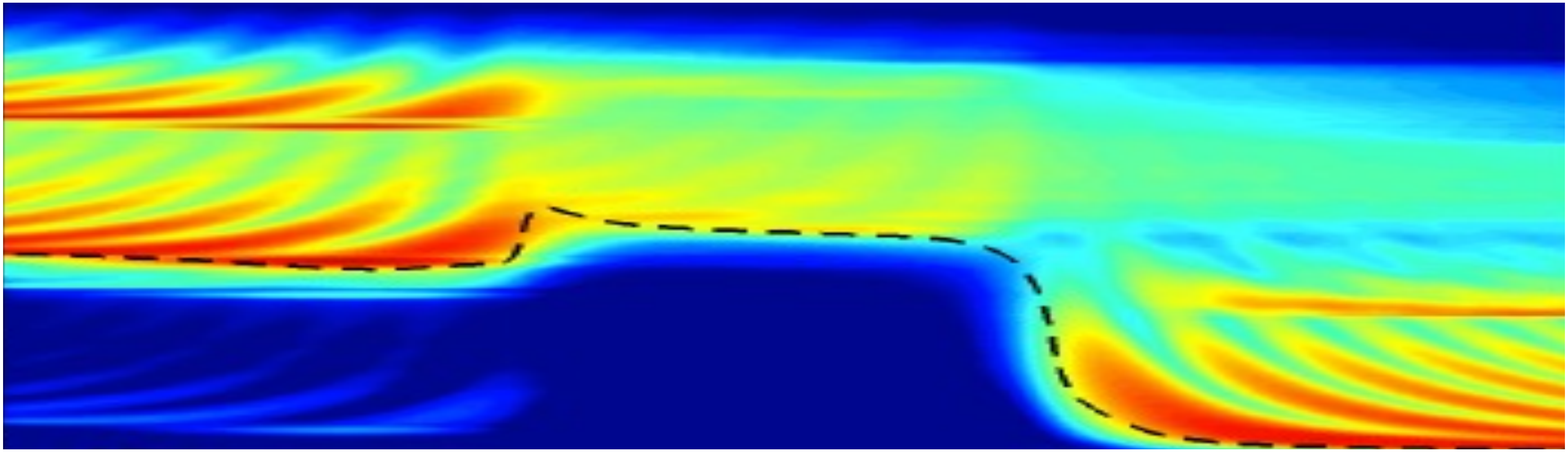

# EECS 16B
# Designing Information Devices and Systems II
# Lecture 10

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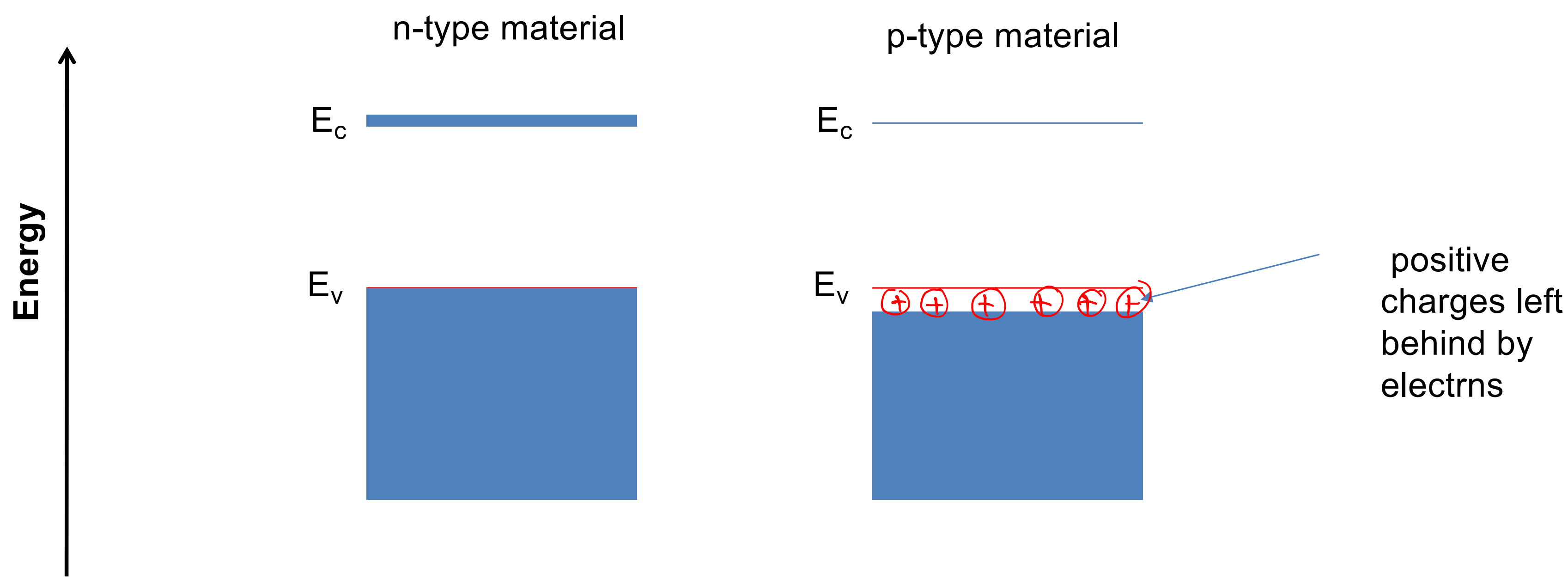
# Devices

