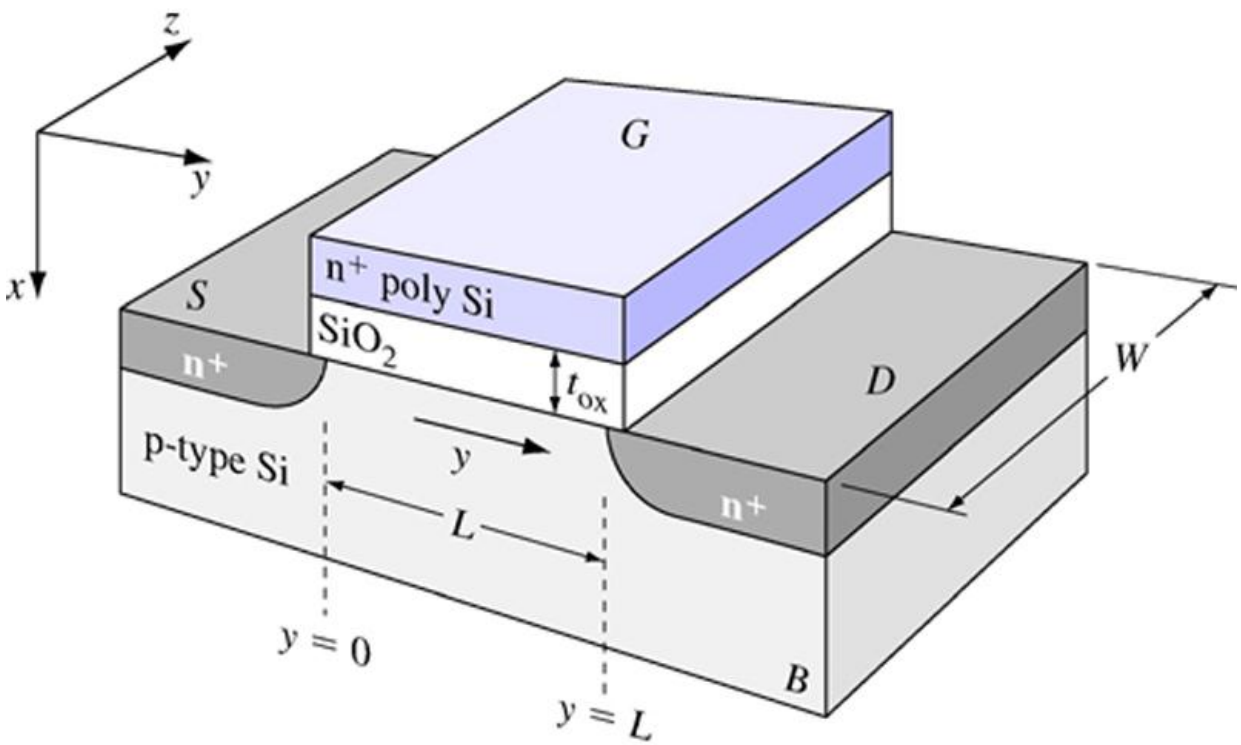
MOSFET Threshold

EECS 320

Introduction to Semiconductor Devices

MOSFET Structure

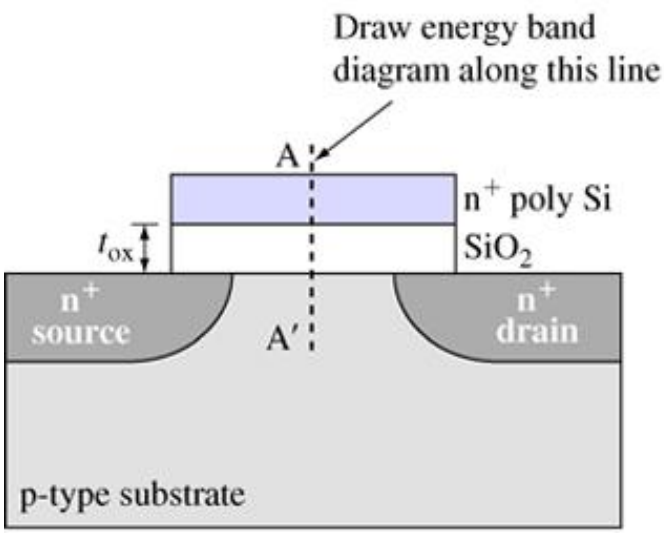
The Idea: Control current flow from source to drain using applied gate voltage

