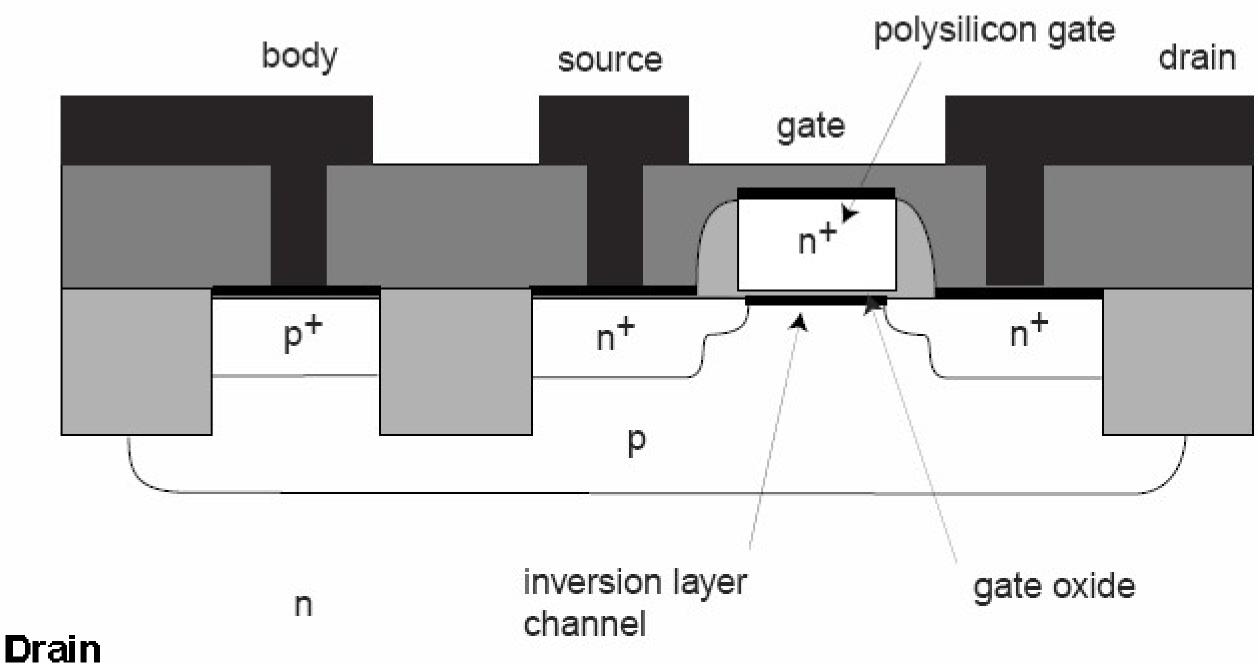
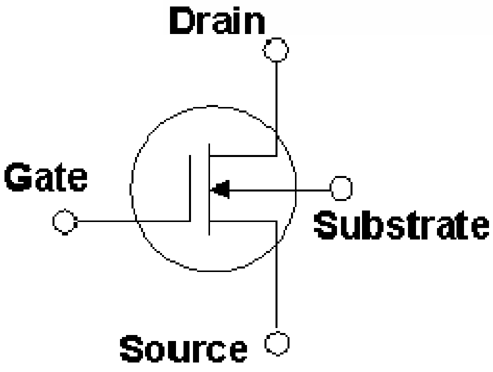
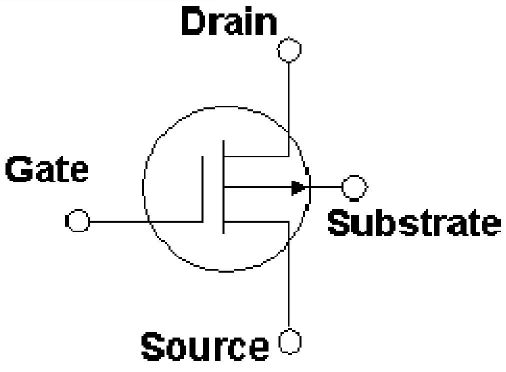
MOSFETs





