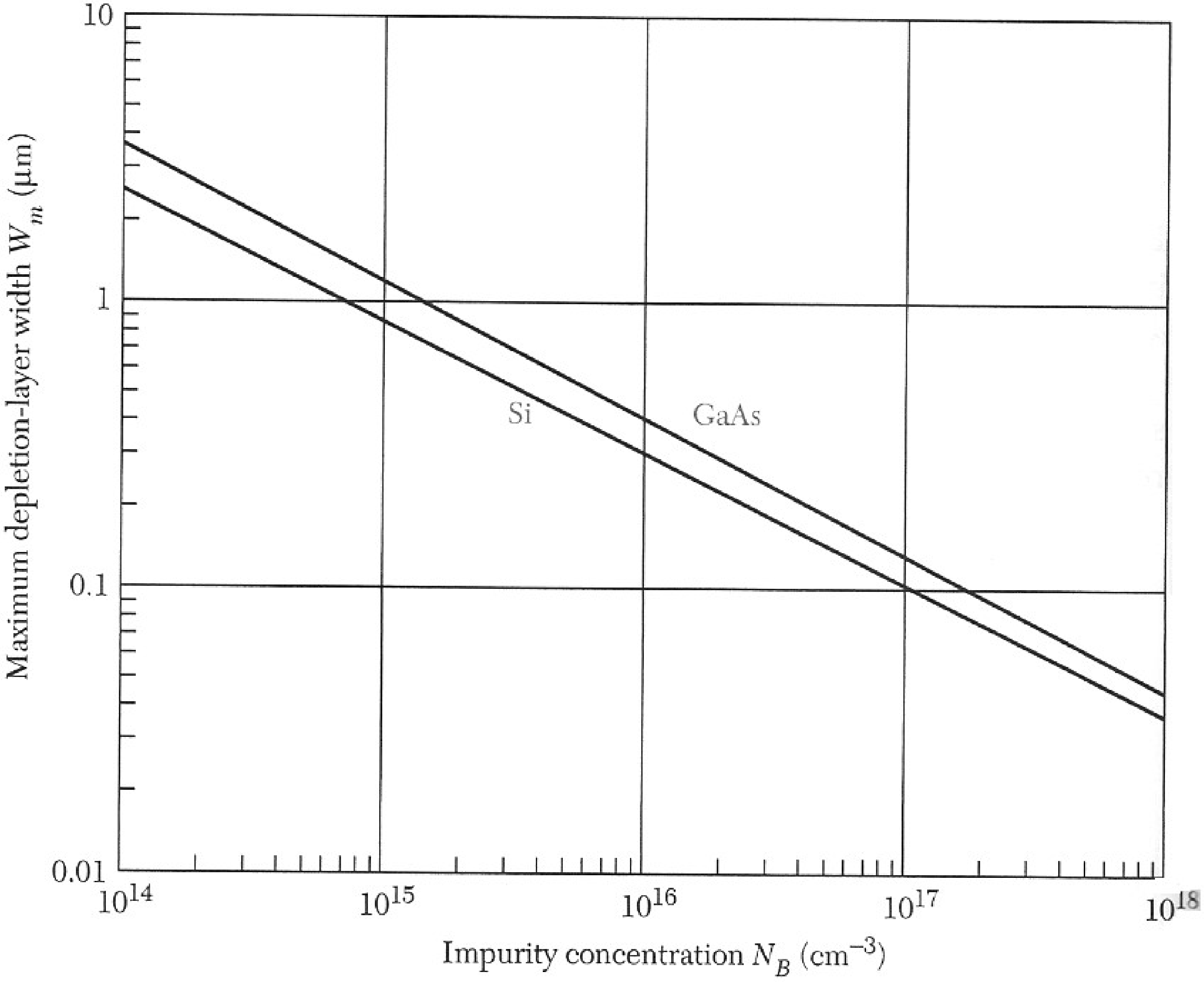
$$V_{IB} = \frac{eN_A x_p^2}{2\varepsilon}$$

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

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

The depletion width remains constant in inversion.