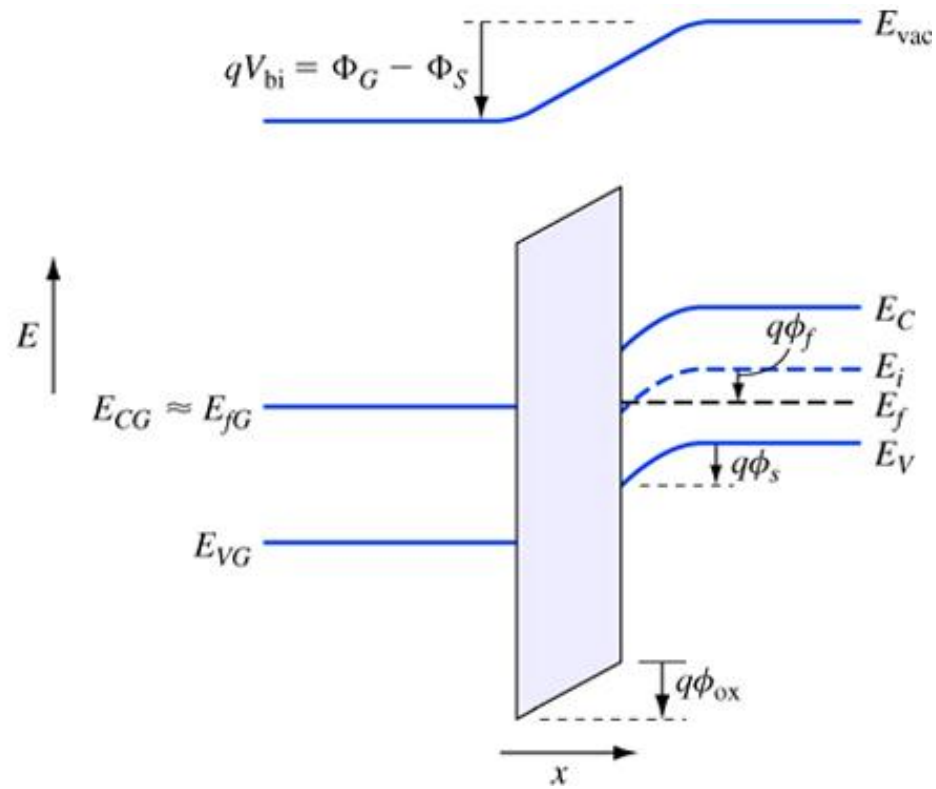


- Our MOS analysis showed that charge at Si/SiO_2 interface is strongly dependent on V_G
- The resistance from source to drain will vary with this charge in the "channel"

Band Diagram

Cross section in channel

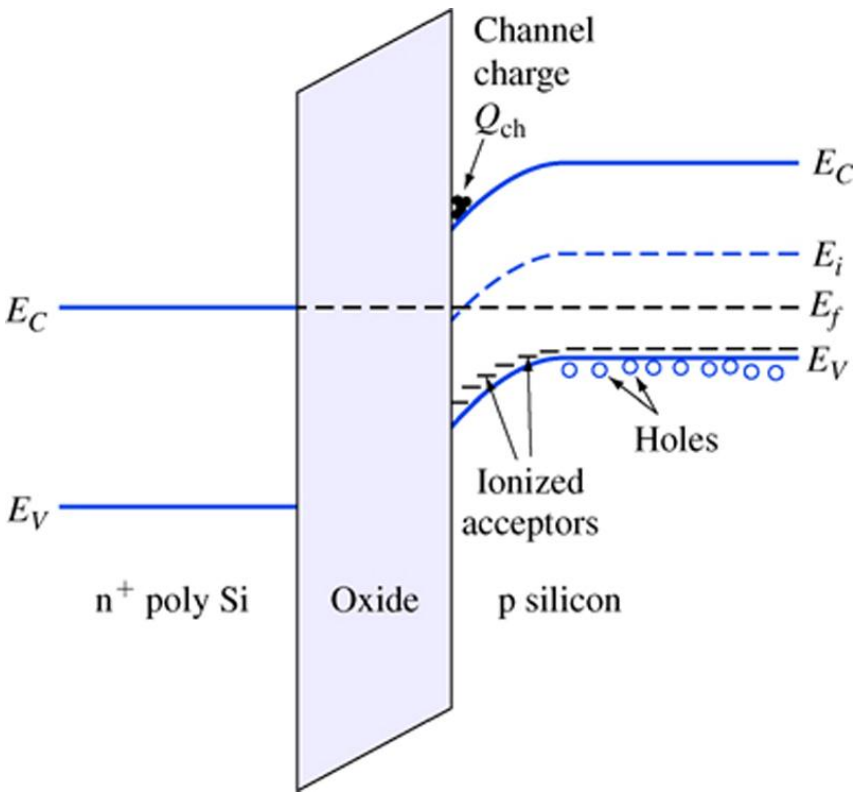




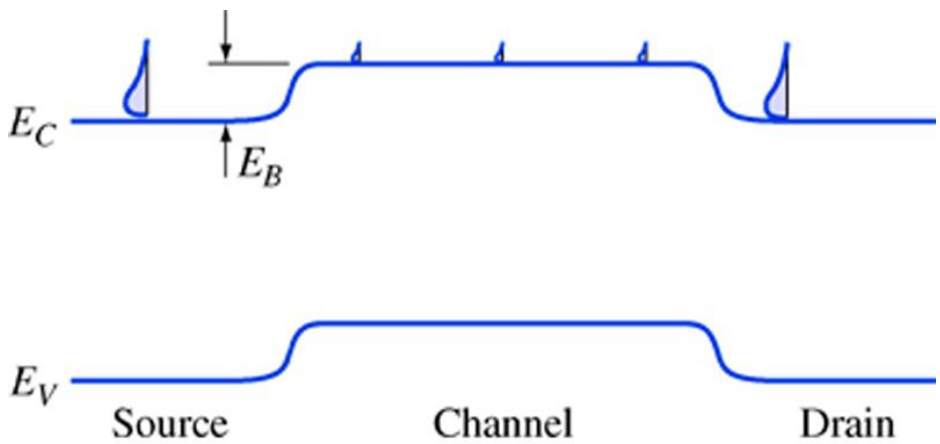
Create inversion layer in channel for current conduction

