PYL-102

Semiconductor

Solar cell

Photodetector

Switch → ON

→ OFF

amplifier.

→ gain.

Led.

logic.

memory.

Band diagram,

Carriers → hole, electrons,

ellective

effective mass,

Fermi-Dirac distribution

→ Carrier. transport.

Carrier. ~~recomb~~ recombination

→ P-n junction.

→ BJT, solar cell, .

Semiconductor →

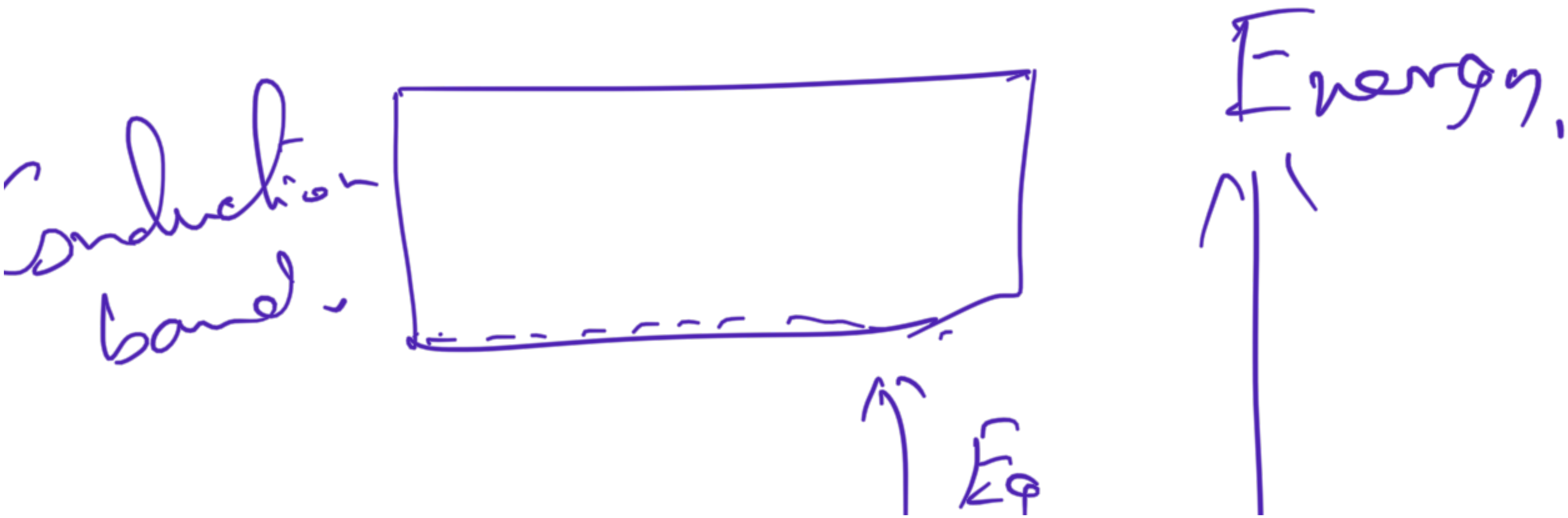
→ Silicon ← Si

→ ~~Ge~~ Germanium → Ge.

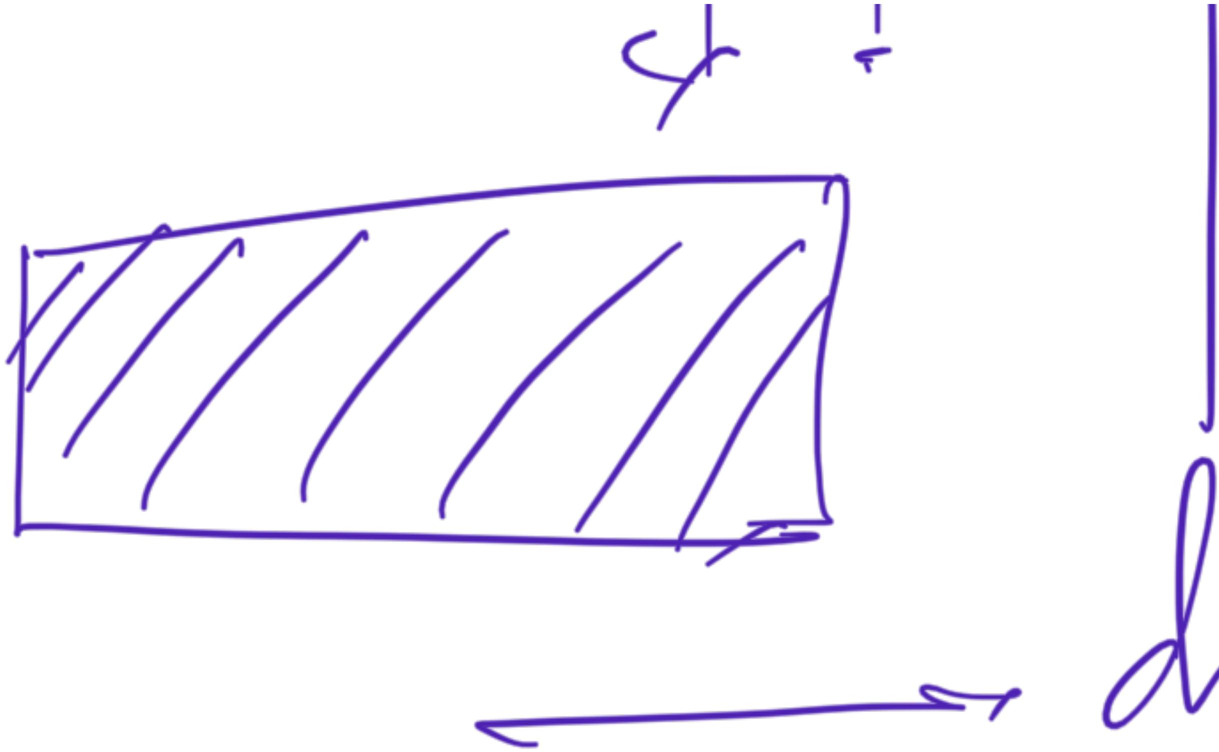
Gallium
Ga.

Arsenic.
As

Gallium Arsenide.
GaAs.

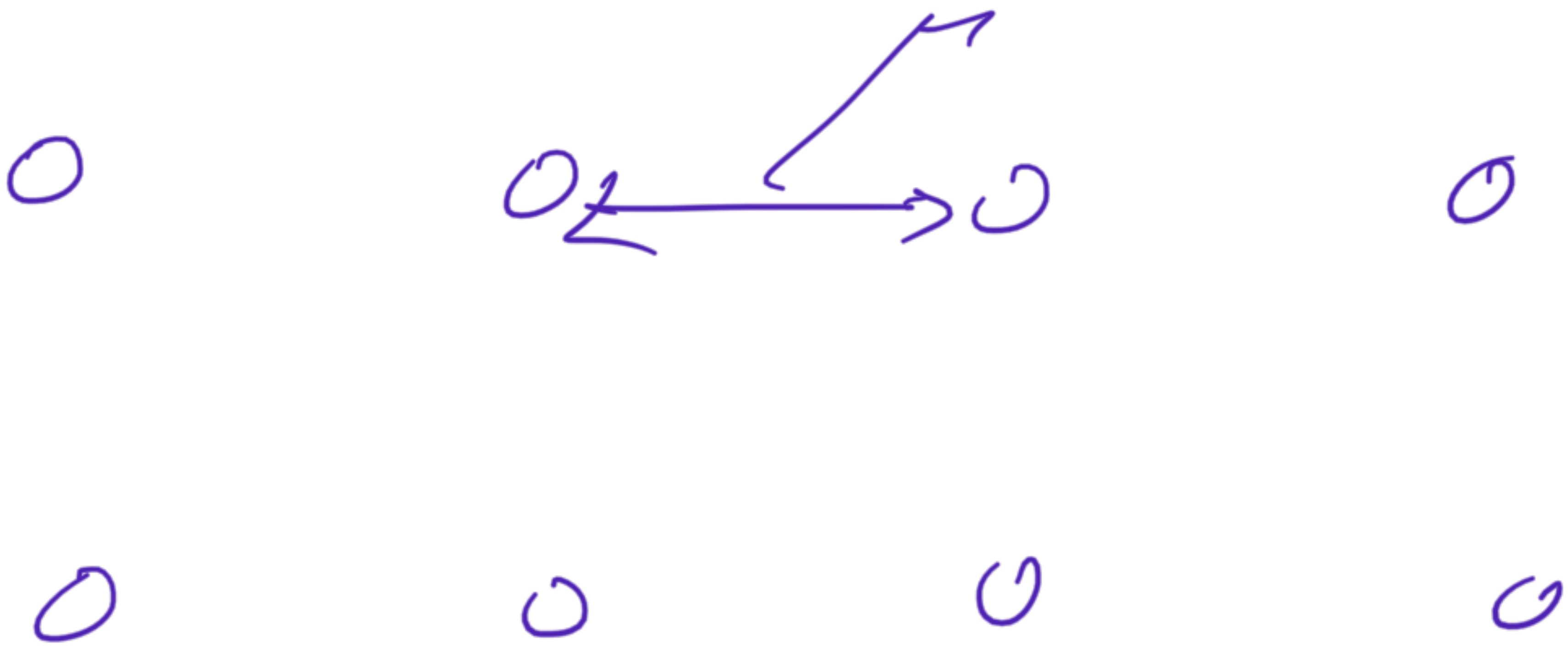


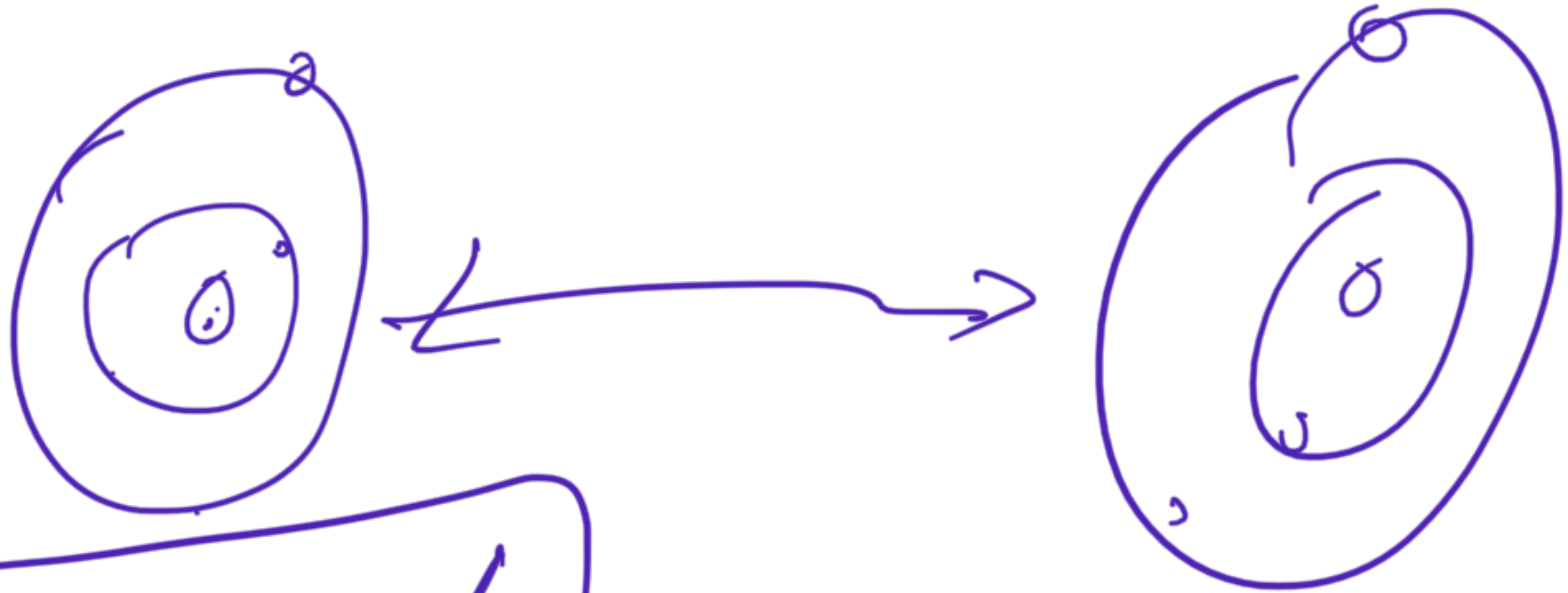
valence band,



distance.

Lattice constant.

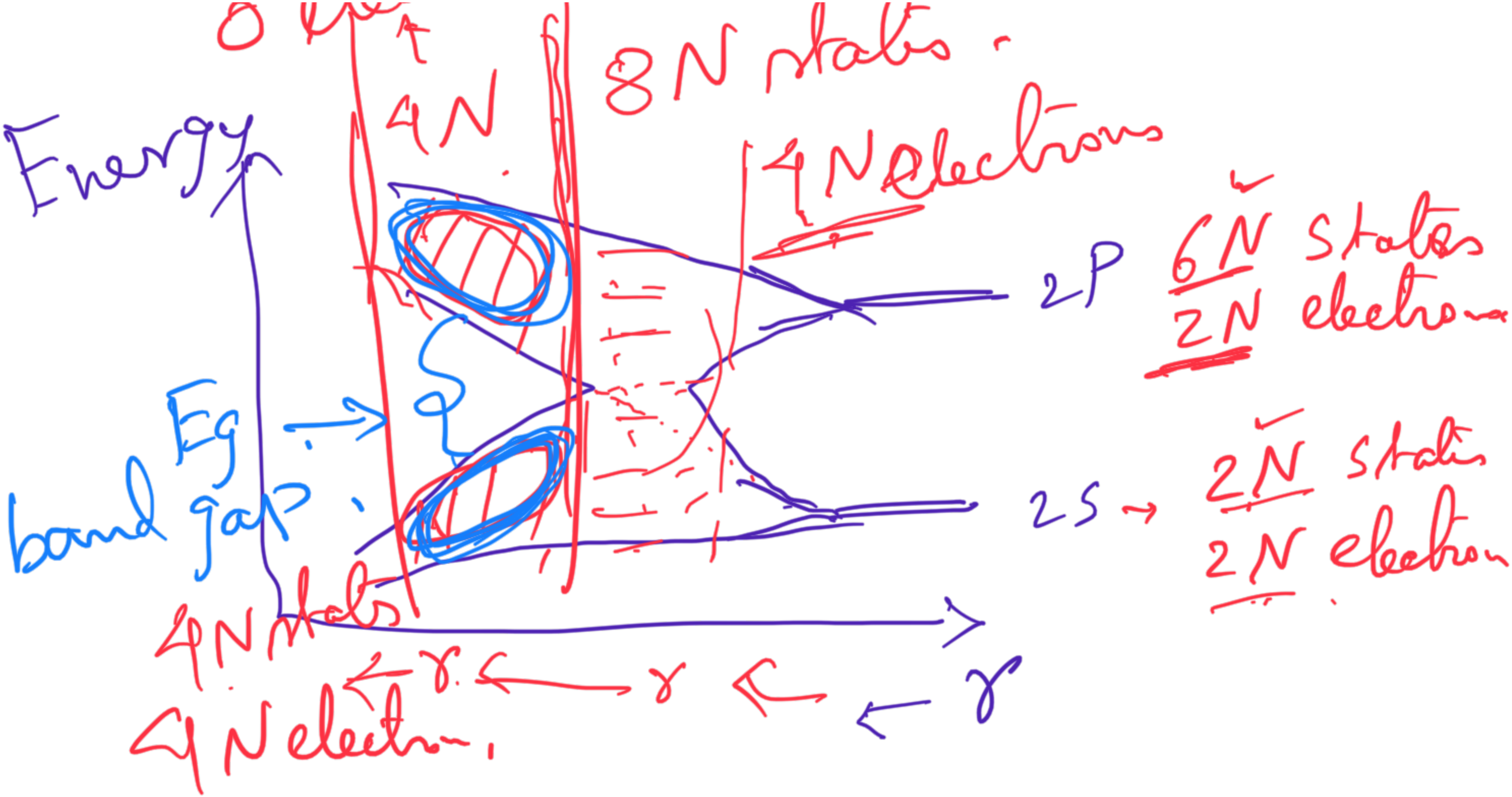




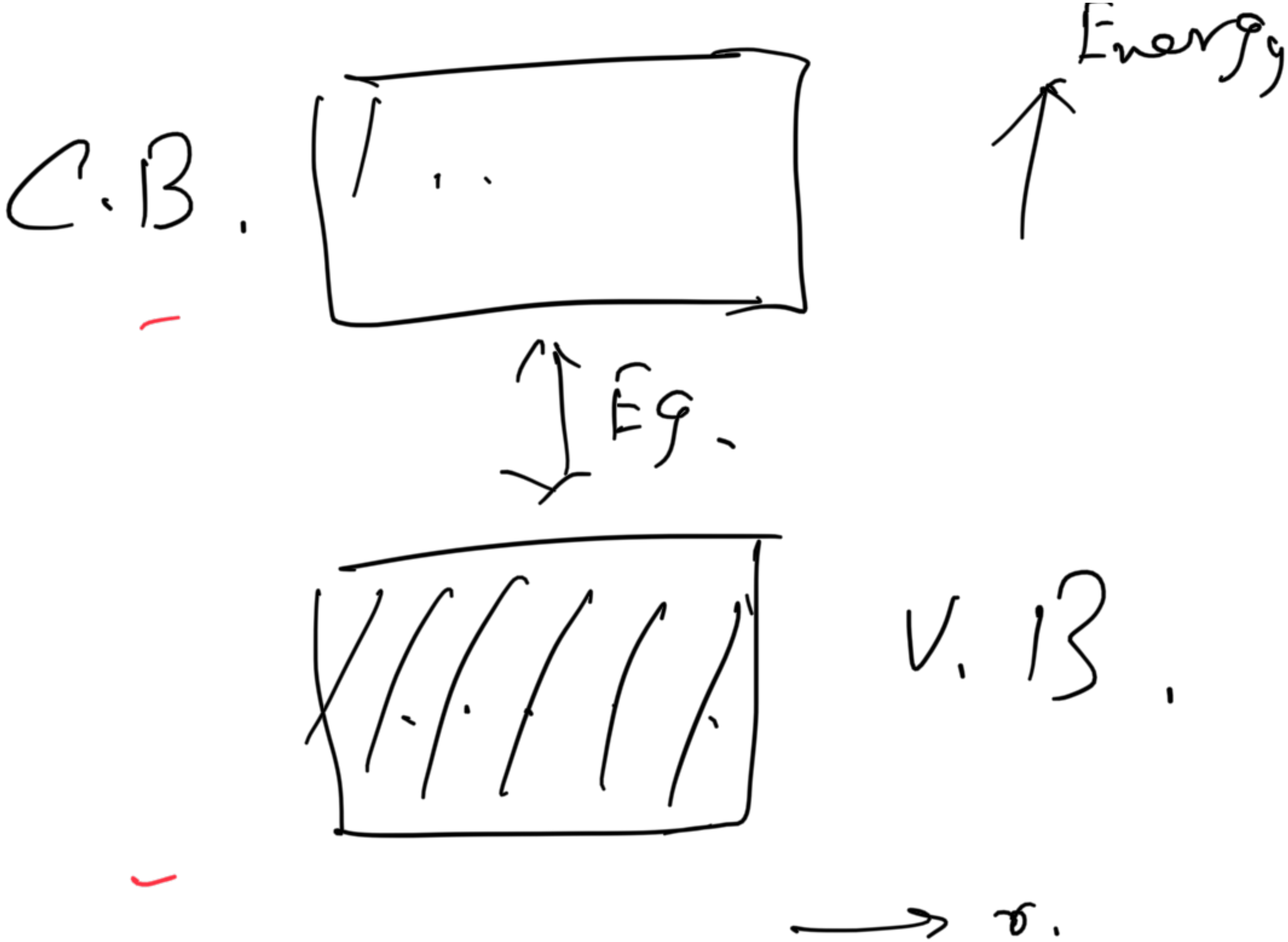
$\boxed{1s^2 2s^2 2p^6}$

A N metals :

~~electron~~ :

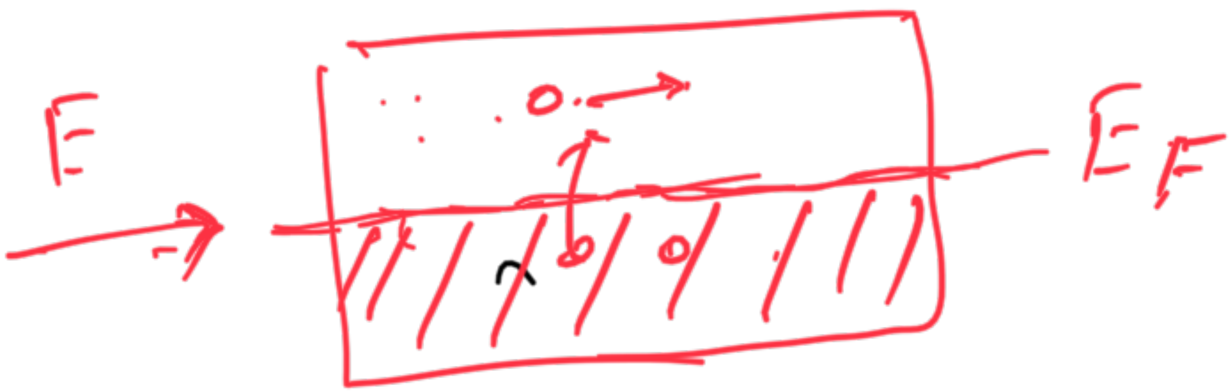


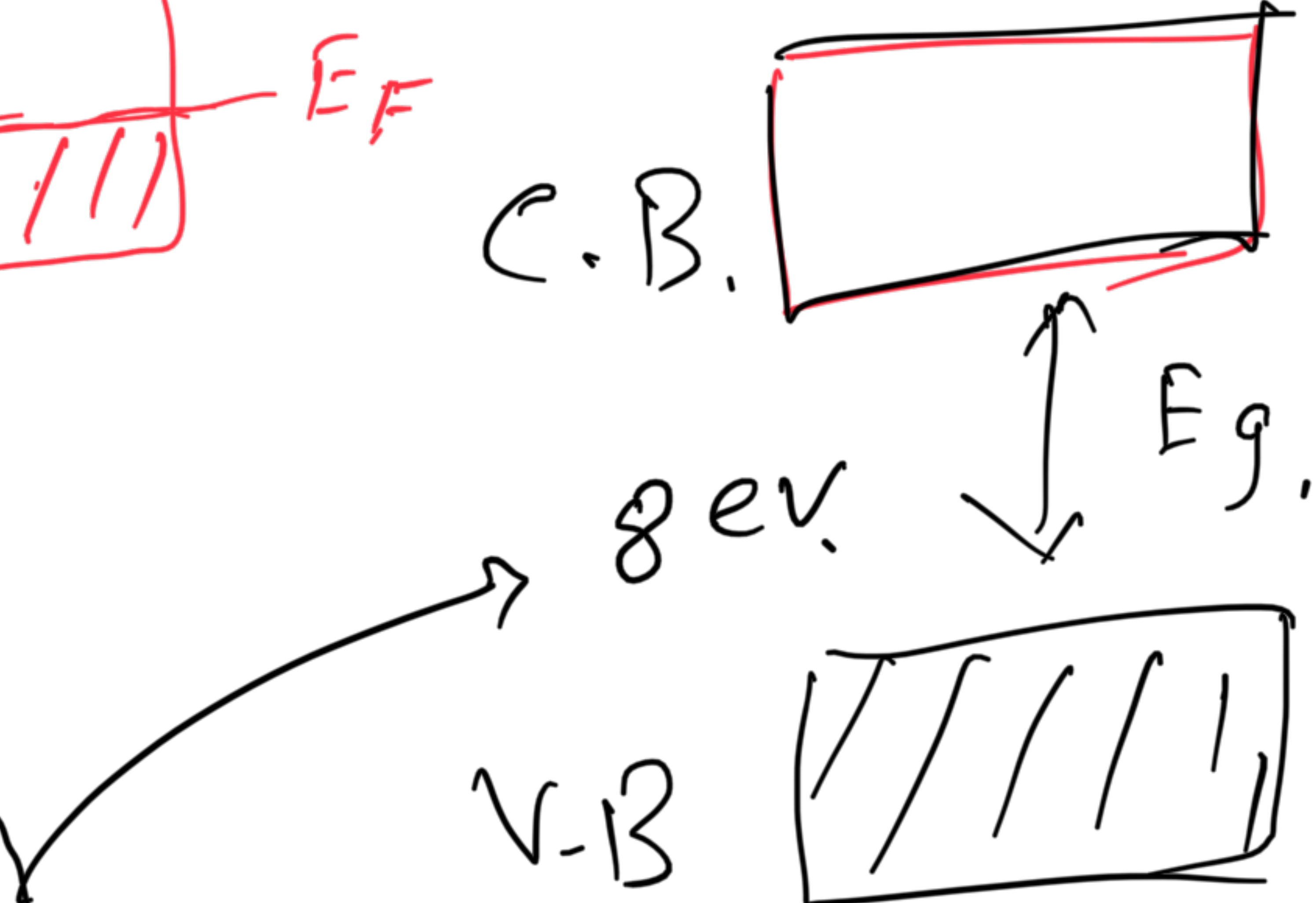
$C \rightarrow 1s^2\, 2s^2\, 2p^2$

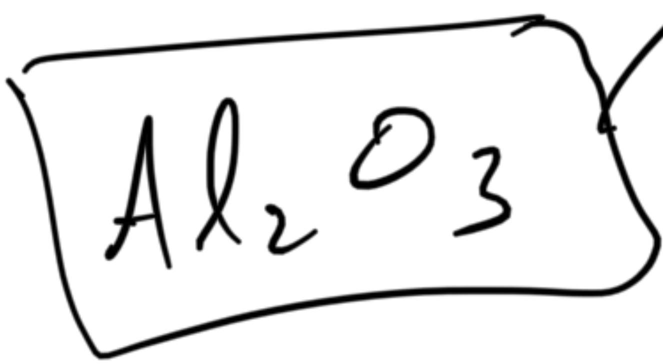

Energy
C.B.
Eg.
V.B.
r.


2p²

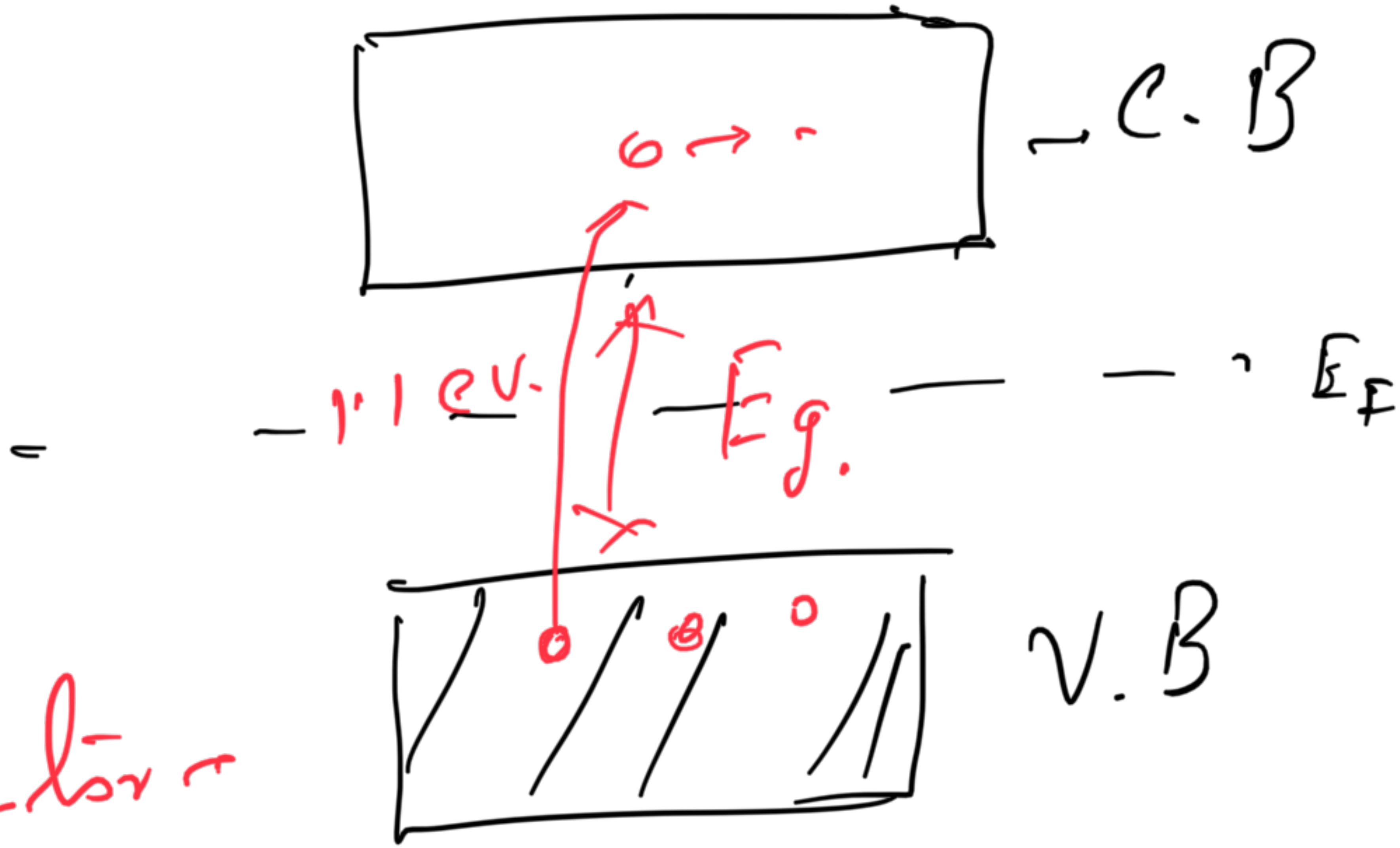

E_g
$2s^2$


E
E_F


C.B.
E_g.
8 ev.
V.B


Al_2O_3

SiO_2



semiconductor

$Si \rightarrow$ 1.1 ev.

$1\,ev = 1.6 \times 10^{-19}\,J$

$Ge \rightarrow$ 0.7 ev.

$K_B T \longrightarrow 300K.$

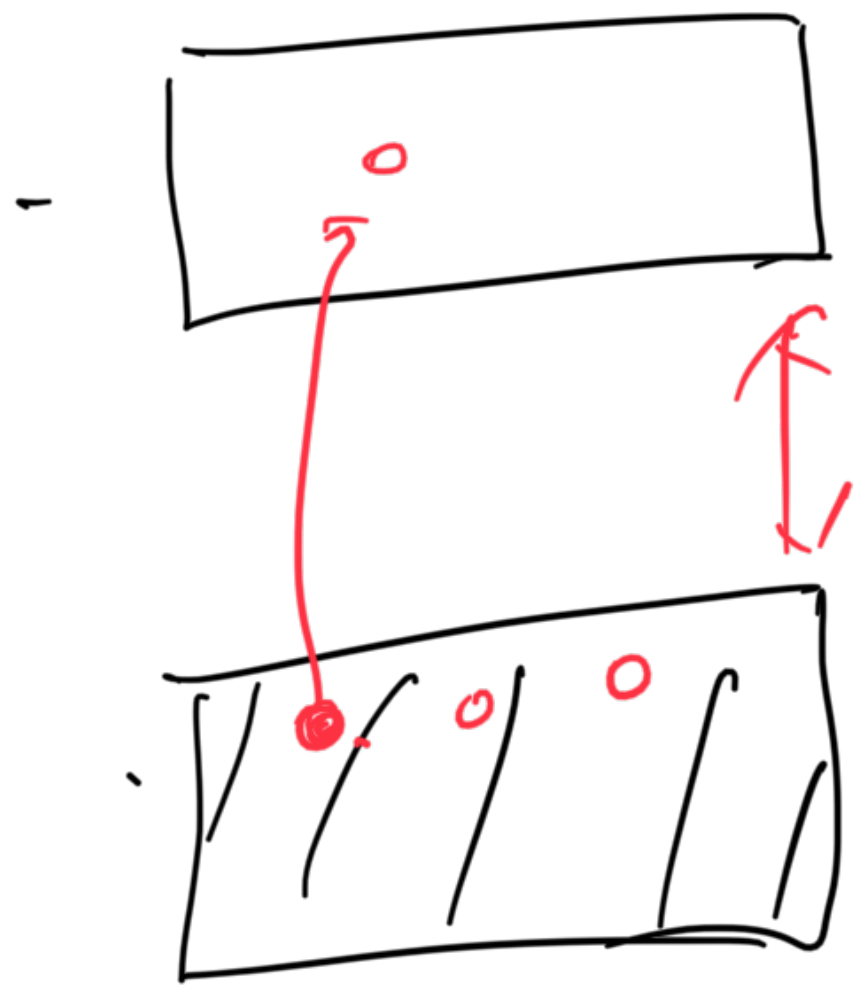
$\searrow$ Boltzman Constant

$= 1.38 \times 10^{-23}$ S.I.

$$K_B T = \frac{1.38 \times 10^{-23} \times 300}{1.6 \times 10^{-19}} \text{ eV}.$$

$$= \underline{\underline{0.0259 \text{ eV}}}.$$

real space.



Si

$E_g = 1.1\ eV.$

$\boxed{26\ meV.}$

real space → ~~cm~~ cm/m.

Reciprocal Space $\rightarrow$ $1/\text{cm} = \frac{1}{\text{distance}}$.

$\frac{2\pi}{\lambda}$ $\rightarrow$ wave vector.

