Lecture after midsem

$$n = \int_{E_{cmin}}^{\infty} D(E)\, f(E)\, dE$$ e^- concentration

$$p = \int_{-\infty}^{E_{vmax}} D(E)\,(1-f(E))\, dE$$ hole concentration

for an intrinsic semiconductor with effective mass of e^- = effective mass of holes

↳ $n = p$ because $f(E) = \frac{E_c + E_v}{2} = 1 - f(E)$

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

$$\overset{n_i}{\overset{|||}{n_0}} = N_c f(E_c) \simeq N_c e^{-(E_c - E_f)/KT}$$

↳ equilibrium e^- carrier concentration

$N_c \rightarrow$ effective density of states for e^-

$$N_c = 2\left(\frac{2\pi m_n^* KT}{h^2}\right)^{3/2} \rightarrow \text{for 3d}$$

(cm^{-3}/m^{-3})

$$\overset{p_i}{\overset{|||}{p_0}} = N_v f(E_v) \simeq e^{-(E_f - E_v)/KT}$$

↳ equilibrium hole carrier concentration

$$N_v = 2\left(\frac{2\pi m_p^* KT}{h^2}\right)^{3/2} \rightarrow \text{for 3d}$$

(cm^{-3}/m^{-3})

m_n^* / m_p^*

$$m^*_{DOS} = (g_v^2 \, m_x \, m_y \, m_z)^{1/3}$$

$g_v \to$ valley degeneracy

$$g_{0d}(E) = g_v \, 2\delta(E - E_c)$$

$$g_{1d}(E) = g_v \frac{1}{\pi\hbar} \sqrt{\frac{m^*}{2(E-E_c)}}$$

$$g_{2d}(E) = g_v \frac{m^*}{\pi\hbar^2}$$

$$g_{3d}(E) = g_v \frac{(2m^*)^{2/3}}{2\pi^2\hbar^3} \sqrt{E - E_c}$$

Si, Ge : Electric and Anisotropic in nature

for Si $\to$ $m_x = m_l$

$m_y = m_z = m_t$

$g_v = 6$

So, $m^*_{DOS} = (6 m_l m_t^2)^{1/3}$

$$m^*_{transport} = \frac{3}{\frac{1}{m_x} + \frac{1}{m_y} + \frac{1}{m_z}}$$

↓

transport effective mass

if $m_x = m_y = m_z \rightarrow m^*_{transport} = m_x$

↳ isotropic case like GaAs

MUSTANG

	Si	Ge	GaAs
N_c	2.8×10^{19}	1.04×10^{19}	4.7×10^{17}
N_v	1.04×10^{19}	6×10^{18}	7×10^{18}

off state current ≡ leakage current

Silicon's off state I is less than that of Ge

for intrinsic semiconductor → $n_o = p_o = n_i = p_i$ →

$$n_i^2 = n_o p_o = N_C N_V e^{-(E_c - E_v)KT}$$

$$= N_C N_V e^{-E_g/K_T}$$ law of mass Action

$$\boxed{n_i = \sqrt{N_C N_V}\, e^{-E_g/2KT}}$$

→ exponentially decreasing with factor of band gap$/_{2KT}$

if $E_g \gg$ → $n_i \lll$ very rapidly

equilibrium → thermodynamically static / stable system

extrinsic ≡ doped / impurity

now, intrinsic → extrinsic : how?

trivalent: p type doping | pentavalent : n type doping

$p > n$ | $n > p$

Charge Neutrality condition (for any system)

$$\underbrace{p - n}_{\text{\# of carriers}} + \underbrace{N_D^+ - N_A^-}_{\text{\# of ions}} = 0 \quad \rightarrow \quad p + N_D = n + N_A$$

hole concen. | e⁻ concn. | (donor) pentavalent | (acceptor) trivalent

Total charge = 0

Electrically Neutral

Intrinsic : $n_i p_i = n_i^2$

Extrinsic : $np = n_i^2$

Amphoteric Dopant : element which can act either as a donor or an acceptor

eg: Silicon for GaAs

acts as donor on Ga site

acts as acceptor on As site

for n type system $\rightarrow$ $n \gg p$

if $N_D \gg N_A$ $\rightarrow$ $N_D + p = N_A + n$

$$N_D = n$$

$$n = N_c e^{-(E_c - E_f)/KT} = N_D$$

$$\frac{-(E_c - E_f)}{KT} = \ln\left(\frac{N_D}{N_c}\right)$$

$$\ln\left(\frac{N_c}{N_D}\right) = \frac{E_c - E_F}{KT}$$

$$E_c - E_F = KT \ln\left(\frac{N_c}{N_D}\right)$$

for higher donor conc, smaller the energy difference $(E_c - E_F)$, fermi level moves closer to the bottom of conduction band

for a p type system, if $N_A \gg N_D$,

$N_A = p$ and similar like before,

$$E_v - E_f = KT \ln\left(\frac{N_A}{N_v}\right)$$

effective mass → average

transport mass → harmonic mean

$$\mu = \frac{e\tau}{m^*}$$

τ → relaxation

mobility ← μ

m^* → effective mass

Carrier generation and Recombination Process

- Photogeneration — light
- Phonon generation
- Impact Ionization — collision

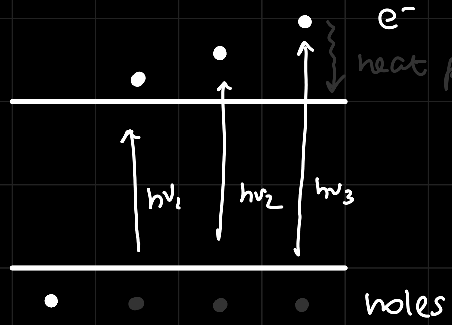
→ Carrier generation : Process through which holes and e^- are generated

→ Recombination : Process in which e^- and holes are annihilated

Temp ↑ $\xrightarrow{\text{how?}}$ Energy ↑ → e^- move to diff E states

① **Photogeneration** : light energy ($h\nu$) is absorbed by e^- and if $h\nu > E_g$, e^- jump from VB to CB and an e^--hole pair is formed

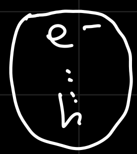
if $h\nu > E_g$



heat produced due to e⁻ wanting stability which is degrading for solar cells

$V_3 > V_2 > V_1$

exciton : e^- and hole pair



if $E_g < h\nu$ → This coulomb attraction is overcome and this pair breaks

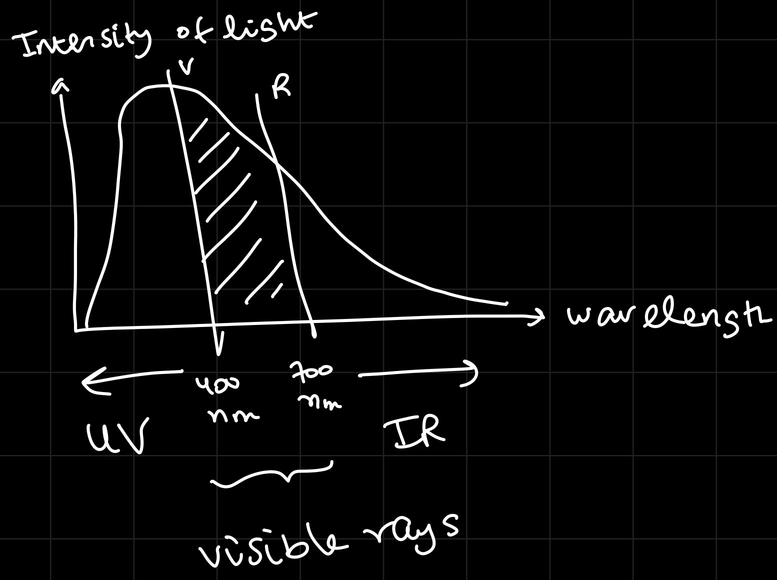
IP	ML	IHCI	DC	com	DSA	BE	P&S	CO	ISA	ELD	M4	S&S	CTD	AP	FNW	IF	PSD	ESD	APA
9	7	8	9	7	7	5	6	8	7	10	8	7	8	9	8	10	8	10	7

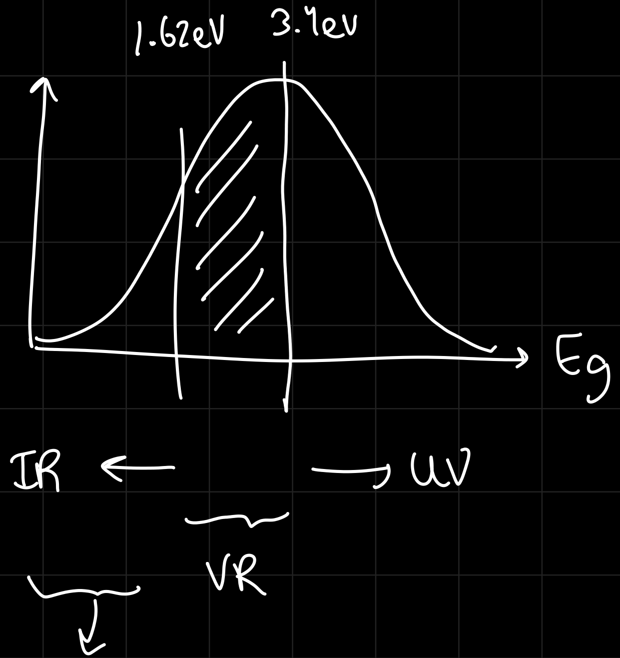
?

