MOSFETs

INEL 6055 - Solid State Electronics

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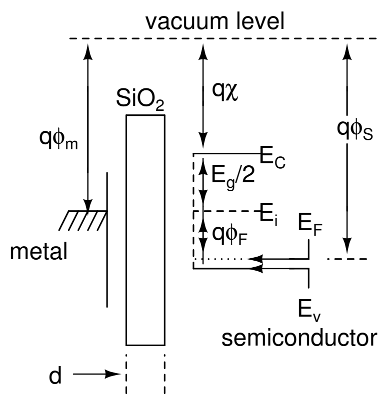
1 MOS Capacitor

1.1 Isolated Metal, SiO_2, Si

Definitions



- $q\phi_S$, $q\phi_m$: semiconductor and metal work functions.
- Electron affinity $q\chi$
- Fermi potential $q\phi_F$: Proportional to doping type and level:
  - P-type: $\phi_F = +\frac{kT}{q} ln \frac{N_A}{n_i}$
  - N-type: $\phi_F = -\frac{kT}{q} ln \frac{N_D}{n_i}$

Last equation (N-type): from textbook eq. (1.67)

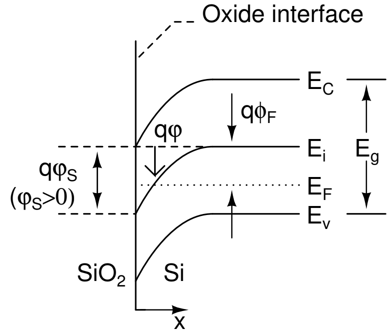
$$E_F - E_V = kTln(N_V/N_A) = \frac{E_g}{2} - q\phi_F$$

$$\frac{N_V}{N_A} = exp\left(\frac{E_g}{2kT} - \frac{q\phi_F}{kT}\right) = exp\left(\frac{E_g}{2kT}\right) exp\left(-\frac{q\phi_F}{kT}\right)$$

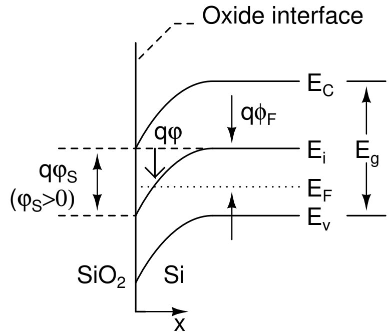
$$N_A exp\left(-\frac{q\phi_F}{kT}\right) = N_V exp\left(-\frac{E_g}{2kT}\right) \approx n_i$$

$$q\phi_F = kTln\left(\frac{N_A}{n_i}\right) \quad (1)$$

1.2 Threshold Voltage



- $\varphi = 0$ on bulk, by definition.
- φ_S: surface potential.
- n and p: function of $\varphi(x)$
- φ is positive when the bands bent downward.



- $\varphi_S < 0$: accumulation of holes
- $\varphi_S = 0$: flat-band condition
- $\phi_F > \varphi_S > 0$: depletion of holes
- $\phi_F = \varphi_S$: midgap with $n_s = n_p = n_i$ (intrinsic concentration)
- $\varphi_S > \phi_F$:inversion

$\varphi(x)$ can be obtained from Poisson's equation

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho_s(x)}{\epsilon_s} \tag{2}$$

Depletion approximation: semiconductor is depleted to width w.

$$\rho_s = -qN_A$$

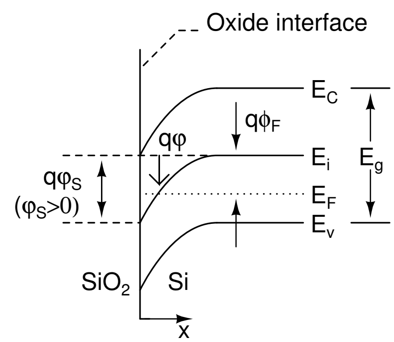
Exact solution:

$$\rho_s = -q\left(p(x) - n(x) + N_D - N_A\right) \tag{3}$$

In the bulk:

$$p_{bulk} - n_{bulk} + N_D - N_A = 0$$

$$N_D - N_A = -(p_{bulk} - n_{bulk}) = -N_A + \frac{n_i^2}{N_A} \tag{4}$$



Near the surface, E_C and E_V are bent down by $q\varphi$.

