Wearable and Flexible Electronics

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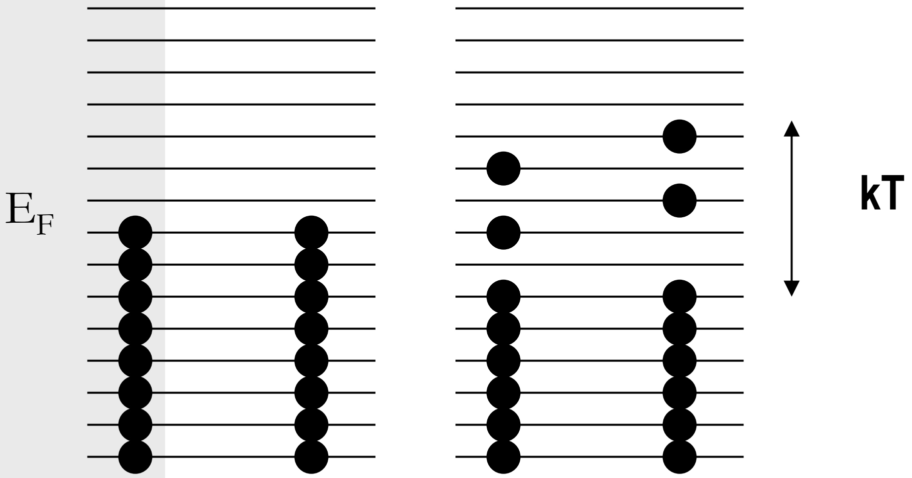
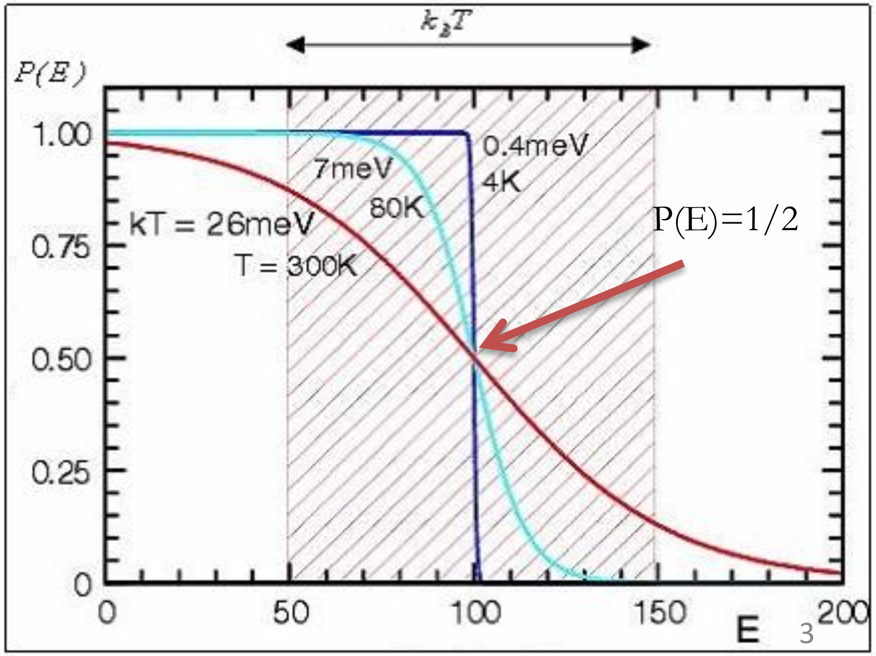
- **Band Diagram and Fermi Energy concept**
- **Doping in Inorganic Semiconductors**
- **MOS and MOSFET**

Fermi Level

- At a certain T it is possible to thermically excite electrons (allowing them to jump on higher levels)
- T>0 very different with respect to T=0 in a small intervall of energies around $K_B T$
- Only those electrones who has an energy that differs from the Fermi Energy of around $K_B T$ are interested in those transitions

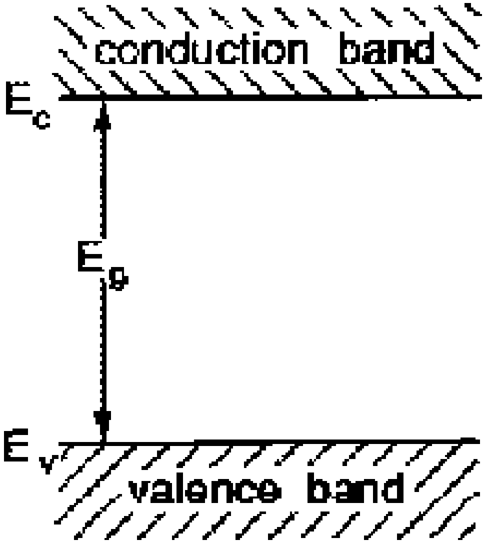




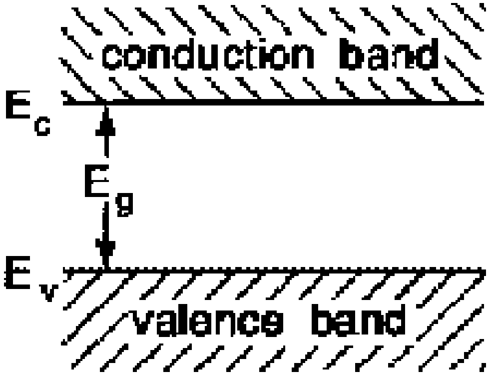
Fermi level

The position of the Fermi Level determines the conduction properties of the material

