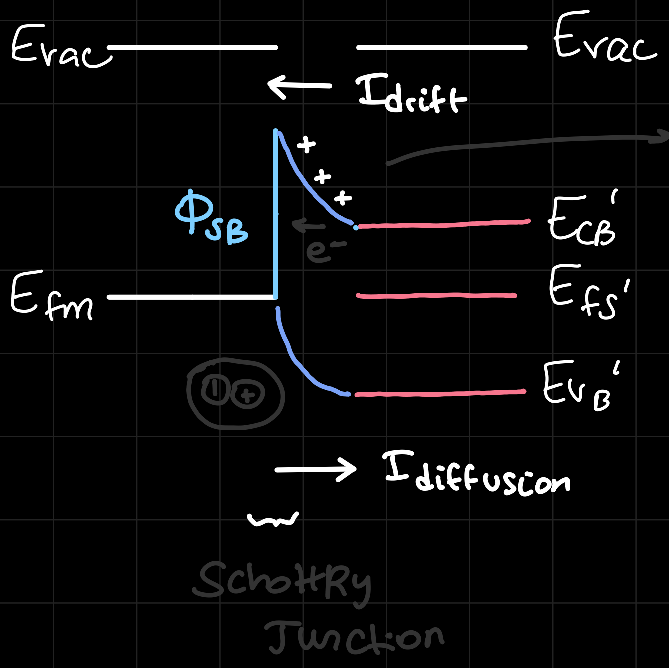
$\phi_m > \phi_s \rightarrow$ schottky effect