- Outline
  - Amplifiers and Devices
  - Vector Differential Equations

- Reading-notes, slides

# Recap: N and P type Materials, Junctions and Devices




*Blue color indicates electrons

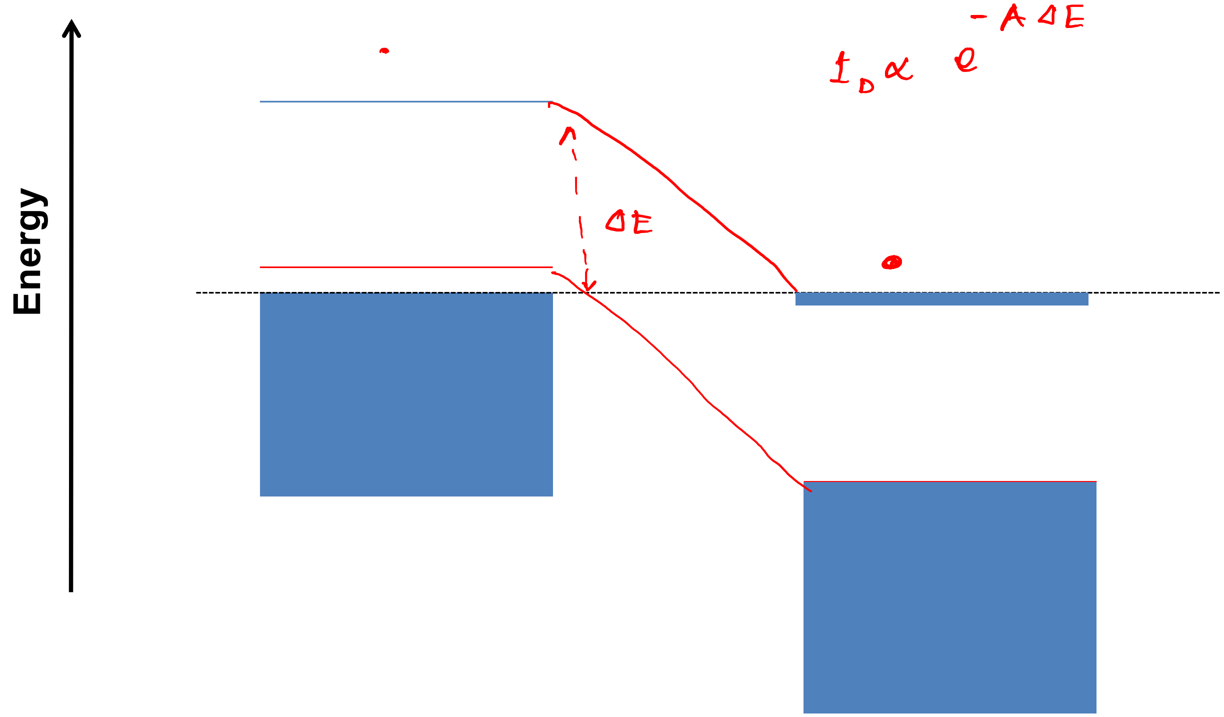
# What does a voltage do?

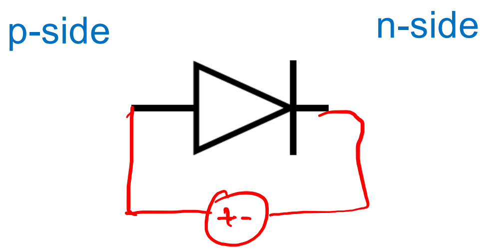
$U = qV$

$= -eV$

Qualitative Picture of a Junction Formation

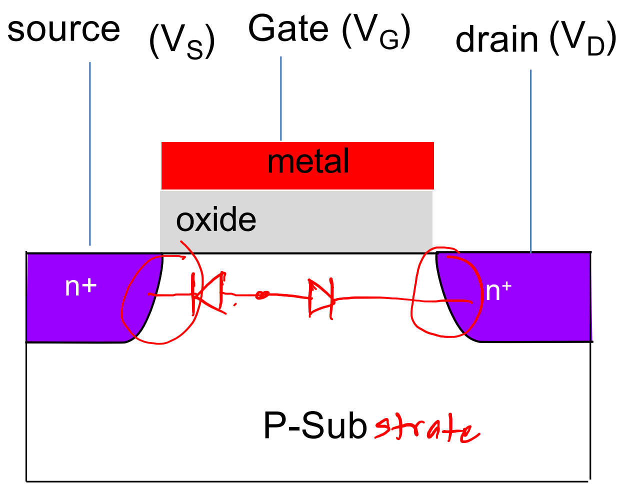
$I_D \propto e^{-A\Delta E}$



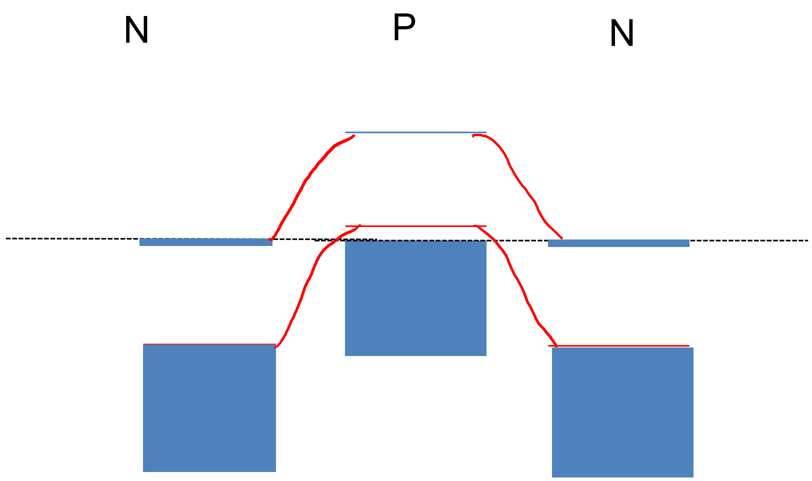



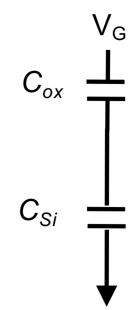

Negative terminal of a battery brings electrons and thereby **increases energy.**

# Recap: Metal-Oxide-Semiconductor Field Effect Transistor (MOSFET)



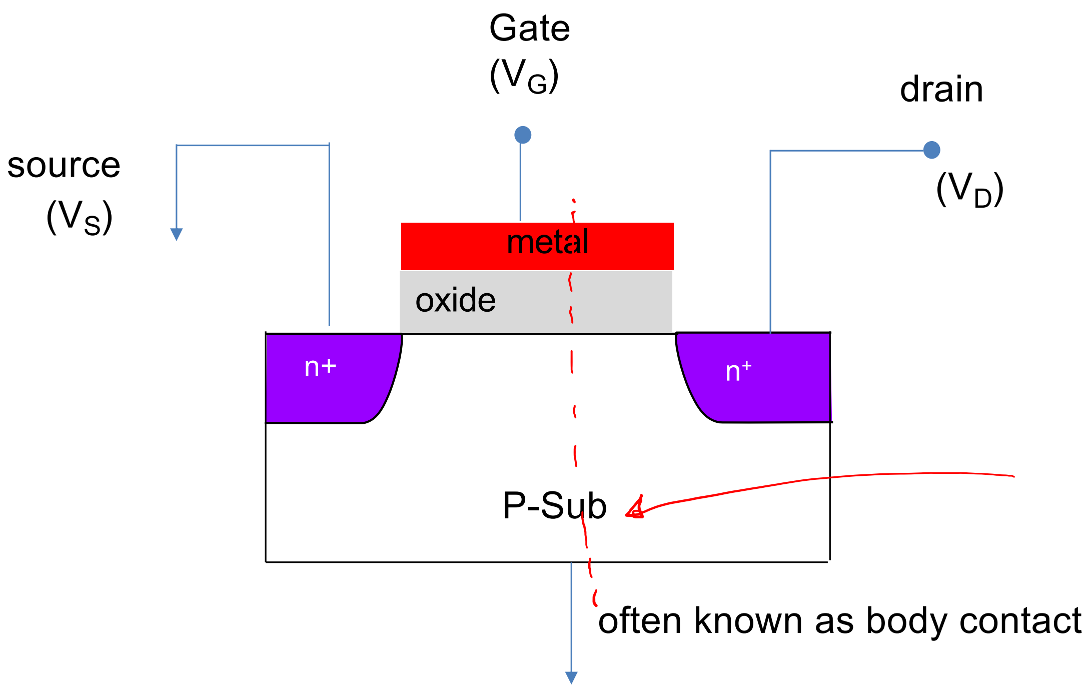

- + or – in the name of n or p type material indicates extent of doping. N+ means doped **heavily** to n type.
- In common MOSFET source and drain voltages are interchangeable