From chapter 1, the bulk electron concentration is

$$n_B = N_C exp\left(-\frac{E_C - E_F}{kT}\right)$$

Due to band bending, $E_C \to E_C - q\varphi$ and, as we approach the $Si - SiO_2$ interface,

$$n(x) = N_C exp\left(-\frac{E_C - q\varphi - E_F}{kT}\right) = n_B exp\left(\frac{q\varphi}{kT}\right)$$

Using $n_B = n_i^2/N_A$,

$$n(x) = \frac{n_i^2}{N_A} exp\left(\frac{q\varphi}{kT}\right) \tag{5}$$

For holes

$$p_B = N_V exp\left(-\frac{E_F - E_V}{kT}\right)$$

and

$$p(x) = N_V exp\left(-\frac{E_F - (E_V - q\varphi)}{kT}\right) = p_B exp\left(-\frac{q\varphi}{kT}\right)$$

$$p(x) = N_A exp\left(-\frac{q\varphi}{kT}\right) \tag{6}$$

Equation 2 becomes

$$\frac{d^2\varphi}{dx^2} = -\frac{q}{\epsilon_s}\left(\underbrace{N_A exp\left(-\frac{q\varphi}{kT}\right)}_{p(x)} - \underbrace{\frac{n_i^2}{N_A} exp\left(\frac{q\varphi}{kT}\right)}_{n(x)} - \underbrace{N_A + \frac{n_i^2}{N_A}}_{N_D - N_A}\right)$$

Or,

$$\frac{d^2\varphi}{dx^2} = -\frac{q}{\epsilon_s}\left(N_A\left(exp\left(-\frac{q\varphi}{kT}\right)-1\right)-\frac{n_i^2}{N_A}\left(exp\left(\frac{q\varphi}{kT}\right)-1\right)\right) \tag{7}$$

Equation 7 can be integrated by multiplying both sides by $\frac{d\varphi}{dx}dx$.
Let

$$u = \frac{d\varphi}{dx}$$

$$\frac{du}{dx} = \frac{d^2\varphi}{dx^2} \equiv g$$

$$dx = \frac{du}{g}$$

Then

$$\int_{\infty}^{x}\frac{d^2\varphi}{dx^2}\frac{d\varphi}{dx}dx = \int_a^b gu\frac{du}{g} = \frac{1}{2}u^2|_a^b = \frac{1}{2}\left(\frac{d\varphi}{dx}\right)^2|_a^b$$

where

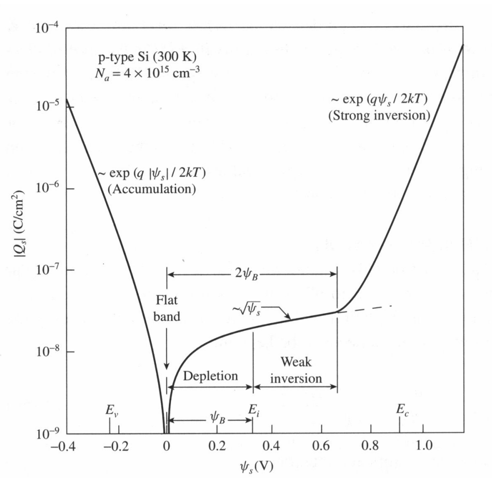
- $a = u(\infty) = \frac{d\varphi}{dx}(\infty) = 0 = \varphi$ (at the bulk)
- and at the surface, $u(x) = \frac{d\varphi}{dx}$.

Thus integration of the left-hand side of 7 yields

$$\frac{1}{2}\left(\frac{d\varphi}{dx}\right)^2 = \frac{1}{2}E^2$$

where E is the electric field. The right-hand side can be integrated straightforwardly to obtain

$$\begin{aligned}\left(\frac{d\varphi}{dx}\right)^2 \quad = \quad & \frac{2kTN_A}{\epsilon_{Si}}\{exp(-\frac{q\varphi}{kT})+\frac{q\varphi}{kT}-1 \\ & +\frac{n_i^2}{N_A^2}(exp(\frac{q\varphi}{kT})-\frac{q\varphi}{kT}-1)\}\end{aligned} \tag{8}$$



Surface charge: $Q_s = -\epsilon_{Si}E_s$; E_s surface elect. field. Ψ_B is our ϕ_F; Ψ_s is our φ_s.