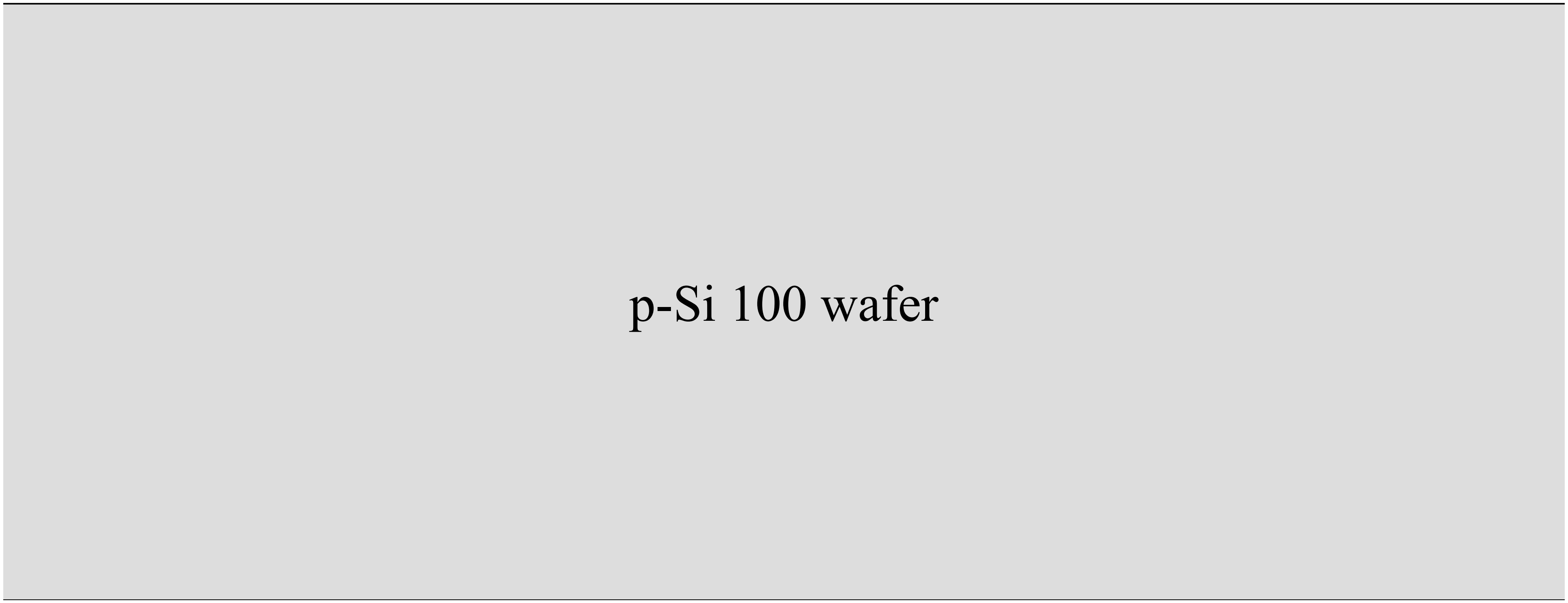
n - channel

functions as a switch
~ 1 billion /chip



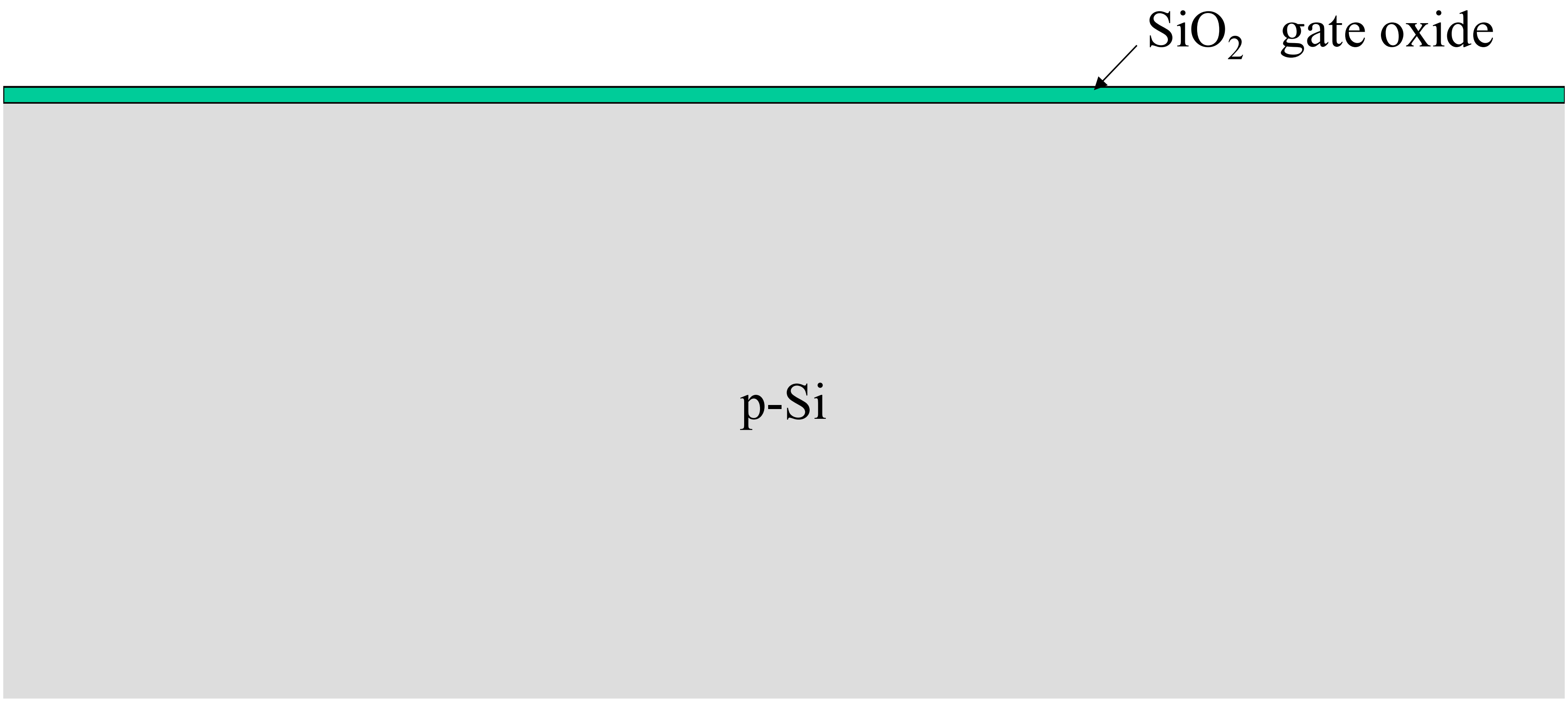
p - channel

Self-aligned fabrication



p-Si 100 wafer

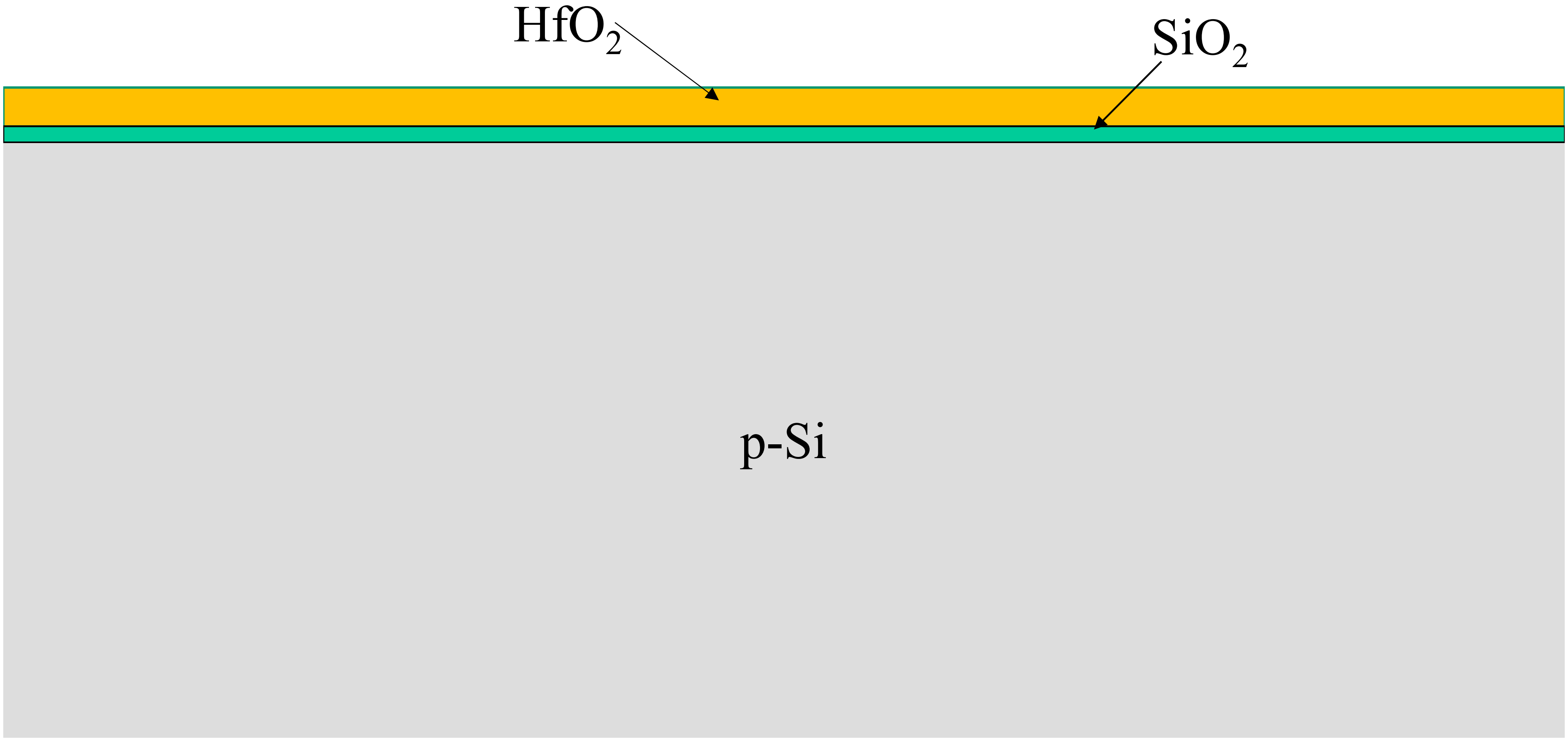
Dry oxidation



SiO_2 gate oxide

p-Si

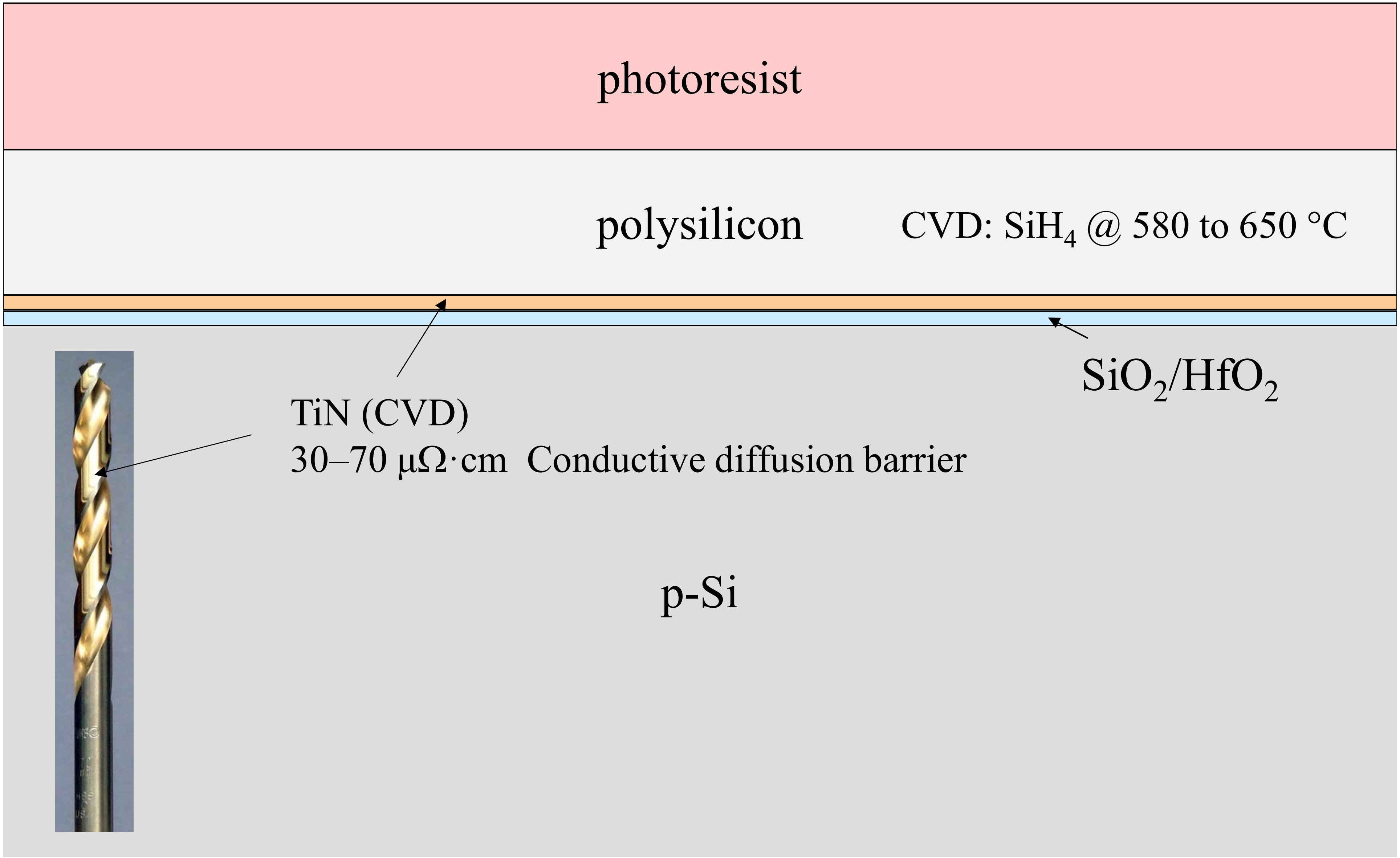
gate oxide



HfO_2

SiO_2

p-Si



photoresist

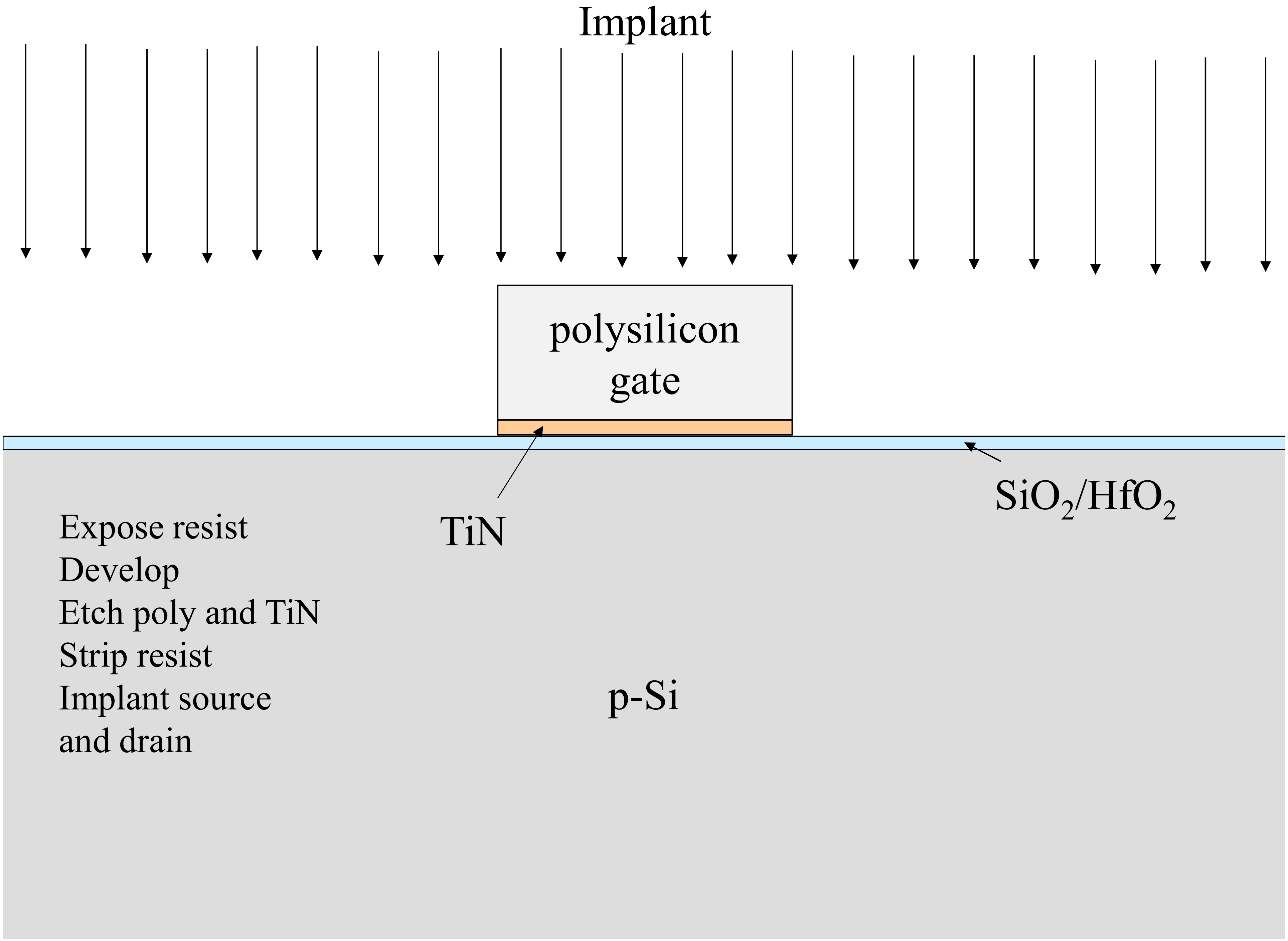
polysilicon

CVD: SiH_4 @ 580 to 650 °C

SiO_2/HfO_2

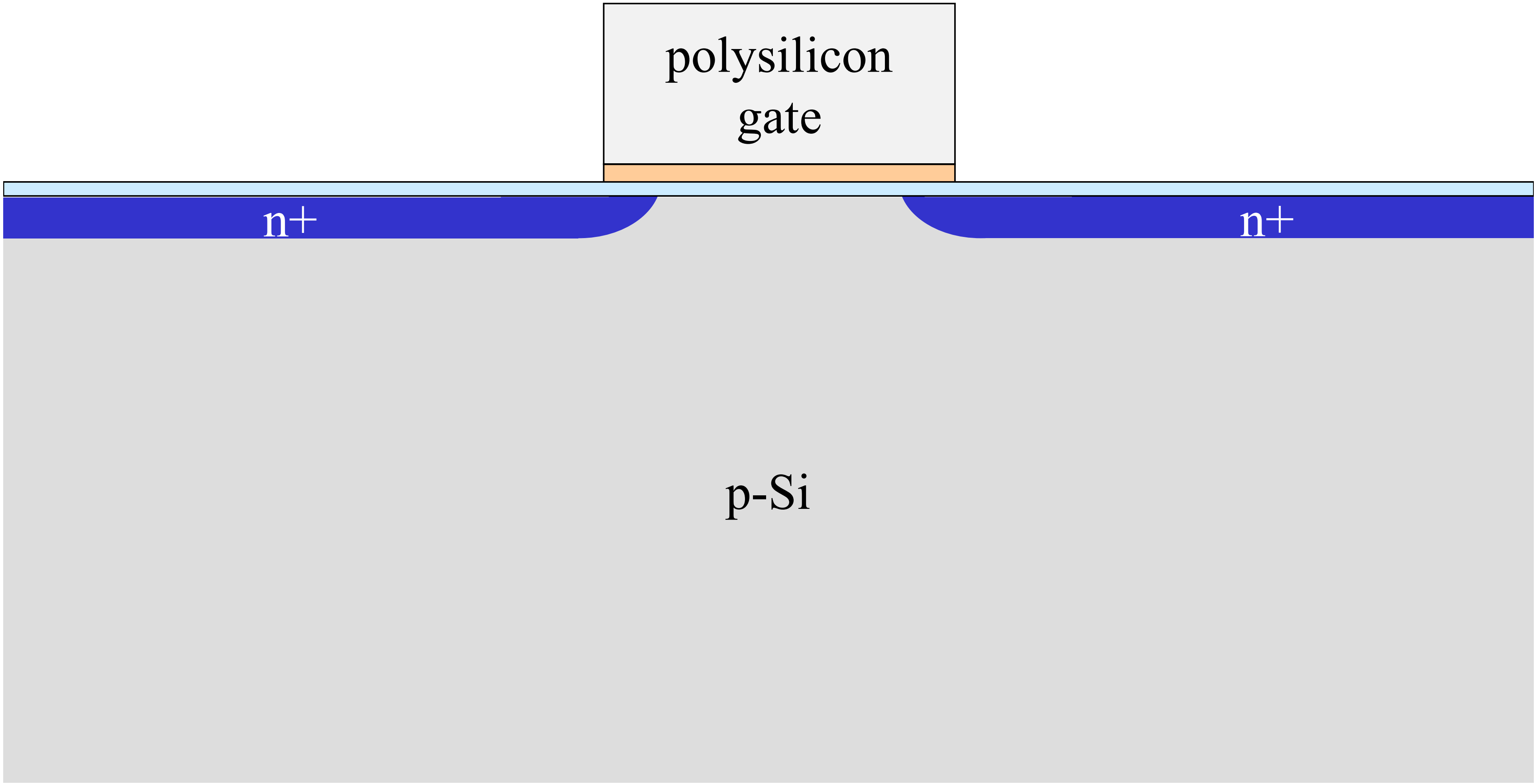
TiN (CVD)
30–70 μΩ·cm Conductive diffusion barrier

p-Si



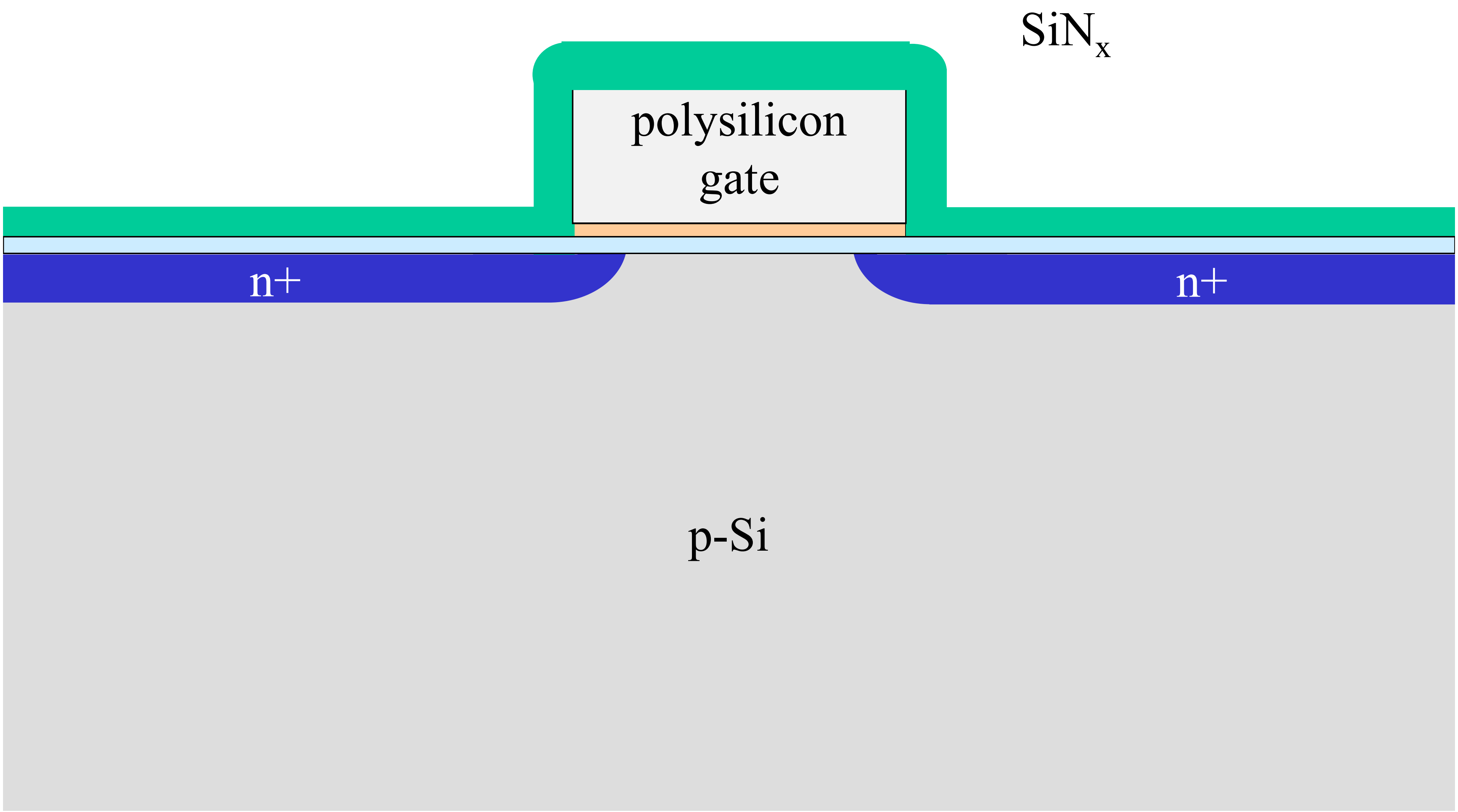
Expose resist
Develop
Etch poly and TiN
Strip resist
Implant source and drain