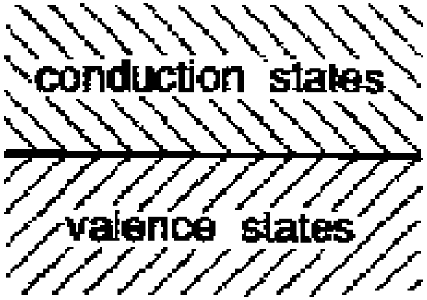
- Valence band
- Conduction band



insulator



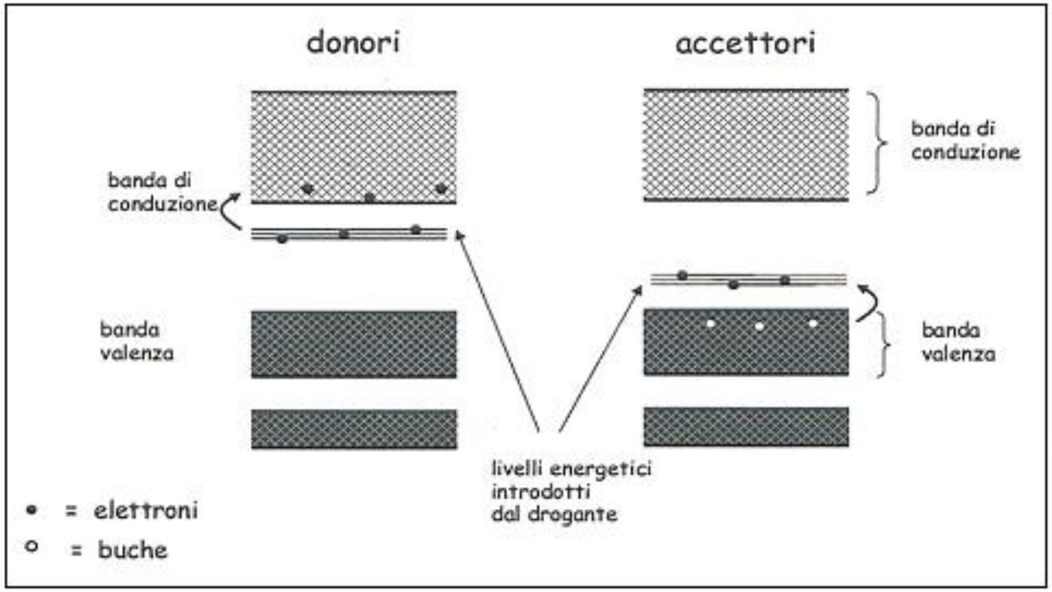
semiconductor



metal

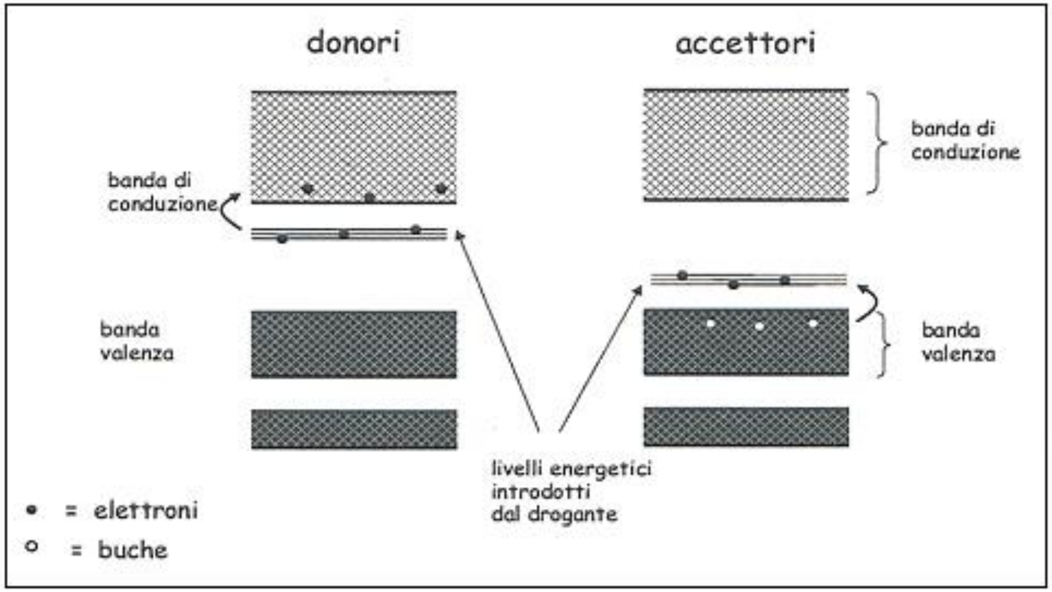
The concept of doping

Doping in inorganic semiconductors



- Donors, occupied states, energeticall very close to the conduction band
- even at very low T the thermal energy can allow some electrons to jump in the conduction band where they will be free to move (a lot of empty states)
- When this happens a donor becomes positively charged
- At room T (300 K) all the donor states have realesed their electrons, all of them are ionized

