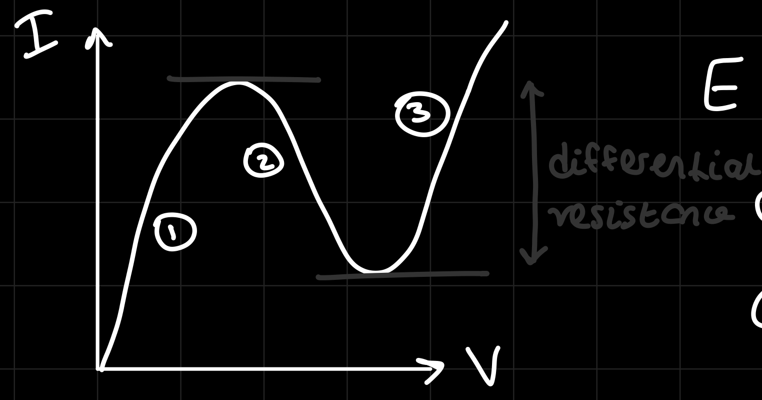
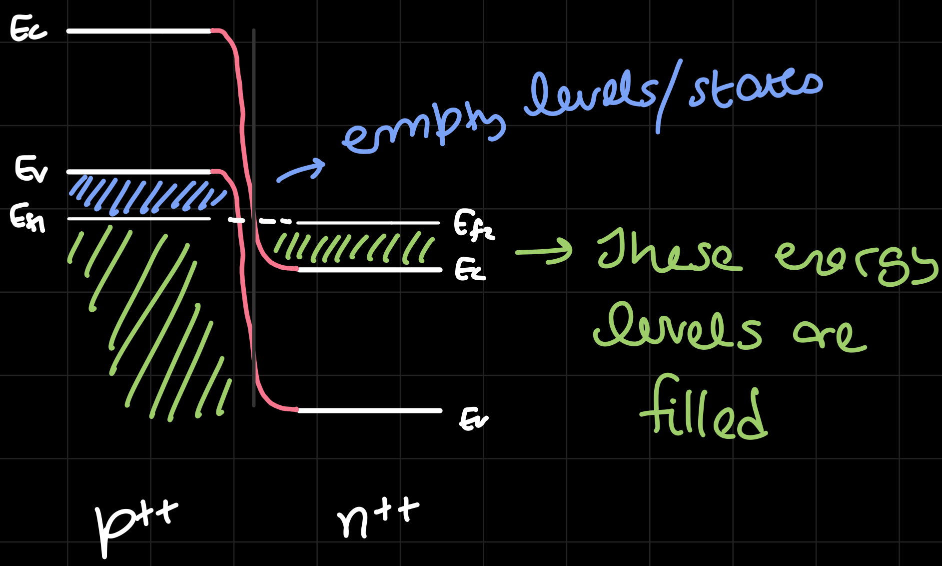
Esaki diode → degenerate semiconductor
(heavily doped $\sim 10^{21}/cm^3$)
n^{++}/p^{++}
E_f lies outside the band gap