$\rightarrow$ K.

$$\hbar = \frac{h}{2\pi} \Rightarrow \hbar K = \frac{h}{2\pi} \times \frac{2\pi}{\lambda}$$

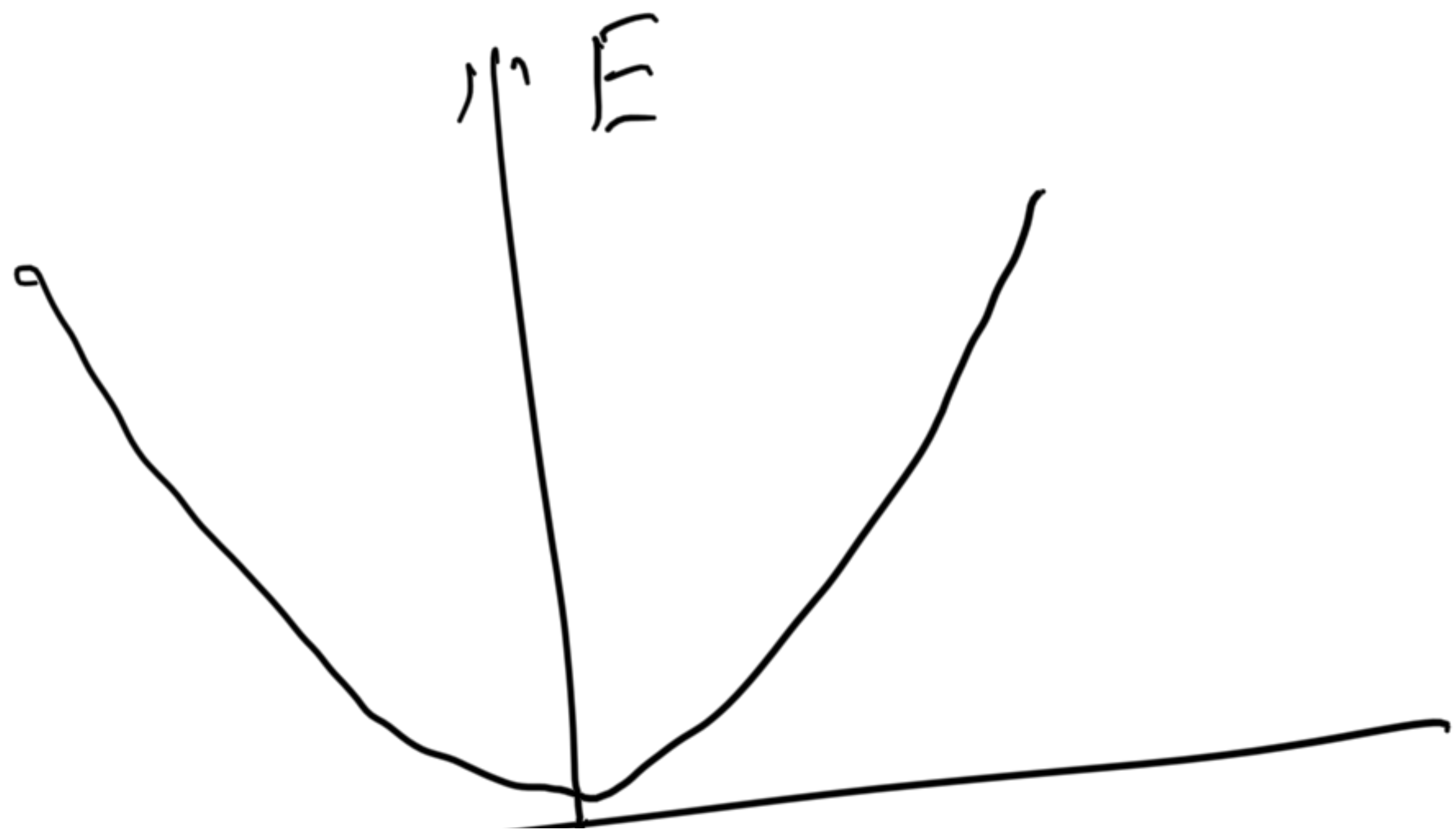
$$= \frac{h}{\lambda} = p$$

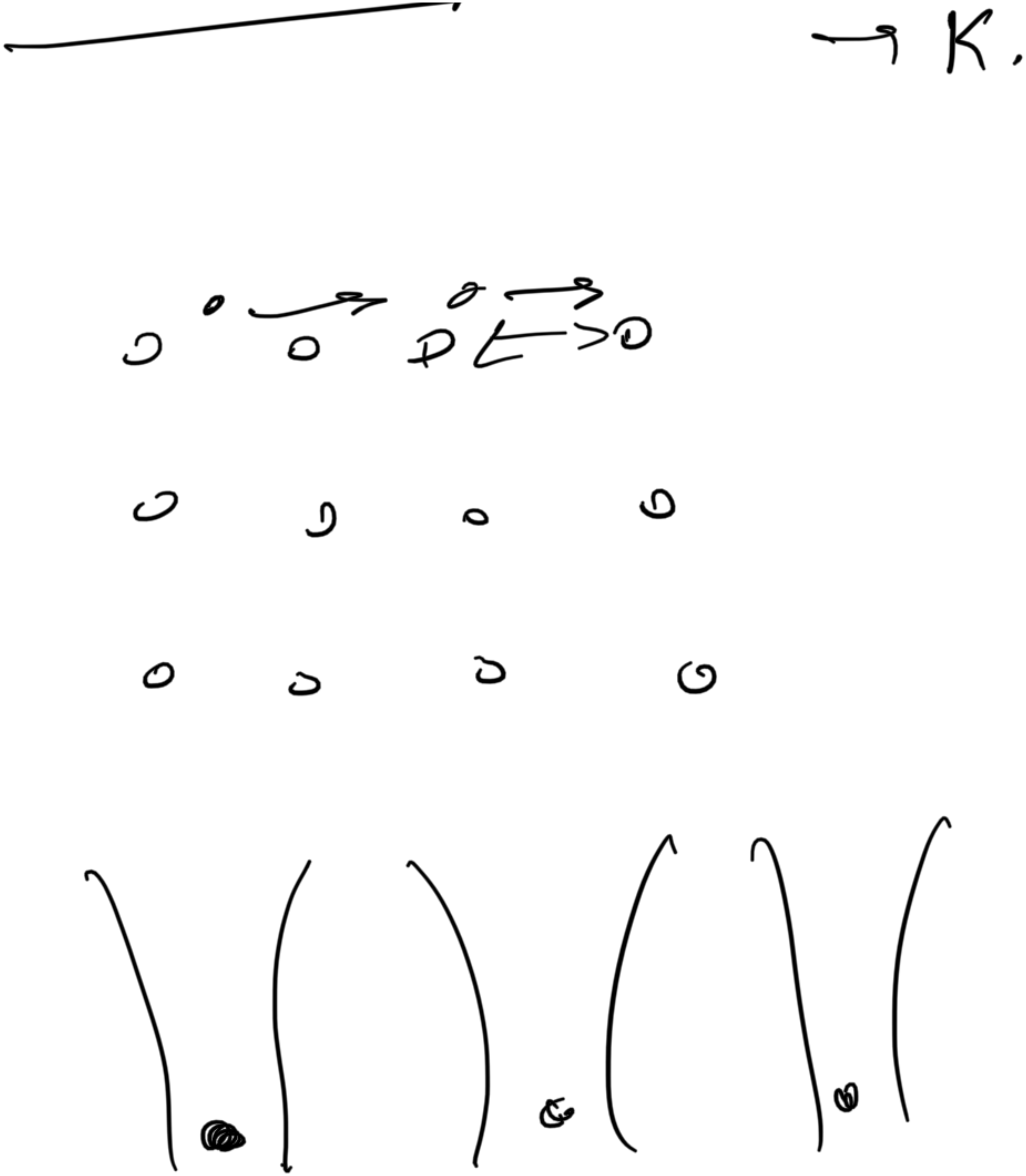
momentum

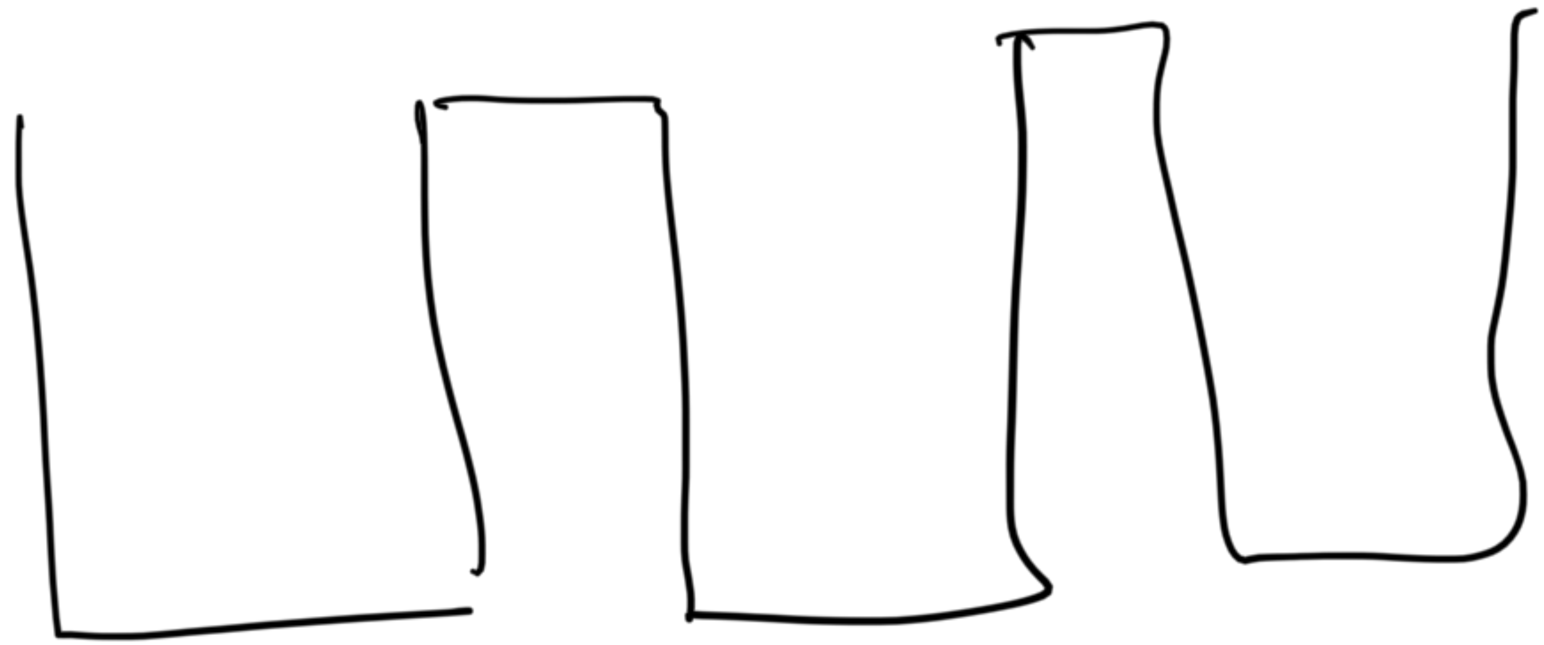
$$\hbar K = p$$

Kinetic energy $= \dfrac{p^2}{2m}$

$$= \boxed{\frac{\hbar^2 k^2}{2m} = E.}$$

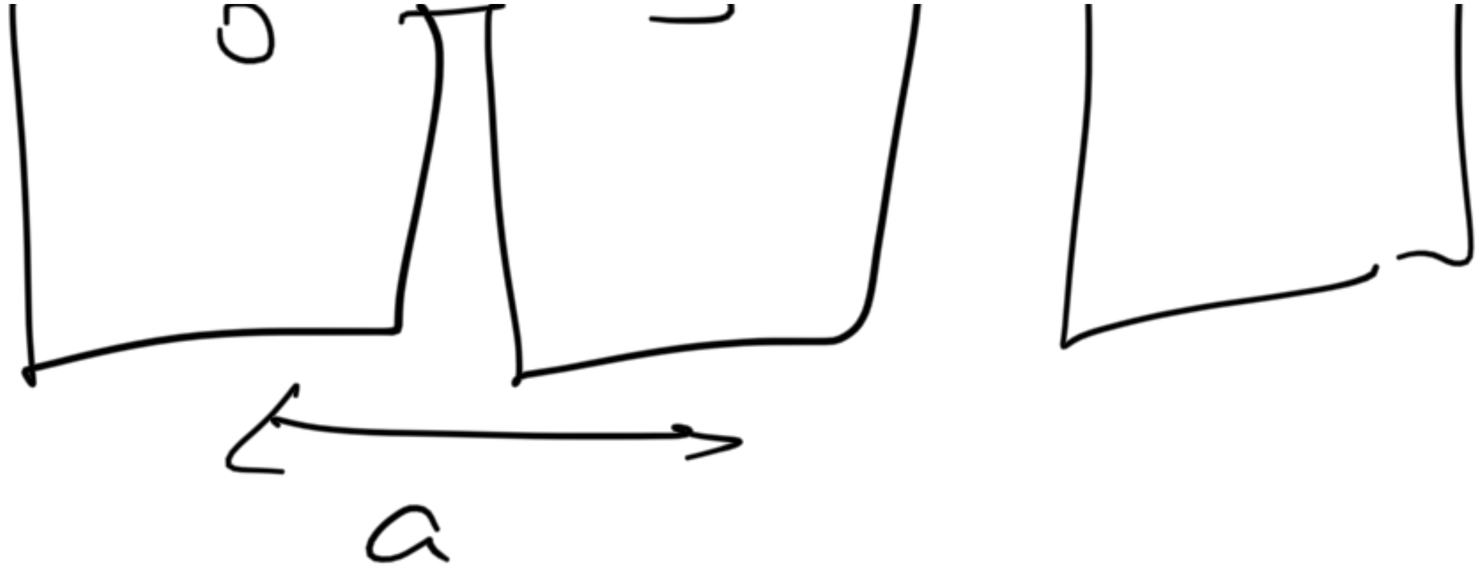


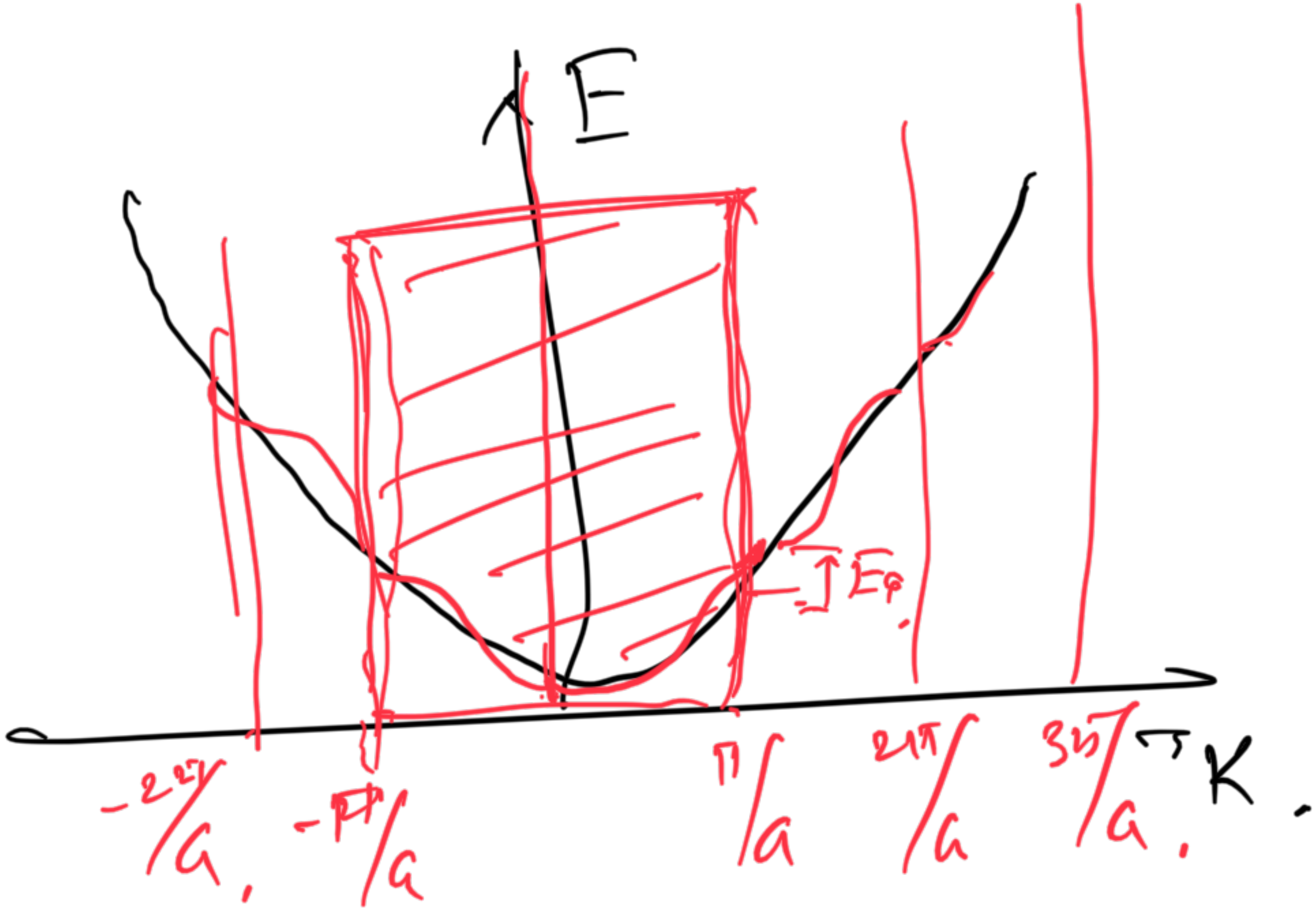

K.



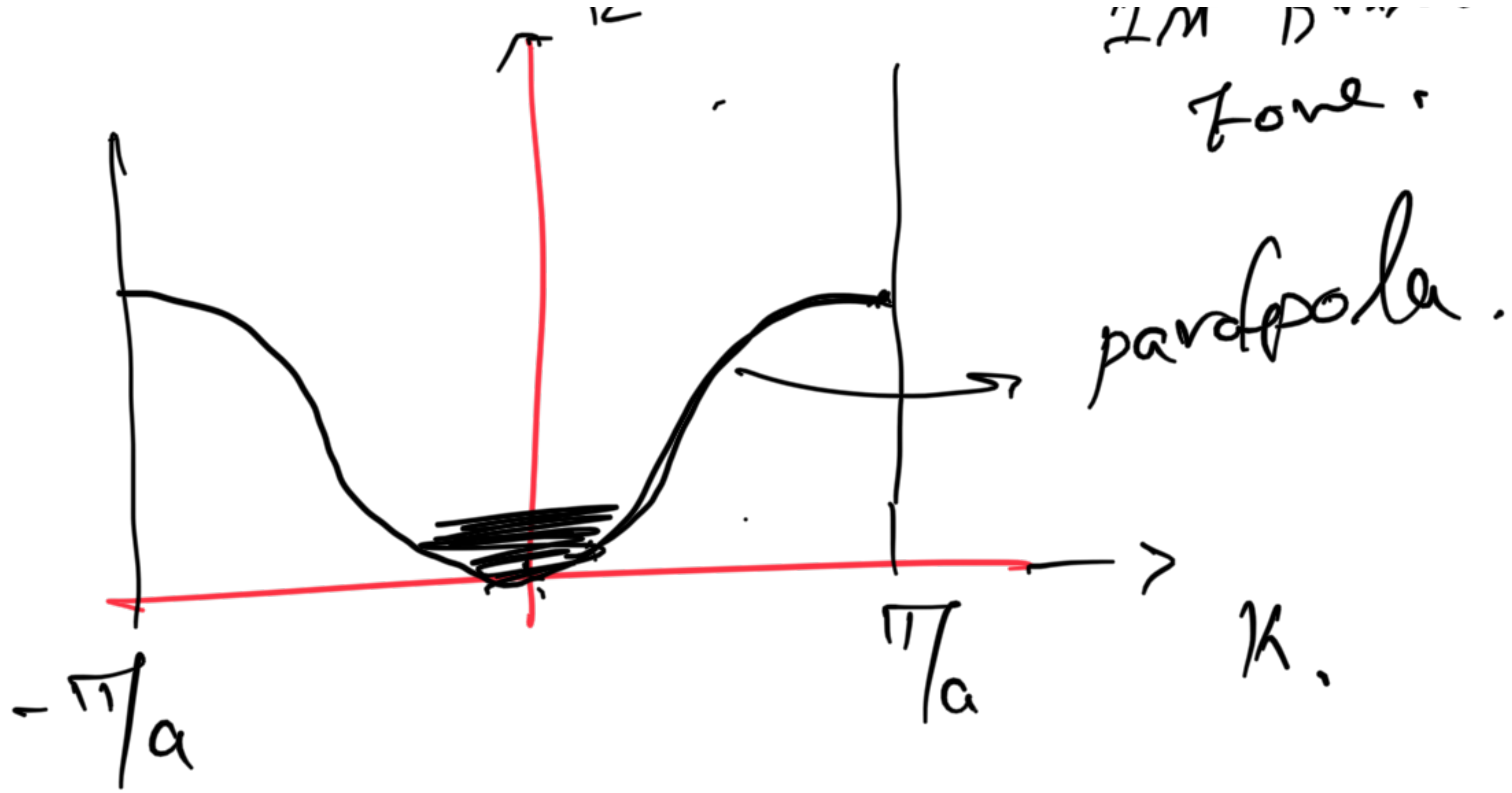
$$\boxed{m_0 = 9.1 \times 10^{-31}\ \text{Kg}.}$$

$$m^* \neq m_0 .$$





Brillouin



$$E = \frac{\hbar^2 k^2}{2m^*}$$

m^* → effective mass of

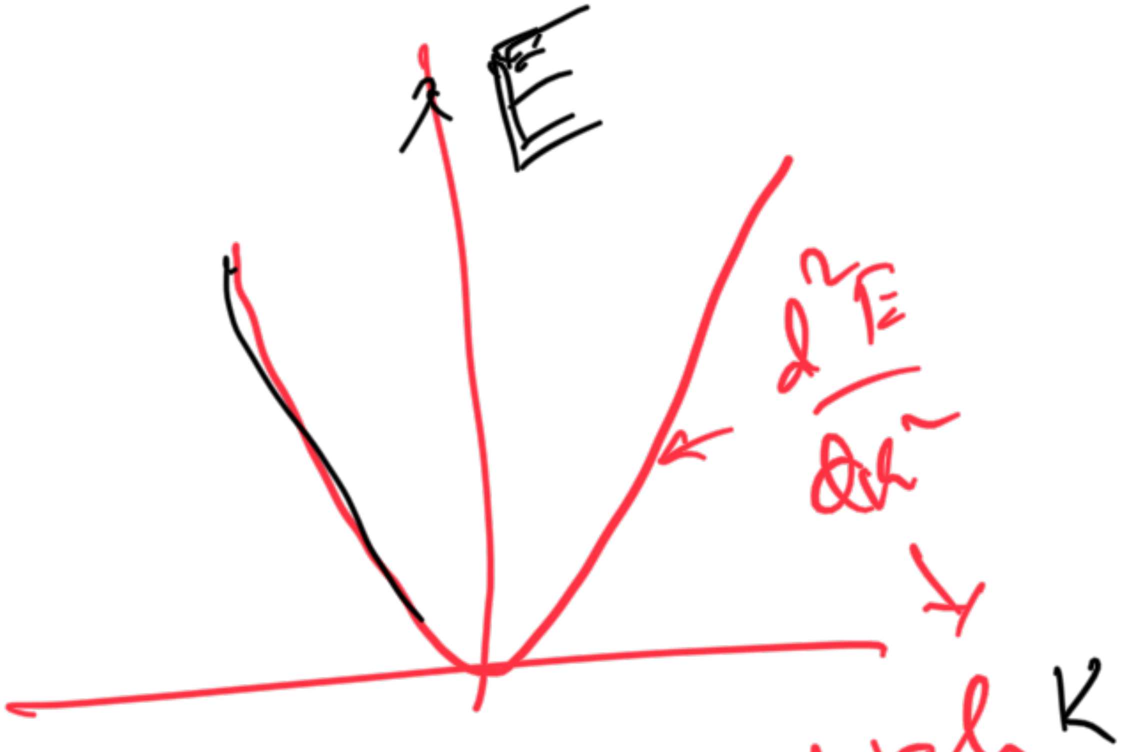
slope.

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m^*} \quad , \quad \frac{d^2E}{dk^2} = \frac{\hbar^2}{m^*}.$$

curvature.

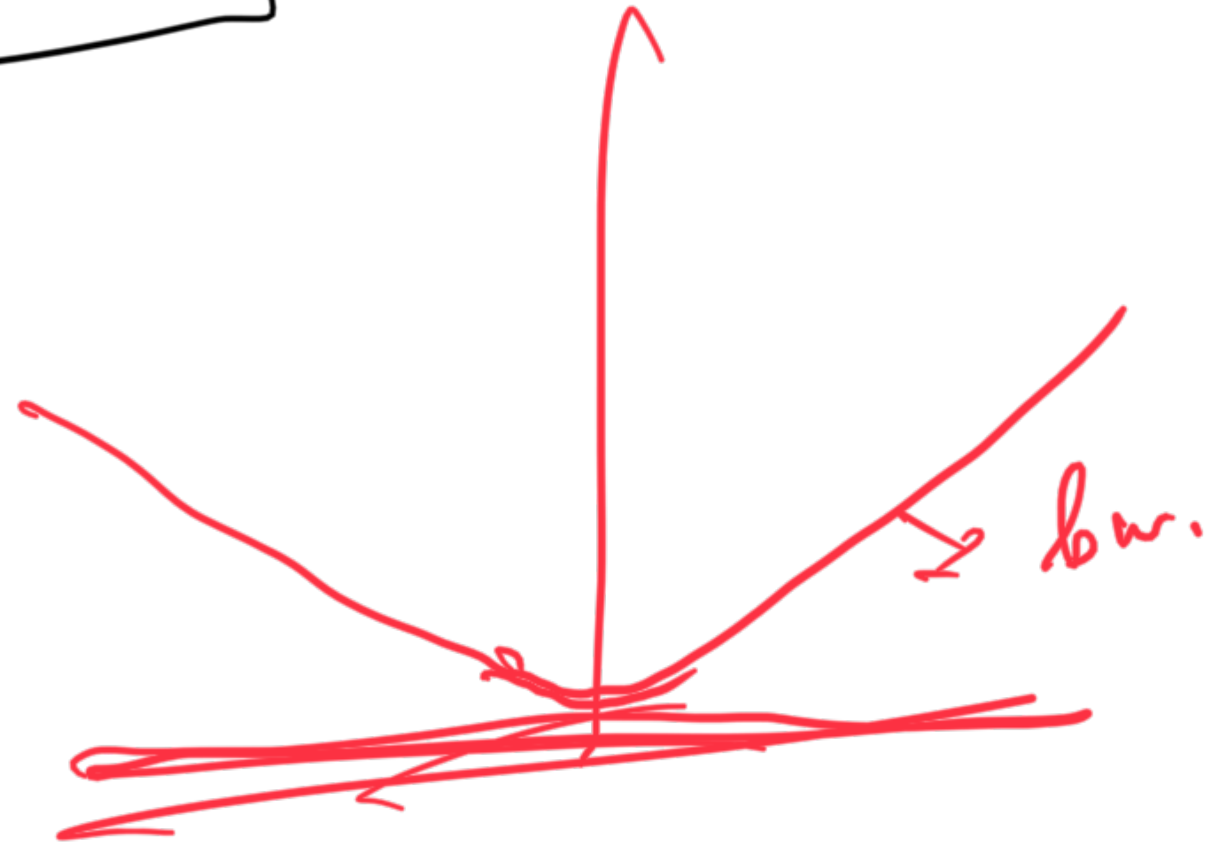
dK

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



high K.

$m^* \rightarrow$ low/small



$m^* \rightarrow$ high.

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

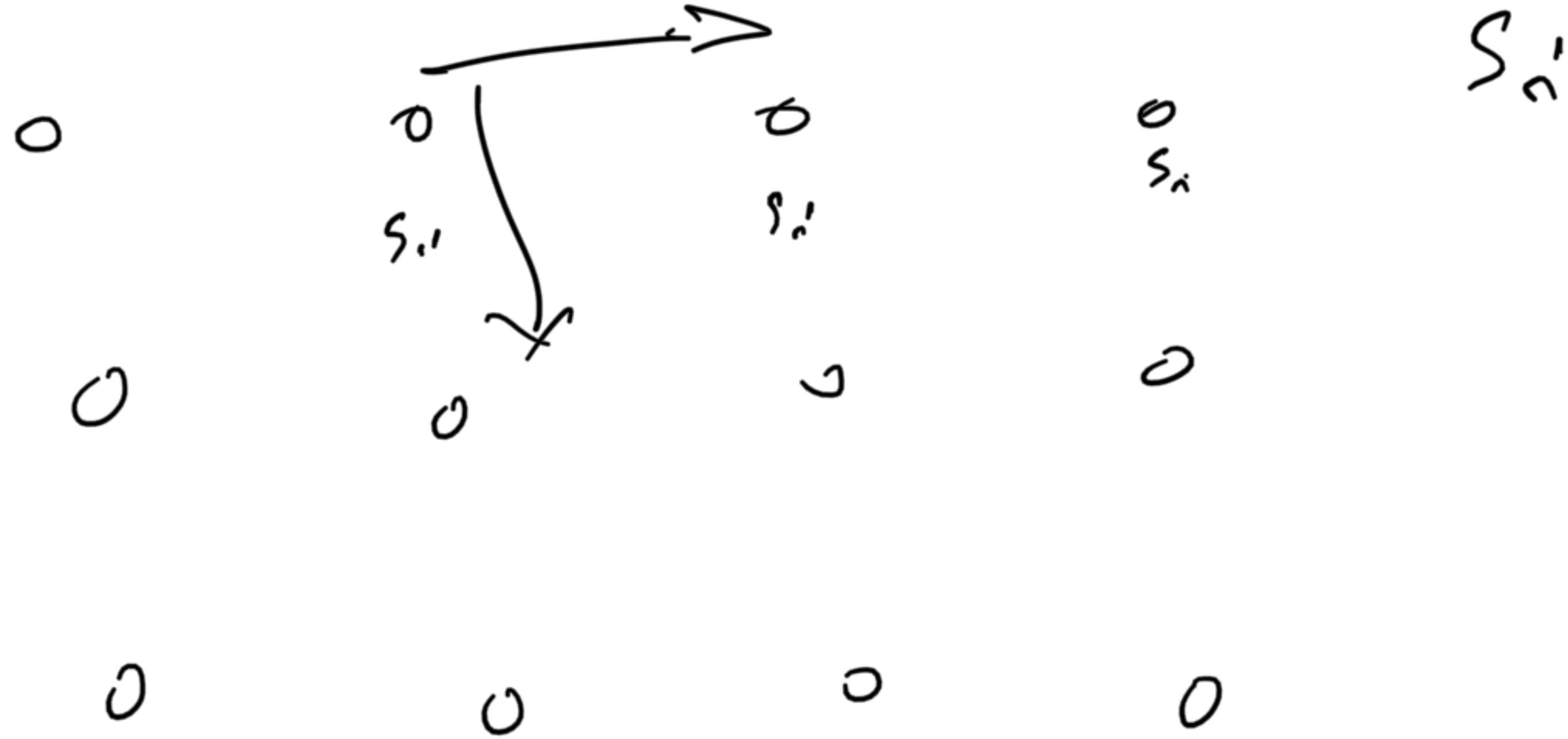
classical law $\rightarrow$ $\boxed{F = ma}$

