Lecture-1 Prof: Santan Chattapadhyay 1·9·2023

Capacitance of Metal Oxide ~~capacitor~~ Semiconductor (MOS).

Si based MOS is the Key

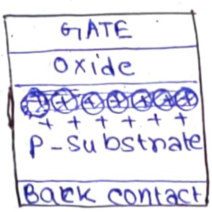
As a material Si is abundant in nature
↓
High quality native oxide ($SiO_2$)
↓
Appropiate mechanical strength

Schematic View →

- A Si substrate (p or n-type)
- $SiO_2$ is grown on it (800°-900°C)
- Ohomic contacts are taken from the top and bottom.
- Sometimes, A Poly-Si layer is grown on $SiO_2$ on which gate ohmic contact is taken.

Different Bias

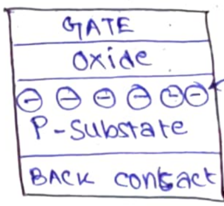
Holes are attracted $V_G < 0$




works as a capacitor

Accumulation

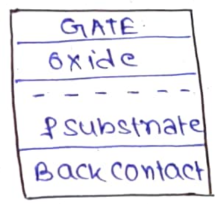
Holes are repelled $V_G > 0$




Immobile changes

Depletion

Electrons are attracted $V_G \gg 0$




Inversion

Current through a capacitor due to application of AC signal is called Displacement Current.

Higher the AC frequency higher the displacement

At zero bias → No accumulation of +ve changes

Depletion region is region which is depleted of any mobile carriers.

Not all dielectrics are insulators but all insulators are dielectric.

The dielectrics which do not have any mobile carrier are called insulator.

$$C_{ox} = \frac{\varepsilon_0 \varepsilon_{ox} A}{t_{ox}} \qquad C_D = \frac{\varepsilon_0 \varepsilon_{Si} A}{\omega_D}$$

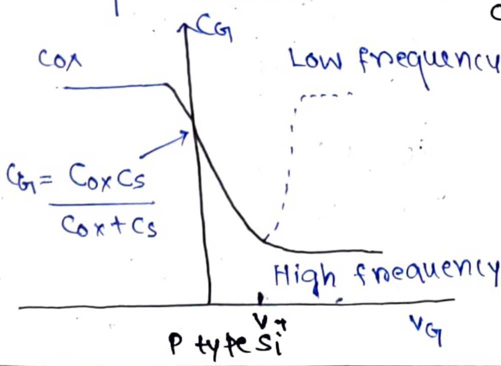
$\omega_D$ → depletion width

work


$R_{ox} \gg R_{Si}$

→ voltage divider

As $V_G$ increases → More holes will be repelled → width of the depletion region will increase → Capacitance will decrease gradually (Two capacitor connected in parallel) → After a certain time when both the electric field will oppose each other the capacitance become constant.




$$C_G = \frac{C_{ox} C_S}{C_{ox} + C_S}$$

Book: SM Sze

Lecture-1 Prof: Abhijit Mullick 1.09.2023

In electronics $e^-$ are transported through Semiconductor, gas and vacuum.

In a semiconductor conductivity can be varied over orders of magnitude by varying impurity doping concentration, temperature and optical excitation.

Device, Analog circuits, Digital circuits, Device/IC Fabrication technology.

1. Computation, 2. Communication, 3. Control and Instrumentation 4. Power Electronics.

**Effective Mass:**

Electrons in a crystal are not completely free, but instead interact with the periodic potential of the lattice. As a result, their 'wave particle' motion can not be expected to the same as that for $e^-$ in free space. Thus, in applying the usual equations of electrodynamics to charge carriers in solids, we must use altered values of particle mass. So for most of the influence of the lattice $e^-$ and holes can be treated as 'almost free' carriers.

For a free $e^-$ $\vec{p} = \hbar k = m\vec{v}$

$$E = \frac{1}{2}m\vec{v}^2 = \frac{p^2}{2m} = \frac{\hbar^2 k^2}{2m} \Rightarrow \frac{dE}{dk} = \frac{\hbar^2 \vec{k}}{m} \Rightarrow \frac{d^2E}{dk^2} = \frac{\hbar^2}{m}$$

$$\Rightarrow m = \frac{\hbar^2}{\frac{d^2E}{dk^2}}$$

The effective mass of an $e^-$ in a band with a given $(E, \vec{k})$ relationship is

$$\boxed{m^* = \frac{\hbar^2}{d^2E/d\vec{k}^2}}$$

From the E-K we can calculate $m^*$

$e^-$'s $m^* \longrightarrow$ conduction band slope

hole $m^* \rightarrow$ valance band slope

- For GaAs the slope of conduction band is higher than Si so the effective mass of $e^-$ in Si is greater than GaAs

At the bottom of the conduction band $\frac{d^2E}{dk^2}$ is +ve

But at the top " " VB $\frac{d^2E}{dk^2}$ is -ve

$\therefore m^*$ is -ve at the (or near the) top of the valance band

The VB $e^-$ with -ve mass and -ve charge move in the electric field in the same directions as holes with +ve mass and position charge.

**Carrier concentrations:**

$$N_c(E) = \frac{4\pi}{h^3}(2m_n^*)^{3/2}(E - E_c)^{1/2} \quad \text{for } E > E_c$$

$$N_v(E) = \frac{4\pi}{h^3}(2m_p^*)^{3/2}(E_v - E)^{1/2} \quad \text{for } E < E_v$$

$N(E)\,dE$ is the density of states per unit volume b/w energy E and E+dE

Fermi - Dirac distribution function $f(E)$ gives the probability that an available energy state at E will be occupied by an $e^-$ at temparature T

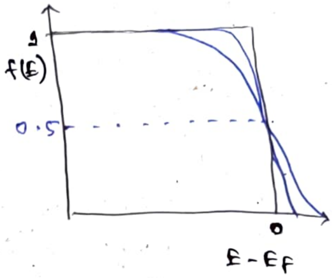
$$f(E) = \frac{1}{1 + e^{(E-E_F)/KT}}$$

properties of $f(E)$:

→ At $T=0$ and $E<E_F$ ; $f(E) = \frac{1}{1+e^{-1/\infty}} = 1$

→ At $T=0$ and $E>E_F$ ; $f(E) = \frac{1}{1+e^{+1/\infty}} = 0$

→ At $T>0$ and $E=E_F$ ; $f(E) = \frac{1}{1+e^0} = \frac{1}{2}$




Carrier Concentration : Electron and hole

$$n_0 = \int_{E_c}^{\infty} N_c(E) f(E) dE$$

For $E-E_F$ greater than several RT, $f(E) = e^{-(E-E_F)/KT}$

$$\therefore n_0 = \frac{4\pi}{h^3}(2m_n^*)^{3/2} \int_{E_c}^{\infty} (E-E_c)^{1/2} e^{-(E-E_F)/KT} dE$$

$$= 2\left(\frac{2\pi m_n^* KT}{h^2}\right)^{3/2} e^{(E_F-E_c)/KT}$$

$\Rightarrow n_0 = N_c \, e^{-(E_c-E_F)/KT}$ where $N_c = 2\left(\frac{2\pi m_n^* KT}{h^2}\right)^{3/2}$

& $N_c$ is called effective density of states in the conduction band.