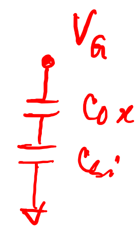


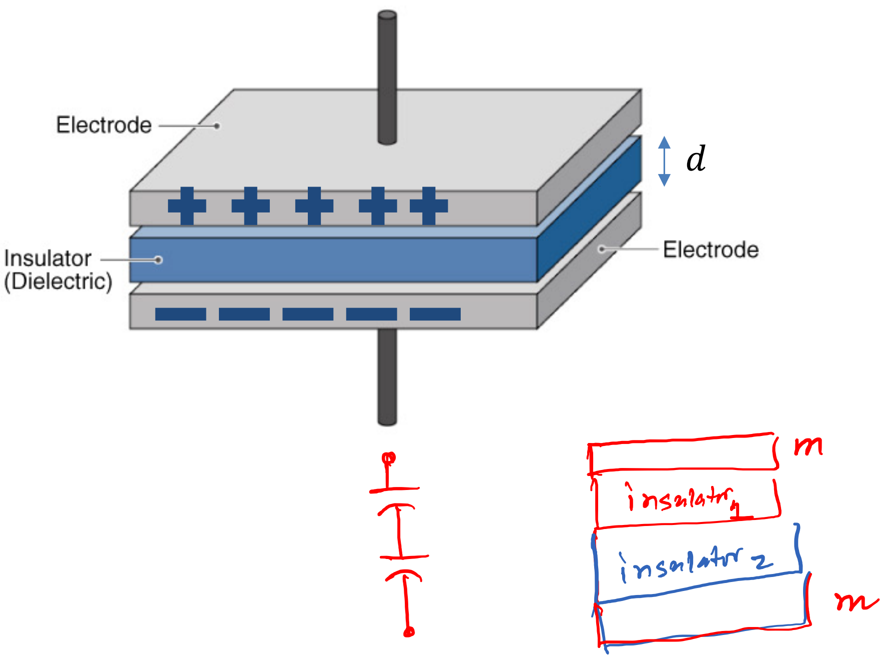

P-type semiconductor in the middle with little to no electrons on the conduction band acts like an insulator