Doping in inorganic semiconductors

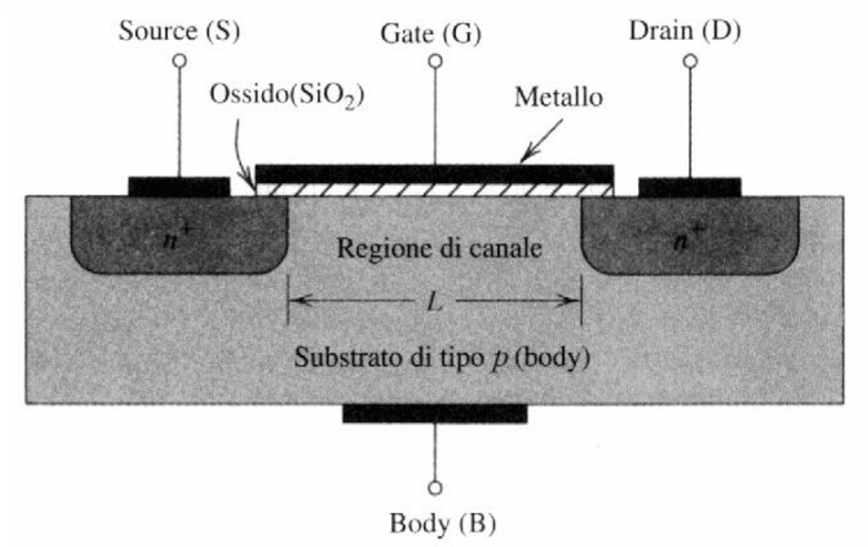


- Acceptors are empty states energetically very close to the valence band
- Even at very low T the thermal energy can allow some electrons to jump from the valence band to these empty states
- An emptystate is created into the valence badn (hole)
- When this happens an acceptor becomes negatively charged
- At room T (300 K) all the acceptor states are ionized

Metal Oxide Field Effect Transistor (MOSFET)

The MOSFET

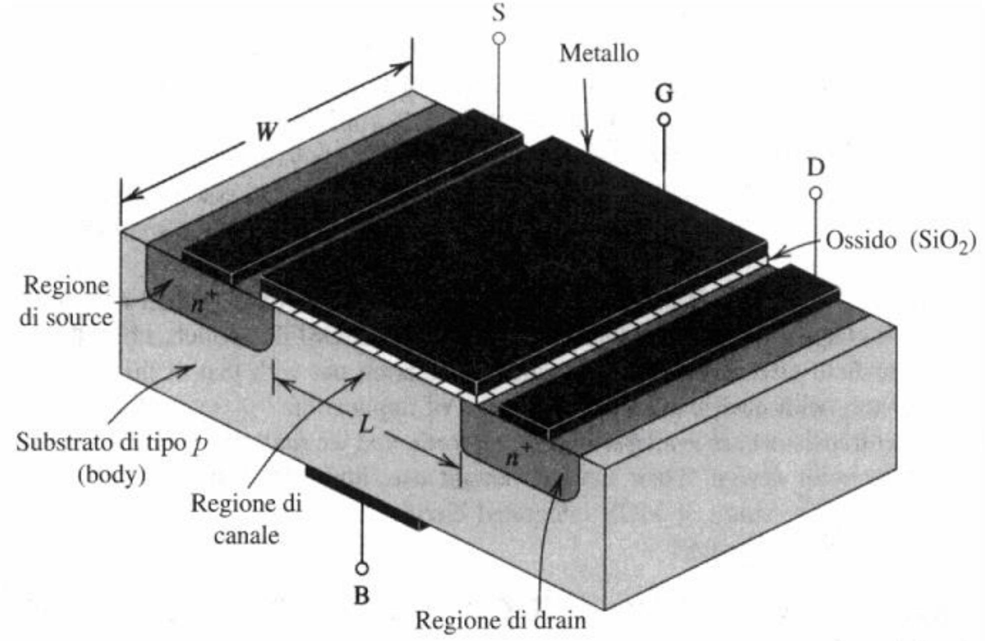
- The core of an nMOSFET is a p doped silicon substrate
- Two n+ diffusions, SOURCE e DRAIN
- The body contact can be ignored in this discussion
- Gate electrode define the channel length on the device, is insulated from the channel by a thin insulator layer.
- Source electrode is generally conneted to ground (common source configuration)



The MOSFET

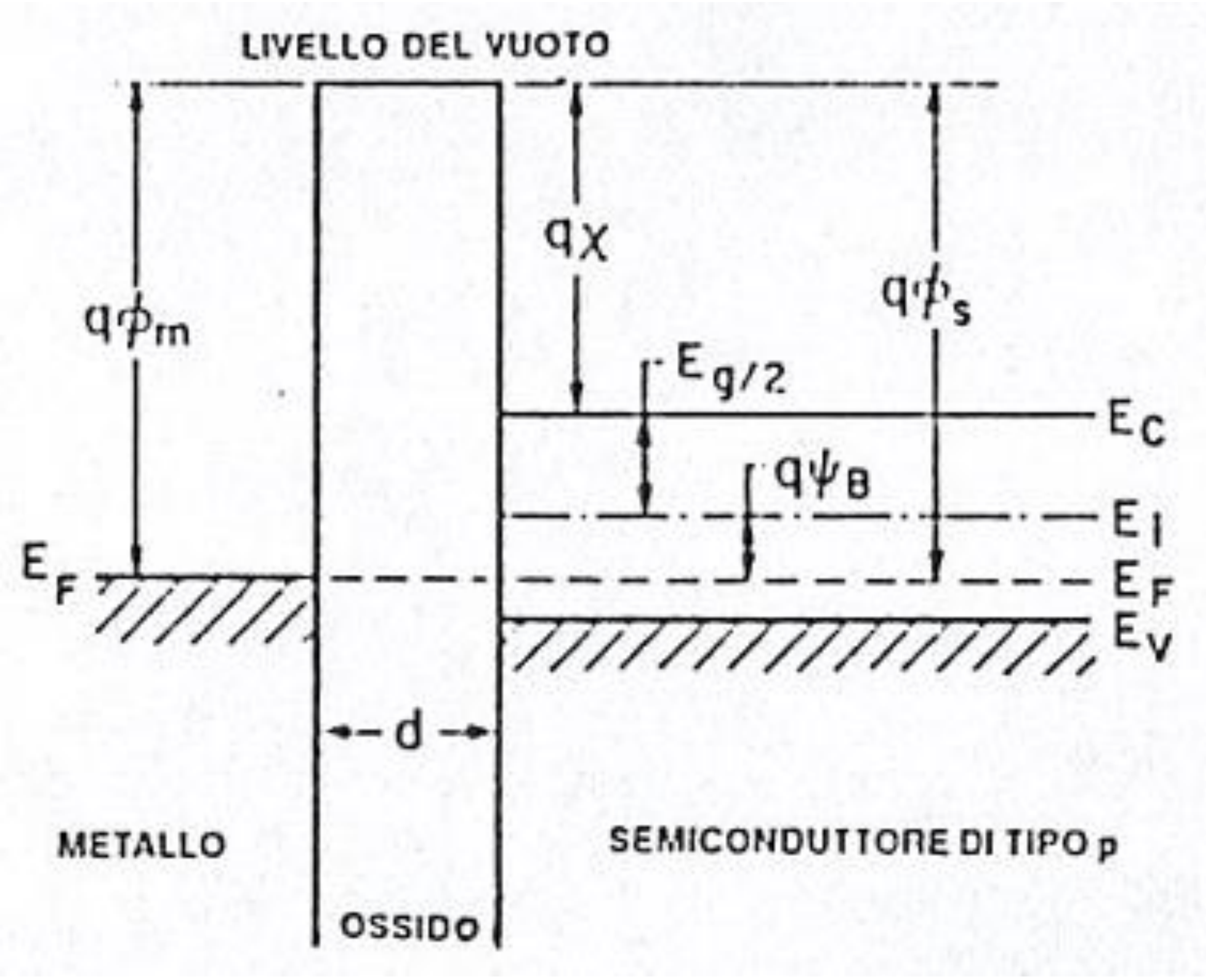
Most meanindgful parameters:

- Channel length L
- Channel width W
- Oxide/insulator thickness d,
- Junction depth r_j
- Substrate doping level N_A



Metal Oxide Semiconductor (MOS)

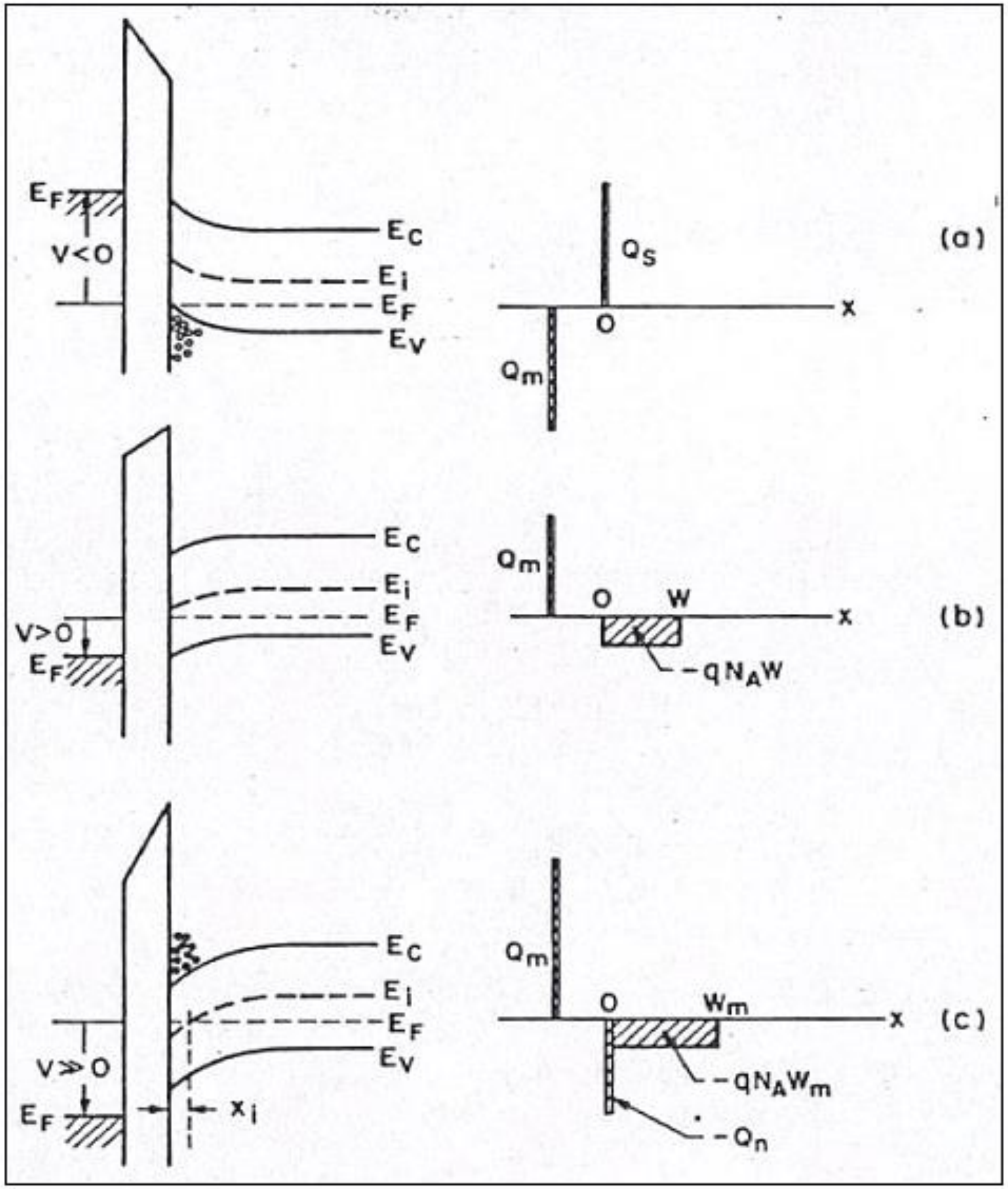
Flat Band Approximation



Metal Oxide Semiconductor (MOS)

$$p = n_i e^{\frac{E_i - E_F}{kT}}$$

$$n = n_i e^{\frac{E_F - E_i}{kT}}$$



MOS Threshold Voltage

Threshold Voltage **(V_T) is the required voltage that create a surface potential at least equal to the inversion potential**