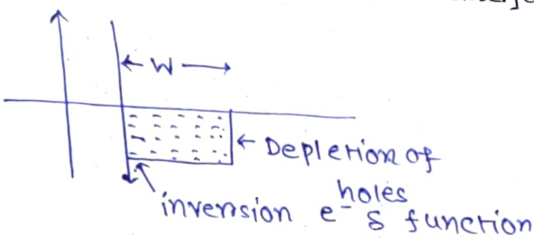
Similerly, $P_0 = \int_{-\infty}^{E_V} N_V(E) [1-f(E)] dE$

$$= 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2} e^{-(E_F-E_V)/KT}$$

$$= N_V \, e^{-(E_F-E_V)/KT}$$

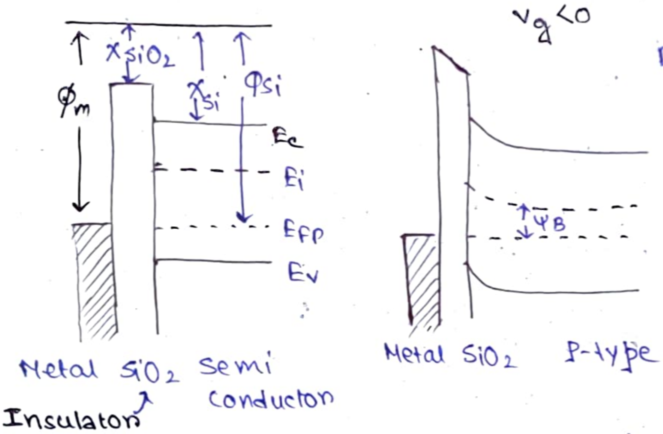
where $N_V = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2}$ is the effective density of states in valance band.

Lecture-2 Prof: Sanatan Chattapadhyay 8.09.2023




For intrinsic Si carrier concentration $\sim 10^{11}$ /cc
Doping concentration of Si $\sim 10^{16} - 10^{17}$ /cc to get a current of mA order.
There is no significance of generation, recombination for doped material.
For Si Generation recombination time gap $\sim$ 10 mA
So in Si device for a frequency 100 Hz the depletio
capacitance is no more → Minority carrier increases.
High frequency → Change in depletion region become negliger

Band diagram in MOS:




Band structure is the energy description of electron in a devic
Work function of a mic is the minimum energy required to expell $e^-$ from fermi level.

When the band bends downward, $\psi_s > 0$; and when it bends upward, $\psi_s < 0$

for $\psi_s < 0$ accumulation of holes (band bends upward) for p-type substrate.

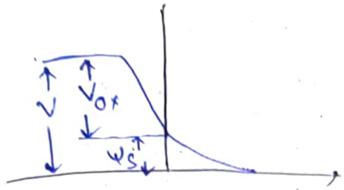
For $\psi_s > 0$ accumulation of $e^-$ for n-type substrate.

for n-type → Fermi level ↑ → Work function decreases
for p-type → Fermi level ↓ → " " increases

Barrier for hole is ~~doward~~ downward.
When a -ve voltage is applied at metal → accumulation of holes occurs at the interface btw the Oxide and semicondu-tor. → As a result the bands will bend upward

In insulator voltage drop is linear but for semiconduct non linear.
Voltage drop accross oxide layer is maximum and the remaining voltage will drop accross the semiconductor

and gradually become zero.



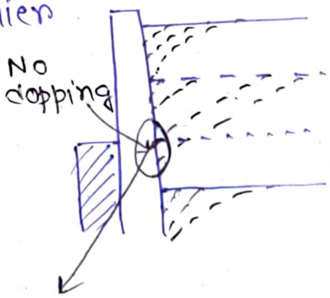

$\psi_B = \frac{KT}{q} \ln\left(\frac{N_A}{n_i}\right)$
↓
Shift of fermi level

Dopping increases → shift of fermi level increases

$N_A$ → Dopping concentration
$n_i$ → Intrinsic carrier concentration
Intrinsic carrier concentration ↑ → ~~Resis~~ Resistance ↓ → Band gap ↓.

How does an inversion layer form?
As voltage increases → holes repels → $\psi_B$ decreases → bending become flat

More increase of voltage → fermi level bends downward → At a certain ~~point~~ time it will overlap with the intrinsic carrier concentration → No majority carrier →
No dopping, only minority carrier due to AC current → Intrinsic semiconductor (0 volt) → And Gradually become n-type as minority carrier increase



MOSFET → uni polar device

Two orthogonal electric field work together to initate the operation of a MOSFET. Vertical field applied from the gate creates a channel for the carriers and lateral electric field drags the carrier from source to the drain, leading to generate a current along the channel.

Vertical electric field → create the channel

Horizontal " " → takes the advantage of channel

Silicide is used instead of pure metal → Resistivity reduced → RC time constant decreases → Device become faster.

**Lecture: 2** Prof: Abhijit Mullick 8.09.2023

Location of Fermi level in intrinsic semiconductor →

$$n_i = p_i$$

$$\Rightarrow N_c e^{-(E_c - E_F)/kT} = N_v e^{-(E_F - E_v)/kT} \Rightarrow \frac{N_c}{N_V} = e^{-(E_F - E_v) + \ldots}$$

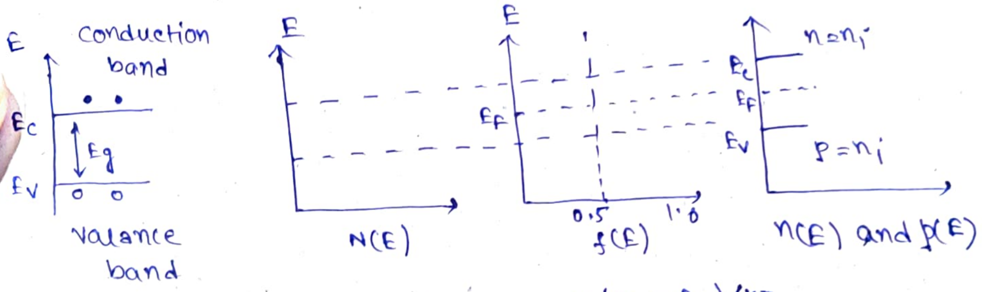
$$\Rightarrow \cancel{+E_c + E_F} = \cancel{-E_F + E_v}$$

$$\Rightarrow \cancel{2E_F = E_c + E_v}$$

$$\Rightarrow \cancel{E_F = \frac{E_c + E_v}{2}}$$

$$E_F = \frac{E_c + E_v}{2} - \frac{KT}{2} \ln \frac{N_c}{N_v}$$

$$= \frac{E_g}{2} - \frac{3RT}{4} \ln \frac{m_n^*}{m_p^*}$$




$$n_0 = N_c e^{-(E_c - E_F)/kT} \cdot \quad p_0 = N_v e^{-(E_F - E_v)/kT}$$

$$n_0 p_0 = N_c N_v e^{-(E_c - E_v)/kT} = N_c N_v e^{-E_g/kT}$$

For intrinsic material $E_F = E_i$ and $n_i = p_i$

$$\therefore n_i = N_c e^{-(E_c - E_i)/kT} \quad p_i = N_v e^{-(E_i - E_v)/kT}$$

$$\therefore n_i p_i = n_i^2 = N_c N_v e^{-E_g/kT} = n_0 p_0$$

$$n_i = 2 \left( \frac{2\pi kT}{h^2} \right)^{3/2} (m_n^* m_p^*) e^{-E_g/2kT}$$

$$E_g = E_{g0} - \beta T \; ; \; E_{g0} \text{ is } E_g \text{ at } T = 0°K$$

Dopping levels are non interacting / discrete because doping density is low (~ 1 dopped particle in 1 M Si atoms)

