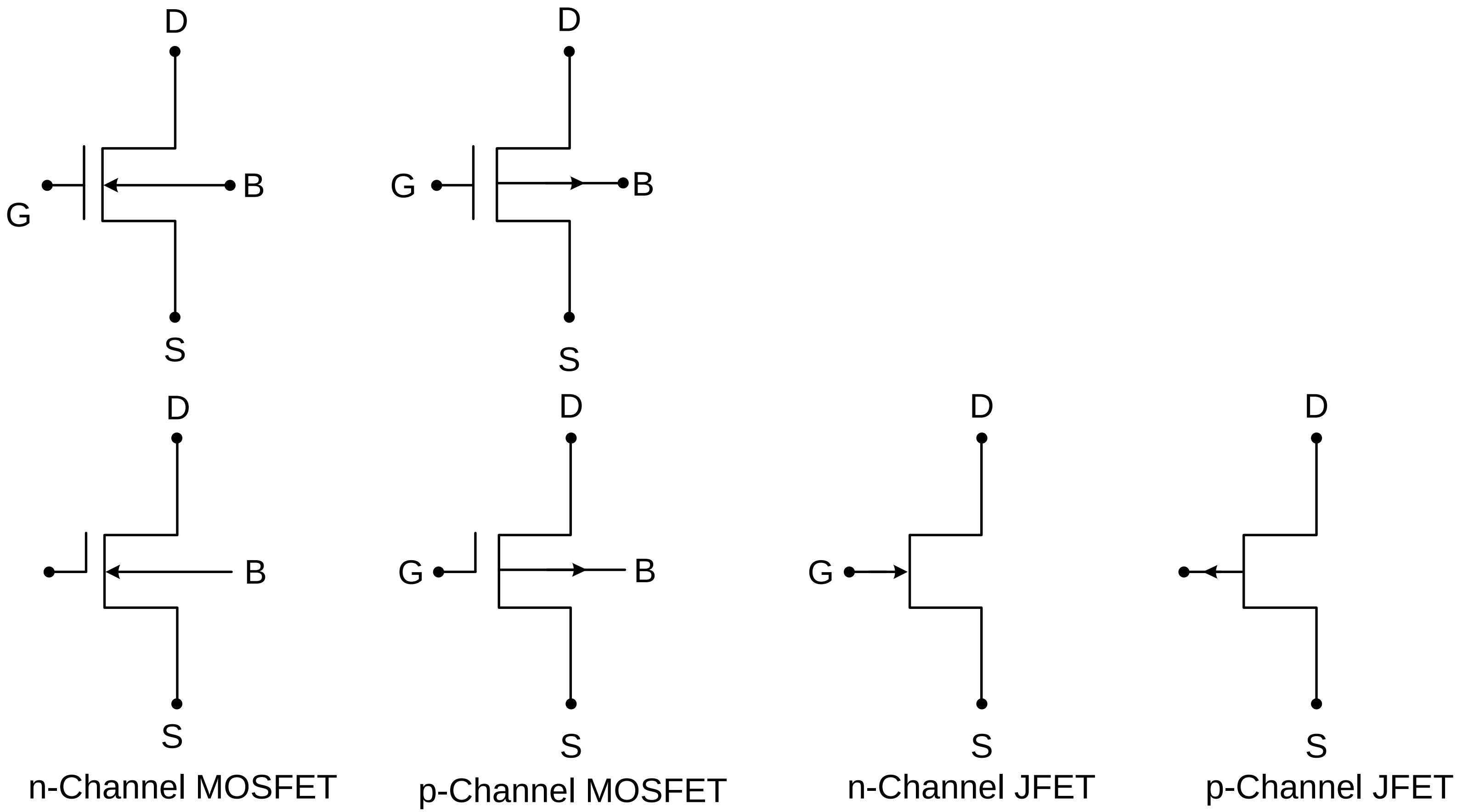
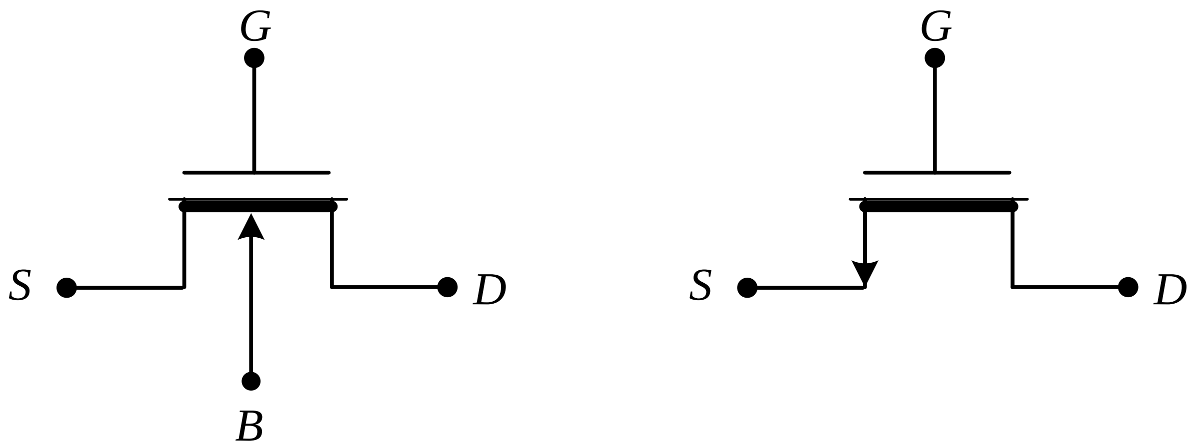
MOSFET

Lecture 1

- FET's


D
G
B
S
D
G
B
S
D
B
S
D
G
B
S
D
G
S
D
S
n-Channel MOSFET
p-Channel MOSFET
n-Channel JFET
p-Channel JFET

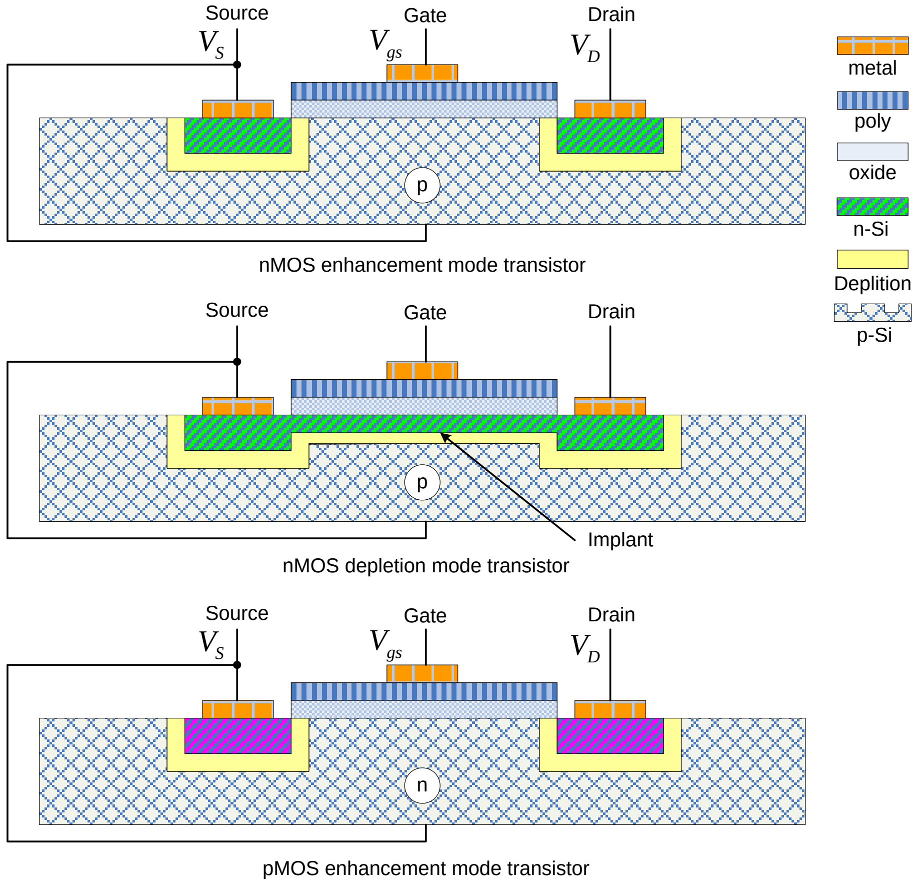
- Four-terminal device



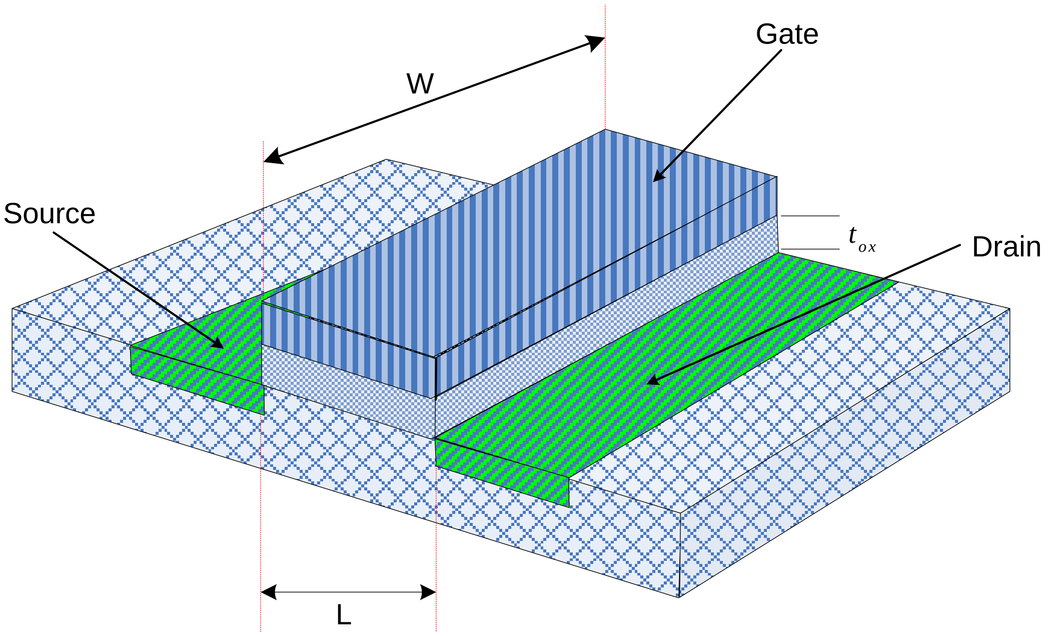
4-treminal depletion-mode nMOS transistor

3-treminal depletion-mode nMOS transistor

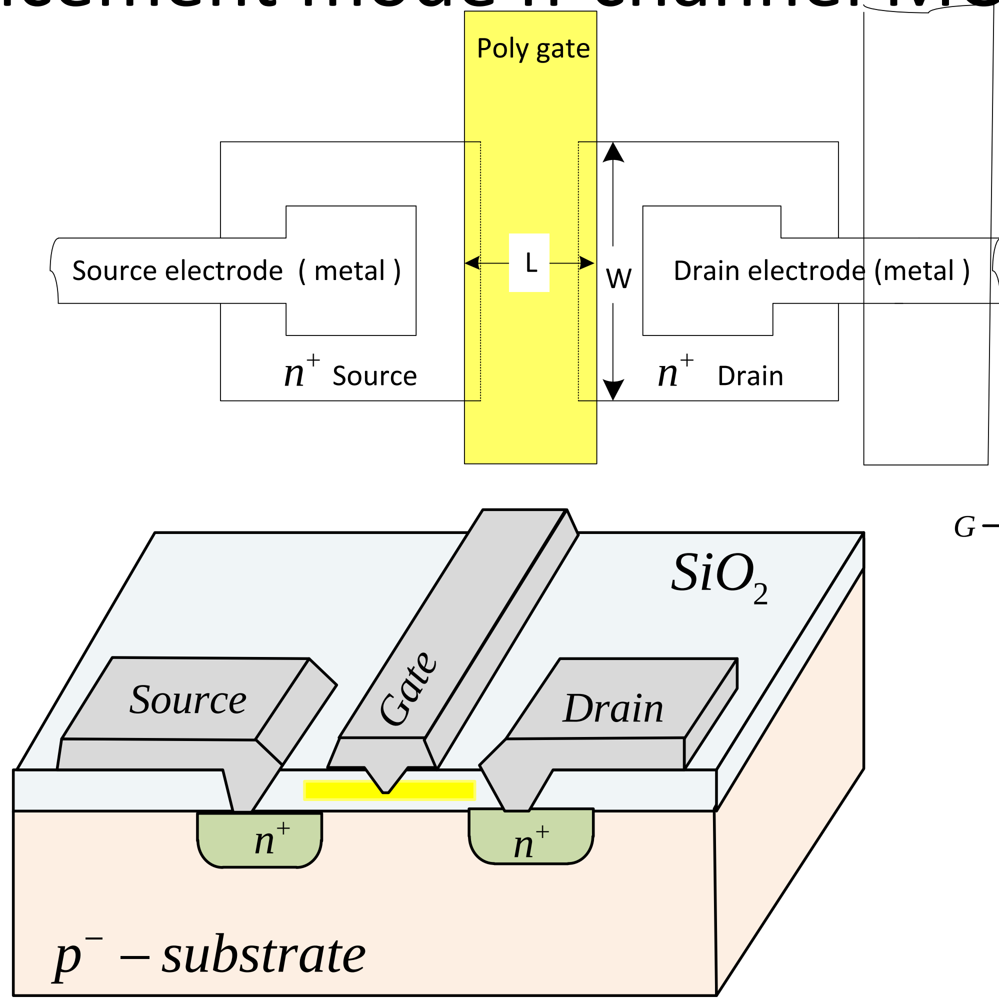
- MOSFET Strutures:

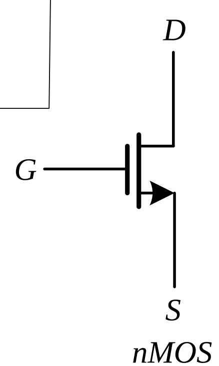


- HOW THE MOS TRANSISTOR WORKS?
- Placement of voltage V_{DS} on the gate to create channel between the drain and source under the insulator.
- Applying a voltage V_{GS} between the drain and source cause current I_{DS} follow between them.

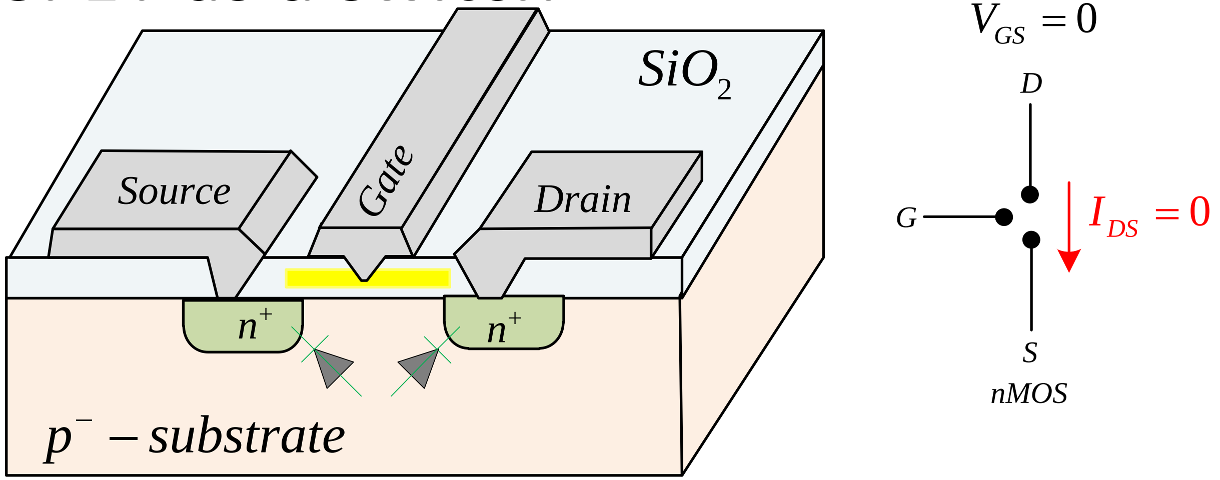


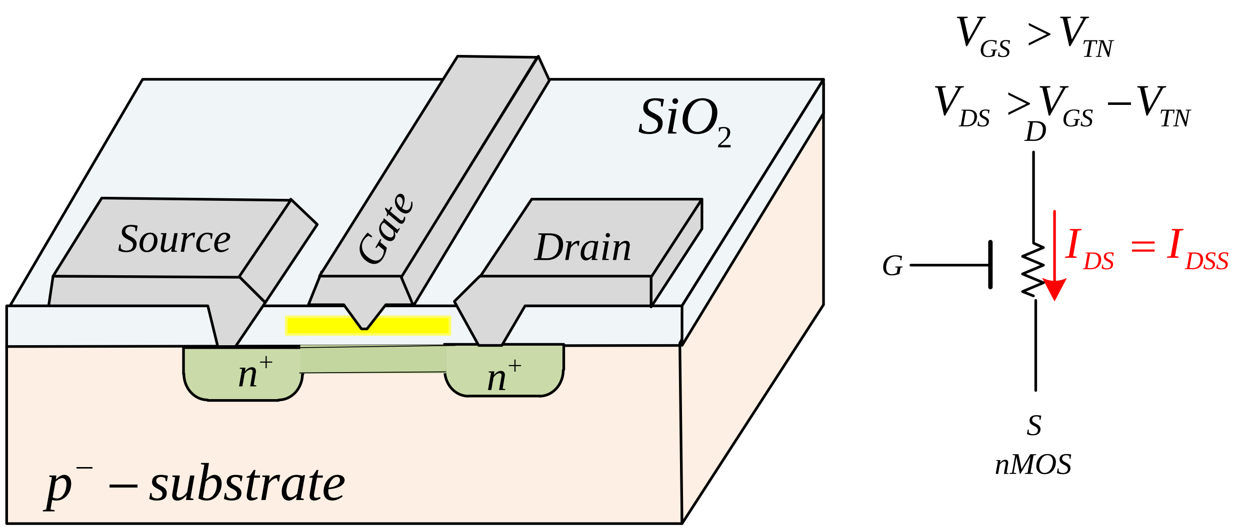
- Enhancement mode n-channel MOS



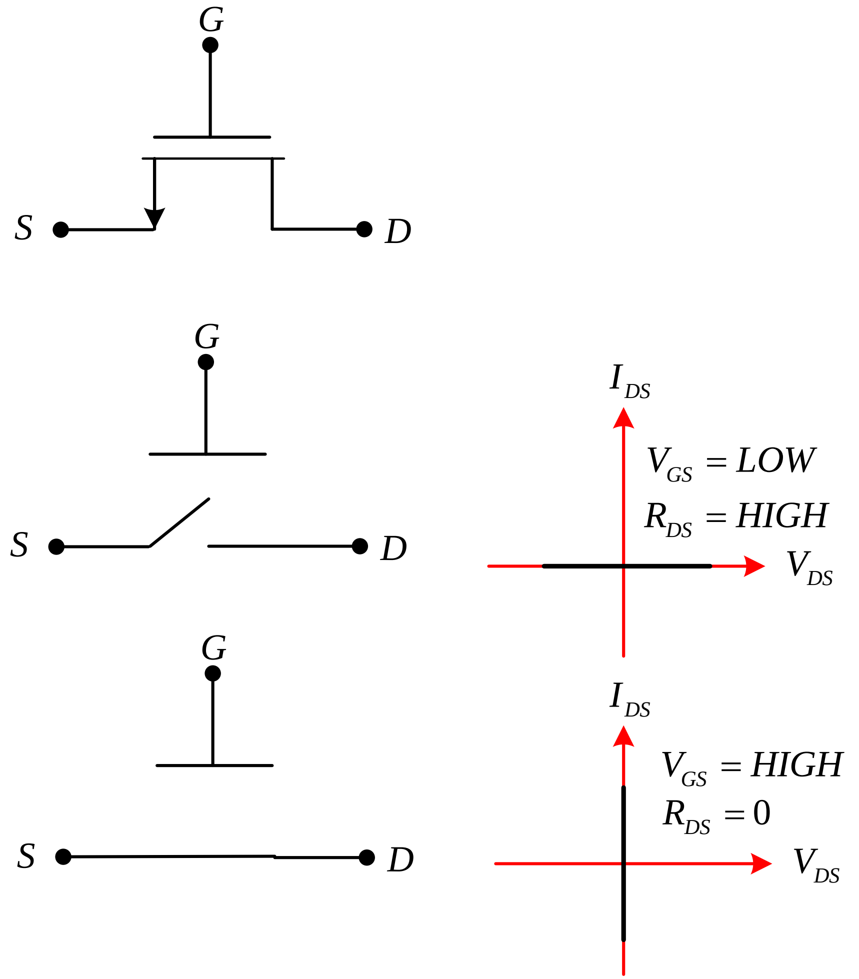


- En-MOSFET as a switch

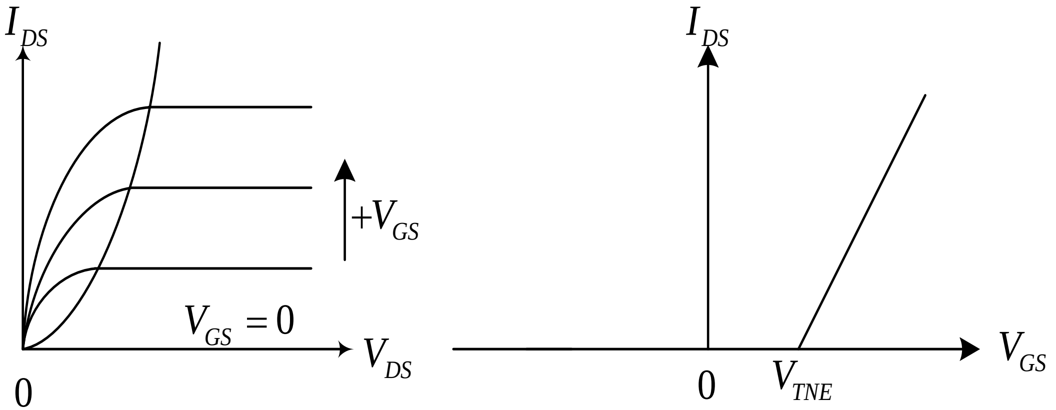




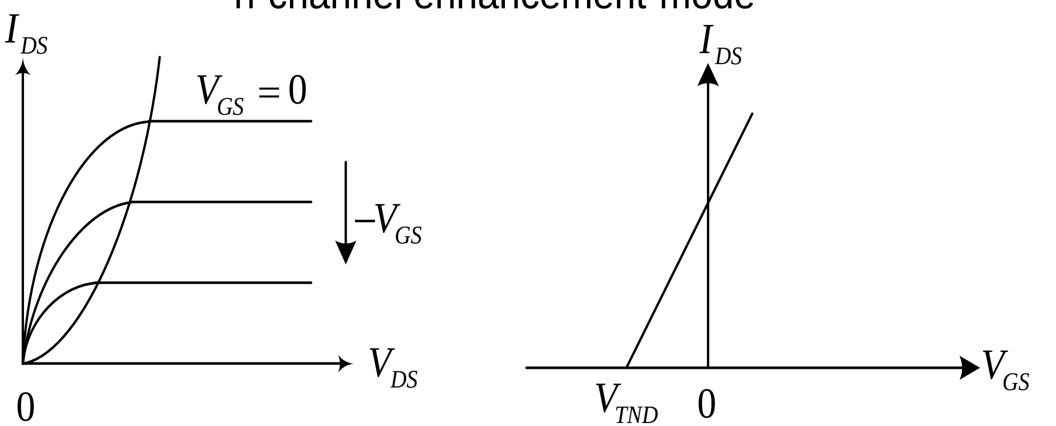
- MOSFET as a switch



- nMOSFET IV-characteristic

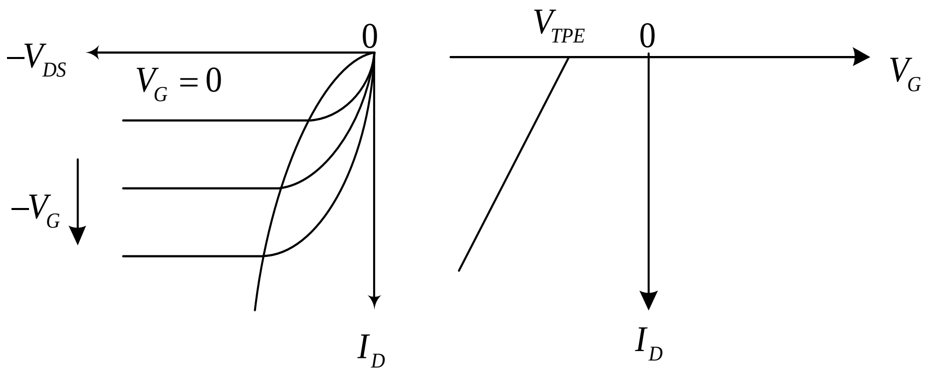


n-channel enhancement-mode

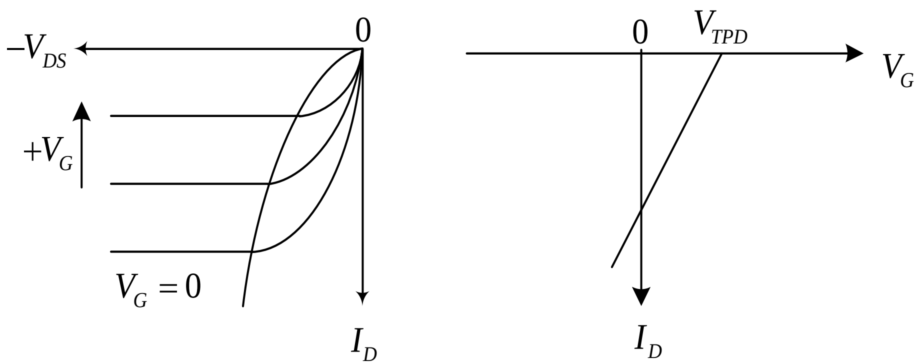


n-channel depletion-mode

- pMOSFET IV-charcateristic



p-channel enhancement-mode



p-channel depletion-mode

- The width of the depletion layer

$$W_d = \sqrt{\frac{2\varepsilon_s V_F}{qN_A}}$$

- The depletion layer (Space charge region) charge per unit area

$$Q_d = \sqrt{2qN_A\varepsilon_{si}V_F}$$

- Fermi Potential

$$V_F = V_T \ln\frac{N_A}{n_i}$$

- Strong inversion

$$2V_F = 2V_T \ln\frac{N_A}{n_i}$$

- The charge in channel for strong inversion

$$Q_{C0} = \sqrt{2qN_A\varepsilon_{si}\left|2V_F\right|}$$

- The charge in channel with applied source-to-bulk voltage

$$Q_C = \sqrt{2qN_A\varepsilon_{si}\left|-2V_F + V_{SB}\right|}$$

- The threshold voltage

$$V_{TN0} = V_{MS} - 2V_F - \frac{Q_B}{C_{OX}} - \frac{Q_{ss}}{C_{OX}} - \frac{Q_I}{C_{OX}}$$

- The threshold voltage alteration

$$V_{TN} = V_{TN0} + \gamma\left(\sqrt{\left|(-2)V_F + V_{SB}\right|} - \sqrt{\left|2V_F\right|}\right)$$

- Body-effect coefficient

$$\gamma = \frac{t_{OX}}{\varepsilon_{OX}}\sqrt{2q\varepsilon_{Si}N_A}$$

- **Example:**
- An nMOS transistor is fabricated on a p-type silicon substrate with a doping density, $N_{Sub} = N_A = 1 \times 10^{16} cm^{-3}$ and the oxide thickness $t_{OX} = 100\,\overset{o}{A}$. Given that $Q_{SS}/q = 3 \times 10^{11} cm^{-2}$ and $V_{MS} = -0.6V$ Calculate the zero-bias threshold voltage V_{TN0}, and the threshold voltage V_{TN} at the substrate bias of $V_{SB} = 2V$.
- **Solution:**
- Oxide capacitance,

$$C_{OX} = \frac{\varepsilon_r\left(SiO_2\right)\varepsilon_o}{t_{OX}} = \frac{3.9 \times 8.854 \times 10^{-14}}{100 \times 10^{-8}} = 345 \frac{nF}{cm^2}$$

- Surface potential at strong inversion,

$$V_S = 2V_F = \frac{2kT}{q} \ln \frac{N_A^-}{n_i} = 0.699V$$

- Body-effect coefficient.

$$\gamma = \frac{\sqrt{2\varepsilon_r(Si)\varepsilon_o q N_A^-}}{C_{OX}} = \frac{\sqrt{2\times 11.7\times 8.854\times 10^{-14}\times 1.6\times 10^{-19}\times 1\times 10^{16}}}{345\times 10^{-9}} = 0.21\sqrt{V}$$

- The flat band voltage

$$V_{FB} = V_{MS} - \frac{Q_{SS}}{C_{OX}} = -0.6 - \frac{1.6\times 10^{-19}\left(3\times 10^{11}\right)}{345\times 10^{-9}} = -0.6 - 0.14 = 0.74V$$

- The threshold voltage for ,

$$V_{T0} = \gamma\sqrt{\left|2V_{Fp}\right|} + \left|2V_{Fp}\right| + V_{FB} = 0.21\times\sqrt{0.699} + 0.699 = 0.88V$$