Self-aligned fabrication



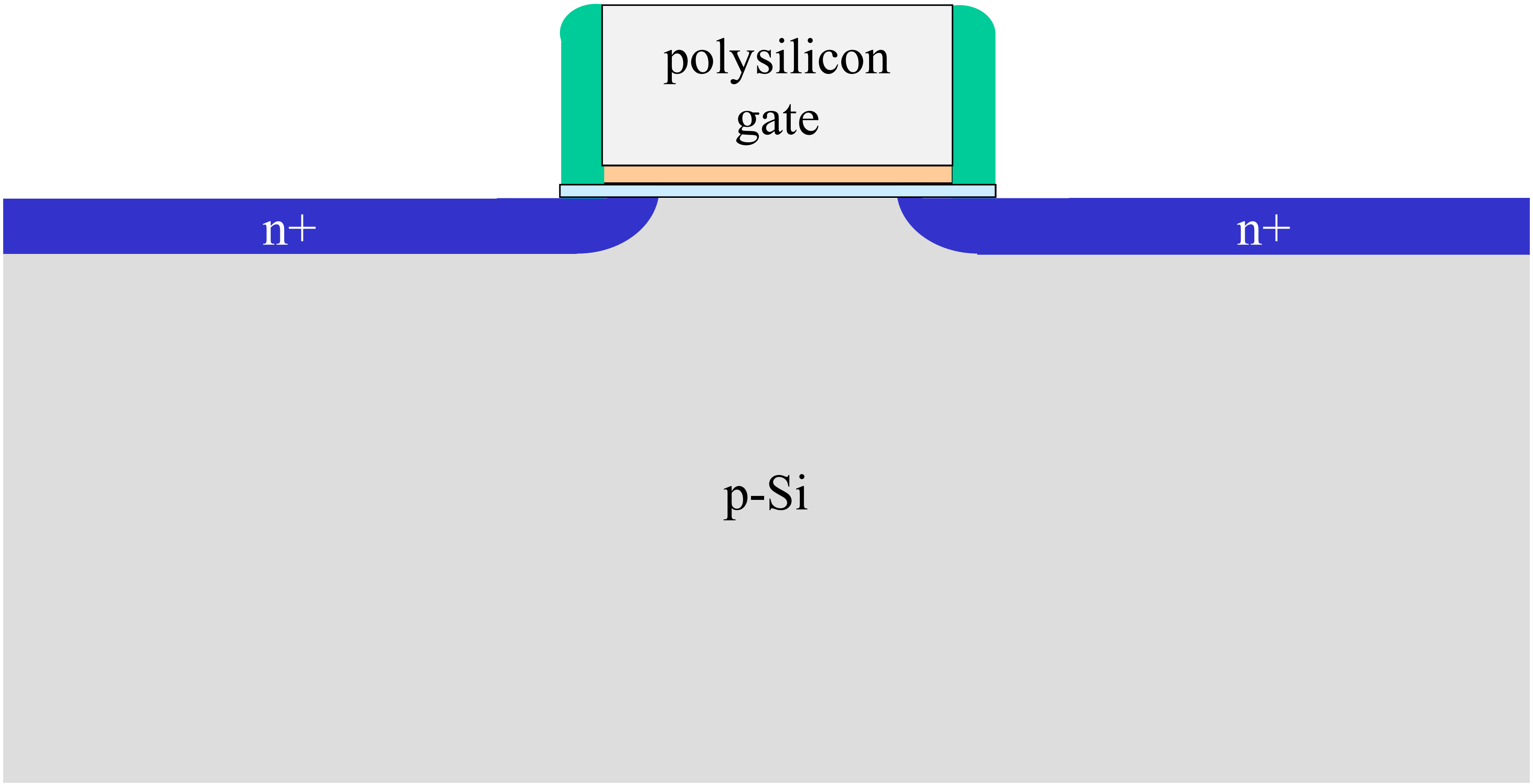
Spacer

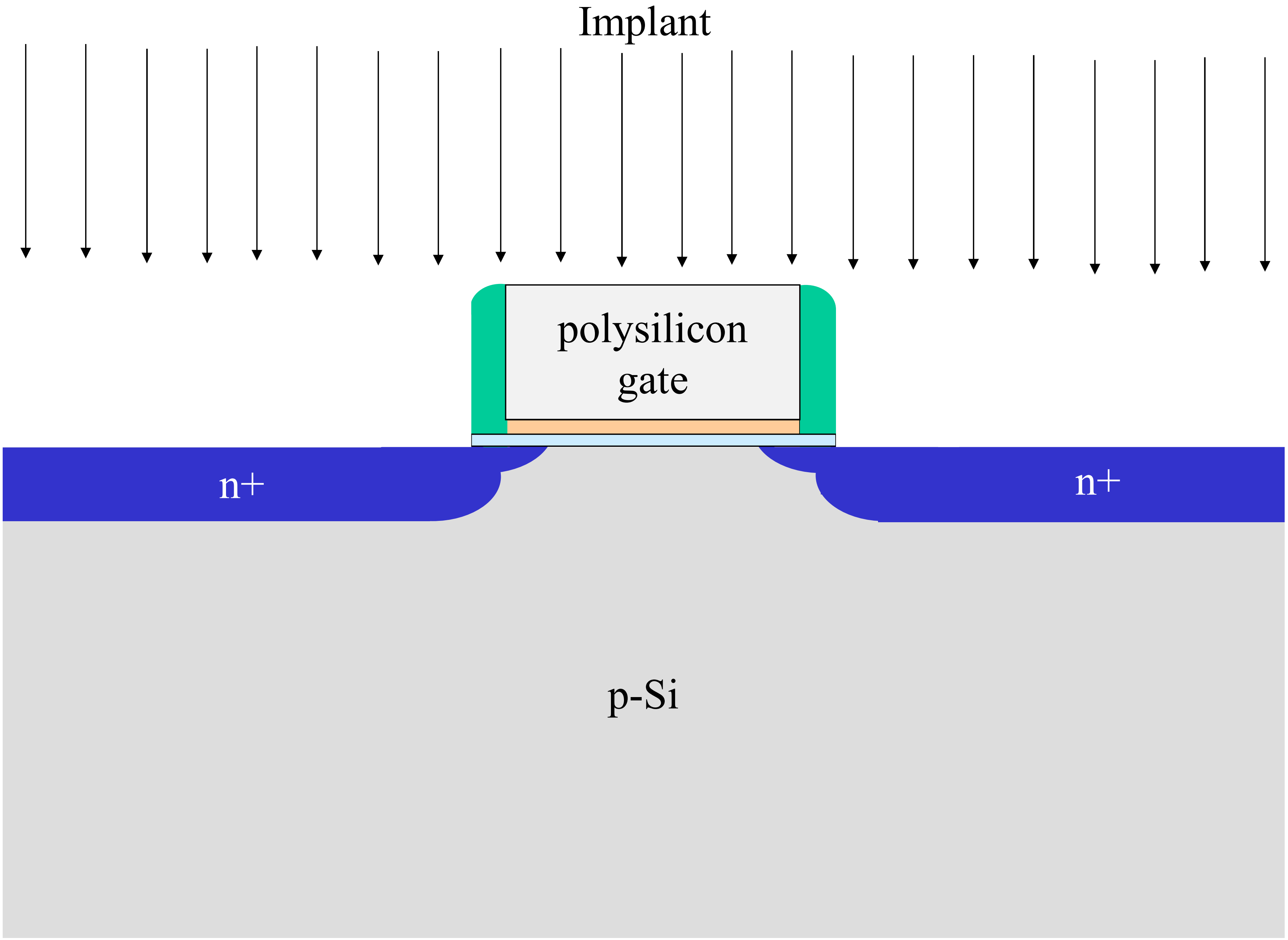
PECVD SiN_x



Spacer

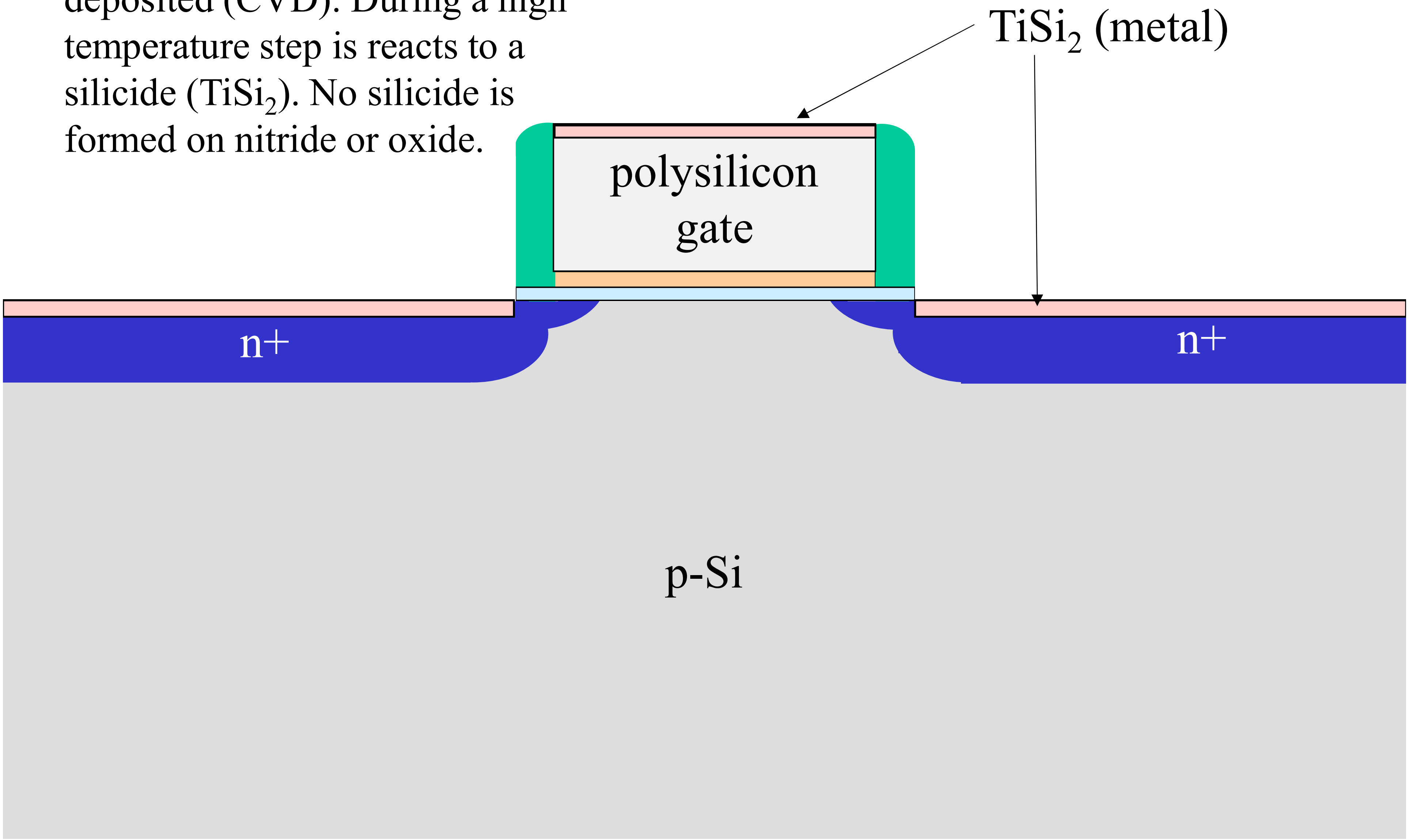
Etch back to
leave only
sidewalls



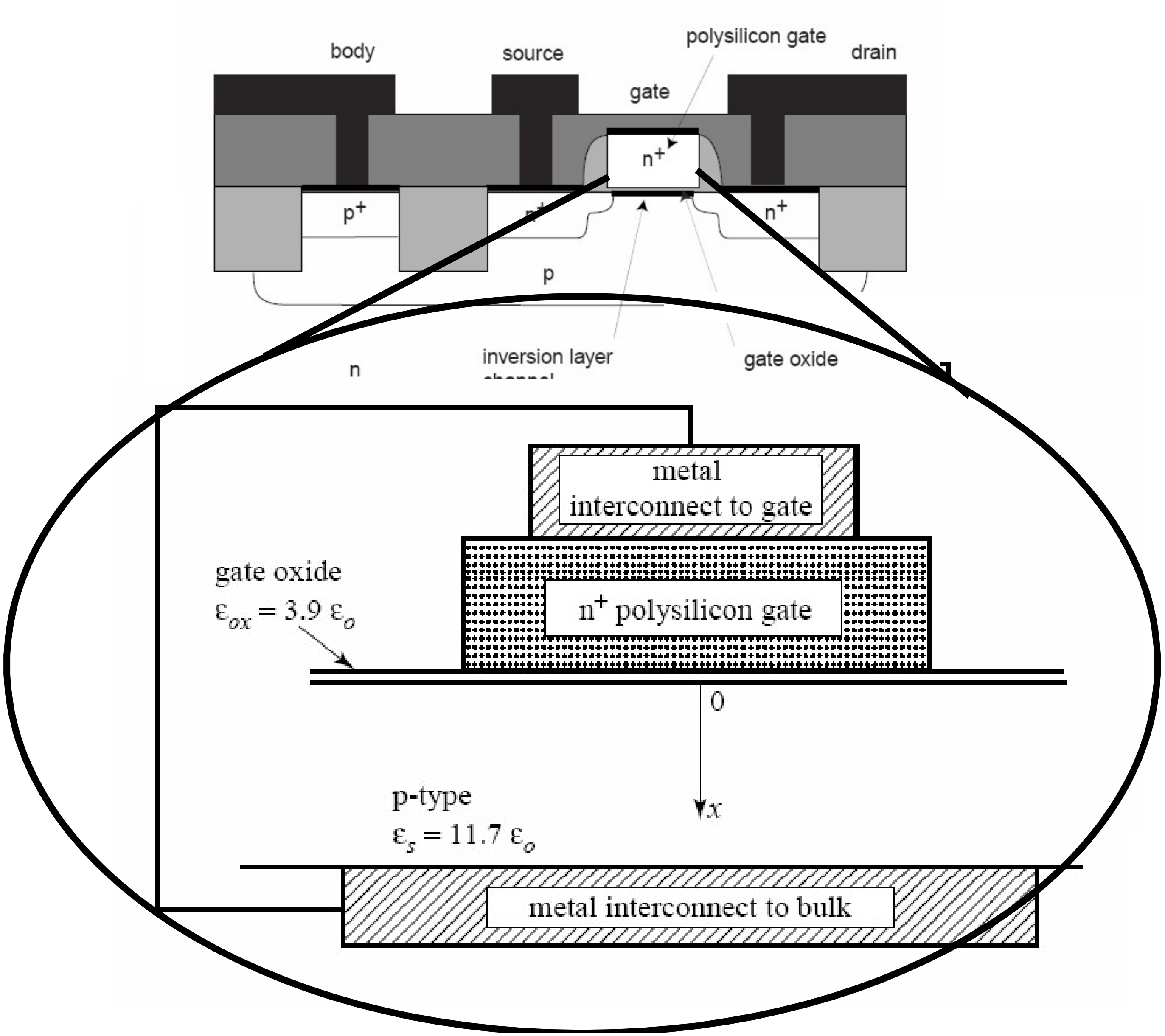

Implant
polysilicon gate
n+
n+
p-Si

Salicide (Self-aligned silicide)

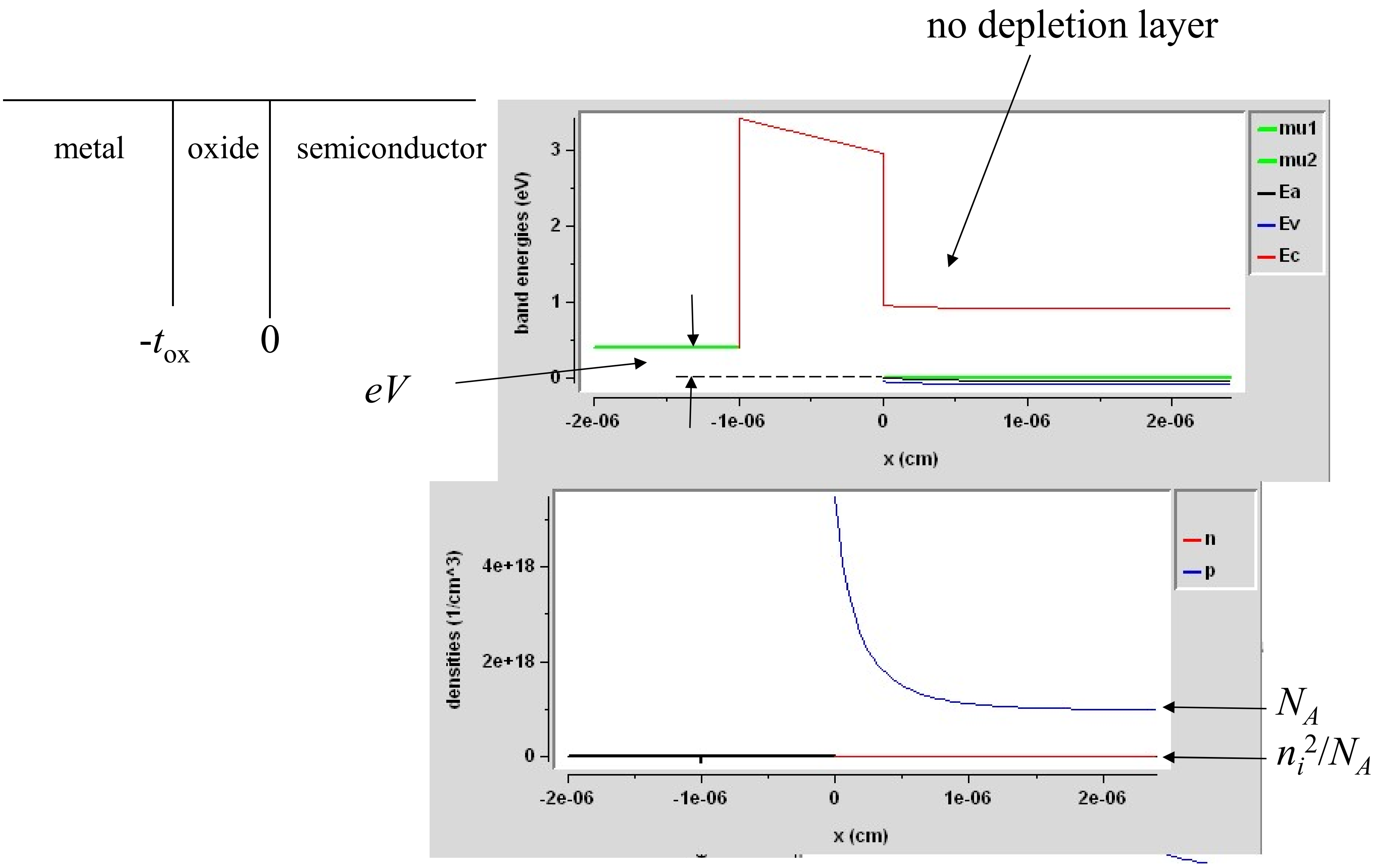
Transition metal (Ti, Co,W) is deposited (CVD). During a high temperature step is reacts to a silicide ($TiSi_2$). No silicide is formed on nitride or oxide.