# Carrier Concentration and Doping:

Since the semiconductor charge is neutral

$$\rho = -q n_0 + q p_0 - q N_a + q N_d = 0$$

free $e^-$, free hole, acceptor, donor

$$\Rightarrow q(p_0 - n_0 + N_d - N_a) = 0$$

$$\Rightarrow n_0^2 - (N_d - N_a) n_0 - n_i^2 = 0 \quad \text{as } p_0 = \frac{n_i^2}{n_0} \quad \text{for } N_d > N_a$$

$$\Rightarrow n_0 = \frac{N_d - N_a}{2} + \frac{N_d - N_a}{2}\sqrt{1 + \frac{4 n_i^2}{(N_d - N_a)^2}}$$

$$= N_d - N_a \quad \text{as } N_d - N_a >> n_i$$

$$= N_d \quad \text{if } N_a = 0$$

$$\therefore n_0 = N_d \text{ and } p_0 = \frac{n_i^2}{N_d}$$

For p type $p_0 = N_a$ and $n_0 = \frac{n_i^2}{N_a}$

Carrier concentration, fermi level and quasi fermi level:

$$n_0 = N_c e^{-(E_c - E_F)/kT} = N_c e^{-(E_c - E_i)/kT} \cdot e^{(E_i - E_F)/kT} = n_i e^{(E_F - E_i)/kT}$$

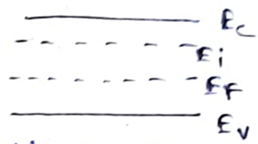
$$p_0 = N_v e^{-(E_F - E_v)/kT} = N_v e^{-(E_i - E_v)/kT} \cdot e^{(E_i - E_F)/kT} = n_i e^{(E_i - E_F)/kT}$$

Non equilibrium state

↳ Quasi fermi level:

$$n = n_i e^{(E_{Fn} - E_i)/kT}$$

and $p = n_i e^{(E_i - E_{Fp})/kT}$




In non equilibrium situation Law of Mass action will not be valid.

Let, $n_i = 10^{10}$    $n_0 = N_D = 10^{16}$ /cm$^3$

$N_D = 10^{16}$ atoms/cm$^3$    $p_0 = \frac{n_i^2}{n_0} = \frac{10^{20}}{10^{16}} = 10^4$ /c.m$^3$

Degenerate semiconductor:

when $N_D \gg N_c$ or $N_A \gg N_v$

one can't use $f(E) = e^{-(E - E_F)/kT}$

$$\therefore n_0 = \int_{E_c}^{\infty} N_c(E) f(E)\, dE \qquad p_0 = \int_{-\infty}^{E_v} N_v(E)\,[1 - f(E)]\, dE$$

can be estimate numerically

For heavily dopped semiconductor $E_F$ is either above $E_c$ or below $E_v$ → degenerate semiconductor.

Extrinsic region → No change in carrier concentration

At low temp. thermal energy is not sufficient to ionize all the donor ipurity atom and therefore $n_0 < N_D$. Also $n_0$ increase as T increases. → Freeze out region

At some temp. the .

MOSFET Lecture - 8 (SC Sir) Date : 15.9.20

The purpose of Gate is to create channel.
Mosfet is terms of operation is of two types → [ Depletion mode / Enhancement ]

Depletion mode is naturally on because we get a current between source and drain in the absence of any gate voltage. So we have to apply some voltage to fix this current at zero.

Enhancement → naturally off → Gate voltage is needed to on

On application of voltages at the gate and S/D regions current flows through the channel.

Soure and drain are highly dopped → $5\times10^{19}\ cm^{-3}$ – $1\times10^{20}\ cm^{-3}$
↳ Ensures to get proper ohomic contact

Channel has moderate doping → If we increase the doping to increase the conductivity ~~after~~ a → 1st current increases but after a certain time the current starts decreasing due to scattering.

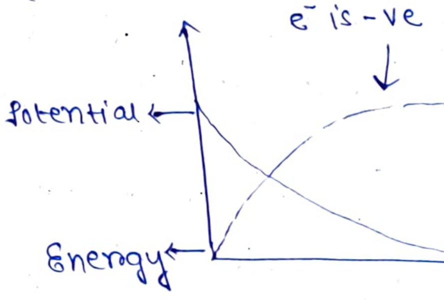
SWS → side wall space ($Si_4N_3$)

Band bending is the amount of voltage drop across the depth of the substrate.

- When a voltage is applied at the gate and another potential or voltage is applied at the drain then the effective potential at any point in the channel will be the difference btw the two voltage. → Channel potential.

Therefore the net potential at any point in the channel will be the resultant value for both the gate voltage and the drain voltage.
Here two electric ~~electric~~ field (vertical and horizontal) act together.

When only gate voltage is applied
→ No lateral electric field
→ Band bending occurs but no current flow as $V_d = 0$
(Equipotential surface) → But as we ...



If you apply ~~drain~~ gate bias only then it will create a channel which is totally uniform from the source to the drain. Now at this situation if you apply a reverse bias at the drain then the amount of inversion charge at the drain region at the channel will be compensated by the depletion charge induced by the applied drain reverse bias. At the voltage when the total inversion charge at the drain ~~...~~-channel junction then the channel at that point will no longer preveal. This particular situation is called the pinch of situation.

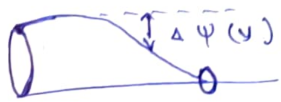
**Charge Sheet Model:**

- channel is very thin → no voltage drop across it
- vertical electric field is very high compared to lateral electric field

$V_c = V_g - V_d \qquad V_g > V_D \rightarrow$ channel exist

- Total charge at the side is equal to the net charge in semiconductor side

$$E_{ox} = \frac{V_G - \psi_s}{t_{ox}}$$ → voltage drop across gate




$$= \frac{V_G - (2\psi_B + \Delta\psi(y))}{t_{ox}}$$

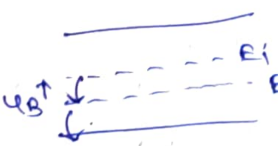
Drain votage drop at ~~...~~ the given point

$\psi_B \rightarrow$ Measure of degree of p-type nature

strong inversion → $2\psi_B$

~~...~~ Amount of p type has to be replaced by amount of n-type

ie; $(\psi_B - (-\psi_B)) = 2\psi_B$




Depletion charge

$Q_B = -qN_A W_m$

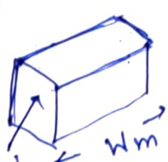
$W_m$ : Maximum Depletion width

$N_A$ : Doping concentration

$q$ : Electronic charge

$$Q_B = -qN_A W_B$$

$$= -\sqrt{2qN_A \epsilon_s (V_D + 2\psi_B)}$$ unit area




Dielectric constant of semiconduction

$$E_s = \sqrt{\frac{2q(2\psi_B + \Delta\psi(y))}{\epsilon_s}}$$

The charge in the inversion layer is given by

$$|Q_n(y)| = [V_G - \Delta\psi(y) - 2$$

$$- \sqrt{2\epsilon_s q N_A (2\psi$$

$I_D(y) = W \cdot |Q_n(y)| \, v(y)$ → Current per unit channe[l] length through a cross-se[ction] at a point y from the sour[ce] channel interface. W is the w[idth] of the device