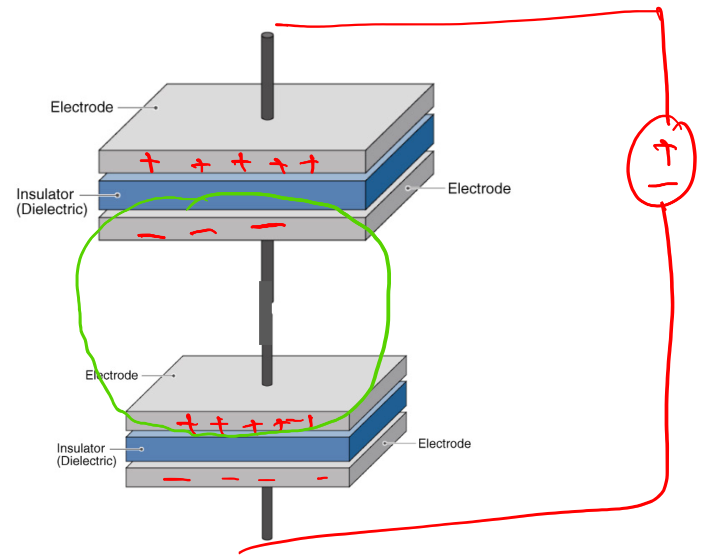
# MOSFET connections



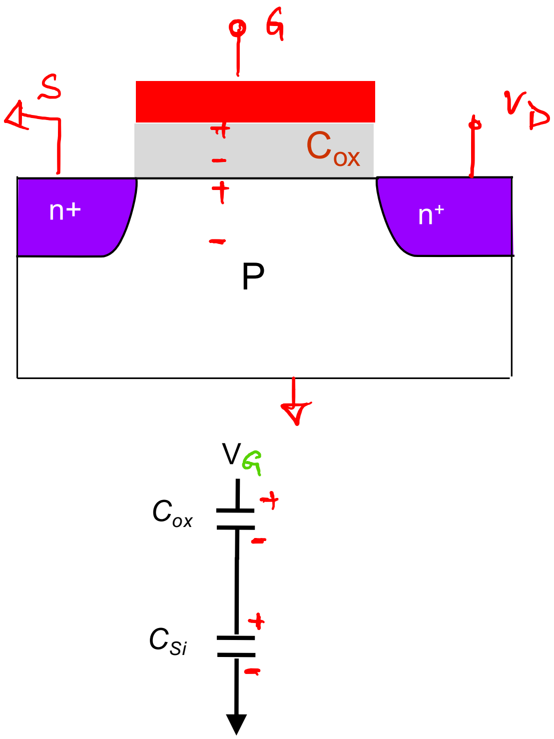



# Recap: Capacitors (Review)

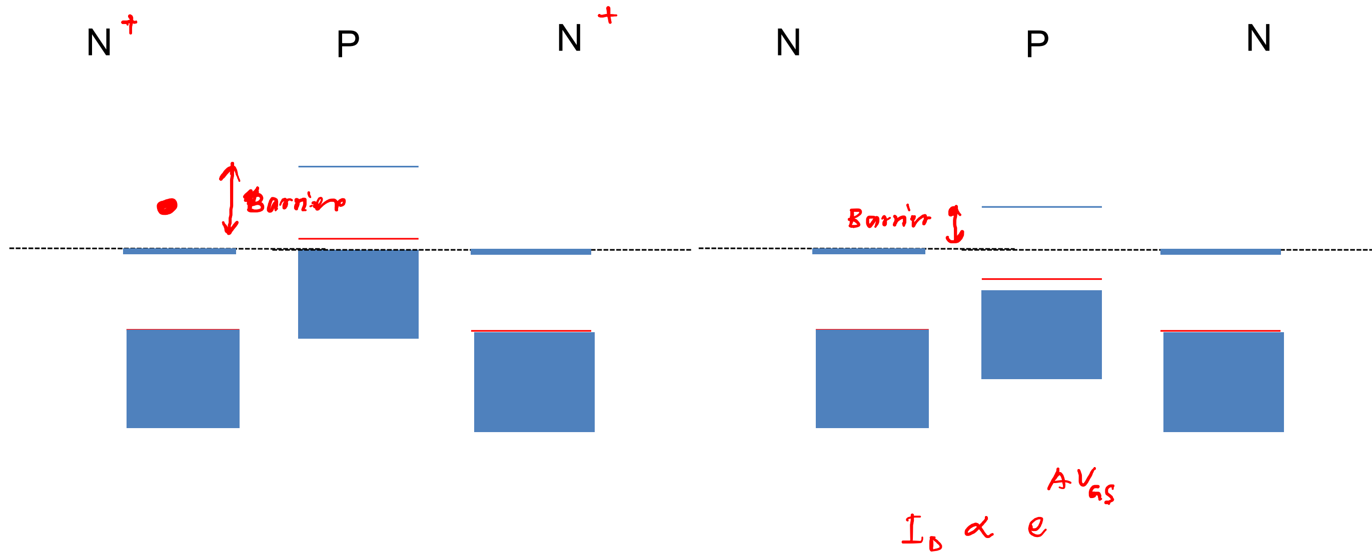


# MOSFET

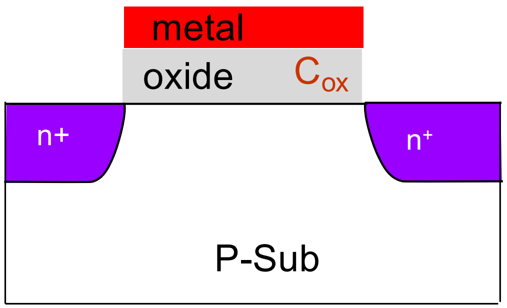


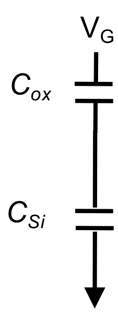
G
S
$V_D$
$C_{ox}$
n+
n+
P
$V_G$
$C_{ox}$
$C_{Si}$

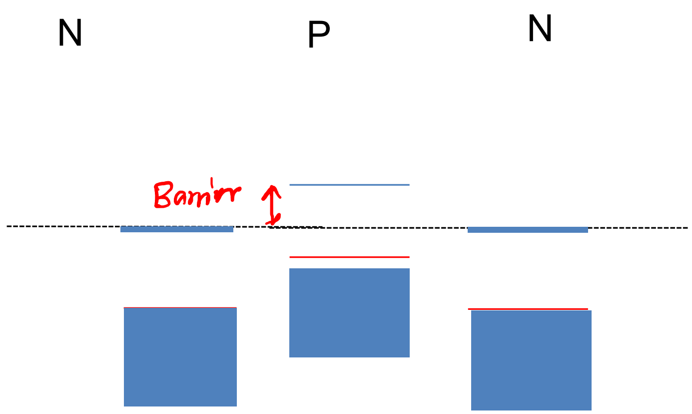



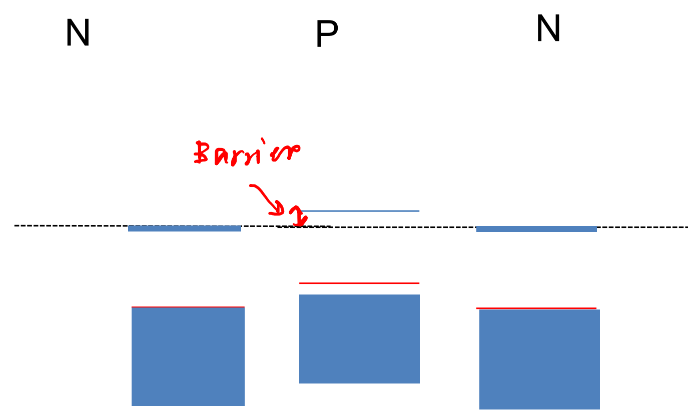
N+
P
N+
N
P
N
Barrier
Barrier
$I_D \propto e^{A V_{GS}}$

# MOSFET



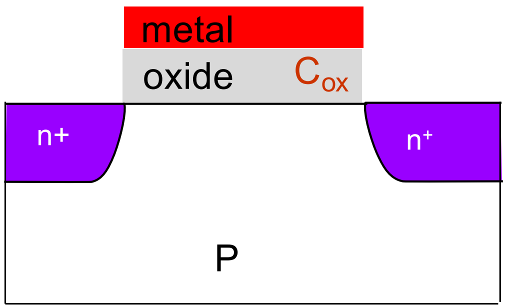



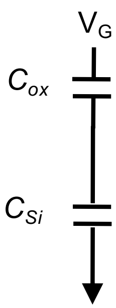




At large gate voltages, one reaches close to maximum charge density achievable in Si. So rate of change in increase in electron density with gate voltage slows down