Depletion width

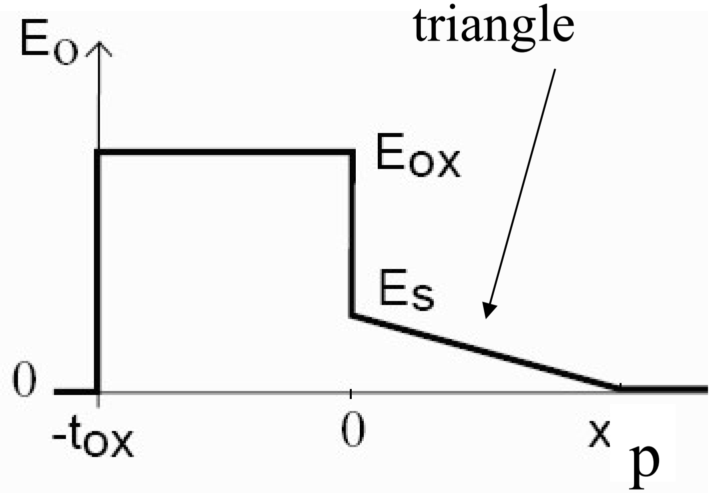


Electric field at semi-oxide interface at strong inversion

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

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

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

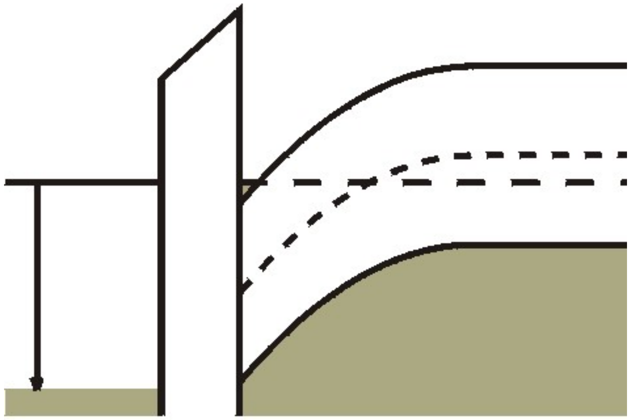


$V_{IB} = E_s x_p/2 =$ area of the triangle

Threshold voltage

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

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

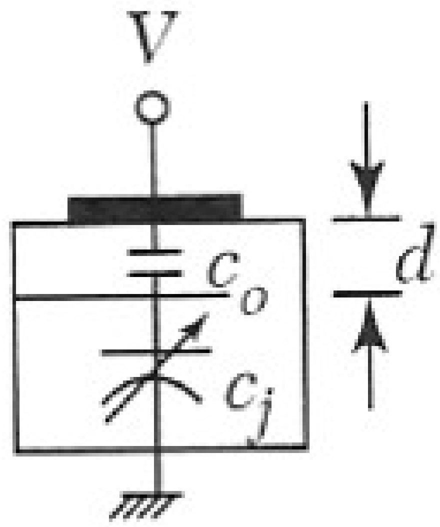


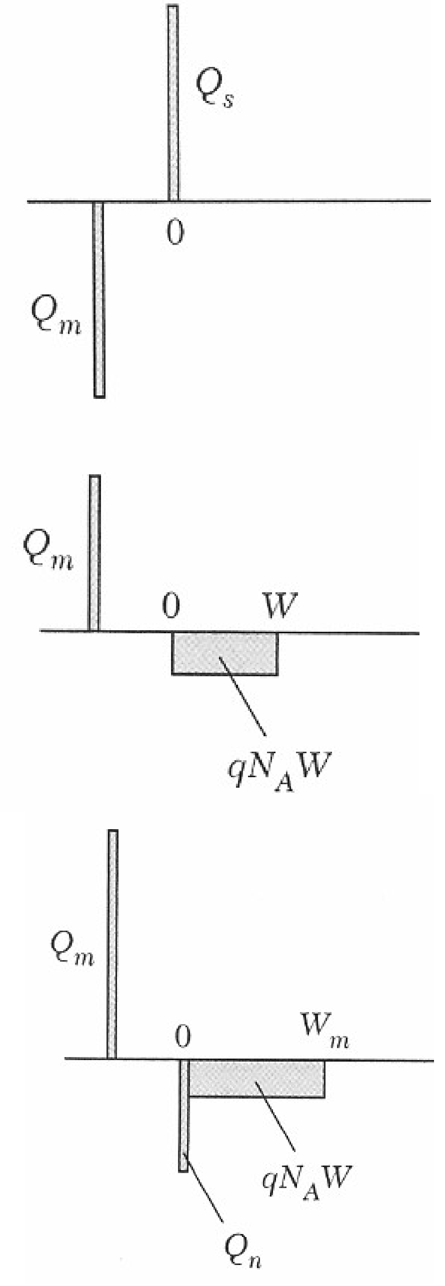
Small V_T requires a small t_{ox} and a large ε_{ox}.

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.

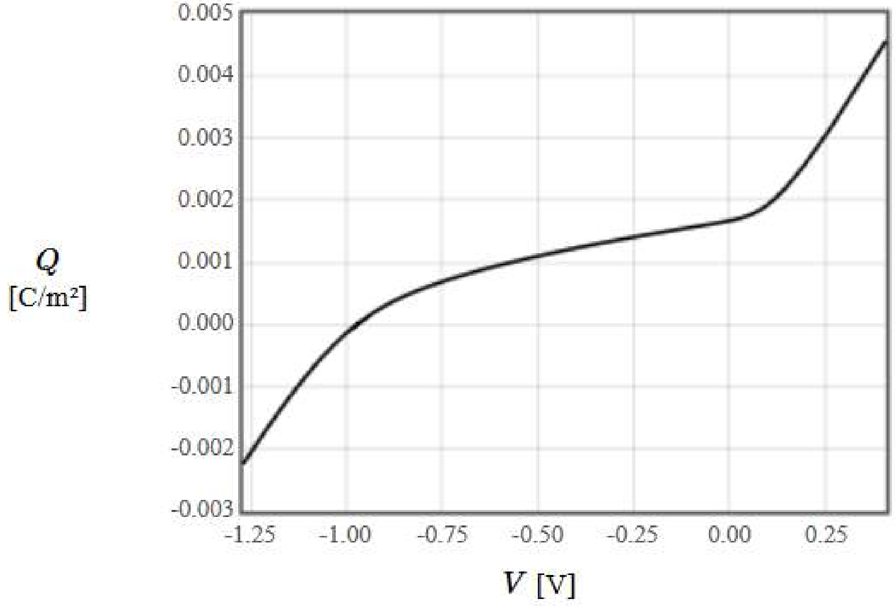
$\phi_m =$ 4.08 eV $\chi_s =$ 4.05 eV

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

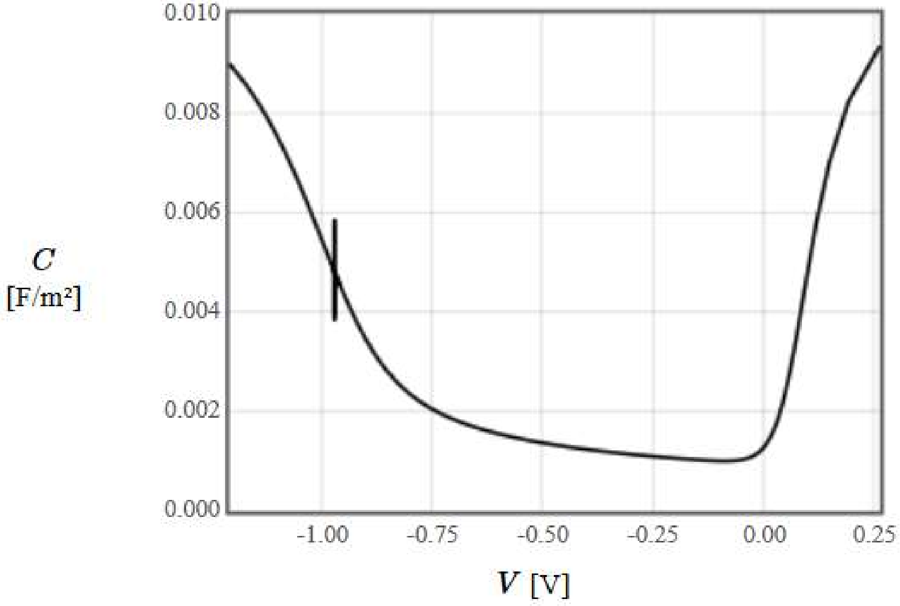
$E_g =$ 1.166-4.73E-4*T*T/(T+636) eV $\epsilon_{semi} =$ 12 $N_v(300) =$ 9.84E18 1/cm³ $N_A =$ 1E17 1/cm³