$v(y) = \mu E(y) = \mu \cdot \frac{\Delta\psi(y)}{dy}$

Electric field at Channel

Aspect ratio

$I_D = \left(\frac{W}{L}\right) \mu C_{ox} (V_G - V_{th}) V_D$

$V_{th} = 2\psi_B + \frac{\sqrt{2\varepsilon_s q N_A (2\psi_B)}}{C_{ox}}$

Thresold voltage → Minimum gate voltage required to create an inversion layer in a MOSFET

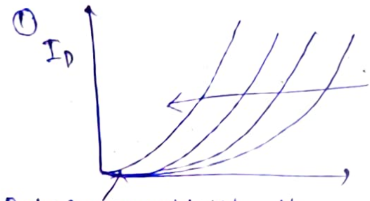
Dopping of the channel increases → $V_{th}$ increases

$C_{ox} = \frac{\varepsilon_{ox}}{t_{ox}}$ $V_{th} \propto t_{ox}$ so $t_{ox} \uparrow$ → $V_{th} \uparrow$

① Transfer Characteristic → $(I_D - V_G)$

② Output Characteristic → $(I_D - V_D)$

①

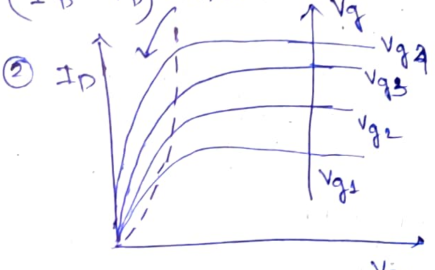



Below thresold vol. $V_G$

Transferr

~~Lecture-3 (AM SIR)~~

②




output characteristic

15.09.2[…]

After crossing the thresold value the current start increasing → After a certain time channel will behave as a resistor → Give linear characteristic

Before subthreshold region → Governed by diffussion mechanism

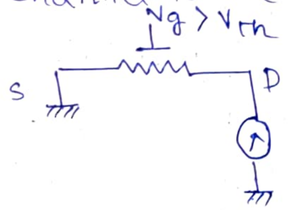
After threshold region → Governed by drift motion

After that → pinch off → saturation region

Thats why MOSFET Used as switch

$V_g - V_{th} = V_D$ → Starting of pinch off

$V_{g1}$ is just above $V_{th}$ → channel formed




$(V_g - V_{th}) > V_D$ → chann[el] exists

$V_D$ increase → At a certain term $(V_g - V_{t[h]})$ $= V_D$ → Gate over drive → This condition is 1st reached btw the chan[nel] end and drain

$(V_g - V_{th})$ creates ~~deplet~~ inversion charges bu[t] $V_d$ destroy it

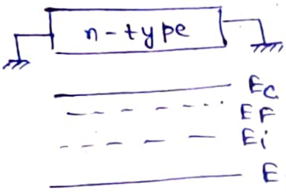
The influence of crystal lattice is incorporated in the effective mass.

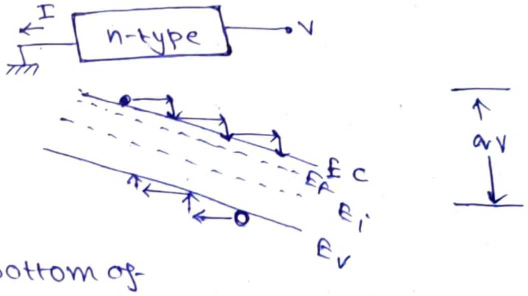
As per theorem of equipartition of energy, average thermal energy is $\frac{1}{2}kT$ per degree of freedom

$\therefore$ K.E of $e^-$ $\frac{1}{2} m_n^* v_{th}^2 = \frac{3}{2}kT$

$$\Rightarrow v_{th} = \sqrt{\frac{3kT}{m_n^*}} \sim 10^7 \text{ cm/s for Si}$$

The $e^-$ therefore move rapidly in all dir. and suffer random scattering from collision with lattice atoms, impurity ions and others. The scattering centers resulting in zero net displacement over a sufficiently long time. The average distance between collision is called mean free path and the average time between two collision is known as mean free time.




$e^-$ prefferes to remain at the bottom of CB and hole at the Top of the VB } → lowest energy

$\vec{\mathcal{E}}$ applied to the semiconductor → $e^-$ experience a force $-q$ that will accelarate them along the field during the time of coulission. Therefore an aditional vel. comp. v called drift vel. is superimposed upon $V_{th}$.

$$-q\vec{\mathcal{E}}\,\underset{\text{mean free time}}{\tau_{cn}} = m_n^* v_d$$

$$\Rightarrow v_{dn} = \frac{-q\tau_c}{m_n^*}\vec{\mathcal{E}} = -\mu_n\vec{\mathcal{E}} \quad \text{where } \mu_n = \frac{q\tau_{cn}}{m_n^*}$$

$$\text{Similarly } v_{dp} = \mu_p\vec{\mathcal{E}} \;;\; \mu_p = \frac{q\tau_{cp}}{m_p^*}$$

$$J_n = -nqv_{d,n} = nq\mu_n\vec{\mathcal{E}} \;;\; J_p = nq\mu_p\vec{\mathcal{E}}$$

$$\therefore J = J_n + J_p = q(n\mu_n + p\mu_p)\vec{\mathcal{E}} = \sigma\vec{\mathcal{E}}$$

$$\text{where } \boxed{\sigma = q(n\mu_n + p\mu_p)} \quad \therefore R = \rho\frac{l}{A} = \frac{1}{\sigma}\frac{l}{A}$$

s lattice vibrations increase with temparature, mobility is educed following $\mu_L \propto T^{-3/2}$.

rrier scatering
- lattice scattering → Results from therm vibration of lattice c $T > 0°K$
- Impurity scattering → Results from colo force interaction

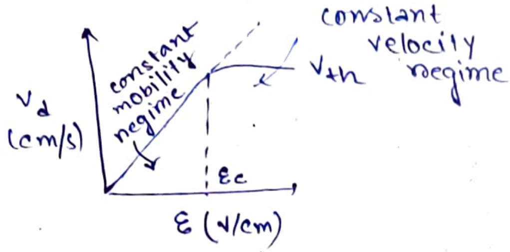
purity scattering decreases with increasing temparature fast moving carrier is likely to be scattered less than a rrier with less momentum. Hence $\mu_I \propto T^{3/2}$

$1/\tau_c \rightarrow$ the no. of collission taking place in unit time.

$$\frac{1}{\tau_c} = \frac{1}{\tau_{c,\,lattice}} + \frac{1}{\tau_{c,\,impurity}}$$

or, $$\boxed{\frac{1}{\mu} = \frac{1}{\mu_L} + \frac{1}{\mu_I}}$$

## High field Effect





## Diffusion of Carriers

$\frac{1}{2}$ of the $e^-$ at $x = -l$ will move left to right across the plane $x = 0$ in a free time $\tau_c$. Hence the average rate of $e^-$ flow per unit area across the plane $x = 0$ is then $F_1 = \frac{\frac{1}{2} n(-l) \cdot 1 \cdot l}{\tau_c}$