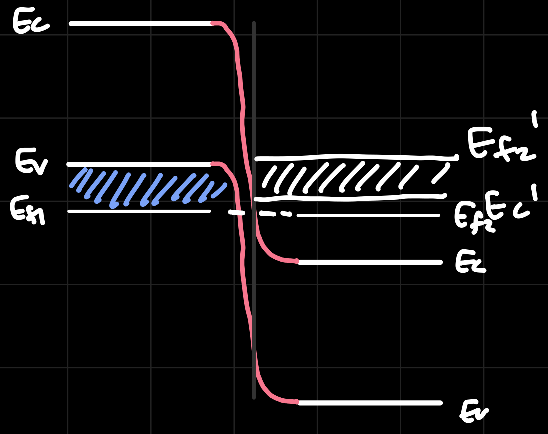


ESAKI diode characteristics



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

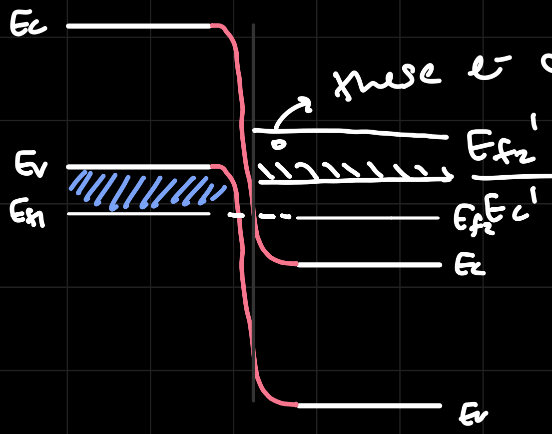
① initial potential bias



all e^- can tunnel through

when increasing V further ②

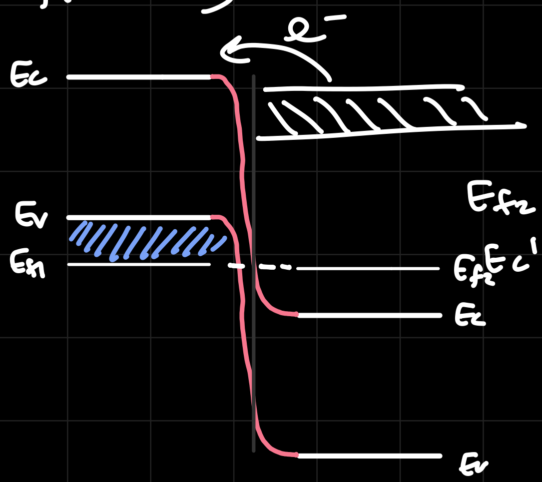
these e^- do not have any empty states to go to on the p side