Submit Si Ge GaAs

Q - V



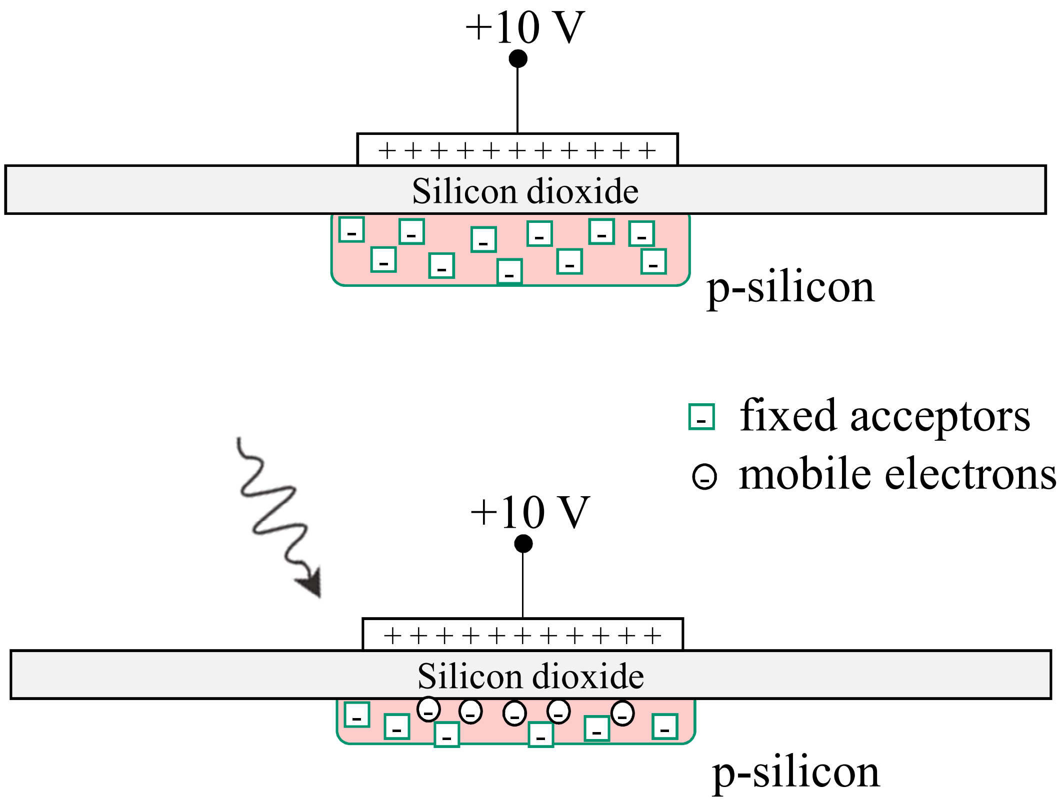
C - V

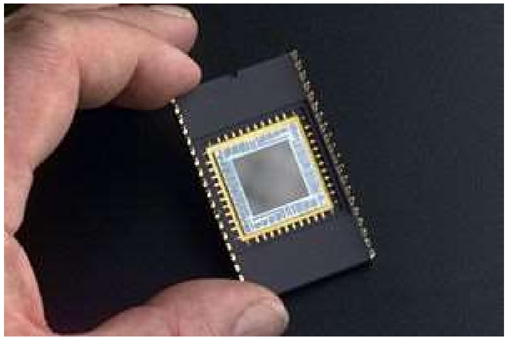


$E_g = 1.12$ eV $n_i = 6.40\text{e+}9$ 1/cm³ $\phi_s = 5.05$ eV $V_{fb} = \phi_m - \phi_s =$ -0.972 V

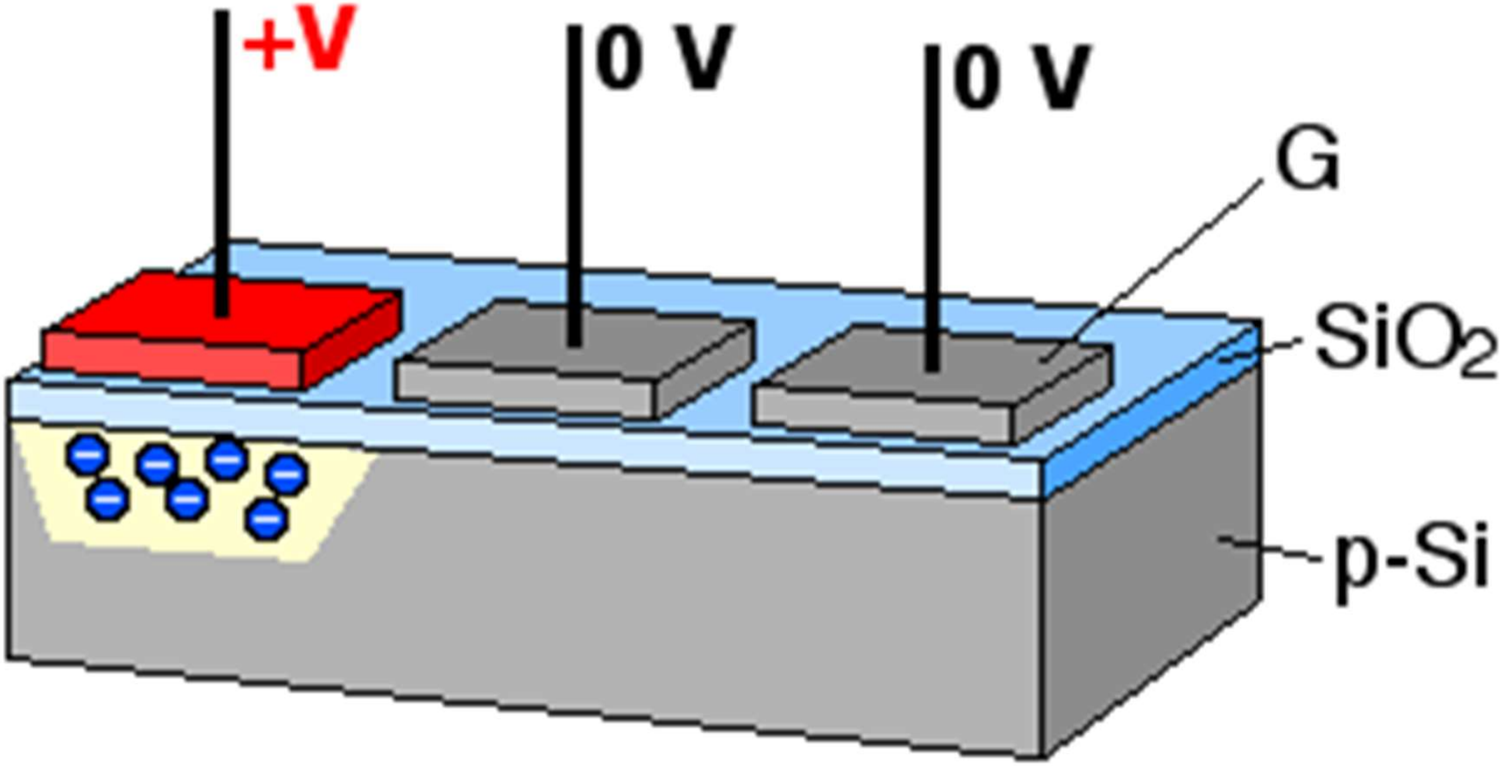
$C_{ox} = \frac{\epsilon_{ox}}{t_{ox}} = 0.0118$ F/m² $V_T = 0.0292$ V

CCD devices


+10 V
+ + + + + + + + + + + +
Silicon dioxide
p-silicon
▣ fixed acceptors
⊖ mobile electrons
+10 V
+ + + + + + + + + + + +
Silicon dioxide
p-silicon