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 bias

↳ $V_{bi}$ decreases with V

↳ depletion width decreases

↳ barrier decreases

↳ ez for e- to pass throug

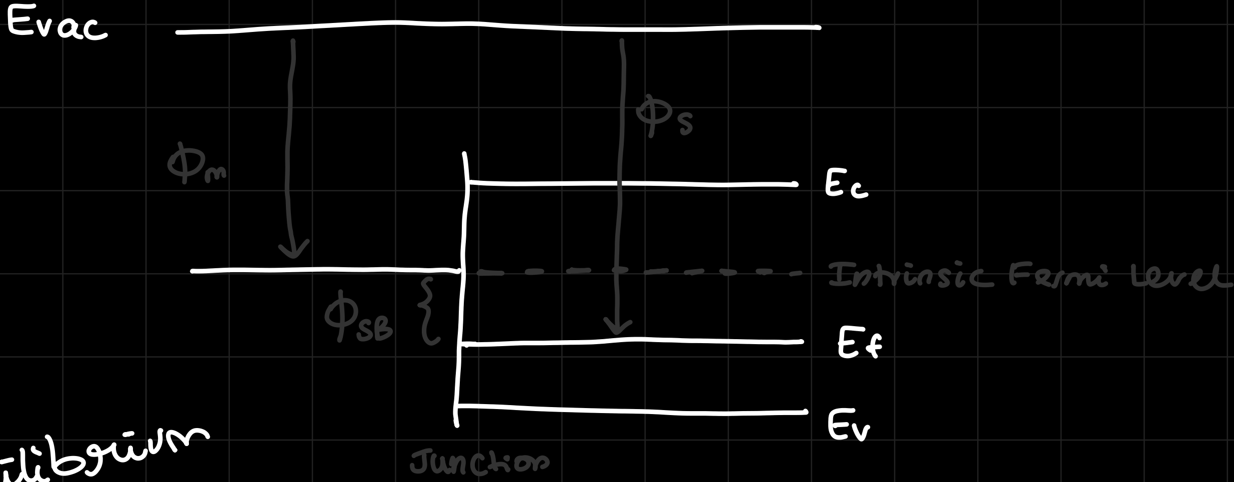
↳ $I_{diff} > I_{drift}$

↳ low band bending

# for OHMIC CONTACT

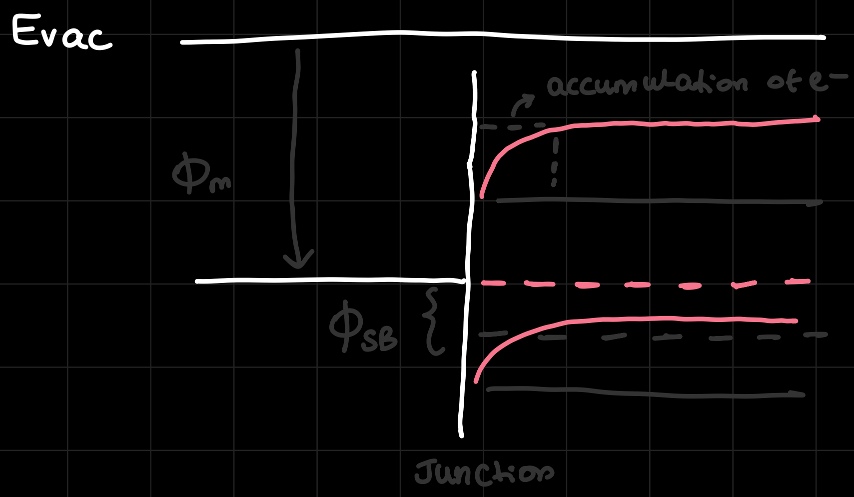
↳ $\phi_m \leq \phi_s$

for P type sc →

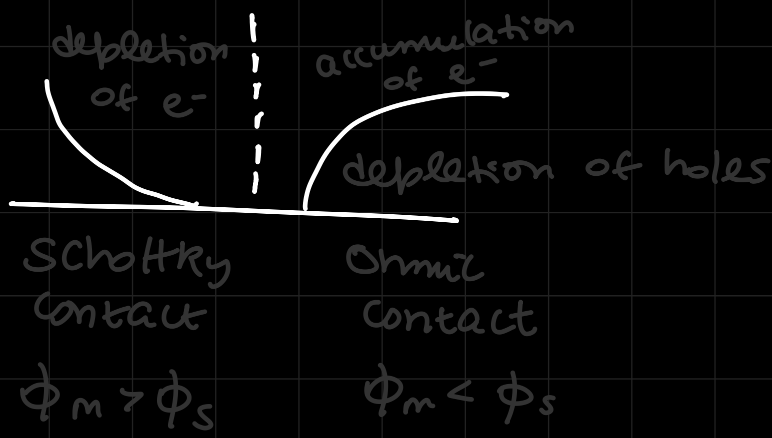


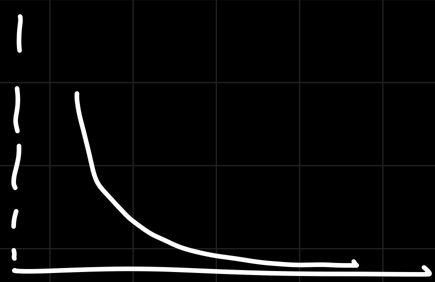

non equilibrium

equilibrium



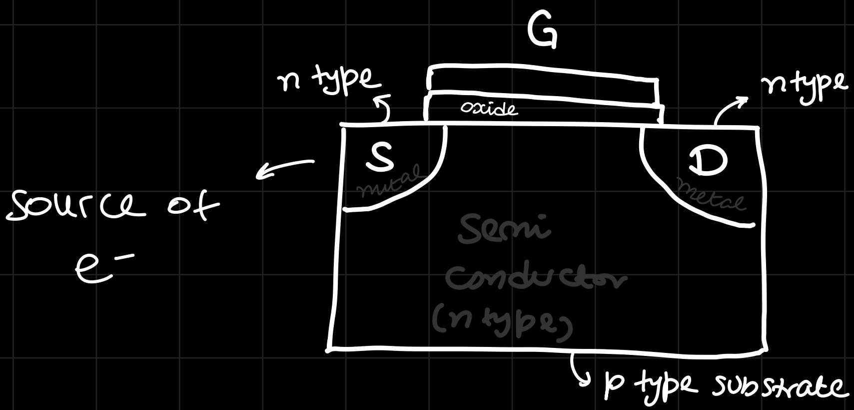

upwards bending



for ptype →

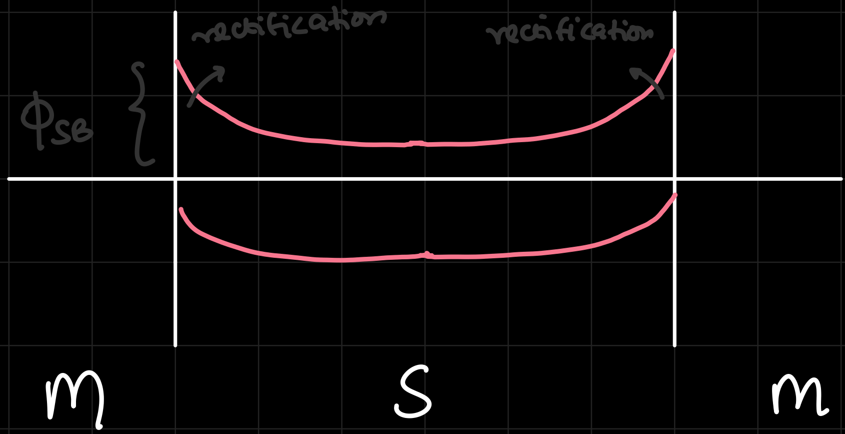
$\phi_m > \phi_s$




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

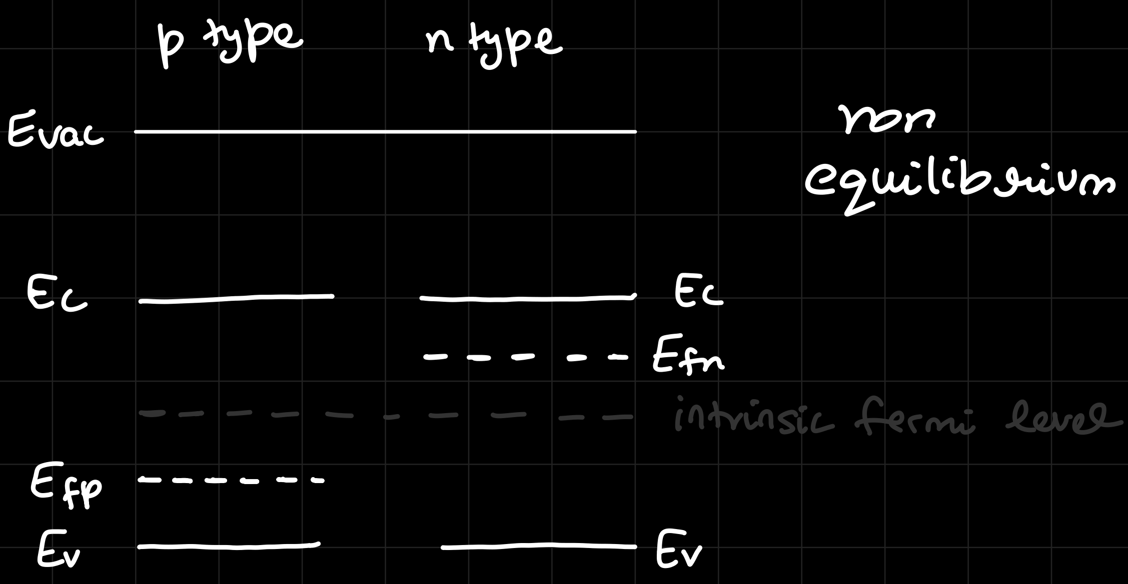
similar to BJT besides the C, B, E region width

Quasi Fermi Level : $E_f$ splits when bias applied

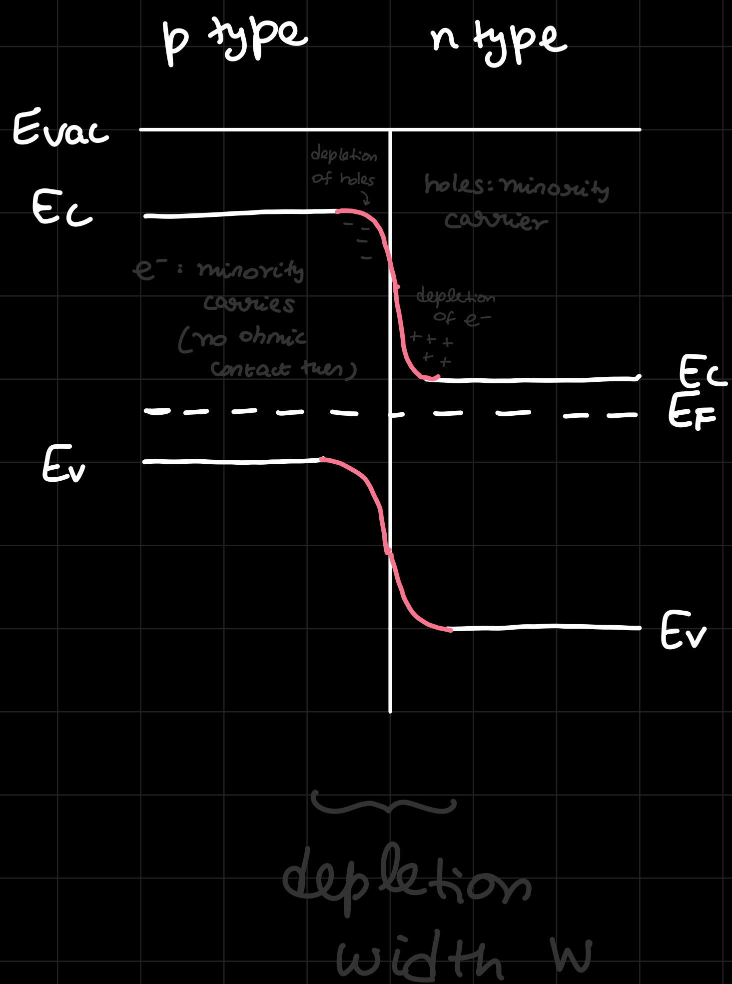
# Homo JUNCTION : between same SC but could have different doping

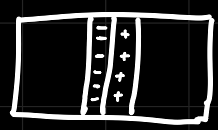
same material → same e- affinity $\chi_e$ ($E_{vac} - E_c$)
and same band gap

## non equilibrium



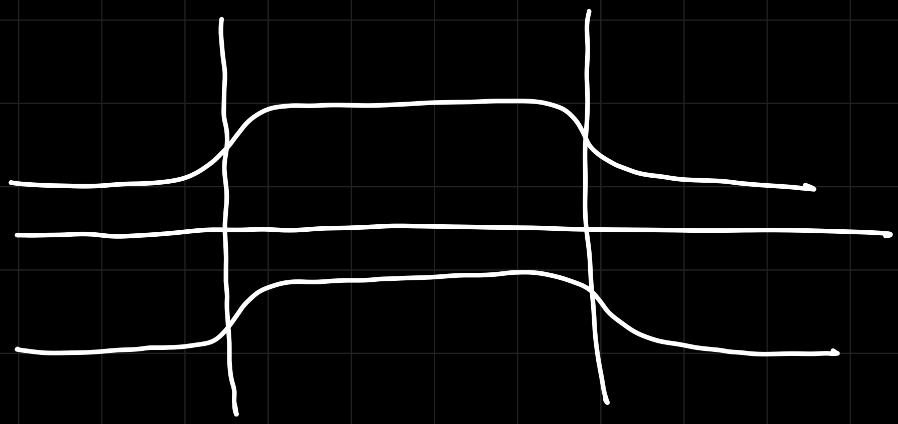

## equilibrium

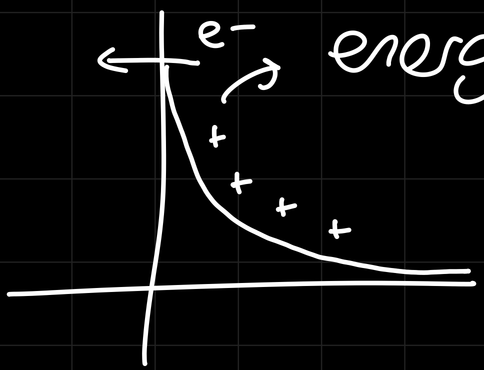


## PN Junction

for npn MOSFET

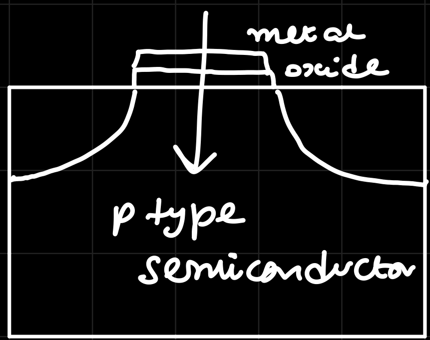





energy goes down

e$^-$ would want to go to the other side

hence depletion of e$^-$




longitudinally,

M → I → S
(insulator)

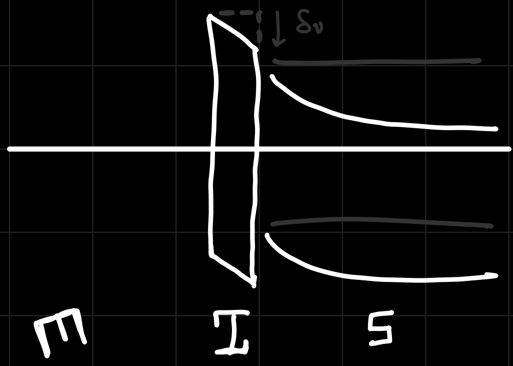
In MSM, replace S → I and 2nd M → S and we achieve the MIS junction metal