MOS capacitor



Accumulation


no depletion layer

metal

oxide

semiconductor

-t_{ox}

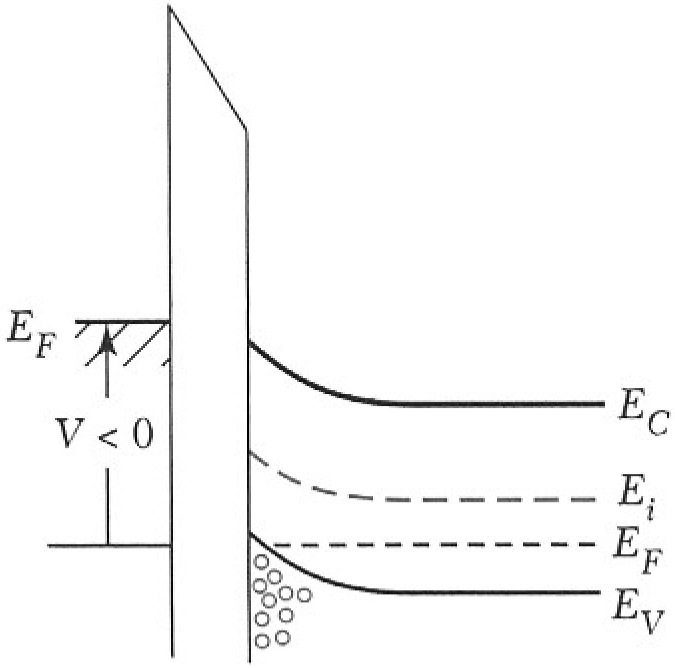
0

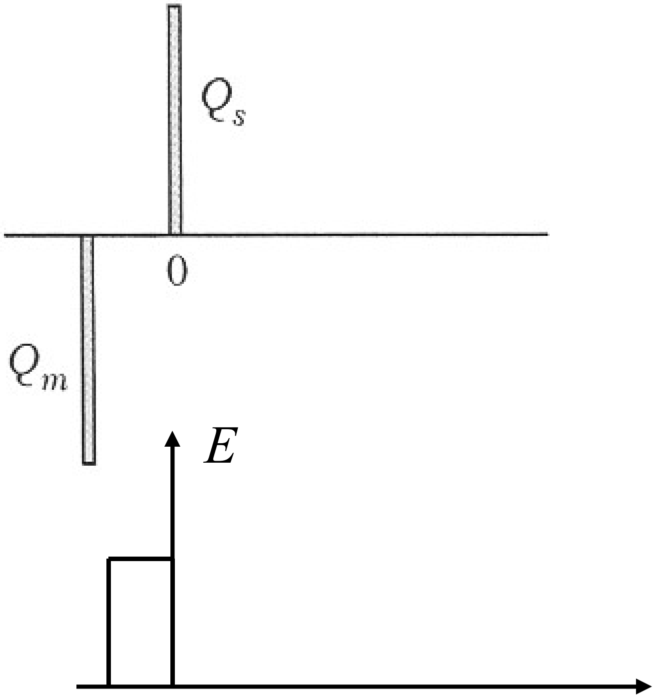
eV

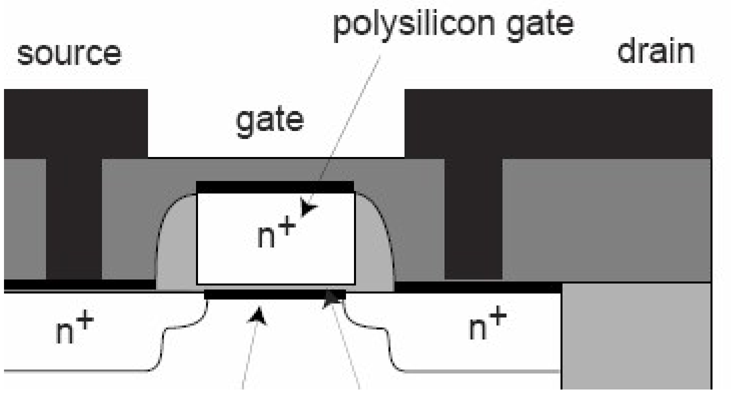
N_A

n_i^2/N_A

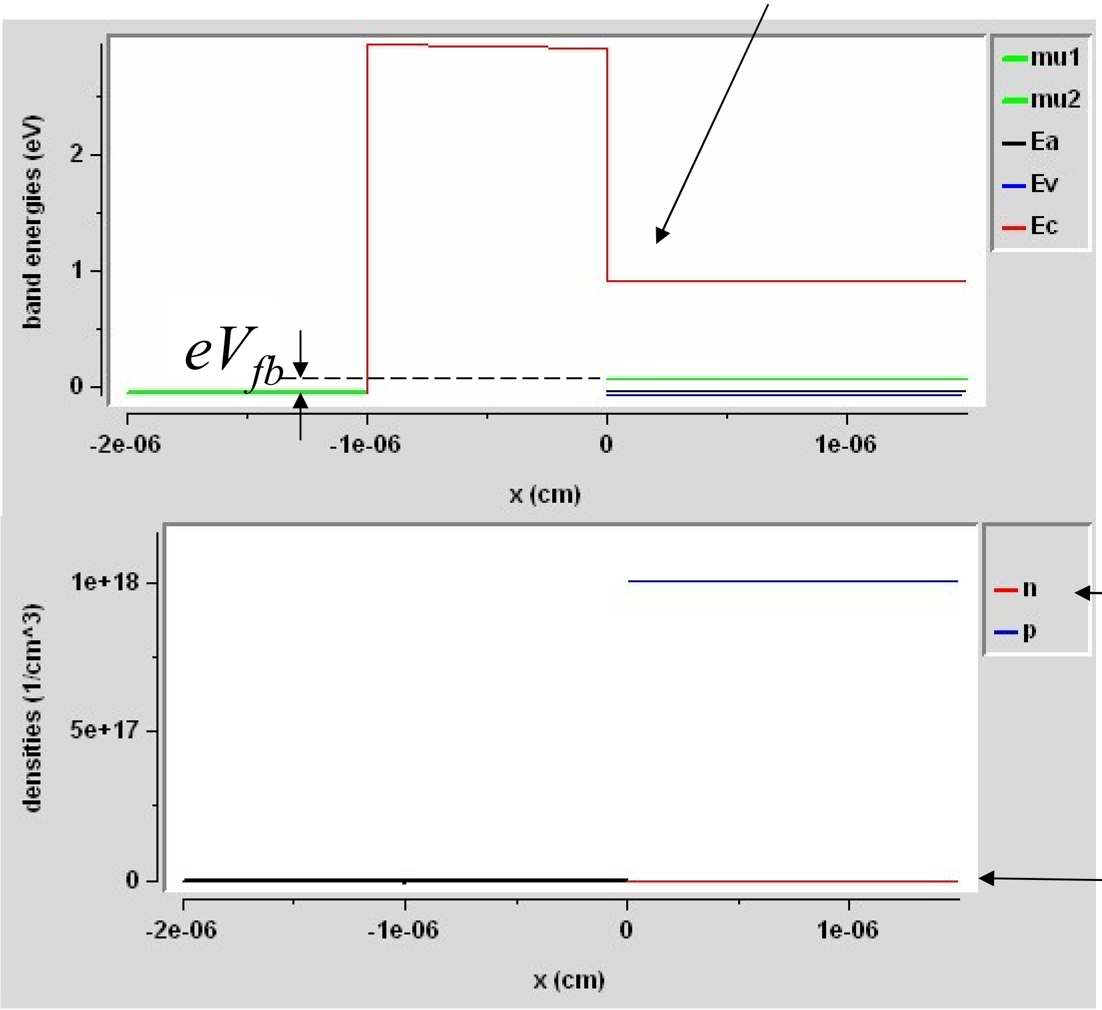
Accumulation







Flat band voltage



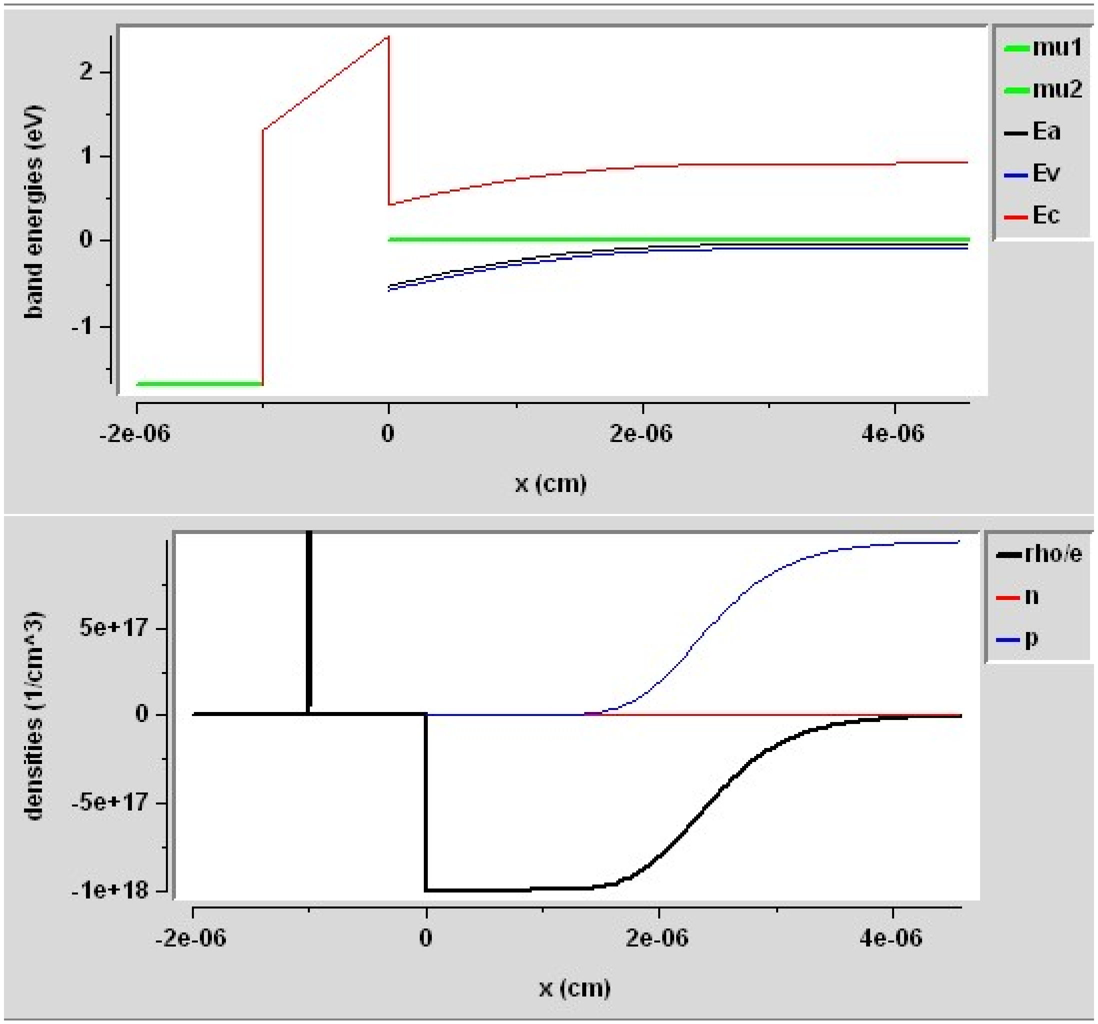
no depletion layer

N_A

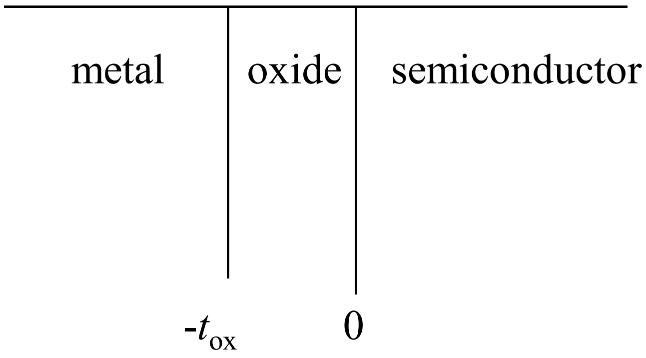
n_i^2/N_A

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

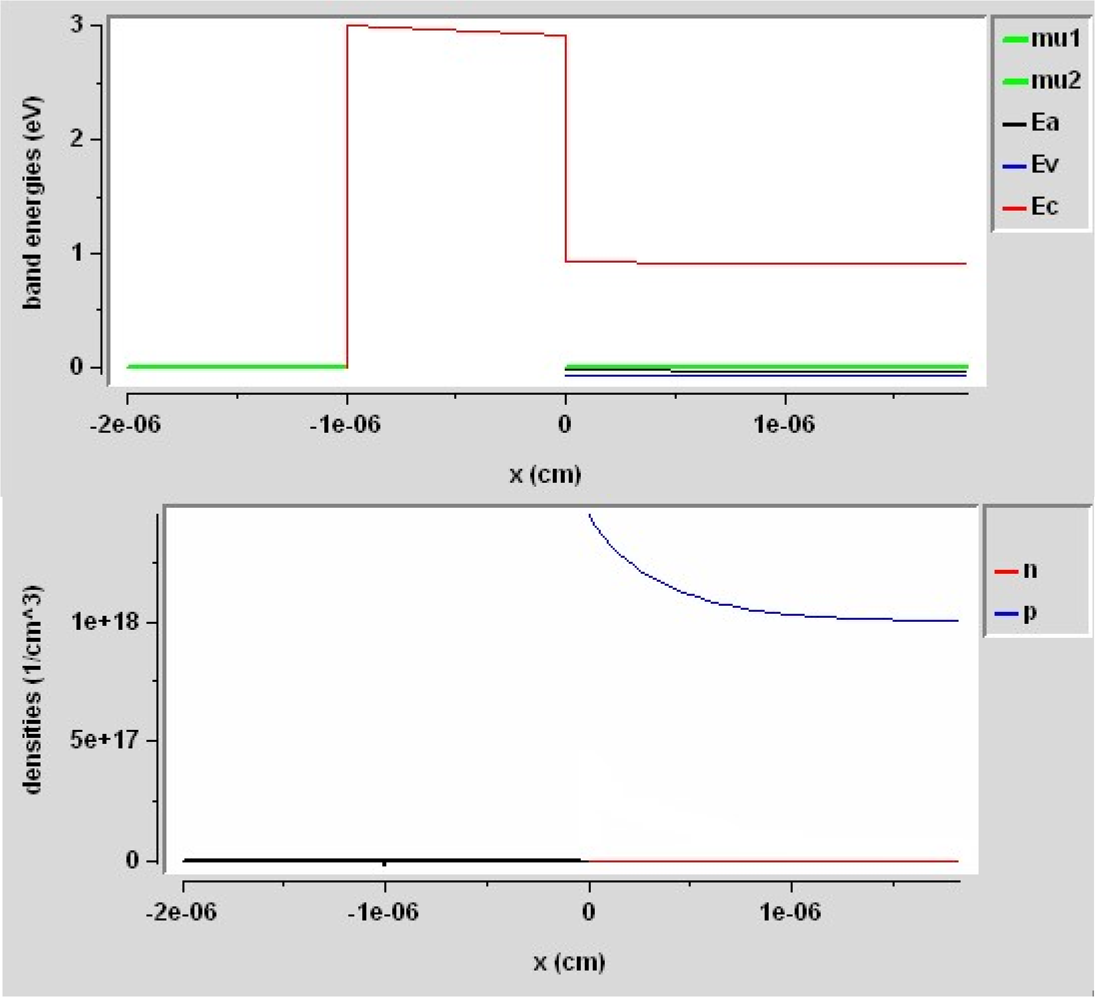
Depletion


mu1
mu2
Ea
Ev
Ec
band energies (eV)
2
1
0
-1
-2e-06
0
2e-06
4e-06
x (cm)
rho/e
n
p
densities (1/cm^3)
5e+17
0
-5e+17
-1e+18
-2e-06
0
2e-06
4e-06
x (cm)

Zero bias



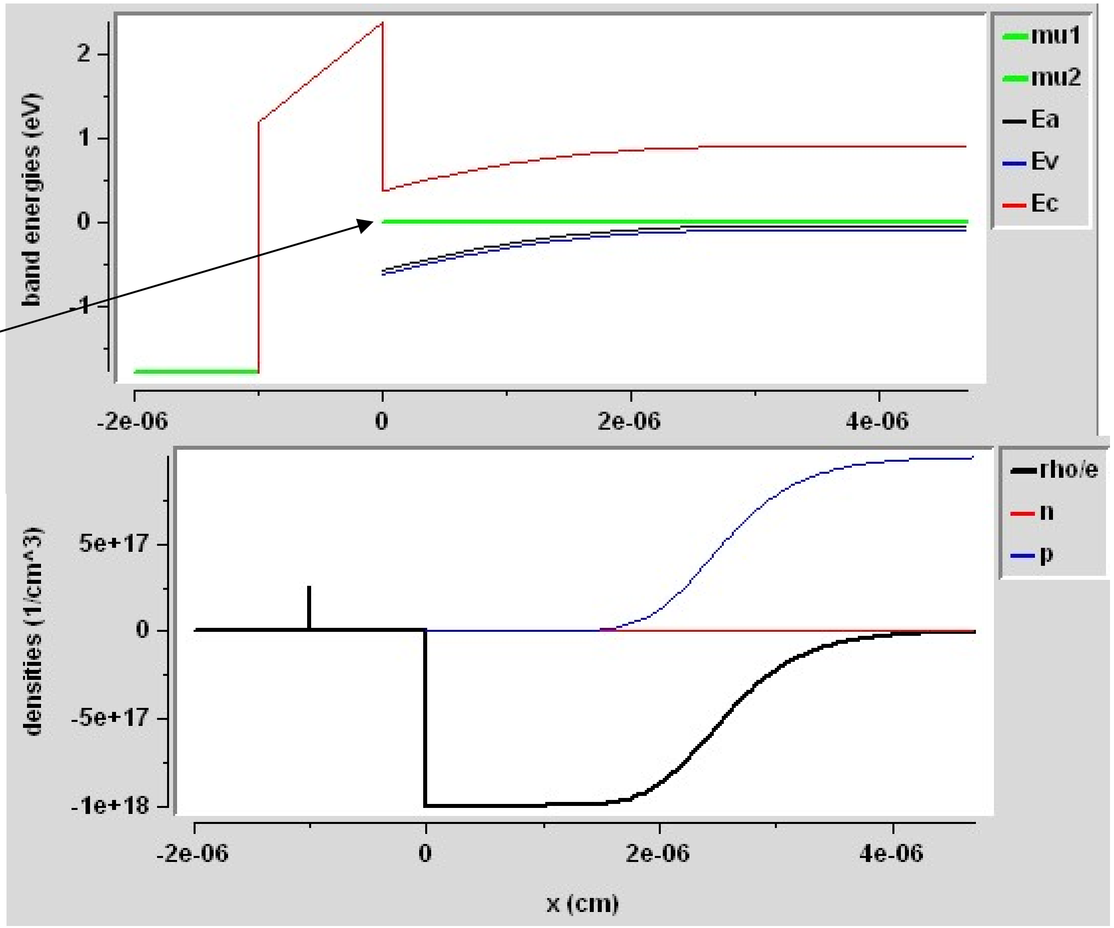
$e\phi_m$
Al 4.1 eV
p+ poly 4.05 eV
n+ poly 5.05 eV