very less overlap

current ↓

finally ③



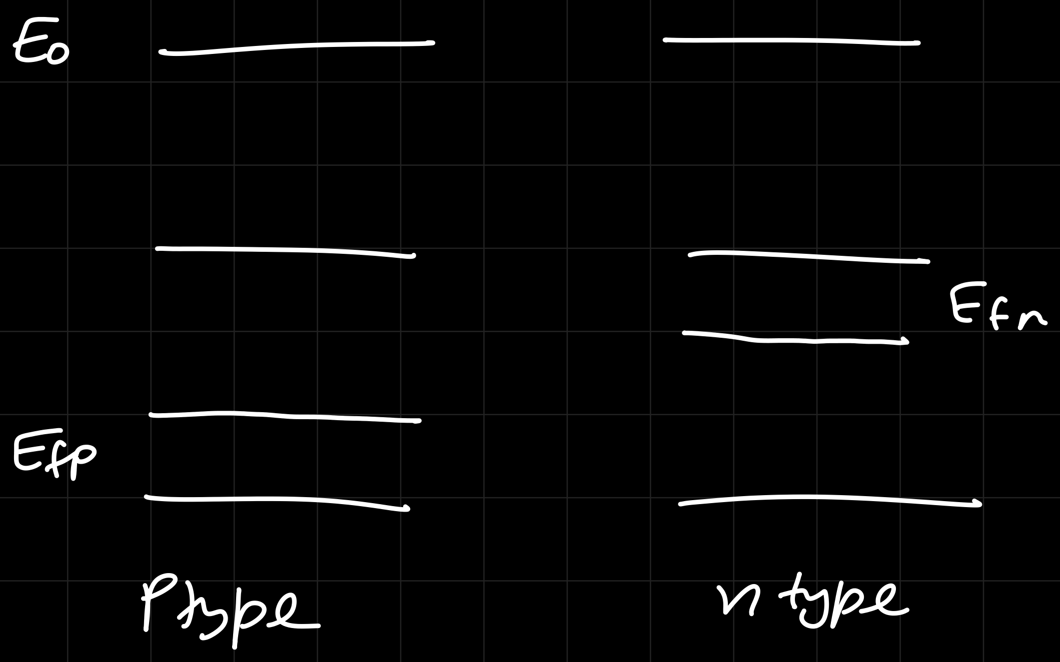
jumps over the barrier at very high V

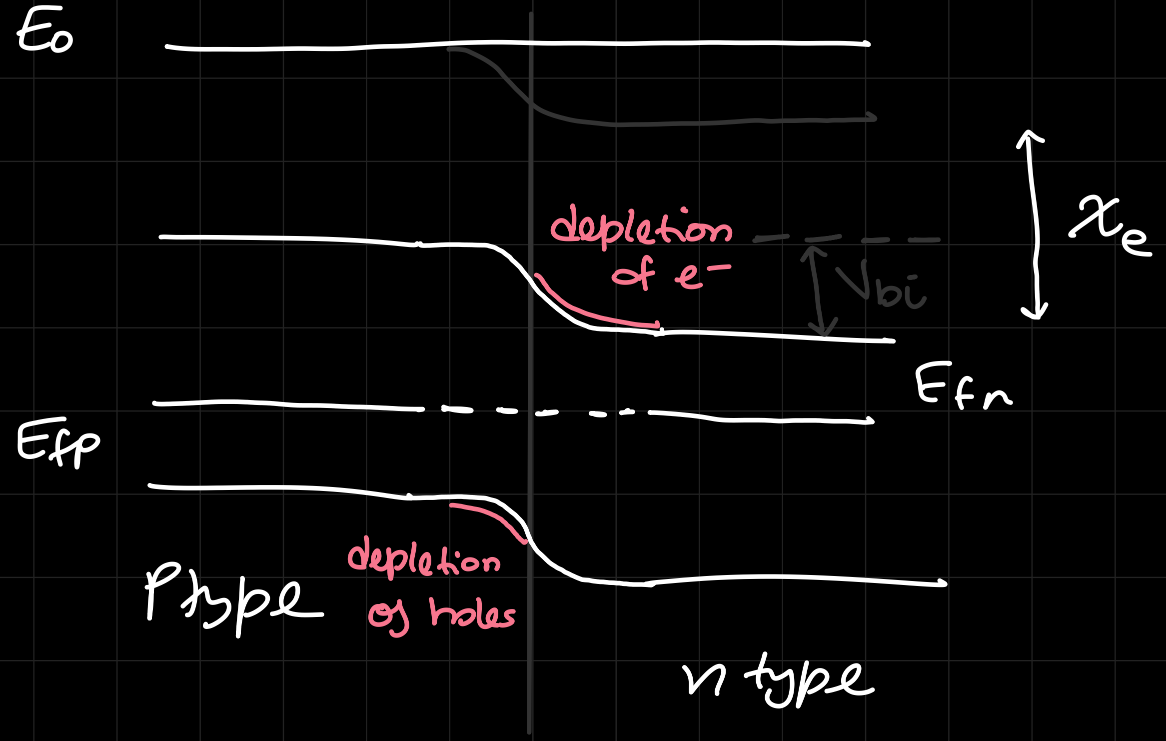
Esaki diode works in forward bias
zener diode (PN) works in reverse bias

diffusion current : current due to difference in concentration

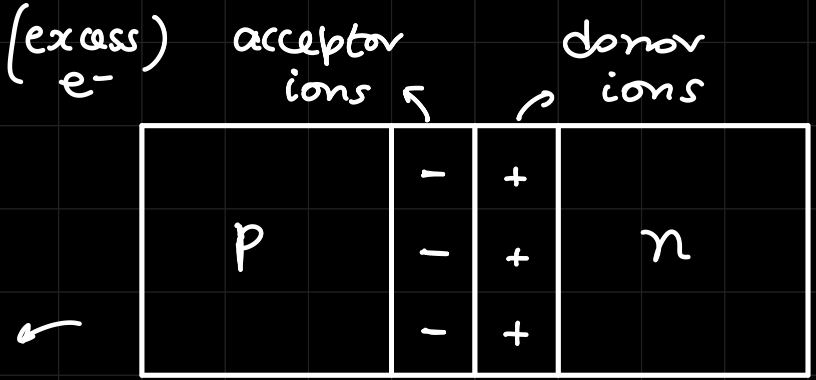
PN Junction : at room temp, diff and drift current cancel each other out and hence net current = 0

note: There exist NN and PP Junctions as well.

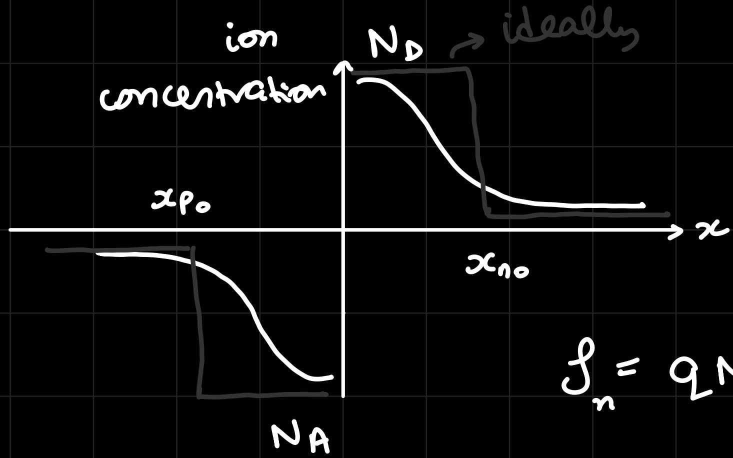




exponentially varying band bending



charge:
$\rho - N_A$
↓
free ions



$\rho_n = qN_D$

$\rho_p = -qN_A$

but $\rho(x)$

$x: 0 \to x_{n0}$

$\rho(x)$

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

$$\rho_0(x) = \begin{cases} -qN_a & : \quad -x_{p_0} < x \leq 0 \\ qN_D & : \quad 0 < x < x_{n_0} \\ 0 & : \quad -x_{p_0} > x \quad \text{or} \quad x > x_{n_0} \end{cases}$$