Insulator → barrier → potential drop

Semi-conductor

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

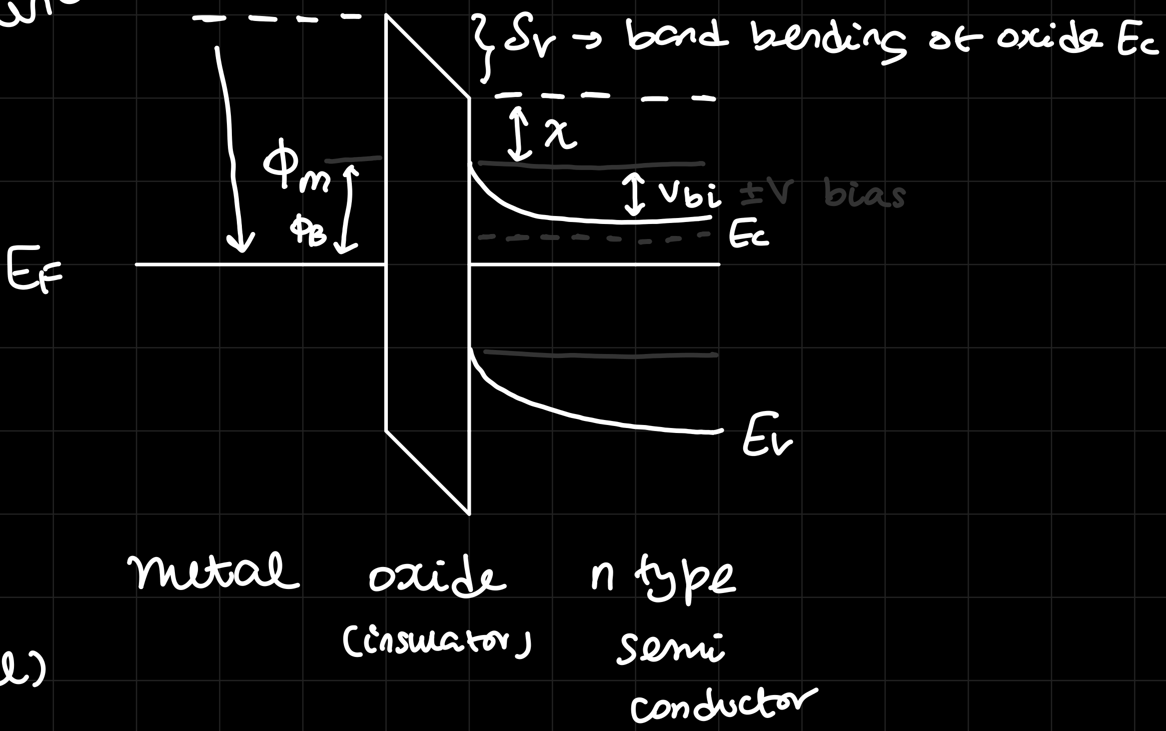
now : $\phi_{SB} = \phi_m - \phi_s - \delta_v$




# Defects: Any impurity

Fermi Level pinning

# MOS Junction




lowers schottky barrier height (not ideal)

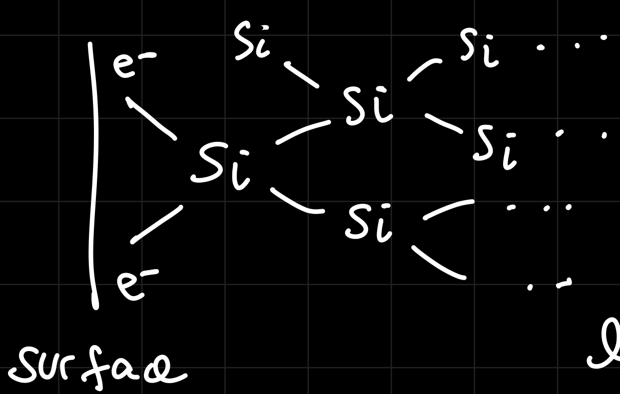
# Fermi Level Pinning

metal induced gap states (≃ impurities)
↳ another origin of interface states that results in "metallic" screening
↳ FERMI LEVEL PINNING

Interface unsaturated bonds ?

possibility of dangling bonds at the surface → excess e- → results in extra states/bonds/levels
↓
these extra levels remain within the band gap
↓

eg

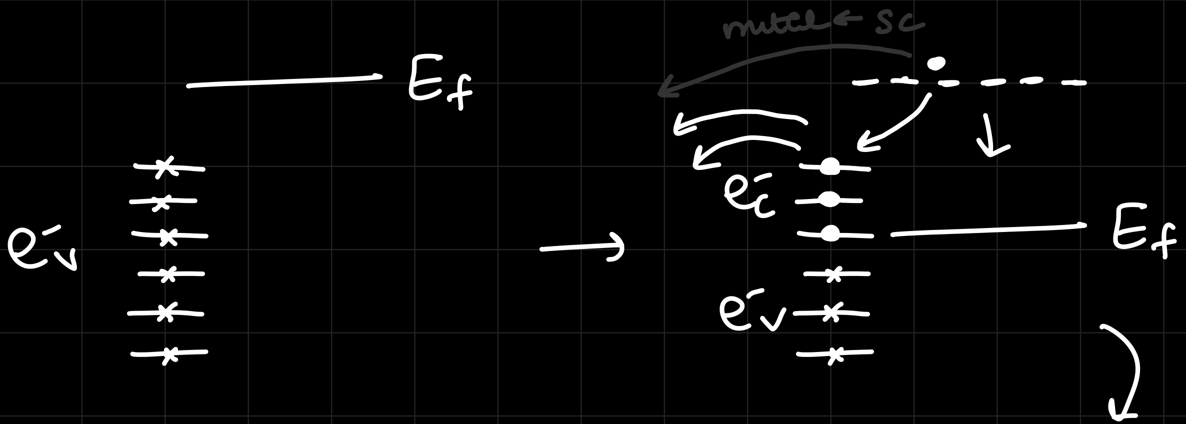


it is observed that the
impurity states take up
1/3rd of the band gap

We have the fermi level at the mid band
of band gap → at $\frac{E_g}{2}$

and we are shifting this $E_f$

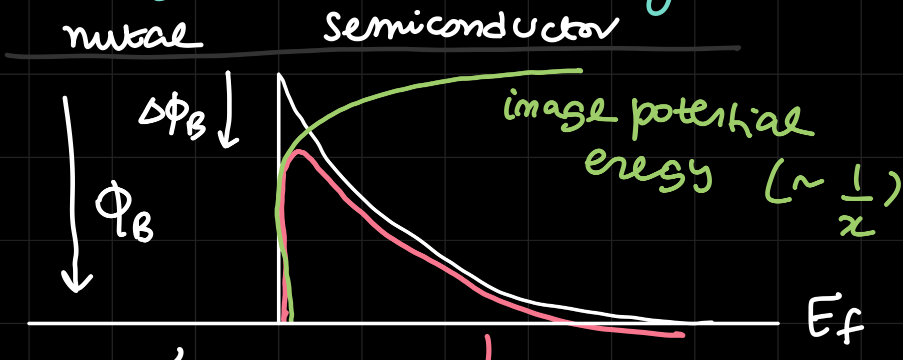
at equilibrium in the M-S Junction, the
System must maintain Charge neutrality
and hence some of the conduction e-
(free e-) go to the metal side
after the fermi level converts the
valence e- to conduction e- when
coming down.




those e- that leave Ef and fill the upper
positions, due to them the Ef thinks it is filled
and hence Ef goes up ↑

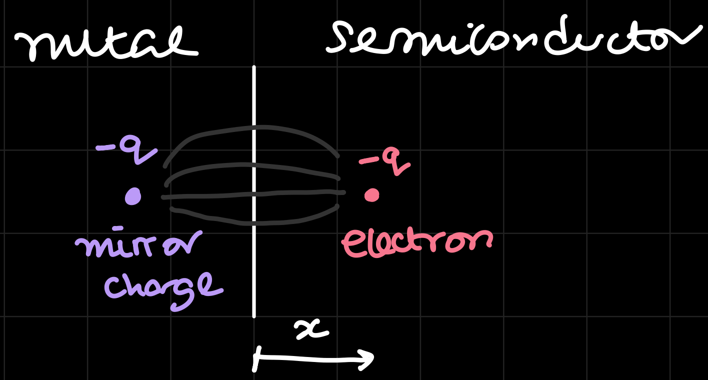
Due to this, the fermi level is restricted

# Modification to the Barrier Potential due to Image Force Lowering




instead of this

we observe this in the Schottky barrier



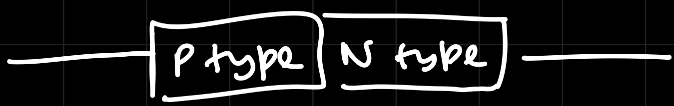

$$F = \frac{1}{4\pi\varepsilon_0} \times \frac{q^2}{(2x)^2} = \frac{q^2}{16\pi\varepsilon_0 x^2}$$