- The threshold voltage for $V_{SB} = 2V$,

$$V_T = V_{T0} + \gamma\left[\sqrt{2V_{Fp} + V_{SB}} - \sqrt{2V_{Fp}}\right] = 0.88 + 0.21\left[\sqrt{0.699+2} + \sqrt{0.699}\right] = 1.05V$$

- The charged induce in channel at point x.

$$Q_C(x) = -C_{OX}\left(V_{GS} - V(x) - V_{TN}\right) = \frac{\varepsilon_{OX}\left(V_{GS} - V(x) - V_{TN}\right)}{t_{OX}}$$

- Current is charge-velocity-width

$$I_{DS} = v_n(x) Q_S(x) W$$

- The drift velocity

$$v_n(x) = -\mu_n \xi(x) = \mu_n \frac{dV}{dx}$$

- The current

$$I_{DS}\,dx = \mu_n C_{OX} W \left(V_{GS} - V(x) - V_{TN}\right) dV$$

- The charged induce in the channel at point x.

$$Q_C(x) = -C_{OX}\left(V_{GS} - V(x) - V_{TN}\right) = \frac{\varepsilon_{OX}\left(V_{GS} - V(x) - V_{TN}\right)}{t_{OX}}$$

- The current is charge-velocity-width

$$I_{DS} = v_n(x)Q_S(x)W$$

- The drift velocity

$$v_n(x) = -\mu_n \xi(x) = \mu_n \frac{dV}{dx}$$

- The current

$$I_{DS}dx = \mu_n C_{OX} W\left(V_{GS} - V(x) - V_{TN}\right)dV$$

- The current

$$I_{DS}dx = \mu_n C_{OX} W \left(V_{GS} - V(x) - V_{TN}\right) dV$$

- Integrating

$$I_{DS}\int_0^L dx = \int_0^{V_{DS}} \mu_n C_{OX} W \left(V_{GS} - V(x) - V_{TN}\right) dV$$

- Results in

$$I_{DS} = \mu_n C_{OX} \frac{W}{L}\left[\left(V_{GS} - V_{TN}\right)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

- Process transconductance parameter $k_n' = \mu_n C_{OX} = \dfrac{\mu_n \varepsilon_{OX}}{t_{OX}}$

$$I_{DS} = k_n' \frac{W}{L}\left[\left(V_{GS} - V_{TN}\right)V_{DS} - \frac{V_{DS}^2}{2}\right]$$

- The gain factor $k_n = k_n' \frac{W}{L} = \mu_n C_{OX} \frac{W}{L}$

$$I_{DS} = k_n \left[\left(V_{GS} - V_{TN} \right) V_{DS} - \frac{V_{DS}^2}{2} \right]$$

- .

- Edge of the saturation current of the En-MOSFET

$$I_D = \frac{1}{2}\mu_n C_{OX}\frac{W}{L}\left(V_{GS} - V_{TN}\right)^2 \quad for \;\; V_{DS} = V_{GS} - V_{TN}$$

- The saturation current of the En-MOSFET

$$I_{DS} = \frac{1}{2}\mu_n C_{OX}\frac{W}{L}\left(V_{GS} - V_{TN}\right)^2\left(1 + \lambda V_{DS}\right)$$

- Channel-length modulation λ

$$r_{DS} = \left[\frac{\partial i_{DS}}{\partial v_{DS}}\right]^{-1} = \frac{1}{\mu_n C_{OX}\frac{W}{L}\left(V_{GS} - V_{TN}\right)}$$

- Trans-conductance expresses the relationship between the output current I_{DS} and the input voltage V_{GS}

$$g_m = \left.\frac{\partial I_{DS}}{\partial V_{GS}}\right|_{V_{DS=\text{Constant}}}$$

- To find expression for g_m in terms of circuit and transistor parameters

$$\frac{Q_C}{I_{DS}} = \tau = \text{ Transit time}$$

$$\partial I_{DS} = \frac{\partial Q_C}{\tau_{SD}}$$

$$\tau_{SD} = \frac{L^2}{\mu V_{DS}}$$

$$\partial I_{DS} = \frac{\partial Q_C V_{DS} \mu}{L^2}$$

- $$\partial I_{DS} = \frac{C_{ox}\partial V_{GS}\mu V_{DS}}{L^2}$$

$$g_m = \frac{\partial I_{DS}}{\partial V_{GS}} = \frac{C_{ox}\mu V_{DS}}{L^2}$$

- In saturation

$$V_{DS} = V_{GS} - V_{TH}$$

$$g_m = \frac{C_{ox}\mu}{L^2}\left(V_{GS} - V_{TH}\right)$$

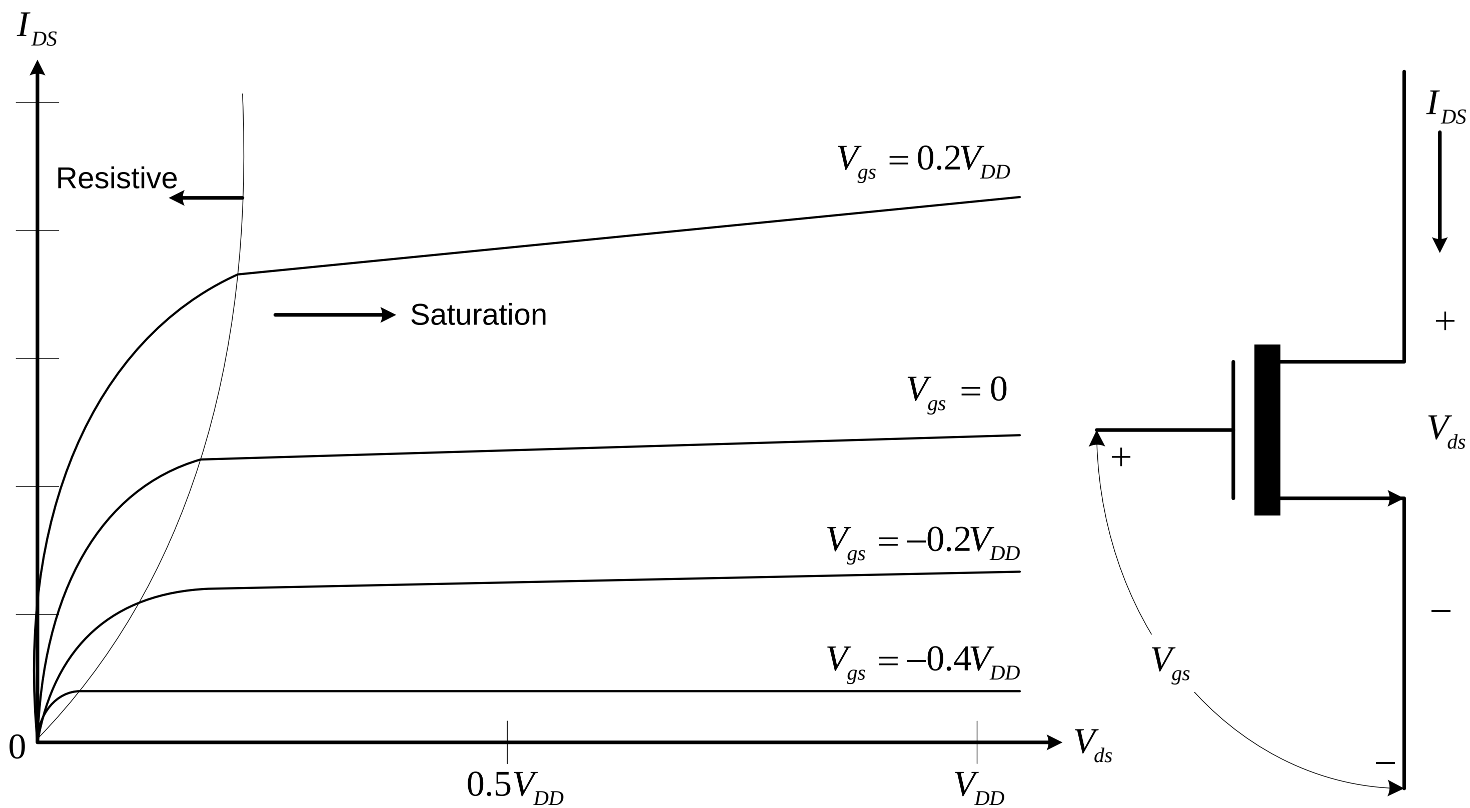
$$C_{ox} = \frac{\varepsilon_r\left(Sio_2\right)\varepsilon_o WL}{t_{ox}}$$