Depletion Approximation

- Depletion region: $\frac{kT}{q} < \varphi < 2\phi_F$
- Keep only the $\frac{q\varphi}{kT}$ on r.h.s. of equation 8, which becomes

$$\frac{d\varphi}{dx} = -\sqrt{\frac{2qN_A\varphi}{\epsilon_{Si}}}$$

or

$$\int_{\varphi_s}^{\varphi} \frac{d\varphi}{\sqrt{\varphi}} = -\int_0^x \sqrt{\frac{2qN_A}{\epsilon_{Si}}}dx$$

The solution is:

$$\varphi = \varphi_s \left(1 - \frac{x}{w_d}\right)^2$$

where

$$w_d = \sqrt{\frac{2\epsilon_{Si}\varphi_s}{qN_A}}$$

is the distance to which the band bending extends, or the depletion layer width. For $\varphi_s = 2\phi_F$, w_d reaches its maximum value w_{dm}.

The total depletion layer charge is

$$Q_d = -qN_A w_d = -\sqrt{2\epsilon_{Si}qN_A\varphi_s}$$

Strong Inversion

- For $\varphi_s > 2\phi_F$, the $(n_i^2/N_A^2)exp(q\varphi/kT)$ term becomes significant and must be taken into account. Equation 8 can then be approximated by

$$\frac{d\varphi}{dx} = -\sqrt{\frac{2kTN_A}{\epsilon_{Si}}\left(\frac{q\varphi}{kT} + \frac{n_i^2}{N_A^2}exp\Big(\frac{q\varphi}{kT}\Big)\right)} \qquad (9)$$

  which can only be integrated numerically.

- When strong inversion occurs, $\varphi_S = 2\phi_F$. The gate voltage at which this happens is called the *threshold voltage* V_T.

Threshold Voltage

- When a gate voltage V_g is applied, part of it appears as a potential drop accross the oxide. The other part appears as band bending in the silicon:

$$V_g = V_{ox} + \varphi_s$$

- The total charge per unit area induced in the silicon is the sum of the depletion and inversion layer charges, Q_i and Q_d. Thus

$$V_{ox} = \frac{-Q_s}{C_{ox}} = -\frac{Q_i + Q_d}{C_{ox}}$$

  where $C_{ox} = \frac{\epsilon_{ox}}{t_{ox}}$.

- Notice that Q_s was given earlier in terms of φ_s, so

$$V_g = \frac{-Q_s}{C_{ox}} + \varphi_s$$

  is an implicit equation that can be solved for φ_s.

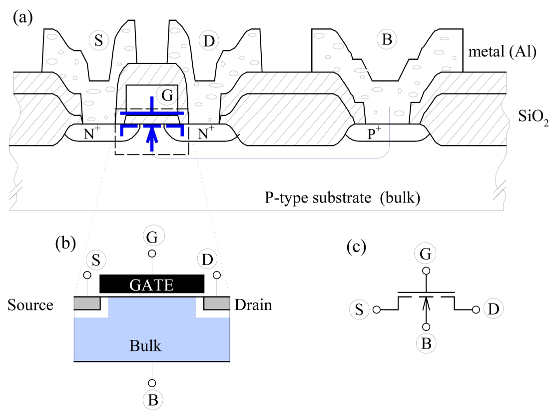


Figure 1: MOSFET Structure

- Due to the work-function difference between the metal and semiconductor, a voltage V_{FB} must be applied between gate and channel to flatten the bands. V_{FB} is called the *flat-band voltage*.
- The effective gate voltage is $V_G - V_{FB}$ and the voltage across the gate oxide is $V_{ox} = (V_G - V_{FB}) - \varphi_S$
- If, for simplicity, we assume that at the onset of strong inversion there is no inversion layer charge, then

$$V_{ox}C_{ox} = ((V_T - V_{FB}) - 2\phi_F)\,C_{ox} = Q_{dm}$$

Rearranging,

$$\begin{aligned} V_T &= V_{FB} + 2\phi_F + \frac{Q_{dm}}{C_{ox}} = V_{FB} + 2\phi_F + \frac{qN_A w_{dm}}{C_{ox}} \\ &= V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F} \end{aligned}$$

where

$$\gamma = \frac{\sqrt{qN_A 2\epsilon_S}}{C_{ox}}$$

is known as the *body factor*.