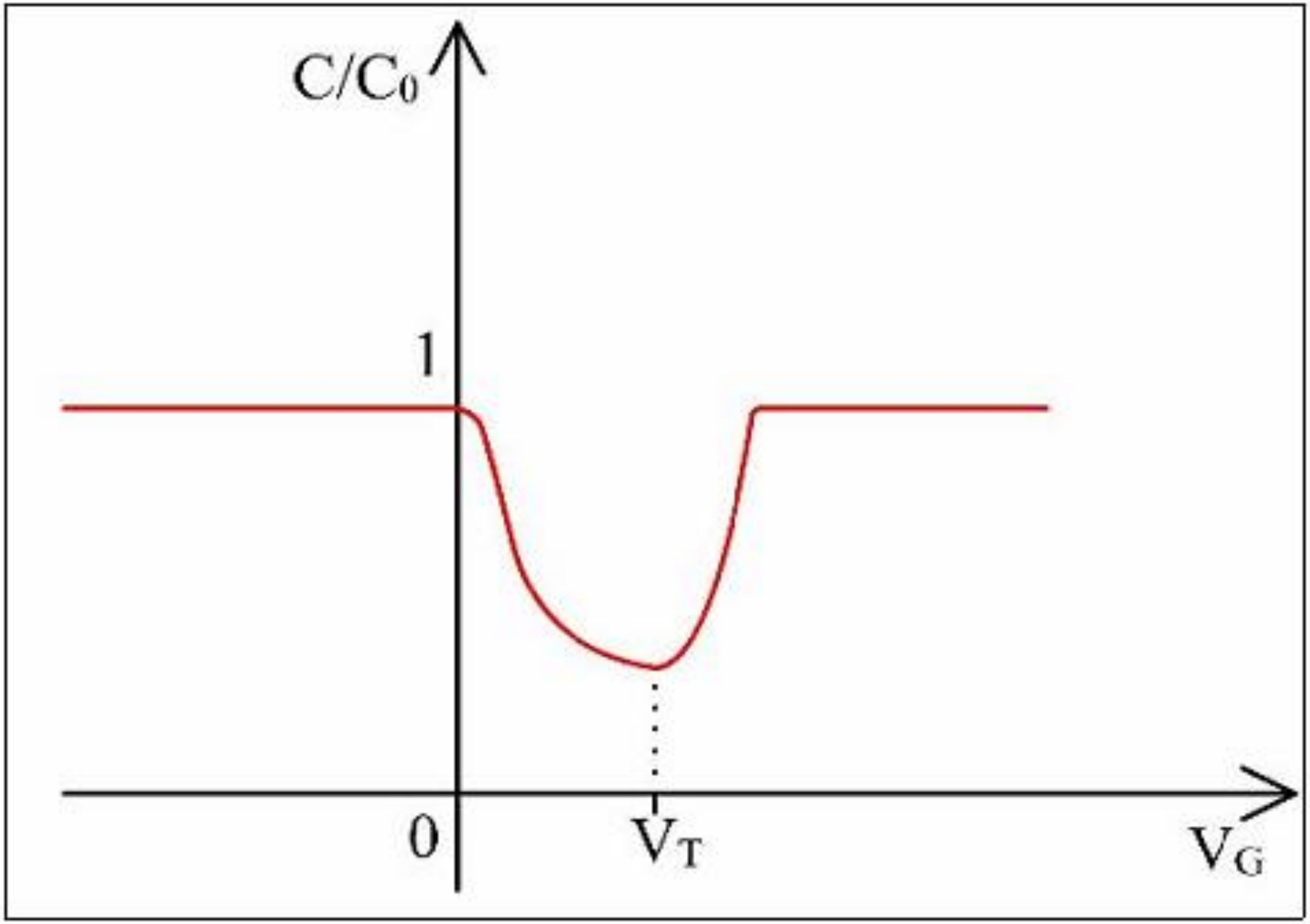
$\psi_S = \psi_{S,inv}$,

Considering that the charge density is qN_AW_m

$$V_T = \frac{qN_AW_m}{C_o} + \psi_{inv}$$

$$= \frac{\sqrt{2\varepsilon_S qN_A(2\psi_B)}}{C_o} + 2\psi_B$$

MOS Capacitance



MOS Capacitance

V<0: ACCUMULATION

High concentration of holes (mobile charges) at the oxide interface. Il MOS behaves as a capacitor: Ctot = Cox.

V>0: DEPLETION

Cox e C_J in series, Ctot decreases

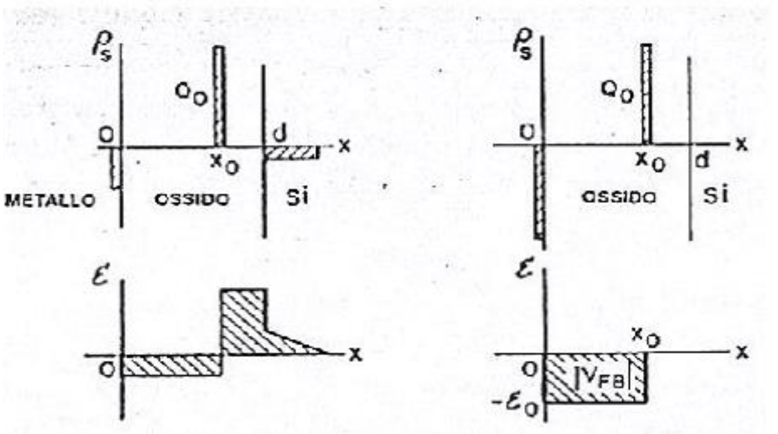
V>>0: INVERSION

High concentration of electrons (mobile charges) at the interface Ctot = Cox.