$$g_m = \mu C_{ox}\frac{W}{L}\left(V_{GS} - V_{TH}\right)$$

- Figure of Merit ω_0

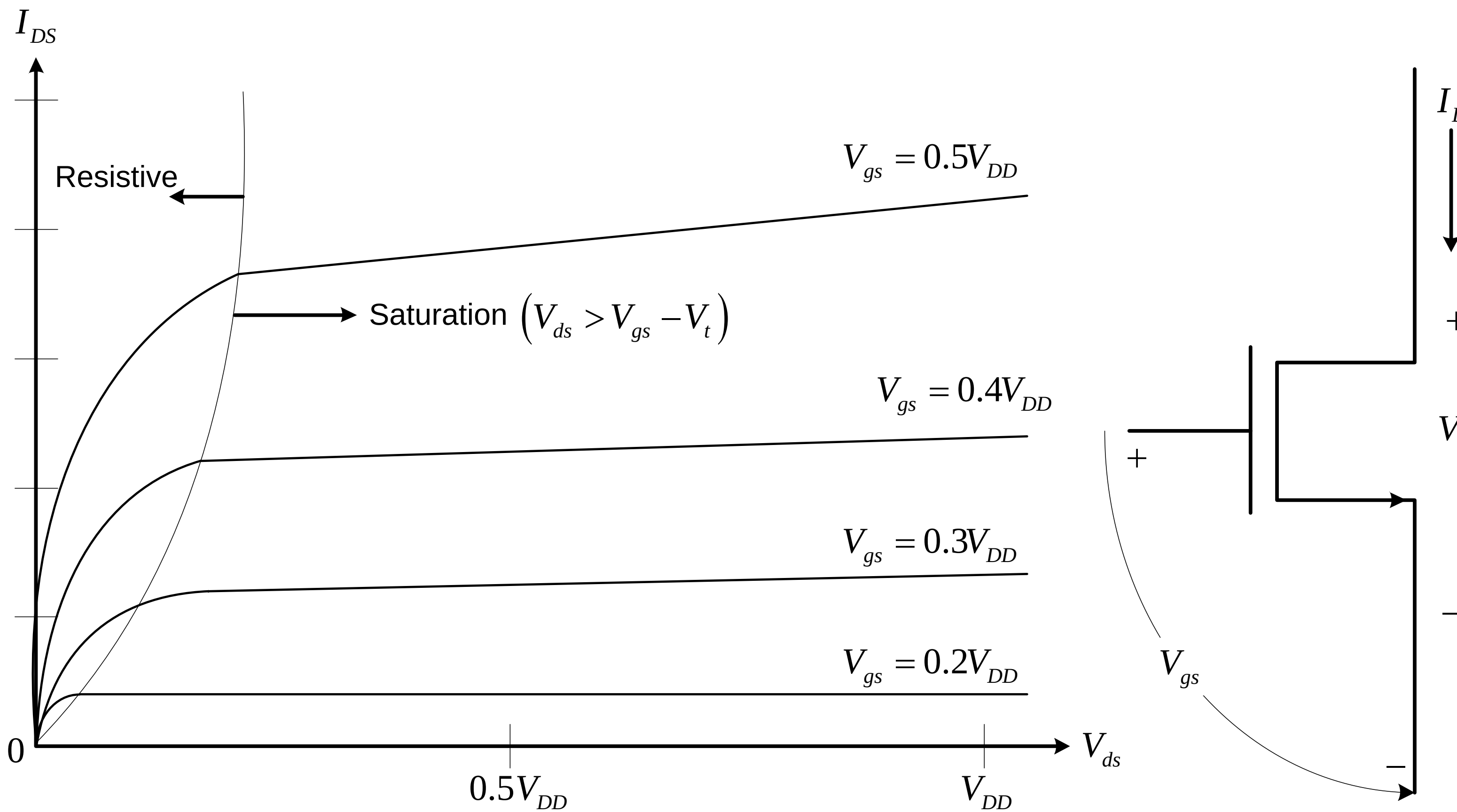
$$\omega_0 = \frac{g_m}{C_{ox}} = \frac{\mu}{L^2}\left(V_{GS} - V_{TH}\right)$$

- Depletion Mode Device.



Depletion mode device

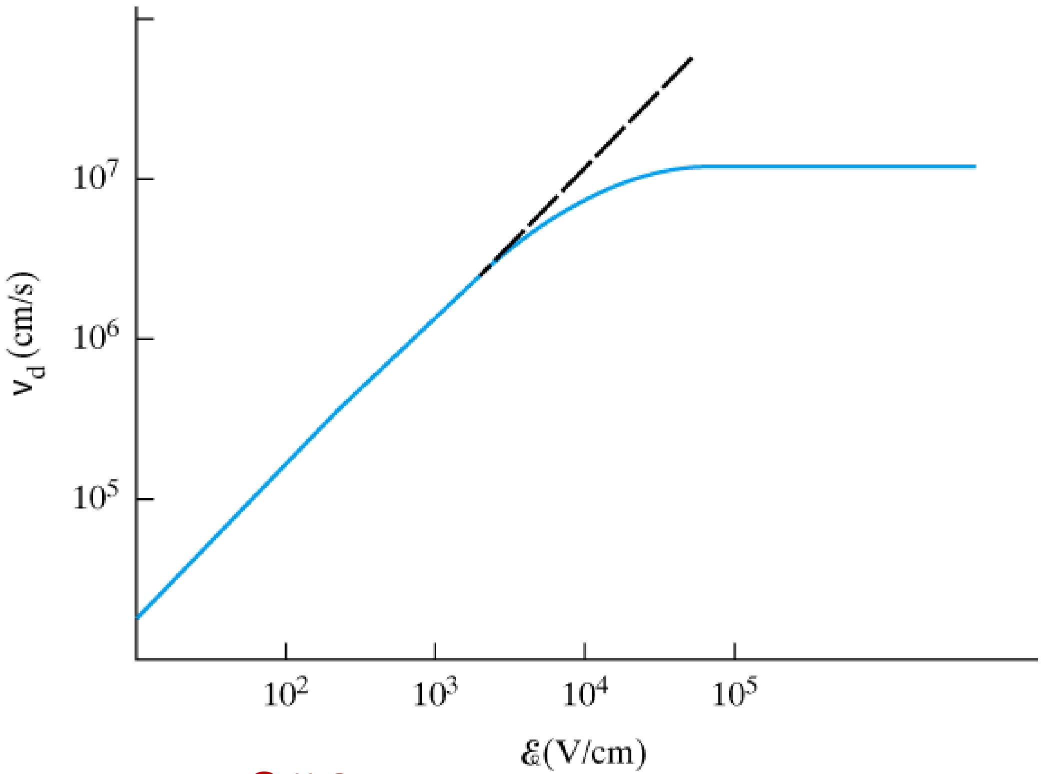
- Enhancement Mode Device.



Enhancement mode device

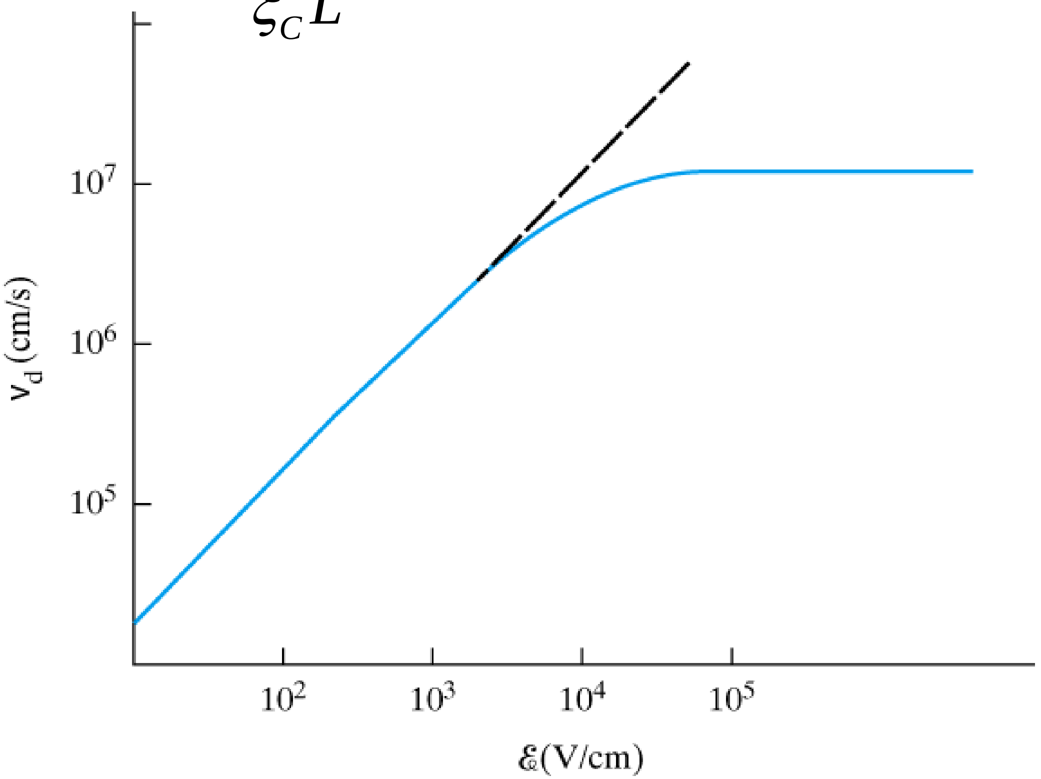
- High field effect (Hot carrier effect)