$$V = -\int \bar{F} \cdot dx$$

$$V(x) = \left( \frac{q^2}{16\pi\varepsilon_0 \cdot x} - q\bar{E}x \right)$$

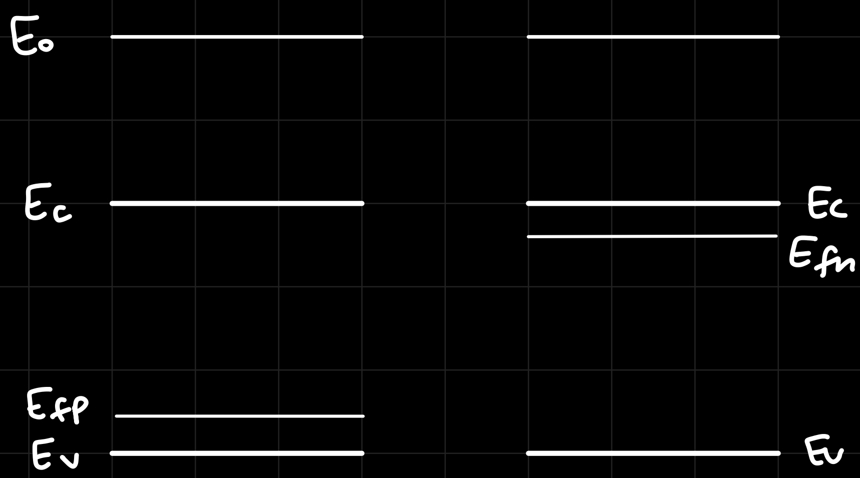
under an Electric Field

# Homojunction

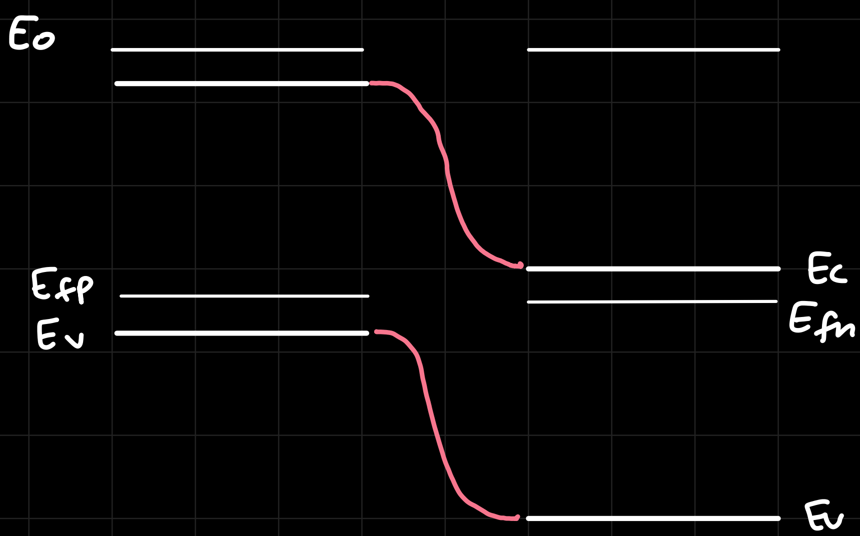



## Heavily Doped Case

### NON EQUILIBRIUM

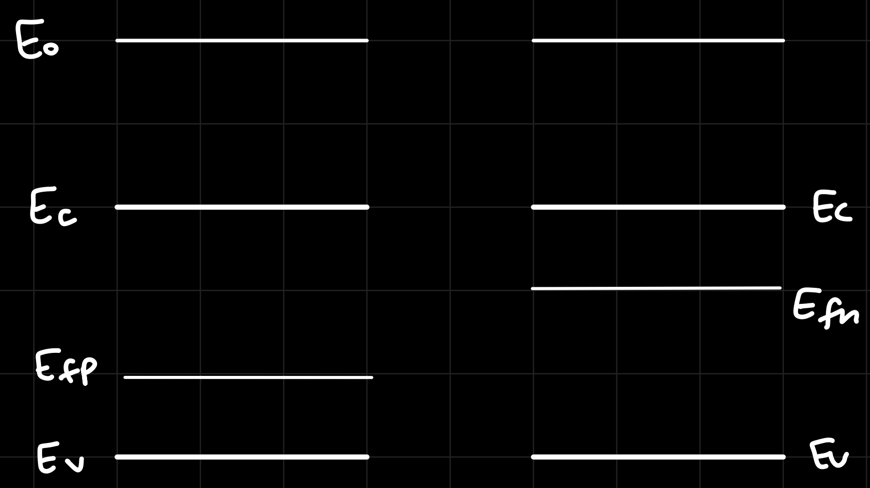



### EQUILIBRIUM

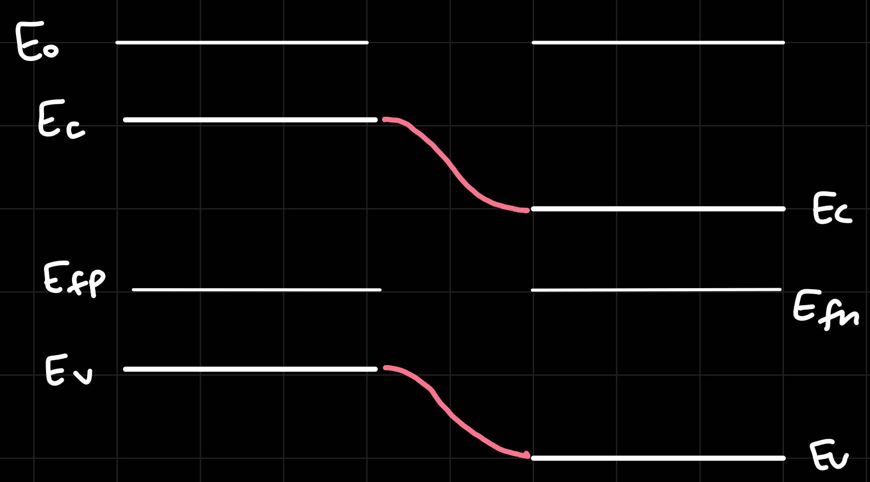


# moderately doped case

## NON EQUILIBRIUM

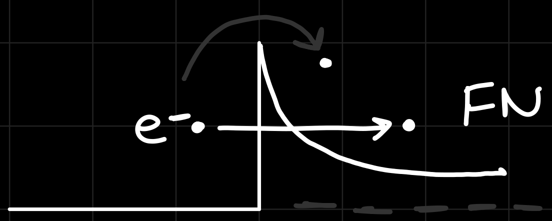



## EQUILIBRIUM



The heavily doped one will have a higher $\bar{E}$ and drift current because of more band bending

In the case of MS Junction, heavily doped → band bending ↑ → $\bar{E}$ ↑ → drift current ↑ (easier to drift to the SC side)
↳ high amount of force on e- on metal side
↓
Instead of all e- passing the potential barrier from above, some "tunnel" through barrier



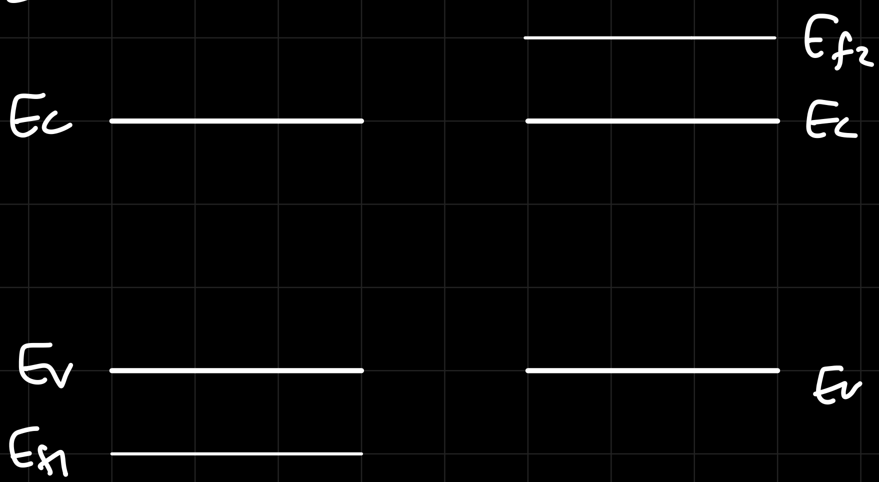

Homojunctions usually dont have dangling bonds and hence no (less) impurity
↳ lesser probability of observing fermi level pinning

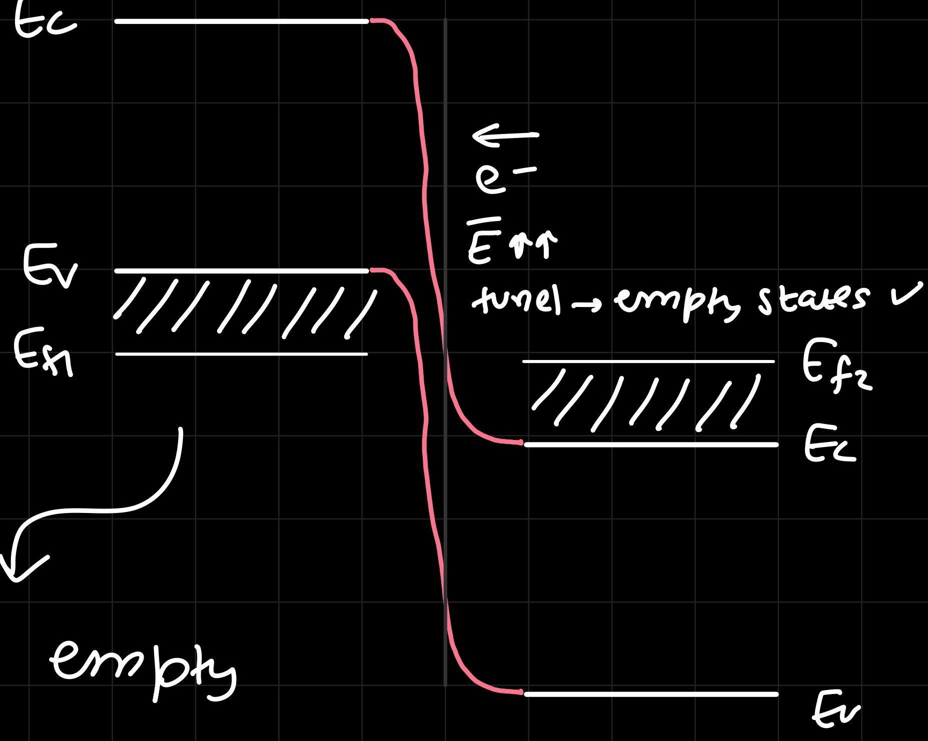
$ GaAs → 3,5 system
↳ too much impurity levels
↳ not ideal