More Band Diagrams

Band diagram in inversion

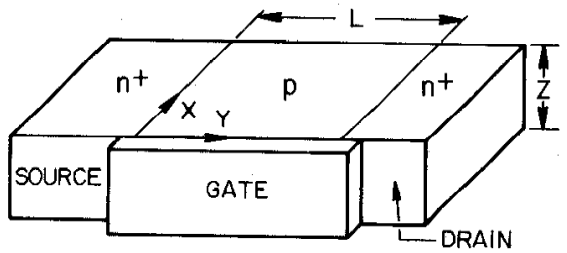


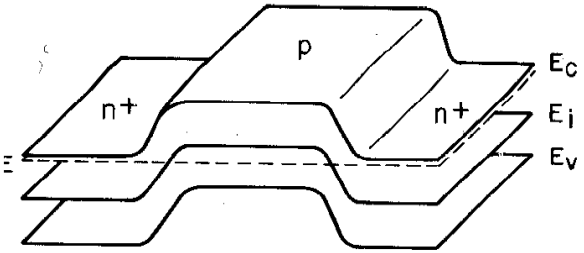
Band diagram along channel



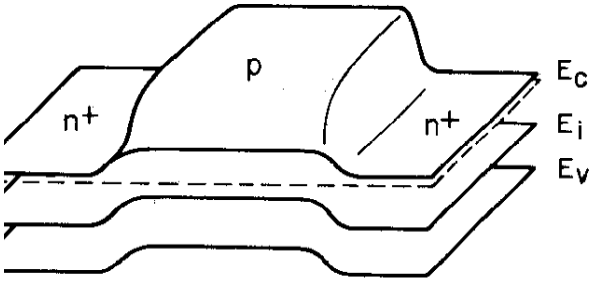
What does PMOS look like?