Non idealities MOS

Charge in the oxide → induces charge into the semiconductor

$$V_{FB} = \Phi_{MS} - \frac{Q_{ox}}{C_{ox}}$$



If the charge is not at the interface

$$V_T = \frac{\sqrt{2\varepsilon_S q N_A (2\psi_B)}}{C_o} + 2\psi_B + \left[\phi_{MS} - \frac{Q_{ox}}{C_{ox}} \frac{x}{d_{ox}} \right]$$

PMOS when $V_{FB} \neq 0$

$$V_T = -\frac{\sqrt{2\varepsilon_S q N_D (2\psi_B)}}{C_o} - 2\psi_B + V_{FB}$$

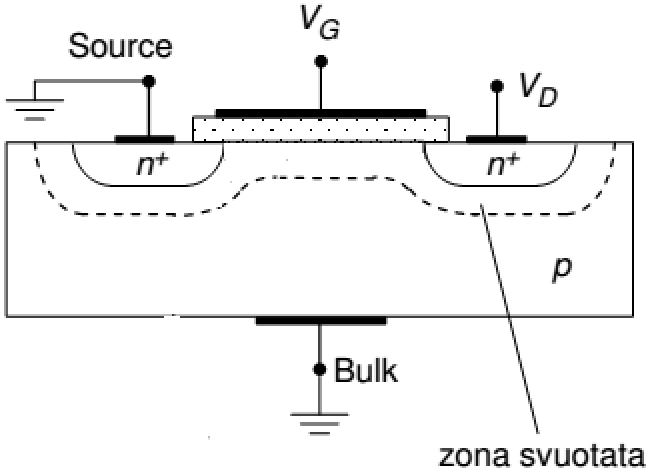
$$V_T = -\frac{\sqrt{2\varepsilon_S q N_D (2\psi_B)}}{C_o} - 2\psi_B + \left[\phi_{MS} - \frac{Q_{ox}}{C_{ox}} \frac{x}{d_{ox}} \right]$$

MOSFET

When no gate voltage is applied

Open circuit

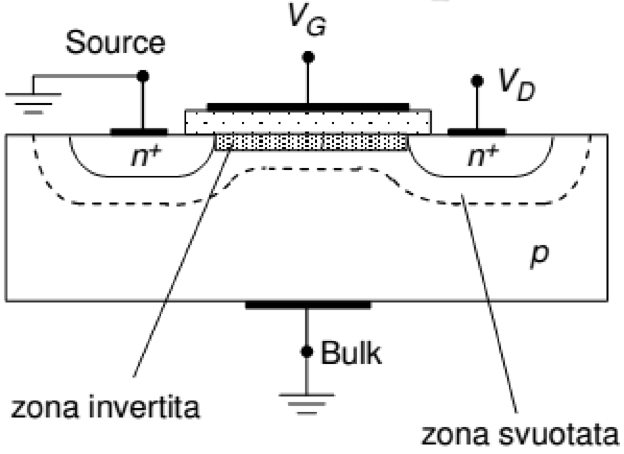
Why?



When a positive voltage is applied a depletion region is created in the substrate, when Vg increases the depletion region increases as well.

when Vg>Vt inversion takes place

The channel is formed



a) $V_D = 0$

MOSFET

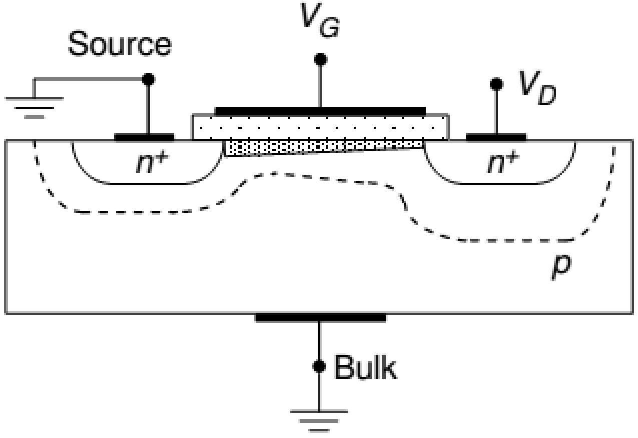
Concept of pinch off

When a V_{DS} is applied the channel becames asmmetric, due to the fact thatthe vertical field is no longer constant along the channel

In fact, $V_{GD}=V_{GS}-V_{DS}$, if V_{DS} increases, V_{GD} decreases

The electrones concentration close to the drain decreases

when $V_{GD}=V_T$ sono we are at the border between inversion and depletion, electrones concentration is 0 the channel is pinched-off