SOLAR CELL

solar spectrum

$$E = h\nu = \frac{hc}{\lambda}$$





the order flips because

$$E \propto \frac{1}{\lambda}$$

energy loss → absorption of light energy ↓

e^- and hole generation less

for Si, $E_g = 1.12$ eV

not good enough

PHONON GENERATION

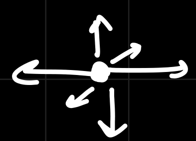
occurs when a semiconductor is under thermal excitation.
Temp ↑ → lattice vibrations increase leading to more photons

due to more lattice vibrations, covalent bonds in semiconductors break and hence e⁻-hole pairs are generated

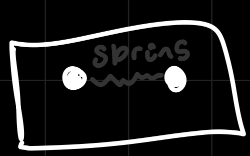
phonons → quantized quasi particles like electrons

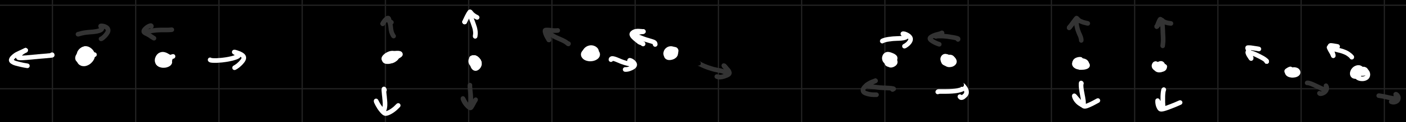
phonon branch/modes

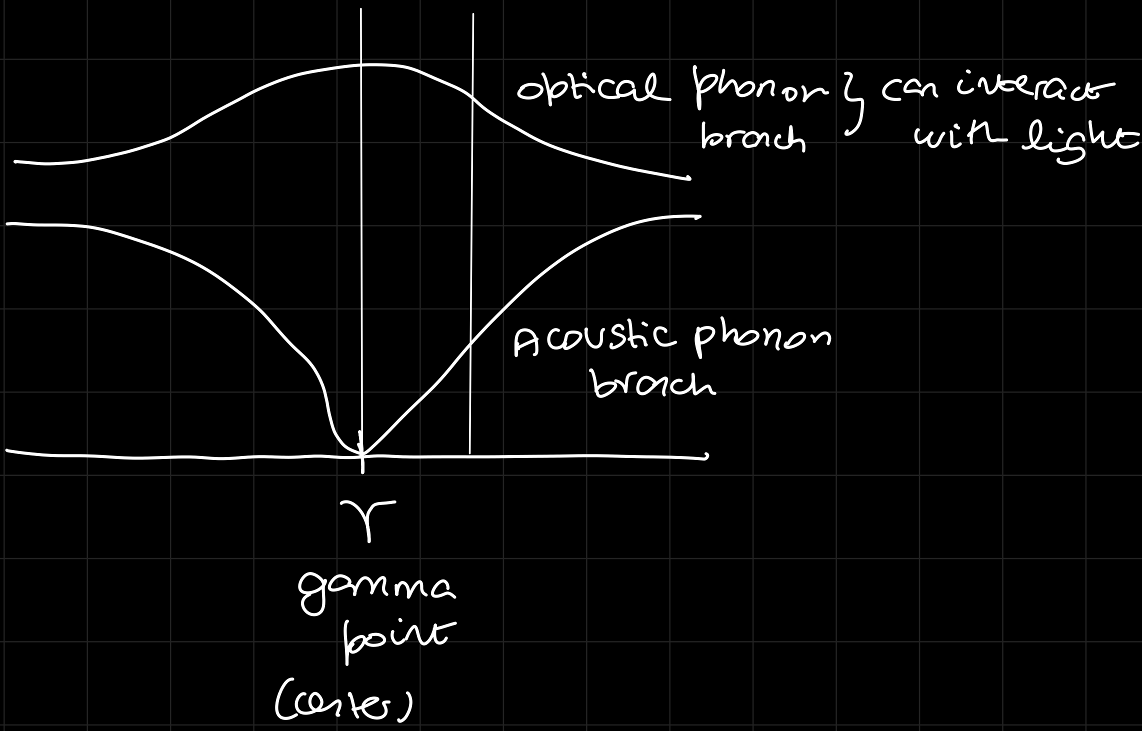
In a 3 dimensional space, a particle can vibrate in atleast 3 directions (x/-x, y/-y, z/-z)



for a two particle system,
6 directions → 3 as a whole body
3 in a harmonic motion wrt each other







③ Impact Ionization:

When a semiconductor is under an Electric Field, e^- gain energy from the applied $\bar{E}$ and hit other atoms.

A bond breaks generating more carriers

Recombination

Free e⁻ in conduction band + Hole $\xrightarrow{\text{recombination}}$ bound e⁻ in valence band

↳ Radiative Recombination

occurs for direct band gap semiconductors like GaAs

e⁻ from CBM → VBM w/o changing momentum and one photon of energy ($h\nu$) is emitted.

Energy is always released as radiation in case of Radiative Recombination

e⁻ which are at higher energy states come down to CB by releasing energy as heat. Then from CB, photon is released when coming down to valence band.

Also called direct recombination.

for a blue LED, we need a material with a band gap of 3.4 eV

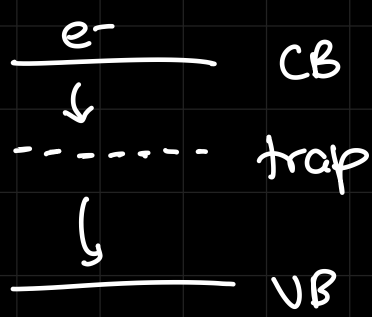
GaN → E_g = 3.3 / 3.5 eV
↳ p type doping is very difficult because Mg doping can only give P type GaN

Mg is trasient element
↳ has d state
↳ but GaN has p state
↳ defect states are observed
↳ defect states are almost flat
↳ curvature → 0
↳ effective mass → ∞
↳ current → 0

* Instead of jumping from CB_{min} → VB_{max}, e^- might jump to Defect states, stays there for some time and then it jumps down VB_{max}

↓

Shockley Read Hall Recombination



Slow process, generates heat. not ideal for LED since light emitted ↓

(c) Auger Recombination

occurs for heavily doped materials

3 carriers are involved.
an e- and a hole recombine and the energy generated is given to the other e- and it jumps to higher energy state, then it releases heat energy to come back to CB

MOSFET : surface dominating transport device

hence the need to smoothen / minimize the irregularities on the surface

$E\downarrow \rightarrow \mu\downarrow \rightarrow I\downarrow$

for a DBGS → Direct Recombination is efficient since k is conserved
but not for an Indirect Band Gap semiconductor.