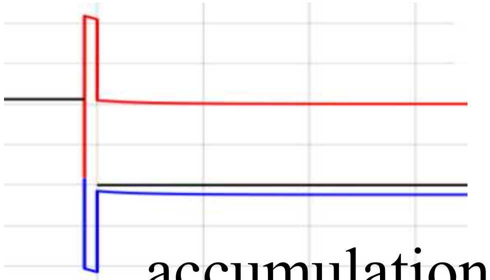
CCD devices



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

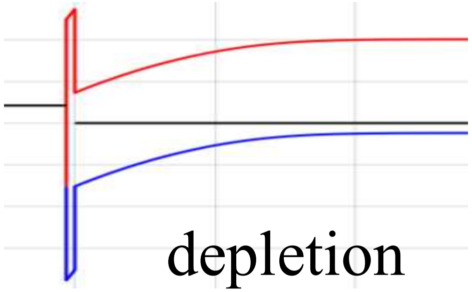
MOSFETs: Gradual Channel Approximation

Gradual channel approximation

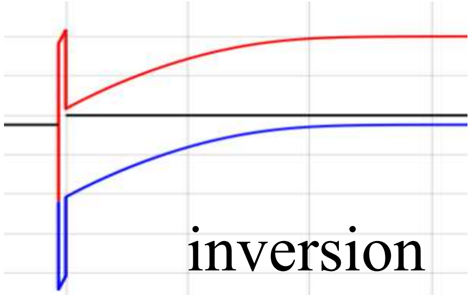


accumulation

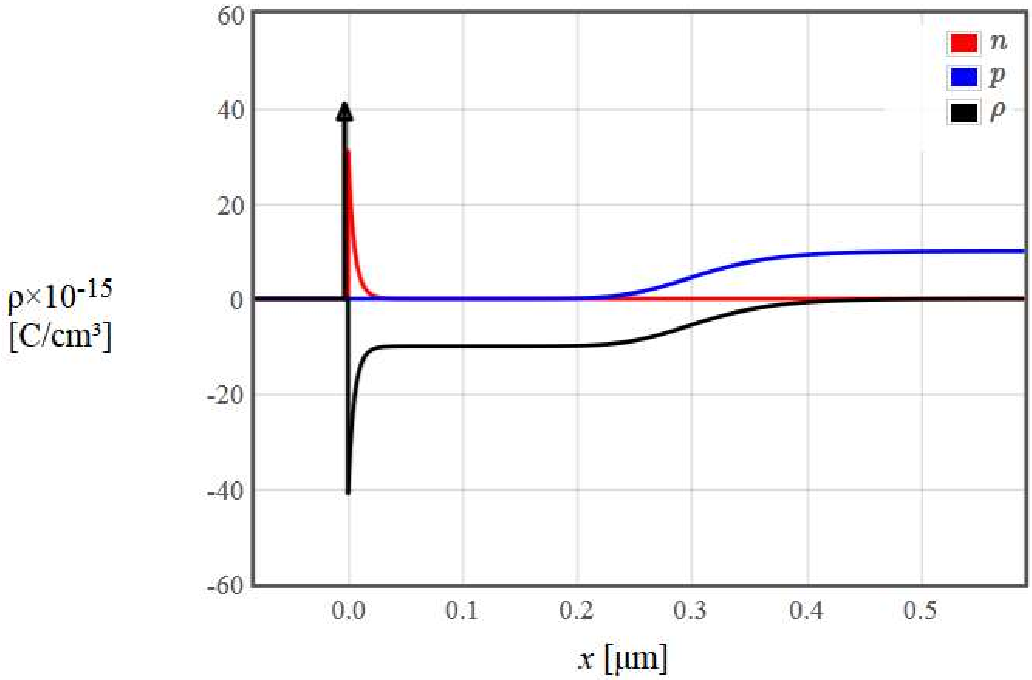
$$Q_{\text{mobile}} = \begin{cases} 0, & \text{for } V_G - V_B < V_T \\ -C_{\text{ox}}(V_G - V_B - V_T) & \text{for } V_G - V_B > V_T \end{cases}$$



depletion



inversion

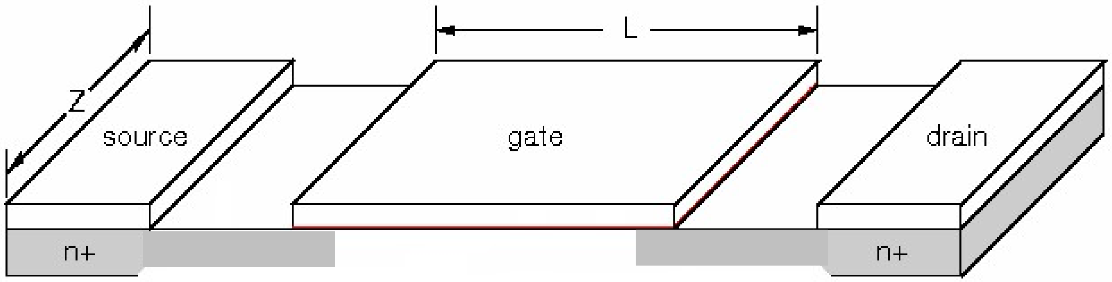


http://lampx.tugraz.at/~hadley/psd/L10/gradualchannelapprox.php

Gradual channel approximation

Ohm's law ⟶ $j = -nev_d = ne\mu_n E_y$

$$I = Ztj = Ztne\mu_n E_y = Ze\mu_n n_s E_y$$



$n_s = nt$ is the sheet charge at the interface.