$$v_n(drift) = \frac{\mu_n \xi}{1 + \frac{\xi}{\xi_C}}$$

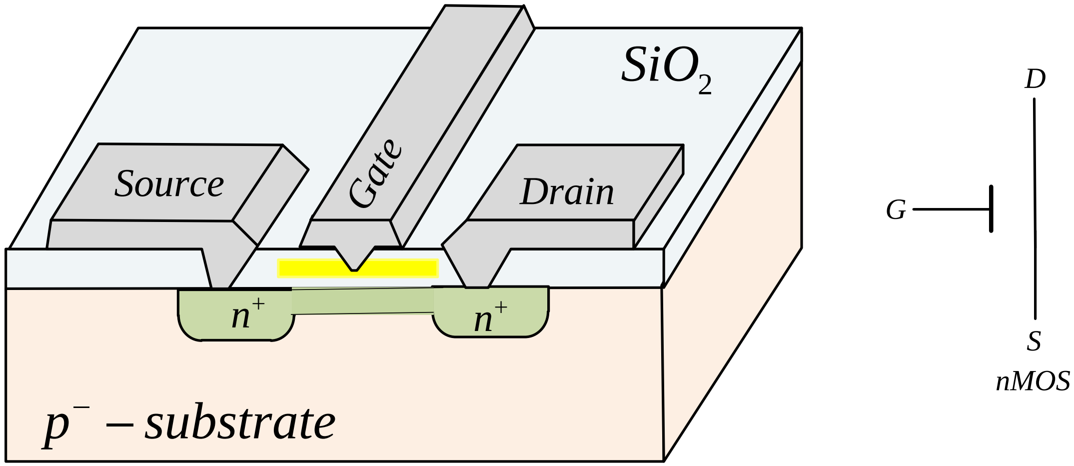


- The current in High field

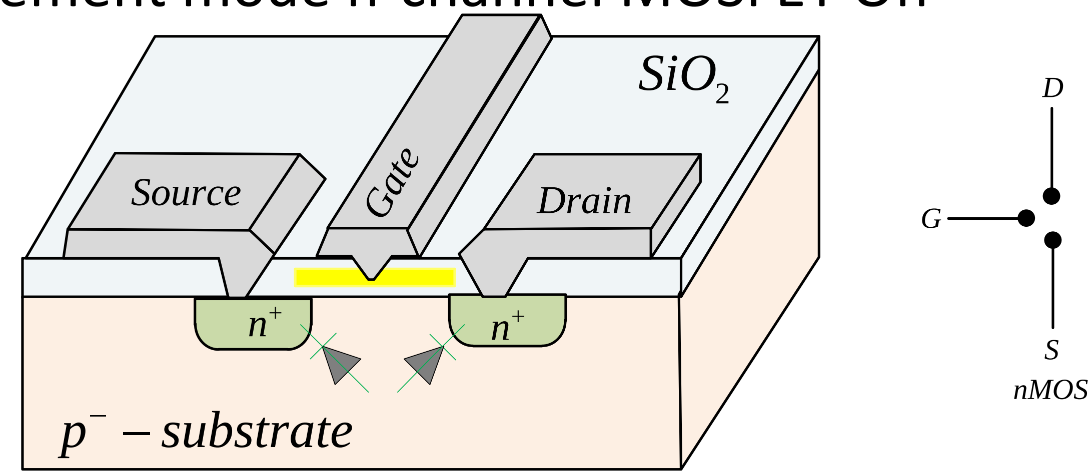
$$I_{DS} = \frac{\mu_n C_{OX}}{1+\dfrac{V_{DS}}{\xi_C L}} \frac{W}{L}\left[(V_{GS} - V_{TN})V_{DS} - \frac{V_{DS}^2}{2}\right]$$



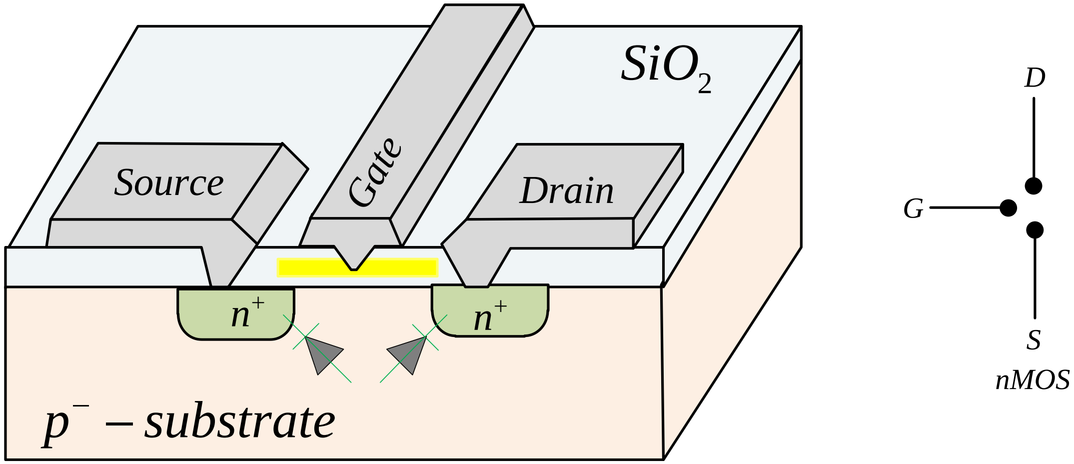
- Depletion mode n-channel MOSFET Off



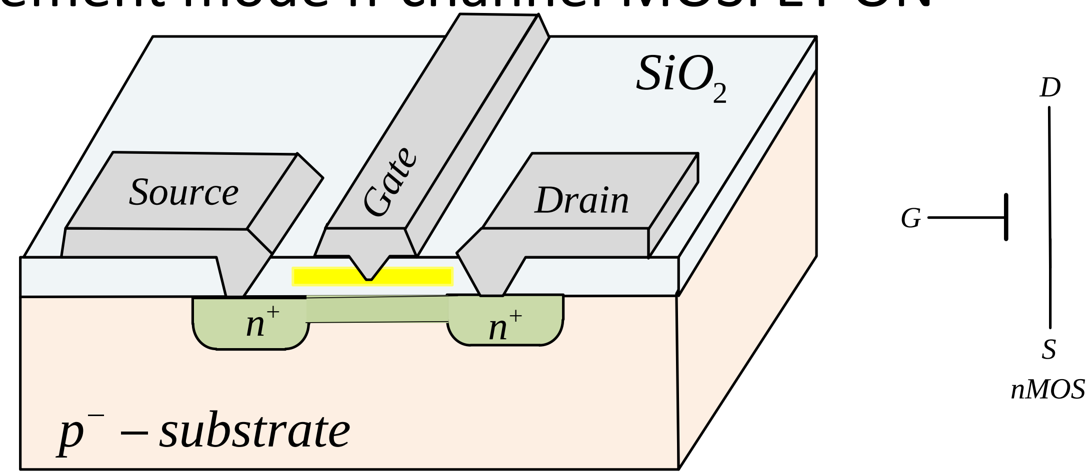
- Enhancement mode n-channel MOSFET Off



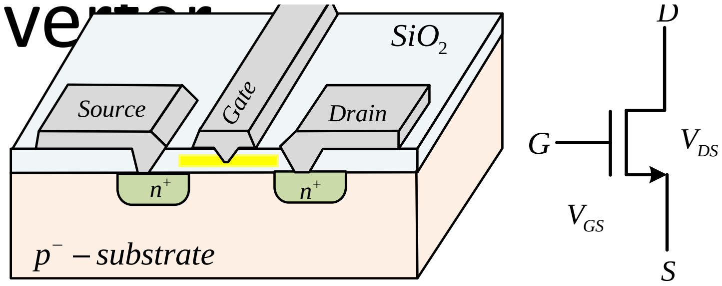
- Depletion mode n-channel MOSFET ON

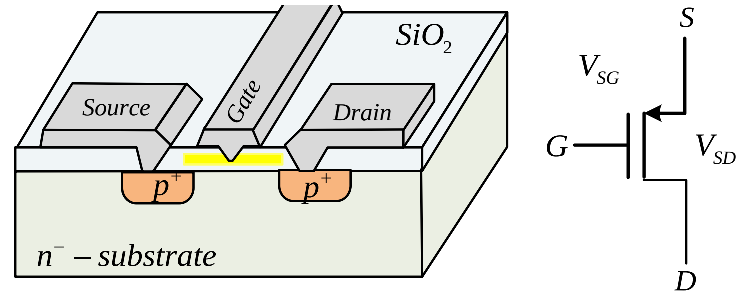


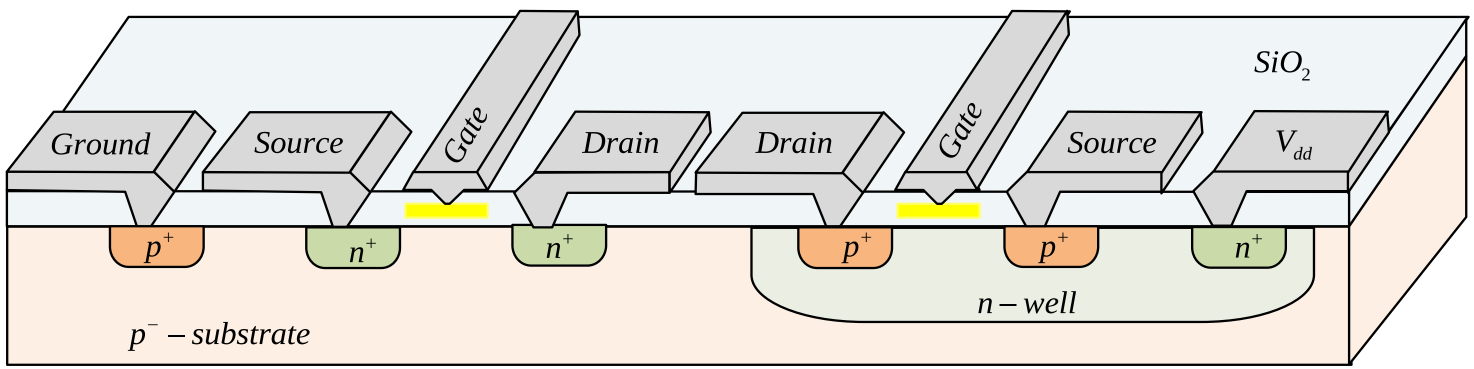
- Enhancement mode n-channel MOSFET ON

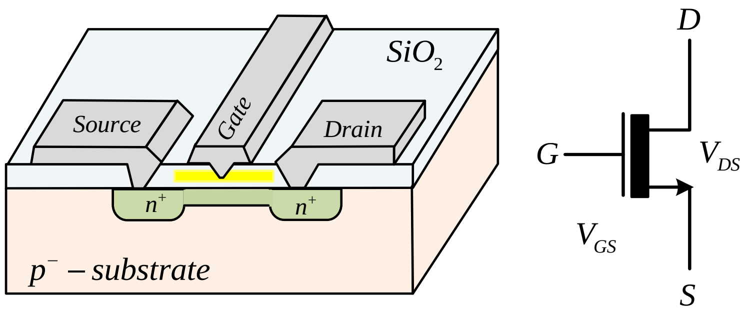


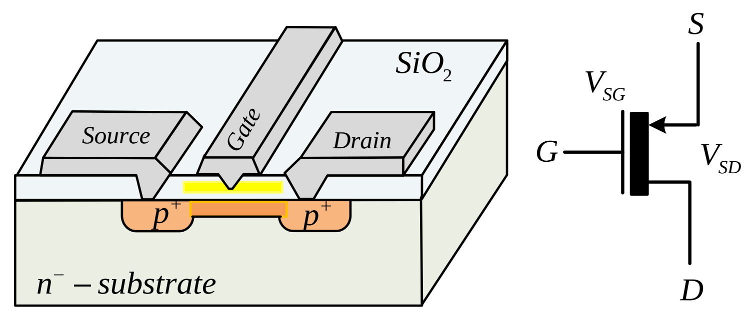
- Inverter


SiO$_2$
Source
Gate
Drain
n^+
n^+
$p^- - substrate$
D
G
V_{DS}
V_{GS}
S


SiO$_2$
Source
Gate
Drain
p^+
p^+
$n^- - substrate$
S
V_{SG}
G
V_{SD}
D


SiO$_2$
Ground
Source
Gate
Drain
Drain
Gate
Source
V_{dd}
p^+
n^+
n^+
p^+
p^+
n^+
$n - well$
$p^- - substrate$


SiO$_2$
Source
Gate
Drain
n^+
n^+
$p^- - substrate$
D
G
V_{DS}
V_{GS}
S


SiO$_2$
Source
Gate
Drain
p^+
p^+
$n^- - substrate$
S
V_{SG}
G
V_{SD}
D

- Switching an enhancement mode MOS transistor form the off the on state consist of applying sufficient gate voltage to neutralize the charges and enable the underlying silicon to undergo an inversion due to the electric field from the gate.
- .

$$V_{TH} = \overbrace{V_{MS} - \frac{Q_{ss}}{C_{OX}}}^{\text{flat band}} \underbrace{- \frac{Q_d}{C_{OX}}}_{\text{Accomodation of the charge in depletion region}} + \underbrace{2V_f}_{\text{induce the inverted region}}$$