Can be in accumulation or depletion depending on workfunctions

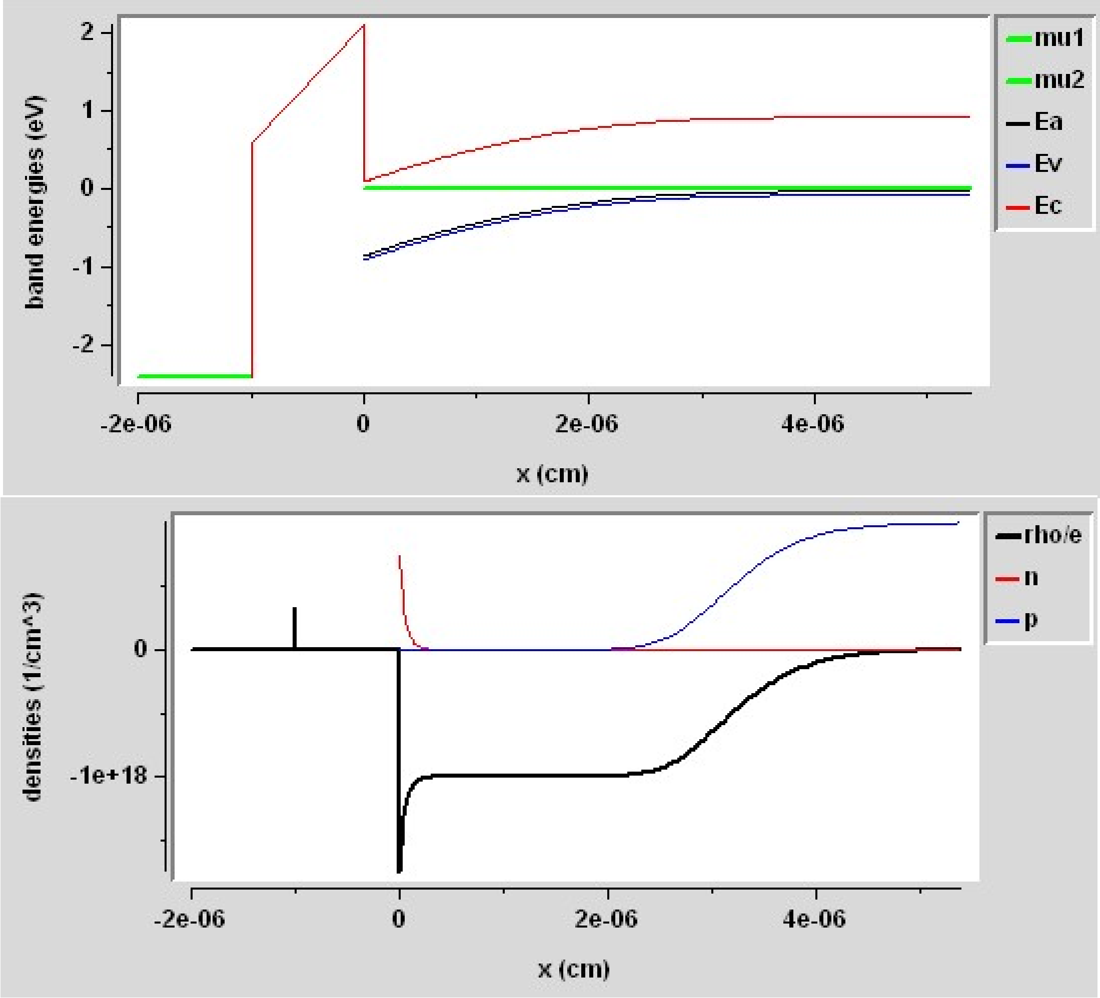
Weak Inversion

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



$n > p$
at the interface

Threshold voltage

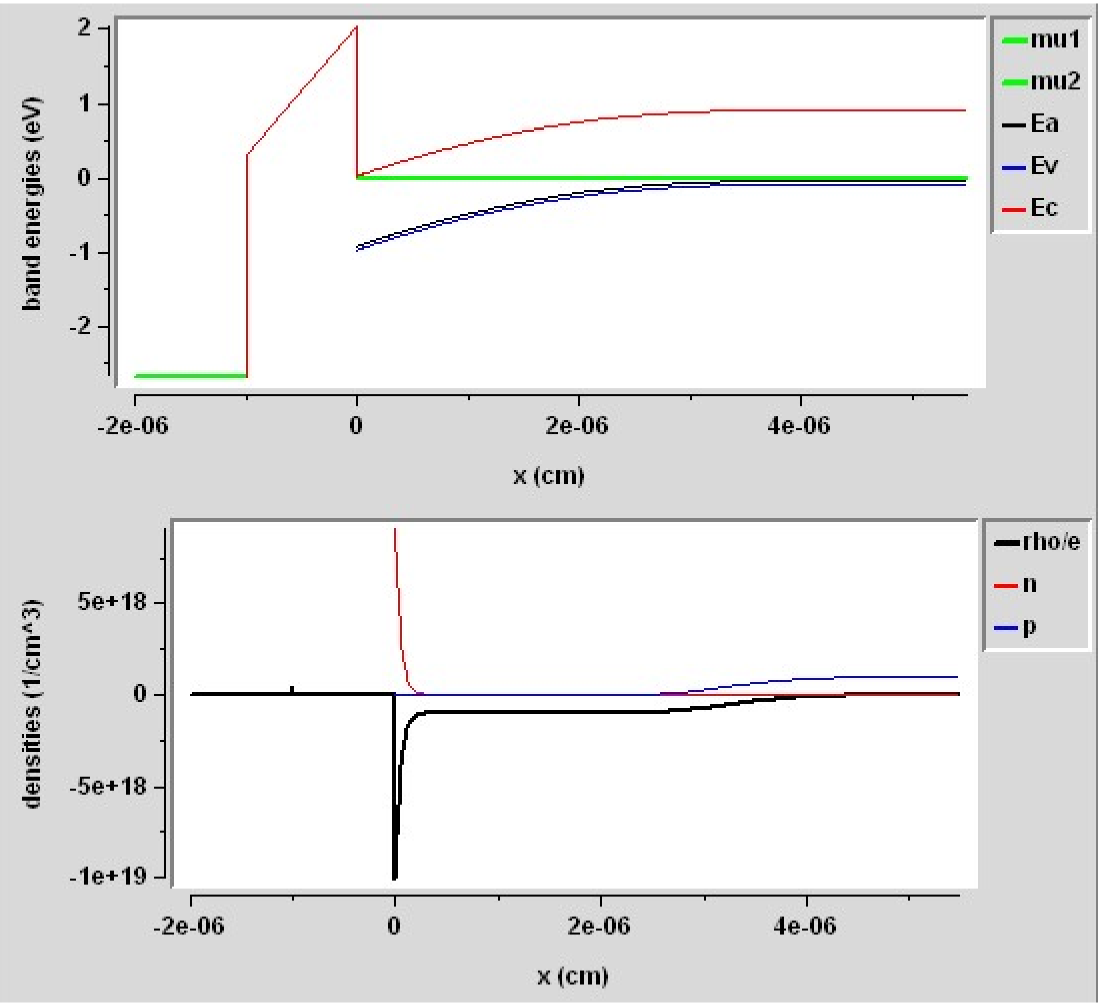


$n = N_A$

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

Inversion

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



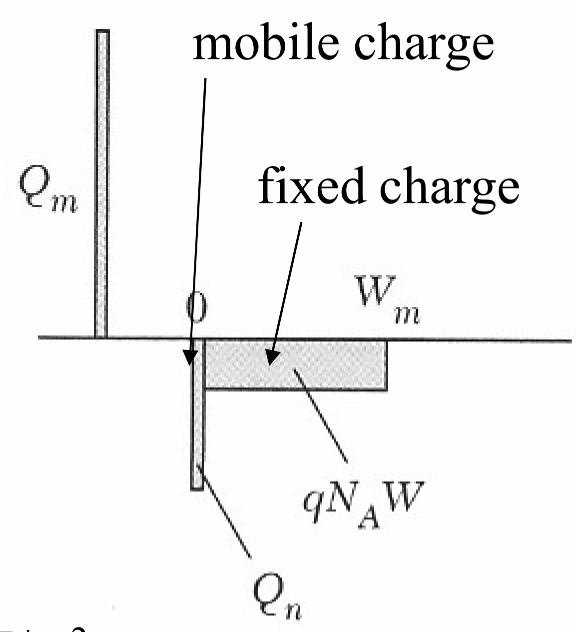
MOS capacitor

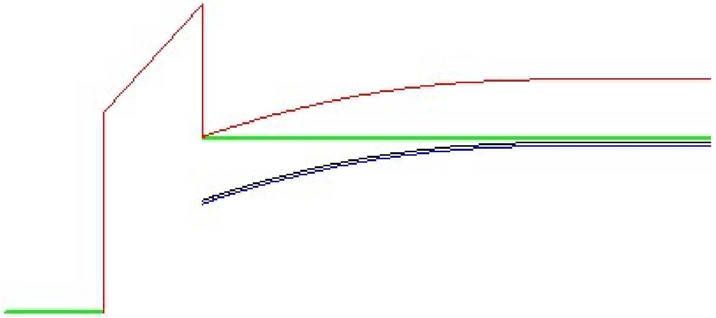
In inversion, the charge in the inversion layer is:

$$Q = -C_{\mathrm{ox}}(V_G - V_B - V_T)$$

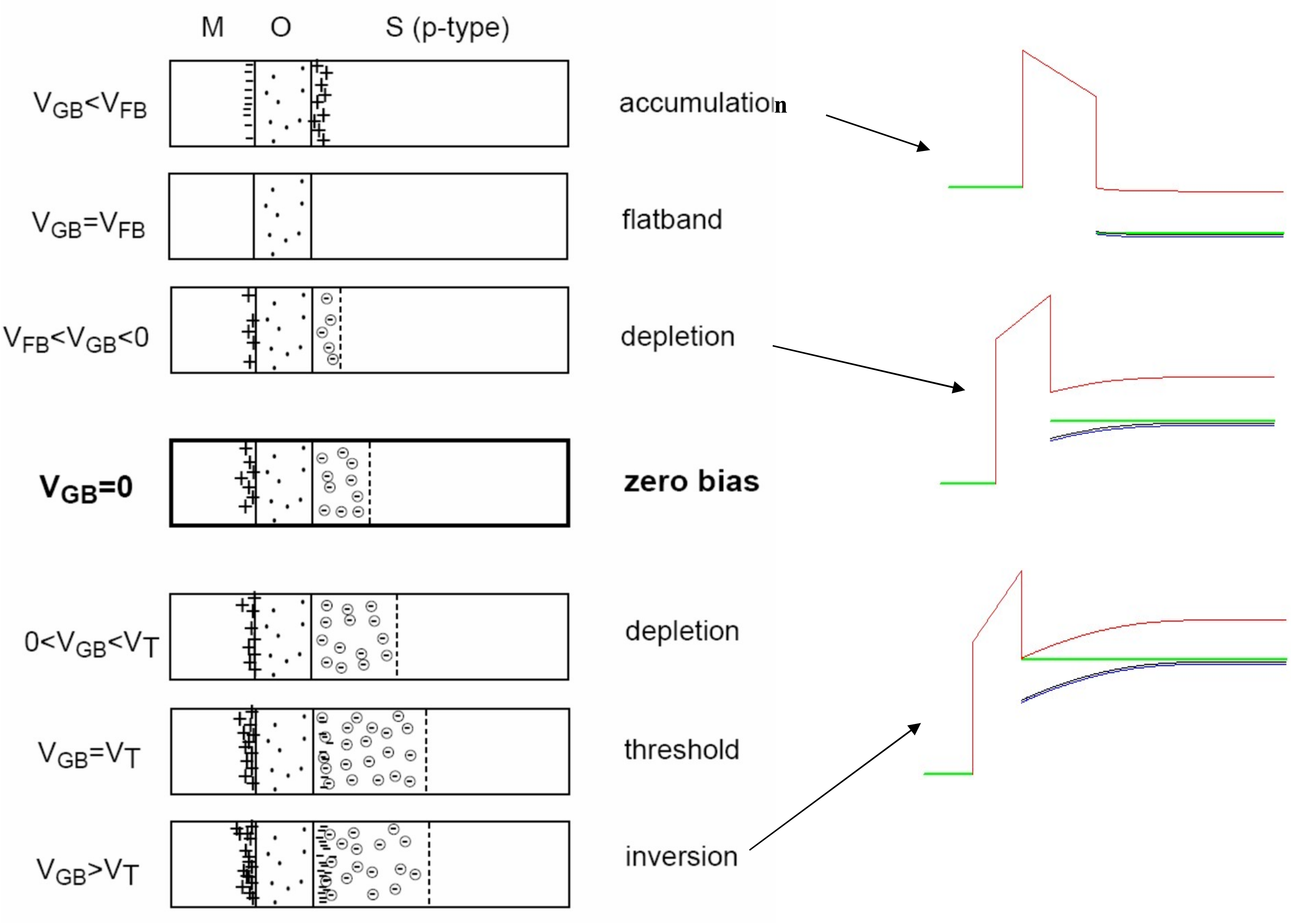
Mobile charge per unit area

Specific capacitance F/m^2





MOS capacitor



M O S (p-type)