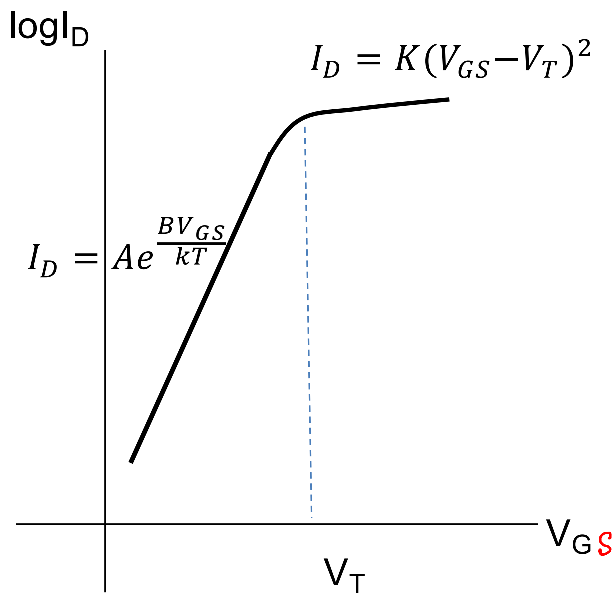
# MOSFETs

Assuming a sufficient $V_{DS}$ is always present



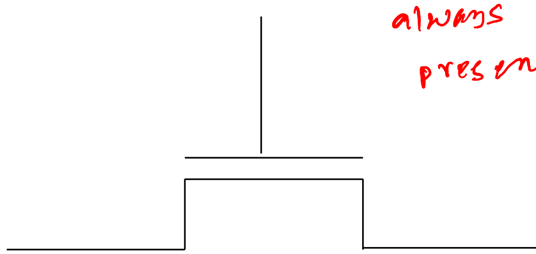



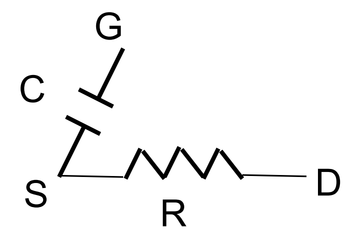

EE105, 130




$V_T \equiv$ Threshold voltage

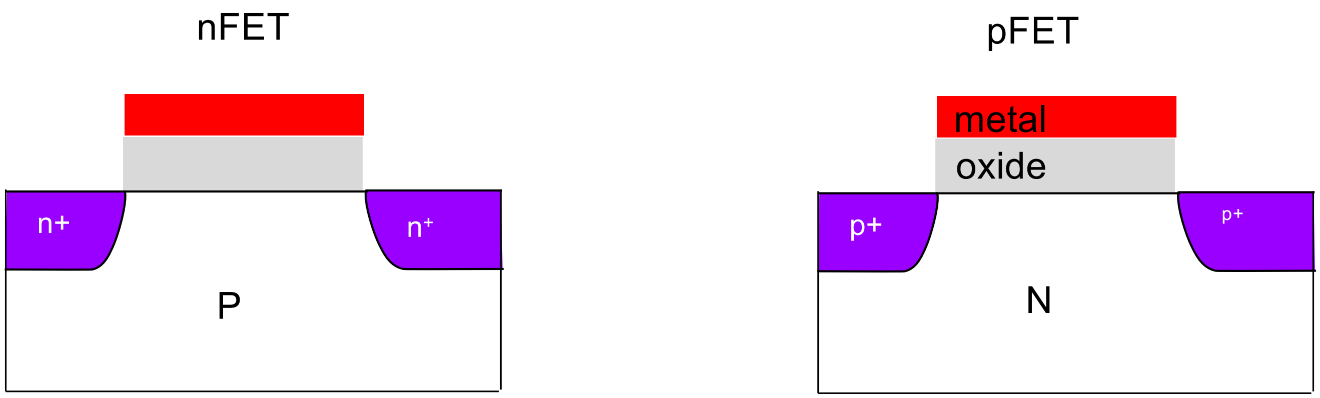
Assuming large $V_{DS}$ is present



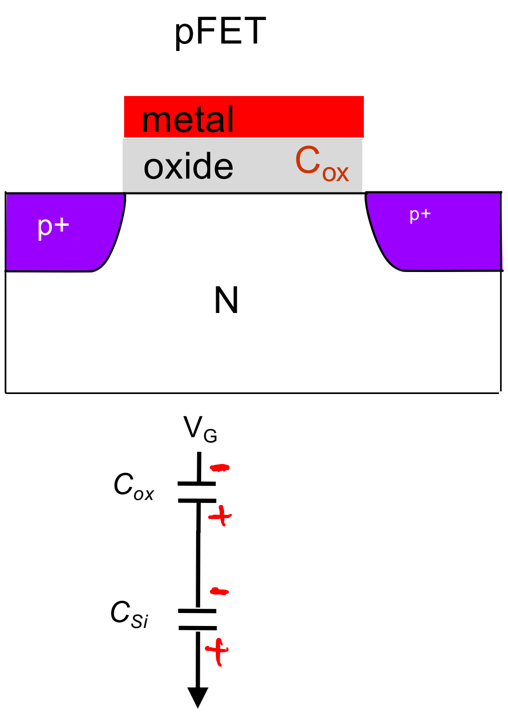


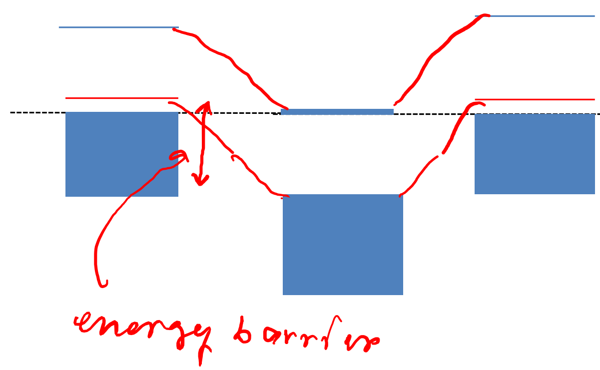

- C is the series combination of Cox and Csi
- $R = [I_{DS}/V_{DS}]^{-1}$

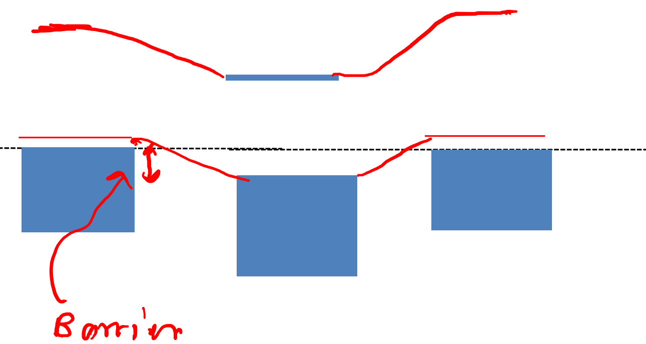
# nFET vs pFET



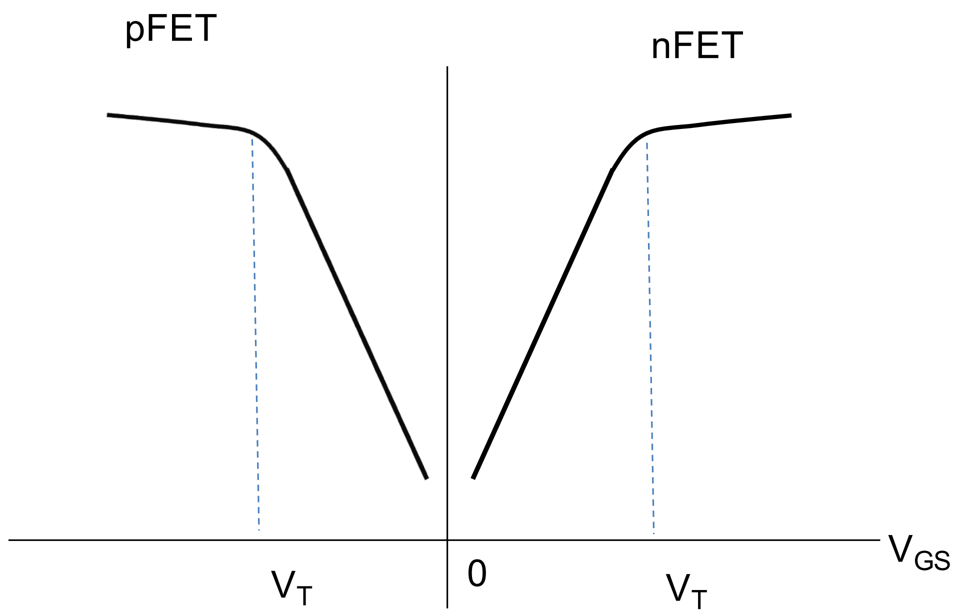
# nFET vs pFET

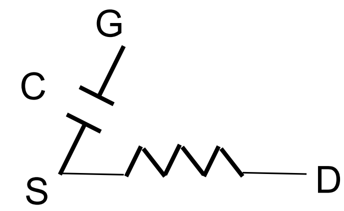


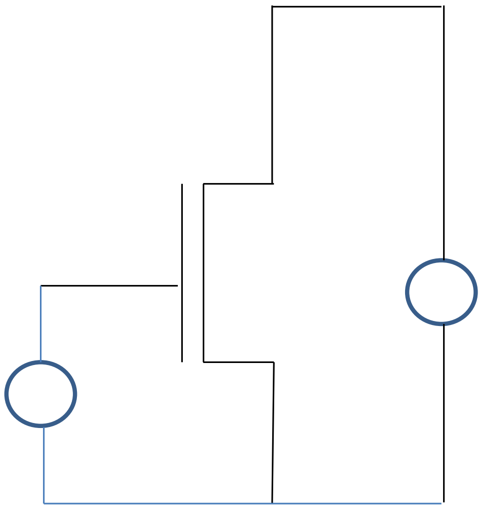