$= \frac{1}{2} n(-l)\, v_{th}$ $\left[\text{As } \frac{l}{v_{th}} = \tau_c \Rightarrow v_{th} = l/\tau_c\right]$

similarly av. rate of $e^-$ at $x = l$ crossing the plane $x = 0$ is $F_2 = \frac{1}{2} n(l) \cdot v_{th}$

Particle flux $F \propto -\frac{dc}{dx} = -D\frac{dc}{dx}$

Net rate of $e^-$ flow from left to right

$F = F_1 - F_2 = \frac{1}{2} v_{th}\left[n(-l) - n(l)\right]$

Approximating the densities at $x = \pm l$

$$F = \frac{1}{2} v_{th} \left\{ \left[n(0) - l\frac{dn}{dx}\right] - \left[n(0) + l\frac{dn}{dx}\right] \right\}$$

$$= -v_{th}\, l \frac{dn}{dx} = -D_n \frac{dn}{dx} \rightarrow \text{Fick's 1st law}$$

$D_n \rightarrow$ Diffusivity

$$J_{n,\,diffusion} = -qF = q D_n \frac{dn}{dx}$$

$$J_{p,\,diffusion} = -q D_p \frac{dp}{dx}$$

$$J_n = q \mu_n n \vec{\mathcal{E}} + q D_n \frac{dn}{dx} \qquad J = J_n + J_p$$

$$J_p = q p \mu_p \vec{\mathcal{E}} - q D_p\, dp/dx$$

## Einstein's Relation:

$$v_{th} = \sqrt{\frac{3KT}{m^*}}, \quad \mu = \frac{q\tau_c}{m^*}, \quad D = \frac{1}{3} v_{th}\, l$$

$$l = v_{th} \cdot \tau_c \Rightarrow v_{th} = l/\tau_c$$

$$\frac{D}{\mu} = \frac{\frac{1}{3} v_{th}\, l}{\frac{q\tau_c}{m^*}} = \frac{1}{3} v_{th}\, l \times \frac{m^*}{q\tau_c} = \frac{1}{3} v_{th}^2 \frac{m^*}{q}$$

$$\Rightarrow \boxed{\frac{D}{\mu} = \frac{KT}{q}}$$

Continuity Equation for Minority Carriers:

$$\frac{\partial p(x,t)}{\partial t} \cdot A\Delta x = \frac{J_p(x)A}{q} - \frac{J_p(x+\Delta x)A}{q} + (G-R)A\Delta x$$

or $$\frac{\partial p(x,t)}{\partial t} = \frac{1}{q}\frac{J_p(x) - J_p(x+\Delta x)}{\Delta x} + G - R$$

$G-R$ = zero is there is no source or sink

As $\Delta x$ approaches zero

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{\delta p}{\tau_p} \text{ in n-type material}$$

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{\delta n}{\tau_p} \text{ in p-type material}$$

$G \rightarrow$ Generation rate ; $R \rightarrow$ Recombination rate

$G = R \propto n_0 p_0 = c n_i^2$

Direct recombination $\longrightarrow$ Radiative

**Minority carrier life time:**

Let us assume that at $t=0$, EHP's are created by a short pulse of light and initial excess $e^-$ and hole conc. are equal i.e; $\Delta n = \Delta p$. Consider that $\delta n(t)$ and $\delta p(t)$ are excess $e^-$ and $h^+$ concentration at $t = t > 0$

$$\frac{dn(t)}{dt} = G - R = cn_i^2 - c[(n_0 + \delta n(t))(p_0 + \delta p(t))]$$

$$= cn_i^2 - cn_i^2 - c[n_0 \delta p(t) + p_0 \delta n(t) + \delta n(t)\delta p(t)]$$

For low level injection [$\delta n(t)\,\delta p(t)$ is neglected]

$$\frac{dn(t)}{dt} = \frac{d\,\delta n(t)}{dt}$$

$$= -cn_0\delta p(t) - cp_0\delta n(t) \longrightarrow [n(t) = n_0 + \delta n(t)]$$

For p-type $n_0\delta p(t) \ll p_0 \delta n(t)$

$$\frac{d\,\delta n(t)}{dt} = -cp_0\delta n(t)$$

$$\Rightarrow \delta n(t) = \Delta n\, e^{-cp_0 t} = \Delta n\, e^{-t/\tau_n}$$

$\tau_n = 1/cp_0 \rightarrow$ Recombination life time

Similarly for n-type

$$\delta p(t) = \Delta p\, e^{-t/\tau_p} \; ; \; \tau_p = \frac{1}{cn_0}$$

Indirect Recombination $\rightarrow$ Using Traps and recombination center

- $e^-$ capature
- $e^-$ emission
- hole capture
- hole emission

$$G = R = cp_0 n_0 = \frac{n_0}{\tau_n}$$

$$G - R = \frac{n_0}{\tau_n} - \frac{n}{\tau_n}$$ ← Conc. changes with time

$$= -\frac{\delta n}{\tau_n}$$ [As we consider $n_0 < n$]

Lecture - 1 (SC SiR)    22.9.2023

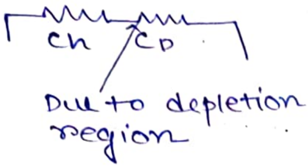
for $(V_g - V_{th}) < V_D$

$V_g$ reducing

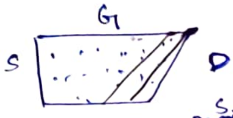
$V_g \rightarrow$ creates inversion charge. so inversion charge is minimum at the bottom

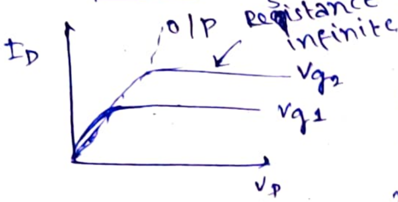
$\leftarrow$ reducing $V_D$

But for ~~gate~~ of $V_D$ effect is less at the source $\rightarrow$ so due to $V_D$ the charges at the bottom of the channel will destroy fast and it gradually decreases at the upper layer as there inversion charge is more.




So now after pinch of depletion region is created which acts as another resistor $\rightarrow$ Now two resistor in series $\rightarrow$ effective resistance is more




For two resistor in series voltage drop is more across the depletion region $\rightarrow$ so even we increase voltage current will no longer increased $\rightarrow$ saturated

o/p Resistance infinite because $dI = 0$  $R = \frac{dV}{dI}$

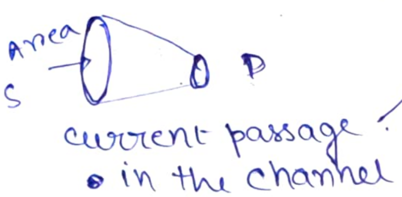
~~i/p " zero almost~~

$(V_g - V_{th}) \rightarrow$ Effective voltage

$V_D$ is ~~creating~~ dragging charges from source to drain $\rightarrow$ creates lateral electric field

~~a~~ when vertical field = lateral electric field $\rightarrow$ channel will destroy

Inversion charges are neutralised by depletion charges




carrier accumation must occurs $\rightarrow$ But it will violate continuity eqn.