$$n_s(y) = -\frac{Q}{e} = \frac{C_{ox}\left(V_G - V_{ch}(y) - V_T\right)}{e}$$

Gradual channel approximation

$$n_s(y) = -\frac{Q(y)}{e} = \frac{C_{ox}(V_G - V_{ch}(y) - V_T)}{e}$$

$$I = Ztj = Ztnev_d = Zen_s\mu_n E_y$$

$$I_D = -Z\mu_n C_{ox}(V_G - V_{ch}(y) - V_T)\frac{dV_{ch}}{dy}$$

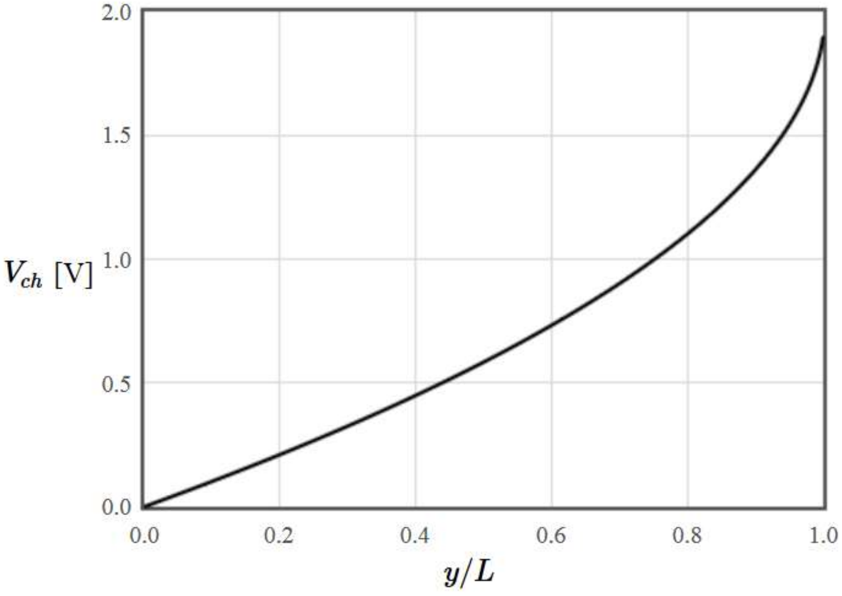
differential equation for V_{ch}

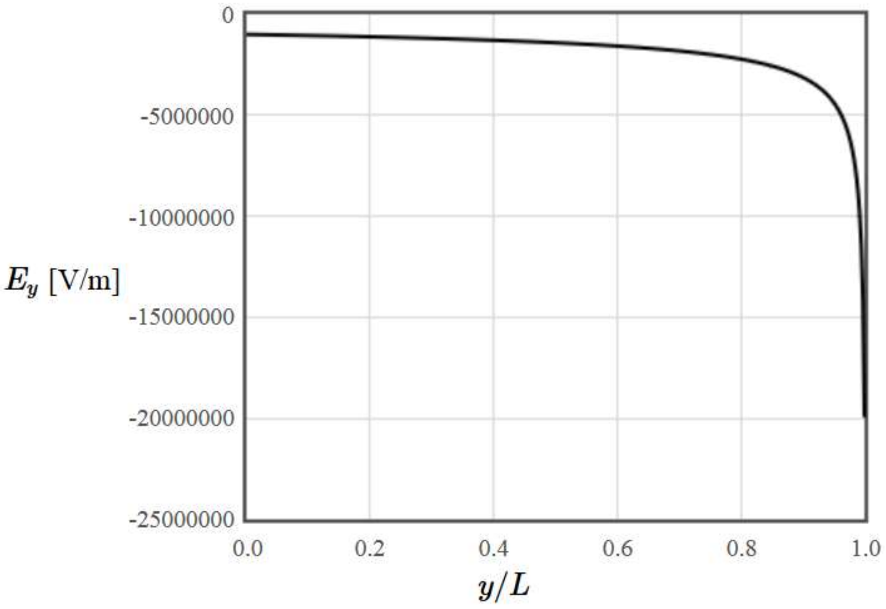
http://lampx.tugraz.at/~hadley/psd/L10/gradualchannelapprox.php

Gradual channel approximation

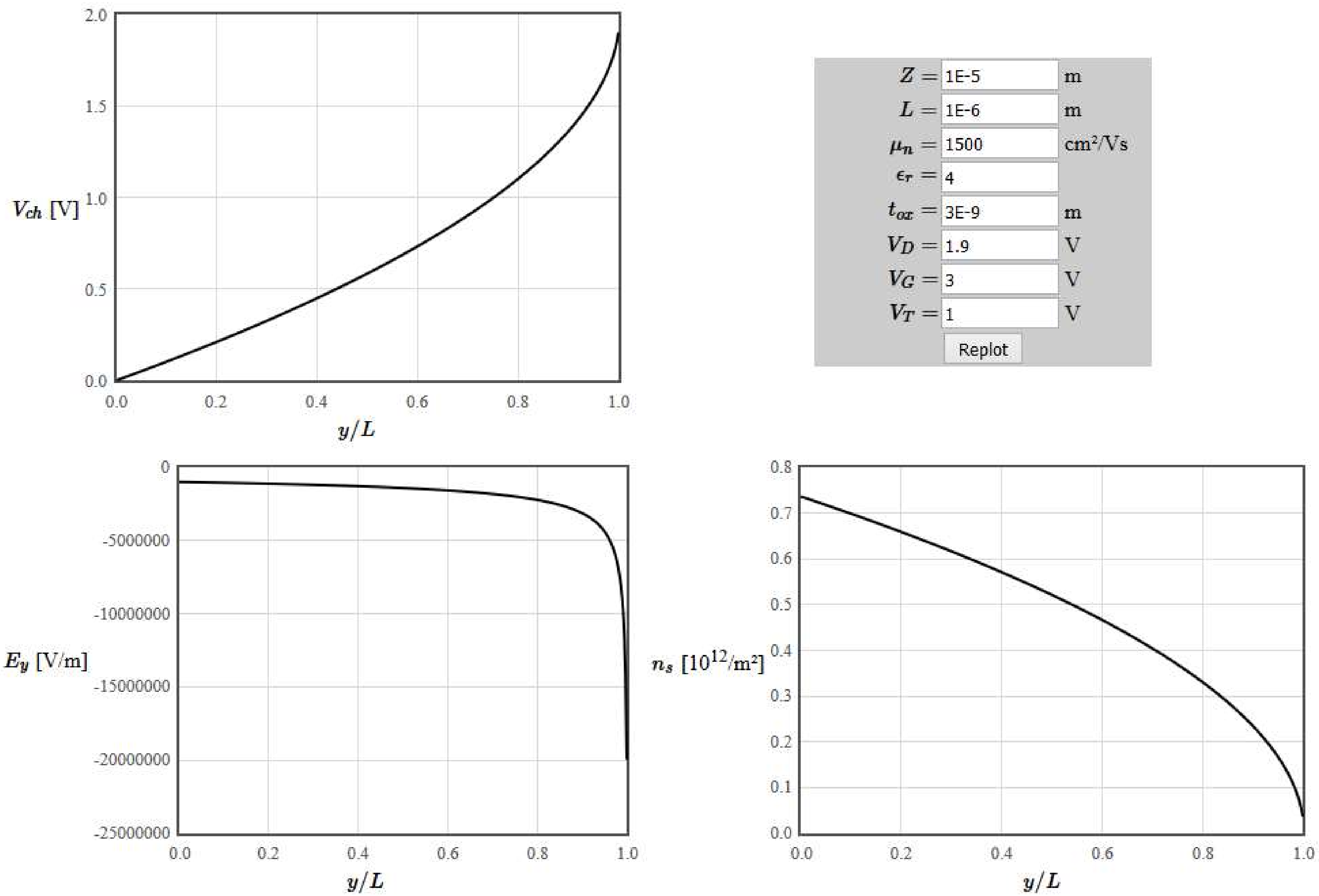
$$V_{ch}(y) = V_G - V_T - \sqrt{(V_G - V_T)^2 - \frac{2I_D y}{Z\mu_n C_{ox}}}$$

$$E_y = -\frac{dV_{ch}}{dy} = -\frac{I_D}{Z\mu_n C_{ox}\sqrt{(V_G - V_T)^2 - \frac{2I_D y}{Z\mu_n C_{ox}}}}$$