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 $\rightarrow \frac{\partial^2 \phi(x)}{\partial x^2} = 0$ $\{$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 $\rho = 0$

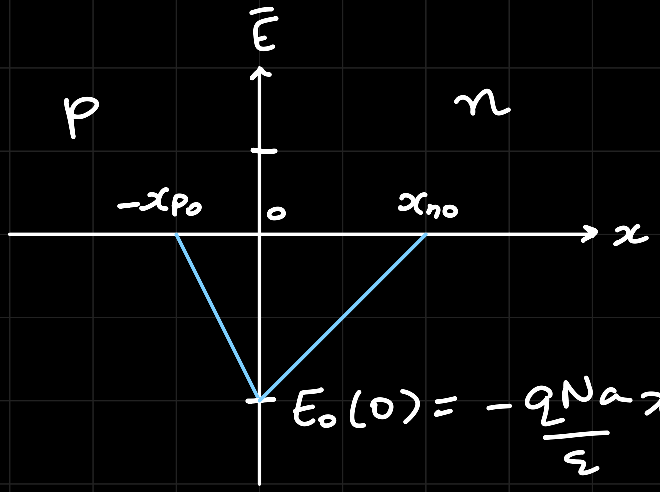
for $x < -x_{p_0}$

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

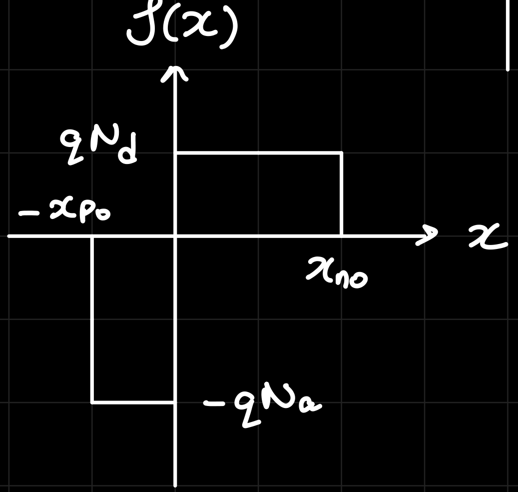
↳ $\bar{E} = 0$

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

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



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



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

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

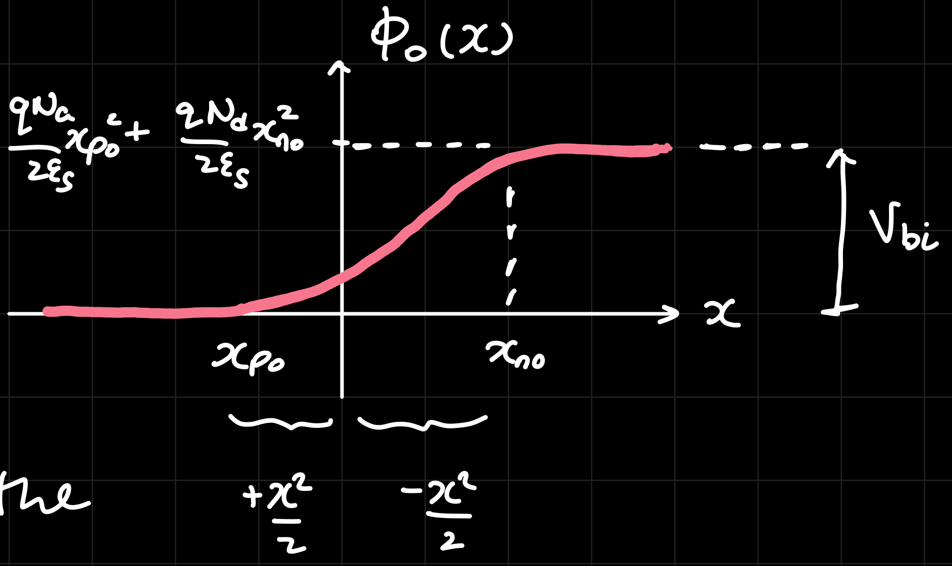
Poisson's Eqn → $\phi(x) = -\int E(x)\,dx + c$

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

so,

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

$$\phi_0 = \frac{qN_a}{2\varepsilon_s}x_{po}^2 + \frac{qN_d x_{no}^2}{2\varepsilon_s}$$



ϕ_0 is the built in voltage

$$\phi_0 = V_{bi}$$

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

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

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

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}