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

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

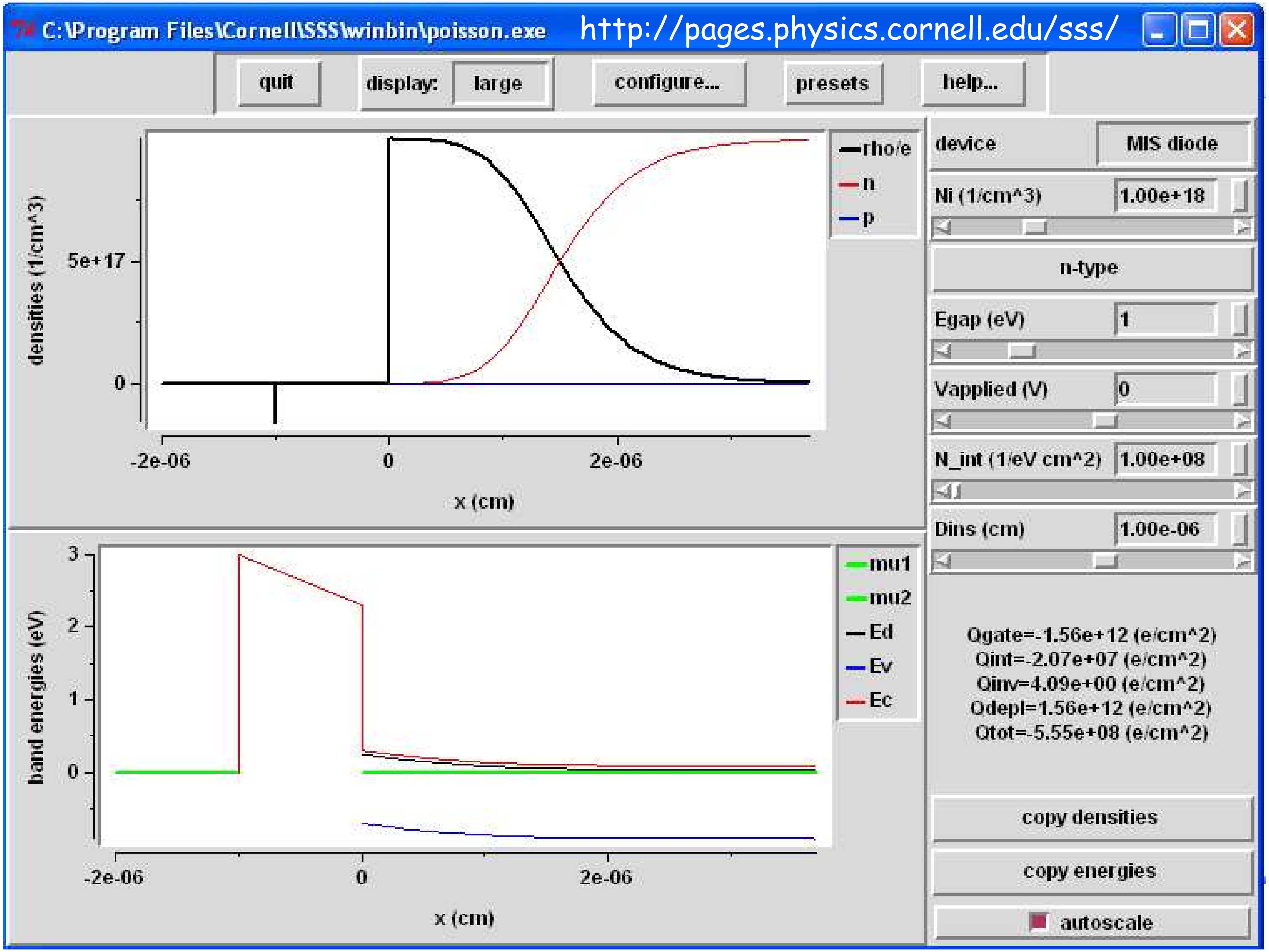
$V_{FB}<V_{GB}<0$ depletion

$V_{GB}=0$ zero bias

$0<V_{GB}<V_T$ depletion

$V_{GB}=V_T$ threshold

$V_{GB}>V_T$ inversion



C:\Program Files\Cornell\SSS\winbin\poisson.exe http://pages.physics.cornell.edu/sss/

device: MIS diode

Ni (1/cm^3): 1.00e+18

n-type

Egap (eV): 1

Vapplied (V): 0

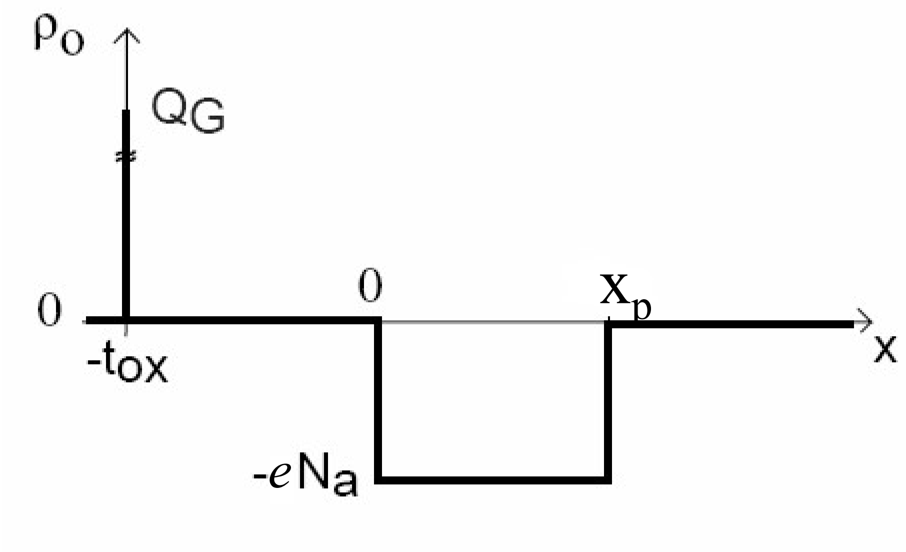
N_int (1/eV cm^2): 1.00e+08

Dins (cm): 1.00e-06

```
Qgate=-1.56e+12 (e/cm^2)
Qint=-2.07e+07 (e/cm^2)
Qinv=4.09e+00 (e/cm^2)
Qdepl=1.56e+12 (e/cm^2)
Qtot=-5.55e+08 (e/cm^2)
```

Poisson equation $$\nabla^2 V = \frac{\rho}{\varepsilon}$$

charge density (depletion)

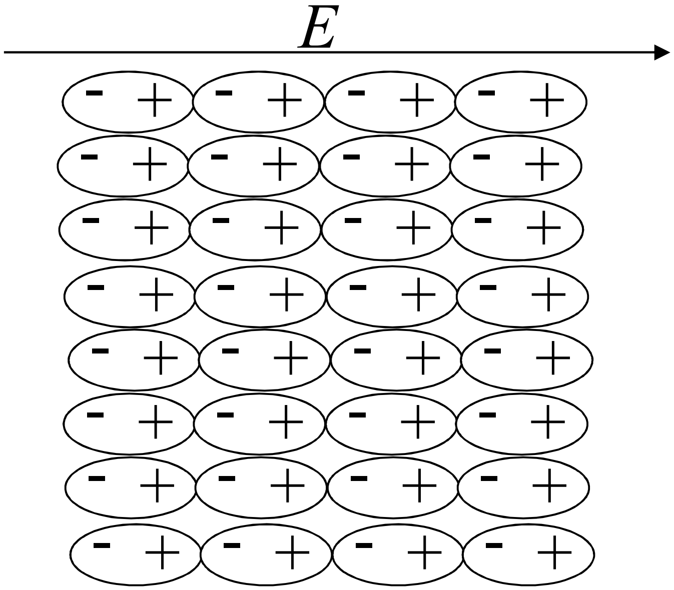


$$-t_{ox} < x < 0 \qquad \rho(x) = 0$$

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

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

electric field (depletion)

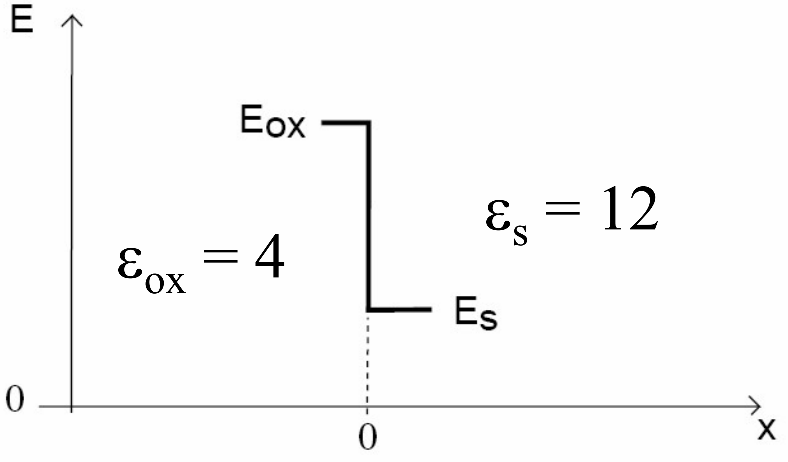


E is decreased by a factor of the dielectric constant

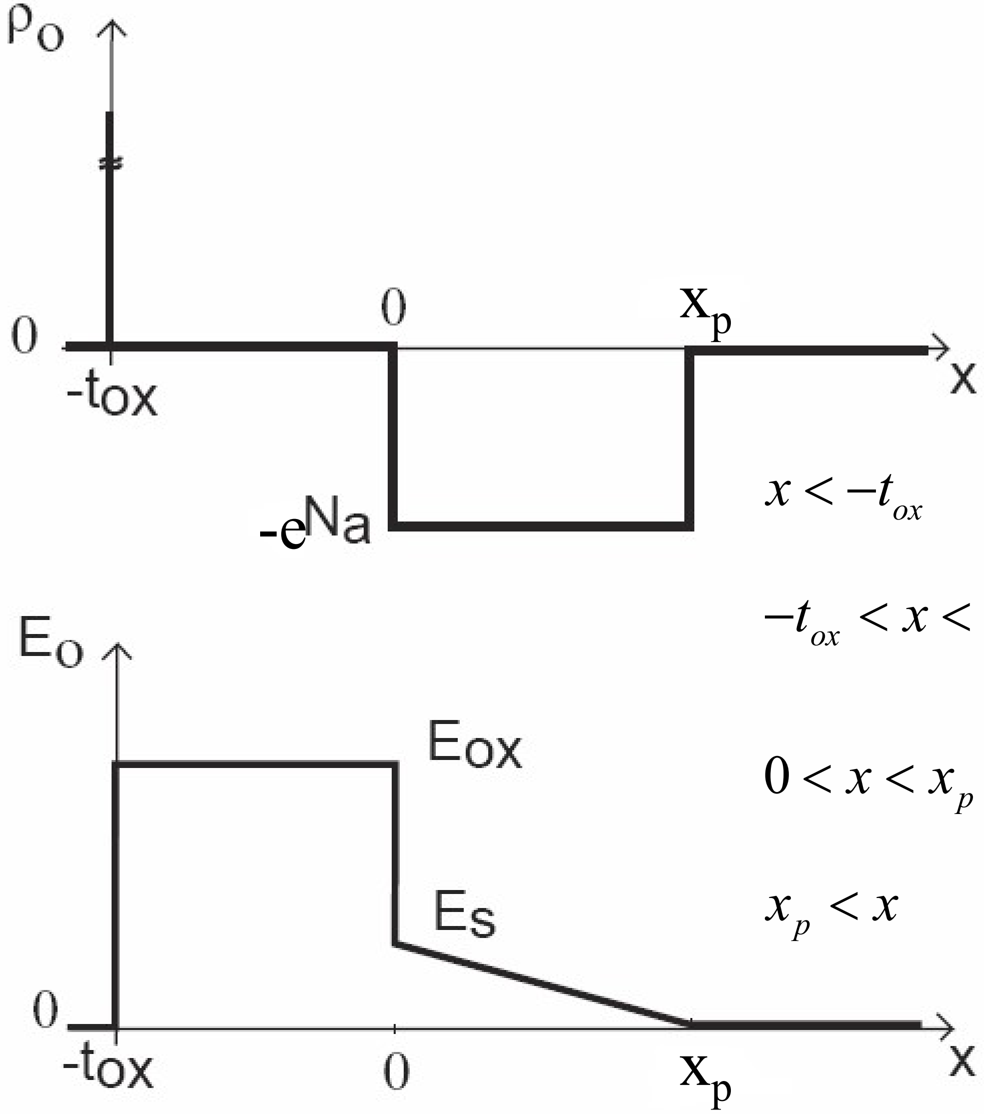
$$\varepsilon_r = \frac{E_{vacuum}}{E_{dielectric}}$$

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

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



electric field



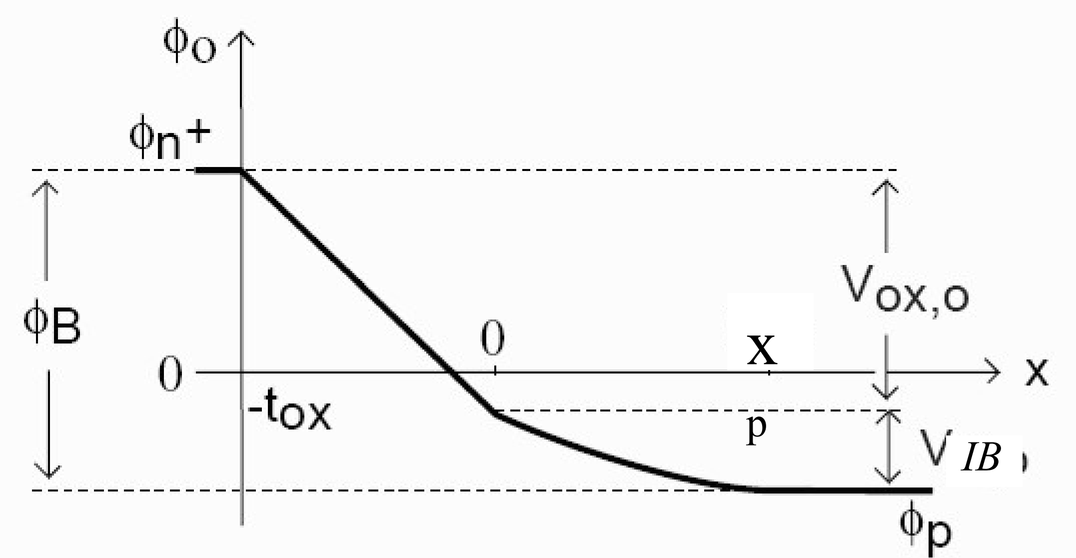
$x < -t_{ox}$ $\qquad$ $E(x) = 0$

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

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

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

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)

Band bending at strong inversion

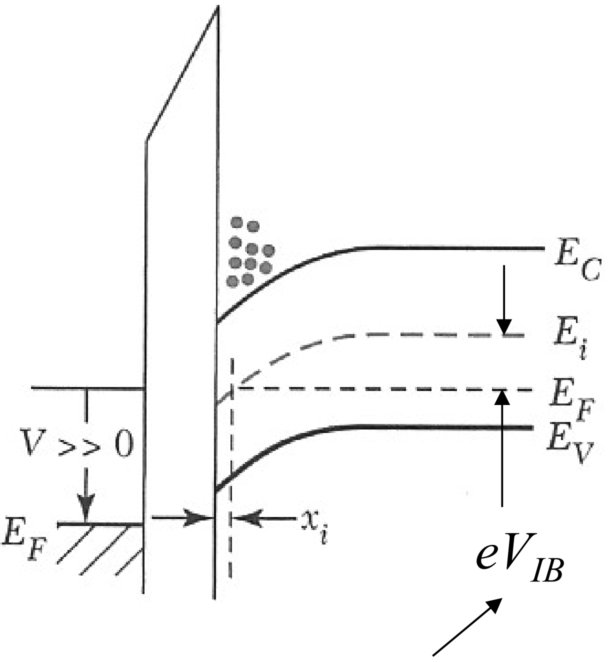
$n = N_A$ at threshold

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

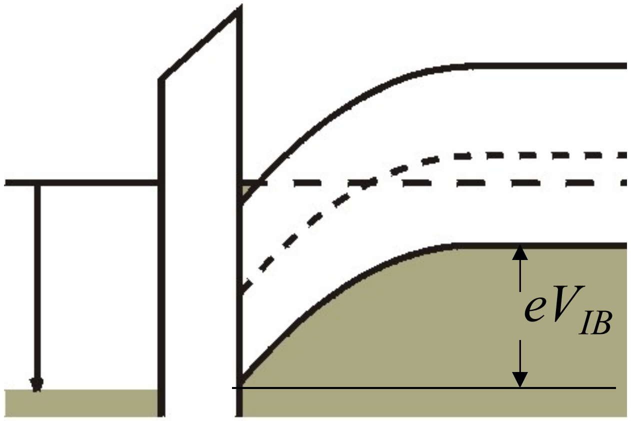
The voltage between the semiconductor-oxide interface and the body

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

Strong inversion

$n_s = N_A$ at the semiconductor-oxide interface

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



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

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

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

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

The depletion width remains constant in inversion.