But actually the velocity of the $e^-$ will ~~the~~ increase from source to drain $\rightarrow$ Because $E \propto V_d \rightarrow$ As electric field ~~xxx~~ increases from source to drain

lower the $V_{th} \rightarrow$ Power consumption is low

leakage current $I_{off} \rightarrow$ should be low $\rightarrow$ ~~because~~ to reduce static power dissipation.

$I_{on} \rightarrow$ increases $\rightarrow$ power dissipation increases but fan out also increases $\rightarrow$ so longer circuit can be drive

Noise margin will be more $\rightarrow$ If $I_{ON} / I_{OF}$ is large

$\hookrightarrow$ Interference of digital data decreases

- Trans-conductance $g_m \rightarrow \frac{dI}{dG}$ in const. $V_D$
  ↳ more → steepness of graph more → good
- out put " → $\frac{dI_d}{dV_d}$ at constant $V_G$
- Drain voltage should be less but if the voltage is very much less then the carrier velocity will decrease. → so to get rid of it mobility ~~so~~ should be increased

source drain resistance depends on the application.

**Lecture-4 (AMSIR)** 22.9.2023

p type

$N_A \, cm^{-3}$

$p_{p0} = N_A \, cm^{-3}$

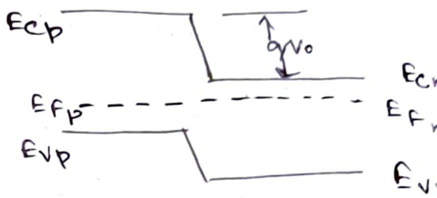
$n_{p0} = \frac{n_i^2}{N_A} \, cm^{-3}$

n-type

$N_D \, cm^{-3}$

$n_{n0} = N_D$

$p_{n0} = n_i^2 / N_D$




| Particle flow | | Current |
|---|---|---|
| → | Hole diffusion | → |
| ← | Hole drift | ← |
| ← - - | $e^-$ diffusion | - - → |
| - - → | $e^-$ drift | ← - - |

Hole drift will be small

**Juction Diode: contact potential:**

In equilibrium

$$J_p = J_n = 0$$

$$J_p = q\mu_p p \vec{E} - qD_p \frac{dp}{dx} = 0$$

$$\Rightarrow q\mu_p p \vec{E} = qD_p \frac{dp}{dx}.$$

$$\Rightarrow -\frac{\mu_p}{D_p} dV(x) = \frac{dp(x)}{dx} \quad \left[\because \vec{E}(x) = -\frac{dV(x)}{dx}\right]$$

$$\Rightarrow -\frac{q}{KT} \int_{V_p}^{V_n} dV(x) = \int_{p_{p0}}^{p_{n0}} \frac{dp(x)}{p(x)}$$

$$\Rightarrow -\frac{q}{KT}(V_n - V_p) = \ln \frac{p_{n0}}{p_{p0}}$$

$$V_0 = V_n - V_p = \frac{KT}{q} \ln \frac{p_{n0}}{p_{p0}}$$

$$p_{p0} = p_{n0} e^{\frac{qV_0}{KT}}.$$

$$n_{p0} = n_{n0} e^{-qV_0/KT}$$

$p_{p0} = N_A$ and $p_{n0} = \frac{n_i^2}{N_D}$

$$\therefore \boxed{V_0 = \frac{KT}{q} \ln \frac{N_A N_D}{n_i^2}}$$

$$\frac{p_{p0}}{p_{n0}} = e^{qV_0/KT} = \frac{N_v e^{-(E_F - E_{vp})/KT}}{N_v e^{-(E_F - E_{vn})/KT}}$$

$$\Rightarrow e^{qV_0/KT} = e^{(E_{vp} - E_{vn})/KT}$$

$$\boxed{qV_0 = E_{vp} - E_{vn}}$$

Charge density:

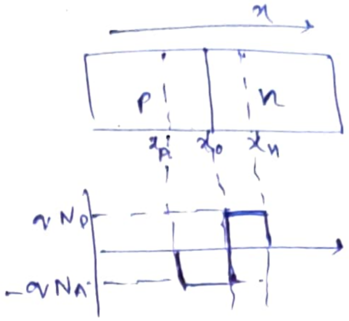
$\rho(x) = q(N_D - N_A + p - n)$

$\rho(x) = 0$ for $0 \le x \le x_p$

$= -qN_A$ for $x_p < x < x_0$

$= qN_D$ for $x_0 < x < x_n$

$= 0$ for $x \geq x_n$




Abrupt juction
doping changes abruptly at the junction

Poisson's Equation:

$$\frac{d^2\varphi(x)}{dx^2} = -\frac{\rho(x)}{\epsilon}$$

$$\Rightarrow \frac{d^2\varphi_p(x)}{dx^2} = \frac{qN_A}{\epsilon_s} \quad \text{for } x_p < x < x_0 \quad \text{---(1)}$$

$$\frac{d^2\varphi_n(x)}{dx^2} = -\frac{qN_D}{\epsilon_s} \quad \text{for } x_0 < x < x_n \quad \text{--(2)}$$

Boundary conditions

$\varphi_p(x_0) = \varphi_n(x_0)$ ---(3)

$\varphi_p(x) = 0$ for $x \le x_p$ --(4)

$\varphi_n(x) = V_0 - V$ for $x \geq x_n$ --(5)

$V \rightarrow$ Applying potential to the n-side.

$$\frac{d\varphi_p(x_0)}{dx} = \frac{d\varphi_n(x_0)}{dx} \quad -$$

$$\frac{d\varphi_p(x)}{dx} = 0 \quad \text{for } x \le \text{--}$$

$$\frac{d\varphi_n(x)}{dx} = 0 \quad \text{for } x \geq \text{---}$$

Integrating eq. (1) and applying (7)

$$\frac{d\varphi_p(x)}{dx} = \frac{qN_A}{\epsilon_s}(x - x_p) \quad \text{----(9)} \quad x_p < x < x_0$$

Integrating eqn. (2) and applying (8)

$$\frac{d\varphi_n(x)}{dx} = \frac{qN_D}{\epsilon_s}(x_n - x) \quad \text{-----(10)} \quad \text{for } x_0 <$$

$$\vec{\mathcal{E}}(x) = \frac{d\varphi}{dx}$$

Integrating (9)

$$\varphi_p(x) = \frac{qN_A}{2\epsilon_s}(x - x_p)^2 \quad \text{------(11)} \quad x_p <$$

Integrating (10)

$$\varphi_n(x) = -\frac{qN_D}{2\epsilon_s}(x_n - x)^2 + (V - V) \quad \text{--(12)} \quad x_0 <$$

$$W = \left[\frac{2\epsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 - V)\right]^{1/2}$$

Junction capacitance

$|Q^+| = qA(x_n - x_0) N_D$ and $|Q^-| = qA(x_0 - x_p) \cdot N_A$

$Q = |Q^+| = |Q^-|$

$= qA(x_n - x_0) N_D = qAN_D \frac{N_A}{N_A + N_D} \cdot W$

$= qA \frac{N_A N_D}{N_A + N_D} \left[ \frac{2\epsilon_s}{q} \frac{N_A + N_D}{N_A N_D} (V_0 - V) \right]^{1/2}$

$= A \left[ 2\epsilon_s q \frac{N_A N_D}{N_A + N_D} \right]^{1/2} (V_0 - V)^{1/2}$

$C_j = \left| \frac{dQ}{dV} \right| = \left| A \left( 2\epsilon_s q \frac{N_A N_D}{N_A + N_D} \right)^{1/2} \cdot \frac{1}{2} (V_0 - V)^{-1/2} (-1) \right|$

$= A \left[ \frac{\epsilon_s q}{2} \left( \frac{N_A N_D}{N_A + N_D} \right) \right]^{1/2} (V_0 - V)^{-1/2}$

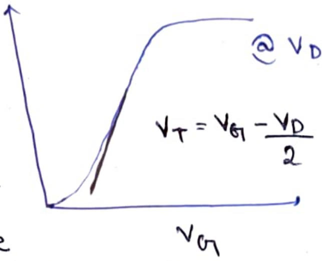
$$\boxed{C_j = \frac{\epsilon_s A}{W}}$$

As $C_j$ depends on V so it is called Variable Reactorr

Lecture - 5 (SC SIR) 29.09.202

The minimum voltage required to accumulate sufficient amoun of inversion charge → Threshold voltage.