# nFET vs pFET




- nFET, $V_{GS}$ and $V_T$ are positive
- pFET, $V_{GS}$ and $V_T$ are negative

# FET as an analog amplifier



When $V_{GS}<V_T$

$$I_D = Ae^{\frac{BV_{GS}}{kT}}$$

Small change in $V_{GS}$ changes $I_D$ exponentially

When $V_{GS}$>VT

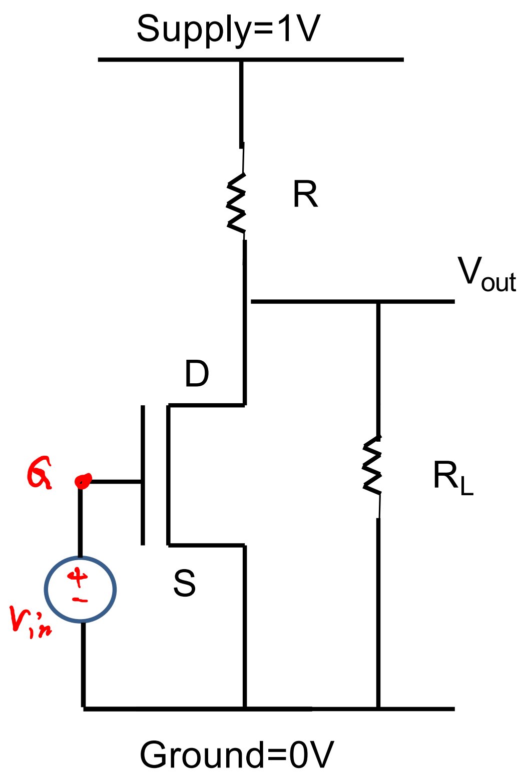
$$I_D = K(V_{GS}-V_T)^2$$

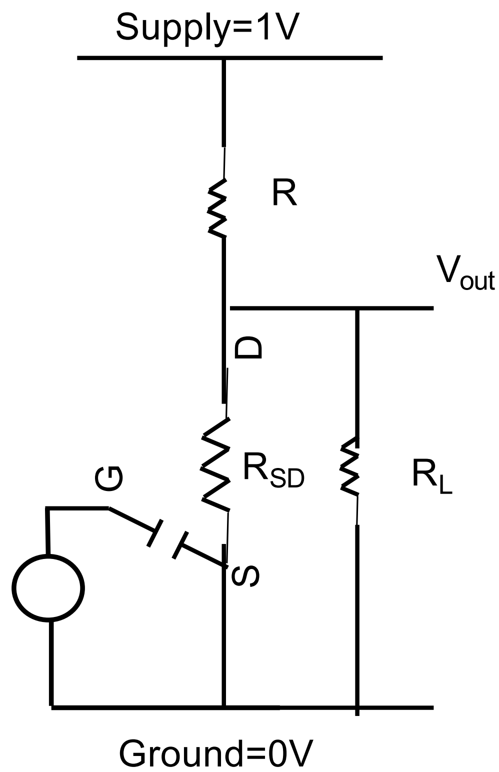
Small change in $V_{GS}$ changes $I_D$ quadratically

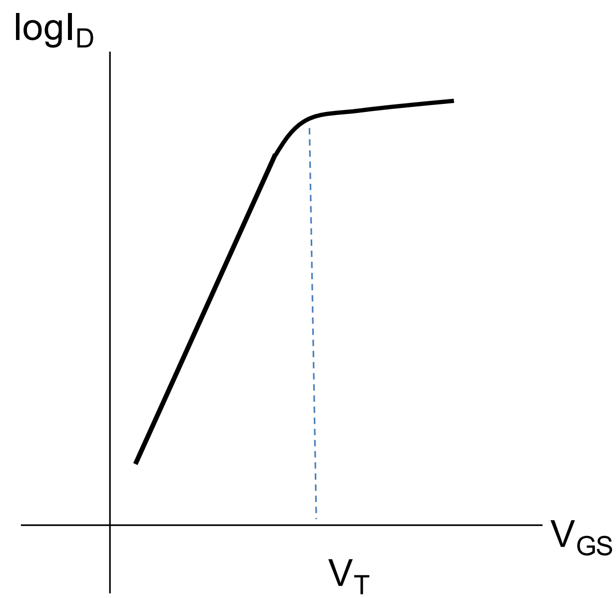
Overall, Large changes in the Drain current can be achieved by changing Gate Voltage

The parameter that is used to quantify the amplification is called **Transconductance** $g_m = \frac{dI_D}{dV_{GS}}$