3D Band Diagrams

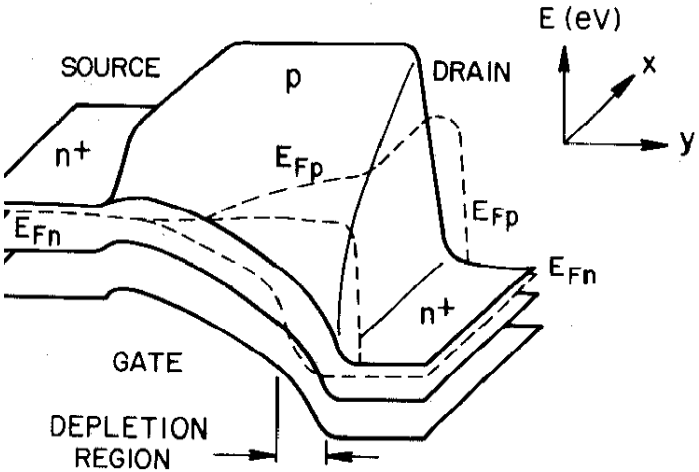




$V_G = V_D = 0$



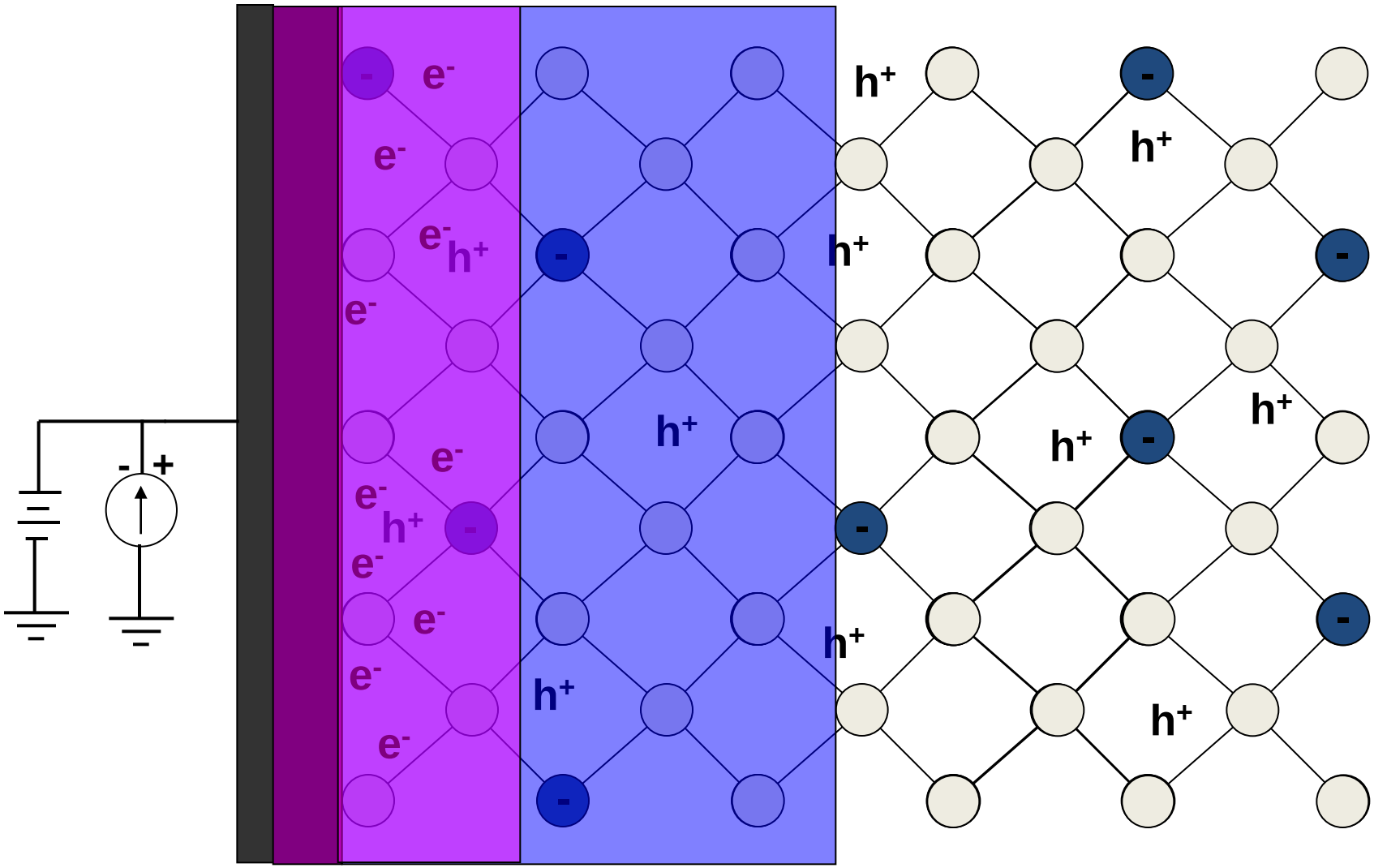
$V_G > 0$
$V_D = 0$



$V_G > V_T$
$V_D > 0$

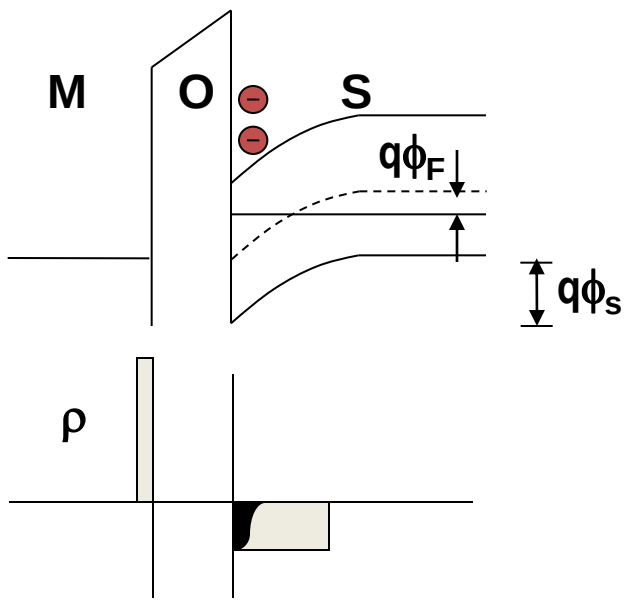
Figures From S.M. Sze
Physics of Semiconductor
Devices

Review of Bias Effects



MOSFET Threshold Voltage

Define condition where channel charge is significant



NMOS

$$V_T = \phi_{MS} + 2|\phi_F| + \frac{\sqrt{4q\varepsilon_S N_A |\phi_F|}}{C_{ox}}$$

$$\phi_F = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

PMOS

$$V_T = \phi_{MS} - 2|\phi_F| - \frac{\sqrt{4q\varepsilon_S N_D |\phi_F|}}{C_{ox}}$$

$$\phi_F = -\frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right)$$

- Define where inversion charge at SiO_2/Si equal to depletion charge
- Mathematically, $\phi_S = 2\phi_F$