$$F = m^* a$$

GaAs $\longrightarrow$ $0.06\, m_0$

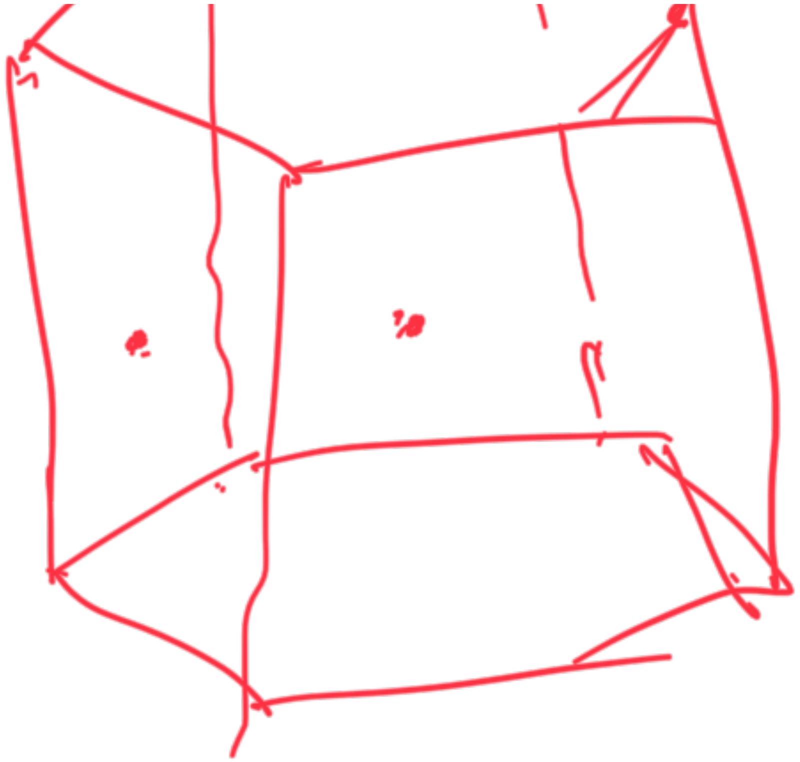
GaN — $0.2 \times m_0$

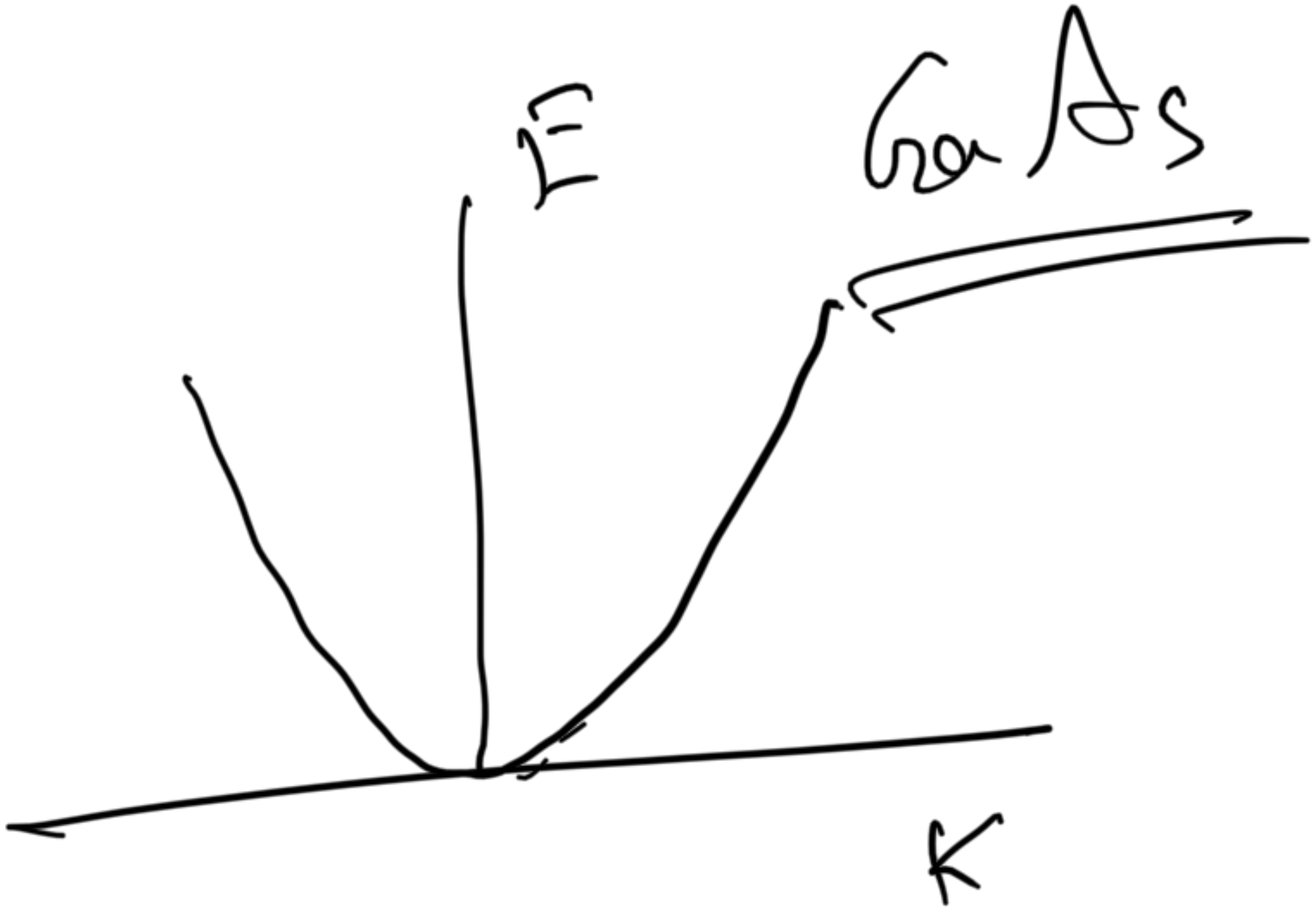
GaN

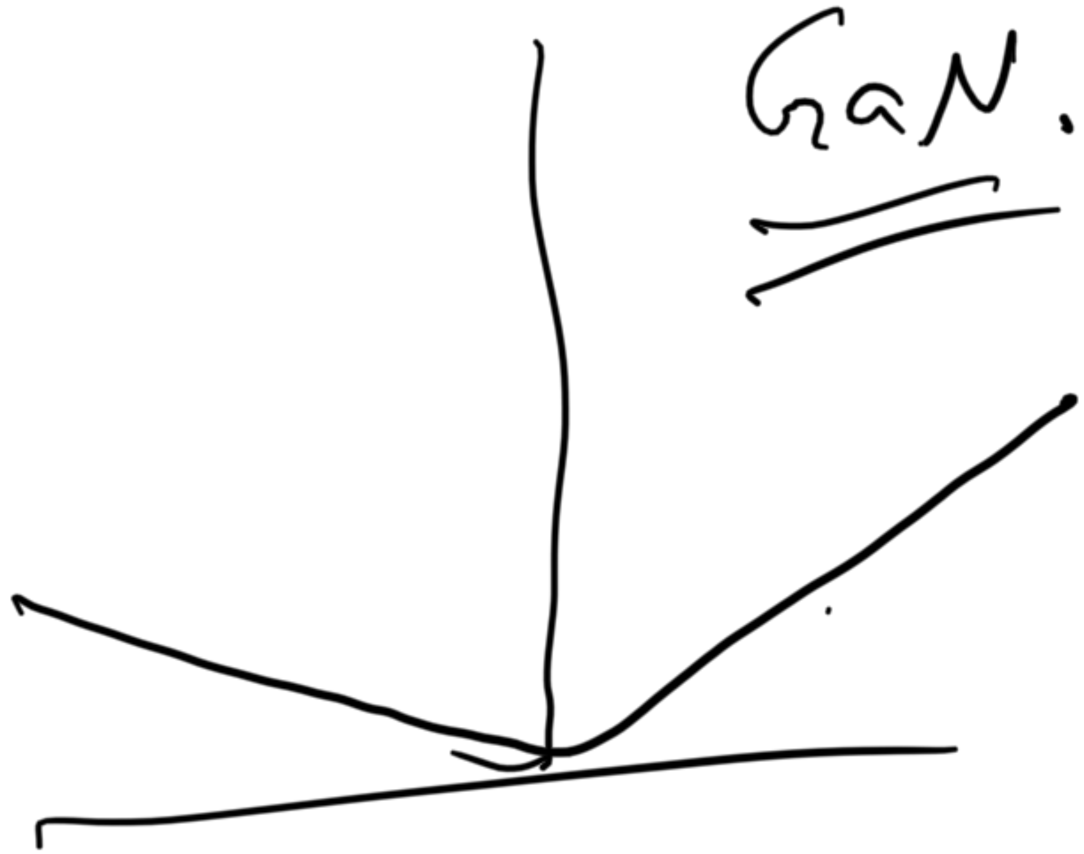


GaN

Z







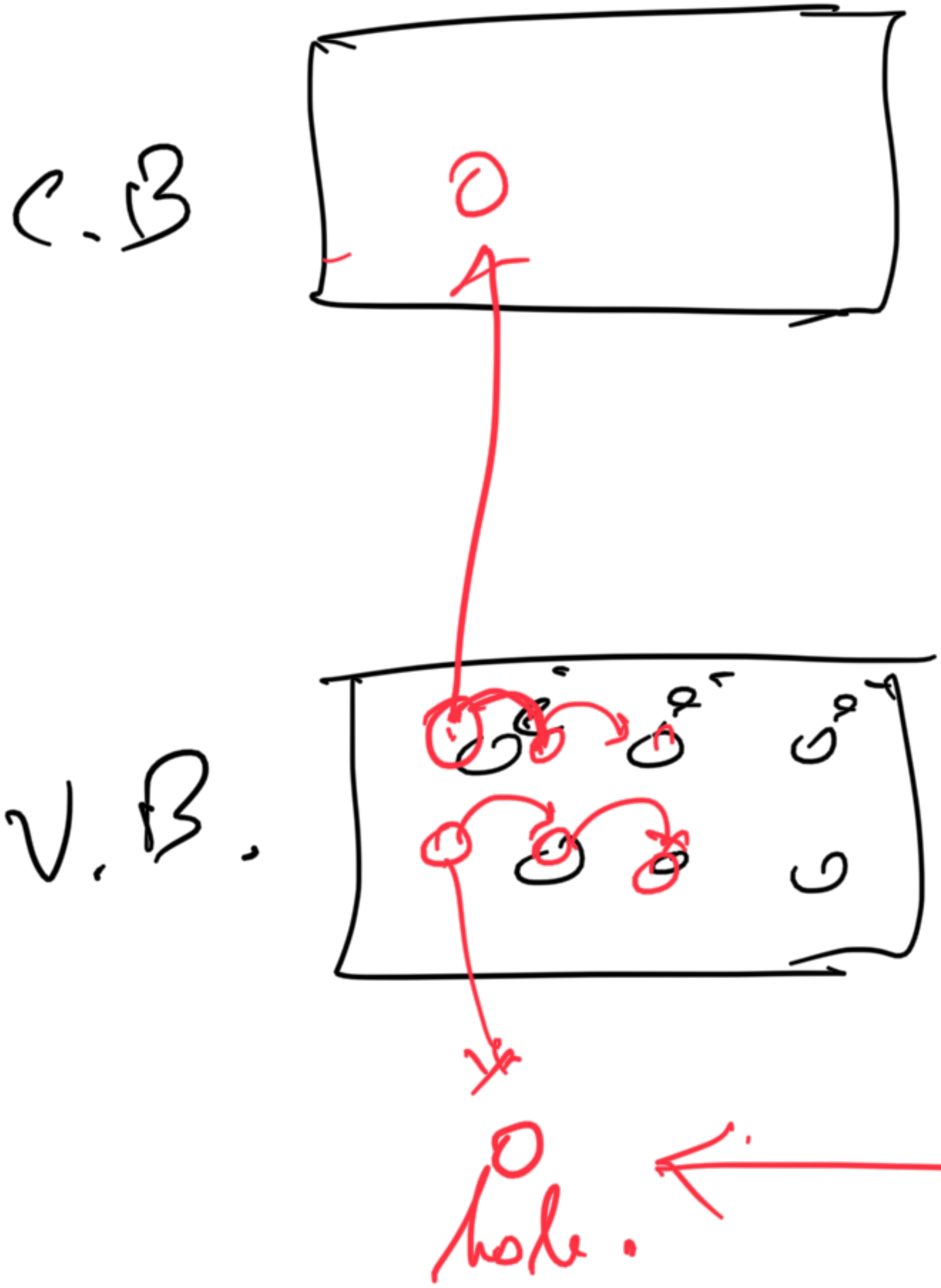
⇒ low.

$\frac{d^2E}{dK^2} \rightarrow$ high, $\longrightarrow$ high

$m^* \rightarrow$ low, $\longrightarrow$ low.

mobility $\propto$ $1/m^*$

$\uparrow$



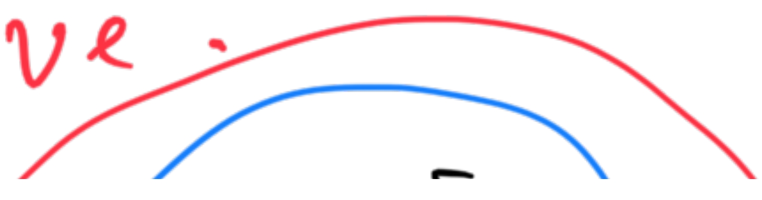
$\longrightarrow \vec{E}$ –

$\longleftarrow \underline{\underline{e^-}}$

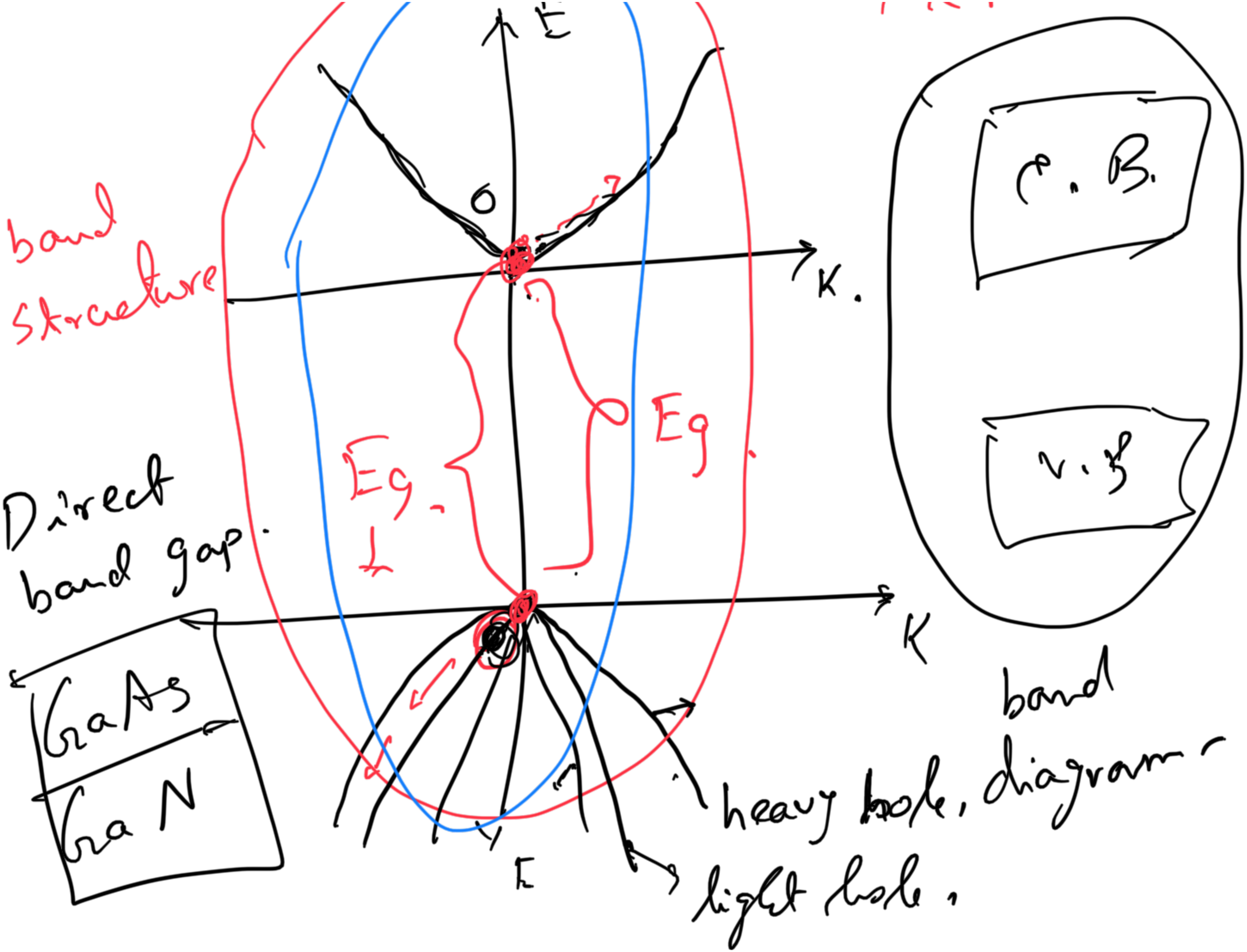
band structure

effective

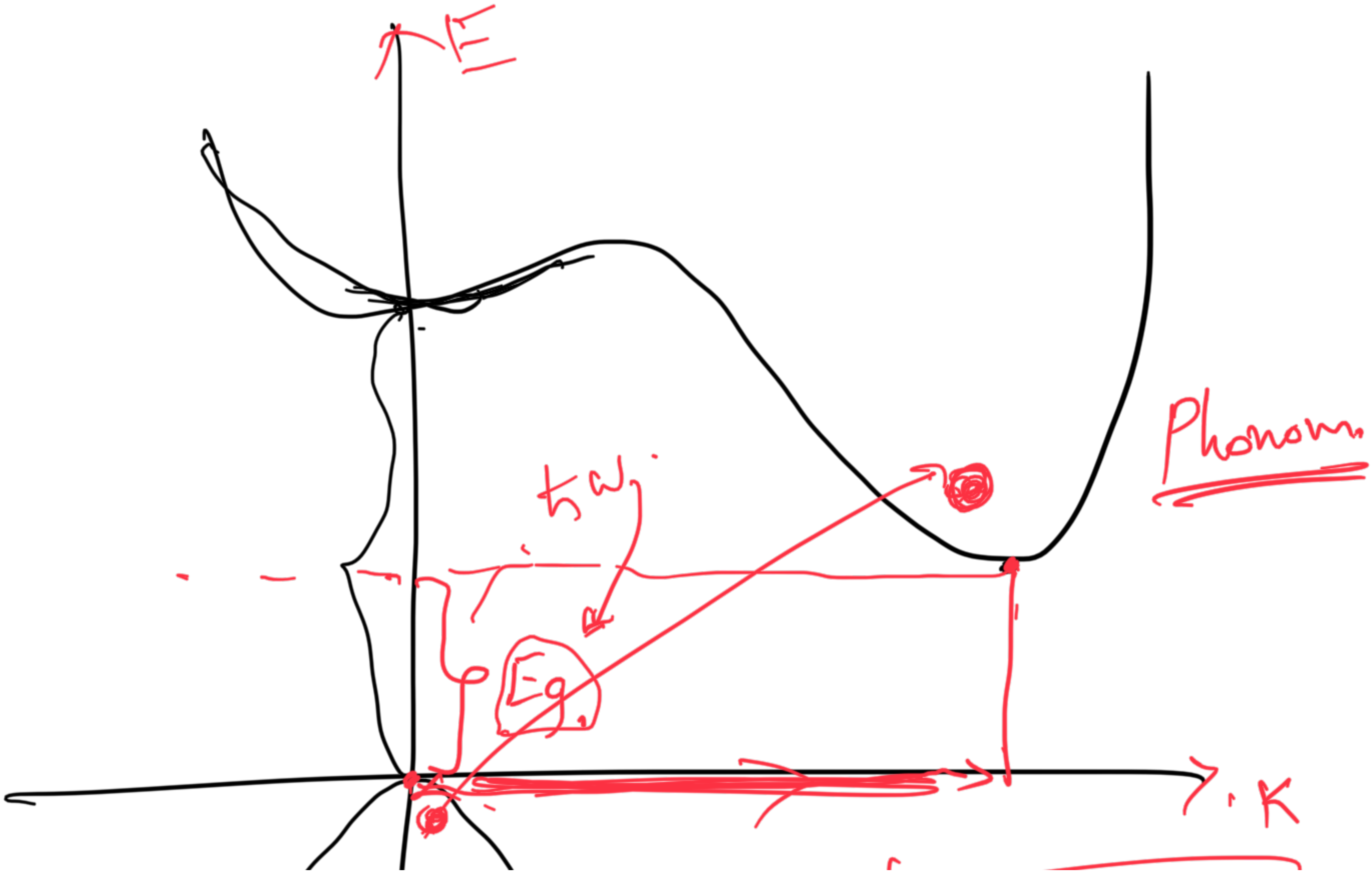
+ve.

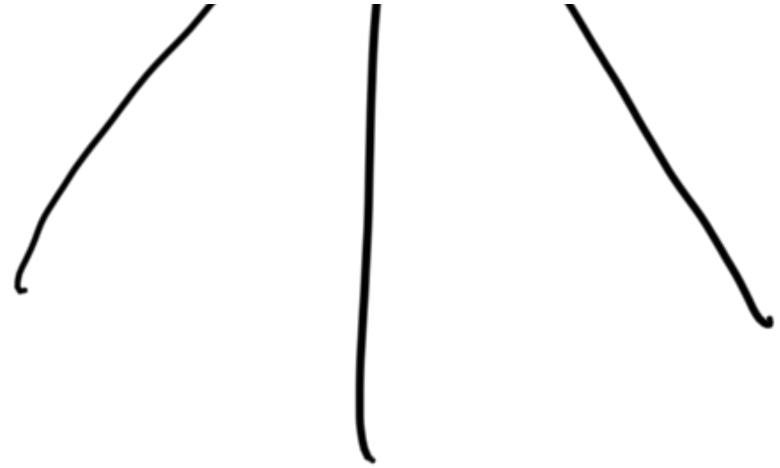


E / K. —



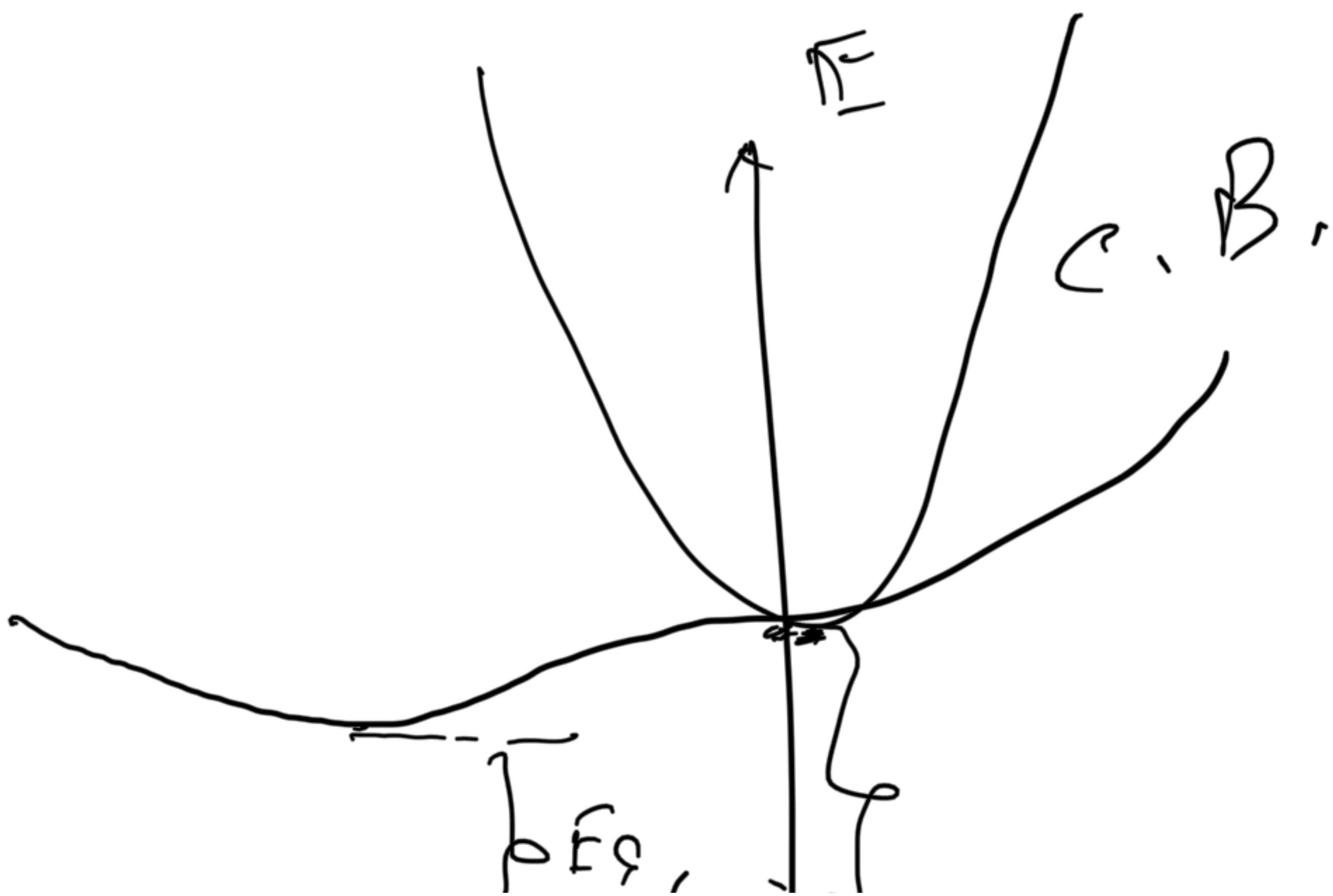
band structure
Direct band gap.
E
K.
K
Eg.
Eg
C.B.
V.B
band
GaAs
GaN
heavy hole, diagram
light hole.

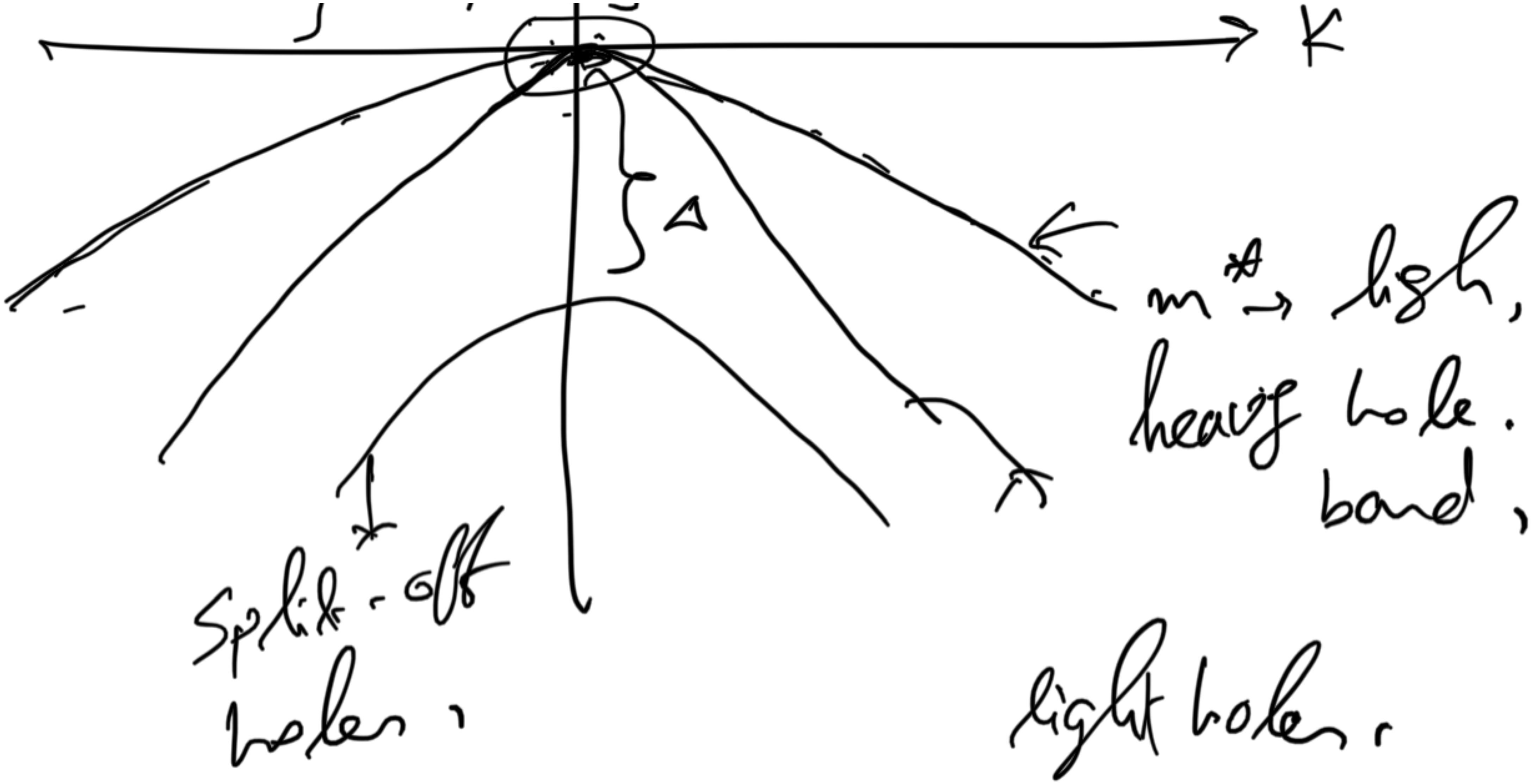

E
ħω
Eg
K
Phonon

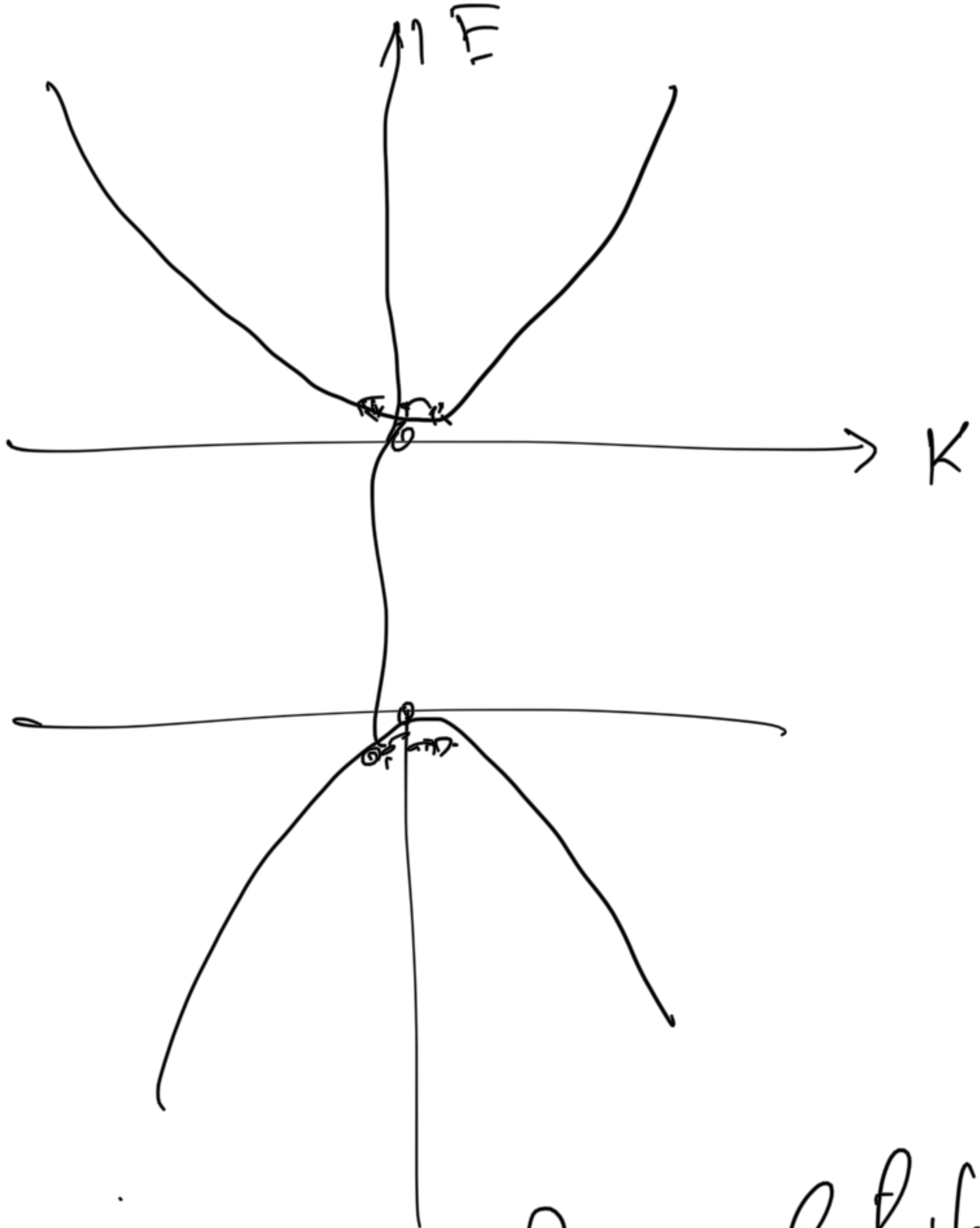


Indirect band gap.

Si ; Ge.

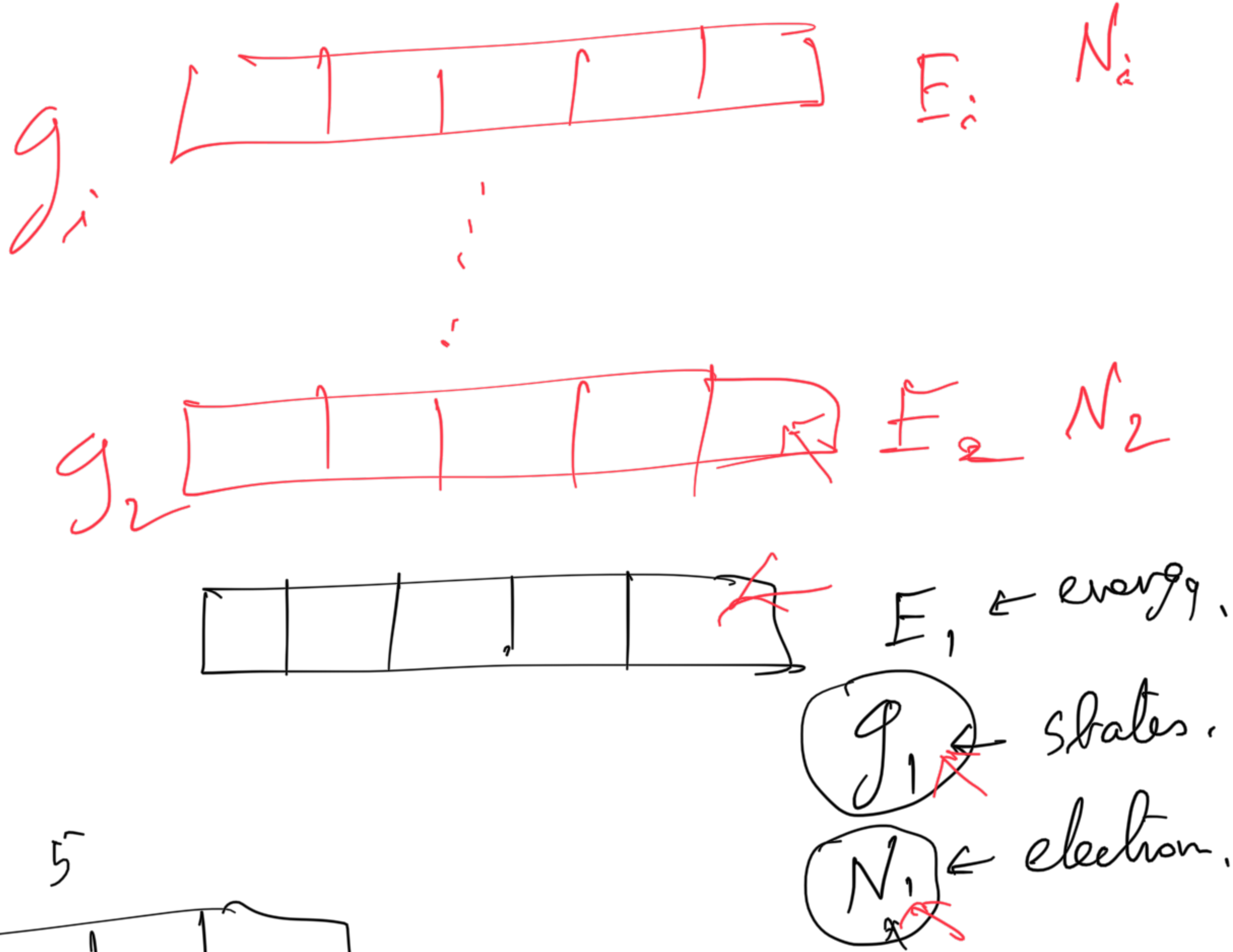



K
Δ
m* → ligh, heavy hole band,
split-off holes,
light holes.

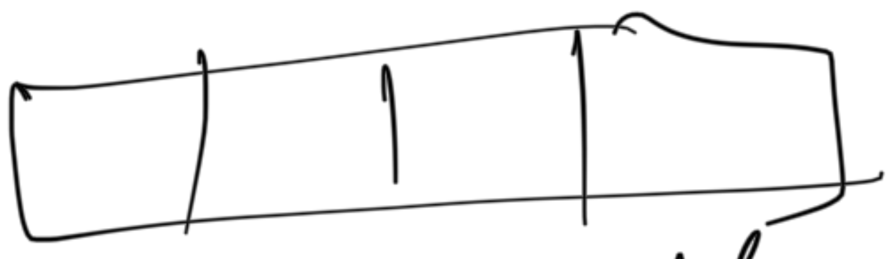


Statistics

Fermi-Dirac distribution



5



(2) marbles.