# FET in digital logic



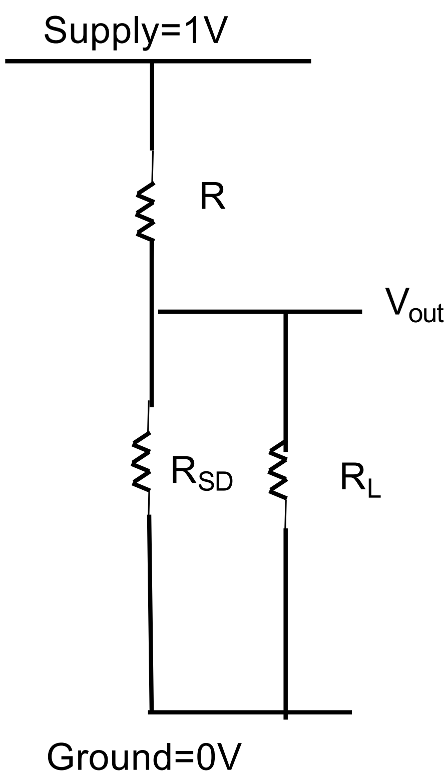



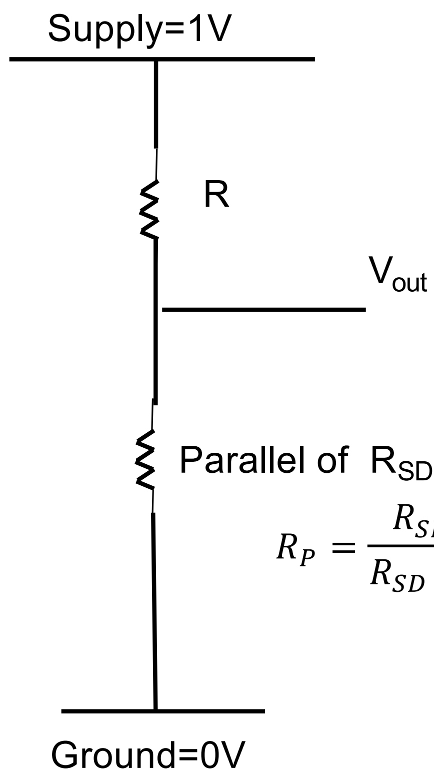




When $V_{GS}$ is High, $R_{SD}$ is low

When $V_{GS}$ is Low, $R_{SD}$ is High

# FET in digital logic




Parallel of $R_{SD}$ and $R_L$

$$R_P = \frac{R_{SD}R_L}{R_{SD} + R_L}$$

$$V_{out} = \frac{R_P}{R + R_P} V_{supply}$$

When $R_{SD} \ll R_L$ $i.e., V_{GS}$ $is$ $high$

$$R_P = \frac{R_{SD}R_L}{R_{SD} + R_L} \approx \frac{R_{SD}}{R_L} \approx 0$$

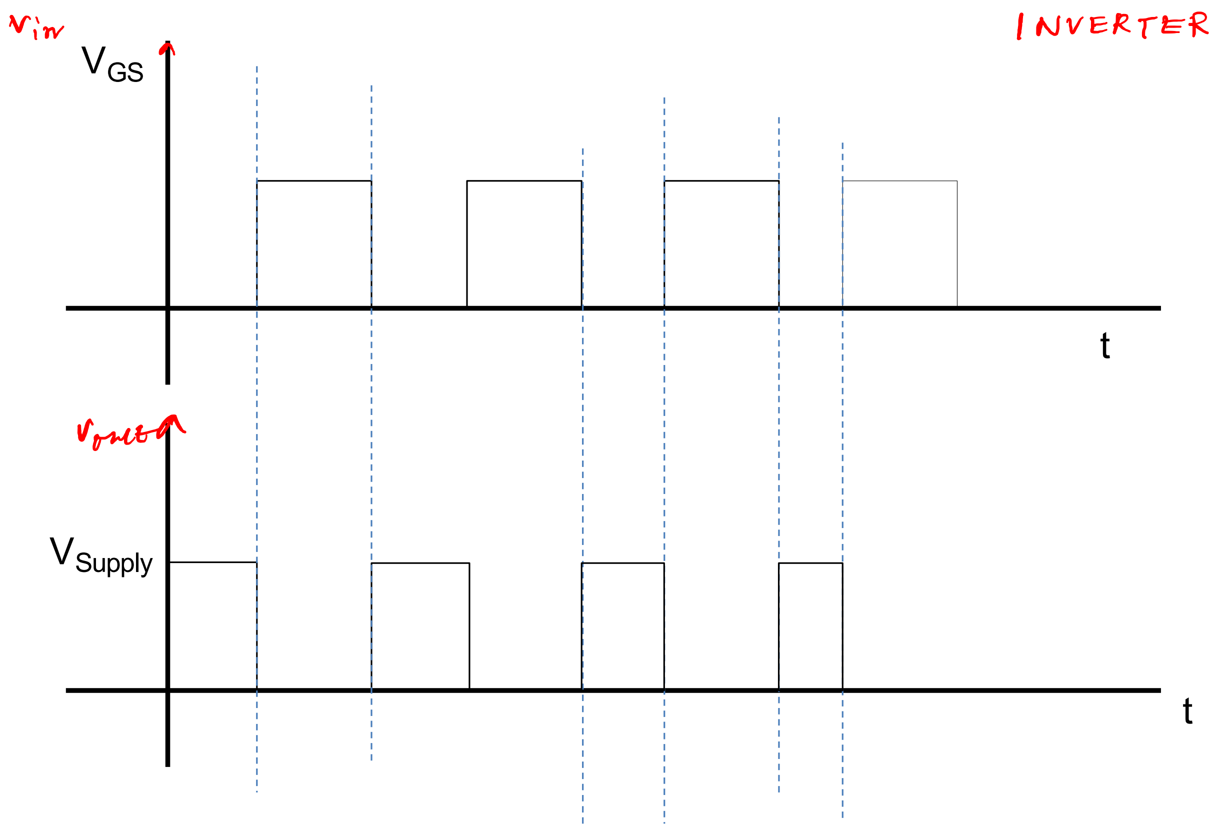
$$V_{out} \approx 0$$

When $R_{SD} \gg R_L$; i.e. when $V_{GS}$ $is$ $low$

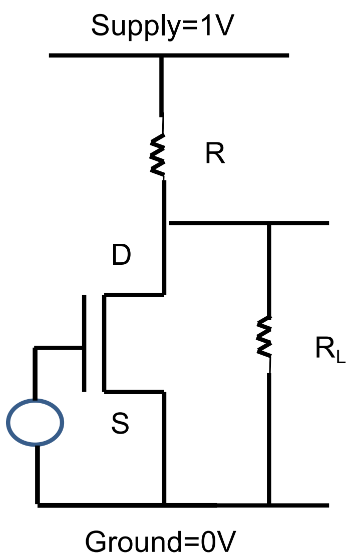
$$R_P = \frac{R_{SD}R_L}{R_{SD} + R_L} \approx R_L$$

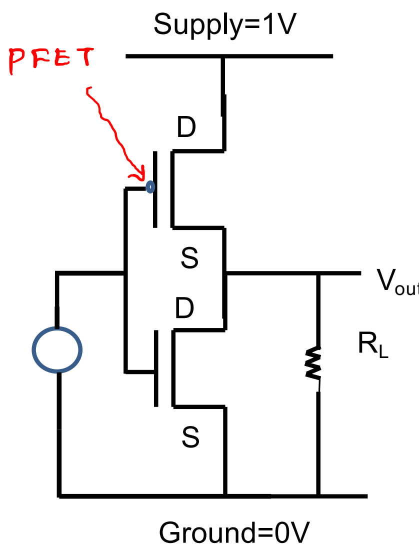
$$V_{out} \approx \frac{R_L}{R \ \ + R_L} V_{supply} \approx V_{supply} \text{ if } R_L \gg \text{R}$$