Need to also account for oxide and interface charges, if present

Threshold Voltage

Inversion when $\phi_S = 2\phi_F$

NMOS
n-channel
p-type substrate

$$V_T = \phi_{MS} + 2|\phi_F| + \frac{\sqrt{4q\varepsilon_S N_A |\phi_F|}}{C_{ox}}$$

$$\phi_F = \frac{kT}{q}\ln\left(\frac{N_A}{n_i}\right)$$

PMOS
p-channel
n-type substrate

$$V_T = \phi_{MS} - 2|\phi_F| - \frac{\sqrt{4q\varepsilon_S N_D |\phi_F|}}{C_{ox}}$$

$$\phi_F = -\frac{kT}{q}\ln\left(\frac{N_D}{n_i}\right)$$

Threshold Voltage

Is V_T typically positive or negative for NMOS, PMOS?

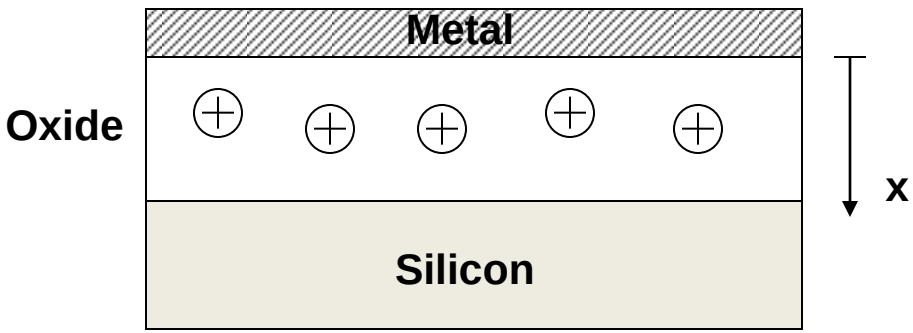
NMOS – positive V_T **PMOS – negative V_T**

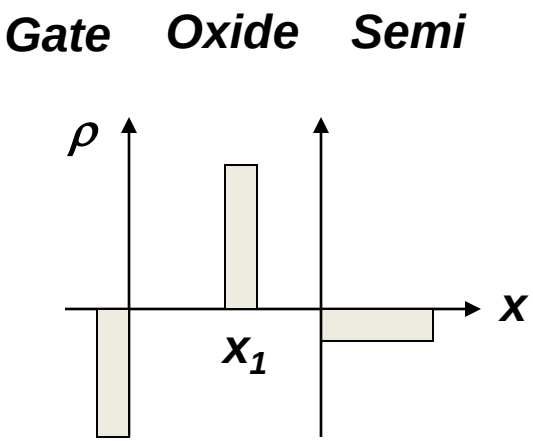
For further inversion, will you apply more positive or negative voltage beyond threshold for NMOS, PMOS?