5!

$${}^5C_2 = \frac{}{2!\,(5-2)!}$$

$$= \frac{5!}{2!\,3!}$$

$$\frac{g_1!}{N_1!\,(g_1-N_1)!}$$

$$\prod^{N}\left[\frac{g_i!}{N_i!\,(g_i-N_i)!}\right]$$

N E_N

g_N

N_N

$i = 1$

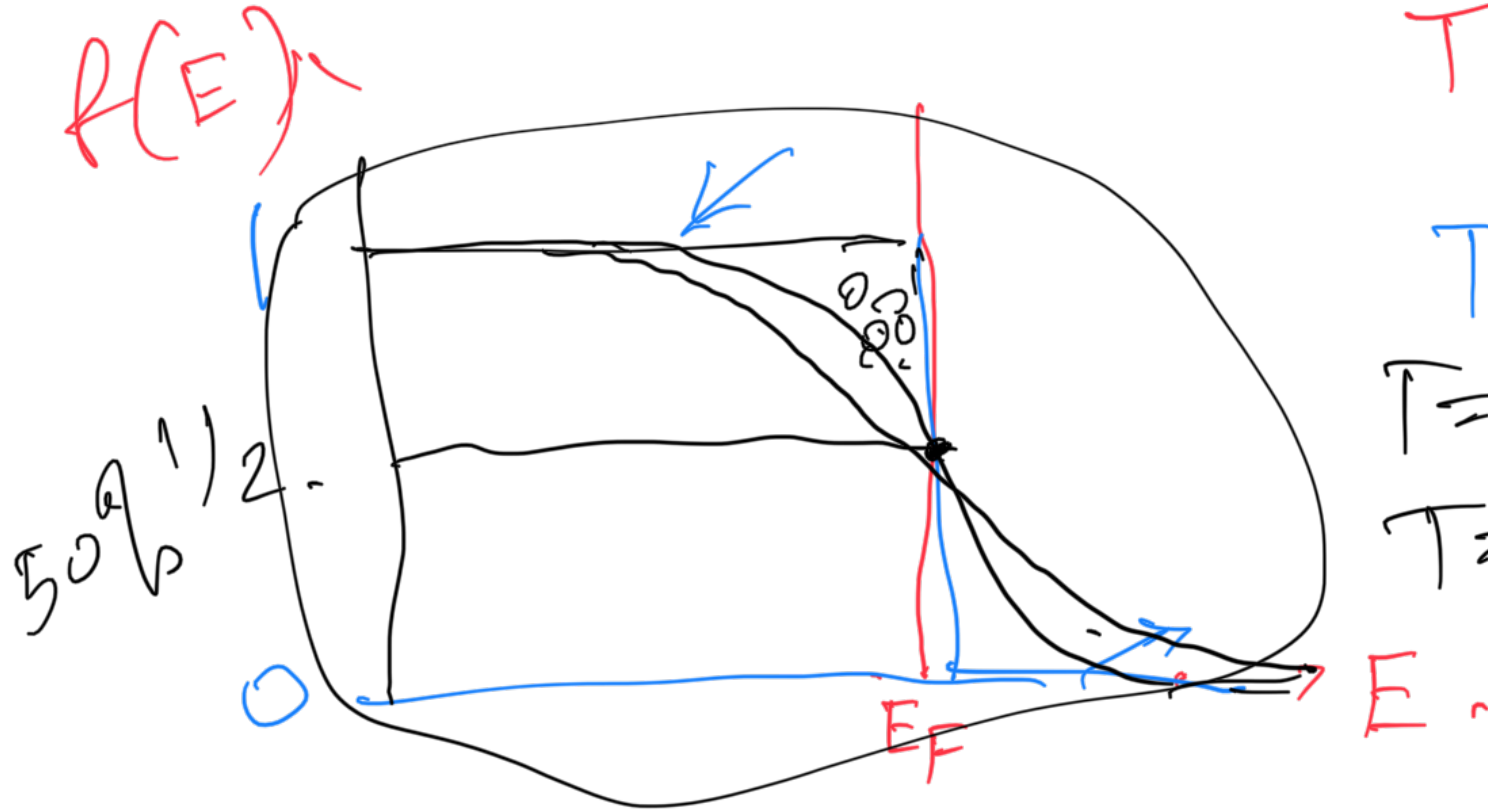
$$\frac{N_i}{g_i} = \underline{\underline{\text{Probability}}}.$$

$$= f(E_i)$$

$$\boxed{f(E_i) = \frac{N_i}{g_i} = \frac{1}{1 + \exp\left(\frac{E_i - E_F}{K_B T}\right)}}$$

$E_F \Rightarrow$ Fermi energy.

$K_B \rightarrow$ Boltzman Constant.



$T = 0$

$T \neq 0$,

$T = 100K$

$T = 200K$

$E_i = E_F \Rightarrow f(E_i)\Big| = \frac{1}{1+1}$

$\Big|_{E=E_F} = \frac{1}{2}.$

50%.

$E_i < E_F \Rightarrow$

$$f(E_i) = \frac{1}{1+\exp\left[-\left(\frac{E_F - E_i}{KT}\right)\right]}$$

$\rightarrow 0$

$$= \frac{1}{1}$$

$E_i > E_F \Rightarrow$

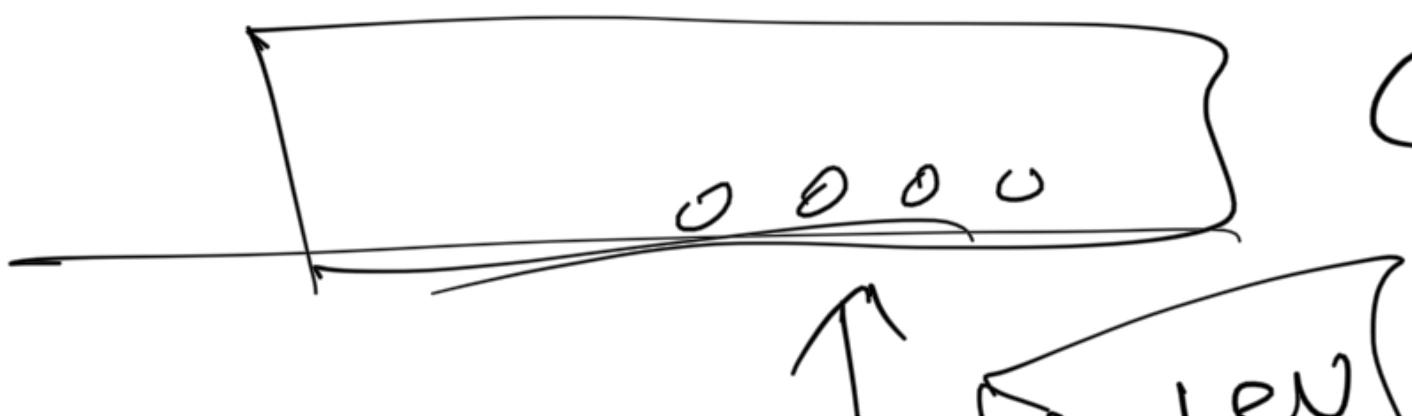
$$\frac{1}{1+\exp\left[\frac{E_i - E_F}{KT}\right]}$$

$1+\exp\left[\frac{\quad}{KT}\right]^{\infty}$

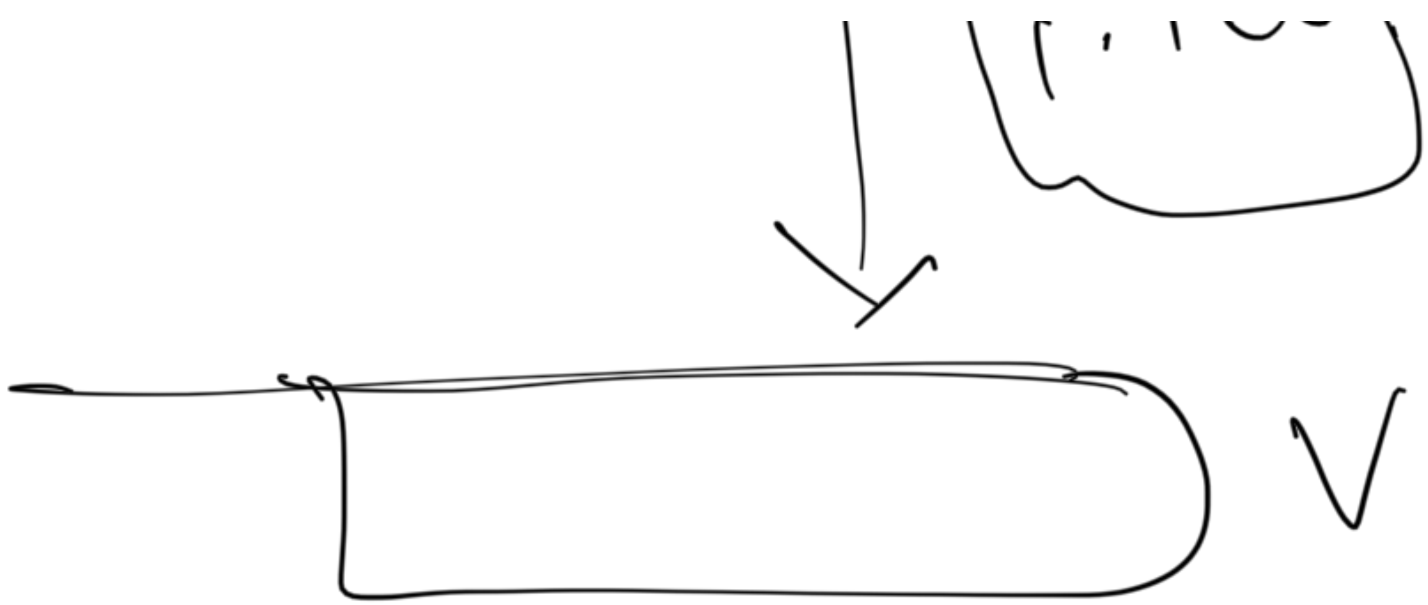
$$= \frac{1}{\infty} = 0$$

$f(E) \rightarrow$ electrons.

$1 - f(E) \longrightarrow$ holes.



C.B

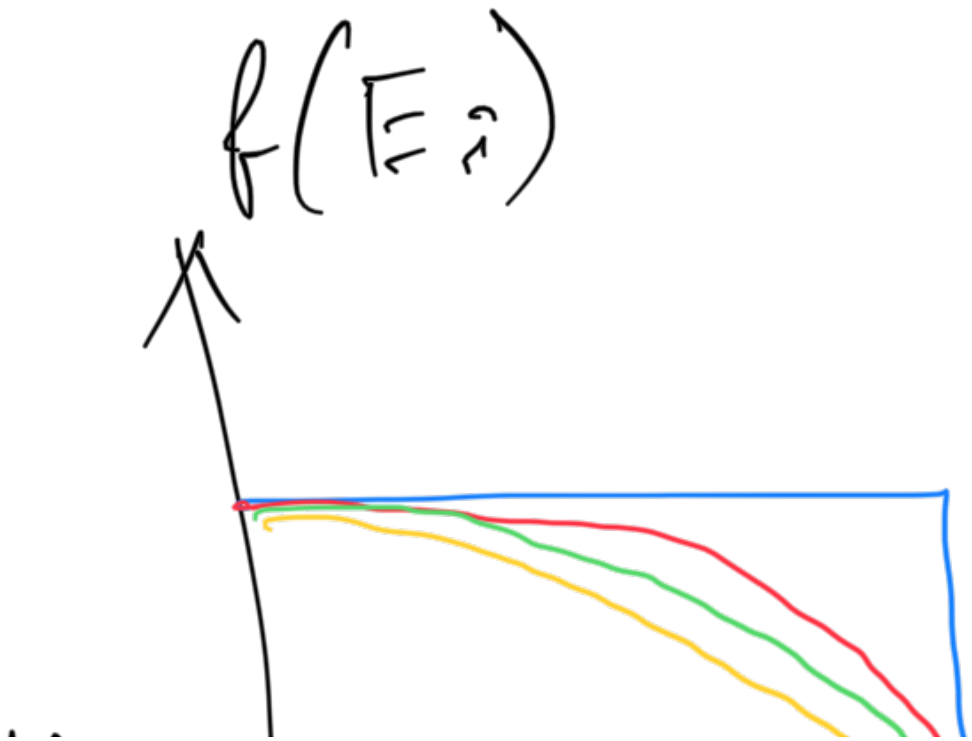


S:

VB.

$$\boxed{K_B T = 0.026\ eV}$$

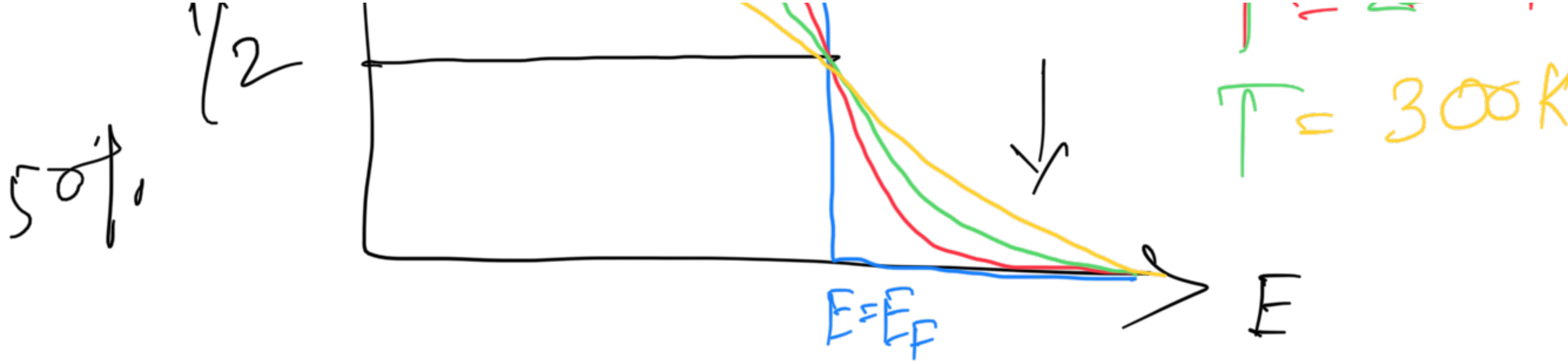
$T = 300K$



T = 0K.

T = 100K.

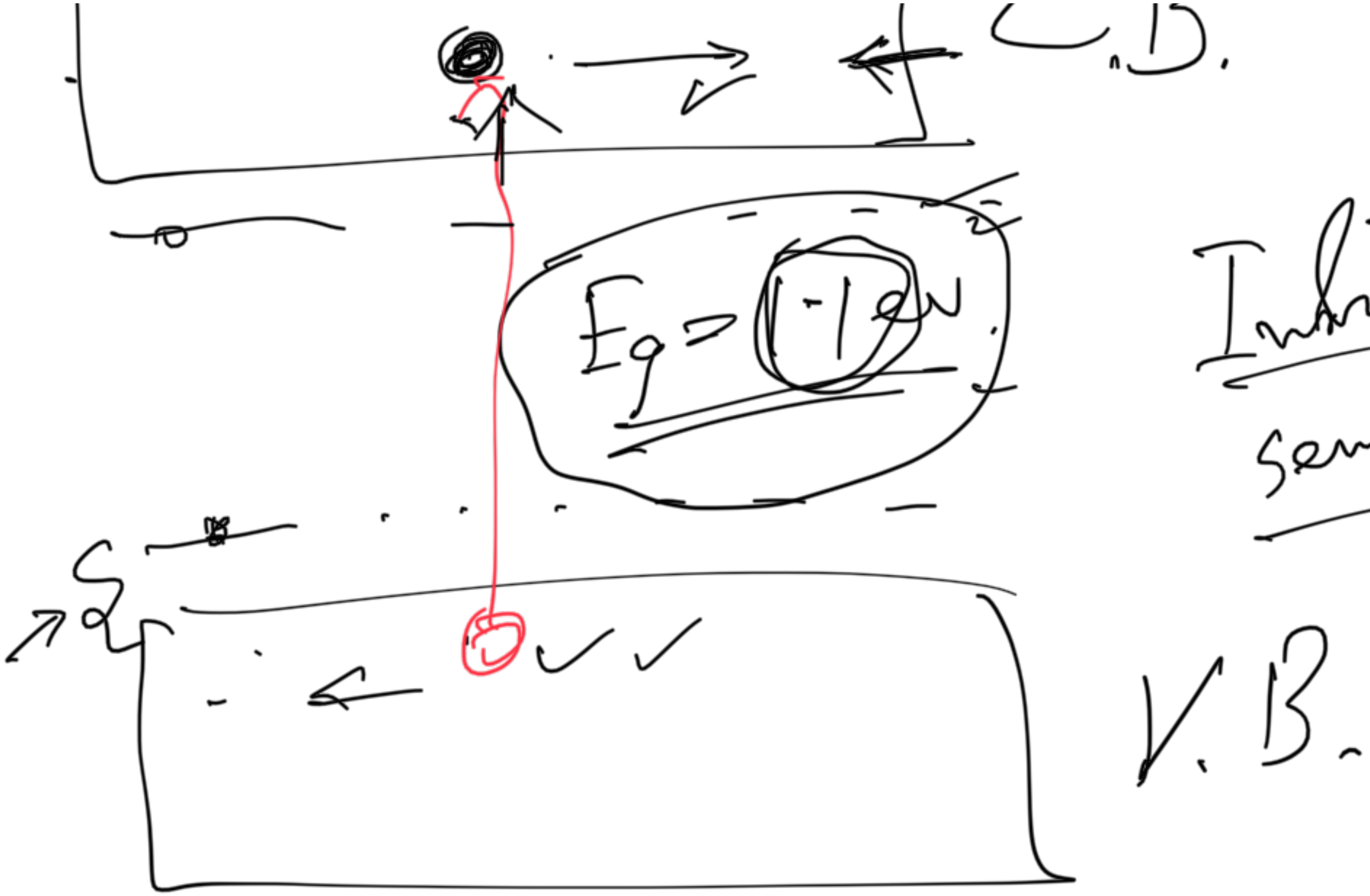
T = 200K



Carrier Concentration

Intrinsic & Extrinsic Semiconductors

Si



Intrinsic semiconductor

Bipolar Conduction

$$\boxed{n = p = n_i}$$

$$\boxed{n \cdot p = n_i^2}$$

$$n_i \Big|_{Si,\ intrinsic} = 1.4 \times 10^{10}\ cm^{-3}$$

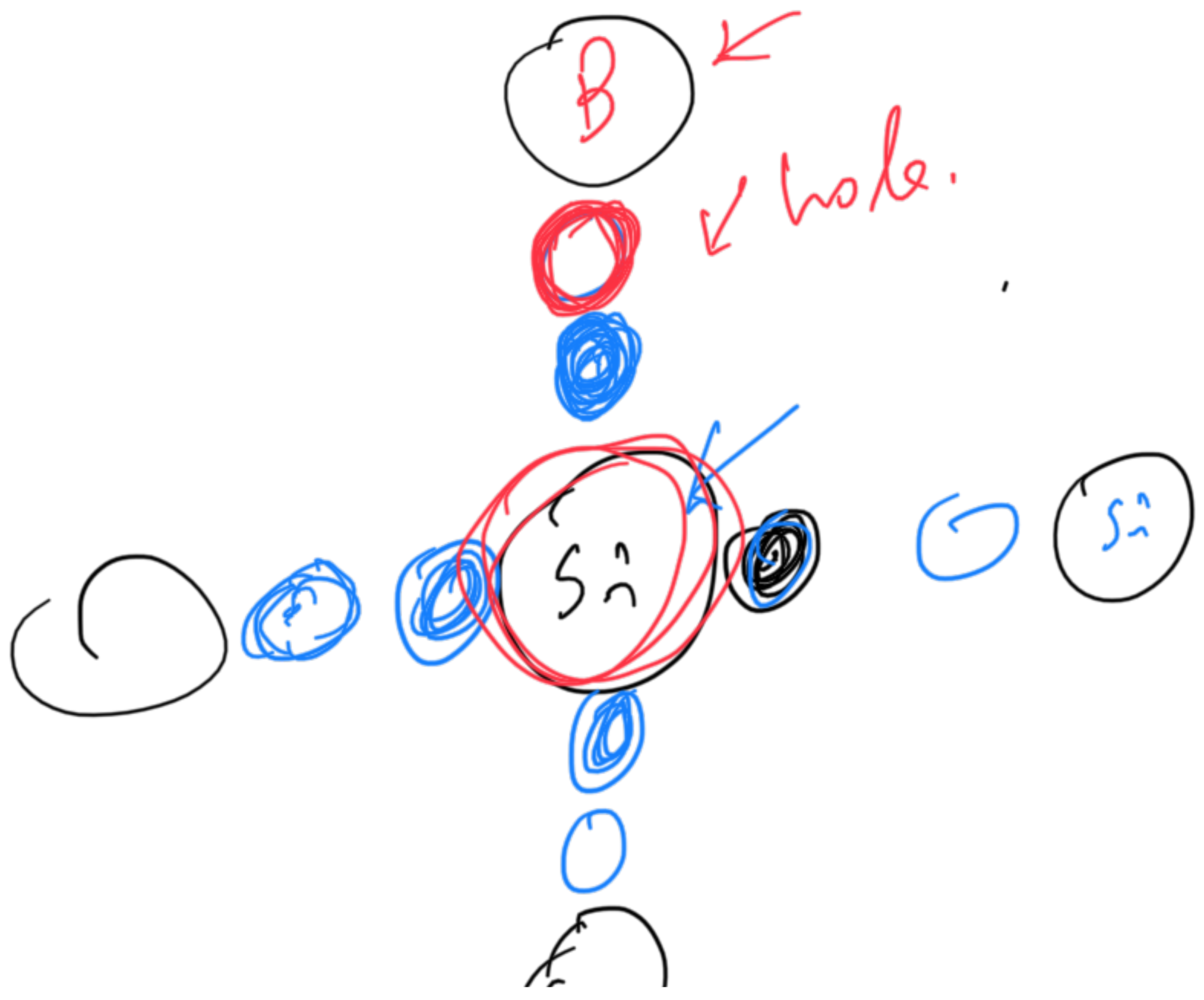
Extrinsic Semiconductors

100 Si

$1/2$ $\boxed{20 \rightarrow 30.}$

14 electron $\rightarrow$ $1s^2 2s^2 2p^6 \, 3s^2 3p^2$

4



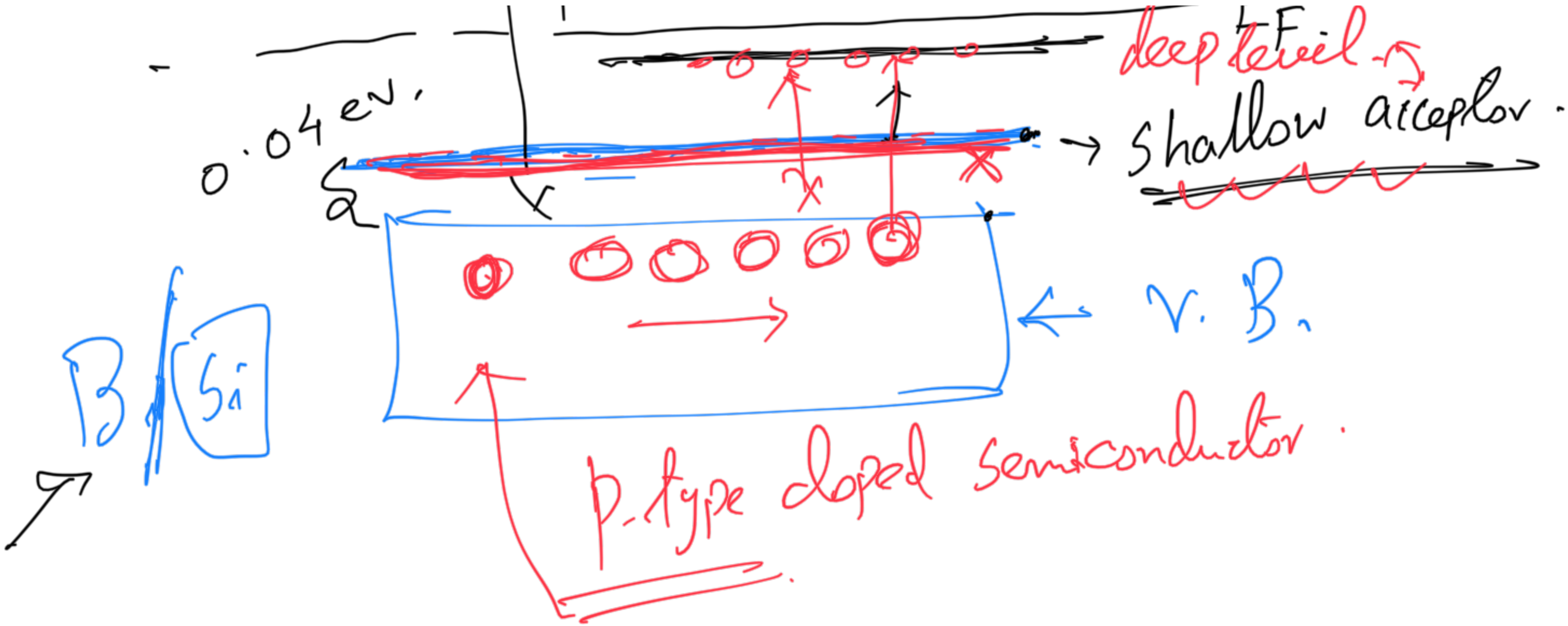
Group - 4.

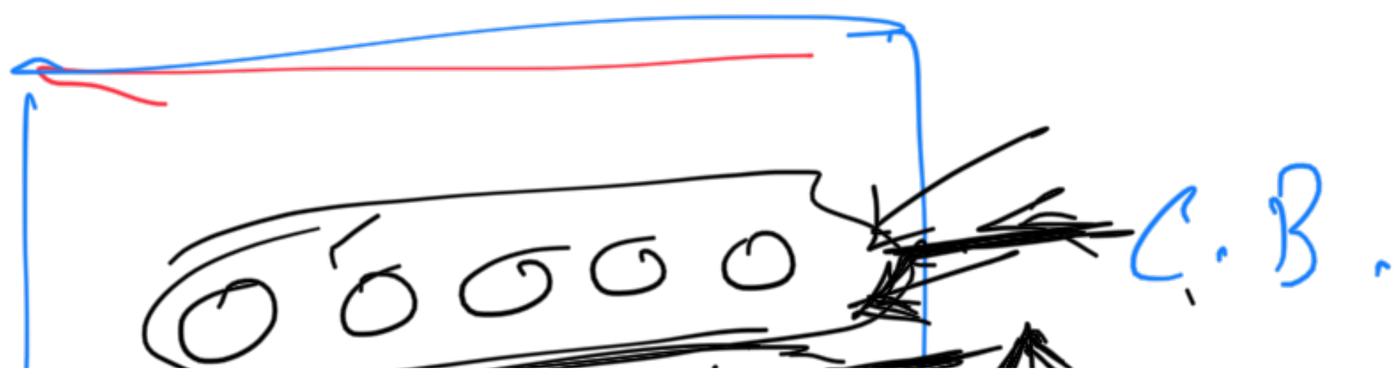
3.

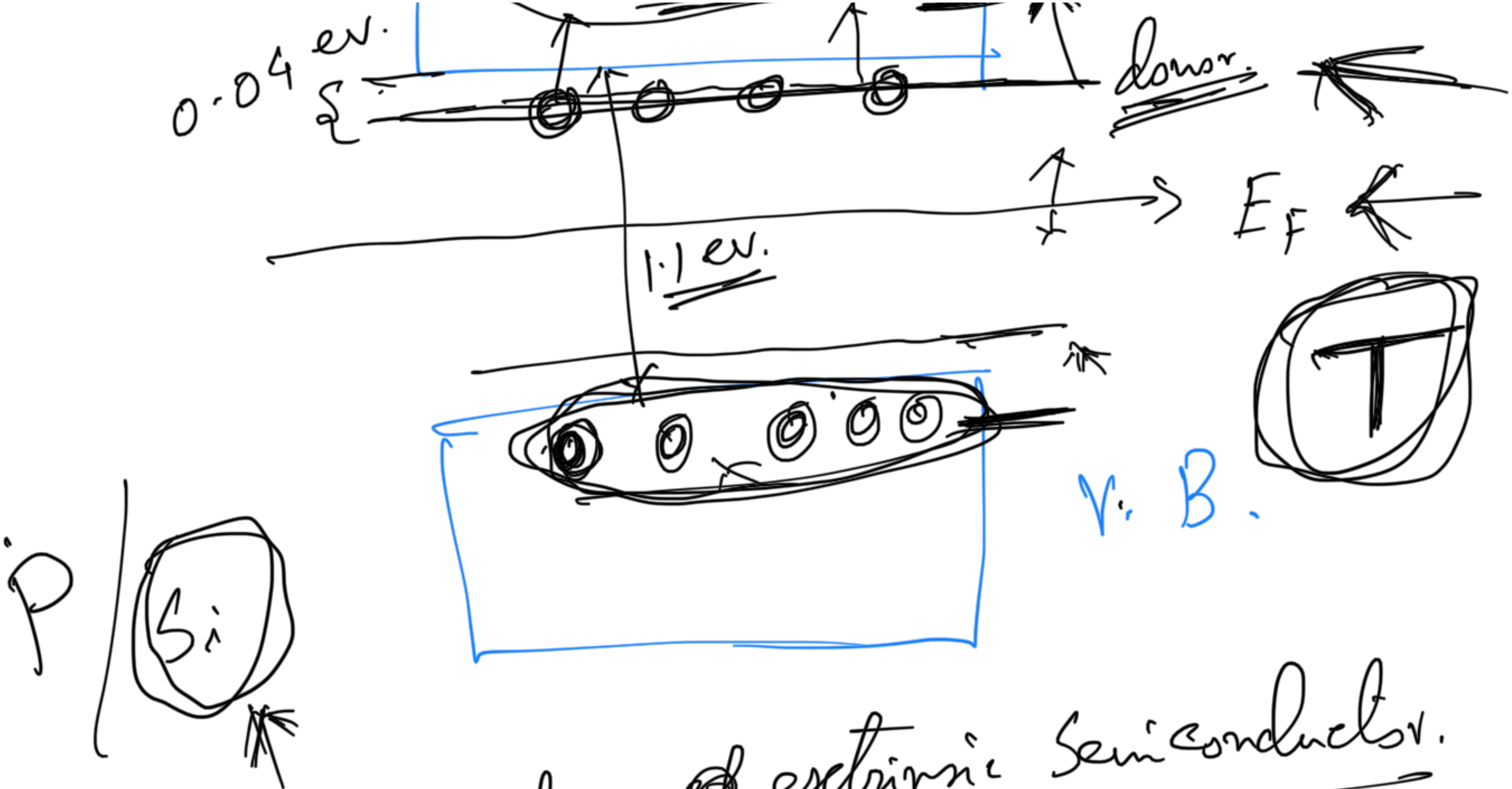
5

C.B.

Prev.