2 MOSFET Devices

MOSFET Operation

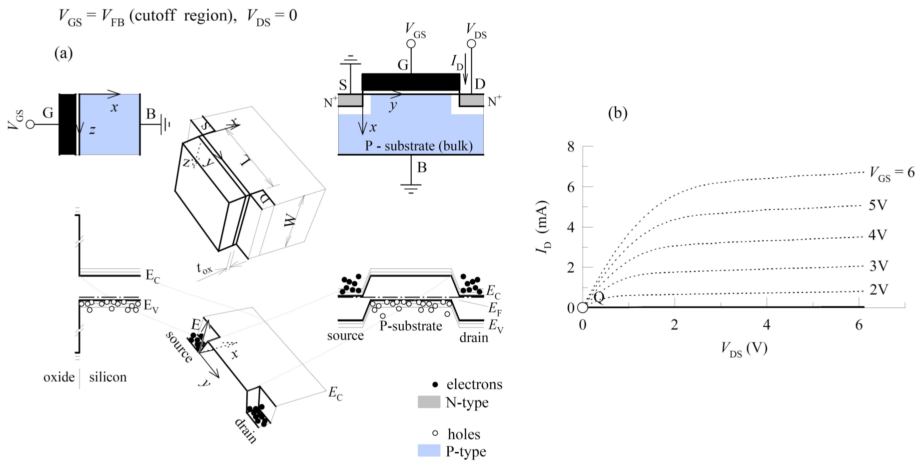
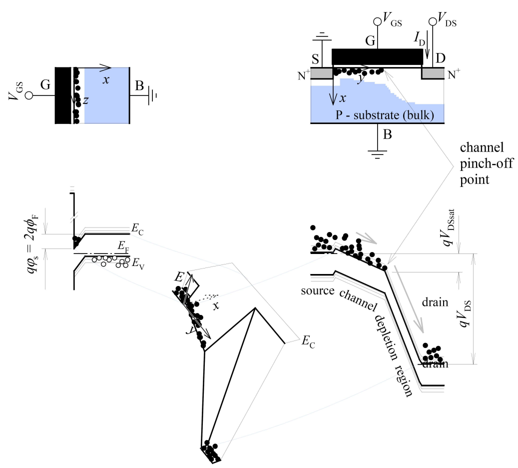


Figure 2: Flat band condition.



- Figure 2 shows the flat band condition.
- Observe that the Fermi level is constant in the y direction.
- This creates an energy barrier that prevents electrons from flowing between source and drain.
- As long as there is an energy barrier between the source and the drain there is no flow of electron.
- MOSFET is in *cutoff*.
- To turn the MOSFET *ON*, a positive voltage that reduces the potential barrier between source and drain should be applied to the gate.
- The energy barrier at the surface is reduced, as seen in figure 3.
- Bands bent at the silicon surface, moving the conduction band toward the Fermi level.

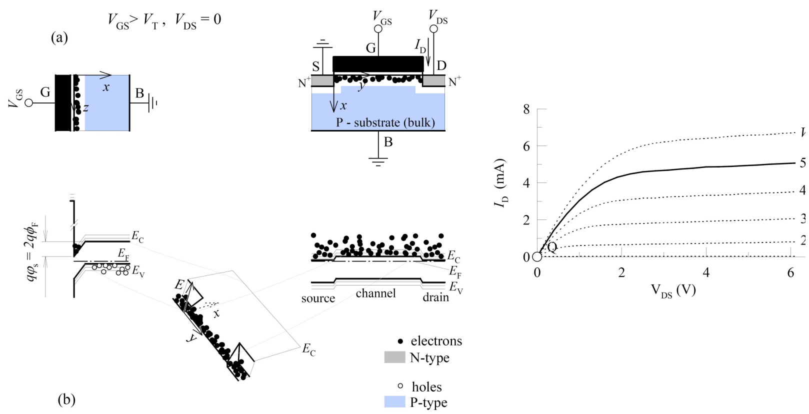


Figure 3: Weak inversion layer.

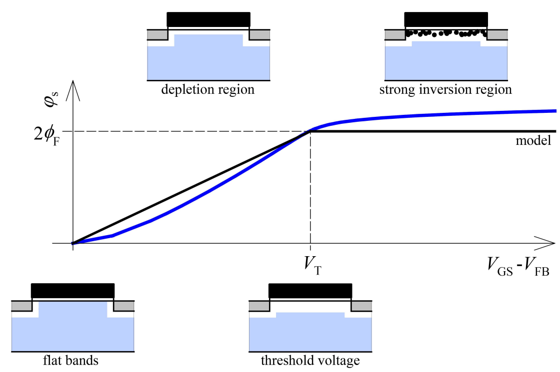


Figure 4: Approximation used.