Contact and Junctions

17/03/25

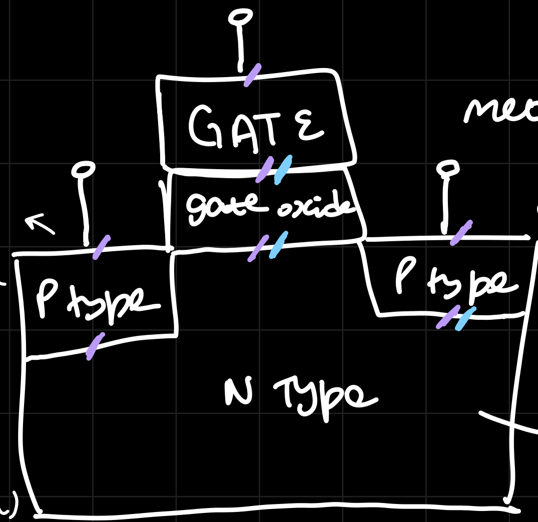
Si : 1.12 eV
Ge : 0.7 eV } band gap

MOSFET

crystalline

metal / poly-crystalline (P-Si)

oxide (SiO_2) amorphous



Si crystalline

if the junction isnt prepared properly, we can observe a voltage barriers - i.e. voltage drop (not ideal)

2x semiconductor - semiconductor → semiconductor - insulator → metal - insulator

# of Junctions = 4 + 3
# of contacts = 3

Junction resistance ∝ voltage drop

for an ideal MOSFET, if we reverse the polarity of the current, it will change the direction but nature remains the same. But if there is junction resistance, we may or may not get same results

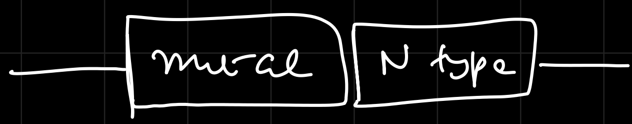
JUNCTIONS

→ HOMOJUNCTIONS : Junction b/w 2 differently doped regions of the same semiconductor

→ HETEROJUNCTION : between 2 different types of materials

→ METAL-SEMICONDUCTOR JUNCTIONS

Metal - semiconductor →

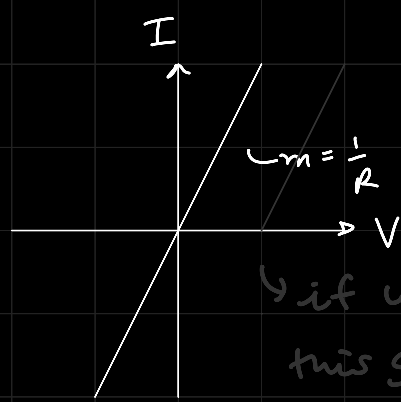


M-S junction

Ohmic → non rectifying contact

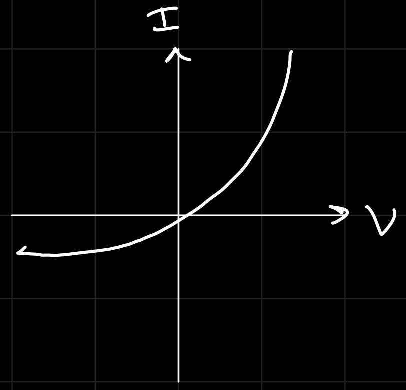
Schottky → Rectifying contact

Ideal ohmic contact (Au - P type Si)

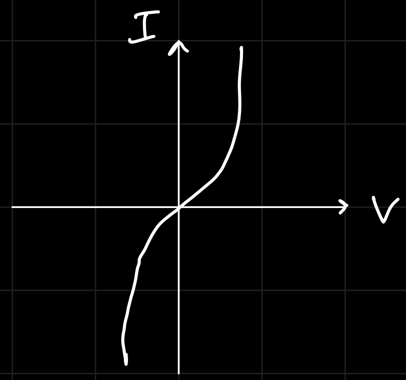


↳ if we have this graph, this is also ohmic but with some volt drop V_c.

Schottky contact
(Al – n type Si)



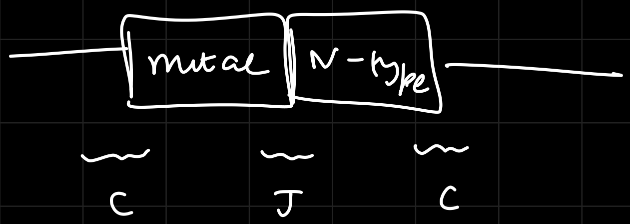
non-linear "ohmic" contact
(Al – n^+ type Si)
heavily doped



↳ linear for very small V

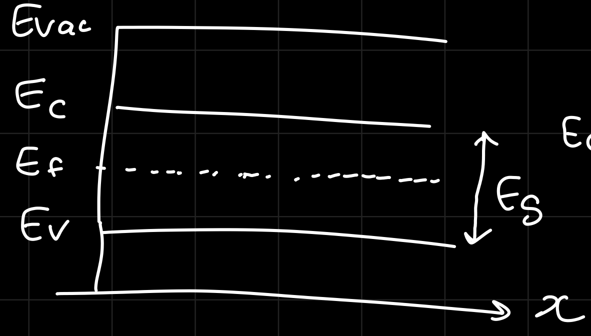
Energy dissipation relation
≡ E–K relation
visualized with an Energy Band Diagram

Closely related to E–x
(real space distance)



reference point for E-x graph
↳ $E_{vac} \Rightarrow E = 0$

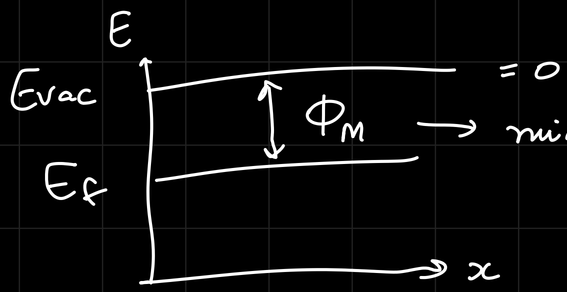
vaccum



$E_c = E_v + E_g$

lets take a metal $(E_c \simeq E_v \simeq E_f)$

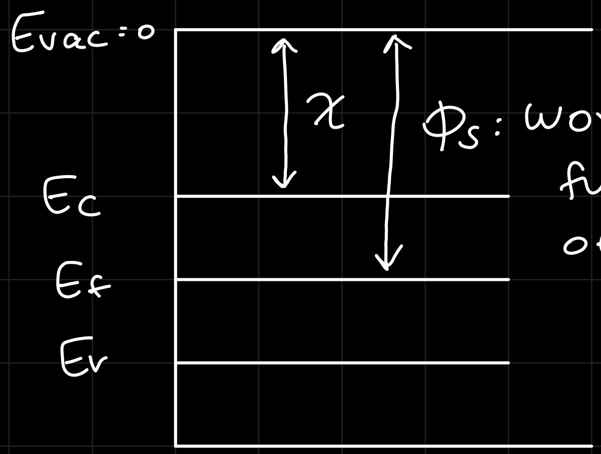
overlap



→ min. energy to excite the e^- to vaccum

= work function of the metal

Now, going back to the semiconductor



ϕ_S: work function of the semiconductor

χ : e^- affinity (chi)