MOSFET Gradual Channel Approximation



$Z =$ 1E-5 m

$L =$ 1E-6 m

$\mu_n =$ 1500 cm²/Vs

$\epsilon_r =$ 4

$t_{ox} =$ 3E-9 m

$V_D =$ 1.9 V

$V_G =$ 3 V

$V_T =$ 1 V

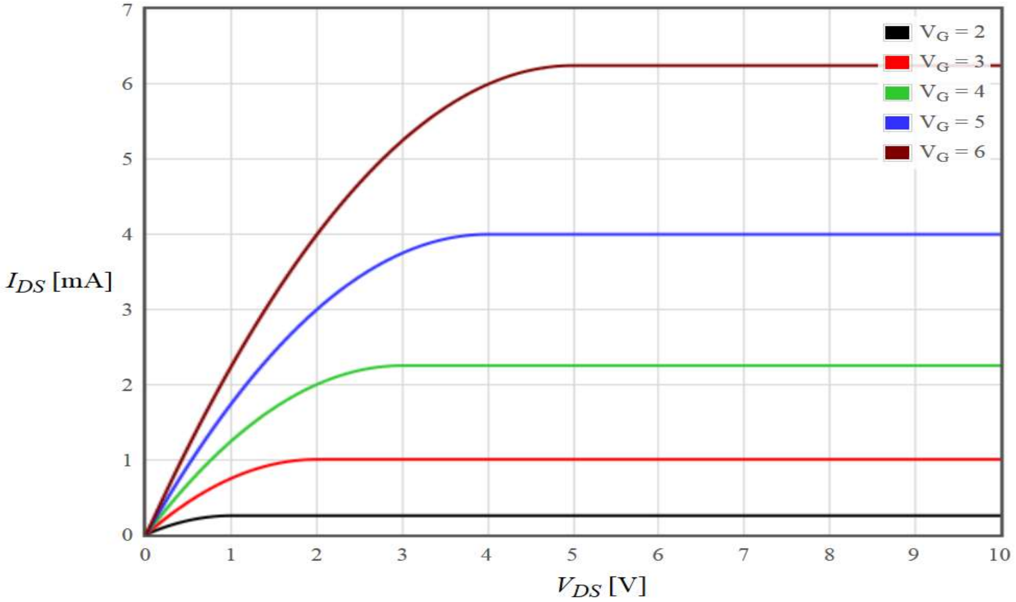
http://lampx.tugraz.at/~hadley/psd/L10/gradualchannelapprox.php

Gradual channel approximation

$$\int_0^L I_D \, \mathrm{d}y = \int_0^{V_D} Z \mu_n C_{ox} (V_G - V_{ch}(y) - V_T) \, \mathrm{d}V$$

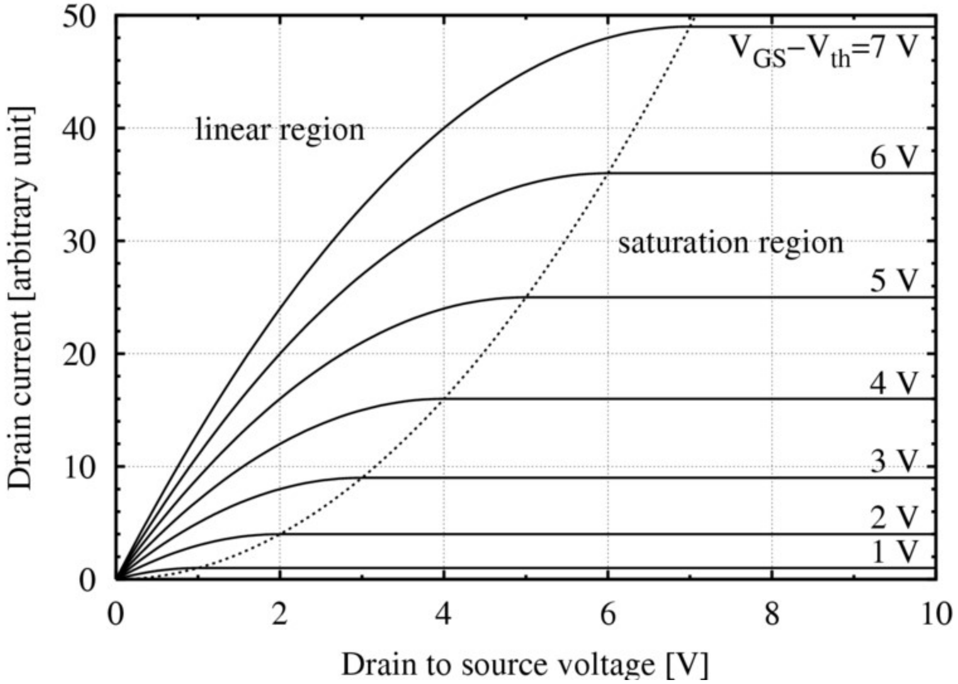
$$\boxed{I_D = \frac{Z}{L} \mu_n C_{ox} \left[(V_G - V_T) V_D - \frac{V_D^2}{2} \right]}$$

Valid in the linear regime (until pinch-off occurs at the drain).



MOSFET-saturation voltage

$$I = \frac{Z}{L}\mu_n C_{ox}\left[\left(V_G - V_T\right)V_D - \frac{V_D^2}{2}\right]$$



At pinch-off, $dI_{ds}/dV_{ds} = 0$

$$\frac{dI}{dV_D} = \frac{Z}{L}\mu_n C_{ox}\left[\left(V_G - V_T\right) - V_D\right] = 0$$

$$V_{sat} = \left(V_G - V_T\right)$$

A MOSFET in saturation is a voltage controlled current source.