0.04 eV
deep level
shallow acceptor
V.B.
B
Si
p-type doped semiconductor

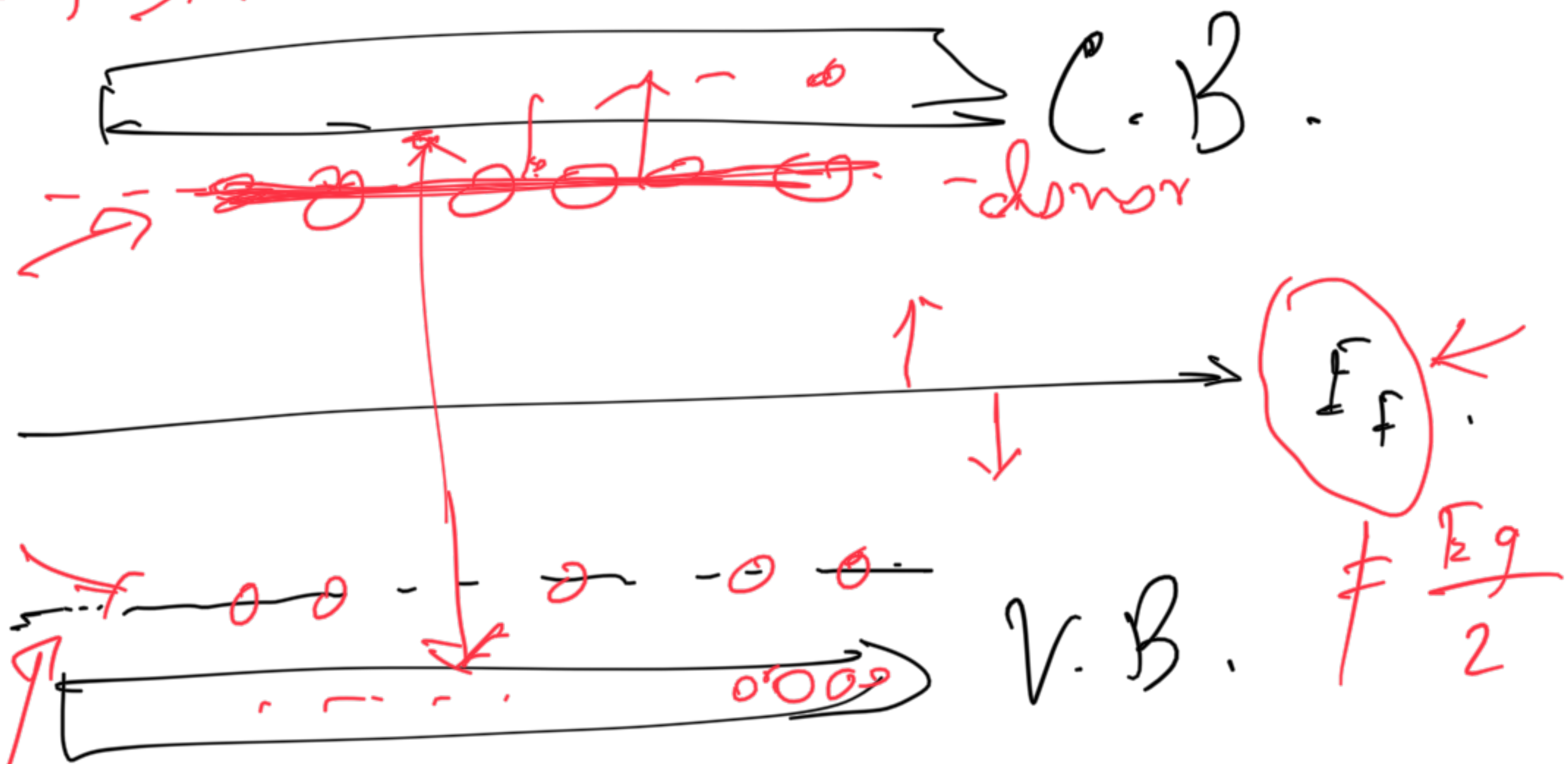

C.B.



n-type extrinsic Semiconductor.

majority → electron

n type



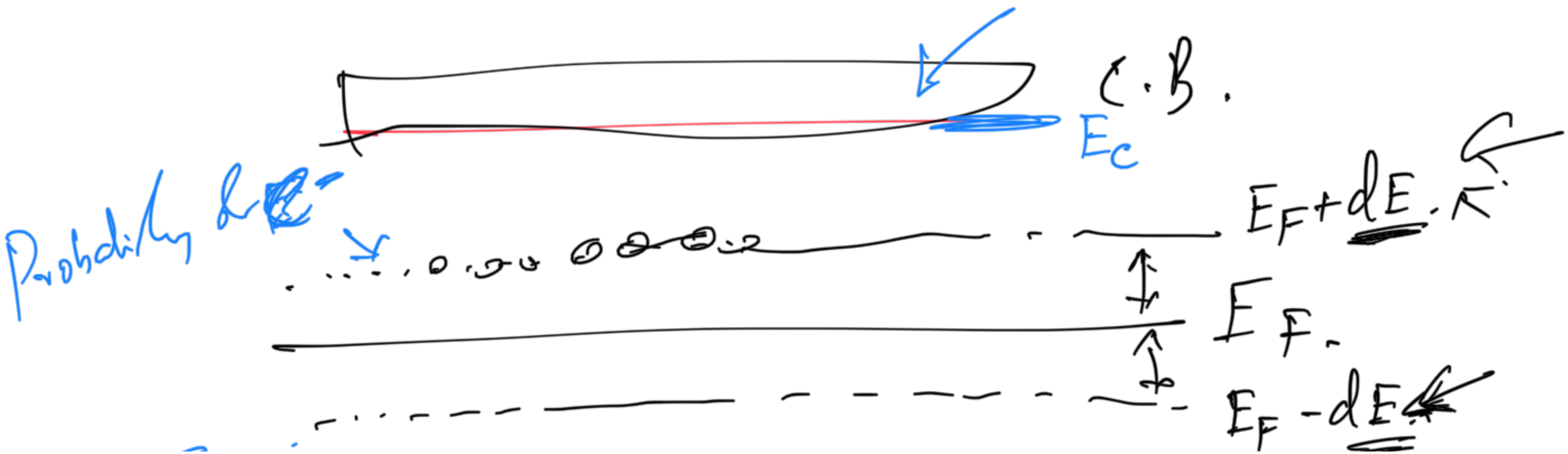
p type →

majority → hole.

minority → electron.

$$f_{F.D.}(E) = \frac{1}{1+\exp\frac{(E-E_F)}{K_BT}}$$

$$E = E_F \Rightarrow f_{F.D.}(E=E_F) = \frac{1}{1+1} = \boxed{\frac{1}{2}}$$



$$\boxed{f_{F.D.}(E_F + dE) = \frac{1}{1+\exp\left(\frac{dE}{KT}\right)}}$$

$$f_{F.D.}(E_F - dE)$$

$$1 - f_{F.D.}(E_F - dE) = 1 - \frac{1}{1+\exp\left(-\frac{dE}{KT}\right)}.$$

$$= \frac{1}{1+\exp\left(\frac{dE}{KT}\right)}$$

---

number density of electrons in the Conduction band $\longrightarrow$

$$n = 2\left(\frac{2\pi m_n^* KT}{h^2}\right)^{3/2} \exp\left[-\frac{E_C - E_F}{KT}\right]$$

E:

$m_n^* \Rightarrow$ effective mass of electrons in C.B.

$$n = \underline{N_c} \exp\left[-\frac{E_c - E_F}{KT}\right]$$

$N_c \Rightarrow$ effective density of states in C.B.

$n_i \Rightarrow$ intrinsic carrier concentration for a intrinsic semiconductor $\leftarrow$ undoped.

$$\boxed{n = n_i \exp \frac{E_F - E_i}{KT}}$$

E_i

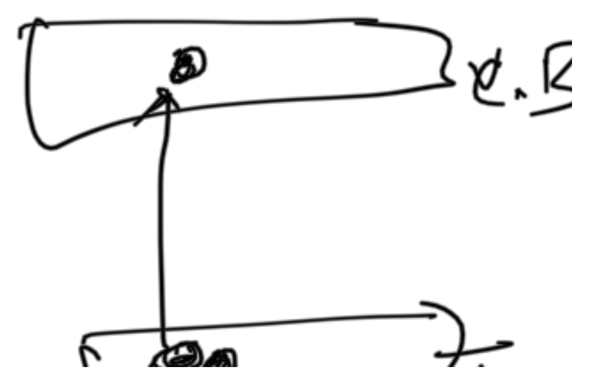
$$\left(\frac{2\pi m_p^* KT}{}\right)^{3/2} \exp\left[-\frac{E_F - E_V}{}\right]$$

$$p = 2\left(\frac{\quad}{h^2}\right)^{\dots}\exp\left[\frac{\quad}{KT}\right]$$

$$= N_V \exp\left[-\frac{E_F - E_V}{KT}\right].$$

$E_V \Rightarrow$ V.B. edge energy value.

$$p = n_i \exp\left[\frac{E_i - E_F}{KT}\right]$$



$$n \cdot p = n_i^2$$

$$n = n_i = \cancel{2}\left(\frac{\cancel{2\pi}\, m_n^* KT}{\cancel{h^2}}\right)^{3/2} \exp\left[-\frac{E_c - E_i}{KT}\right]$$

$$p = n_i = \cancel{2}\left(\frac{\cancel{2\pi}\, m_p^* KT}{\cancel{h^2}}\right)^{3/2} \exp\left[-\frac{E_i - E_v}{KT}\right]$$

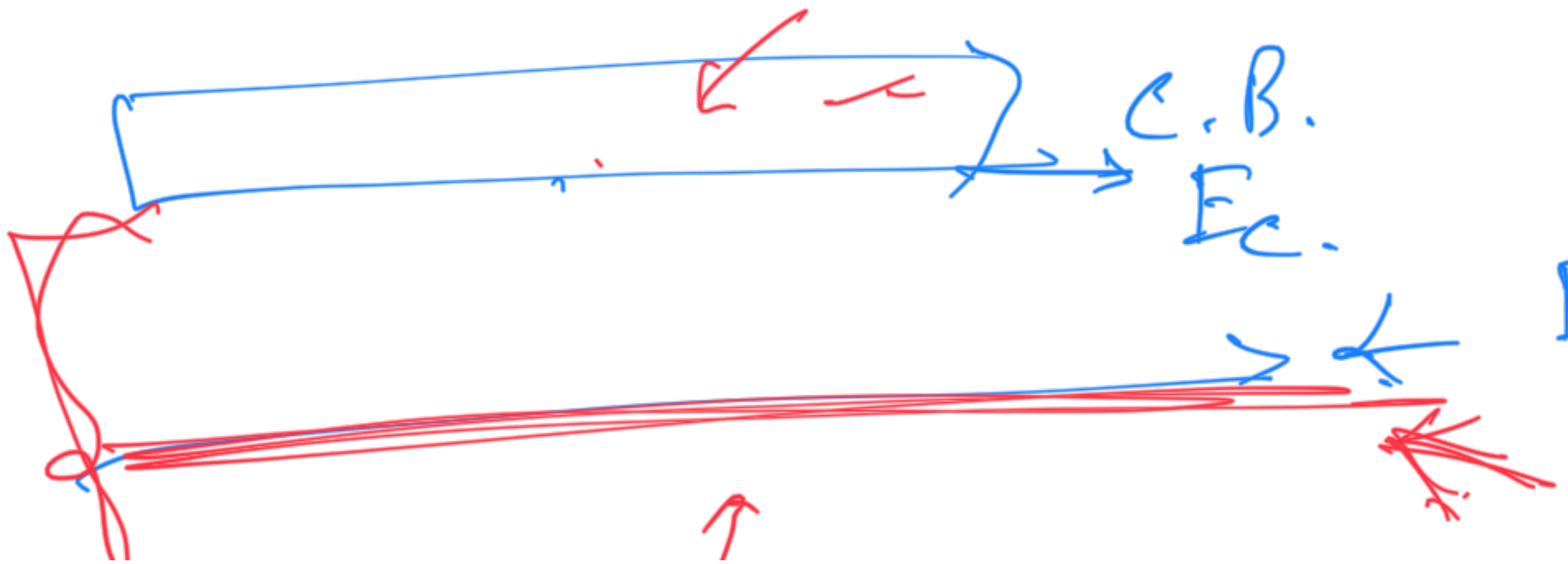
$$n_i = p_i$$

$$\left(\frac{m_n^*}{m_p^*}\right)^{3/2} = \exp\left(\frac{E_v + E_c - 2E_i}{KT}\right)$$

$$E_v + E_c - 2E_i = \frac{3}{2} KT \ln\left(\frac{m_n^*}{m_p^*}\right)$$

$$\boxed{E_i = \frac{E_v + E_c}{2} + \frac{3}{4} KT \ln\left(\frac{m_p^*}{m_n^*}\right)}$$

$$\frac{d^2E}{dk^2}$$

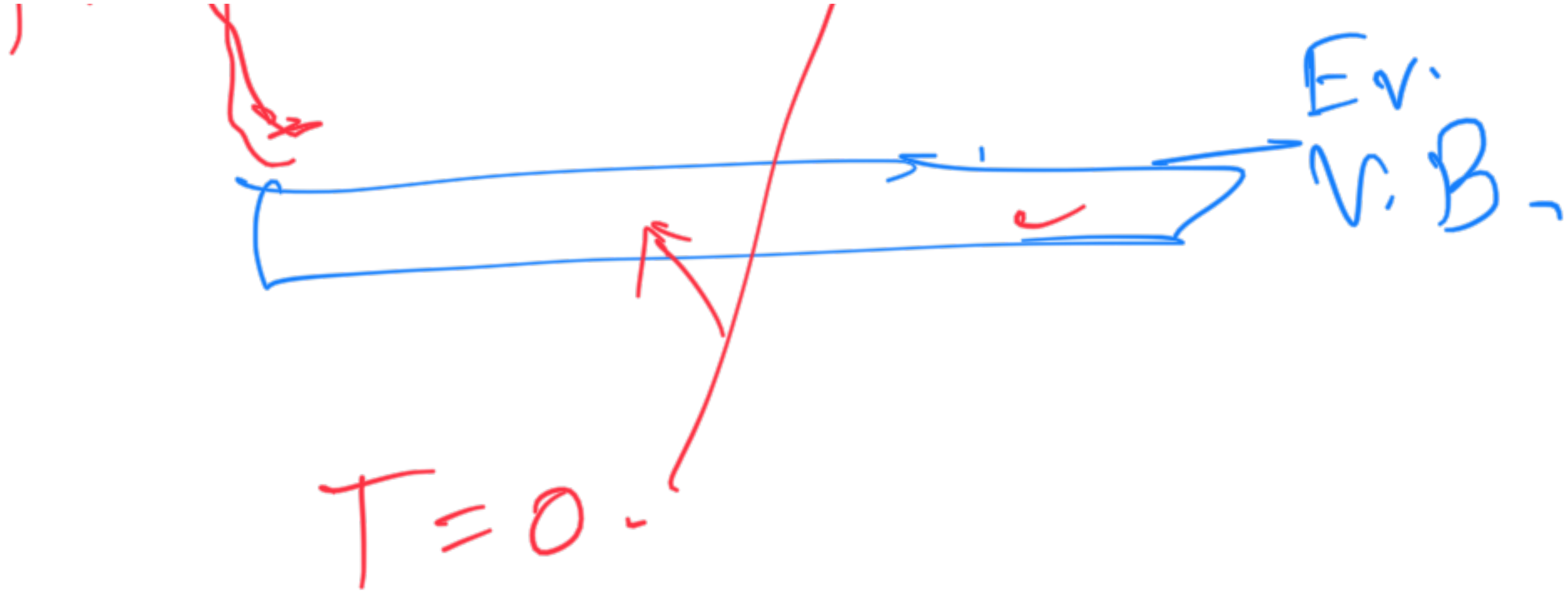


C.B.

E_c

$\frac{E_v + E_c}{2}$

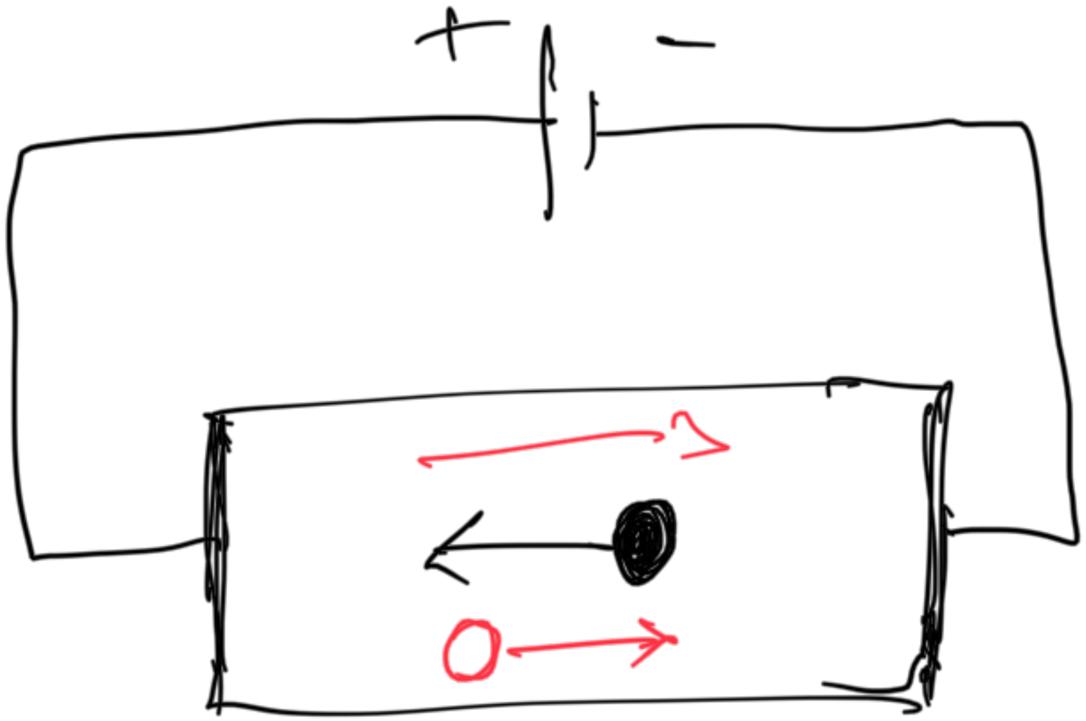
E_g



Ev.
V. B.
T = 0.

Carrier Mobility

Carrier Drift



n-Si → e^-

p-Si → h.

$\longrightarrow$ Electric field E.

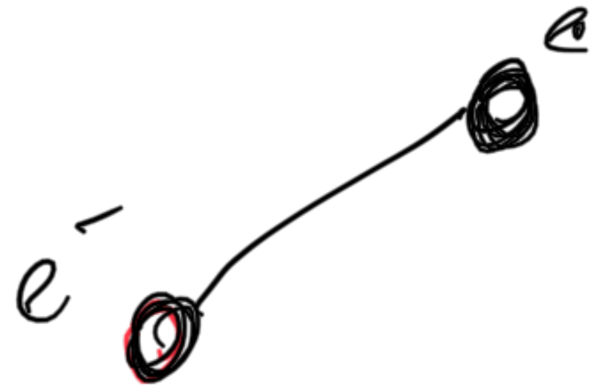
$\longleftarrow$ El movement.

Electron

→ Current flow

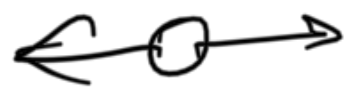
→ hole movement.

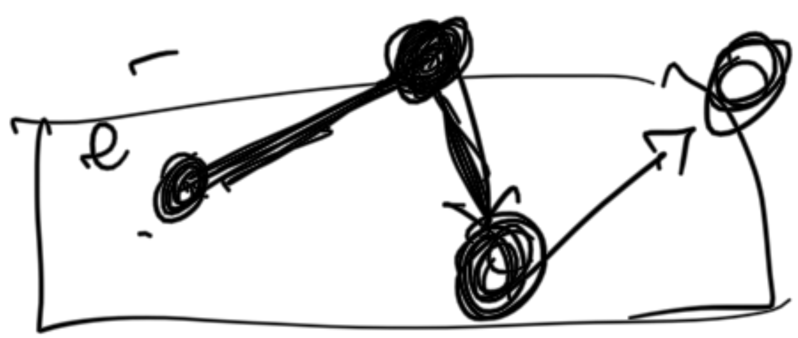
Carrier drift → V_d → drift velocity.



atomic vibration.

↑ phonon.





$T \neq 0$.

Thermal energy $\rightarrow \boxed{E_T}$.

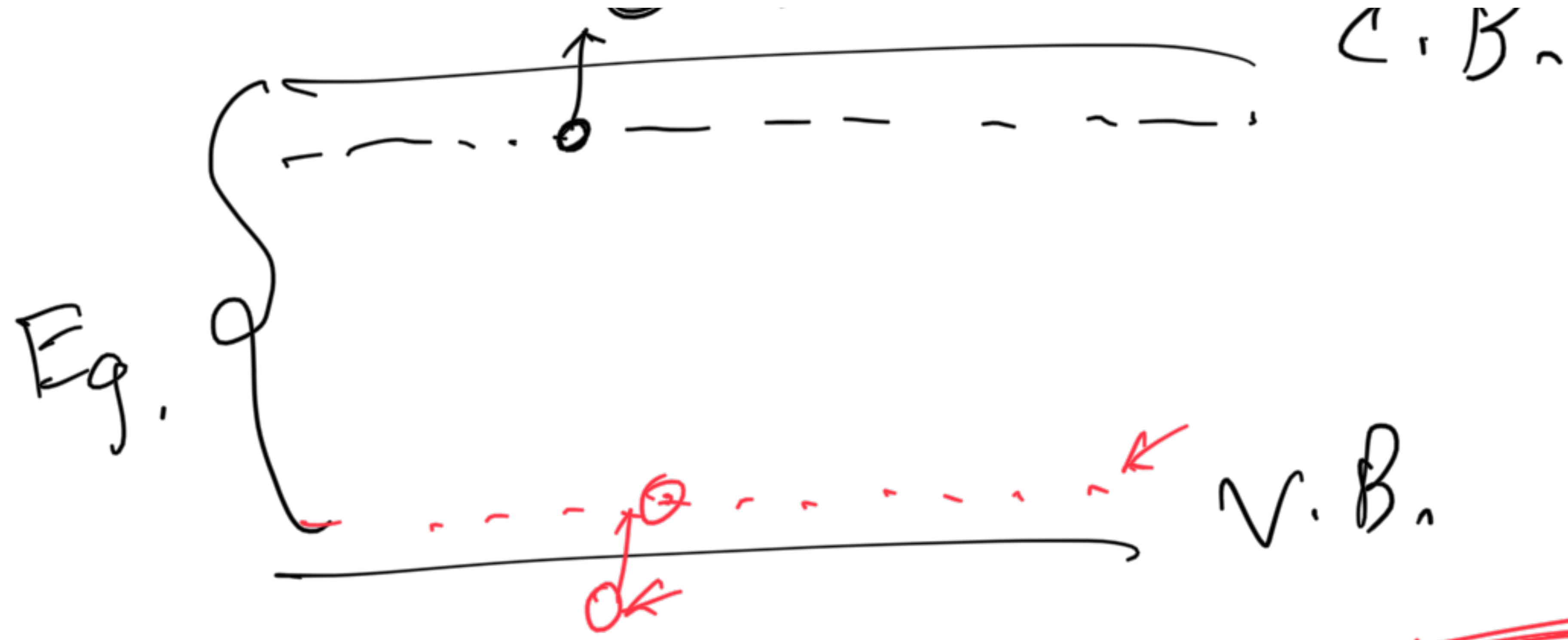
$$\frac{1}{2} m^* v^2 = E_T$$

$$\boxed{v_e = \sqrt{\frac{2}{m^*} E_T}}$$

$\boxed{n - Si}$ P $\longrightarrow$ Si sites p^+

e e^+

$\longrightarrow$



p-Si → B → Si

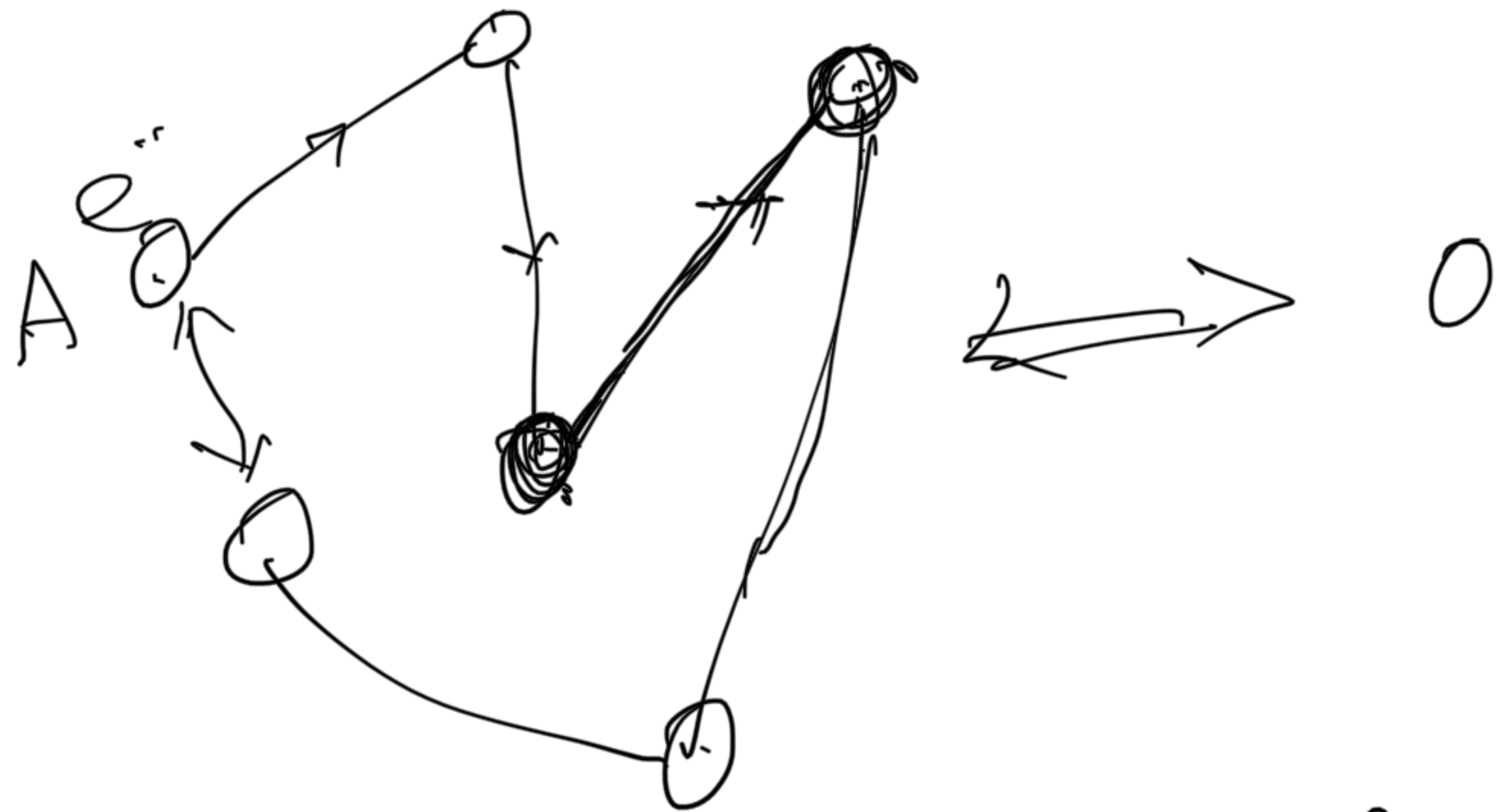
hole

B^-

phonons.

collision →

ionized impurity.



$\tau \rightarrow$ time between two collision,

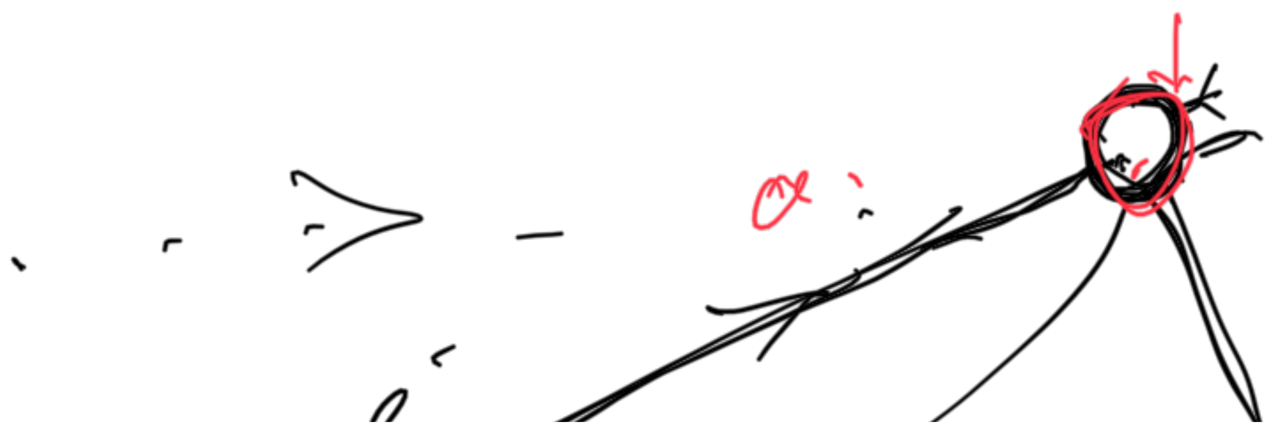
→ relaxation time.

→ mean free time.

apply Electric field → E.

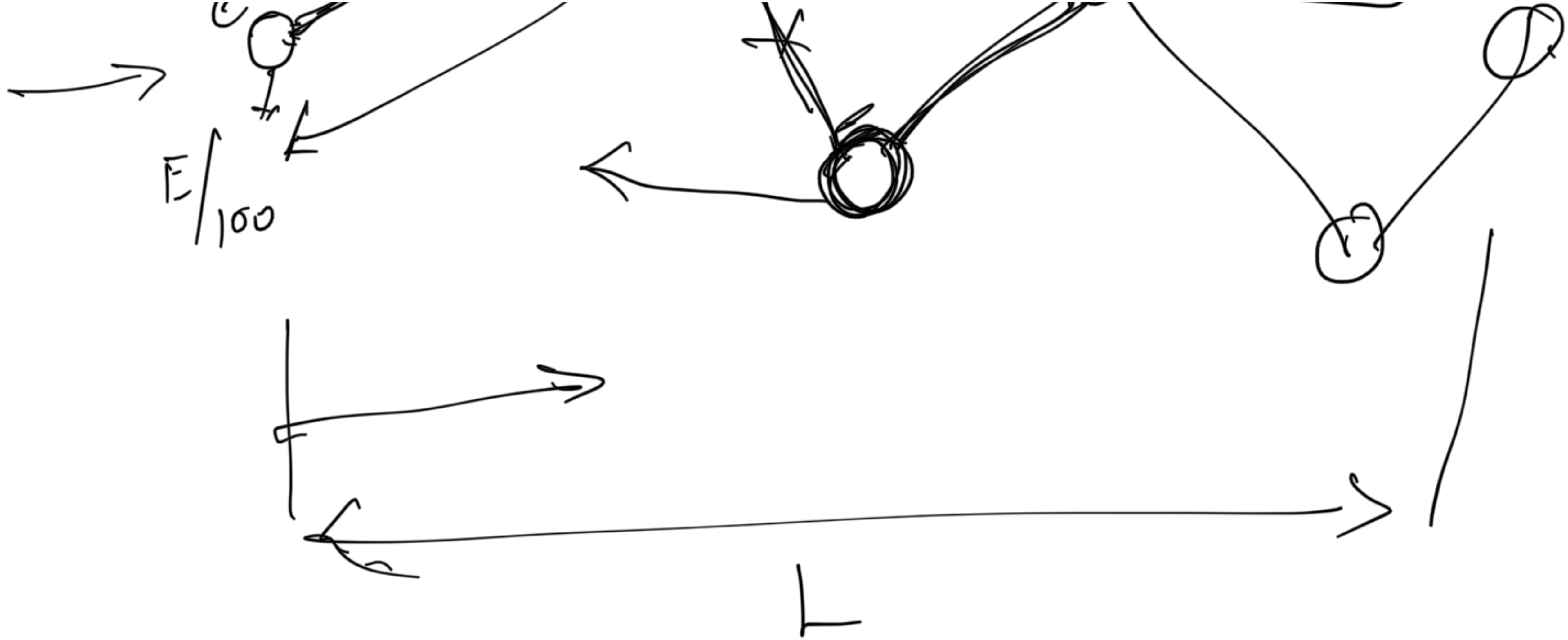
$$\boxed{F = qE}$$

$T \neq 0$, 100K.



τ, a.

E | 100



$$v_d = a . \tau .$$

drift velocity

$$a = \frac{\text{Force}}{\text{mass}}$$

$$= \frac{qE}{m^*}$$

$$V_d = \frac{q E \tau}{m^*} = \mu E$$

μ → mobility of carriers.

$$\boxed{V_d = \mu E}$$

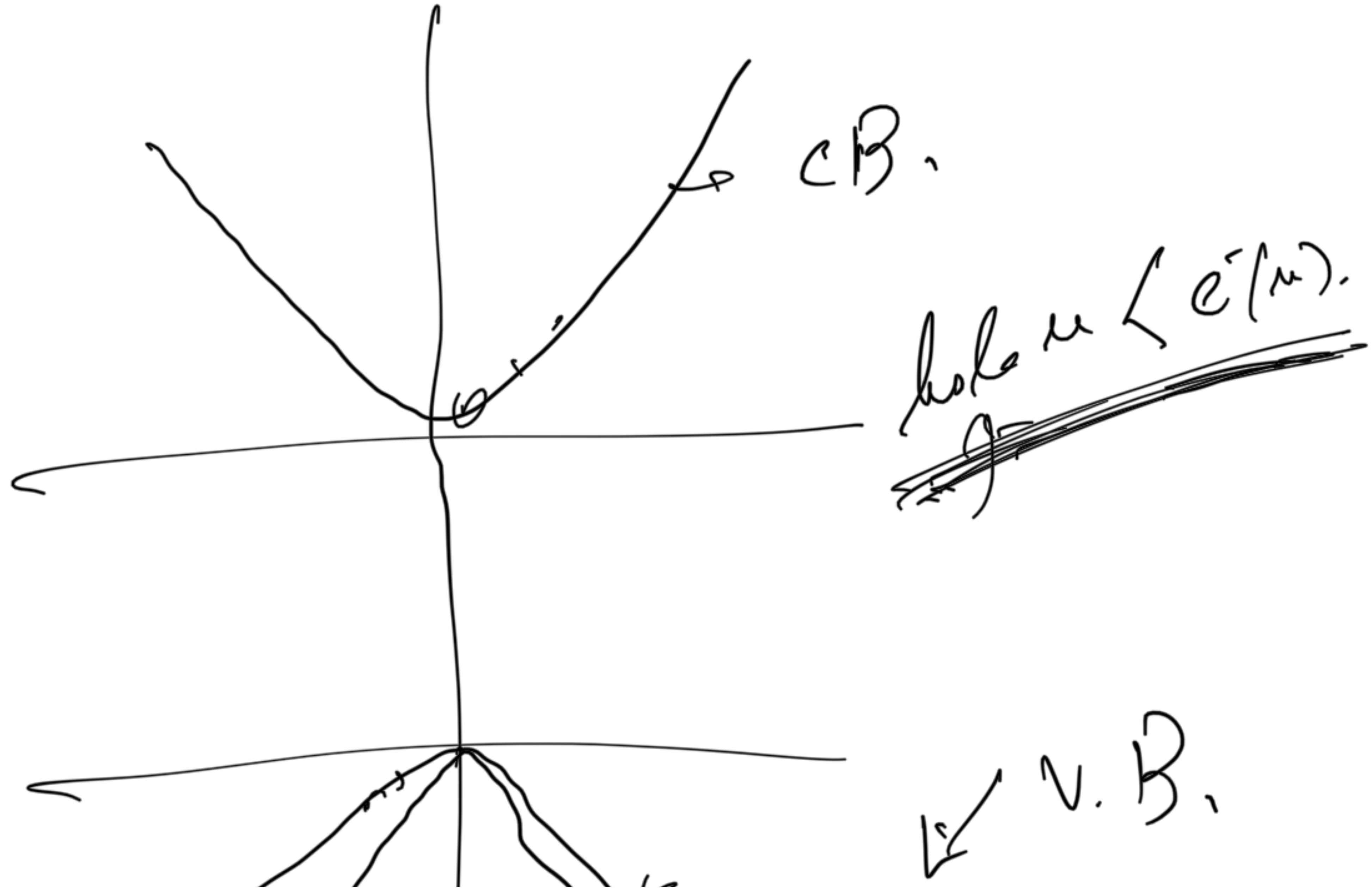
$E = V cm^{-1}$

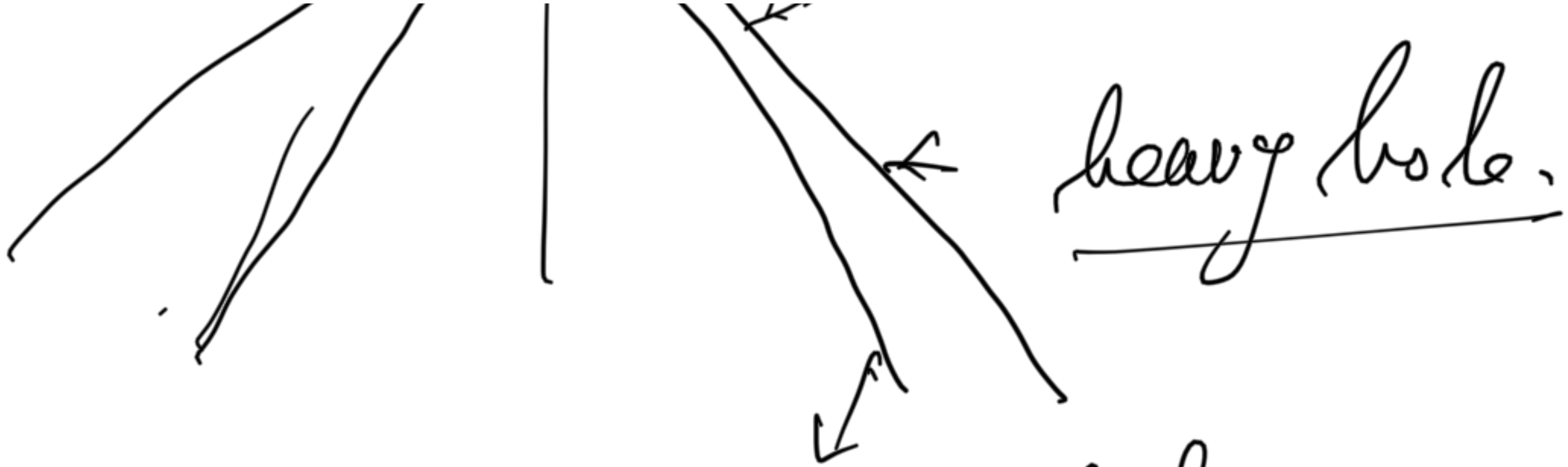
$\mu = cm^2 V^{-1} s^{-1}$

$$\frac{q \tau}{\;}$$

$\mu =$ m^*.

$$m^* = \hbar^2 \Big/ \frac{d^2E}{dk^2}$$





large curvature. → low m^*

high μ.