Q_{SS} = Charge density at Si:Sio$_2$ interface

Q_d = The Charge/unit area in the depletion layer beneath the oxide

C_{OX} = Capacitance/unit gate area

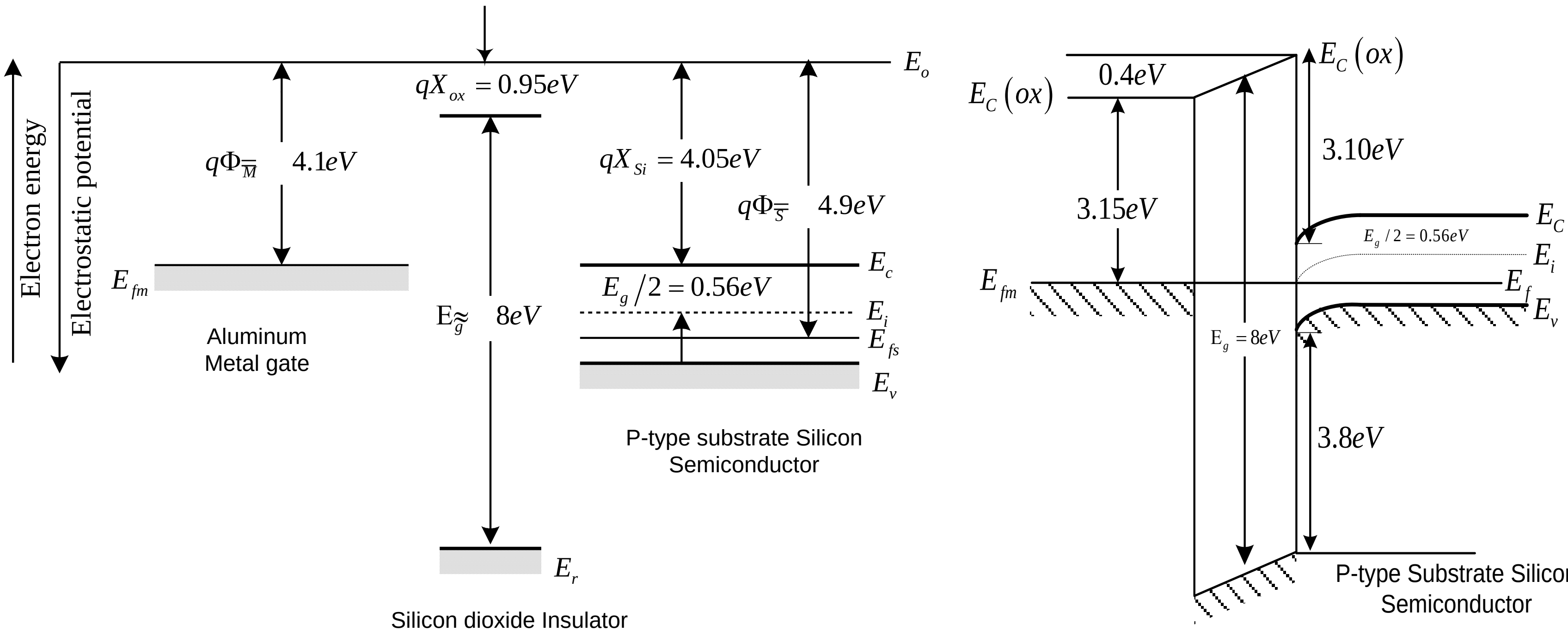
V_{MS} = Work function difference between gate and *Si*

V_f = Fermi level potential between inverted surface and bulk *Si*

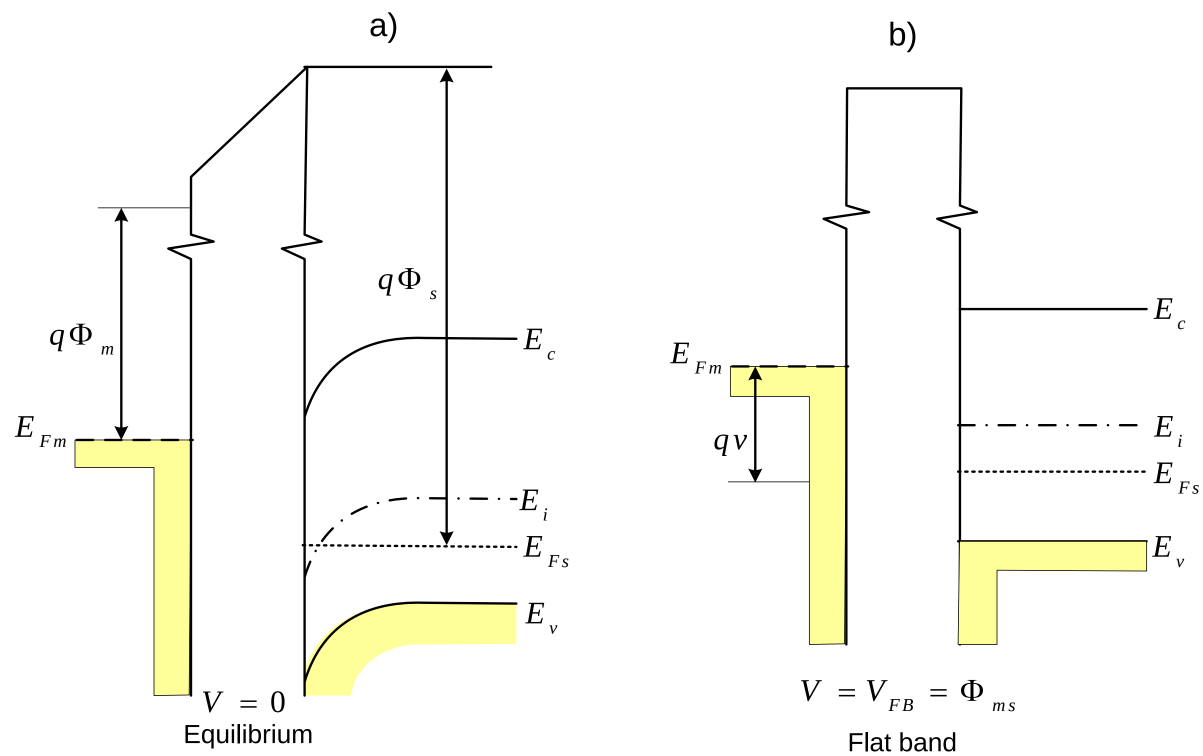
- Influence of materials parameters on threshold voltage, the threshold voltage equation indicating signs of the various contributions

$V_{TH} =$	V_{ms}	$-\dfrac{Q_{SS}}{C_{ox}}$	$-\dfrac{Q_d}{C_{ox}}$	$+2V_F$
	$(-)$	$(-)$	$(+)$ n channel $(-)$ p channel	$(+)$ n channel $(-)$ p channel

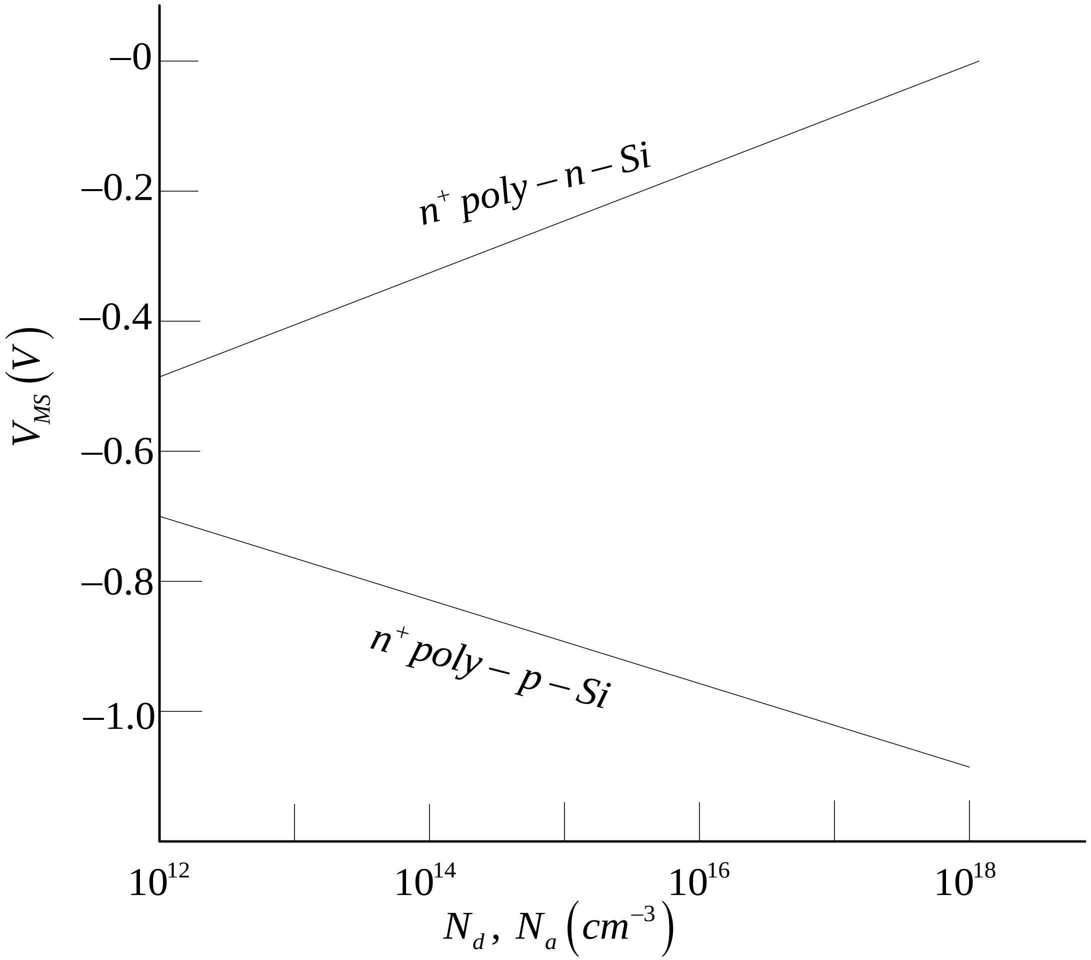
- Effect of a negative work function difference
  - Band bending and formation of negative charge at the semiconductor surface. $(V_{ms} < 0)$



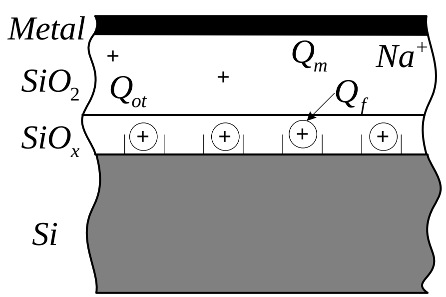
- Effect of a negative work function difference $(V_{MS} < 0)$
  - a) Band bending and formation of negative charge at the semiconductor surface.
  - b) Achievement of the flat band condition by application of a negative voltage.



- Variation of the metal-semiconductor work function potential difference V_{MS} with substrate doping concentration, for n^+ poly-si.



- Effects of charges in the oxide and at the interface:
  - a) definitions of charge density (C/cm²) due to various sources
  - b) representing these charges as an equivalent sheet of positive charge Q_i at the oxide-semiconductor interface.
- This positive charge induces an equivalent negative charge in the semiconductor, which requires a negative gate voltage to achieve the flat band condition.