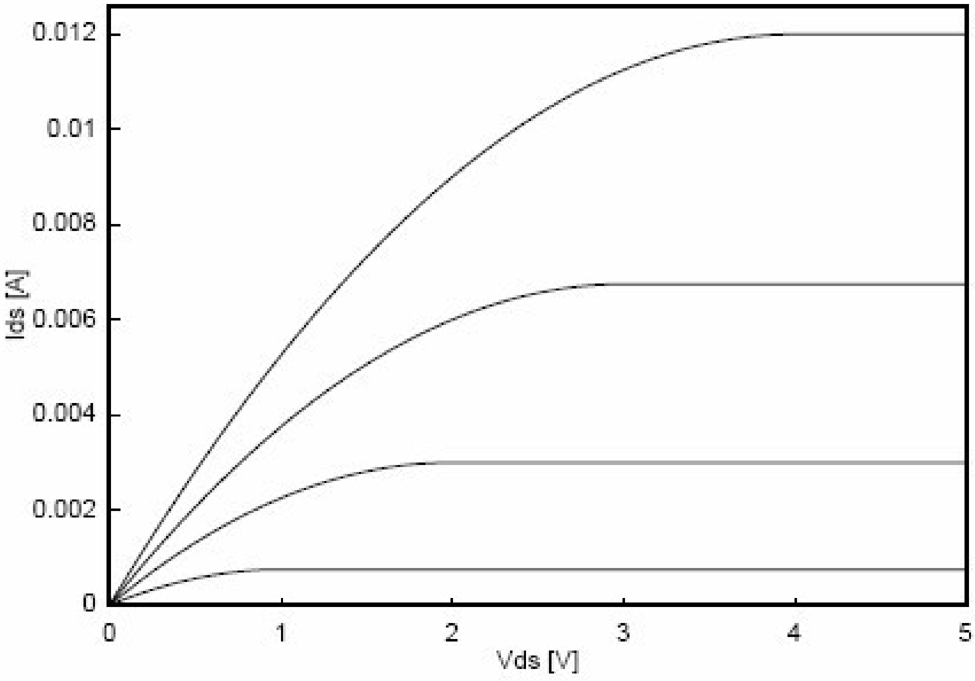
MOSFET - saturation current

Use the saturation voltage at pinch-off to determine the saturation current

$$V_{sat} = \left(V_G - V_T\right)$$

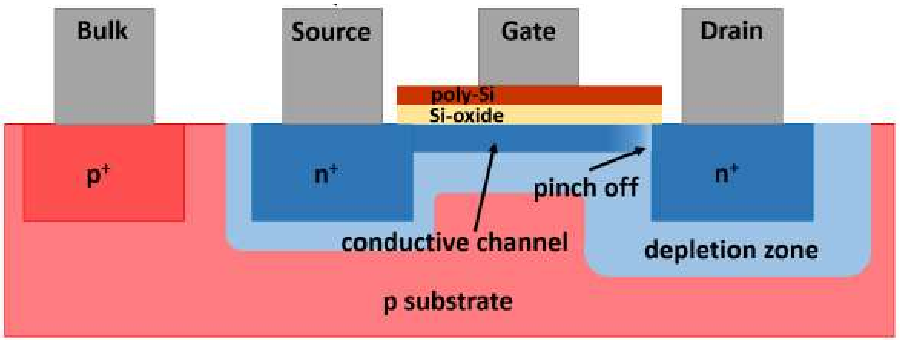
$$I = \frac{Z}{L}\mu_n C_{ox}\left[\left(V_G - V_T\right)V_D - \frac{V_D^2}{2}\right]$$

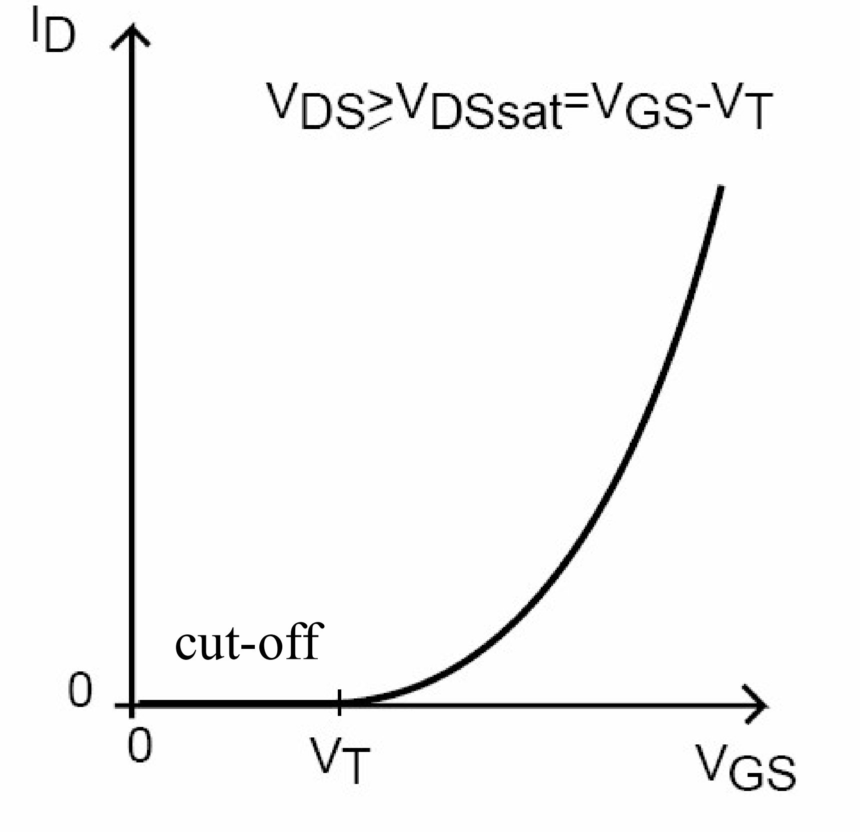
$$I_{sat} = \frac{Z}{2L}\mu_n C_{ox}\left(V_G - V_T\right)^2$$

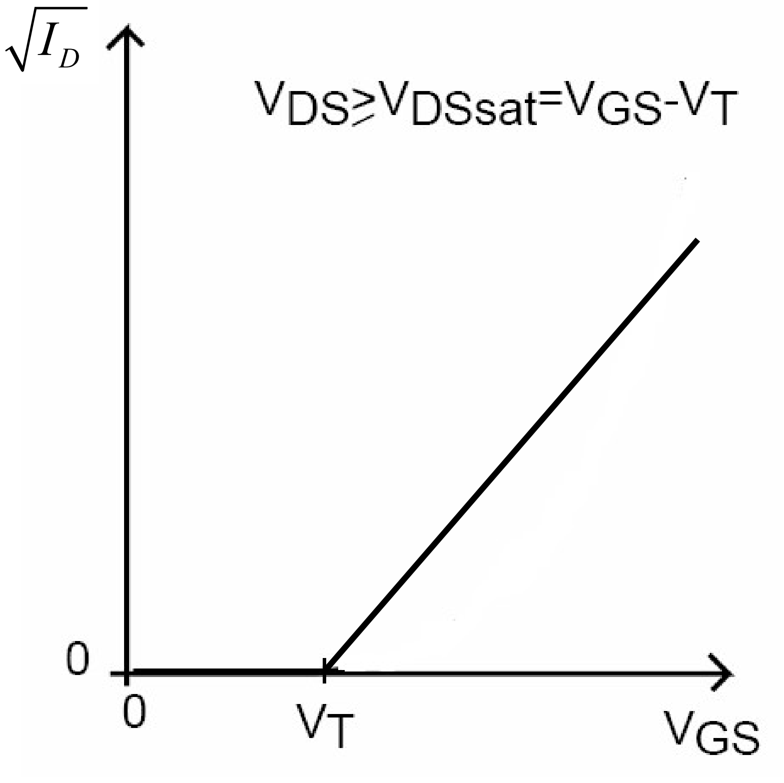


MOSFET (saturation regime)

$$I_{sat} = \frac{Z}{2L}\mu_n C_{ox}\left(V_{GS} - V_T\right)^2$$







MOSFET (linear regime)