NMOS – more positive V_G **PMOS – more negative V_G**

Oxide Charge

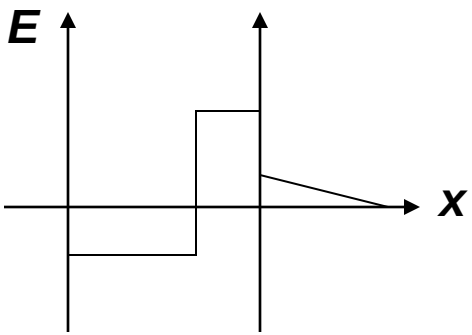
Charge in oxide changes V_T





$$Q_{ox} = \frac{\varepsilon_{ox}}{A} \oint E_{ox} dA$$

$$\Delta V_T = -\int_0^{x_1} E_{ox} dx = -\frac{Q_{ox}}{\varepsilon_{ox}} x_1 = -\frac{qN_f}{\varepsilon_{ox}} x_1$$

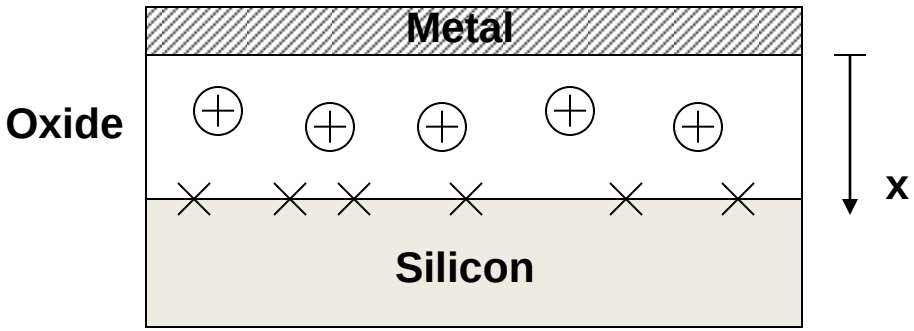


Largest effect when $x_1 = x_{ox}$

Oxide charge lowers V_{FB}

Oxide Charge

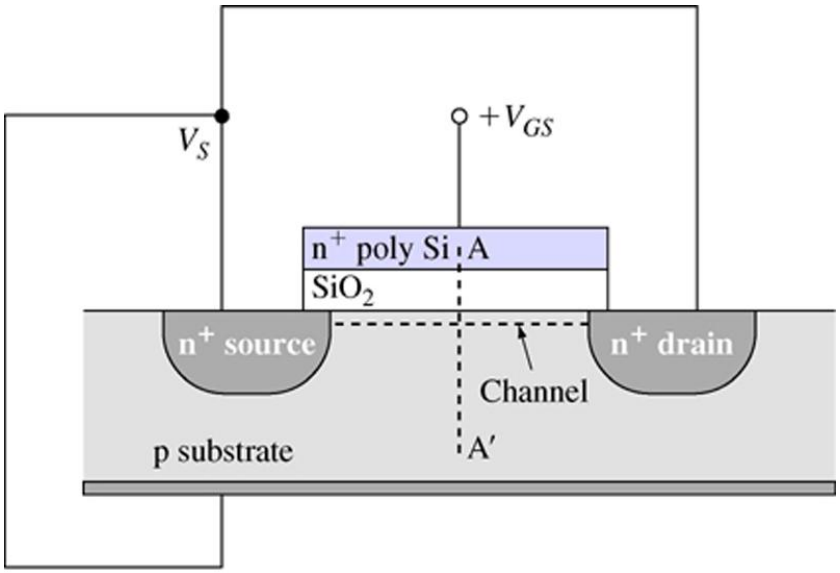
Charge in oxide changes V_T

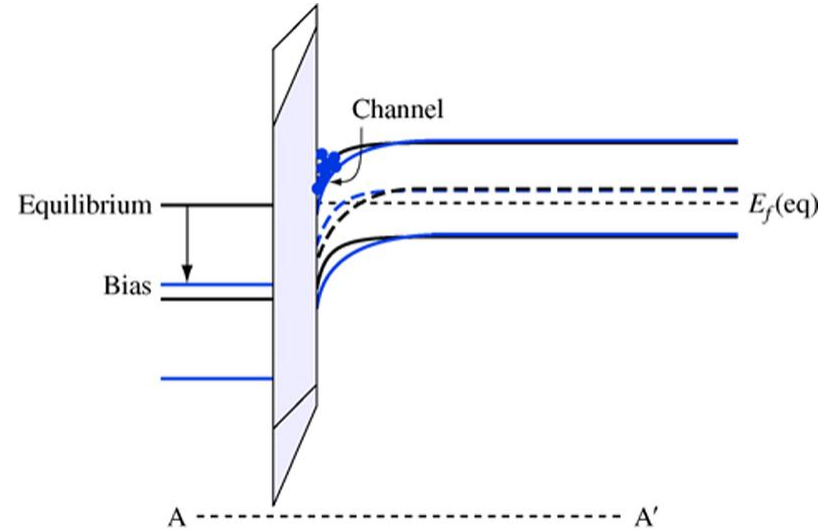


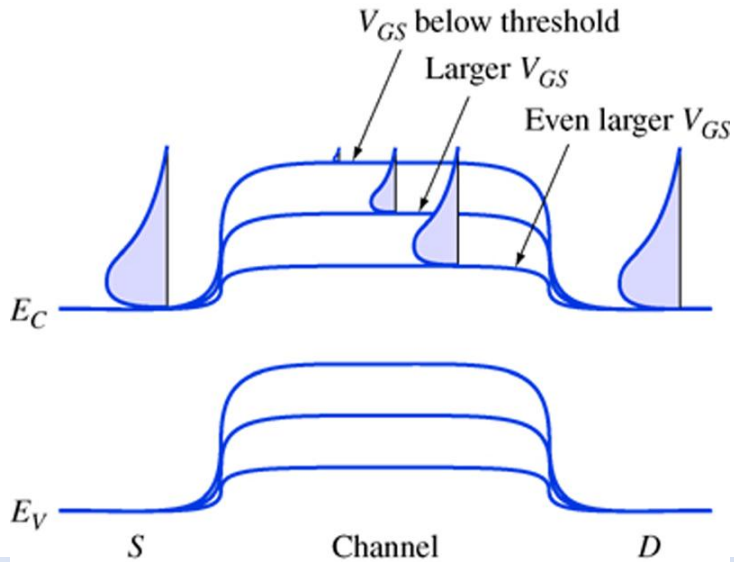
- **Fixed charge**
- **Mobile ions**
- **Interface traps**

$$\Delta V_T = -\frac{Q_f}{C_{ox}} - \frac{Q_M \gamma_M}{C_{ox}} - \frac{Q_{IT}(\phi_S)}{C_{ox}}$$

MOSFET Under Bias



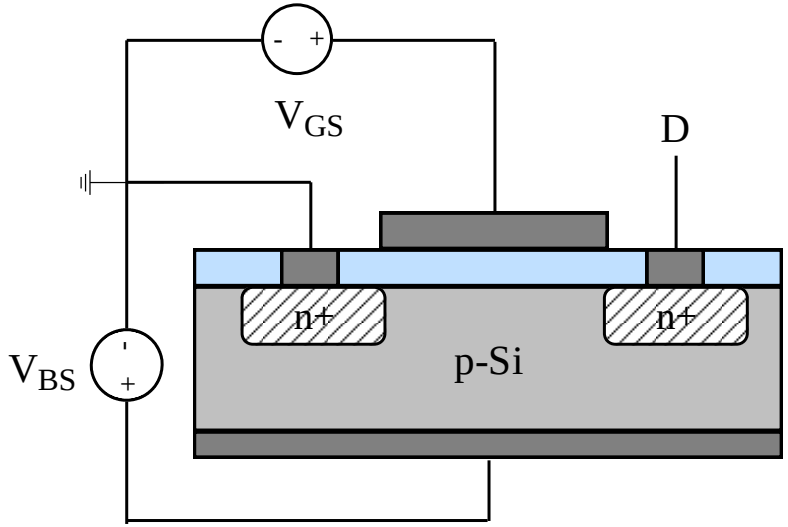




- Increasing V_{GS} increases channel charge
- Channel more conductive
- More current flows from source to drain

Back Biasing – Body Effect

Substrate bias acts as a second "gate", changes inversion point and V_T



Adjust threshold condition

$$2\phi_F \Rightarrow 2\phi_F - V_{BS}$$

V_{BS} negative for n-channel, positive for p-channel (S-B pn diode *reverse biased*)

$$\Delta V_T = \pm \frac{\sqrt{2q\varepsilon_S N_A}}{C_{ox}} \left(\sqrt{|2\phi_F - V_{BS}|} - \sqrt{2|\phi_F|} \right)$$