Threshold voltage increases with
- the increase of substrate doping concentration
- the oxide thickness → As the votage drop ~~xxx~~ across the oxide become more
- The difference between the metal and semiconductor work functions.




when $I_D = 0$
$V_g = V_{th}$
as $I_D = \frac{W}{L} C_{ox} \mu (V_g - V_t$

$$V_{th} = V_{FB} + 2\psi_B + \frac{\sqrt{2\epsilon_s q N_A (2\psi_B)}}{C_{ox}}$$

More inversion voltage is required → (As already a band bending is present) → so to mange it more voltage is required.

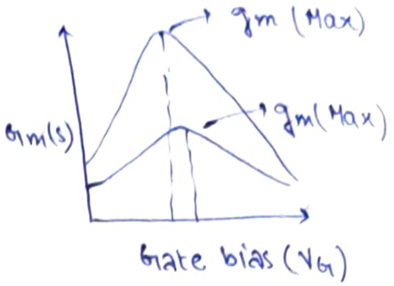
$I_{off}$ is the root cause of static power dissipation

$I_{ON}$ sets up the driving capability of a device if it is at a output of a circuit. It also indicates the level of dynamic power dissipation.

$I_{off}$ Good → $I_{ON}$ Bad → so we consider a new parameter

$I_{ON}/I_{Off}$

Trans conductance ($g_m$) →




$$I_D = \frac{\varepsilon_{ox}\varepsilon_0 \mu}{t_{ox}} \frac{W}{L} (V_G - V_{th}) V_D$$

$$g_m = \left.\frac{\partial I_D}{\partial V_G}\right|_{V_D = const.}$$

$$= \frac{\mu \varepsilon_{ins} \varepsilon_0}{t_{ox}} \frac{W}{L} V_{DS}$$

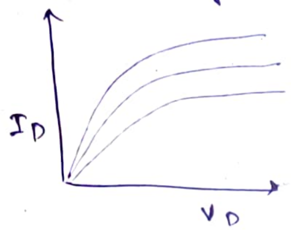
In the linear region gradient is maximum → $g_m$(Max)

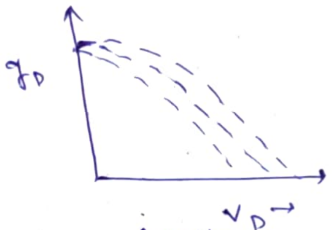
Trans conductance large → High speed device

Rate of change of drain current w.r.t gate voltage for a given drain voltage → Transconductance

Rate of change of drain current w.r.t drain voltage for a given gate voltage → Output conductance

$$g_d = \left.\frac{\partial I_D}{\partial V_D}\right|_{V_G = const.} = \frac{\mu \varepsilon_{ins} \varepsilon_{ox}}{t_{ox}} \frac{W}{L} (V_{gs} - V_{th})$$




At saturation region resistance is tending to infinite → conductance almost tending to zero.

Sub threshold Swing (SS):

Direct measurement of the speed of the MOSFET.

- It is the voltage required to change the drain current by one decade.
- It is the inverse of sub threshold slope.

$$SS = \left(\frac{d(\log_{10} I_D)}{dV_G}\right)^{-1} = \ln(10) \cdot \frac{k_B T}{q} \left(1 + \frac{C_D}{C_{ox}}\right)$$

For classical mosfet $\frac{C_D}{C_{ox}}$ has finite value

SS has a minimum value (60mV / decade) → Speed limitation. (At $T = 300K$ and $C_D = C_{ox}$ is close to zero)

SS lower → Faster MOSFET

- Performance improves.

Geometric parameter
width (W)
Gate length ($L_g$)
and oxide thickness

Material parameter
$\mu$ and
$\epsilon$

W must increase but it will affect device integrity (large no. of device sho component should accumulate in a small chip) → so tox and L must decreases to improve the performance. (Down scalling)
('The gradual miniaturisation of device dimension has been the preffered rule of mosfet technology'.

Target
- More functionality
- Higher packing density
- Higher speed
- less power consumption

Constant field scalling → ratio of vertical and lateral electric field should remain same.

If you continue to scale down the MOSFET device dimension then if the scalling is not performed in both the lateral and vertical dimensions then it may happen that the lateral electric field will be more than the virtical electric field. At this situation the virtical electric field will loose the control over the MOSFET. This situation is called the loss of electrostatic integrity of the device.

If the capacitance of the MOSFET remains unchanged → then other parameters will also remains constant

$$C = \frac{\varepsilon_{SiO_2}}{t_{SiO_2}} = \frac{\varepsilon_{hk}}{t_{hk}}$$ → Changing $\varepsilon$ and t in such a way so that C remains constant

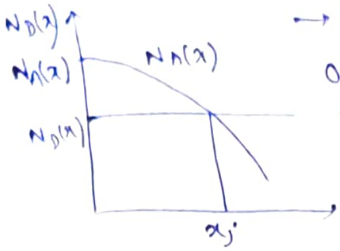
$$t_{hk} = \frac{\varepsilon_{hk}}{\varepsilon_{SiO_2}} t_{SiO_2}.$$

ultra thin $SiO_2$ will give huge amount of leakage current → Not good → so we have to change the material → $\varepsilon$ change so $t_{hk}$ will increase → less leakage current.

High-k → High dielectric constant material ($HfO_2$, $TiO_2$, $La_2O_3$, $ZrO_2$, $Ta_2O_5$). Best

Benefit of scalling:
$I_{DS}$ ↑ as L ↓ (decreased effective R)
Gate area ↓ as L ↓ (decreased load 'C')
Therefore RC ↓ (implies faster switch)

Lecture-5 (AM SIR)




→ Linearly Graded junction

Only Minority carriers are affected by the applying electric field.

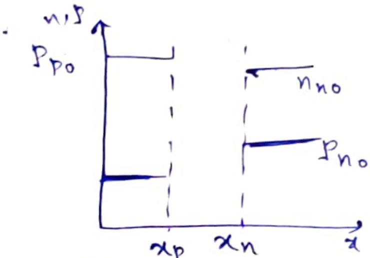
Diffussion happes for majority carrier.