$e^-$ movement
↳ drift
↳ diffusion
↳ tunelling

Zener diode: reverse bias
heavily doped
very high band bending
very high $\bar{E}$
tunneling ✓
in break down region

non equilibrium






above $E_f$, empty states (no holes)

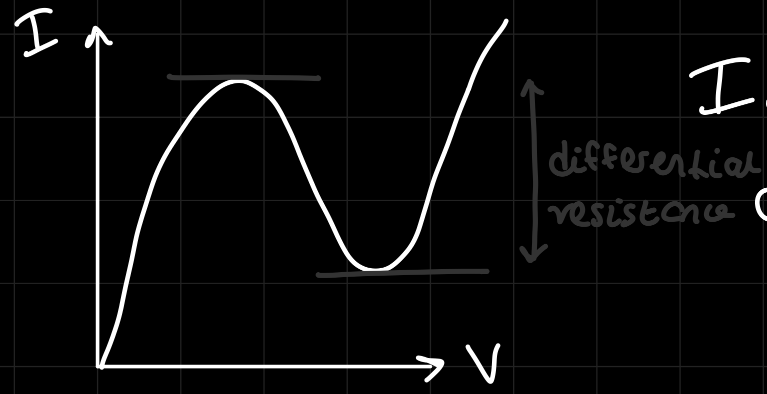
below $E_f$, filled $e^-$ states

barrier height is very high ($V_{bi}$)
↳ ~ no drift current

Apply a small amount of forward bias, $E_f$ at the n side goes up along with its $E_c$ and $E_v$ to maintain band gap

or with n type at reference, p type goes down

due to the high $\vec{E}$ the free $e^-$ go toward the p types' empty states




ISAKI
diode

non linear characteristics

absolute Resistance $= \frac{V}{I}$

differential Resistance $= \frac{dV}{dI}$

for the above characteristic, we have a region where current is reducing with increase in potential

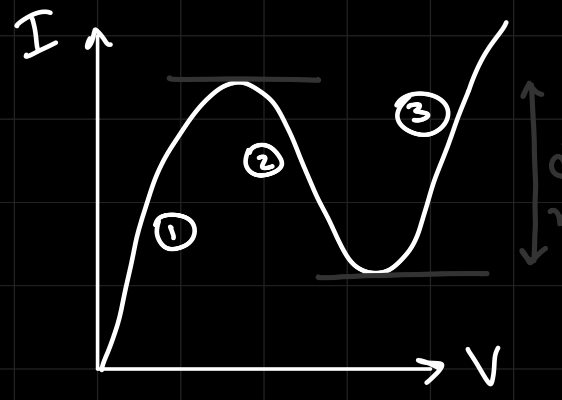
so, we get $R = \frac{dv\ (+)}{dI\ (-)}$

$\equiv$ Negative Differential Resistance

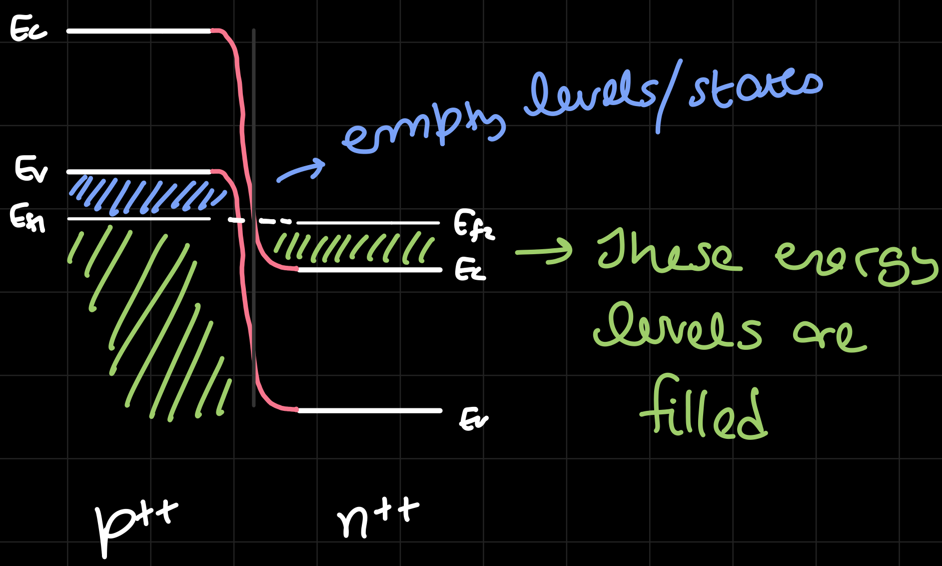
$\equiv$ NDR diode

useful for amplifiers

Esaki diode → degenerate semiconductor
(heavily doped $\sim 10^{21}/cm^3$)
$n^{++}/p^{++}$
$E_f$ lies outside the band gap

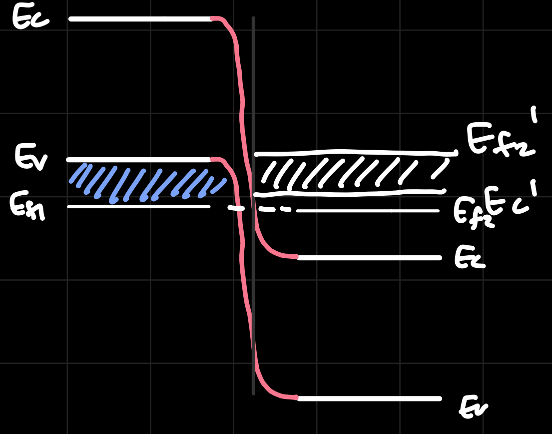



ESAKI diode characteristics




When the potential applied, $n^{++}$ side's fermi level goes up and some e− from n side "tunnel" through the barrier towards p side and we observe maximum current

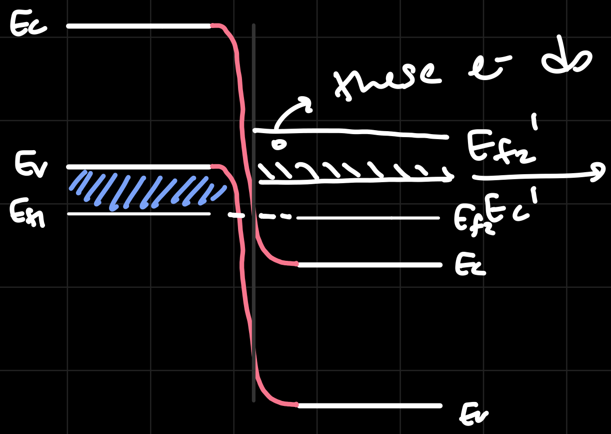
① initial potential bias




all e⁻ can tunnel through

when increasing V further ②

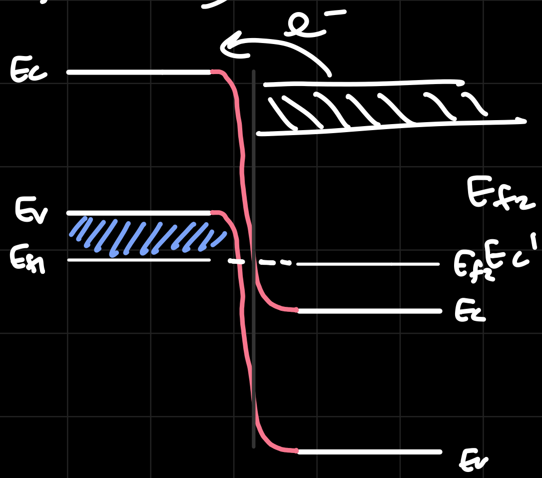
these e⁻ do not have any empty states to go to on the p side