V_d ↑ low field region.

High field region

cm/s

$T \neq 0.$

Carrier mobility

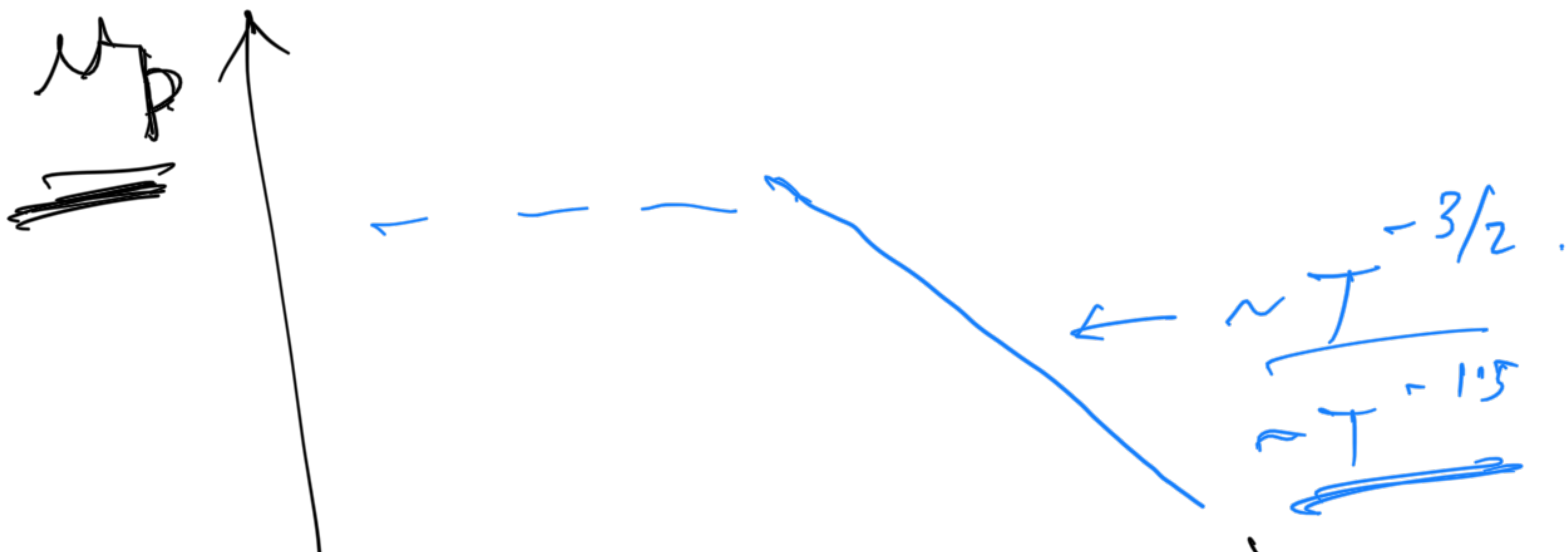
E ($V\,cm^{-1}$)

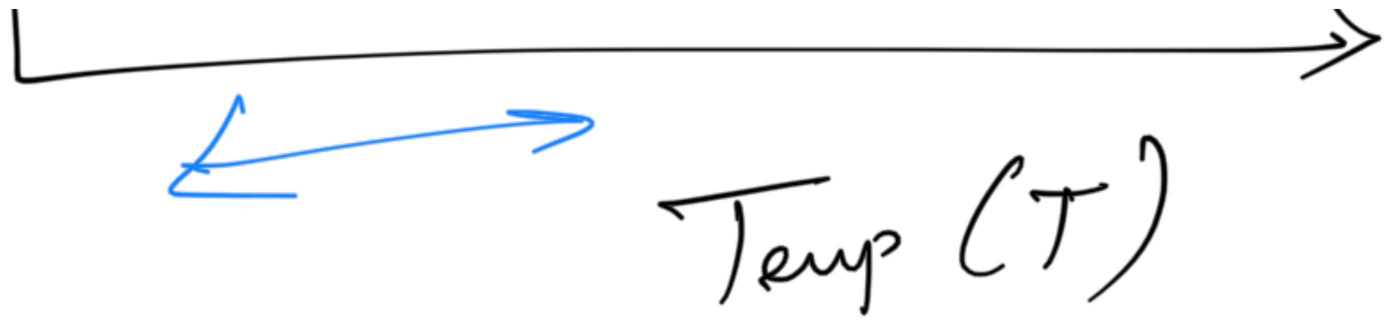
$$\boxed{v_d = \mu E}$$

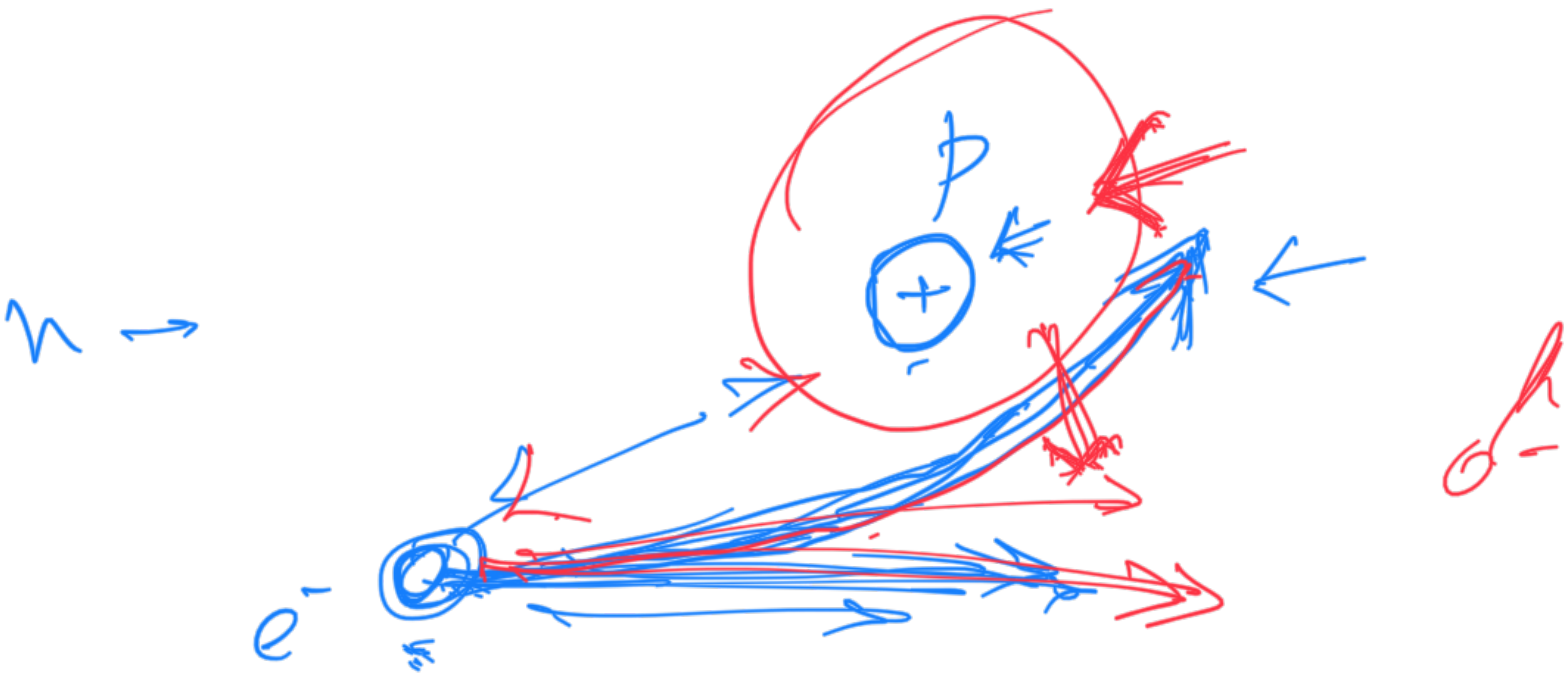
Phonon.

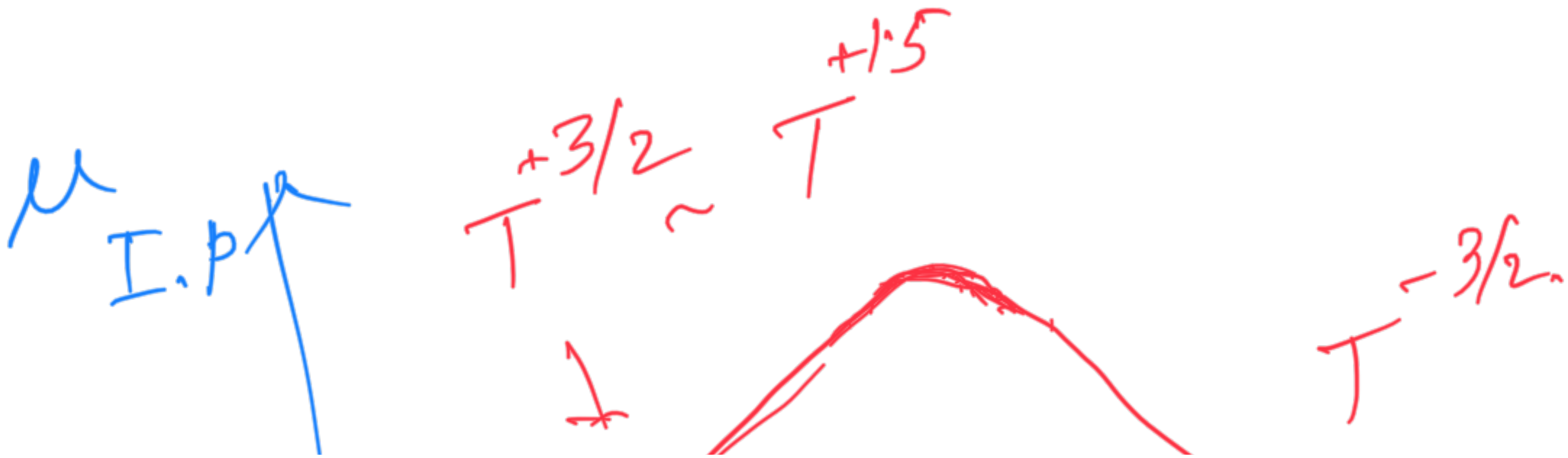
Scattering

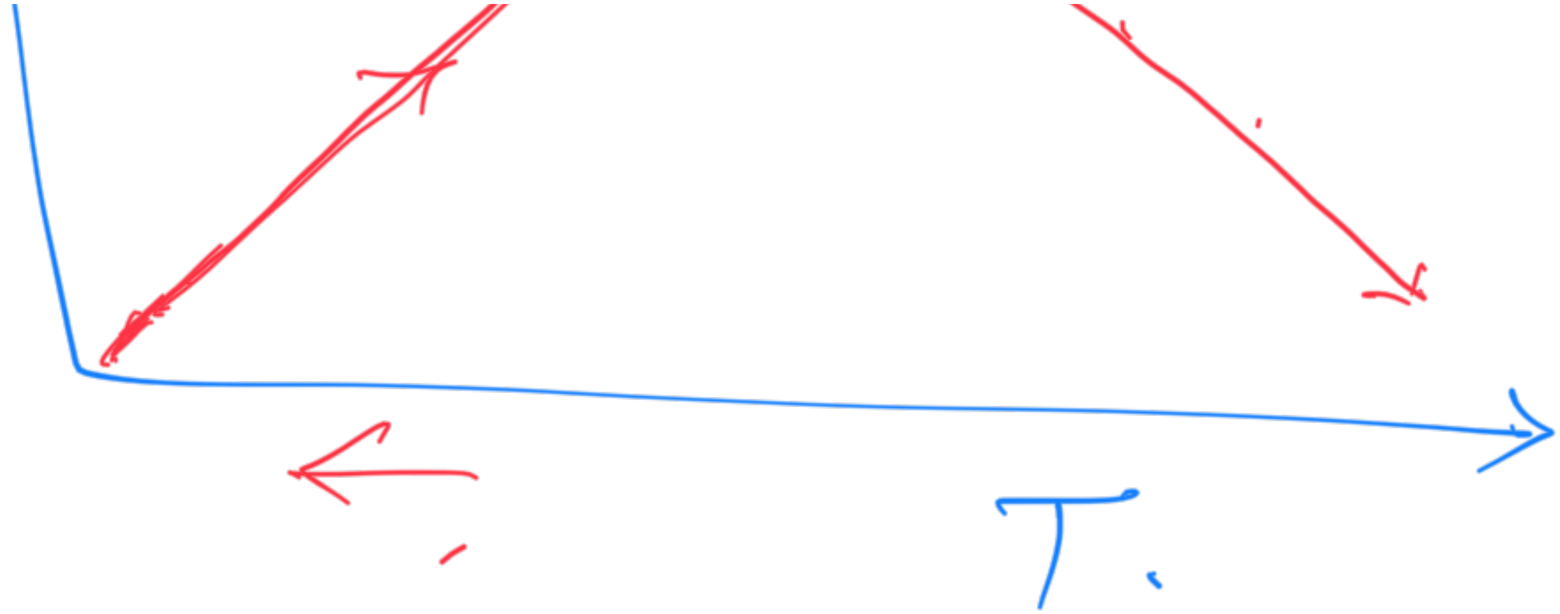
$\boxed{\text{Ionized charge centre.}}$

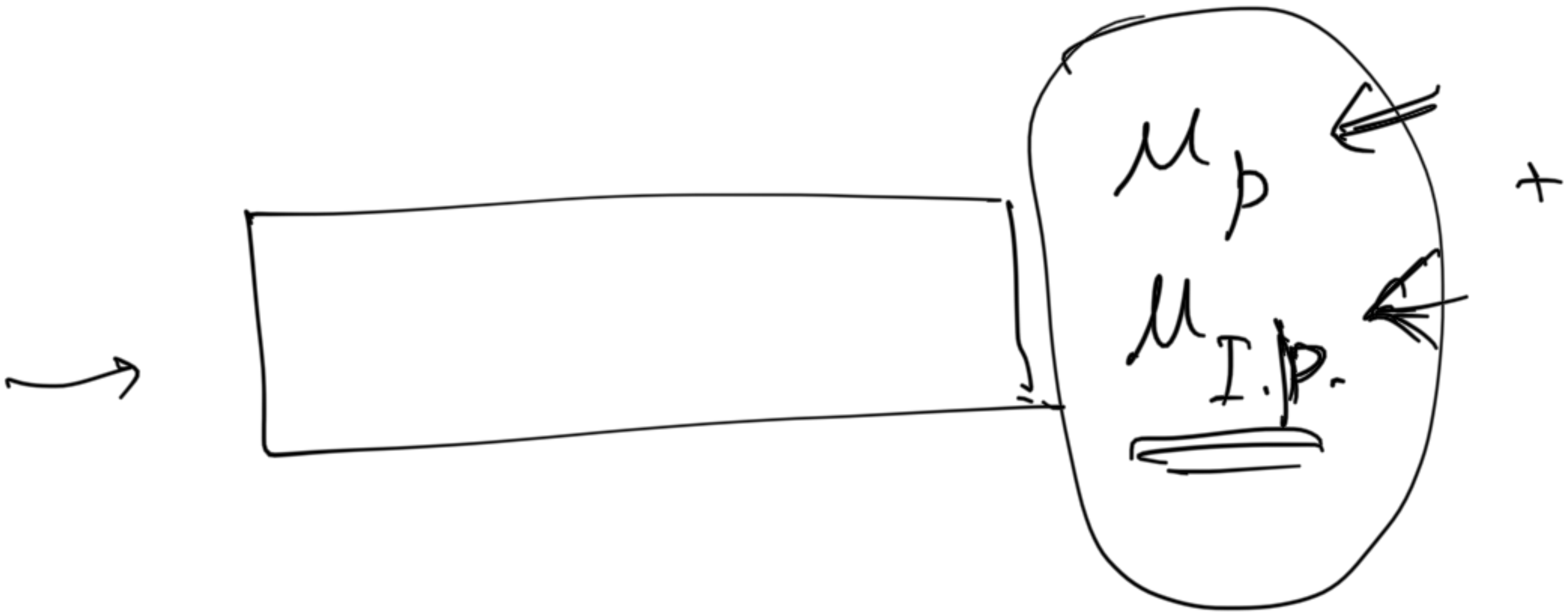


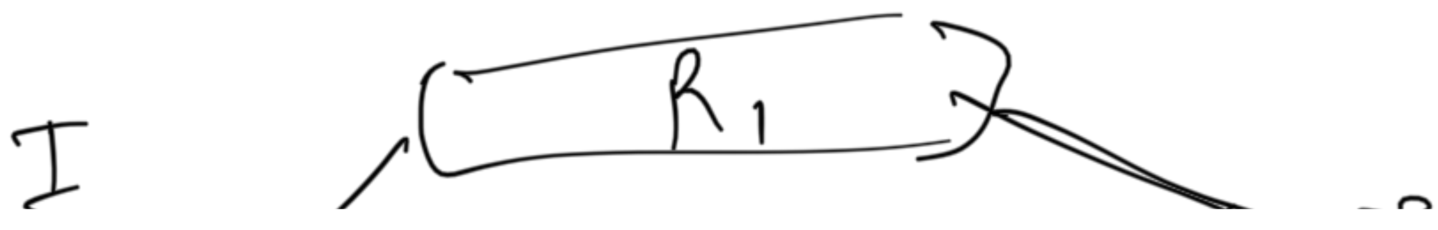

Temp (T)

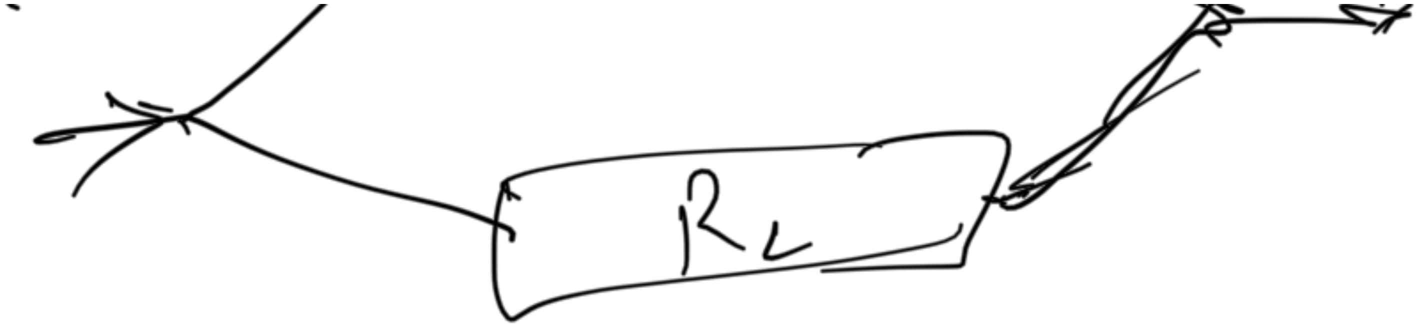

p
+
n
e⁻


μ I.p
T^{+3/2} ~ T^{+1.5}
T^{-3/2}


T.


μ_p
$\mu_{I.P.}$
+


I
R_1



$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2},$$

$$\boxed{\frac{1}{\mu_T} = \frac{1}{\mu_p} + \frac{1}{\mu_{I.p.}}}$$

$$\mu_p = 400 \ \mathrm{cm^2/Vs}.$$

$$\mu_{I.P} = 500\ cm^2/Vs.$$

$$\frac{1}{\mu_T} = \frac{1}{400} + \frac{1}{500} \Rightarrow \boxed{\mu_T = 220\ cm^2/Vs}$$

$220\ cm^2/Vs.$

Effect of Doping.

doping.

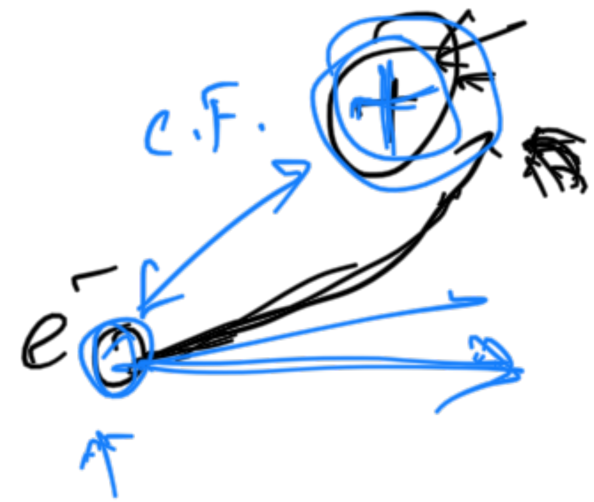
Low do… → $\mu_{I.P.}$

High doping.

n → p

Low doping.

I.P → low.

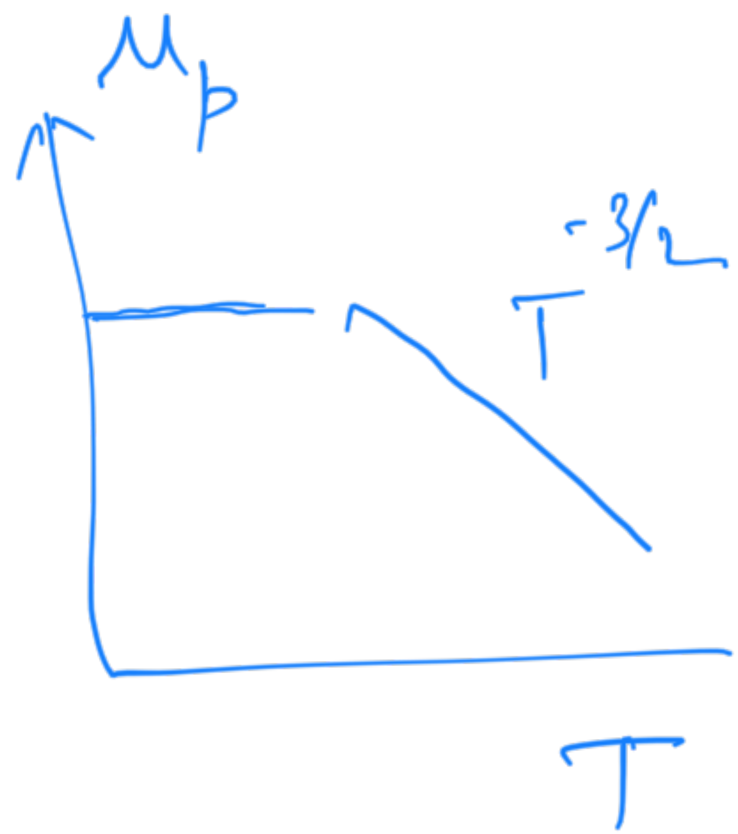


$\mu_{I.P}\uparrow$ → increase.

$$\frac{1}{\mu_T} = \frac{1}{\mu_p} \gg \frac{1}{\mu_{I.P.}}$$

high.

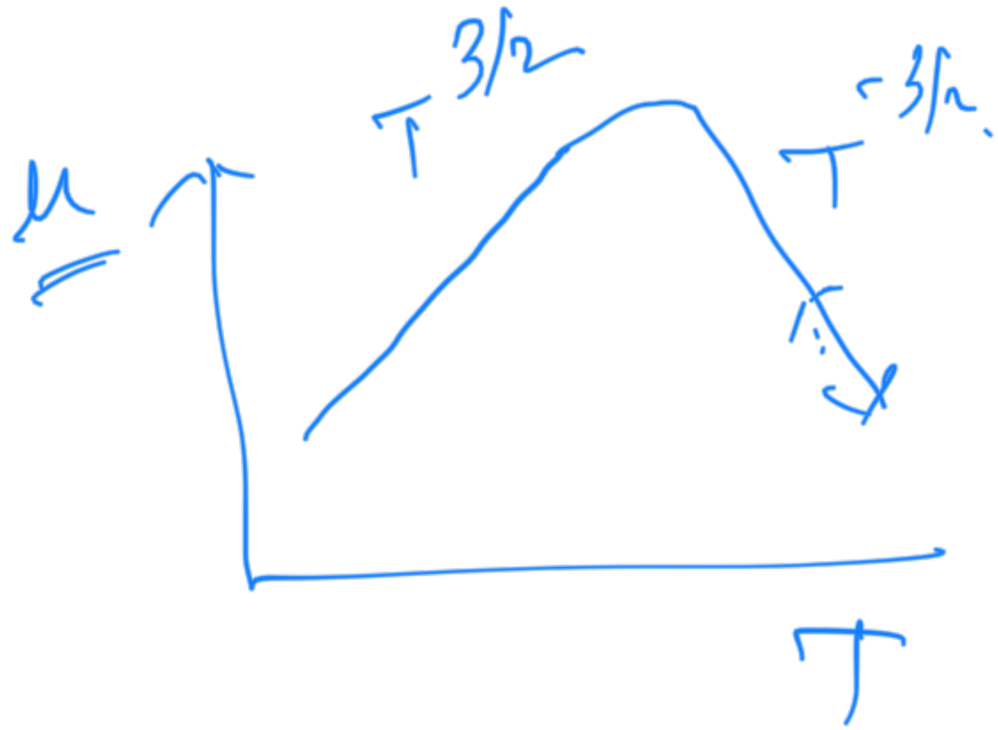
$$\left.\frac{1}{\mu_T}\right|_{\text{low dop.}} \Rightarrow \sim \frac{1}{\mu_p}.$$



High doping.

$$\frac{1}{\mu_T} = \frac{1}{\mu_p} + \frac{1}{\mu_{I.P.}}$$ low.

$$\left.\frac{1}{\mu_T}\right|_{\text{high dope}} \approx \frac{1}{\mu_{I.P.}}$$



Ohm's Law

Current density $\rightarrow$ J.

$J = \text{charge} \times \text{flux}$.

$= q \times n v_d$.

$\boxed{v_d = \mu E}$

$\boxed{J = q n \mu E}$

$= \sigma E$

$\boxed{\sigma = q n \mu}$

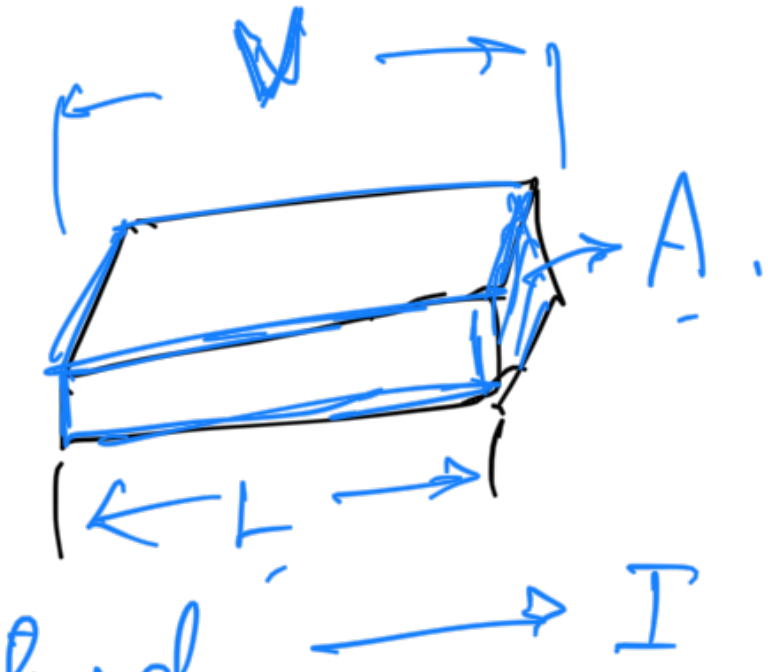
$\sigma \rightarrow$ <u>Conductivity</u>.

Resistivity $\rightarrow$ $\rho = \dfrac{1}{\sigma}$

$$R = \frac{\rho L}{A}.$$

Resistance.

cross-sectional area.



$$\boxed{E = \frac{V}{L}}$$

$$J = \frac{I}{A} = \sigma E.$$

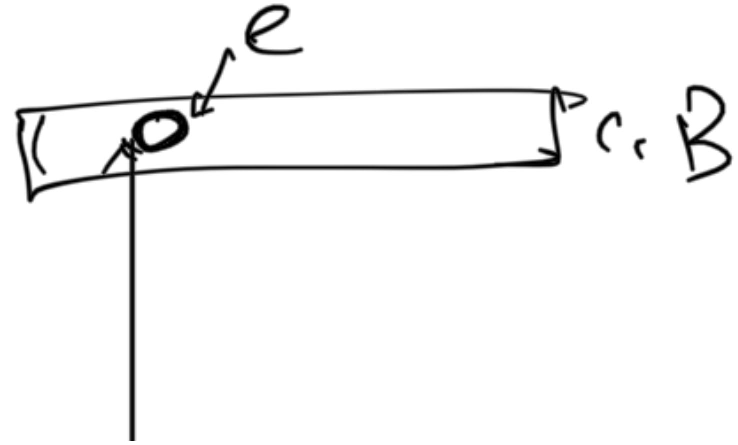
$$\frac{I}{A} = \sigma \cdot \frac{V}{L} = \frac{V}{\rho L}.$$

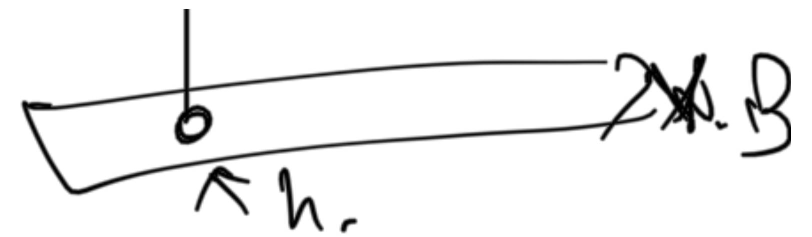
$$V = \frac{LI}{A}\rho.$$

$$\boxed{V = R \times I}$$ ← Ohm's Law.

$$J = q\, n\, \mu\, E.$$

Intrinsic Semiconductor →





$$J_n = n q \mu_n E$$

$$J_p = p q \mu_p E.$$

$$\underline{n_i = n = p} \Rightarrow \text{Total current.}$$

Addition of $J_n + J_p$.

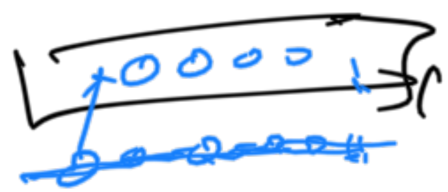
$$J = J_n + J_p$$

$$= n_i\, q \,[\mu_n + \mu_p]$$

$$\boxed{\sigma_i = \frac{J}{E} = n_i q(\mu_n + \mu_p)}$$

intrinsic conductivity

Extrinsic Semiconductors.



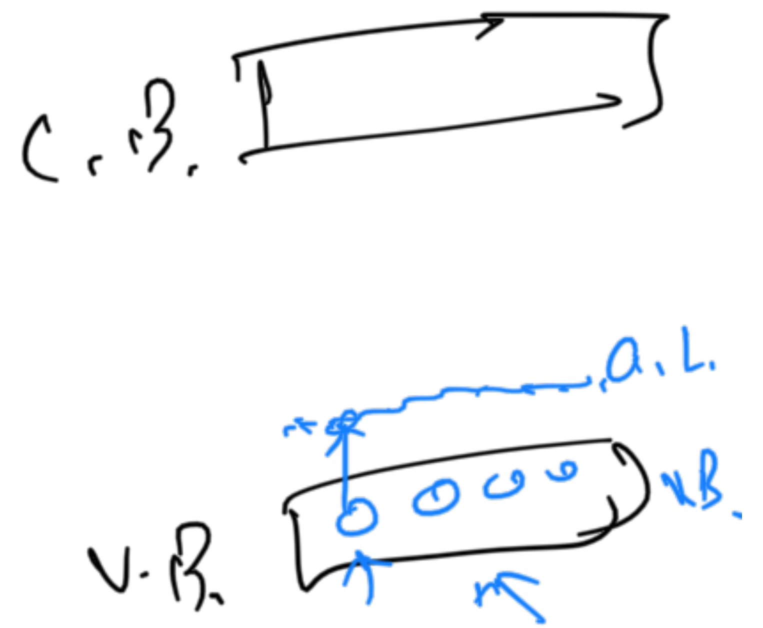
C.B.

n type $\rightarrow$ $n \gg p$.

$$\boxed{\sigma_n = q N_d \mu_n}$$

N_d = donor concentration. ← P dope in Si.

p type → $p \gg n$.