- Once the Fermi level is closer to the conduction band than to the valence band, the probability of occupancy of conduction band states is higher than that of the valence band states.
- The electron concentration becomes larger than the hole concentration.
- The inversion layer as been created.
- When $\varphi_S = 2\phi_F$, strong inversion is reached.
- Further increases in the gate voltage cause a quick increase in the electron concentration in the inversion layer. The additional gate voltage appears across the oxide and φ_S remains constant.

- The gate voltage required for $\varphi_S = 2\phi_F$ is the *threshold voltage*, V_T.
- When a positive effective voltage $V_{GS} - V_{FB}$ is applied to the gate, holes are rejected from the region under the gate. The charge due to the uncompensated acceptor atom ions left behind is called the *depletion region charge*. The associated charge density, Q_d, can be expressed in C/m^2.
- The following approximation is used:

- the inversion-layer charge is neglected if the gate voltage is below V_T; under this conditions, the only uncompensated charge in the silicon substrate is Q_d.
- the surface potential is pinned at

$$\varphi_S \approx 2\phi_F$$

for $V_{GS} > V_T$. Increases beyond V_T produce the inversion layer charge Q_I,

$$Q_I = (V_{GS} - V_T)\, C_{ox}$$

- Situation is similar to two caps in series. One fraction of the effective applied voltage appears across the oxide capacitor, the other across the depletion region.
- The voltage drop across the oxide is given as the difference between the effective gate potential on one side of the oxide and the surface potential. Thus

$$V_{GS} - V_{FB} - \varphi_S = \frac{Q_d + Q_I}{C_{ox}}$$

- At the onset of strong inversion, the surface potential is $\varphi_S = 2\phi_F$, $V_{GS} = V_T$, and $Q_I = 0$; thus

$$V_T - V_{FB} - 2\phi_F \,|= \frac{Q_d}{C_{ox}}$$

and

$$V_T = V_{FB} + 2\phi_F + \frac{Q_d}{C_{ox}}$$

- In chapter 2, we found that

$$Q_d = qN_A w_m = \sqrt{2\epsilon_s q N_A (2\phi_F)}$$

- In terms of the *body factor*, $\gamma = \frac{\sqrt{2\epsilon_s q N_A}}{C_{ox}}$, the threshold voltage can be expressed as

$$V_T = V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F}$$

This expression is valid if the substrate and the source are at the same potential.

- In figure 3,
  - The situation for $V_{DS} = 0$ is shown.
  - There is no drain current and the quiescent point remains at the origin.
- If a positive voltage is applied to the drain, the conduction band at the drain is lowered with respect to the source and electrons flow from source to drain. This is shown in figure 32.
- The drain current magnitude is determined by the amount of voltage applied to the drain and by the density of charge in the inversion layer.
- Since

$$Q_I = (V_{GS} - V_T)\, C_{ox}$$

the drain current can be expressed

$$I_D = \beta(V_{GS} - V_T)V_{DS}$$

where β is a proportionality factor.

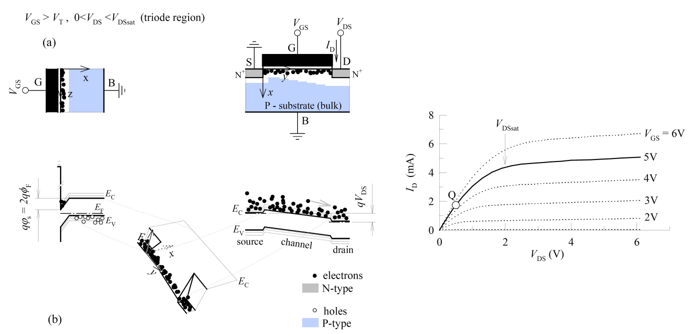


Figure 5: Triode region.

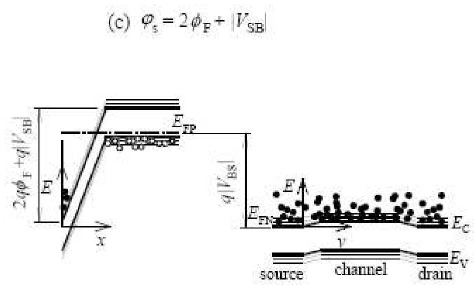


Figure 6: Strong inversion, including the effect of the source-bulk potential.