very less overlap

current ↓

finally ③



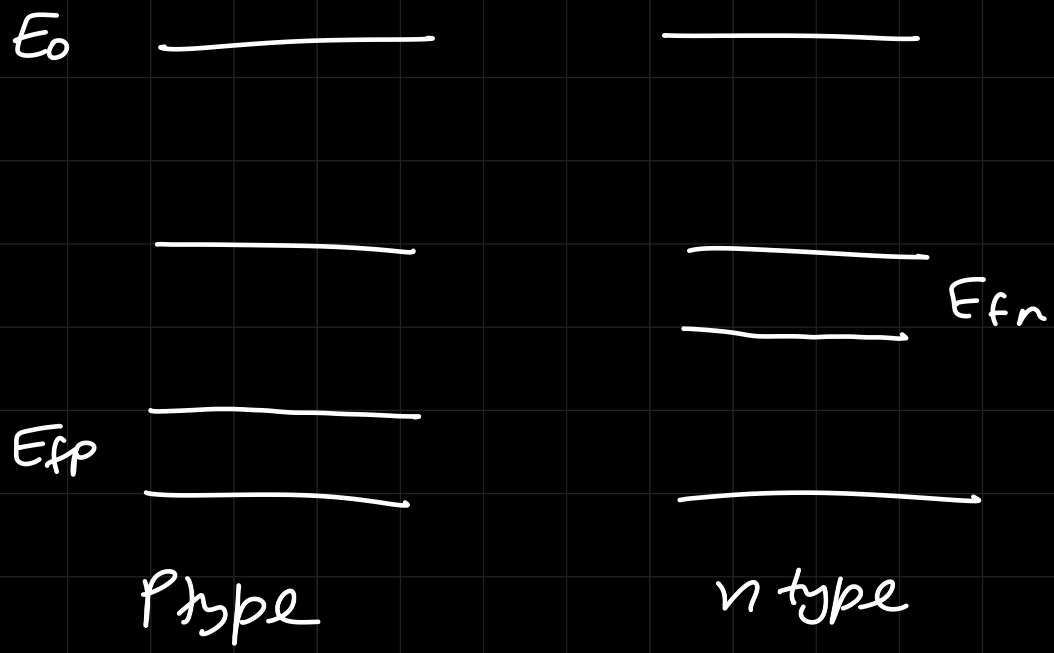

jumps over the barrier at very high V

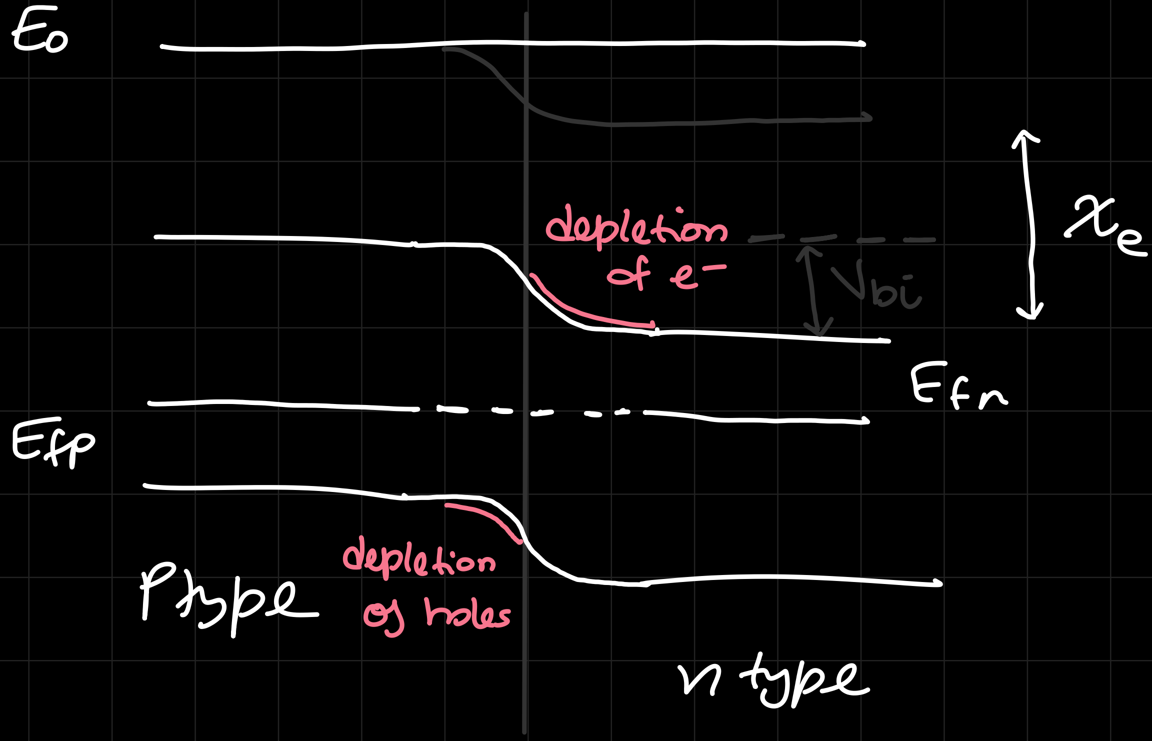
Esaki diode works in forward bias
zener diode (PN) works in reverse bias

diffusion current : current due to difference in concentration

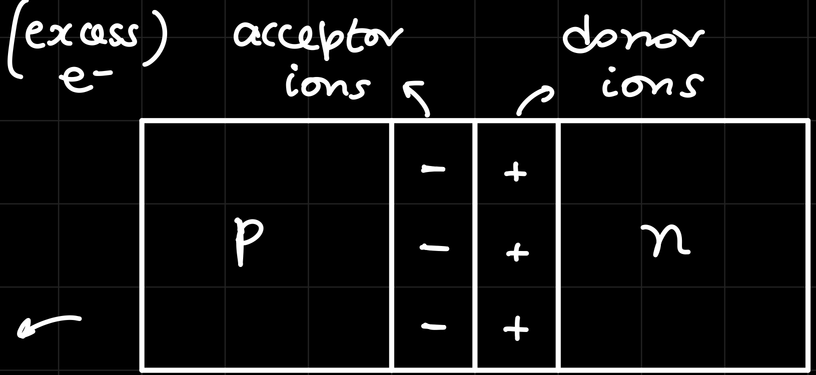
# PN Junction : at room temp, diff and drift current cancel each other out and hence net current = 0

note: There exist NN and PP Junctions as well.

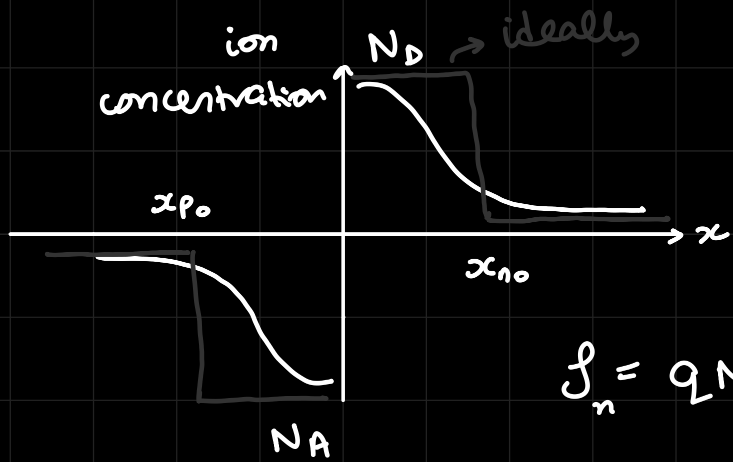





exponentially varying band bending




charge:
$\rho_- N_A$
↓
free ions




$\rho_n = qN_D$

$\rho_p = -qN_A$

but $\rho(x)$

$x: 0 \to x_{n0}$

$\rho(x)$

$x: -x_{p0} \to 0$

$$
\rho_0(x) = \begin{cases} -qN_a & : \quad -x_{p0} < x \leq 0 \\ qN_D & : \quad 0 < x < x_{n0} \\ 0 & : \quad -x_{p0} > x \quad \text{or} \quad x > x_{n0} \end{cases}
$$

# Gauss Law

$$
\oint_S E \cdot da = \frac{1}{\varepsilon} \oint_V \rho \cdot dV = \frac{Q_{enc}}{\varepsilon_0}
$$

$$
\frac{dE}{dx} = \frac{\rho}{\varepsilon_0}
$$

$$
E(x) - E(x_0) = \frac{1}{\varepsilon} \int_{x_0}^{x} \rho(x)\, dx
$$

$$
\frac{\partial^2 \phi(x)}{\partial x^2} = -\nabla E = -\frac{\rho(x)}{\varepsilon_0}
$$

$$
\phi(x) - \phi(x_0) = \int_{x_0}^{x} -E(x)\, dx
$$

laplacian $\rightarrow \dfrac{\partial^2 \phi(x)}{\partial x^2} = 0$ $\{$no need$\}$ $\because$ enclosed charge for $\rho = -qN_a \quad : -x_{p_0} < x \leq 0$

$\bar{E} = ?$

$$\frac{dE}{dx} = -\frac{qN_A}{\varepsilon}$$

$$\int dE = \frac{-qN_A}{\varepsilon} \int dx$$

$$\bar{E}_{(x)} = -\frac{qN_A x}{\varepsilon} + c$$

↳ const

find using boundary condition

we know $\rho = 0$

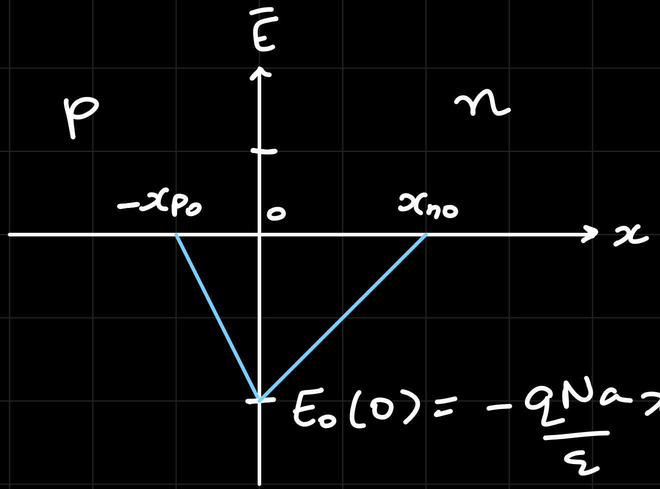
for $x < -x_{p_0}$

so at $x = -x_{p_0}$ (boundary)