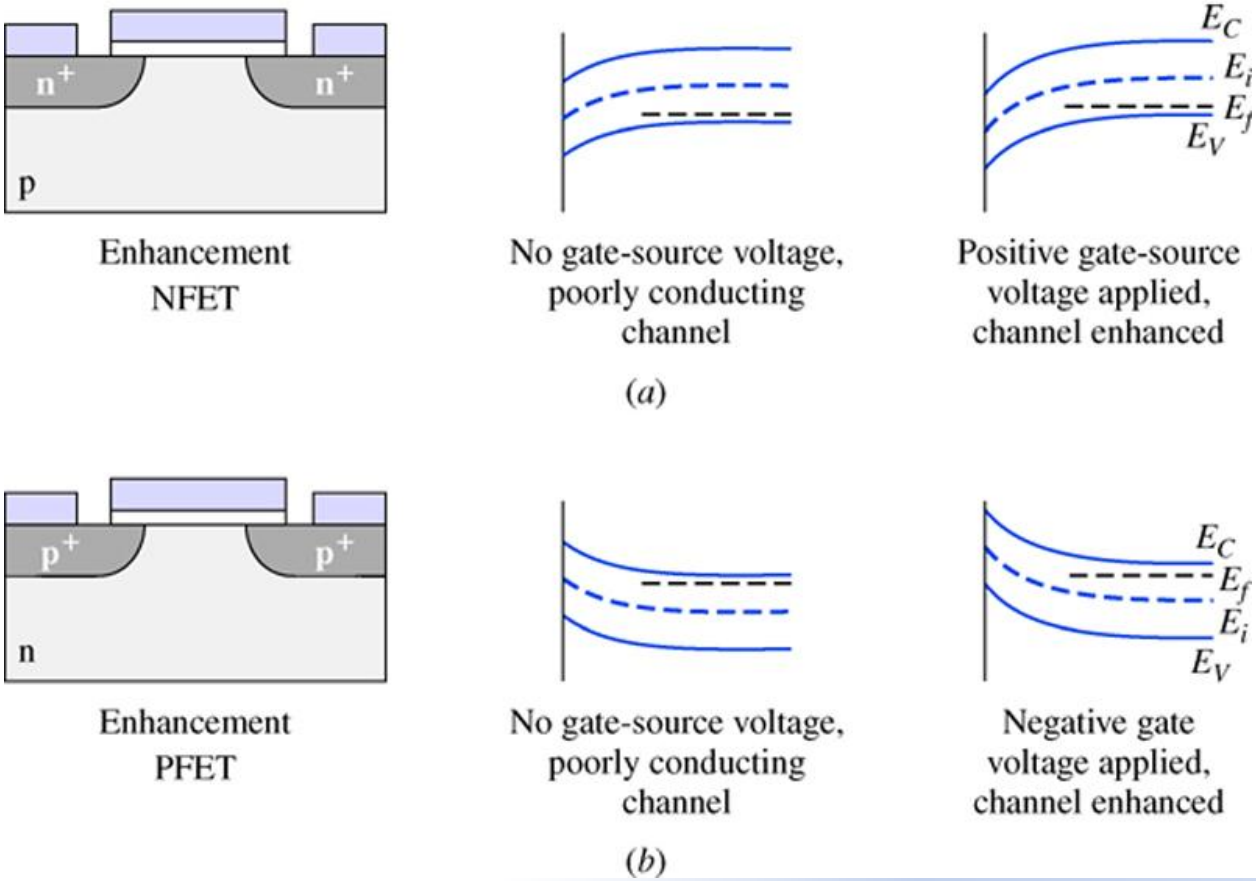
$$\Delta V_T = \gamma \left(\sqrt{|2\phi_F - V_{BS}|} - \sqrt{2|\phi_F|} \right)$$

γ = body effect parameter
+ for n-channel
- for p-channel

Band Picture for Body Effect

Enhancement Mode MOSFET

- Normally Off
- Need to apply gate voltage to turn on

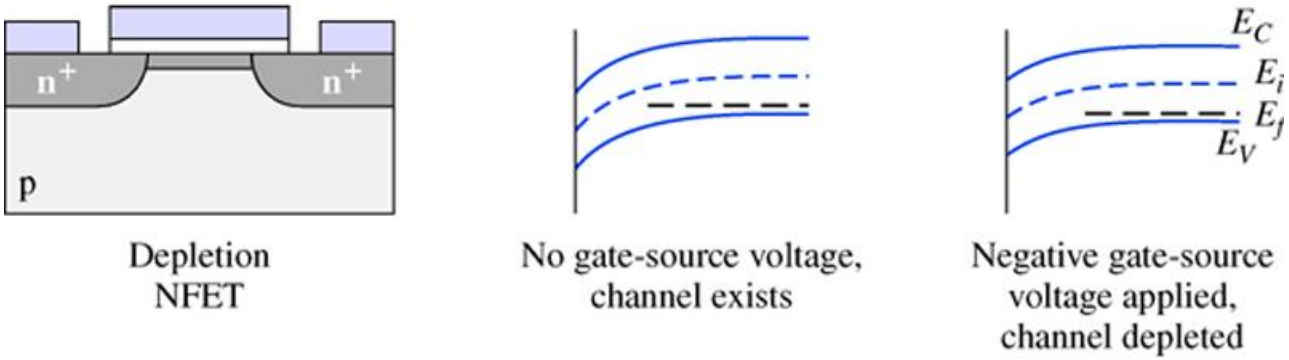


$V_T>0$

$V_T<0$

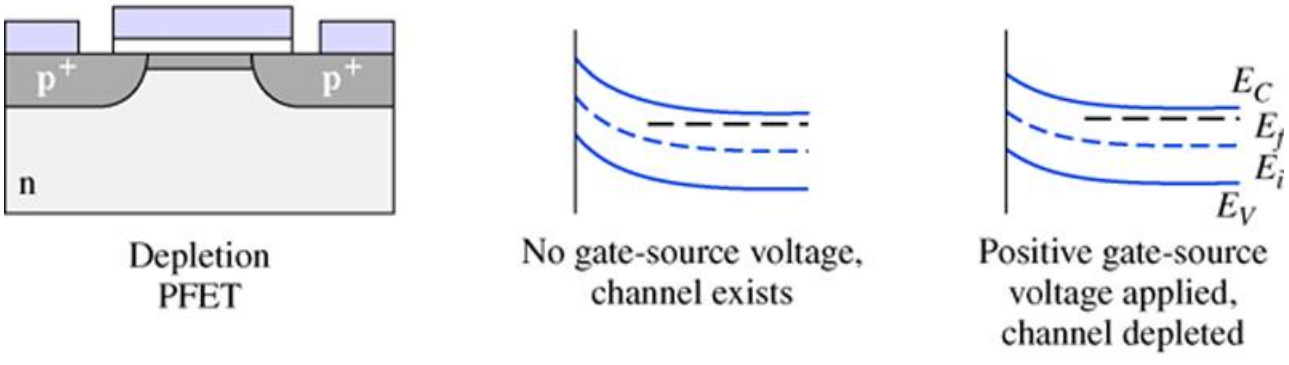
Depletion Mode MOSFET

- Normally On
- Need to apply gate voltage to turn off



$V_T<0$

(c)