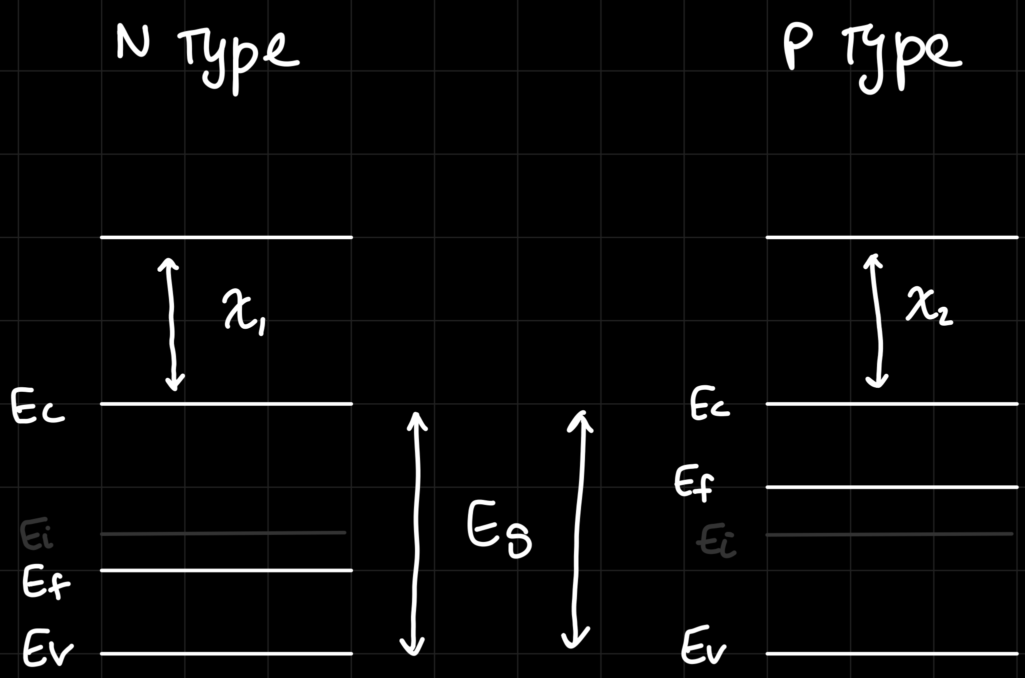
for semiconductors, we need 3 params

ϕ_S, χ, E_g

ϕ_s : work func can change with doping

χ and E_g : uniform properties

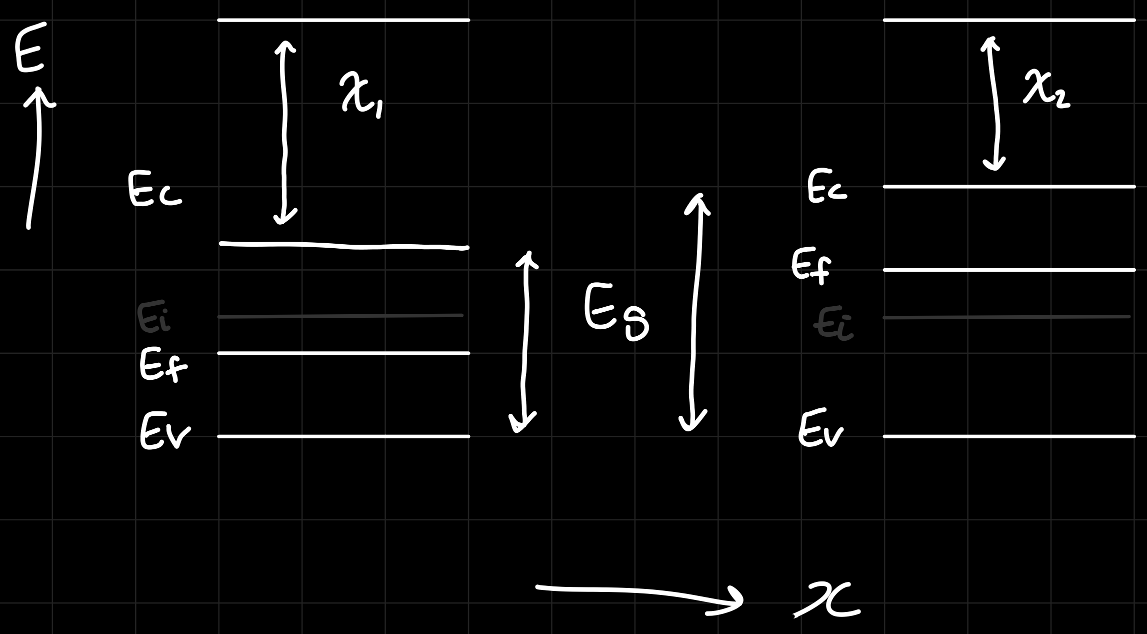
$$\phi_{s\,p\text{-type}} > \phi_{s\,n\text{-type}}$$



Same band gap

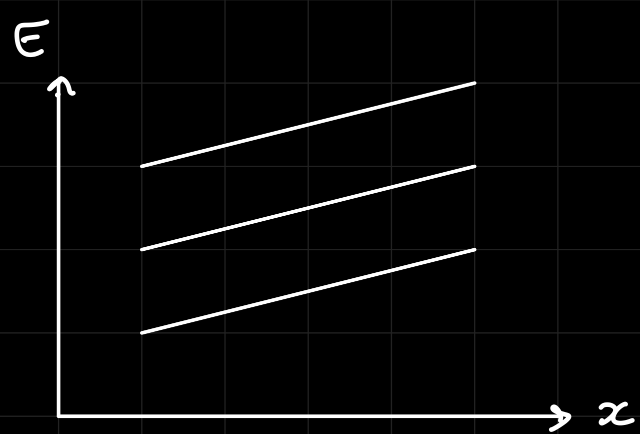
uniform χ : $\chi_1 = \chi_2$

N Type P Type



different E_g

→ What if E_c, E_v, E_f are varying with x

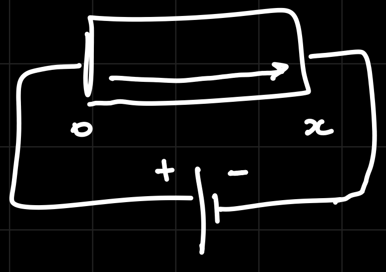


$$E = -\frac{dU}{dx}$$

if $U = \text{const} \rightarrow E = 0$

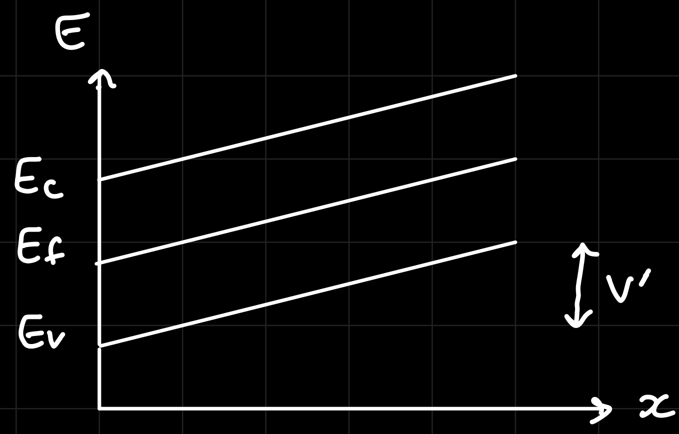
elif $U(x) \rightarrow E = \text{constant}$

$U = kx$



$V = 0$

$V = V'$



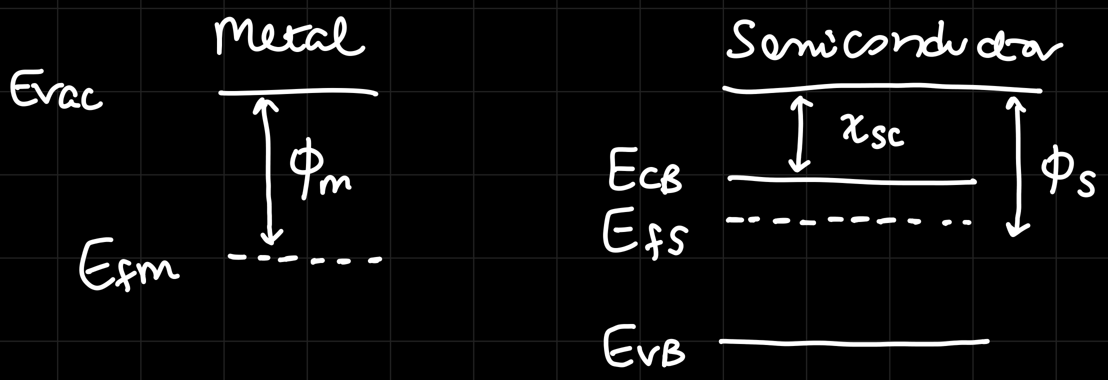
Energy Band Bending

Slope determines direction of $\bar{E}$

Ideal MS contact

- → no oxide layer between the metal & the semiconductor (no gap)
- → no inter mixing and no inter diffusion between the metal and the semiconductor
- → no impurities at the MS interface

Individually, M and S are at equilibrium but as a single system (junction), it is at non equilibrium state because there are 2 E_f levels.