2.1 Body Effect

- If a voltage is applied from source to substrate, the energy barrier seen by source's electrons is increased.
- The barrier between source/drain and substrate is increased by qV_{SB}. See figure 34 and compare (a) with figure 3.
- As a consequence, the potential needs to be increased to $\varphi_S = 2\phi_F + V_{SB}$. In the other hand, the gate-to-bulk voltage is increased to $V_{GS} + V_{SB} - V_{FB}$ and the effect of V_{SB} cancels.

- The bulk voltage affects Q_d through its dependence on the surface potential.
  - when $V_{SB} = 0$ under strong inversion
  $$Q_d/C_{ox} = \gamma\sqrt{\varphi_S} = \gamma\sqrt{2\phi_F}$$
  - When V_{SB} is applied, $\varphi_S = 2\phi_F + V_{SB}$ and
  $$Q_d/C_{ox} = \gamma\sqrt{2\phi_F + V_{SB}}$$
  - The threshold voltage expression is also modified
  $$V_T = V_{FB} + 2\phi_F + \gamma\sqrt{2\phi_F + V_{SB}}$$

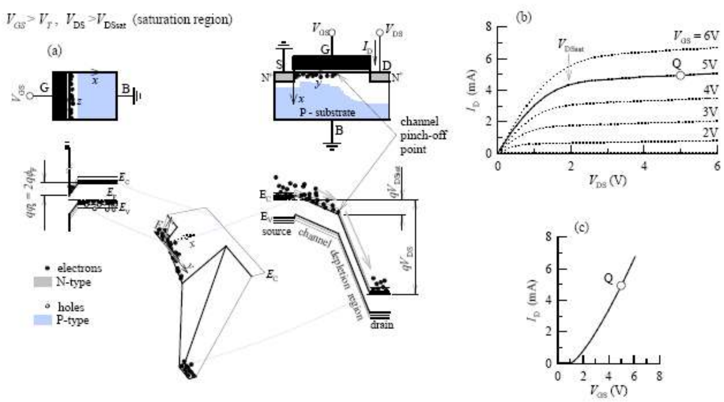


Figure 7: Saturation.

– The change in threshold voltage is

$$\Delta V_T = V_T(V_{SB}) - V_T(0)$$
$$= \gamma(\sqrt{2\phi_F + V_{SB}} - \sqrt{2\phi_F})$$

2.2 Saturation

- Previous discussion assumes inversion region exists along the bulk at both source and drain sides.
- If a positive voltage is applied to the drain, electrons flow from source to drain.
- The positive drain voltage reduces the difference between the gate and drain voltages.
- There is a point at which $V_{GD} < V_T$ and the inversion region disappears at the drain side.
- This is called *channel pinch-off*.
- A depletion region is formed at the drain side.
  - This depletion region, however, has little effect on the drain current
  - The current is limited by the electron concentration at the pinch-off point.
  - The electron concentration is controlled by the gate-to-source voltage.
  - The drain current is controlled by the gate voltage.
- The MOSFET works like a voltage-controlled current source.
- This operating regime is called *saturation region*.
- Very small devices are *short-channel* MOSFETs.
  - In these devices the drain current saturates at smaller drain-to-source voltages.
  - The small size of the device makes the electric field in the channel very large.
  - Carrier mobility is reduced due to the large electric field.
  - This can happen before channel pinch-off.

Note: For p-channel MOSFETs use:

$$V_T = V_{FB} - 2 \mid \phi_F \mid - \gamma\sqrt{2 \mid \phi_F \mid + \mid V_{SB} \mid}$$

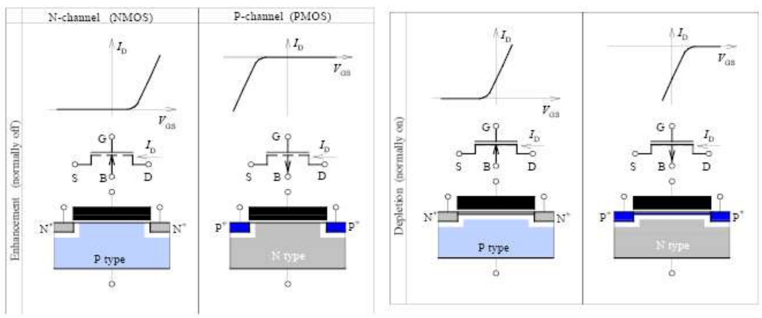


Figure 8: Types of MOSFET