Depletion width in strong inversion

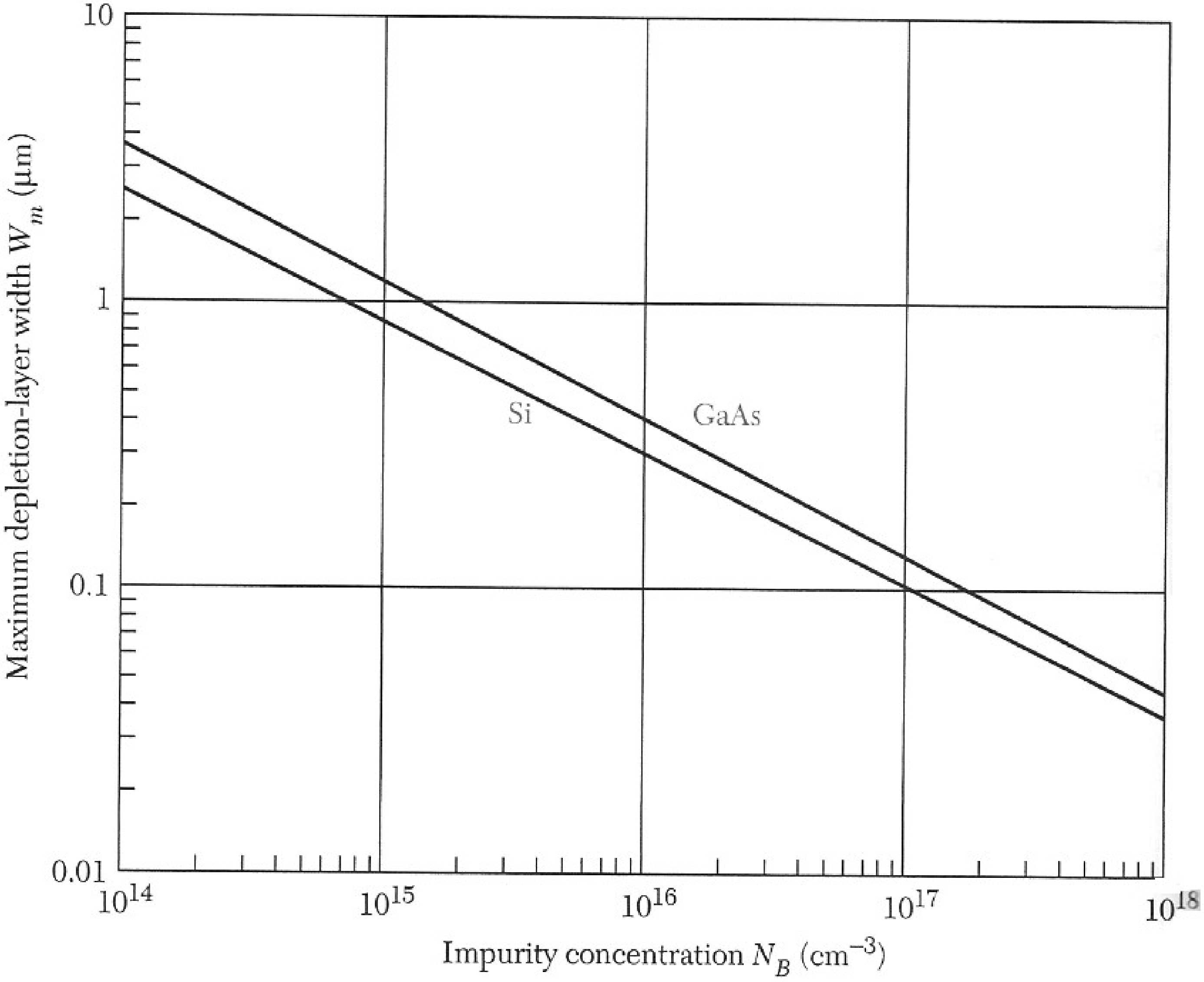
$$V_{IB} = \frac{eN_A x_p^2}{2\varepsilon}$$

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

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

The depletion width remains constant in inversion.

Depletion width

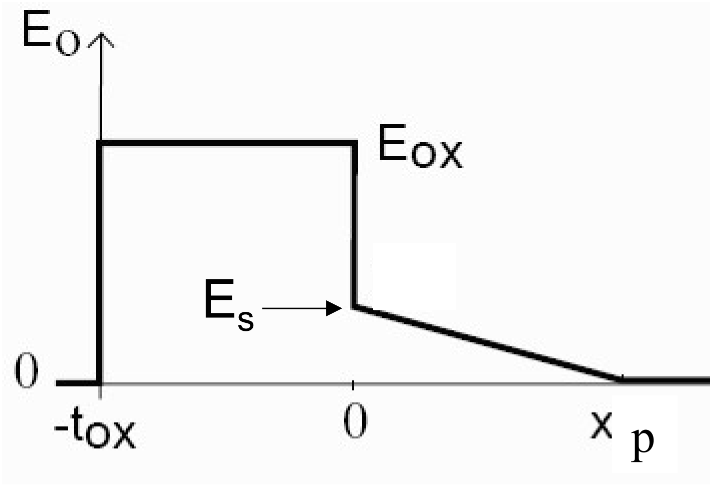


Electric field at semi-oxide interface at strong inversion

$$x_{p(\max)} = 2\sqrt{\frac{\varepsilon_{semi}}{e^2 N_A} k_B T \ln\left(\frac{N_A}{n_i}\right)}$$

$$E_s = \frac{eN_A x_p}{\varepsilon_{semi}} = 2\sqrt{\frac{N_A}{\varepsilon_{semi}} k_B T \ln\left(\frac{N_A}{n_i}\right)}$$

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



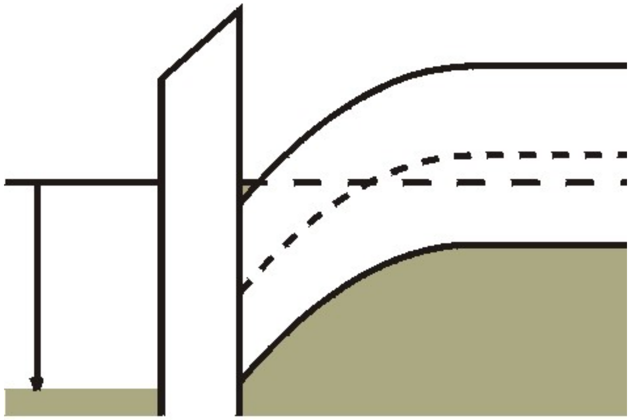
Threshold voltage

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

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

$$\frac{\varepsilon t_{ox}}{\varepsilon_{ox}} E_{inversion}$$

$$V_{IB}$$

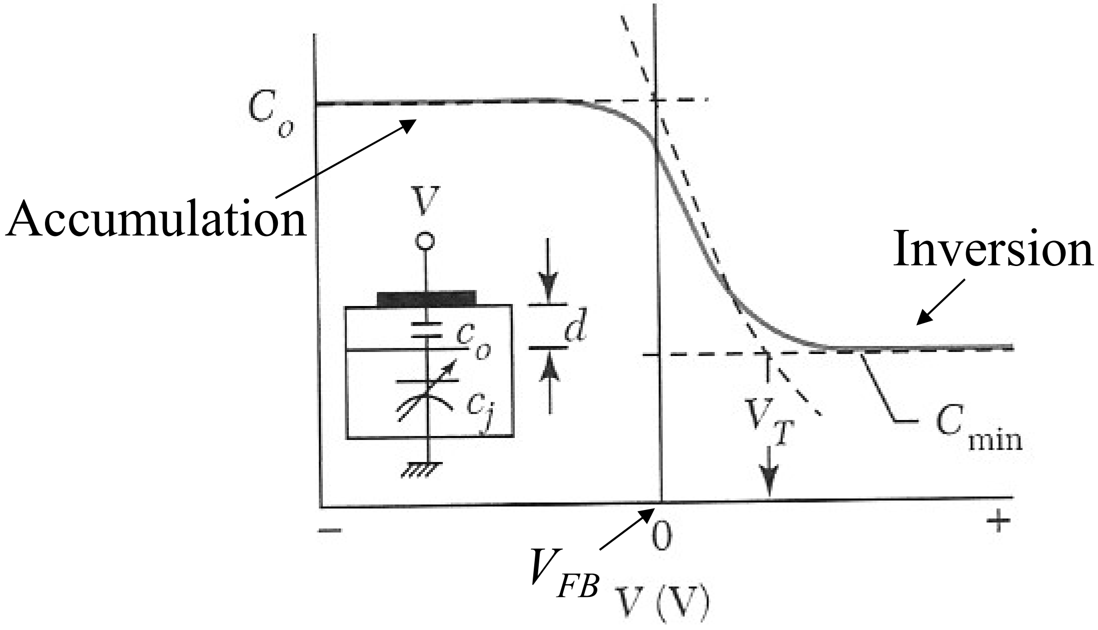


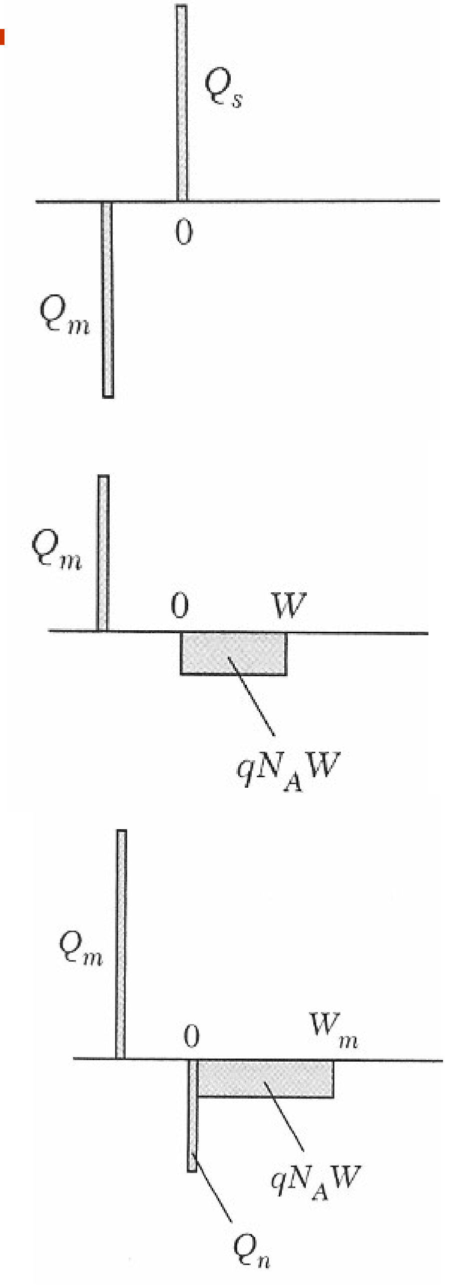
Small V_T requires a small t_{ox} and a large ε_{ox}.

MOS capacitance

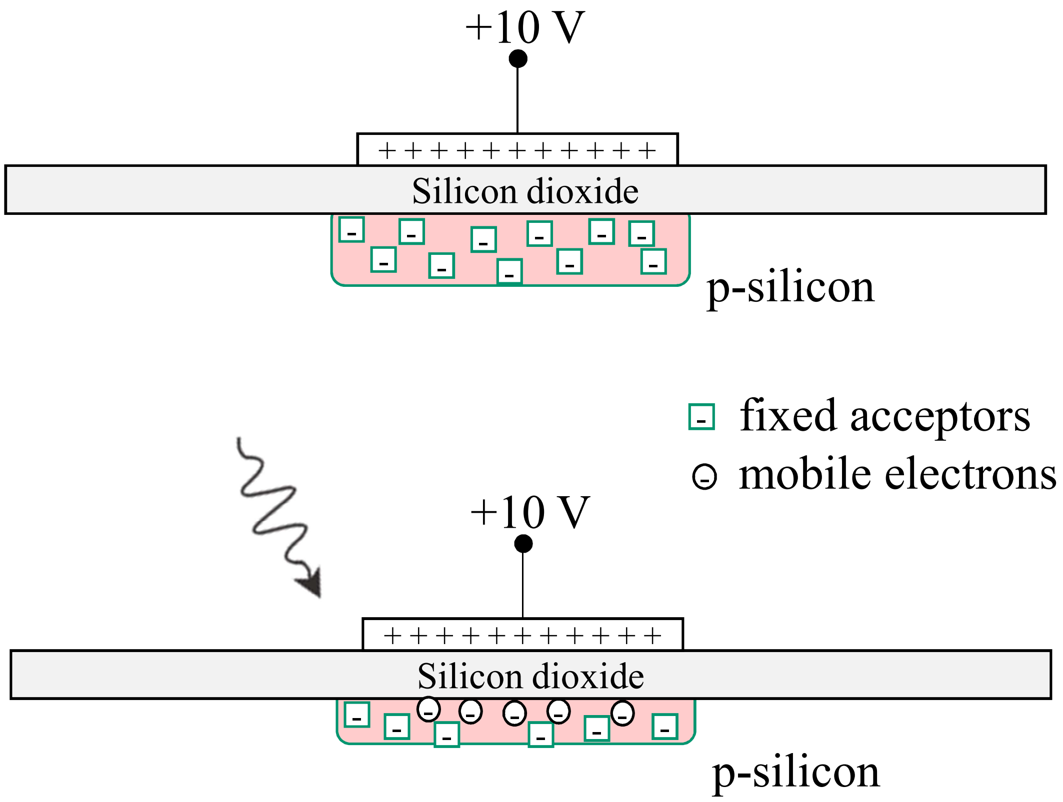
$$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}} \qquad C_j = \frac{\varepsilon_{semi}}{x_p}$$

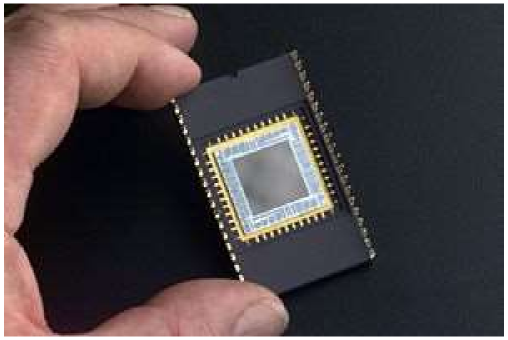
$$C = \left(\frac{1}{C_{ox}} + \frac{1}{C_j} \right)^{-1}$$



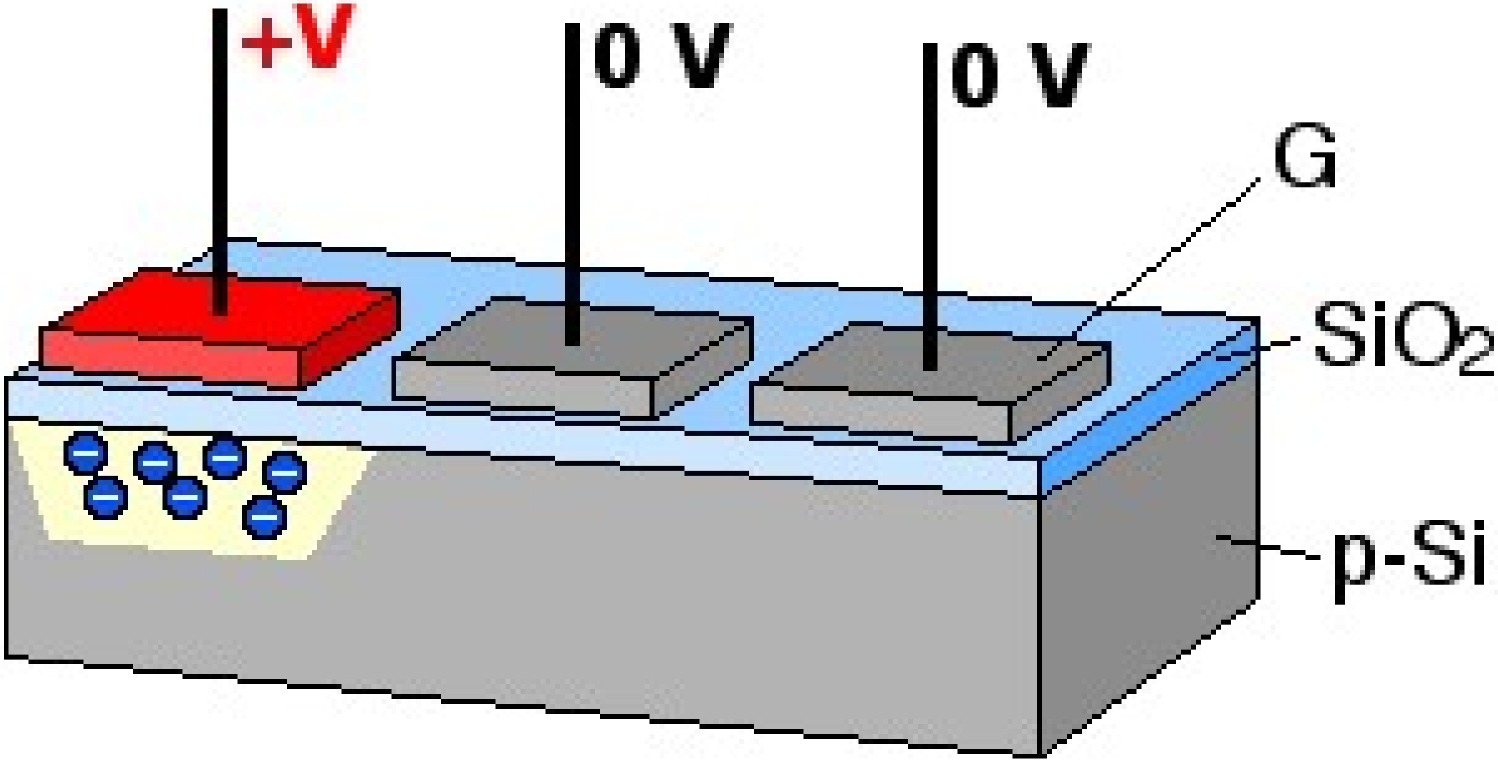


CCD devices


+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

Gradual channel approximation

n_s is the sheet charge at the interface.