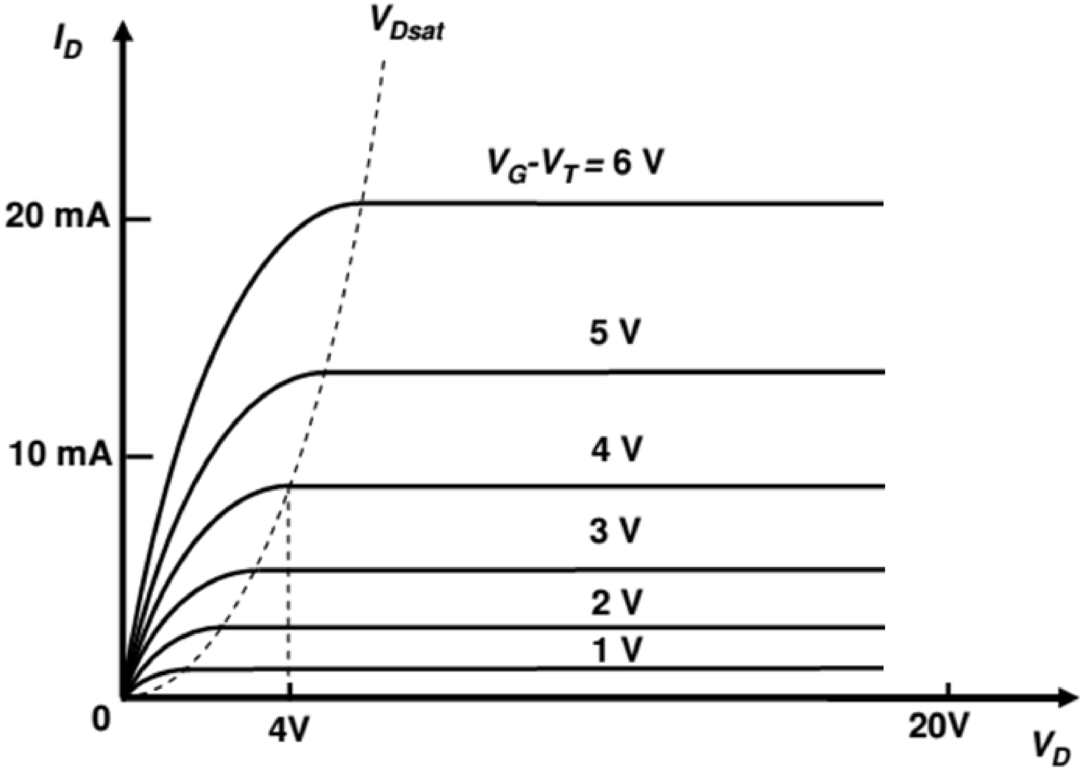


b) $0 < V_D < V_G - V_T$

MOSFET

Three working regions

1. $V_{GS} < V_{Th}$ the device is switched off
2. $V_{GS} > V_{Th}$ e $V_{DS} < V_{GS} - V_{Th}$ linear region, triode
3. $V_{GS} > V_{Th}$ e $V_{DS} > V_{GS} - V_{Th}$ saturation region



MOSFET: linear region

$$I_D \cong \frac{Z\mu_n}{L} C_{ox}\left[V_G - V_T - \frac{V_D}{2}\right]V_D$$

$$g_D = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G=\mathrm{cos}t} = \frac{Z\mu_n}{L} C_{ox}\left[V_G - V_T\right]$$

conductance

$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D=\mathrm{cos}t} = \frac{Z\mu_n}{L} C_{ox} V_D$$

transconductance

MOSFET: saturation region

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

Pinch off

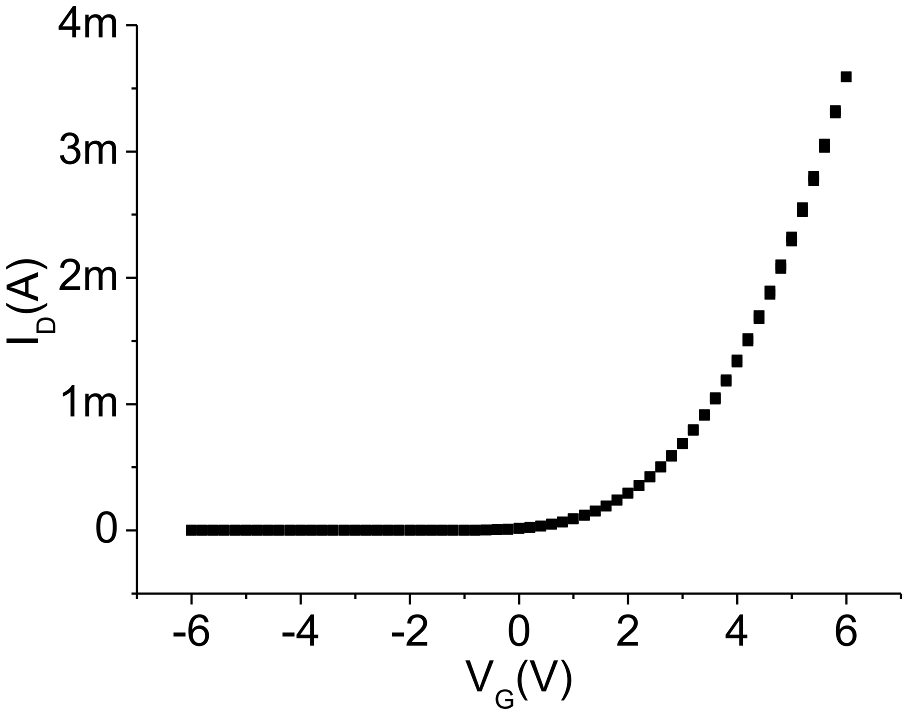
$$V_D = V_{Dsat} = V_G - V_T$$

$$g_{msat} = \frac{Z\mu_n}{L} C_{ox} (V_G - V_T) = g_{dlin}$$

transconductance

$$g_D = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G = \cos t} = 0$$

conductance



MOSFET

La conduttanza è data dalla pendenza della caratteristica di uscita in regione lineare
Dipende dalla Vg

La transcoduttanza in regione lineare è costante per una data Vd
È la pendenza della transcaratteristica

La transconduttanza in regione di saturazione dipende da Vg, ma non da Vd!
È la pendenza della retta tangente alla transcaratteristica per un determinato valore di Vg

MOSFET

Enhancement Mode, when the channel is not formed $V_{GS} = 0$ V

Depletion Mode When the channel is already formed at $V_{GS} = 0$ V

MOSFET

Depletion MOSFET (n channel)

We have current flowing into the channel when Vg=0

Negative threshold voltages

Enhancment MOSFET (n channel)