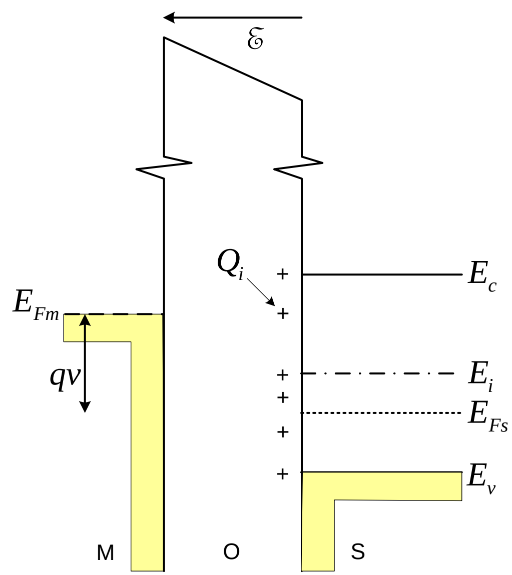


Q_m Mobile ionic charge

Q_{ot} Oxide trapped charge

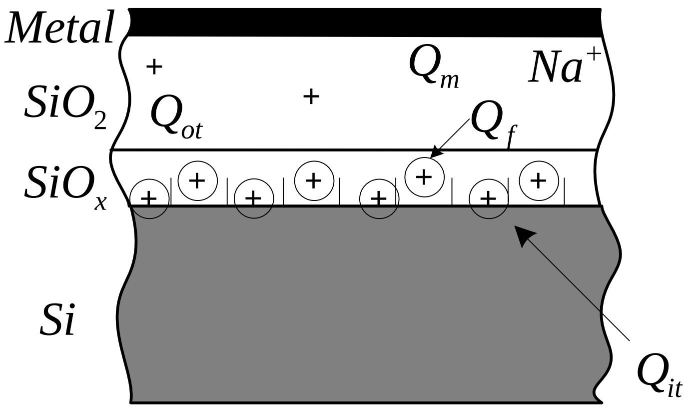
Q_f Oxide fixed charge

Q_{it} Interface trap charge



$$V = V_{FB} = -\frac{Q_i}{C_i}$$

- Effects of charges in the oxide and at the interface:

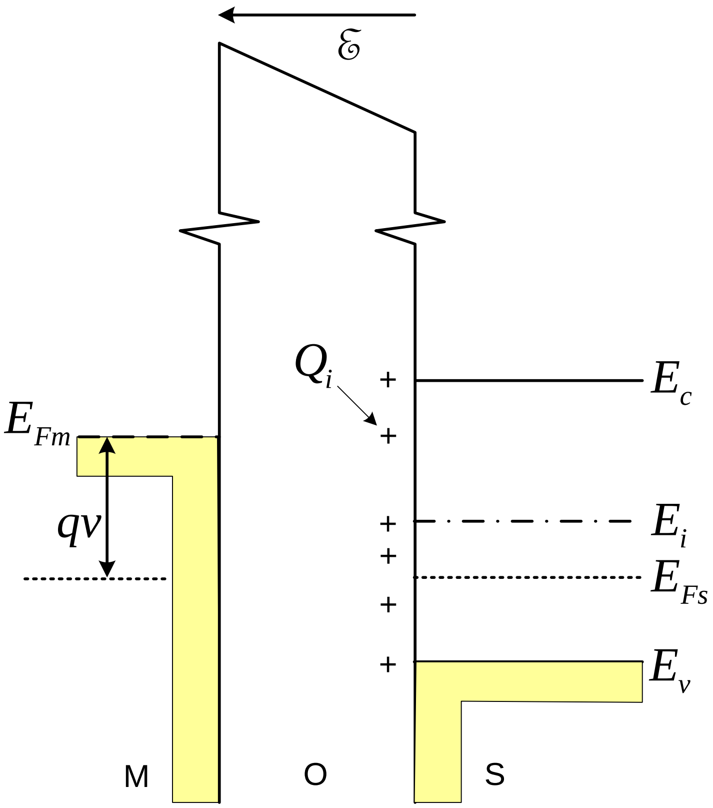


Q_m Mobile ionic charge

Q_{ot} Oxide trapped charge

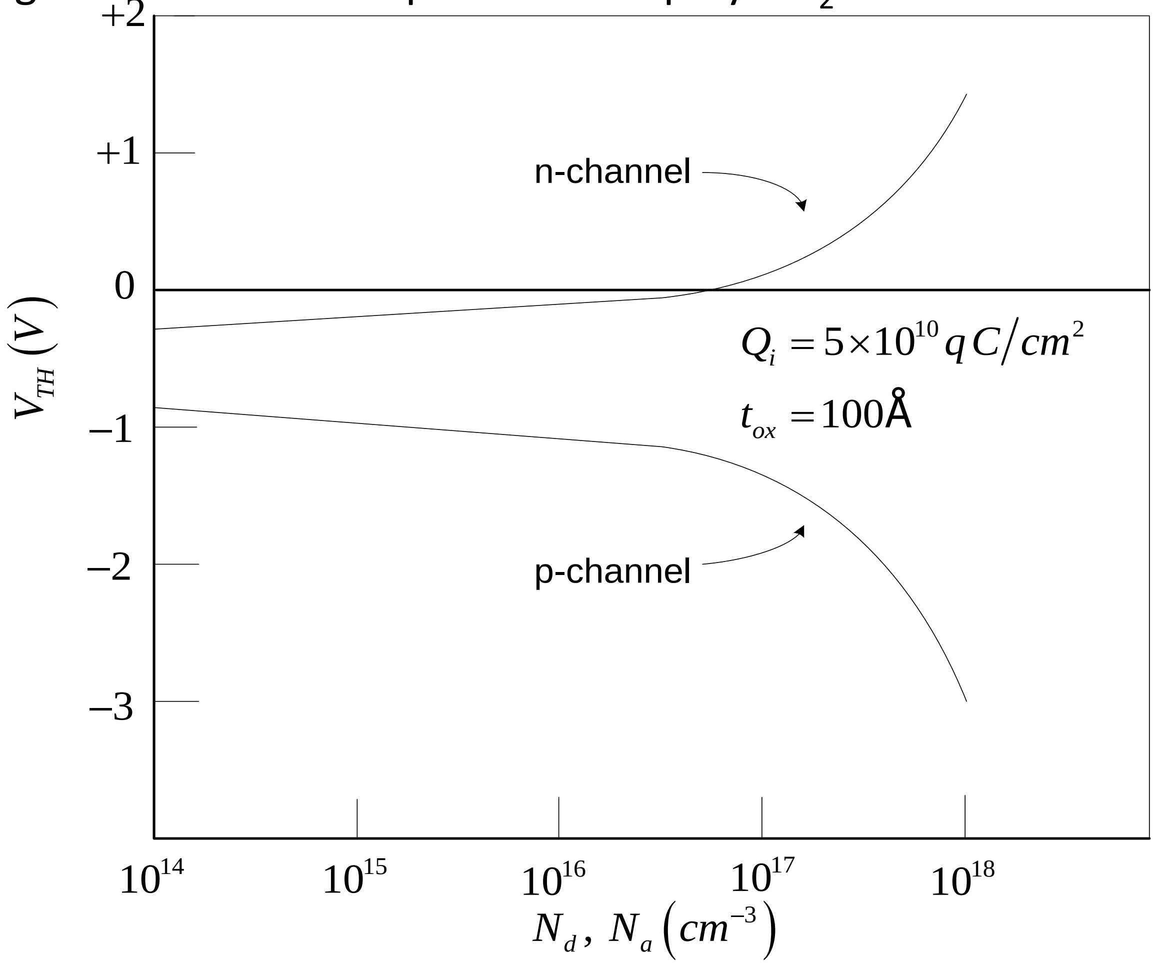
Q_f Oxide fixed charge

Q_{it} Interface trap charge



$$V = V_{FB} = -\frac{Q_i}{C_i} = -\frac{Q_{ox}}{C_{ox}}$$

- Influence of materials parameters on threshold voltage, variation of V_{TH} with substrate doping for n-channel and p-channel n^+ poly-SiO_2-Si devices.



- For poly silicon gate and Si-Substrate, the value of V_{MS} is negative as well as the value of $\frac{-Q_{SS}}{C_{ox}}$
- For n-MOS

$$Q_d = \sqrt{2\varepsilon_r(Si)\varepsilon_o qN\left(2\phi_{fn} + V_{SB}\right)}$$

$$V_{FN} = \frac{kT}{q}\ln\frac{N}{n_i}\ \text{Volts}$$

$$Q_{SS} = (1.5\ \text{to}\ 8)\times 10^{-8}\, coulombs/m^2$$

- Depending on crystal orientation and where

$V_{SB} =$ Substrate bias voltage (negative w.r.t. source for nMOS/ positive for pMOS)

$q = 1.6\times 10^{-19}$ coulomb

$N =$ Impurity concentration in the substrate (N_A or N_D as appropriate)