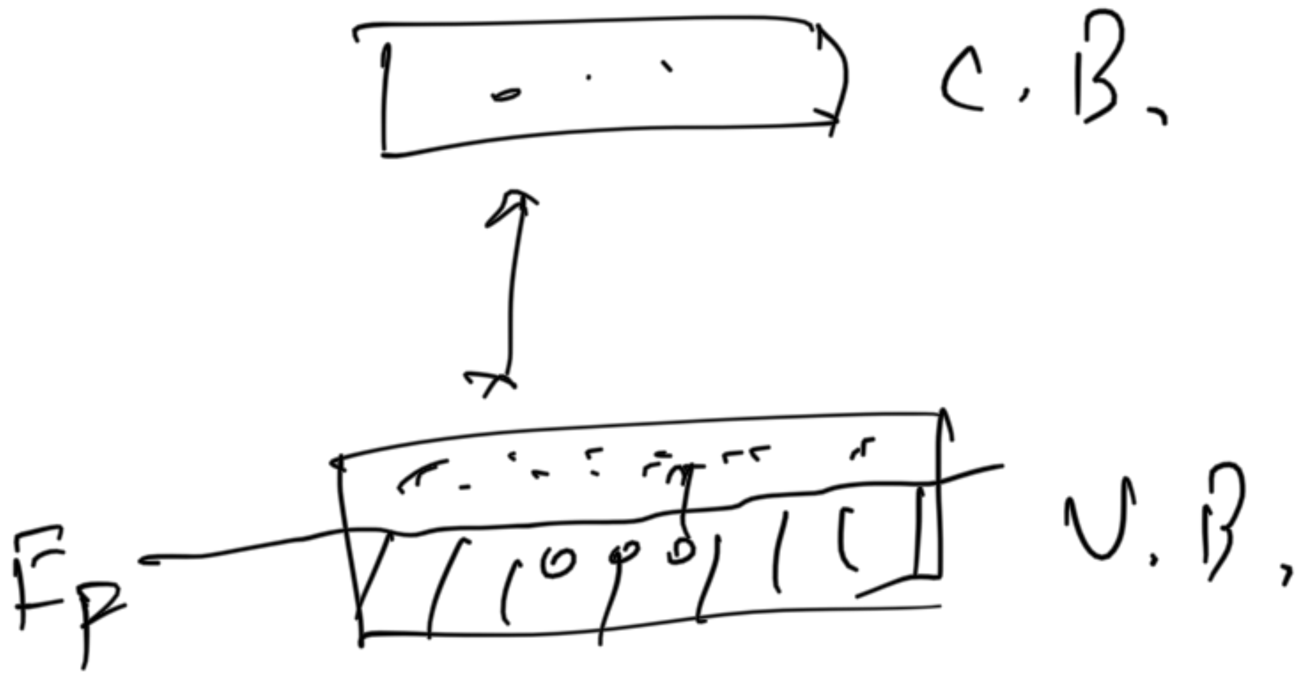


$$\boxed{\sigma_p = q N_a \mu_p}$$

N_a = acceptor concentration.

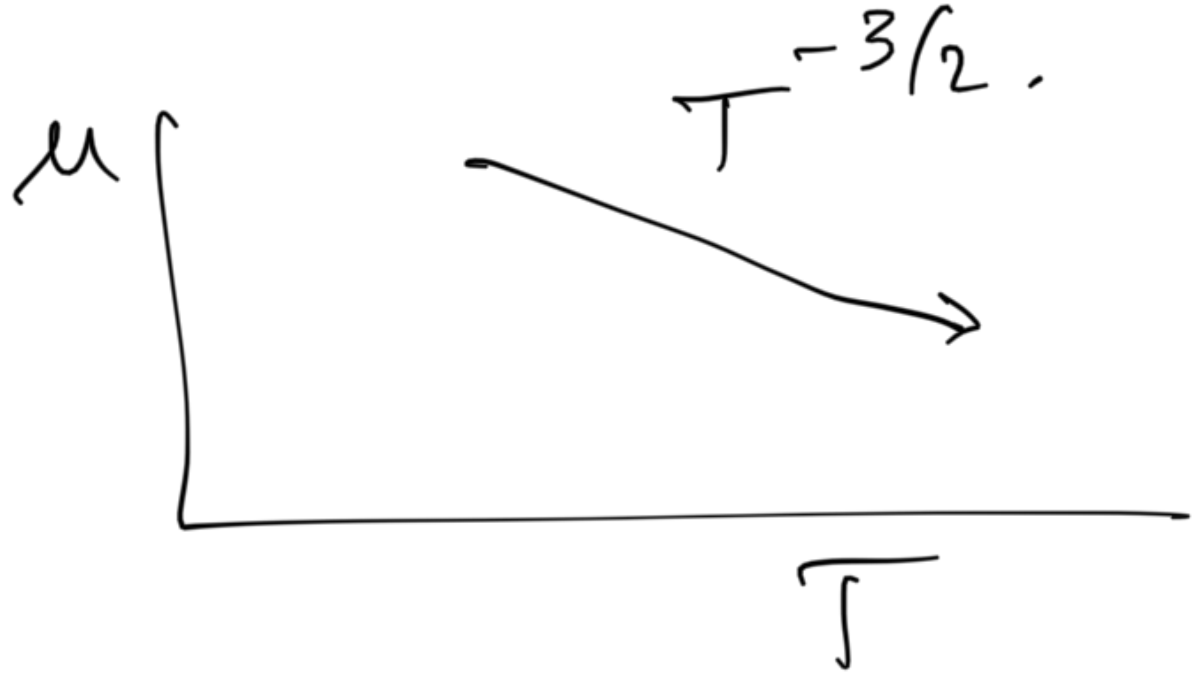
How. Resistivity Varies with T, in metal & Semiconductor.

Metal $\Rightarrow$



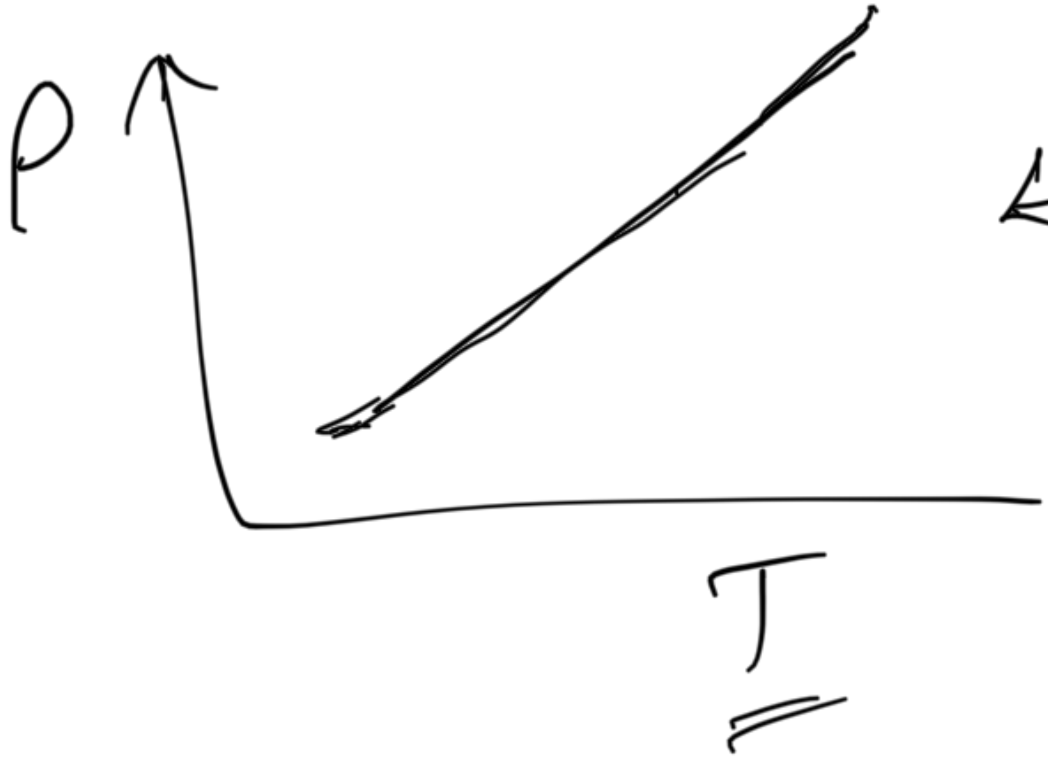
$n \Rightarrow$ does not change with T.

$\mu \rightarrow$ decreases with T.



$$\boxed{\sigma = q n \mu}$$

$$\rho \propto \frac{1}{\sigma} \propto \frac{1}{\mu}.$$

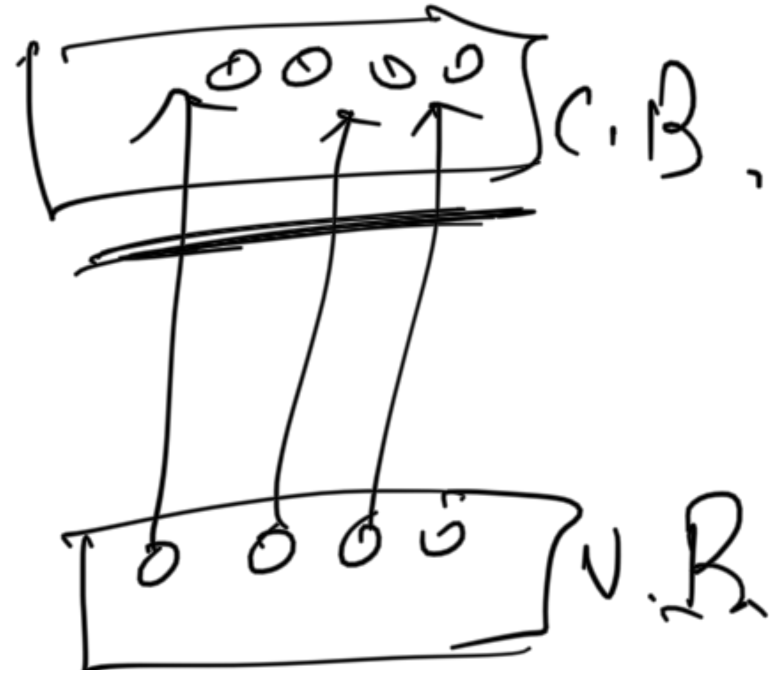


← Metal.

Semiconductor

$n \longrightarrow$ Increases with T.

$\sim N_c \exp -\left(\frac{E_c}{KT}\right).$



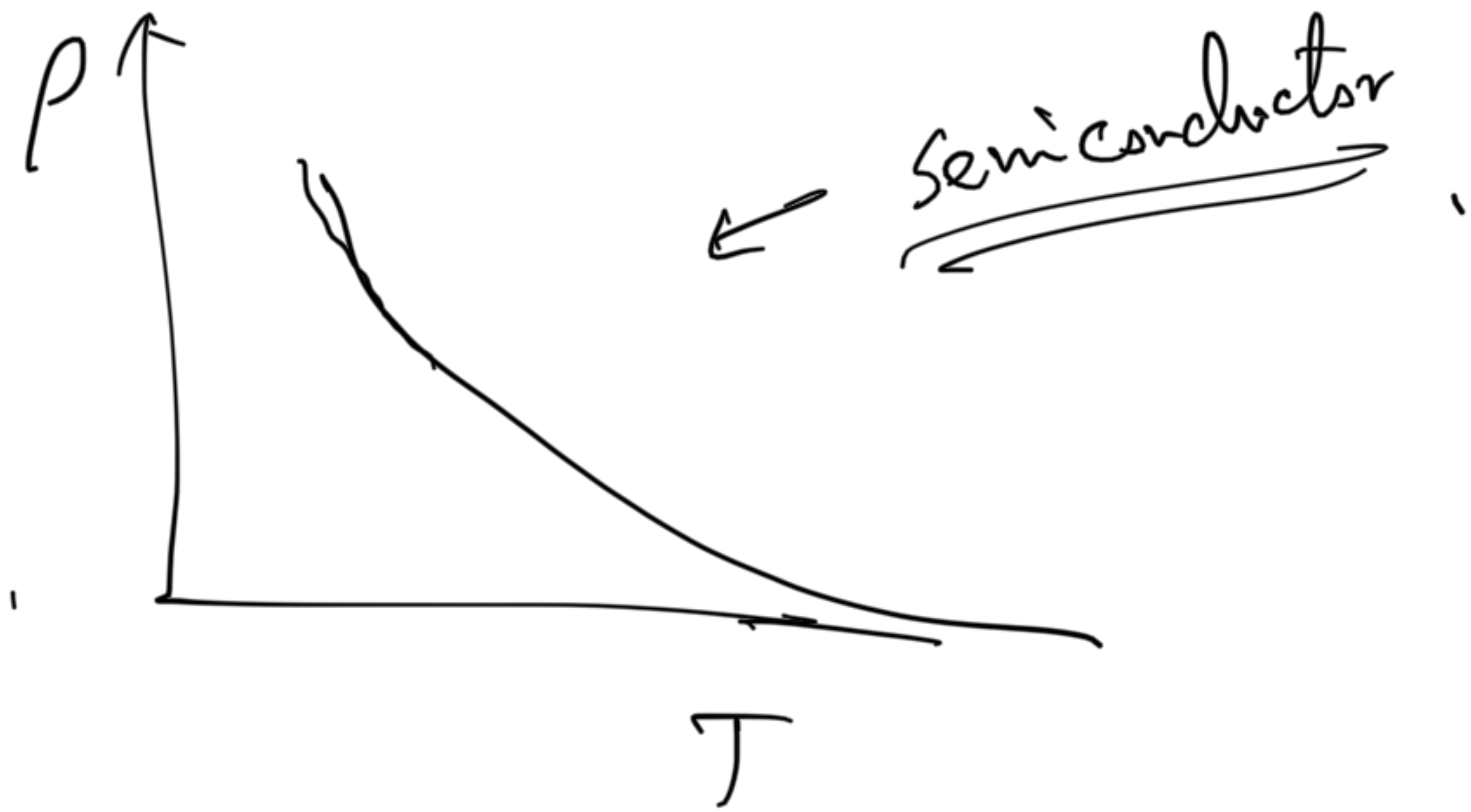
$\underline{\underline{n}} \propto \uparrow$ exponentially with T.

$\mu \longrightarrow$ decreases. $T^{-3/2}$

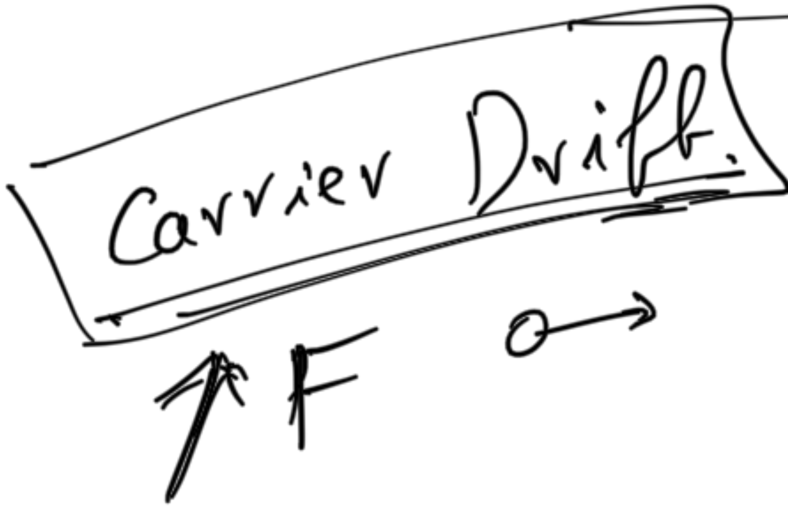
$$\boxed{\sigma = e\, n\, \mu} \longrightarrow T^{-3/2}$$

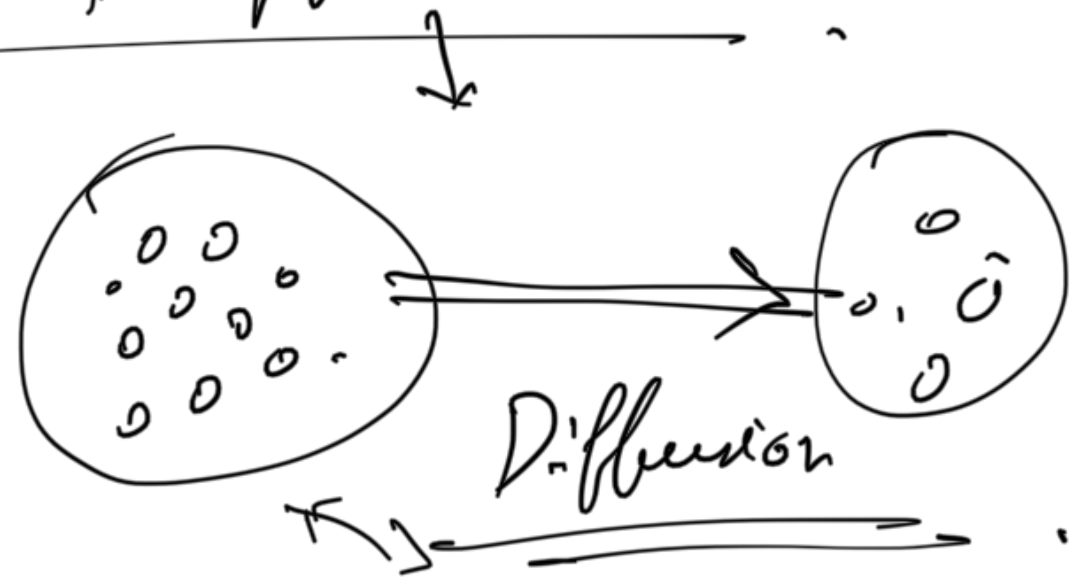
exponentially

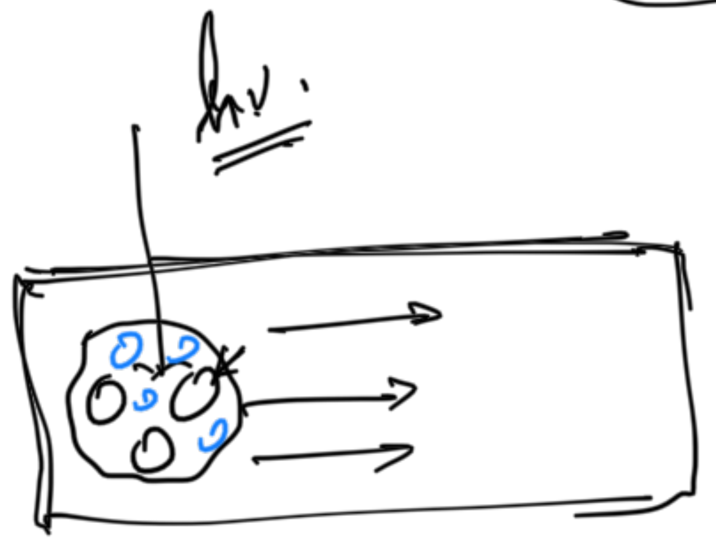
$$\rho = \frac{1}{\sigma}$$

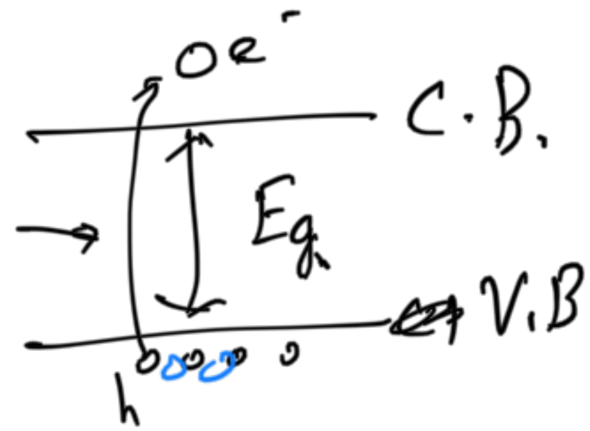


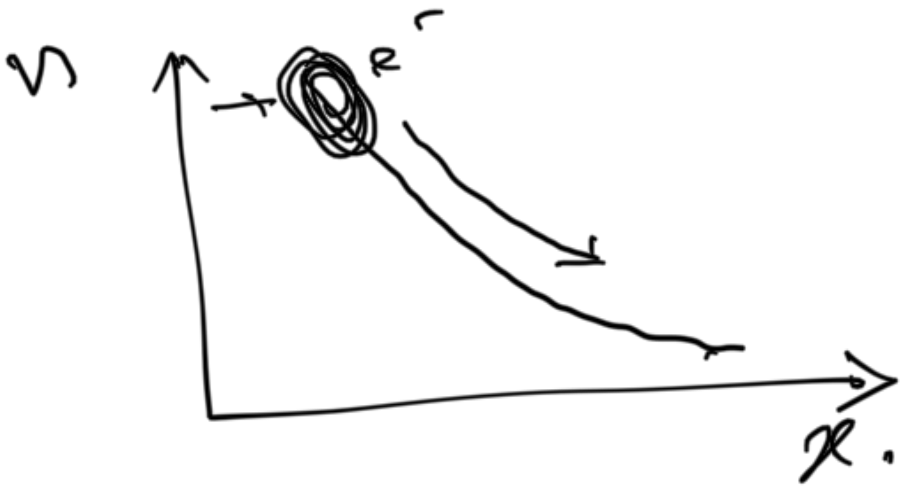
Carrier Diffusion



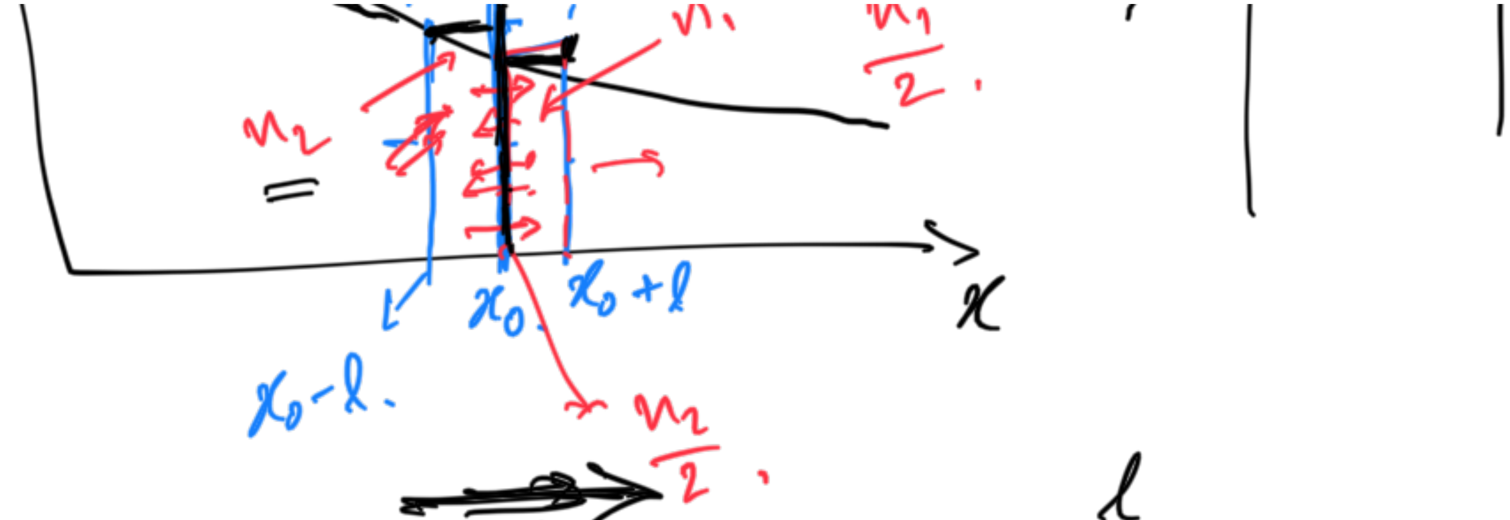








$T \neq 0$



$\underline{\underline{n_2 > n_1}}$

l

$\tau \to$ Relaxation time.

$l \to$ mean free path.

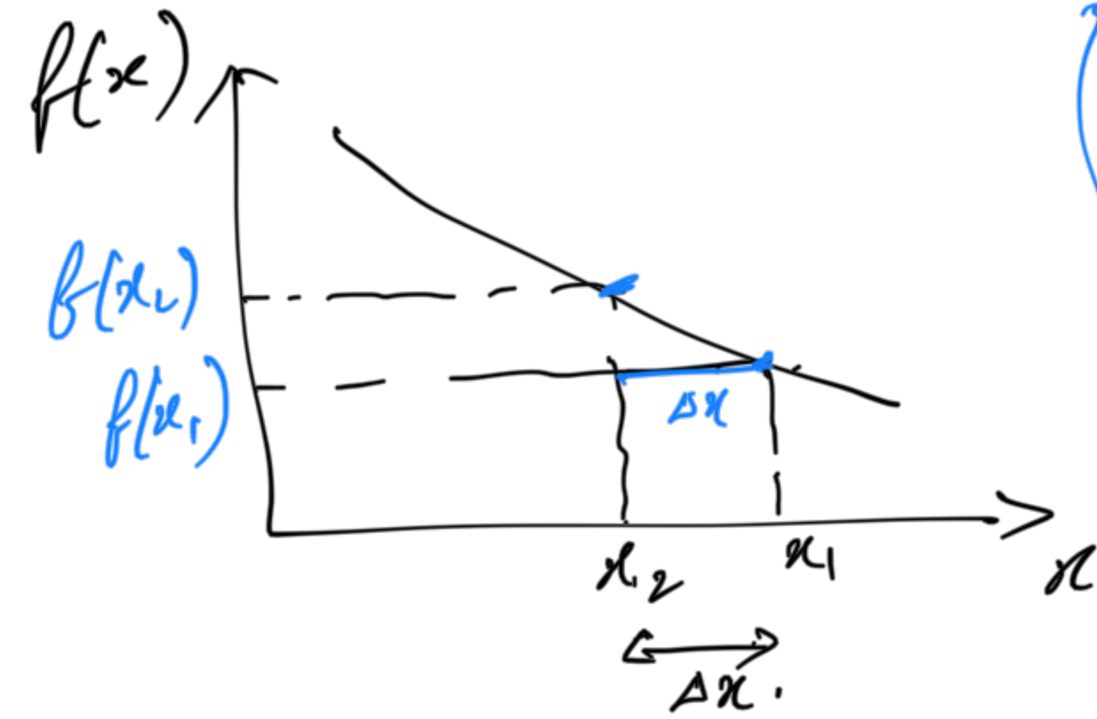
net electron moving $\to \dfrac{n_2}{2} - \dfrac{n_1}{2} = \dfrac{(n_2 - n_1)}{2}$.

net flux of carriers moving towards right $\to$

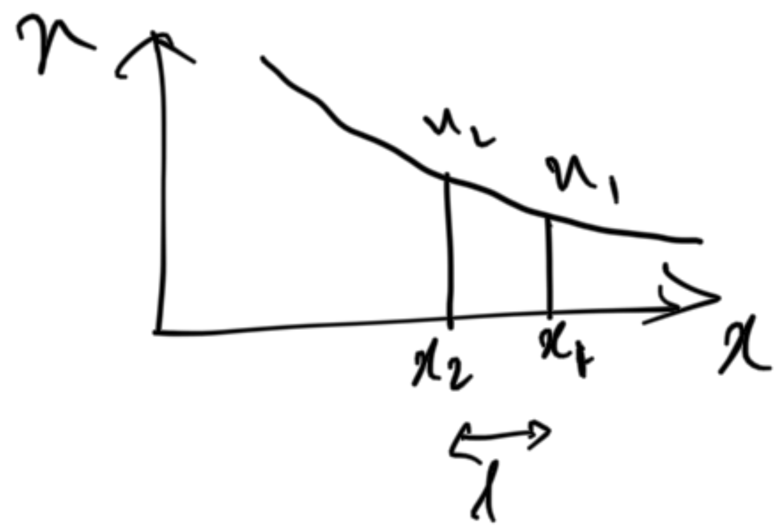
$$\to \left(\frac{n_2 - n_1}{2}\right) \times \underline{\underline{\text{velocity}}} \to \frac{l}{\tau}.$$

$(n_2 - n_1) \quad l$

$$\boxed{\text{flux} = \frac{(n_2 \ldots)}{2} \times \frac{\lambda}{\tau}.}$$



$$\boxed{f(x_2) - f(x_1) = -\frac{\partial f(x)}{\partial x} \times \Delta x.}$$



$$\boxed{n_2 - n_1 = -\frac{\partial n}{\partial x} \times l.}$$

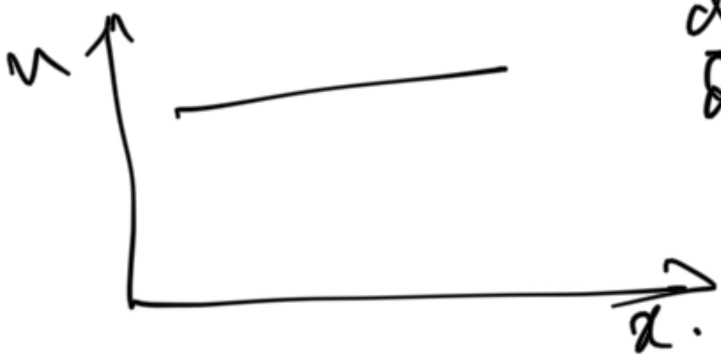
$$\text{Diffusion flux} = \left(-\frac{\partial n}{\partial x} \times l\right) \times \frac{1}{2}\frac{l}{\tau}$$

$$\boxed{\text{Diffusion flux} = -\frac{l^2}{2\tau}\frac{dn}{dx}}$$

D_n.

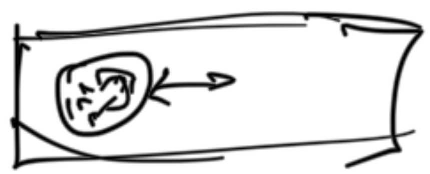
$$\boxed{\text{flux} = -D_n\frac{dn}{dx}}$$

$$D_n = \frac{l^2}{2\tau} \Rightarrow \frac{m^2 s^{-1}}{\text{S.I.}}$$



$\frac{dn}{dx} = 0$.

flux = 0. $\longrightarrow$ <u>No diffusion</u>.



Diffusion Current = $-q \times$ flux

n type extrin. S.C.

$$J_n = q D_n \frac{\partial n}{\partial x}$$

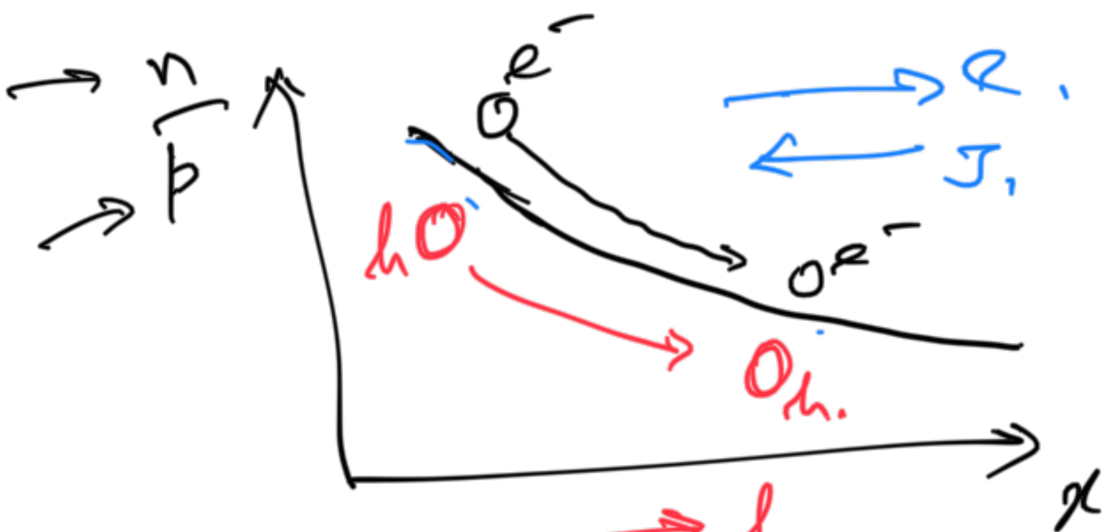
$A\,m^{-2}$

S.I.

p type → h → $\boxed{J_p = -q D_p \frac{\partial p}{\partial x}}$

Total Current → $J_n + J_p \Rightarrow \boxed{J_{Total} = q D_n \frac{\partial n}{\partial x} - q D_p \frac{\partial p}{\partial x}}$

-ve.



→ e.

← J.

J → -ve.

→ h.

→ J. → $\frac{\partial p}{\partial x}$ → -ve.

J → +ve.

$$\boxed{J_T\Big|_{\text{Diffusion}} = qD_n \frac{\partial n}{\partial x} - qD_p \frac{\partial p}{\partial x}}$$

$$\boxed{J_T\Big|_{\text{Drift}} = q\, n\, \mu\, E}$$

Einstein Relation

In equ^m $\longrightarrow$ No net current flow in the device.