No current flowing into the channel when Vg=0

Positive threshold voltages

MOSFET

Depletion MOSFET (p channel)

We have current flowing into the channel when Vg=0

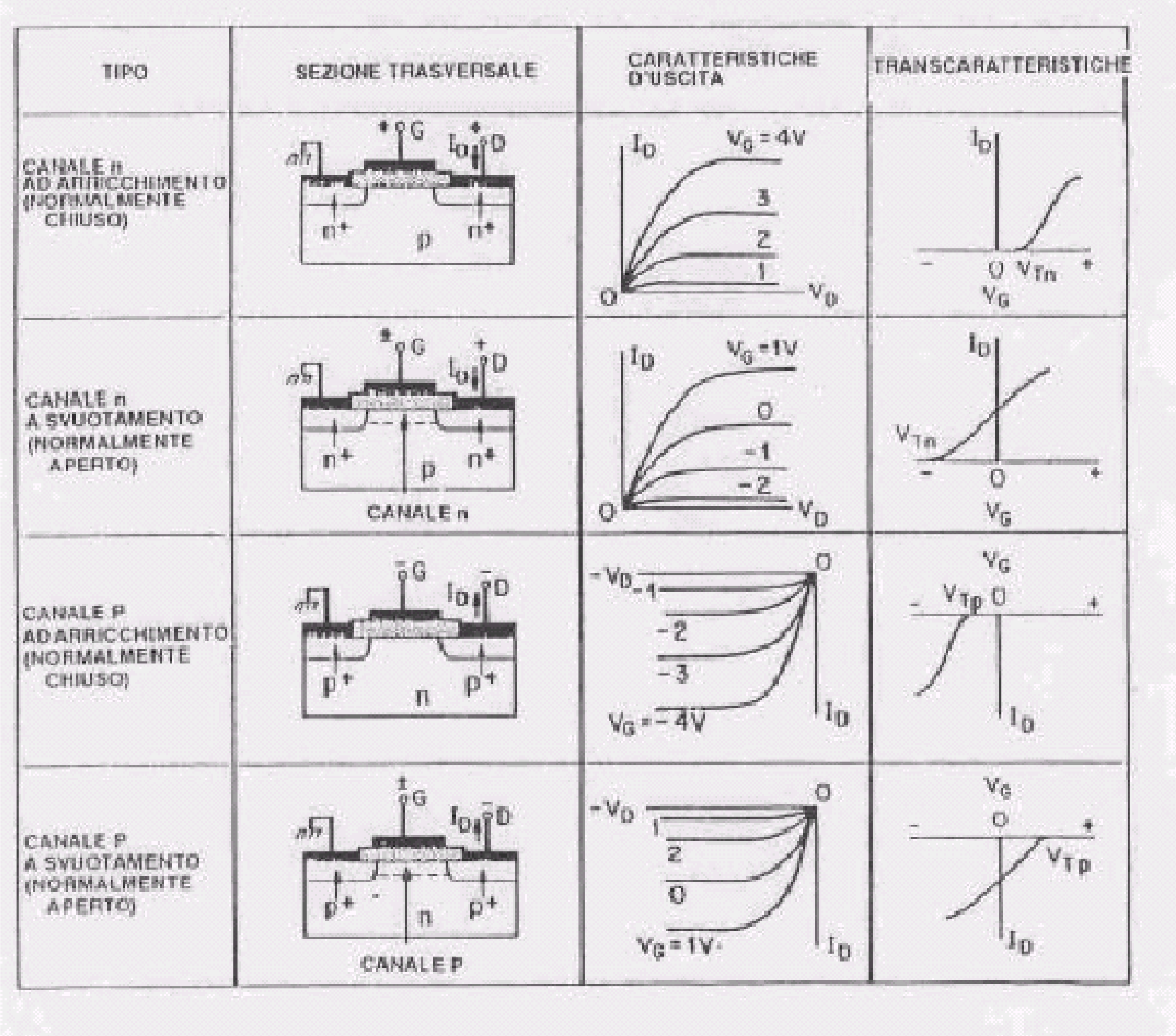
Positive threshold voltages

Enhancment MOSFET (p channel)

No current flowing into the channel when Vg=0

Negative threshold voltages

MOSFET



TIPO	SEZIONE TRASVERSALE	CARATTERISTICHE D'USCITA	TRANSCARATTERISTICHE
CANALE n AD ARRICCHIMENTO (NORMALMENTE CHIUSO)	+G I_D +D n^+ p n^+	I_D $V_G = 4V$ 3 2 1 O V_D	I_D – O V_{Tn} + V_G
CANALE n A SVUOTAMENTO (NORMALMENTE APERTO)	+G I_D +D n^+ p n^+ CANALE n	I_D $V_G = 1V$ 0 –1 –2 O V_D	I_D V_{Tn} – 0 + V_G
CANALE P AD ARRICCHIMENTO (NORMALMENTE CHIUSO)	–G I_D –D p^+ n p^+	$-V_D$ –1 –2 –3 $V_G = -4V$ O I_D	V_G – V_{Tp} 0 + I_D
CANALE P A SVUOTAMENTO (NORMALMENTE APERTO)	+G I_D –D p^+ n p^+ CANALE P	$-V_D$ 1 2 0 $V_G = 1V$ O I_D	V_G – 0 + V_{Tp} I_D

MOSFET

How can we estimete mobility and threshold voltage from the electrical characteristics?

$$I_D = \frac{Z\mu_n}{L} C_{ox} [V_G - V_T] V_D$$

Regime lineare

$$I_D = \frac{Z\mu_n}{2L} C_{ox} (V_G - V_T)^2$$

Regime di saturazione

MOSFET

Estimate the mobility and threshold voltage of this devices

Missing data?

Saturation regime

W/L =100

Cox = 150 nF/cm^2