Diffussion is opposed by the electric field

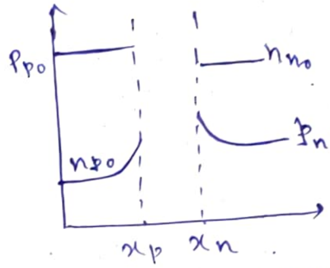
After applying forward bias → Minority carrier is less → Drift current is less.

The role of bias is to reduce the junction potential.

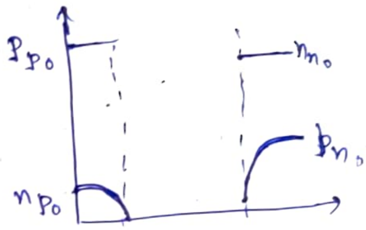
Reverse bias → we will get reverse saturation current due to the drift of minority carrier.




Equilibrium




Forward bias




Reverse bias

$$p_{po} = p_{no}\, e^{qV_0/KT}$$

$$n_{no} = n_{po}\, e^{qV_0/KT}$$

$$p_p(x_p) = p_n(x_n)\, e^{\frac{q(V_0-V)}{KT}}$$

$$p_{po} = p_n(x_n)\, e^{q(V_0-V)/KT}$$

$$p_n(x_n) = p_{po}\, e^{-qV_0/KT}\, e^{qV/KT}$$

$$p_n(x_n) = p_{no}\, e^{qV/KT}$$

and $n_p(x_p) = n_{po}\, e^{qV/KT}$

Reverse bias

$$p_p(x_p) = p_n(x_n)\, e^{q(V_0+V)/KT}$$

$$p_{po} = p_n(x_n)\, e^{q(V_0+V)/KT}$$

I-V Characteristic →

$$\frac{\partial p(x,t)}{\partial t} = -\frac{1}{q}\frac{\partial J_p}{\partial x} - \frac{p-}{\tau_p}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{\partial J_n}{\partial x} - \frac{n-n}{\tau_n}$$

Outside the depletion reg

$\bar{\mathcal{E}} = 0$

$$\frac{\partial J_p}{\partial x} = \frac{\partial}{\partial x}\left(p q \mu_p \bar{\mathcal{E}} - qD\right.$$

$$= -qD_p \frac{\partial^2}{\partial x}$$

$$\frac{\partial J_n}{\partial x} = qD_n \frac{\partial^2 n}{\partial x^2}$$

Hence $\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \frac{p - p_0}{\tau_p}$

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} - \frac{n - n_0}{\tau_n}$$

steady state $\frac{\partial p}{\partial t} = \frac{\partial n}{\partial t} = 0$

$$\therefore \frac{d^2 p}{dx^2} = \frac{p - p_{no}}{D_p \tau_p} \quad [\text{As } p_0 = p_{no} \text{ at } n \text{ side}]$$

$$\frac{d^2 n}{dx^2} = \frac{n - n_{po}}{D_n \tau_n} \quad [\text{As } n_0 = n_{po} \text{ at } p\text{-side}]$$

$$\frac{d^2(p - p_{no})}{dx^2} = \frac{p - p_{no}}{L_p^2} \quad [L_p = \sqrt{D_p \tau_p} \text{ is called diffusion length of holes}]$$

$$\frac{d^2(n - n_{po})}{dx^2} = \frac{n - n_{po}}{L_n^2} \quad [L_n = \sqrt{D_n \tau_n}, \text{ diffusion length of } e^-]$$

There is a average distance upto which $e^-$ and holes can diffuse → Diffusion length

Sol: $p - p_{no} = A e^{x/L_p} + B e^{-x/L_p}$

Since $p = p_{no}$ at $x = \infty$, $A = 0$

$$\therefore p - p_{no} = B e^{-x/L_p}$$

Again $p = p_n(x_n)$ at $x = x_n$

$$\Rightarrow B = [p_n(x_n) - p_{xo}] e^{x_n/L_p}$$

$$= (p_{no} e^{qV/KT} - p_{no}) e^{x_n/L_p}$$

$$p - p_{no} = p_{no}(e^{qV/KT} - 1) e^{-(x - x_n)/L_p}$$

$$\delta p(x) = \Delta p_{x_n} e^{-(x - x_n)/L_p}$$

$$J_p = -q D_p \frac{\partial p}{\partial x} = -q D_p p_{no} (e^{qV/KT} - 1) e^{-(x - x_n)/L_p} \left(-\frac{1}{L_p}\right)$$

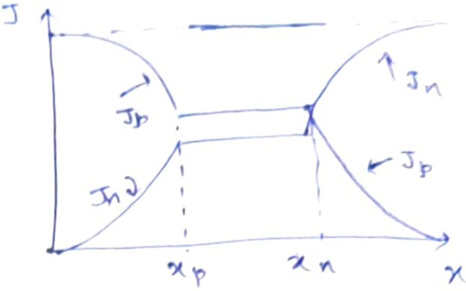
$$= q \frac{D_p}{L_p} p_{no} (e^{qV/KT} - 1) e^{-(x - x_n)/L_p}$$

$$\therefore J_p \big|_{x = x_n} = q \frac{D_p}{L_p} p_{no} (e^{qV/KT} - 1)$$

for p region

$$J_n(x) = q D_n \frac{\partial n}{\partial x} = q \frac{D_n}{L_n} n_{po} (e^{qV/KT} - 1) e^{-(x_p - x)/L_n}$$

$$J_n \big|_{x = x_p} = q \frac{D_n}{L_n} n_{po} (e^{qV/KT} - 1)$$




holes are recombined with the $e^-$ from the n-side after diffusion
→ So no. $e^-$ decreases but as the n-side is connected with the -ve terminal of the battery so ~~it~~ it will again supply sufficient $e^-$ ($J_n$ in the right side)

Considering no generation recombination in the depletion region, both $J_p$ and $J_n$ are const.

$$J = J_p + J_n = q\left(\frac{D_p}{L_p} p_{no} + \frac{D_n}{L_n} n_{po}\right)\left(e^{qV/kT} - 1\right)$$

$$J = J_0\left(e^{qV/kT} - 1\right)$$

$$I = J \times A = I_0\left(e^{qV/kT} - 1\right)$$

large Band gap → less $n_i$

* For Ge Band gap is small → so $n_i$ is large as a result reverse saturation current is more. ($I_0 \propto n_i^2$)

Diffusion capacitance is applicable for forward Bias only.

$I_0$ gets doubled for every 10°C rise in temparature

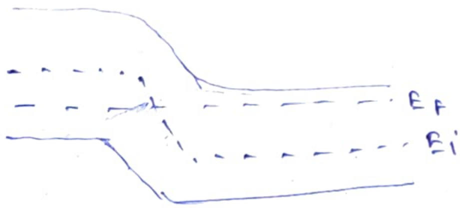
Si

$n_0 p_0 = n_i^2$ → A device is in equilibrium must hold it

$n_0 = n_i e^{E_F - E_i/kT}$ $\quad p_0 = n_i e^{E_i - E_F/kT}$

$\rho(x) = q(N_D^+ + p - N_A^- - n)$

Considering all other term negligeble $\quad \rho(x) = qN_D^+ - qN_A^-$




In the depletion region there are still many carriers but their concentration is negliegeb[le] compared to the concentra-tion of the immobile io[ns]

Breakdown Mechanism → ~~Stef~~ self Study

$n$ → Ideality factor
comes due to the current component (recombination)