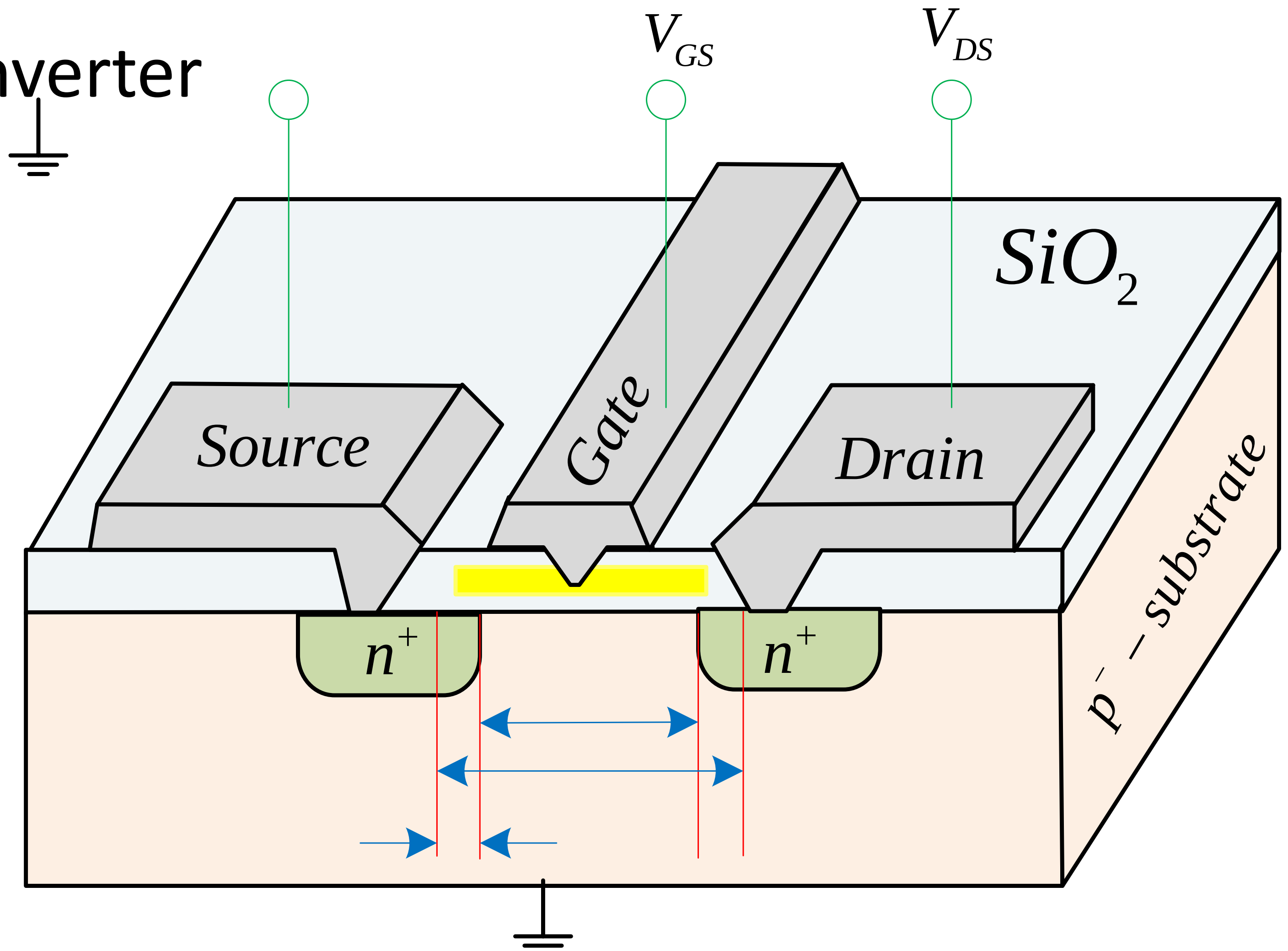
- Some parameters

$$\varepsilon_r(Si) = \text{ relative permitivity of Silicon } = 11.7$$

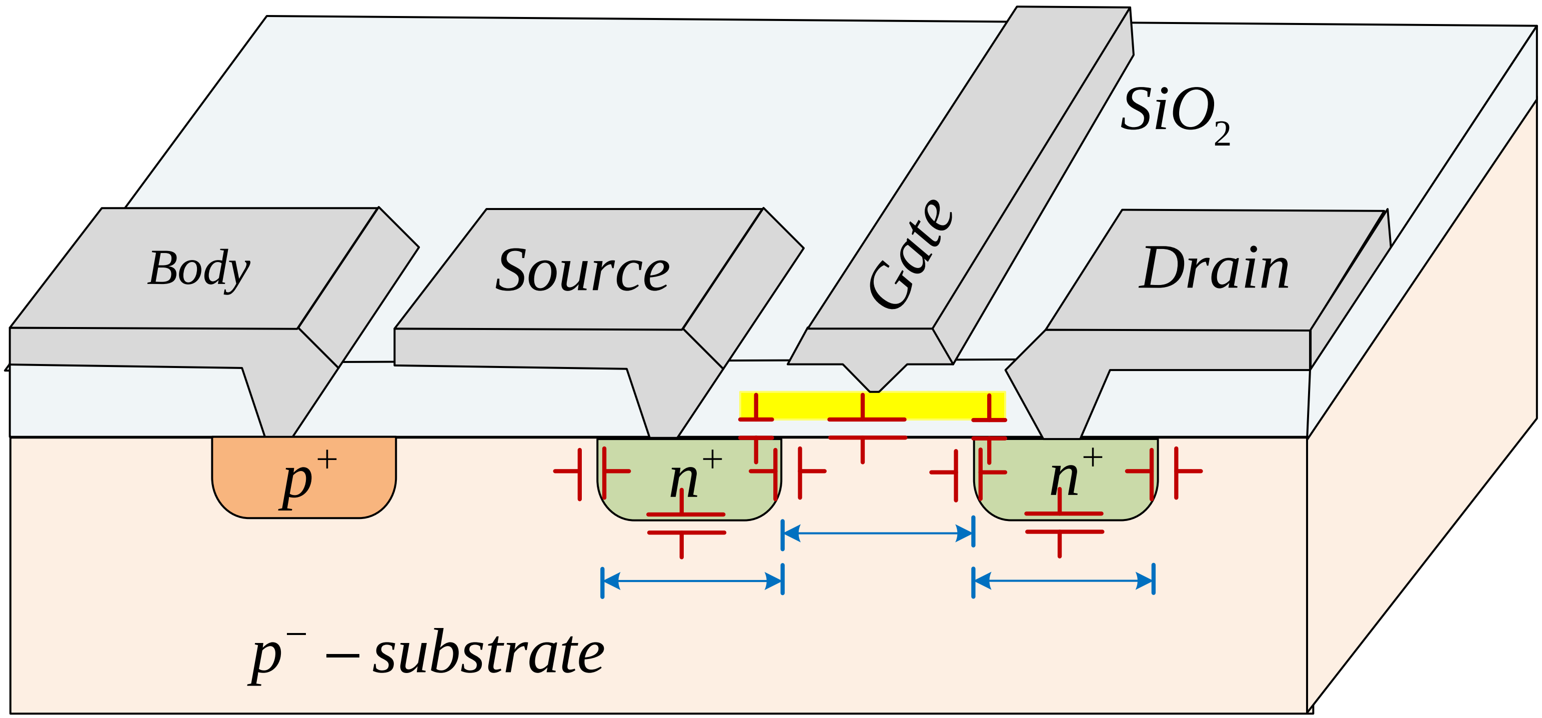
$$n_i = \text{ intrinsic electron concentration } = 1.5\times 10$$

$$k = \text{ Boltzmann's constant } = 1.38\times 10^{-23}\ joule/k^{\circ}$$

- Inverter

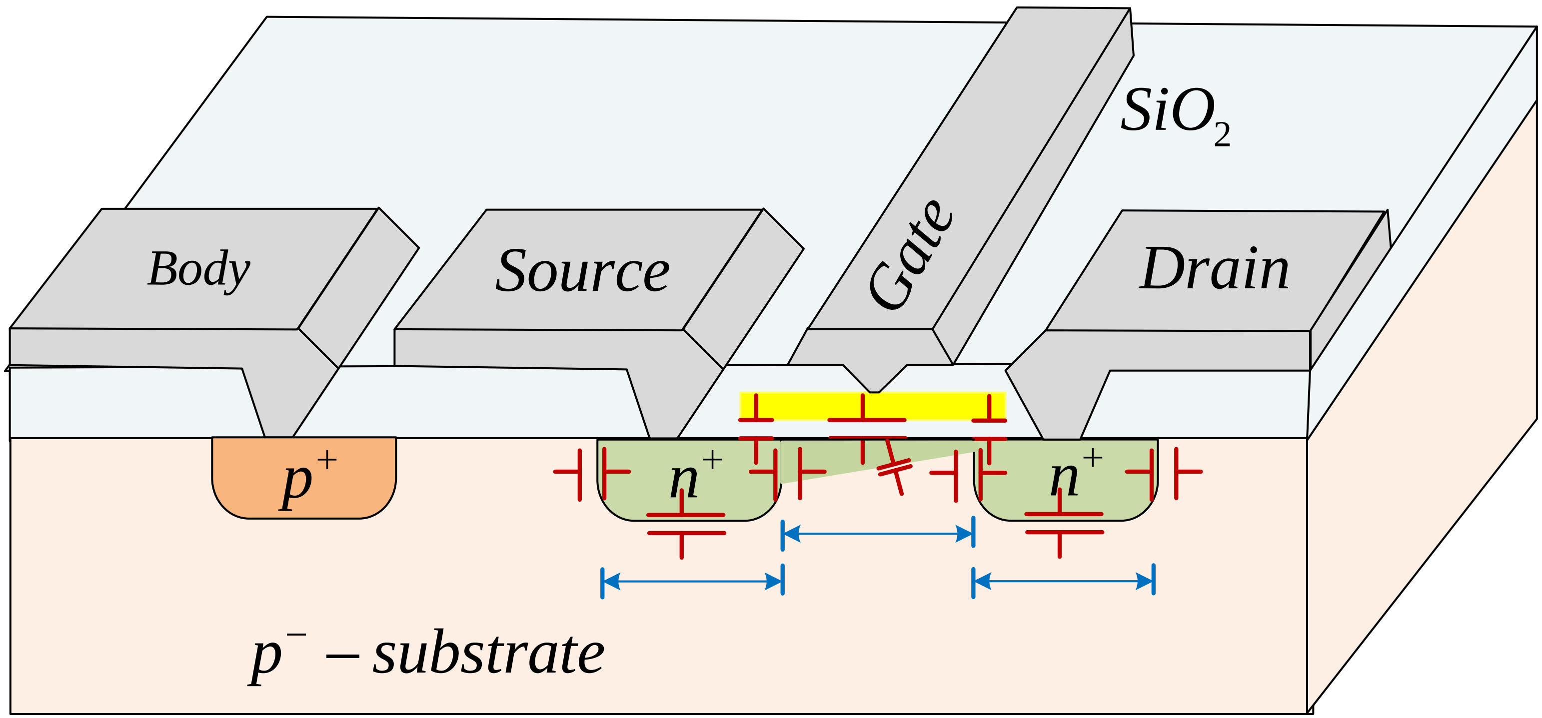


- Parasitic capacitors in the cut-off $V_{GS} < V_{TN}$



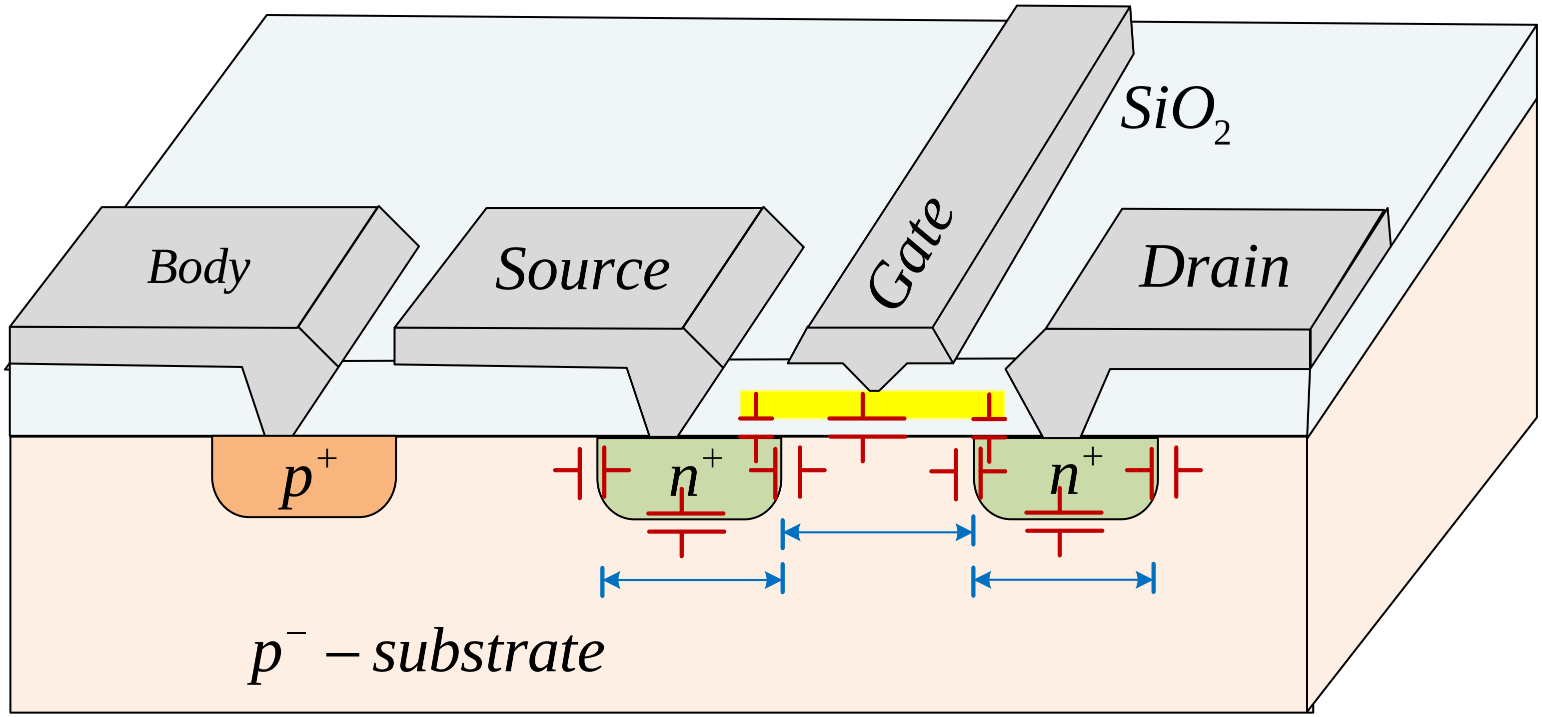
$$C_{gsol} = C_{gdol} = C_{OX} W L_{ol}$$
$$C_{gb} = C_{OX} W L$$

- Parasitic capacitors in the saturation $V_{GS} > V_{TN}$ & $V_{DS} > V_{GS} - V_{TN}$



$$C_{gse} = C_{gde} = C_{OX}$$

- Parasitic capacitors in the cut-off



- Parasitic capacitors

	C_{gsi}	C_{gse}	C_{gb}	C_{gdi}	C_{gde}	C_{sbi}	$C_{sbe} = C_{dbe}$
Cut-off	0	$C_{OX} L_{ov} W$	0	0	$C_{OX} L_{ov} W$	0	$C_{js} \Delta W + C_{jssw} (2\Delta + 2W)$
Saturation	$\frac{2}{3} C_{OX} LW$	$C_{OX} L_{ov} W$	0	$\frac{1}{3} C_{OX} LW$	$C_{OX} L_{ov} W$	$\frac{2}{3} C_{js} LW$	$C_{js} \Delta W + C_{jssw} (2\Delta + W)$
Resistive	$\frac{1}{2} C_{OX} LW$	$C_{OX} L_{ov} W$	$C_{OX} LW$	$\frac{1}{2} C_{OX} LW$	$C_{OX} L_{ov} W$	$\frac{1}{2} C_{js} LW$	$C_{js} \Delta W + C_{jssw} (2\Delta + W)$