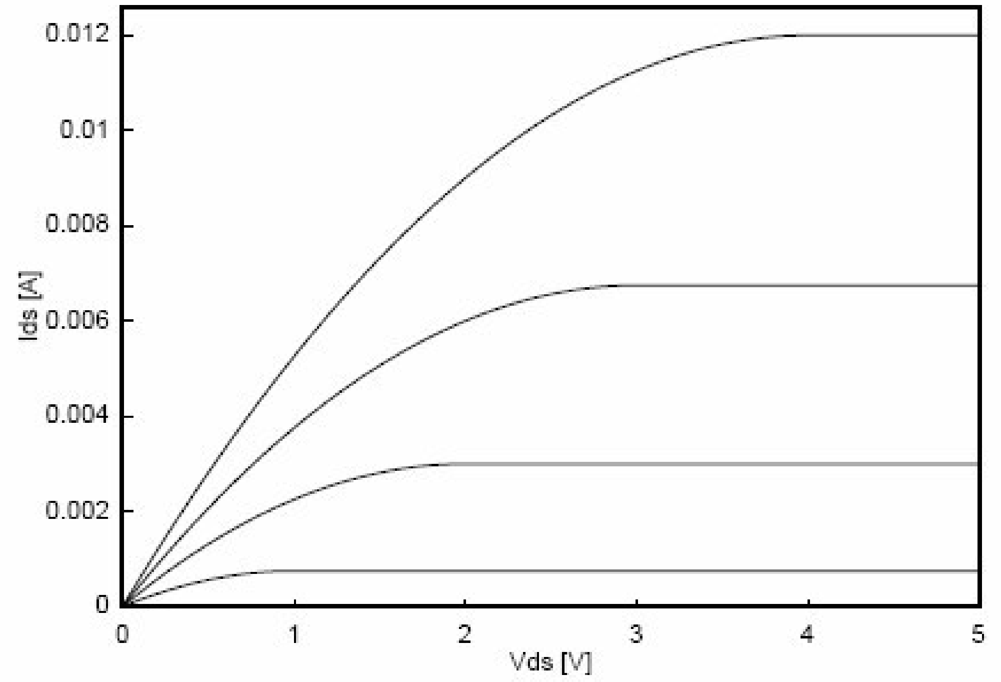
Channel conductance in the linear regime. For small V_D

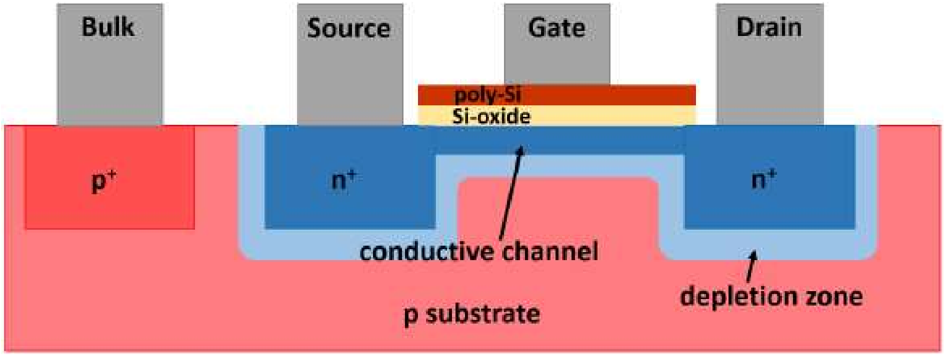
$$I \approx \frac{Z}{L}\mu_n C_{ox}\left[\left(V_G - V_T\right)V_D\right]$$

$$g_D = \frac{dI_D}{dV_D} = \frac{Z}{L}\mu_n C_{ox}\left(V_G - V_T\right)$$

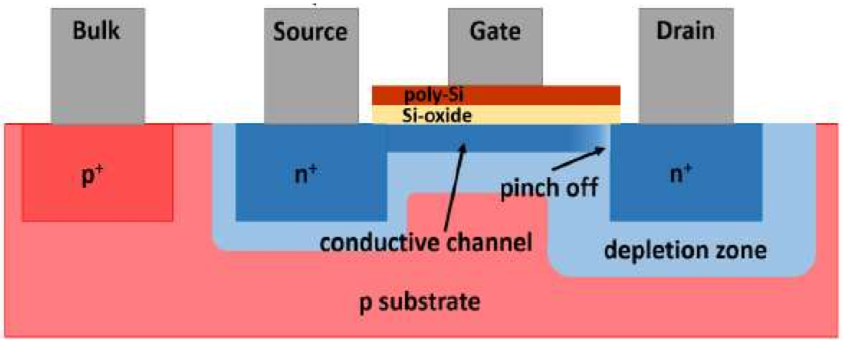
Transconductance

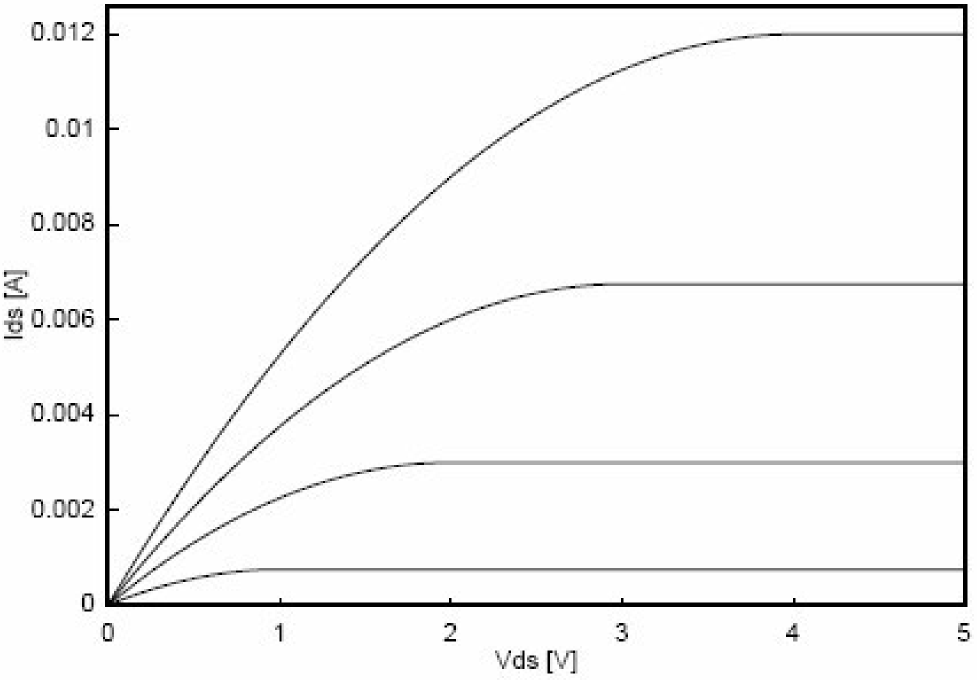
$$g_m = \frac{dI_D}{dV_G} = \frac{Z}{L}\mu_n C_{ox} V_D$$





MOSFET (saturation regime)





$$I_{sat} = \frac{Z}{2L}\mu_n C_{ox}\left(V_G - V_T\right)^2$$

Transconductance

$$g_m = \frac{dI_D}{dV_G} = \frac{Z}{L}\mu_n C_{ox}\left(V_G - V_T\right)$$

A MOSFET in the saturation regime acts like a voltage controlled current source.