$V_T>0$

(d)

Summarize V_T Effects

NMOS

$$V_T = \phi_{MS} + 2|\phi_F| + \frac{\sqrt{4q\varepsilon_S N_A |\phi_F|}}{C_{ox}}$$

PMOS

$$V_T = \phi_{MS} - 2|\phi_F| - \frac{\sqrt{4q\varepsilon_S N_D |\phi_F|}}{C_{ox}}$$

+

Oxide charge

$$\Delta V_T = -\frac{Q_f}{C_{ox}} - \frac{Q_M \gamma_M}{C_{ox}} - \frac{Q_{IT}(\phi_S)}{C_{ox}}$$

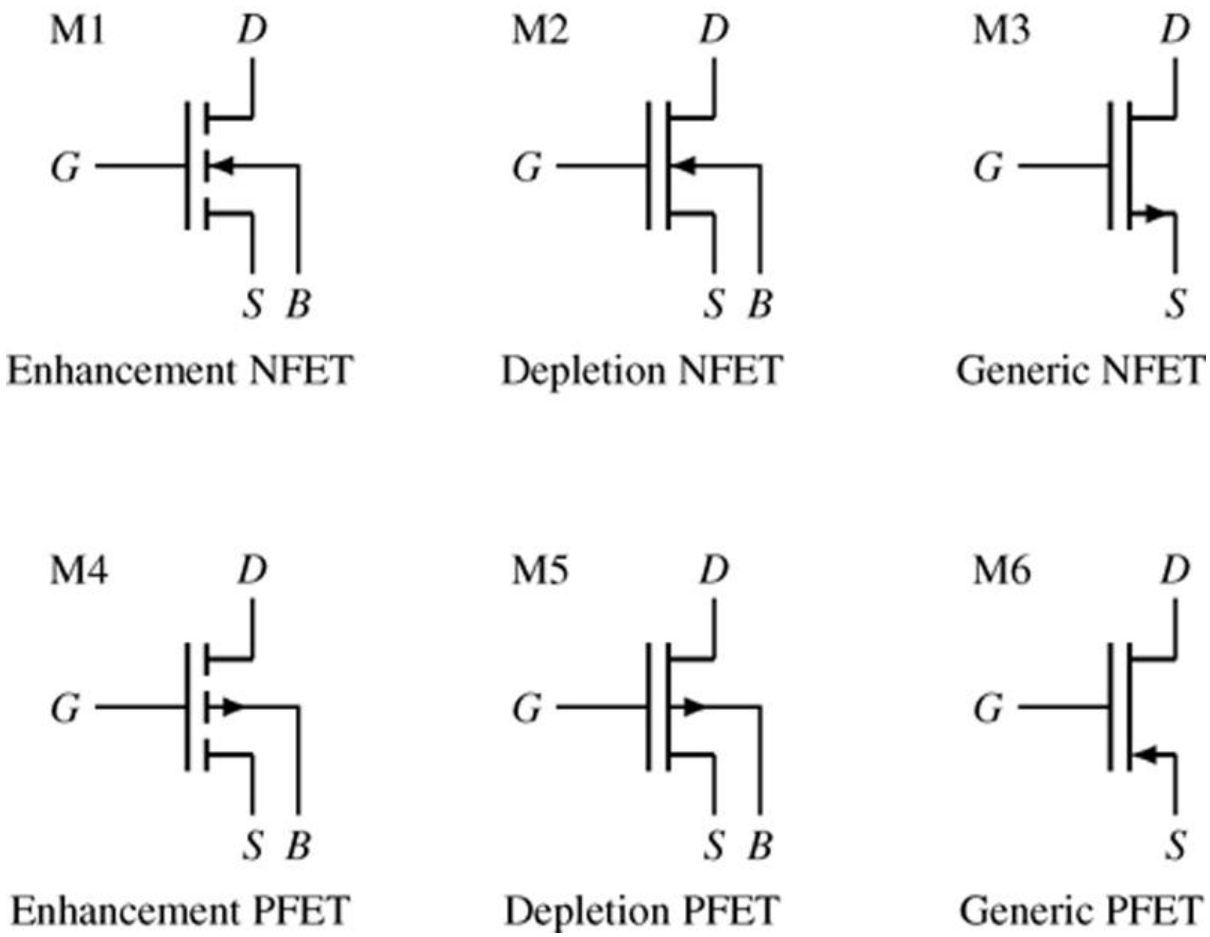
+

Body Effect

$$\Delta V_T = \pm \frac{\sqrt{2q\varepsilon_S N_A}}{C_{ox}} \left(\sqrt{|2\phi_F - V_{BS}|} - \sqrt{2|\phi_F|} \right)$$

$$\Delta V_T = \gamma \left(\sqrt{|2\phi_F - V_{BS}|} - \sqrt{2|\phi_F|} \right)$$

Circuit Symbols



There are other variations for these!