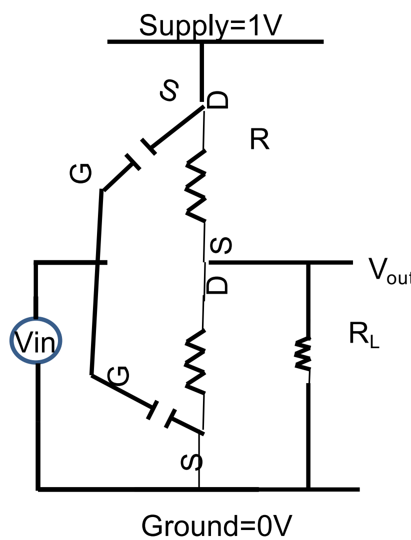
# FET in digital logic

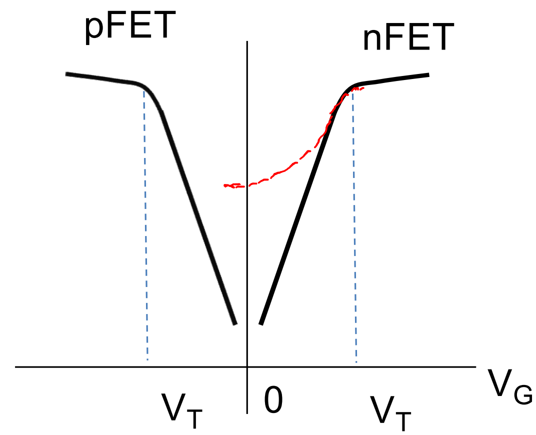


# CMOS (complimentary mos)




**Vin=1V**

$V_{GS}$ for nFET is HIGH→ $R_{SD}$ is LOW

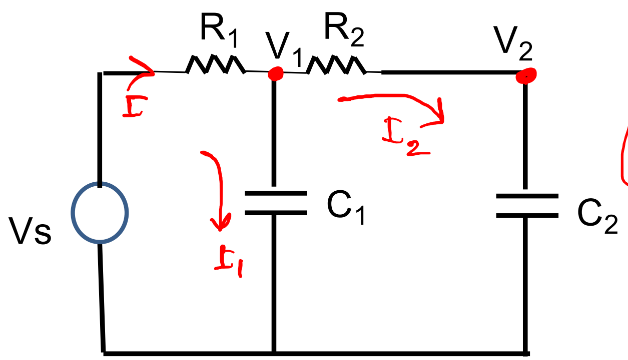
$V_{GS}$ for pFET is LOW→ $R_{SD}$ is high

**Vin=0 V**

$V_{GS}$ for nFET is LOW→ $R_{SD}$ is HIGH

$V_{GS}$ for pFET is HIGH **NEGATIVE**→ $R_{SD}$ is LOW

# Vector Differential Equations




$$V_1 = I_2 R_2 + V_2 = R_2 C_2 \frac{dV_2}{dt} + V_2$$

$$\frac{dV_2}{dt} = \frac{1}{R_2 C_2} V_1 - \frac{1}{R_2 C_2} V_2$$

Substitute

$$V_s - V_1 = I R_1 \qquad ; I = I_1 + I_2 = C_1 \frac{dV_1}{dt} + C_2 \frac{dV_2}{dt}$$

$$V_s - V_1 = (C_1 \frac{dV_1}{dt} + C_2 \frac{dV_2}{dt}) R_1$$

$$R_2 (V_s - V_1) = (R_2 C_1 \frac{dV_1}{dt} + R_2 C_2 \frac{dV_2}{dt}) R_1$$

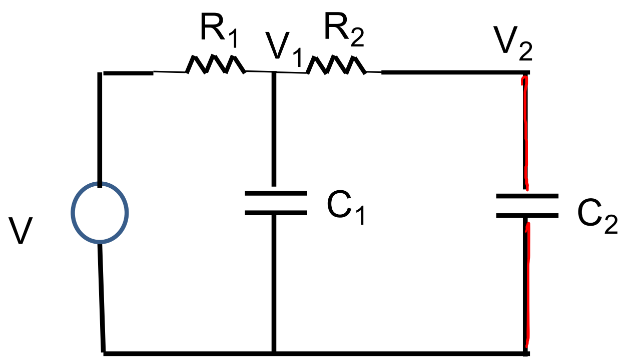
$$\frac{dV_1}{dt} = -(\frac{1}{R_2 C_1} + \frac{1}{R_1 C_1}) V_1 + \frac{1}{R_2 C_1} V_2 + \frac{1}{R_1 C_1} V_s$$

$$\frac{dV_2}{dt} = \frac{1}{R_2 C_2} V_1 - \frac{1}{R_2 C_2} V_2$$

$$\frac{dV_1}{dt} = -\frac{1 + \frac{R_2}{R_1}}{R_2 C_1} V_1 + \frac{1}{R_2 C_1} V_2 + \frac{1}{R_1 C_1} V_s$$

$$\frac{dV_1}{dt} = -(\frac{1}{R_2 C_1} + \frac{1}{R_1 C_1}) V_1 + \frac{1}{R_2 C_1} V_2 + \frac{1}{R_1 C_1} V_s$$

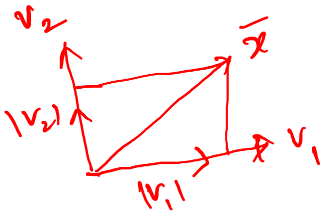
# Vector Differential Equations




$$\frac{dV_1}{dt} = -\left(\frac{1}{R_2C_1} + \frac{1}{R_1C_1}\right)V_1 + \frac{1}{R_2C_1}V_2 + \frac{1}{R_1C_1}V_s$$

$$\frac{dV_2}{dt} = \frac{1}{R_2C_2}V_1 - \frac{1}{R_2C_2}V_2$$

$$\frac{d}{dt}\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \overbrace{\begin{bmatrix} -\left(\frac{1}{R_2C_1} + \frac{1}{R_1C_1}\right) & \frac{1}{R_2C_1} \\ \frac{1}{R_2C_2} & -\frac{1}{R_2C_2} \end{bmatrix}}^{A} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{R_1C_1}V_s \\ 0 \end{bmatrix}$$




$\Downarrow$

$$\frac{d}{dt}\bar{x} = A\bar{x} + \bar{b}$$

Vector differential equation

$$\bar{x} = \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}$$

$$\bar{b} = \begin{bmatrix} \frac{1}{R_1C_1}V_s \\ 0 \end{bmatrix}$$

$$\frac{dy}{dt} = ay + b$$

$$\frac{d}{dt}\bar{x} = A\bar{x} + \bar{b}$$

$$\bar{b} = B\bar{u}$$

$\Downarrow$

Matrix

$$\frac{d}{dt}\bar{x} = A\bar{x} + B\bar{u}$$

$$\begin{bmatrix} x & x & x \\ x & x & x \\ x & x & x \end{bmatrix} \xRightarrow{\text{Diagonalization}} \begin{bmatrix} x & & \\ & x & \\ & & x \end{bmatrix}$$