for equilibrium → $E_{fm} = E_{fs}$

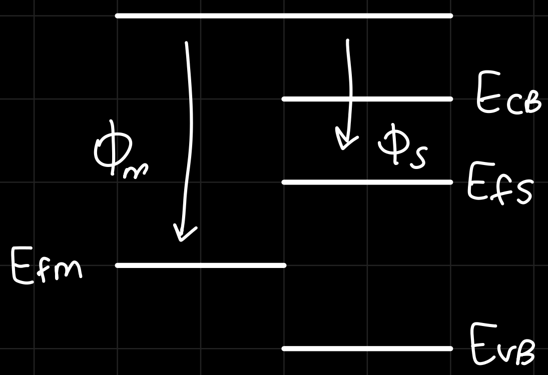
↳ tries to attain lowest energy level if not at equilibrium

either $E_{fm} \uparrow$ OR $E_{fs} \downarrow$ or simultaneously

metals have e^- and hence taking out e^- will not make much diff in E_{fm}

but for semiconductors, E_{fs} can easily move

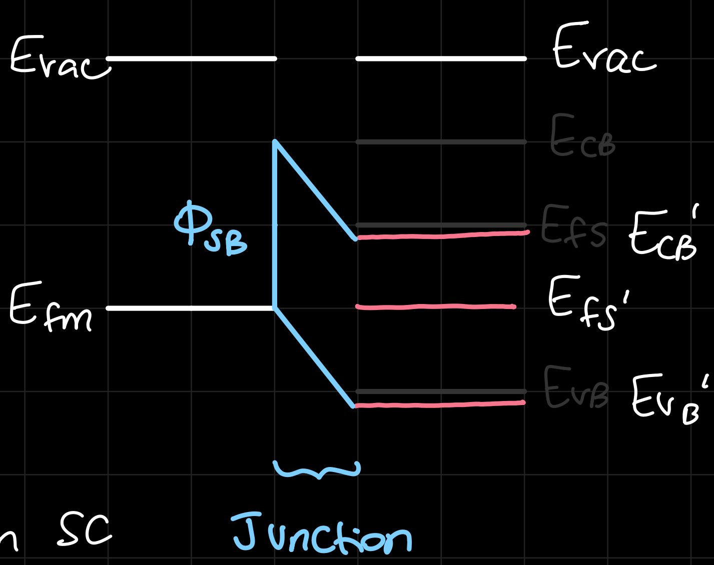
So, we assume E_{fm} as static and E_{fs} moves ↓



assuming n type semiconductor so,

$$\phi_m > \phi_s$$

if we want E_{fs} to go down, E_{CB}, E_{VB}, E_g, χ_e and even intrinsic fermi level should also go down that much so that the properties of the semiconductor remains the same.

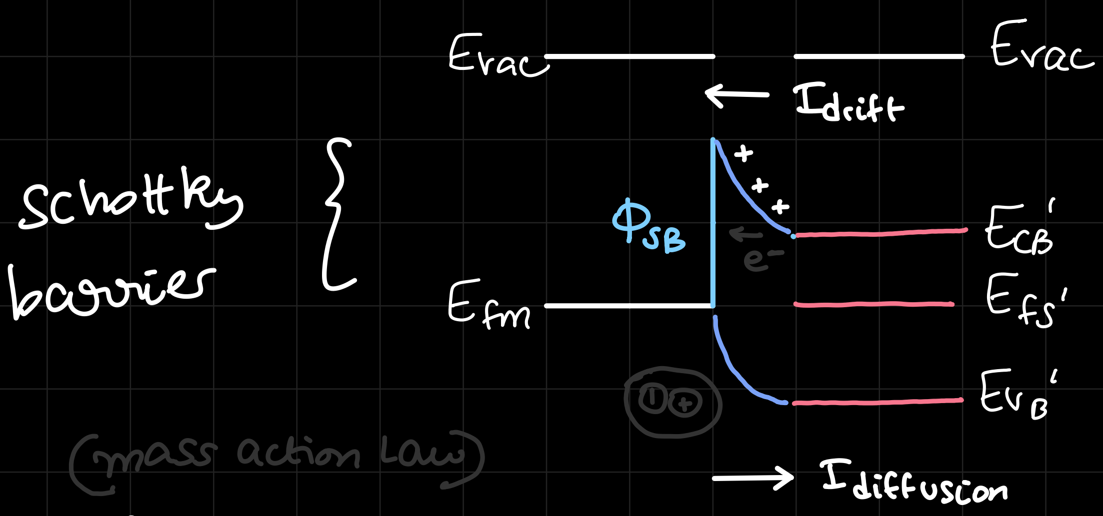


We need to remove e⁻ from SC to make E_f go ↓ and those e⁻ move from SC to e⁻ until equilibrium is reached

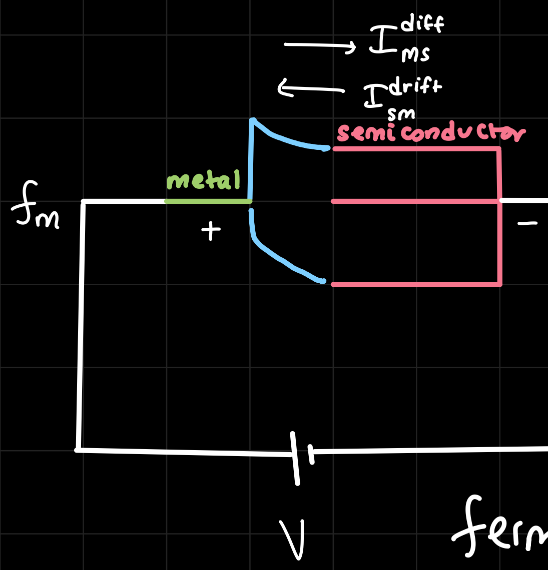
e^- from semiconductor side diffuse to the metal side
↳ static ions appear
↳ band bending takes place

diffusion current is generated from SC → m
(opposite to flow of e^-)

drift current generated from M → S

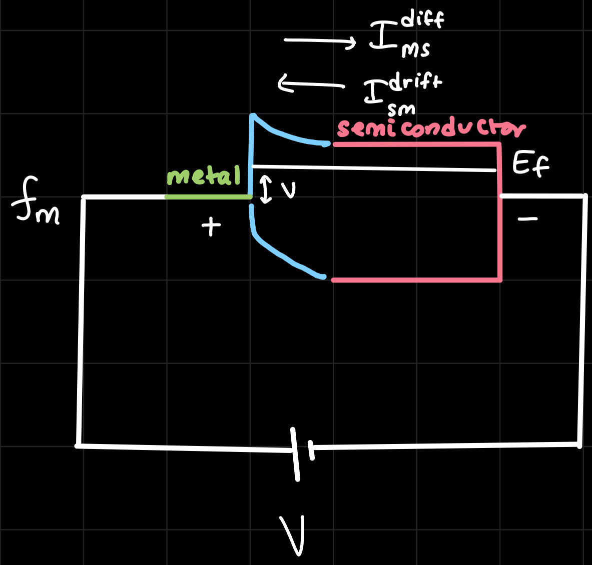


(mass action law)
m → s
to maintain equilibrium,
holes are being generated
at the E_{VB} side



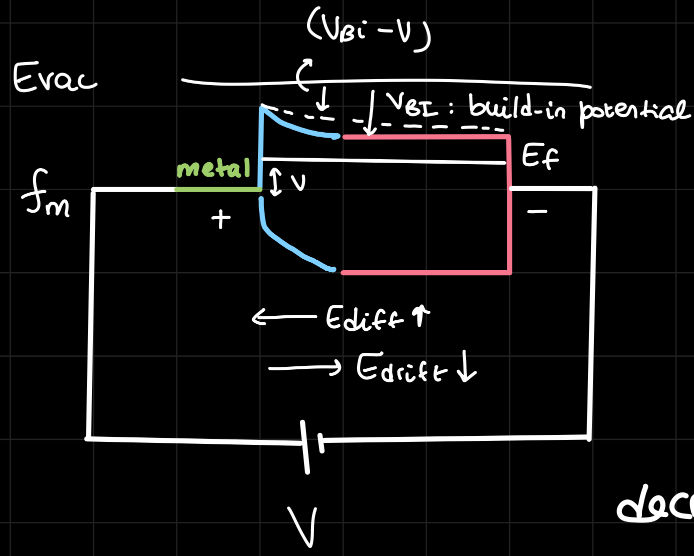
fermi level shifts due to this
chemical potential