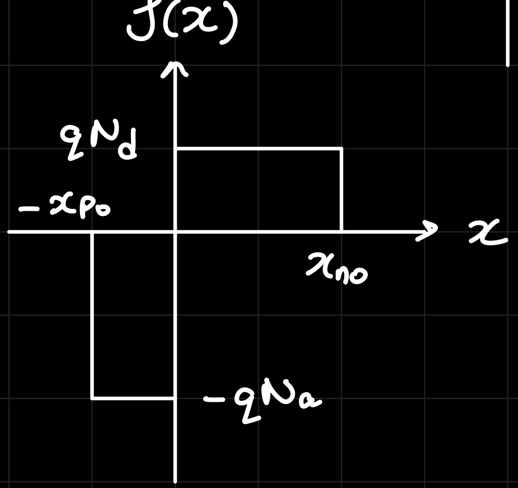
↳ $\bar{E} = 0$

$$\bar{E}(x) = \begin{cases} -\frac{qN_a}{\varepsilon}(x + x_{p_0}) & : -x_{p_0} < x < 0 \\ \frac{qN_D}{\varepsilon}(x - x_{n_0}) & : 0 < x < x_{n_0} \end{cases}$$

max $\bar{E}$ is $E_0$ at $x = 0$




$$E_0(0) = -\frac{qN_a x_{po}}{\varepsilon} = -\frac{qN_D x_{no}}{\varepsilon}$$




$$\frac{N_a}{N_d} = \frac{x_{no}}{x_{po}}$$

OR

① — $N_a x_{po} = N_d x_{no}$

only at $x = 0$

note:

hole density > $e^-$ density

→ p side less doped wrt n side

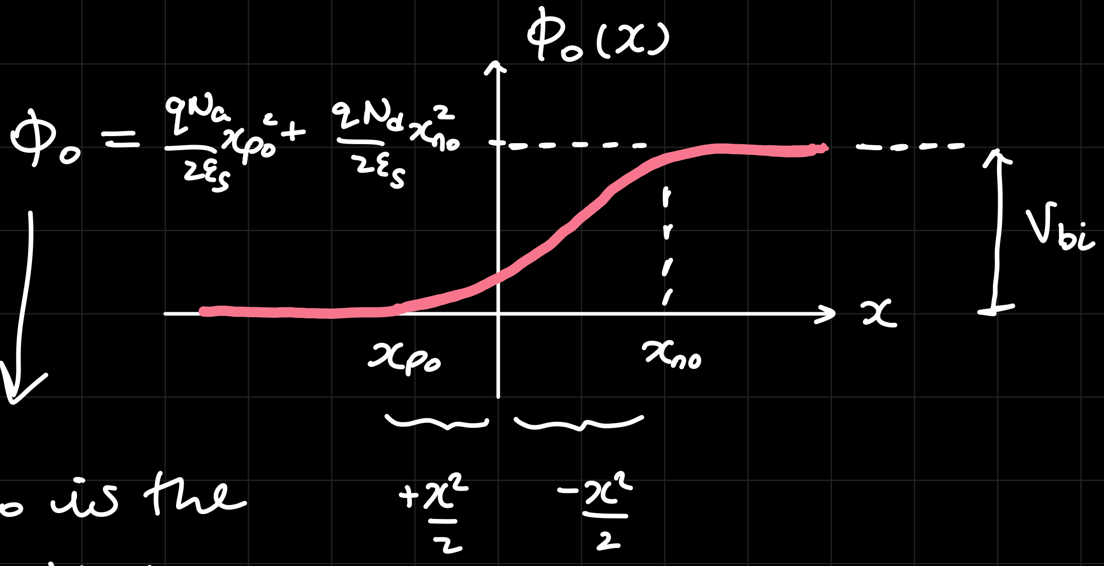
hence $\bar{E}$ graph is not a perfect triangle

Poisson's Eq$^n$ → $\phi(x) = -\int E(x)\,dx + c$

$\bar{E}$ and potential are continuous at $x=0$

so,

$$\phi(x) = \begin{cases} \dfrac{qN_a}{\varepsilon_s}\left[x_{po}x + \dfrac{x^2}{2} + \dfrac{x_{po}^2}{2}\right] & : -x_{po} < x < 0 \\ \dfrac{qN_d}{\varepsilon_s}\left(x_{no}x - \dfrac{x^2}{2}\right) + \dfrac{qN_a x_{po}^2}{2\varepsilon} & : 0 < x < x_{no} \end{cases}$$




$\phi_o$ is the built in voltage

$$\phi_o = V_{bi}$$

$$V_{bi} = \frac{qN_a}{2\varepsilon_s}x_{po}^2 + \frac{qN_d}{2\varepsilon_s}x_{no}^2$$

depletion width $= x_{no} - (-x_{po})$

$$= x_{no} + x_{po}$$

from ① $\rightarrow$ $N_a x_{po} = N_d x_{no}$

$$x_{po} = \frac{N_d}{N_a} x_{no}$$

$$W = x_{no}\left(1 + \frac{N_d}{N_a}\right)$$

if $N_a, N_D >>$, $W \downarrow$

So, for high doping we have small depletion width

low concentration = wider width $\leftarrow$

if $N_a, N_d \uparrow \rightarrow W \downarrow \rightarrow$ band bending $\downarrow$

$$W = \frac{2\varepsilon_s V_{bi}}{q}\left[\frac{N_a + N_d}{N_a \cdot N_d}\right]^{1/2}$$

note: $W \propto V_{bi}$

Reverse bias $\rightarrow V_{bi}' = V_{bi} + qV \rightarrow W\uparrow \rightarrow E\downarrow \quad I\downarrow$
Forward bias $\rightarrow V_{bi}' = V_{bi} - qV \rightarrow W\downarrow \rightarrow E\uparrow \quad I\uparrow$

diffusion current = − drift current
for pn junction

$$V_{bi} = \frac{KT}{q}\ln\left[\frac{N_A N_D}{n_i^2}\right]$$

$$\left.\begin{aligned} \text{drift current} &= qp\mu_p E \\ \text{diffusion current} &= qD_p\frac{dP}{dx} \end{aligned}\right\} \text{for p side}$$

$$q p \mu_p E = q D_p \frac{dp}{dx}$$

$$p \mu_p \left[ -\frac{dV}{dx} \right] = D_p \frac{dp}{dx}$$

$$-\mu_p \int_{x_1}^{x_2} dV = D_p \int_{p_n}^{p_p} \frac{1}{p} dp$$

diffusion coeff

$$V(x_{p_0} - x_{n_0}) = \frac{D_p}{\mu_p} \ln\left(\frac{p_p}{p_n}\right)$$

mobility

$$\frac{D_p}{\mu_p} = \frac{KT}{q}$$ : Einstein relation

and $p_p \simeq N_A$

and $p_n n = n_i^2$ (mass action law)