$$n_s(y) = \frac{Q(y)}{e} = \frac{-C_{ox}\left(V_G - V_{ch}(y) - V_T\right)}{e} \quad \Rightarrow \quad I = Ztj = Ze\mu_n n_s E_y$$

$$I = -Z\mu_n C_{ox}\left(V_G - V_{ch}(y) - V_T\right)E_y$$

$$E_y = -\frac{dV_{ch}}{dy}$$

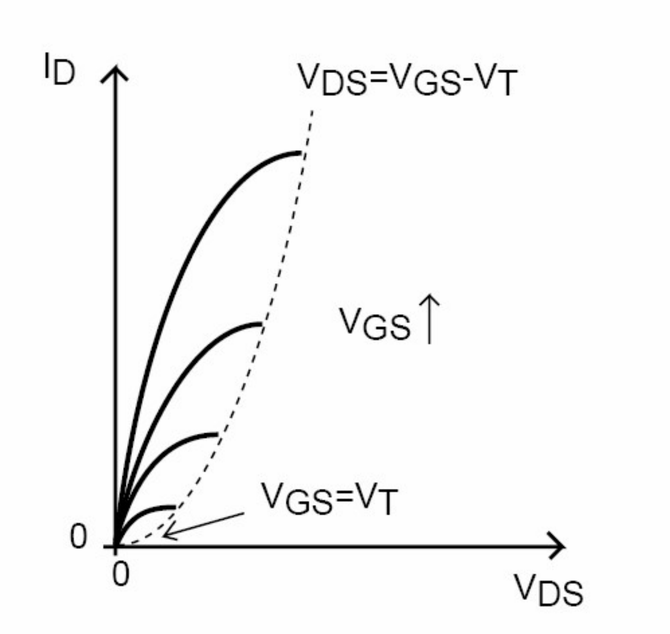
$$I = Z\mu_n C_{ox}\left(V_G - V_{ch}(y) - V_T\right)\frac{dV_{ch}}{dy}$$

Gradual channel approximation

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

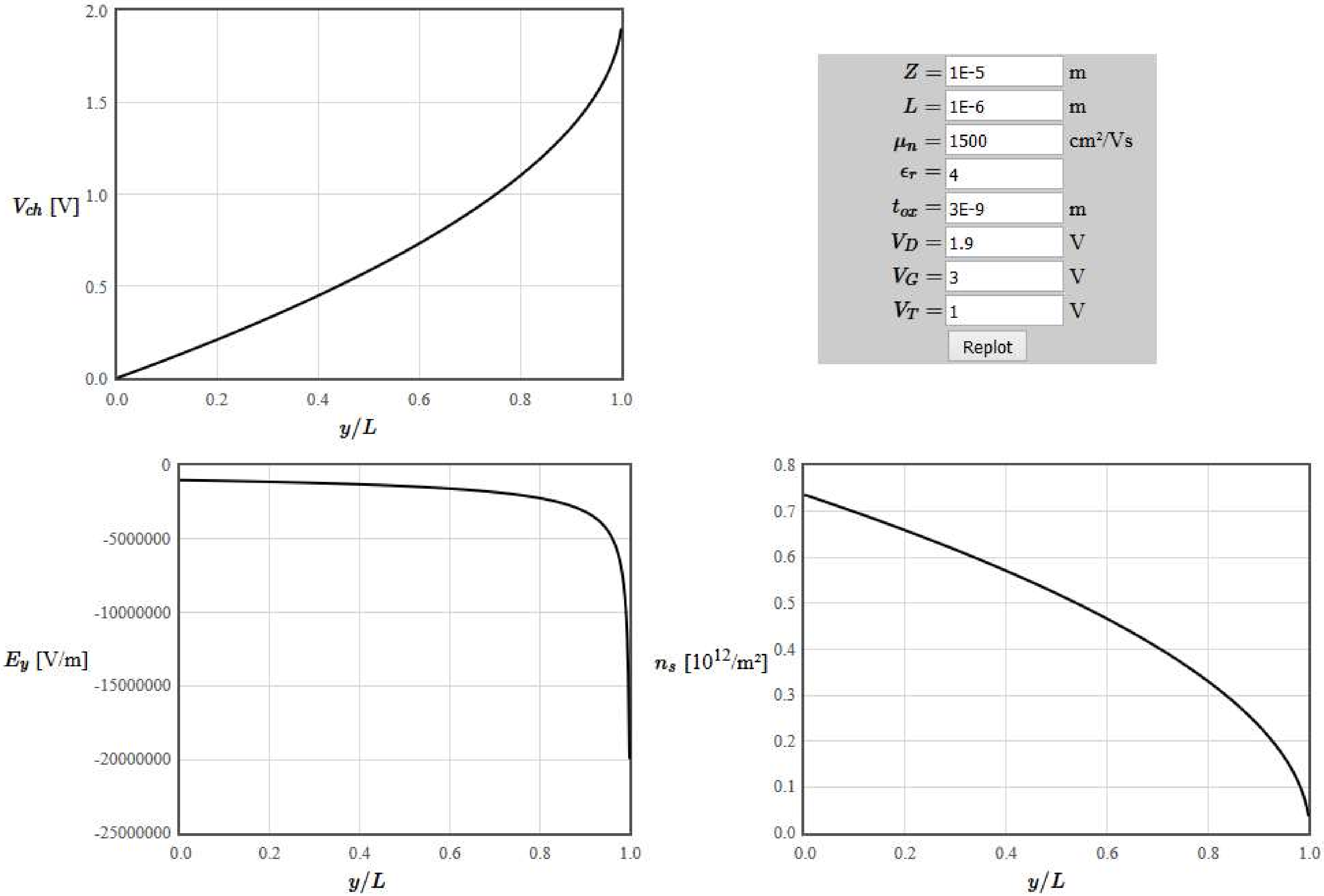
$$\int_0^L I\,dy = \int_0^{V_{DS}} Z\mu_n C_{ox}\left(V_G - V_{ch}(y) - V_T\right)dV_{ch}$$

$$\boxed{I = \frac{Z}{L}\mu_n C_{ox}\left[\left(V_{GS} - V_T\right)V_{DS} - \frac{V_{DS}^2}{2}\right]}$$



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

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

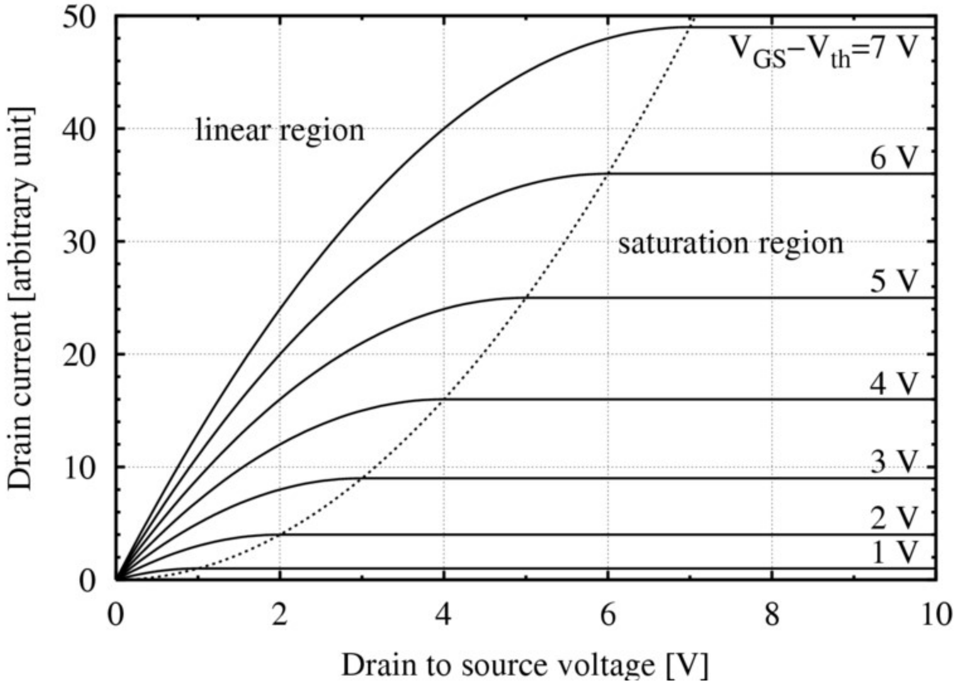
$V_G =$ 3 V

$V_T =$ 1 V

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

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.

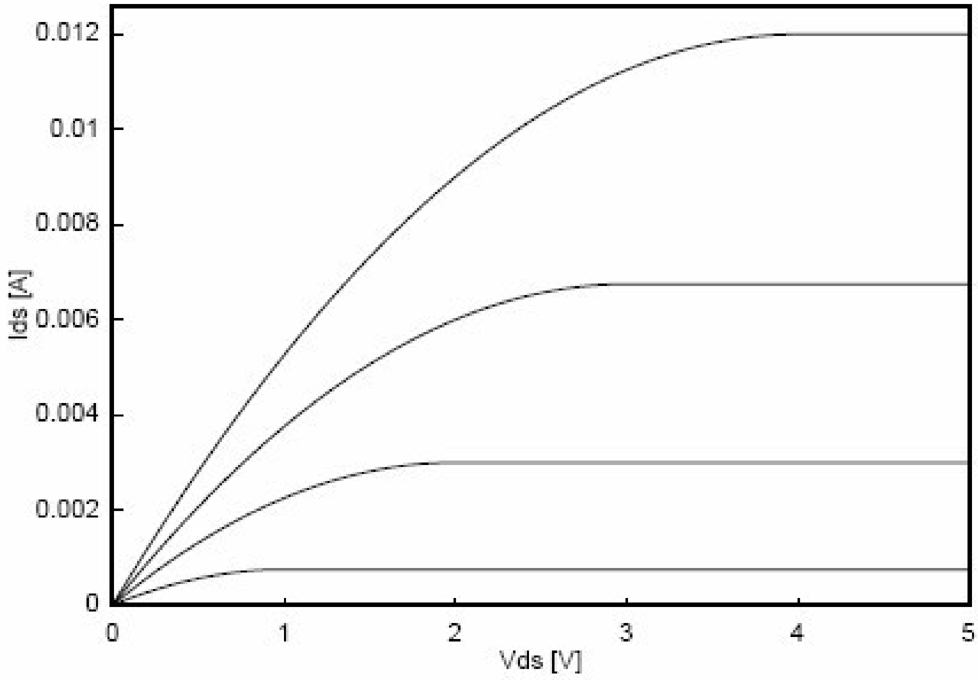
MOSFET - saturation current

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 (linear regime)

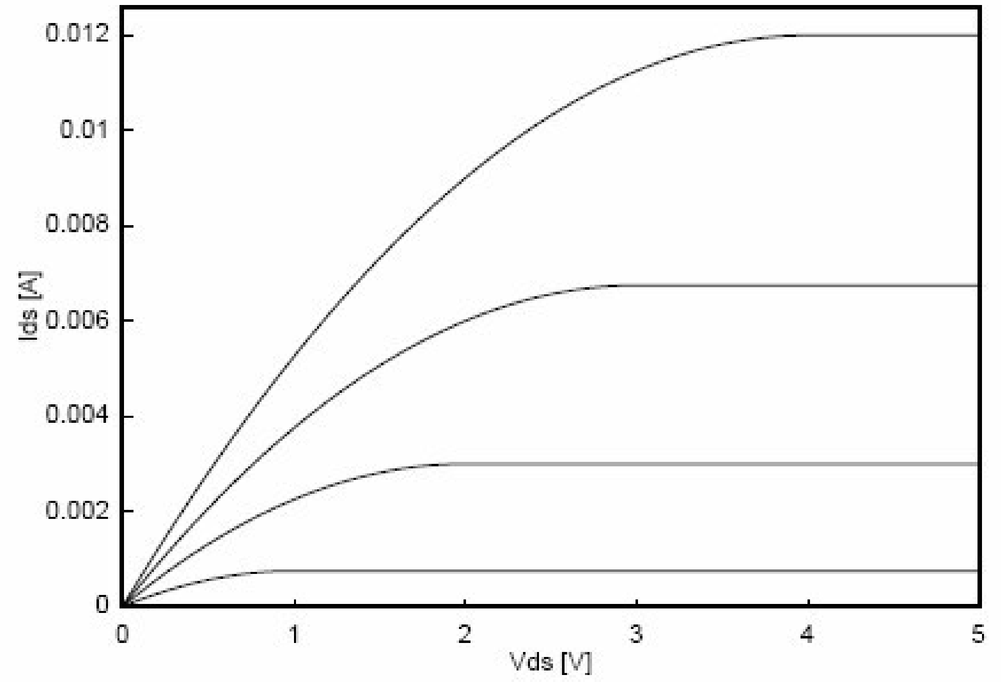
Channel conductance in the linear regime. For small V_D

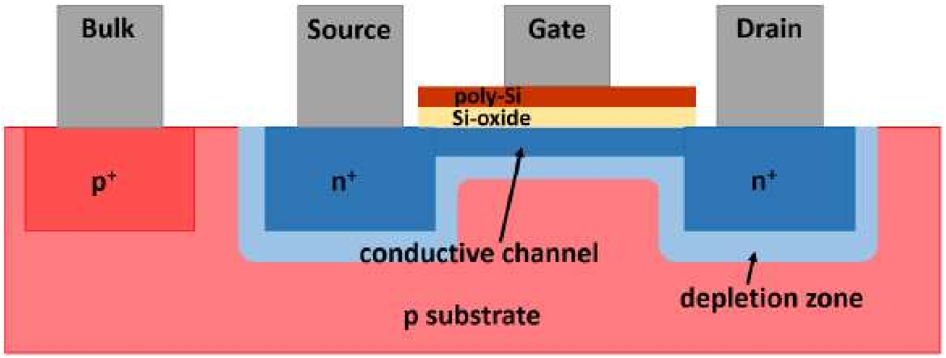
$$I \approx \frac{Z}{L}\mu_n C_{ox}\left[\left(V_G - V_T\right)V_D\right]$$

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

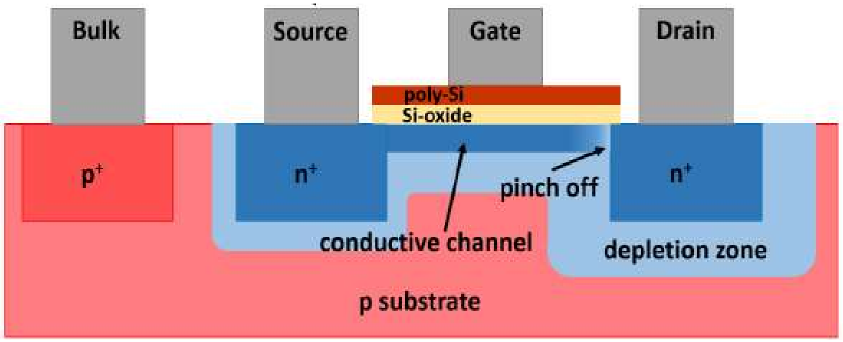
Transconductance

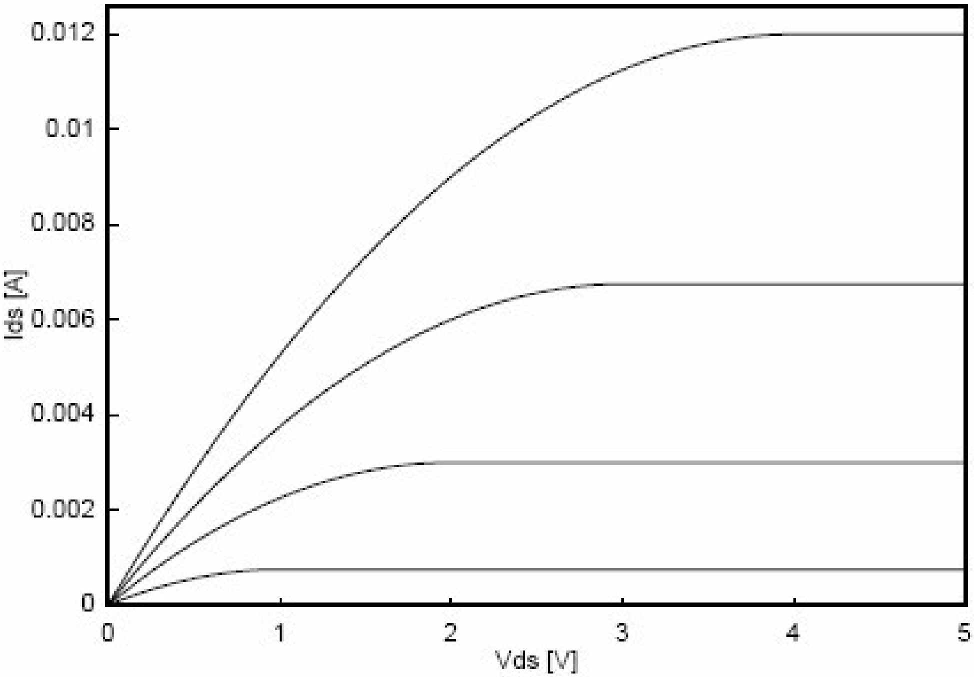
$$g_m = \frac{dI_D}{dV_G} = \frac{Z}{L}\mu_n C_{ox} V_D$$





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.

MOSFET (saturation regime)

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