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



→ non equilibrium state

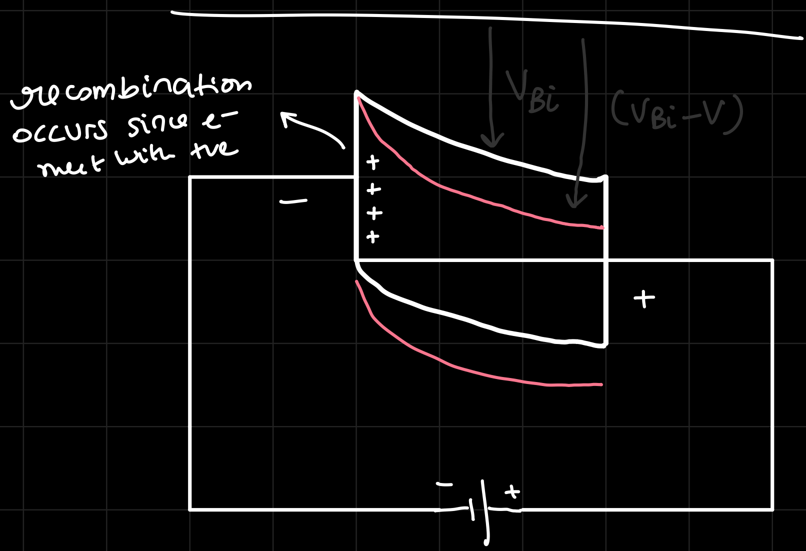
So other properties must change as well like the band bending



$$\bar{E} = \frac{dE_c(k)}{dk}$$

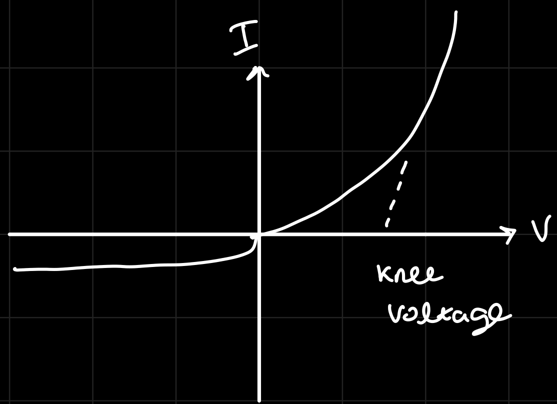
$\bar{E}$ is defined by the band bending and since the bending decreases when we apply a potential bias, and hence $I_{drift} \downarrow$ and since the barrier height $\downarrow$, e- faces less barrier and hence diffusion current $\uparrow$.

Reverse Bias Potential



reverse bias : intuitively $f_m \uparrow$ but it is ez to see $f_{sc}\downarrow$ rather than $f_m\uparrow$ and hence band bending ↑

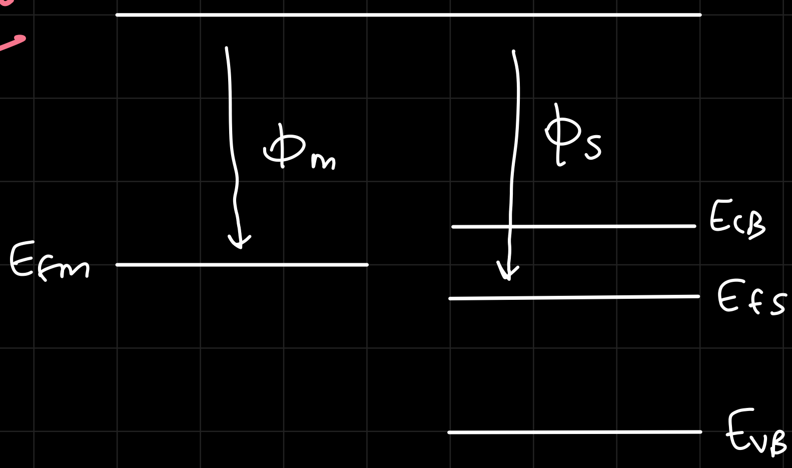
Idiffusion : negligible



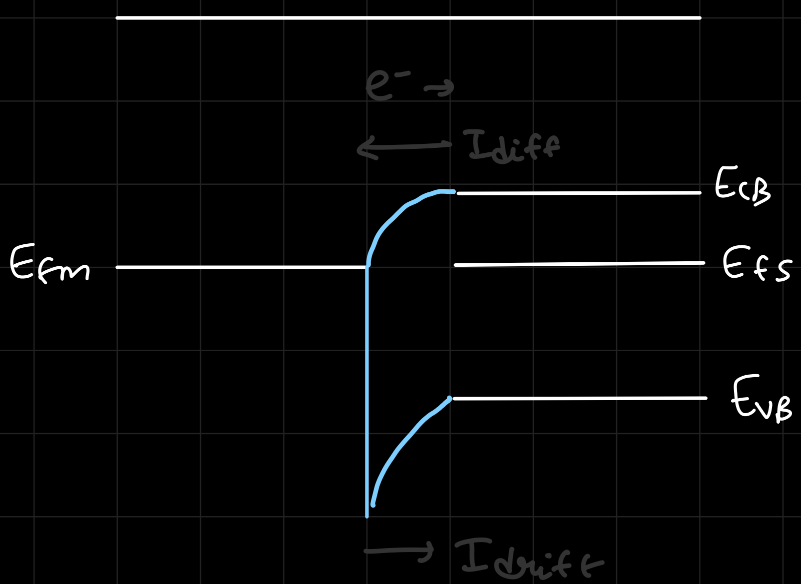
Schottky barrier

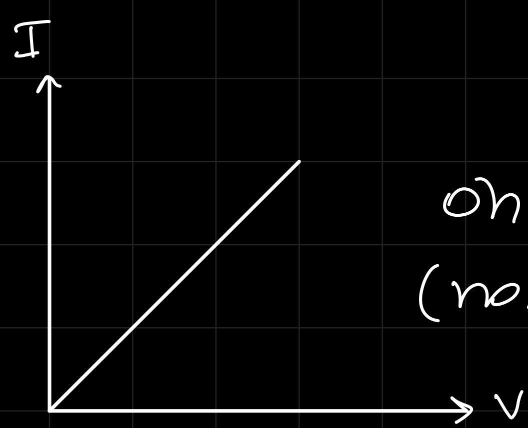
A PN Junction has a similar IV characteristic graph but a higher knee voltage

$\phi_m < \phi_s$



now E_{fs} should go up ↑
needs e^-
so, e^- travels from $m \to s$





ohmic
(non rectifying)

$\phi_m < \phi_s \rightarrow$ Ohmic

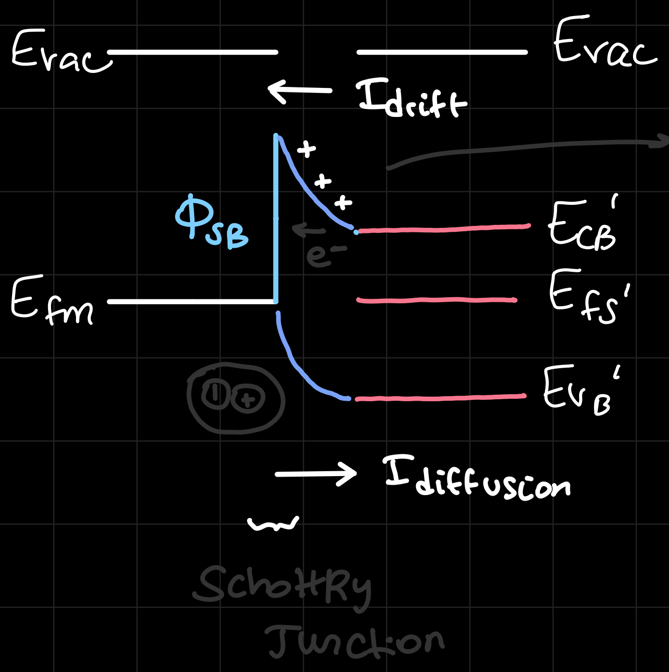
$\phi_m = \phi_s \rightarrow$ Ohmic (~0 drift current)