$$p_n N_D = n_i^2$$

$$V(x_{p_0} - x_{n_0}) = \frac{KT}{q} \ln\left[\frac{N_A}{n_i^2/N_D}\right]$$

(unit: Volts) $$V_{bi} = \frac{KT}{q} \ln\left[\frac{N_A N_D}{n_i^2}\right]$$

now we have 2 formulas for $V_{bi}$

# Lecture after quiz-3

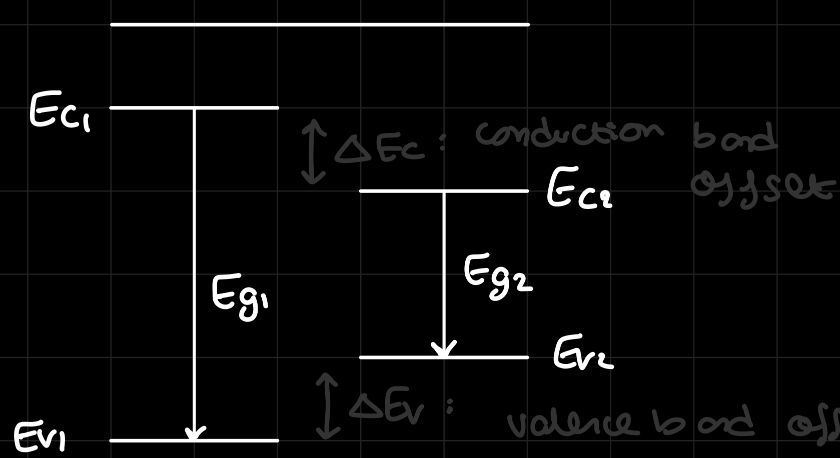
→ HETERO Junctions

Hetero structure devices : devices with a position dependent alloy composition

→ Type of hetero junctions

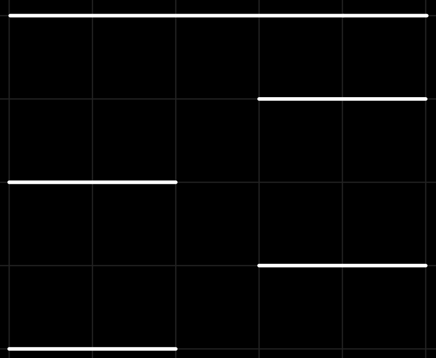
Straddling Gap
Staggered gap
Broken gap

① Staggered gap




$E_{c1} > E_{c2}$ , $E_{v1} < E_{v2}$

(2) Staggered Gap



$E_{c1} < E_{c2}$

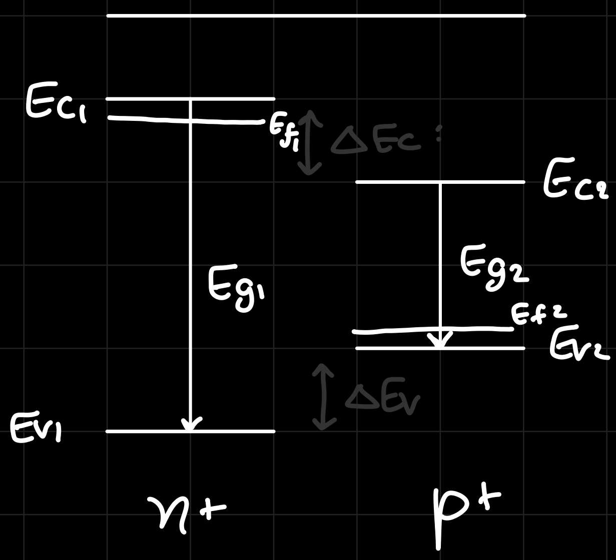
$E_{v1} < E_{v2}$

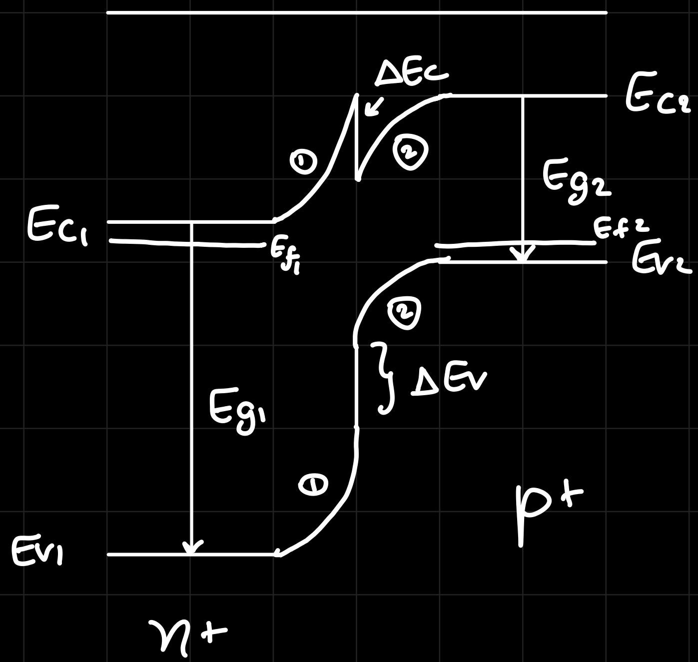
(3) Broken Gap

$E_{c2} > E_{v2} > E_{c1} > E_{v1}$

eg: $Al_{0.3}Ga_{0.7}As$

before contact



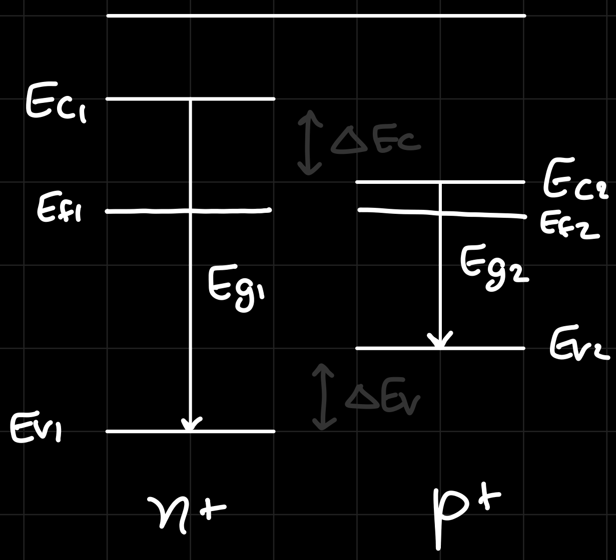



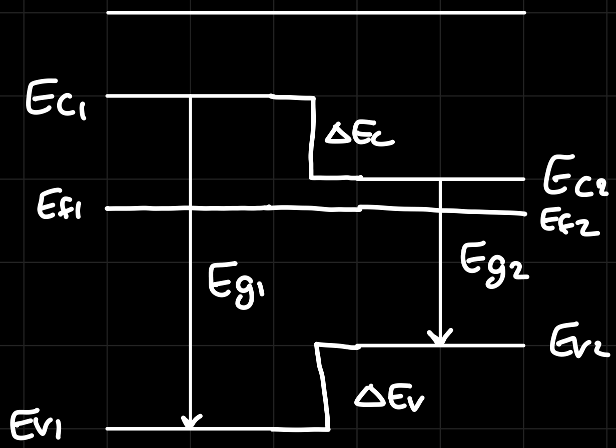

① : e⁻ depleted

② : e⁻ accumulated

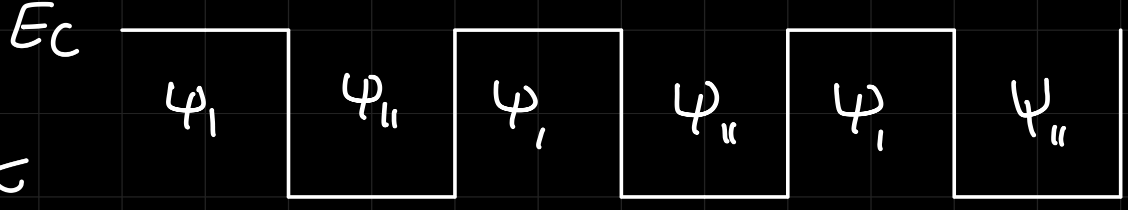
how to determine $\overline{E}$ for the sudden jump due to the offsets?

How about we choose doping so that no band bending required ($E_f$ const)




what if we add more such SC pairs?



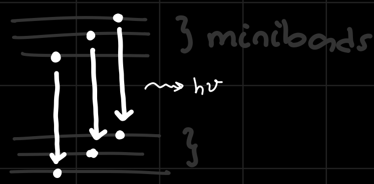

we get quantum well

Kronig Penny Model
quantized periodicity

This conduction band will form mini bands. We can also think about valence band similarly.

miniband (super lattice design)

quantum cascade laser

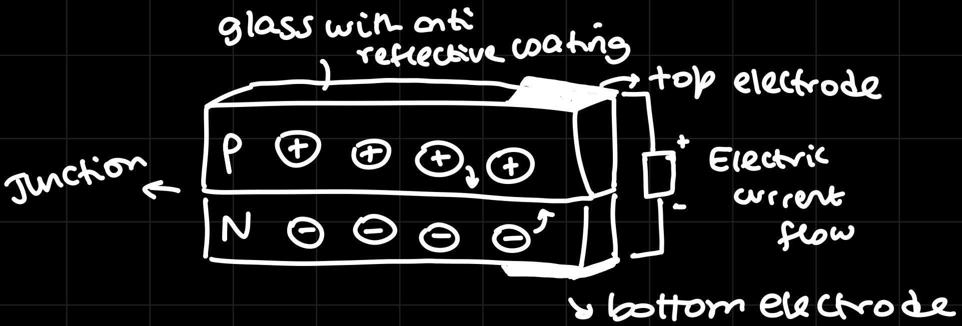




if the distance of traversal is kept constant, we can achieve a radiation of same freq with very high intensity (LASER)

# SOLAR CELL

$h\nu$ absorbed : free $e^-$ → electron hole pair generated
↓
This charge is held in a solar cell

Utilizes a PN Junction




Works in unbiased mode

The charges in the depletion region must be immediately separated ($h\nu$) and stored

$$\boxed{I = I_{ph} - I_d}$$

$I_{ph}$ → photogenerated current

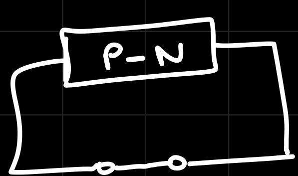
$I_d$ → like leakage current
→ diode/dark current due to thermal excitation inside the device

need to minimize $I_D$ and maximize $I_{ph}$

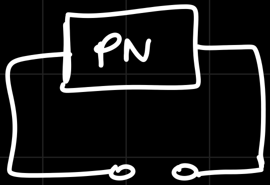
$$I = I_{ph} - I_0\left(e^{\frac{qV}{k_BT}} - 1\right)$$

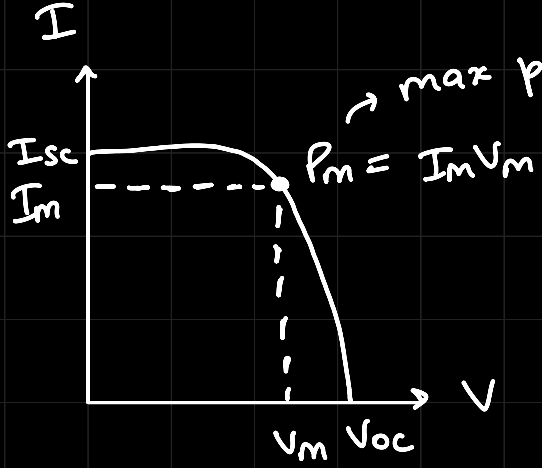
* <u>short circuit current</u> : max I generated with no bias/resistance

$I_{sc}$



* Open ckt voltage ($V_{oc}$) : max V generated in open ckt condition




→ max power point of a solar cell

# SOLAR Efficiency (Schockley - Queisser Limit)

The max efficiency for a single pn junction solar cell is 33.7%
at $E_g$ = 1.4eV

but Si → $E_g$ = 1.1 eV
resulting in $\eta_{max}$ = 32% only

visible range : 1.6eV → 3.4eV
but $\eta_{33.7}$ → $E_g$ = 1.4eV < 1.6eV

we get better $\eta$ efficiency by stacking layers of diff materials (with varying band gaps) to capture wider range of frequency spectrum.

≡ Tandem solar cell

Theoretically, we got 50% - 52% $\eta$

Still we use Si because practical use case wise, it offers mix of $\eta$ and complexity.