$\phi_m > \phi_s \rightarrow$ Schottky

We have taken lightly doped n type semiconductor

$\phi_m > \phi_s \rightarrow$ schottky effect

SB → schottky barrier



$e^- \leftarrow$ So +ve ions remain and hence called depletion region for e^- and only till band bending

since $I_{diffusion} > I_{drift}$

due to motion of e^-

↳ hence called a majority carrier device because we have a N type semiconductor

for a schottky barrier → majority carrier based device

Whereas most other are minority " " eg: MOSFET

$\phi_{SB} = \phi_m - \phi_s = V_{bi}$

forward biás

↳ V_{bi} decreases with V

↳ depletion width decreases

↳ barrier decreases

↳ ez for e- to pass throug

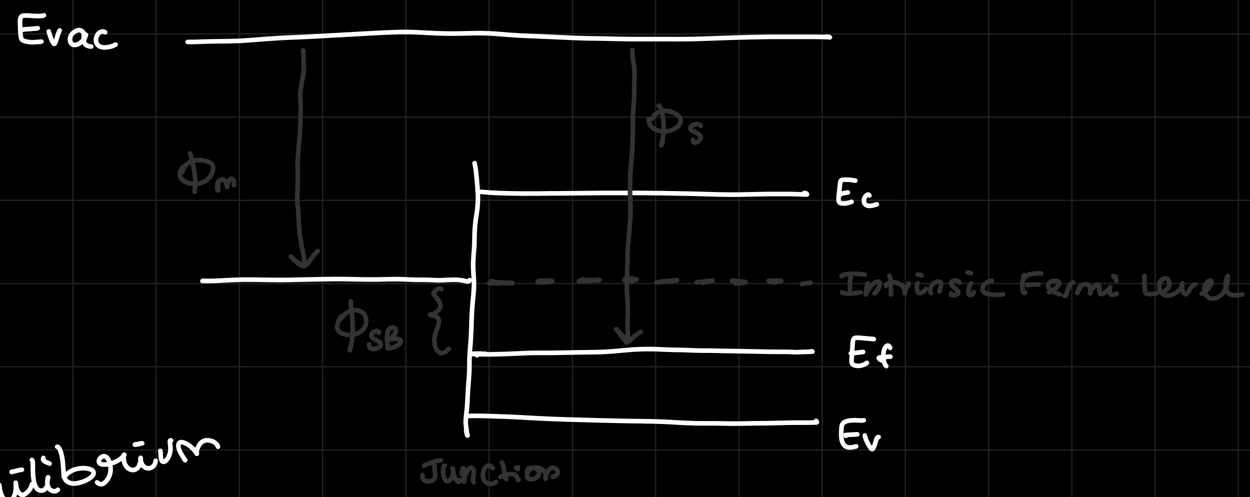
↳ $I_{diff} > I_{drift}$

↳ low band bending

for OHMIC CONTACT

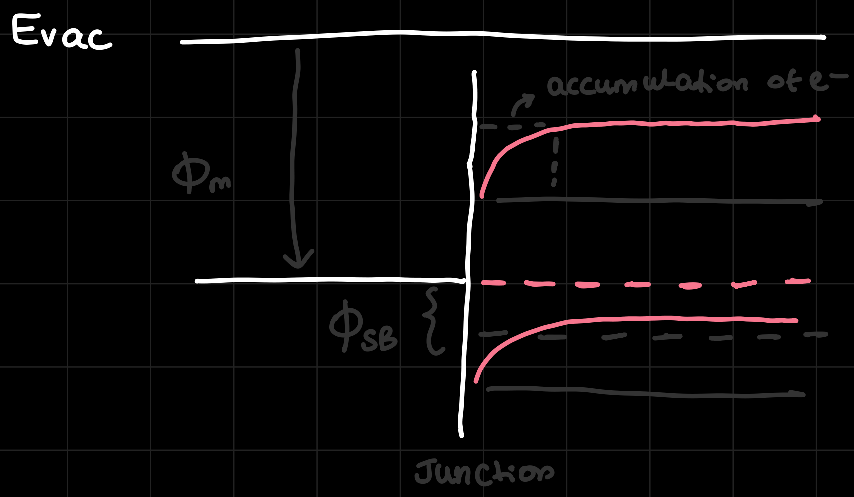
↳ $\phi_m \leq \phi_s$

for P type sc →

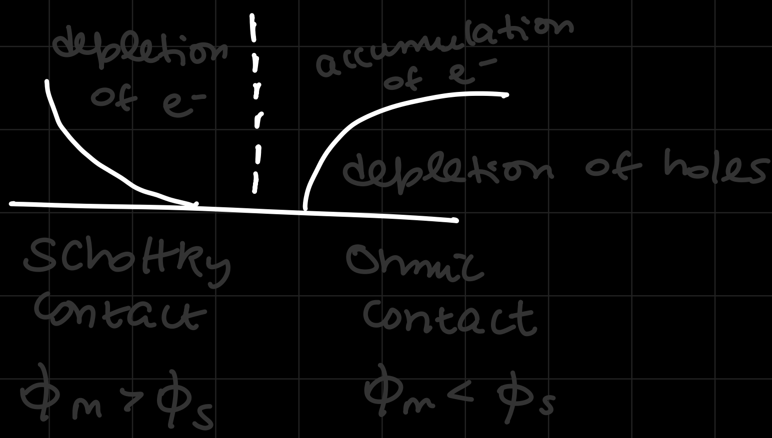


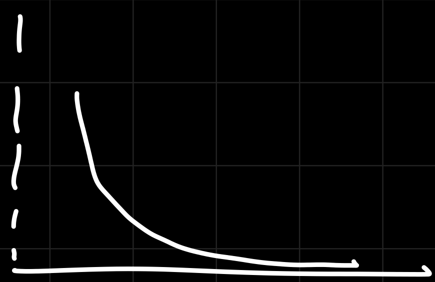
non equilibrium

equilibrium



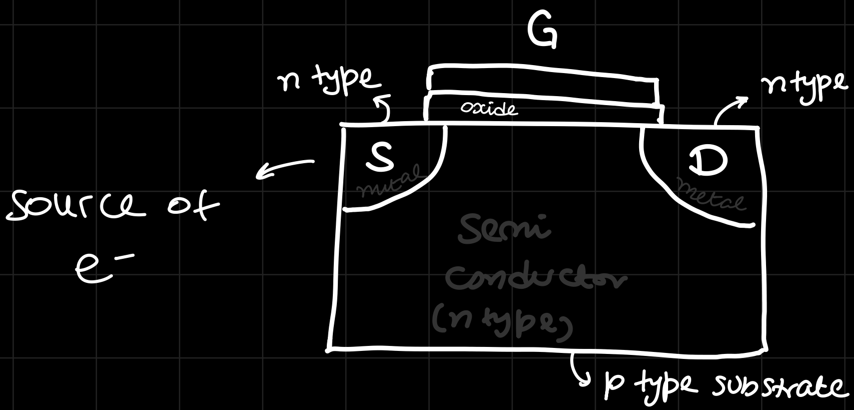
upwards bending





for p-type →

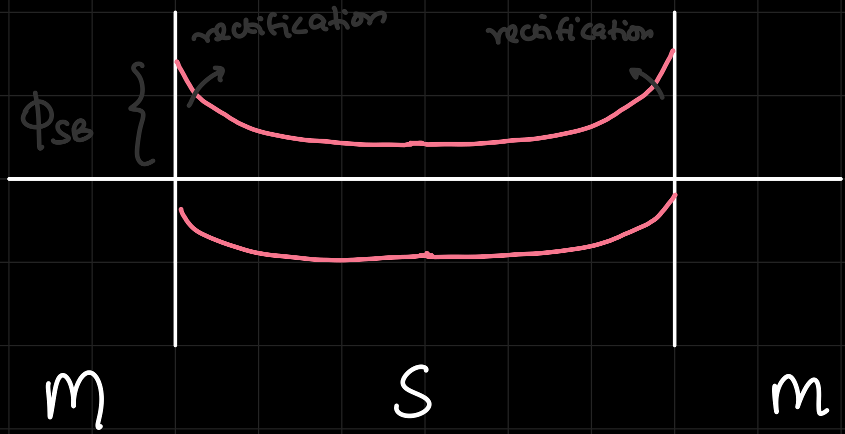
$\phi_m > \phi_s$



lets replace the SC in SRC & drain by a metal in a MOSFET which contact would we need?

↳ Schottky (~PN Junction)

lateral diagram →



NPN Junction

similar to BJT besides the C,B,E region width

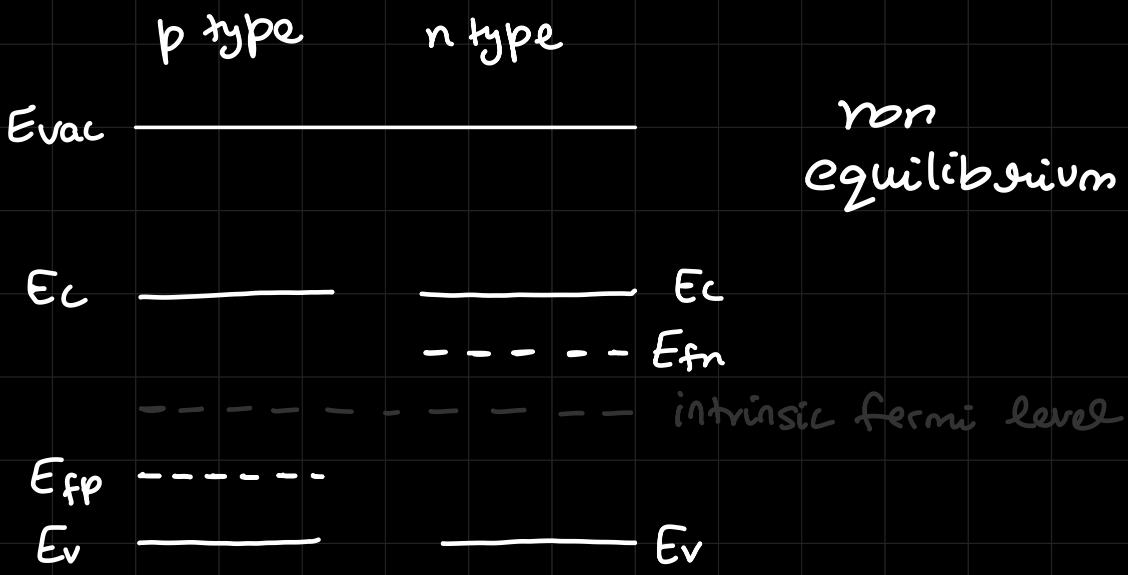
quasi Fermi Level : E_f splits when bias applied

Homo JUNCTION : between same SC but could have different doping

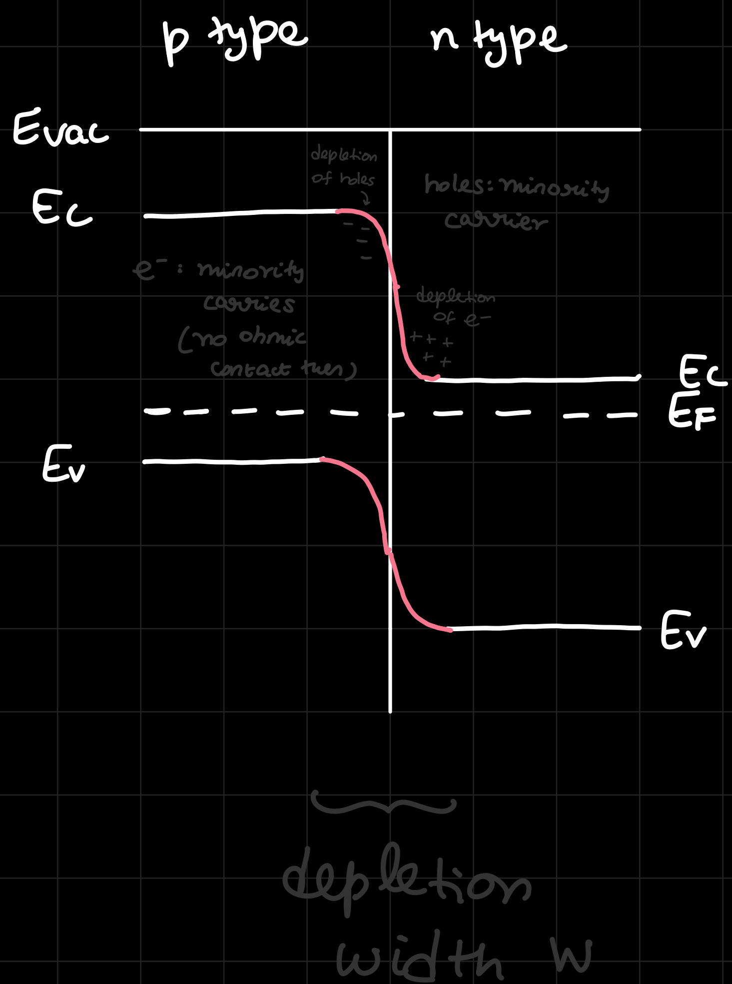
same material → same e- affinity χ_e ($E_{vac} - E_c$)

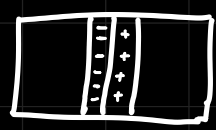
and same band gap

non equilibrium



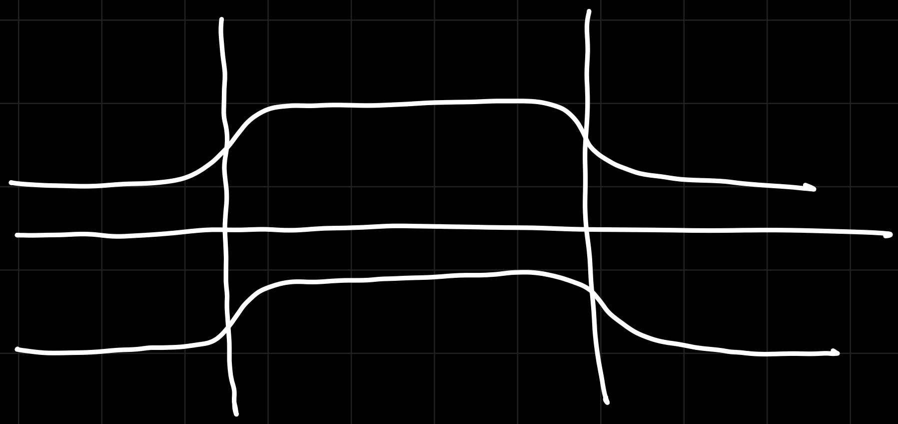
equilibrium

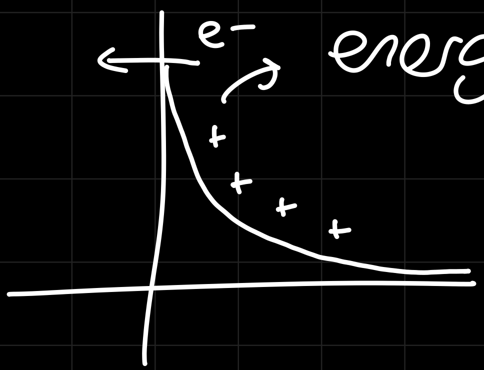




PN Junction

for npn MOSFET

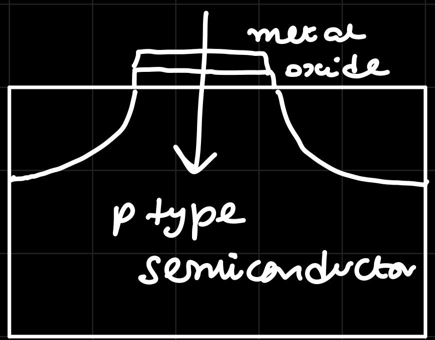




e^- → energy goes down

e^- would want to go to the other side

hence depletion of e^-



longitudinally,

M → I → S
(insulator)

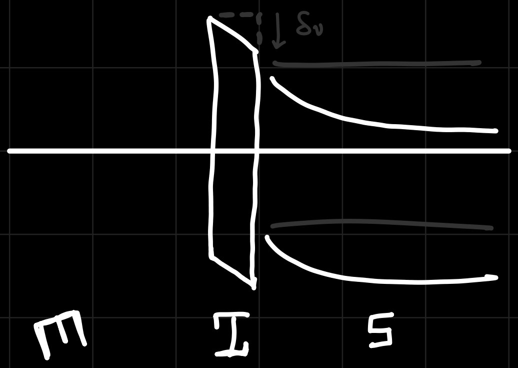
In MSM, replace S → I and 2nd M → S and we achieve the MIS junction metal

Insulator → barier → potential drop

Semi-conductor

earlier : $\phi_{SB} = \phi_m - \phi_s$

now : $\phi_{SB} = \phi_m - \phi_s - \delta_v$



Defects: Any impurity

Fermi level pinning