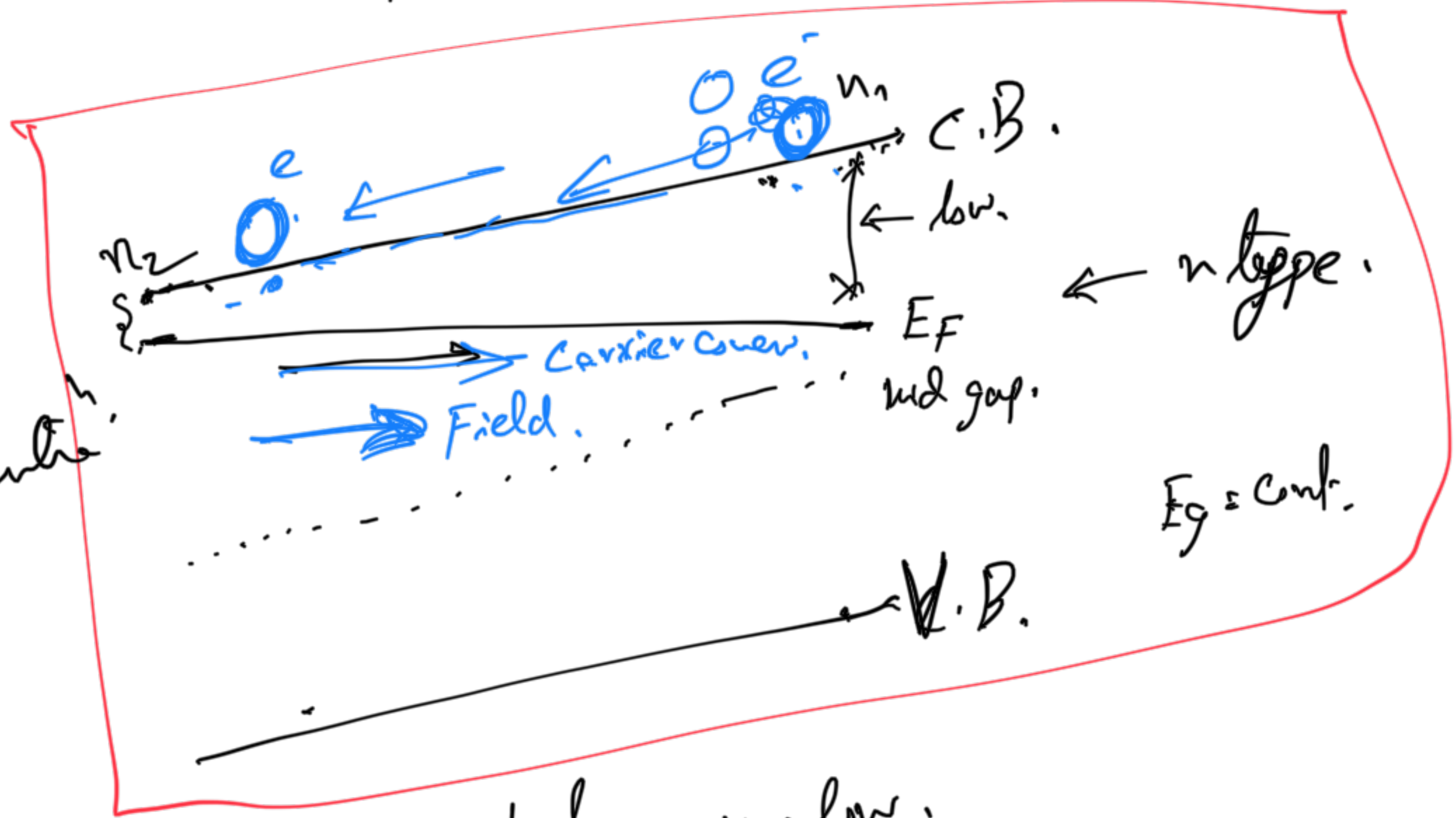
$$= 0$$

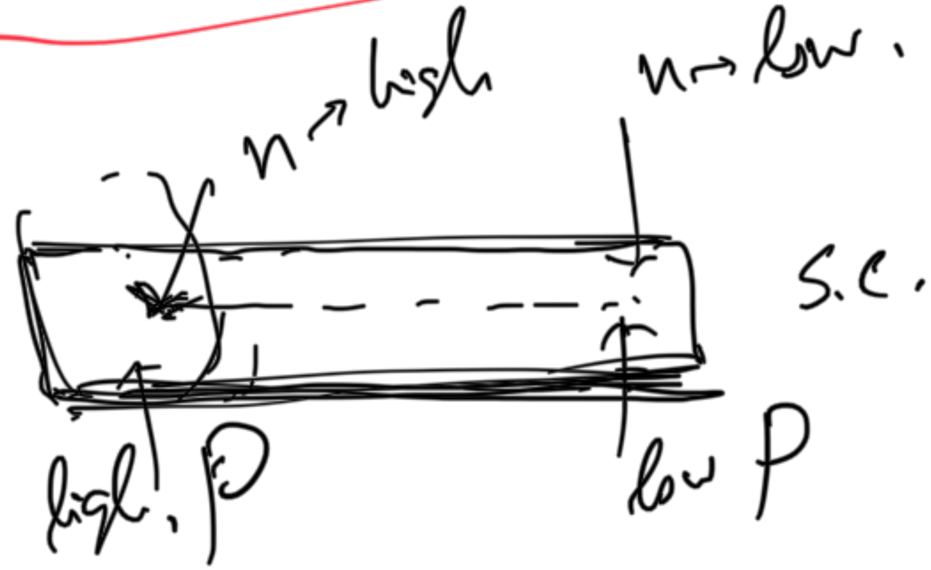
$$\boxed{J_T = J_{Drift} + J_{Diffusion}}$$

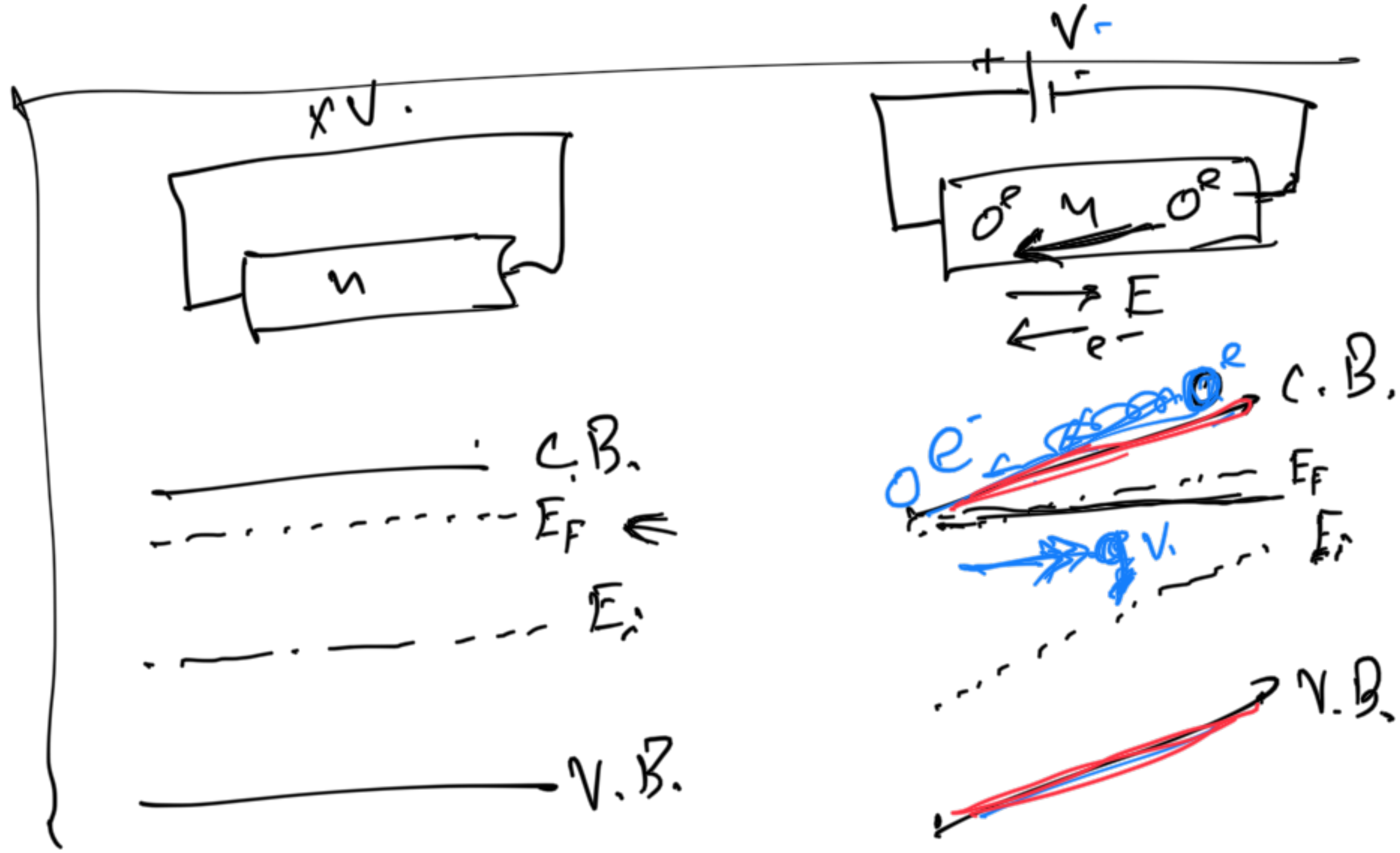
$n_2 > n_1$

uniform gradient of carrier concentration

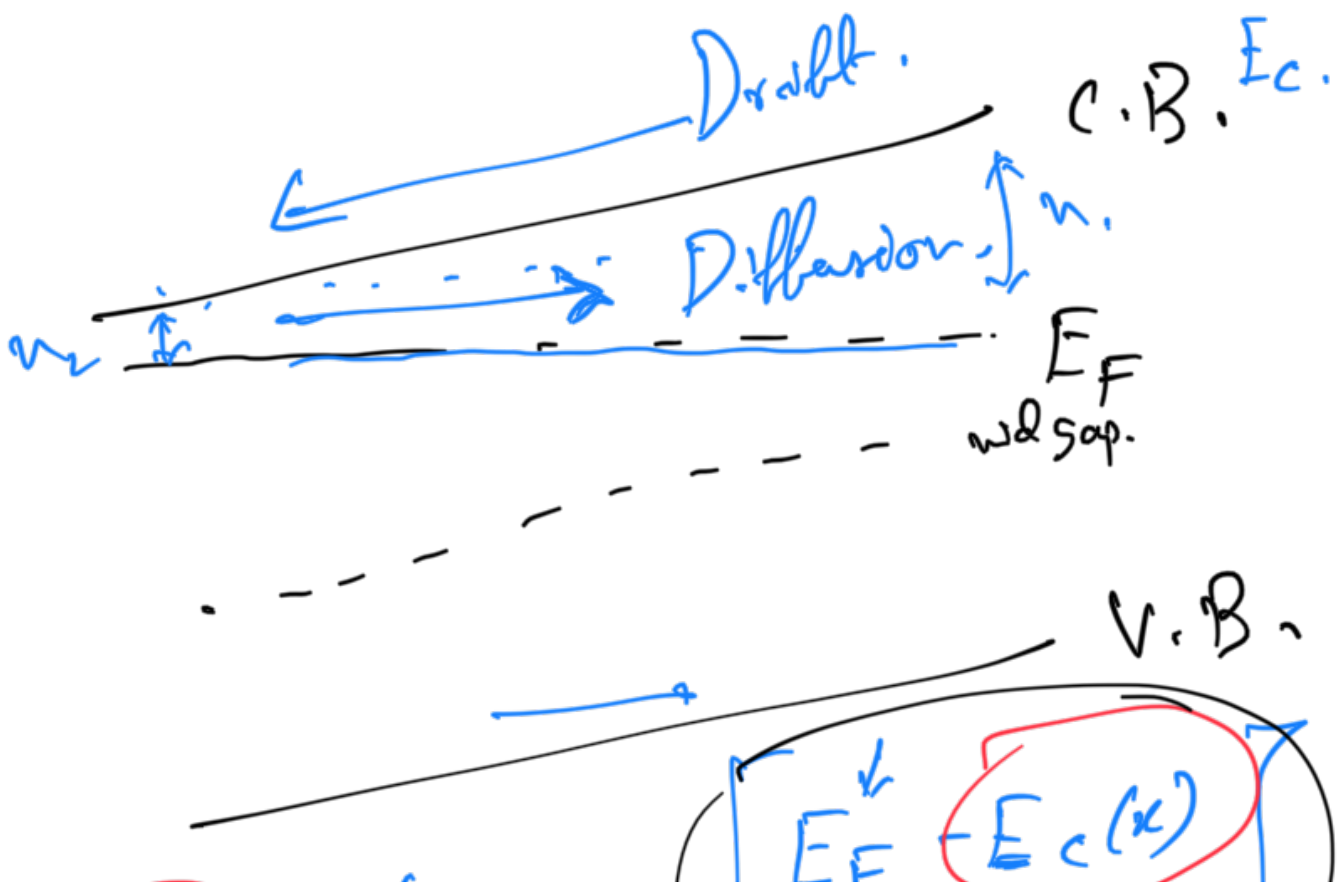
$n_2 > n_1$





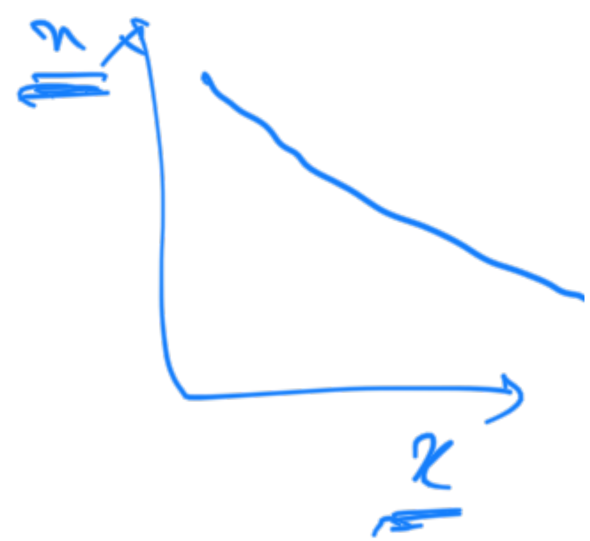


xV.
n
V
+
-
O^p
M
O^R
E
e^-
C.B.
E_F
E_i
V.B.
e^-
e
C.B.
E_F
V_i
E_i
V.B.



Drift.
C.B. E_c.
n_1
Diffusion.
n_2
E_F
mid gap.
V.B.
$E_F - E_c(x)$

$n_2 > n_1$



n
x

$$n(x) = N_c \exp\left[\frac{\cdots}{K_B T}\right]$$

$$\frac{dn}{dx} = N_c \times \left(-\frac{1}{K_B T}\right)\frac{dE_c(x)}{dx} \exp\left[\frac{E_F - E_c(x)}{K_B T}\right]$$

$$\boxed{\frac{dn}{dx} = n(x)\left(-\frac{1}{K_B T}\right)\frac{dE_c(x)}{dx}}$$

$$J_T \Rightarrow q\mu n(x) E + q D_n \frac{dn(x)}{dx} = 0.$$

$$q D_n \frac{dn(x)}{dx} = -q\mu_n n(x) E.$$

$$\cdots \left(-\frac{1}{\cdots}\right)\frac{dE_c(x)}{dx} = -\cancel{q}\,\mu_n \cancel{n(x)} E$$

$$q\, D_n\, n(x) \left(\frac{+\ \ }{K_B T} \right) dx$$

$$E \Rightarrow \frac{1}{q} \frac{dE_c(x)}{dx}$$

$$D_n \frac{1}{K_B T} \frac{dE_c(x)}{dx} = \frac{\mu_n}{q} \frac{dE_c(x)}{dx}$$

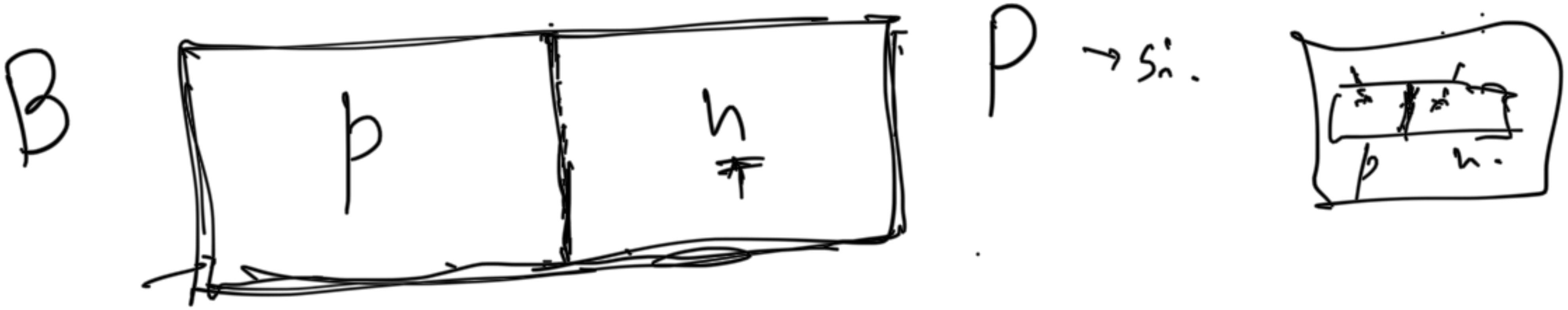
$$\boxed{D_n = \frac{K_B T}{q} \mu_n}$$

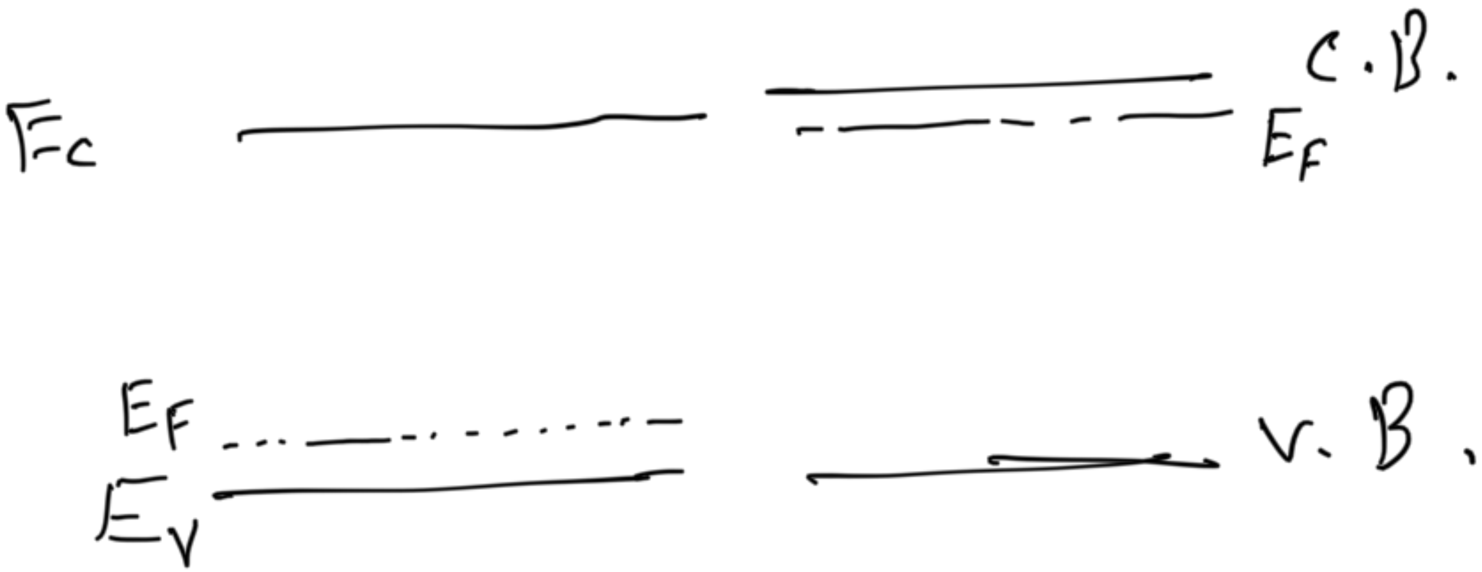
n type ex. S.C.

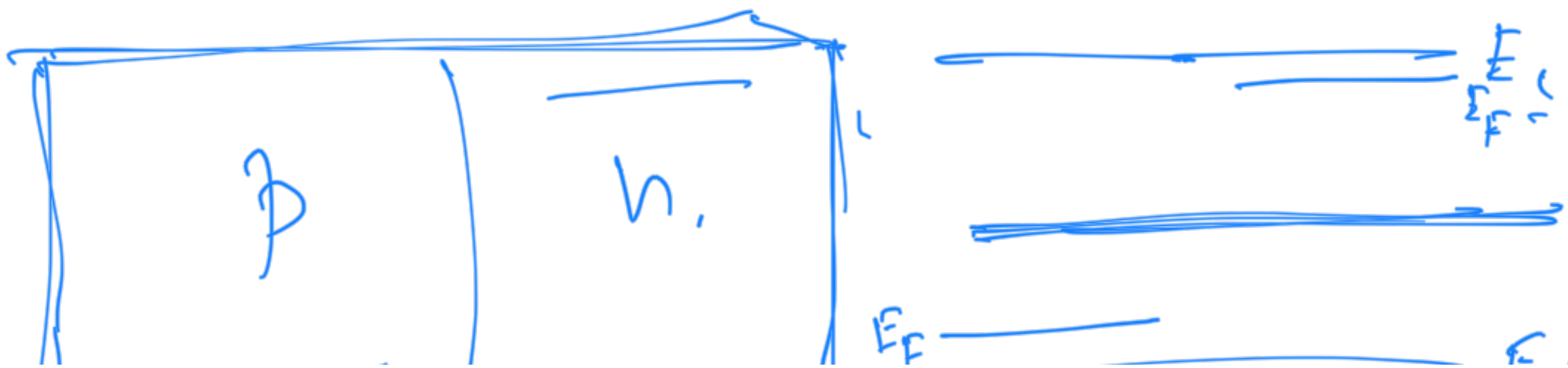
$$\boxed{D_p = \frac{K_B T}{q} \mu_p}$$

High Diffusion $\Longrightarrow$ high drift

p-n junction







Under. eq^m $\rightarrow$ E_F is independent of x

$$\boxed{\frac{dE_F}{dx} = 0} \leftarrow$$

$p \rightarrow$ $J_p = 0 \Rightarrow J_{Drift} + J_{Diffusion} = 0.$

$$q \mu_p p E - q D_p \frac{dp}{dx} = 0.$$

$$D_p = \frac{K_B T}{q} \mu_p$$

$$\cancel{q} \mu_p p \times \frac{1}{\cancel{q}} \frac{dE_i}{dx} - \cancel{q} \times \frac{K_B T}{\cancel{q}} \mu_p \frac{dp}{dx} = 0$$

$$J_p = \mu_p \left[p \frac{dE_i}{dx} - K_B T \frac{dp}{dx} \right] = 0$$

$$J_p = \mu_p \Big[\quad \frac{d}{dx} \qquad \frac{}{dx} \Big] =$$

$$p = n_i \exp\left[\frac{E_i - E_F}{K_B T}\right]$$

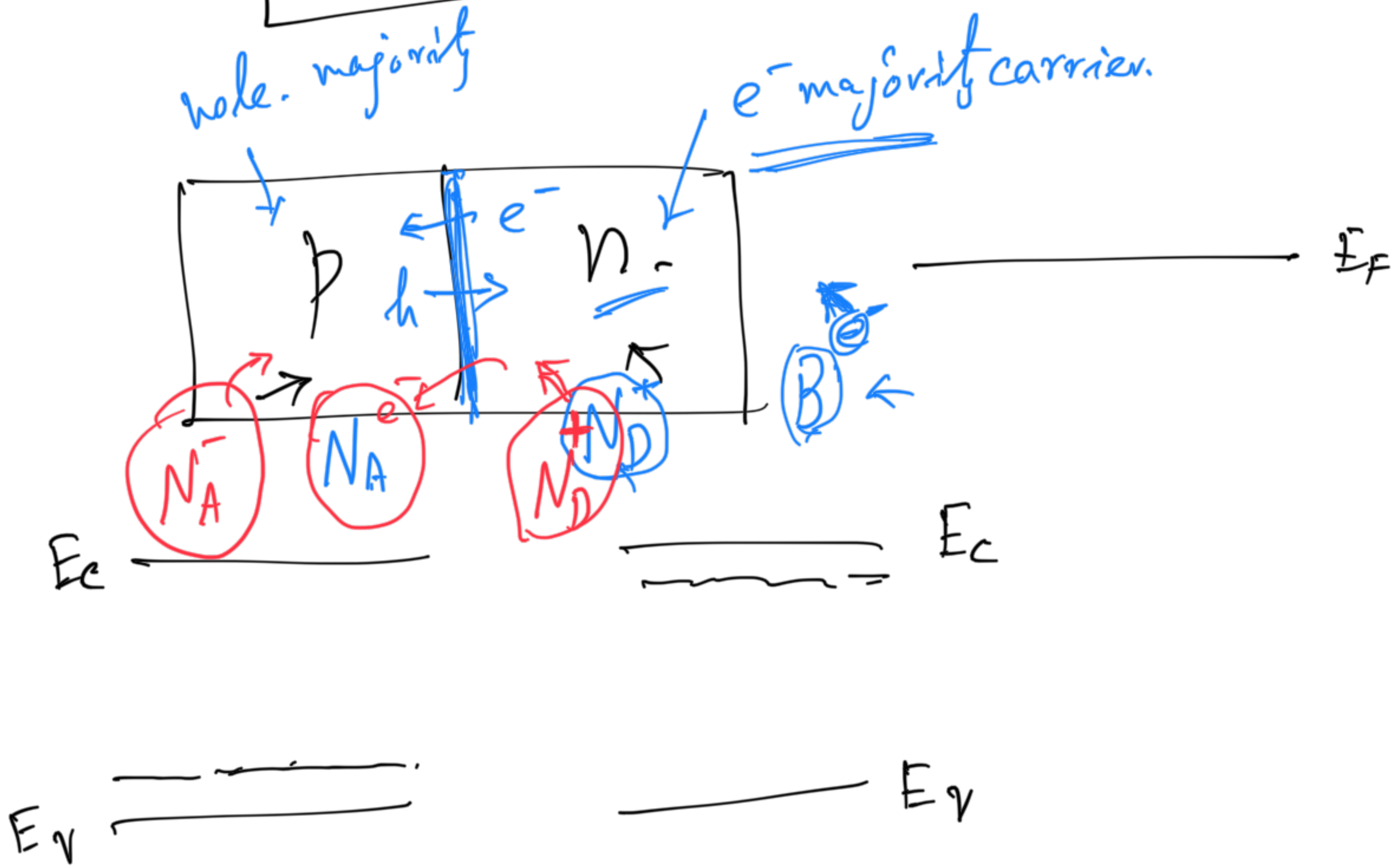
$$\frac{dp}{dx} = n_i \exp\left[\frac{E_i - E_F}{K_B T}\right] \times \frac{d}{dx}\left[\frac{E_i - E_F}{K_B T}\right]$$

$$= \frac{p}{K_B T}\left[\frac{dE_i}{dx} - \frac{dE_F}{dx}\right]$$

$$J_p = \mu_p \left[\cancel{p\frac{dE_i}{dx}} - \cancel{p\frac{dE_i}{dx}} + p\frac{dE_F}{dx}\right]$$

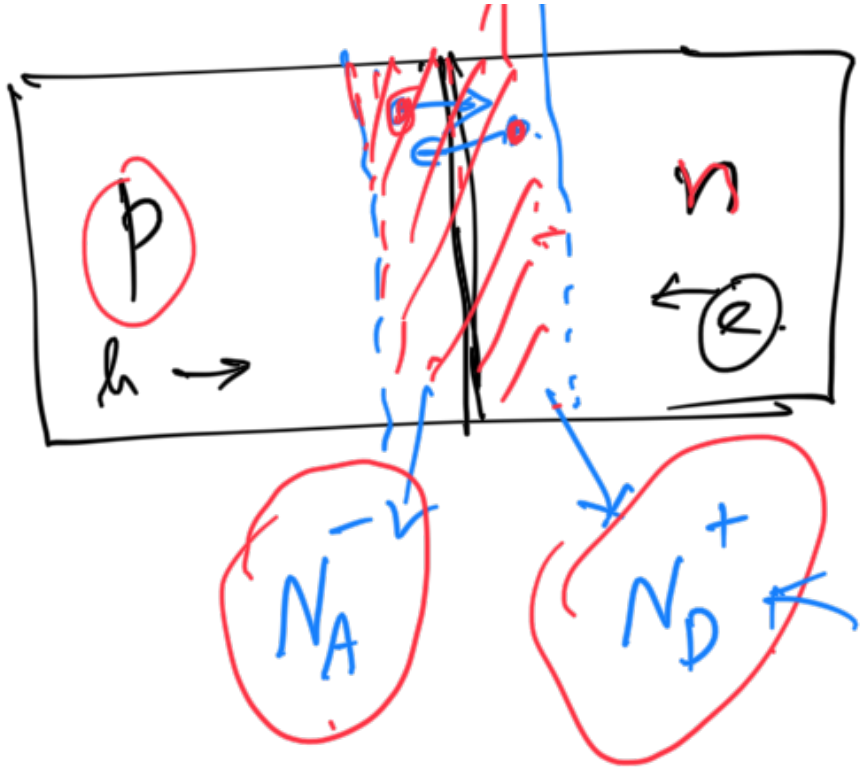
$$= \mu_p \, p \, \frac{dE_F}{dx} \Rightarrow 0$$

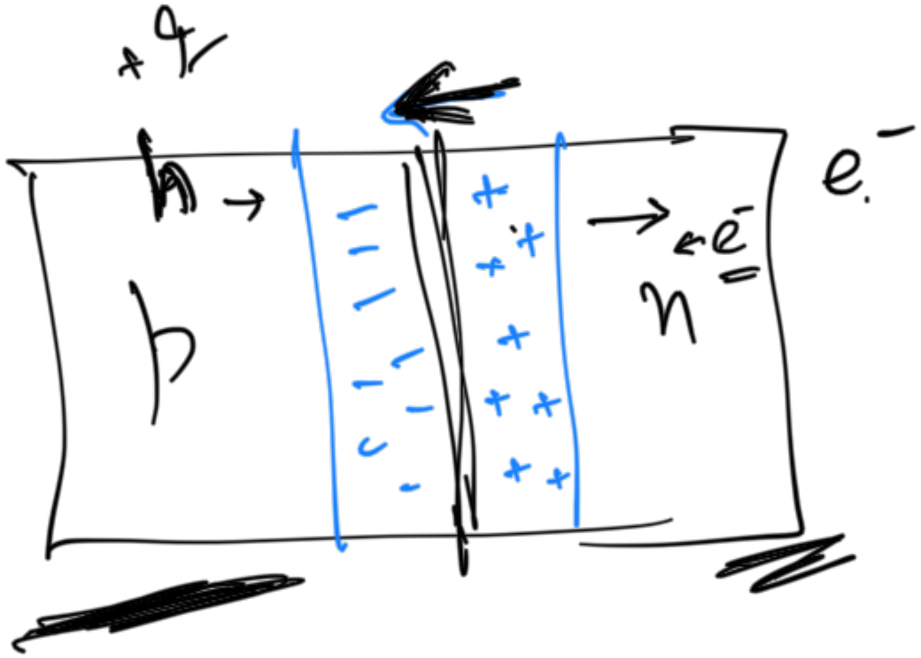
$$\boxed{\frac{dE_F}{dx} = 0}$$

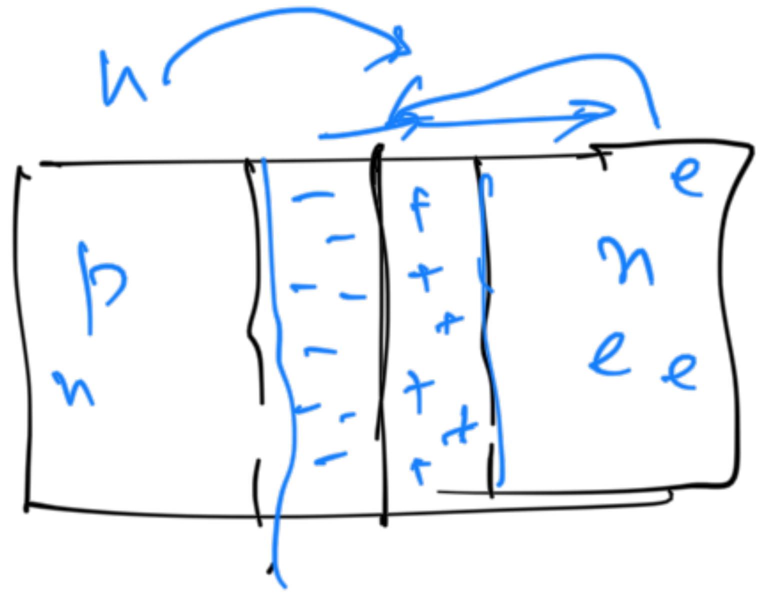


Depletion region


e & h → recombine


p
h →
n
e
N_A^-
N_D^+


+q
h →
p
n
e⁻


h
p
h
n
e
e e

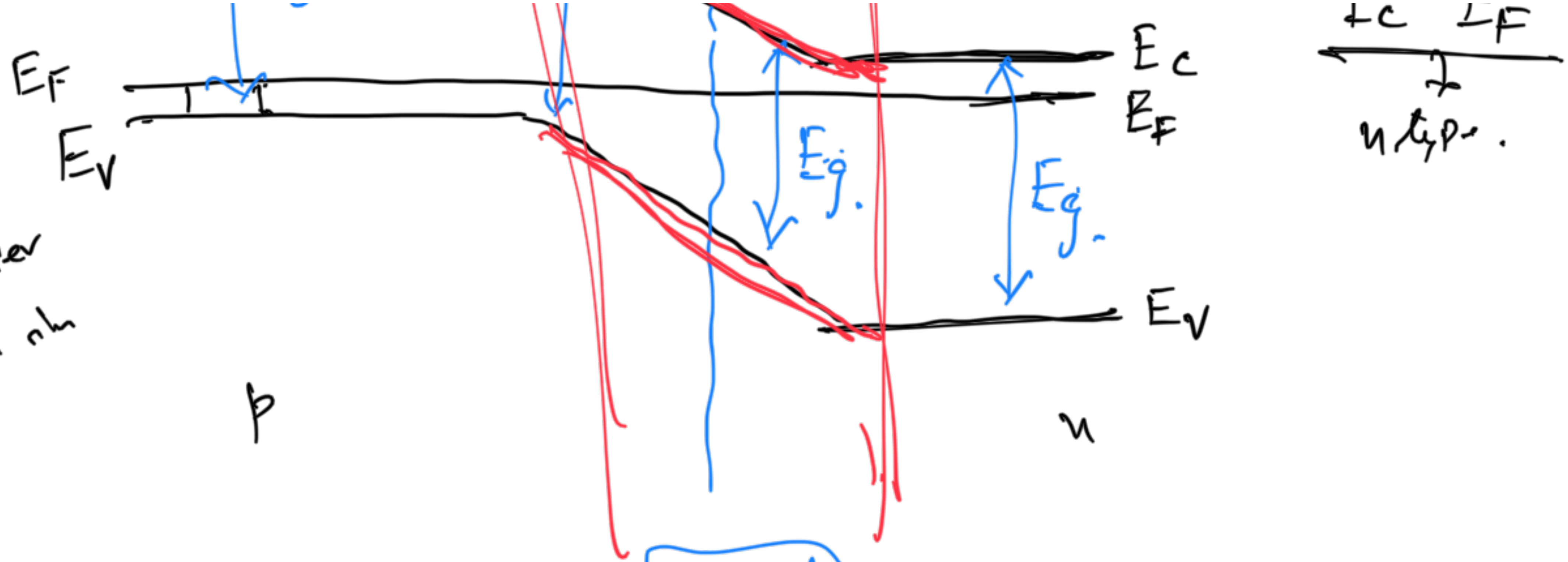
T = R.T.

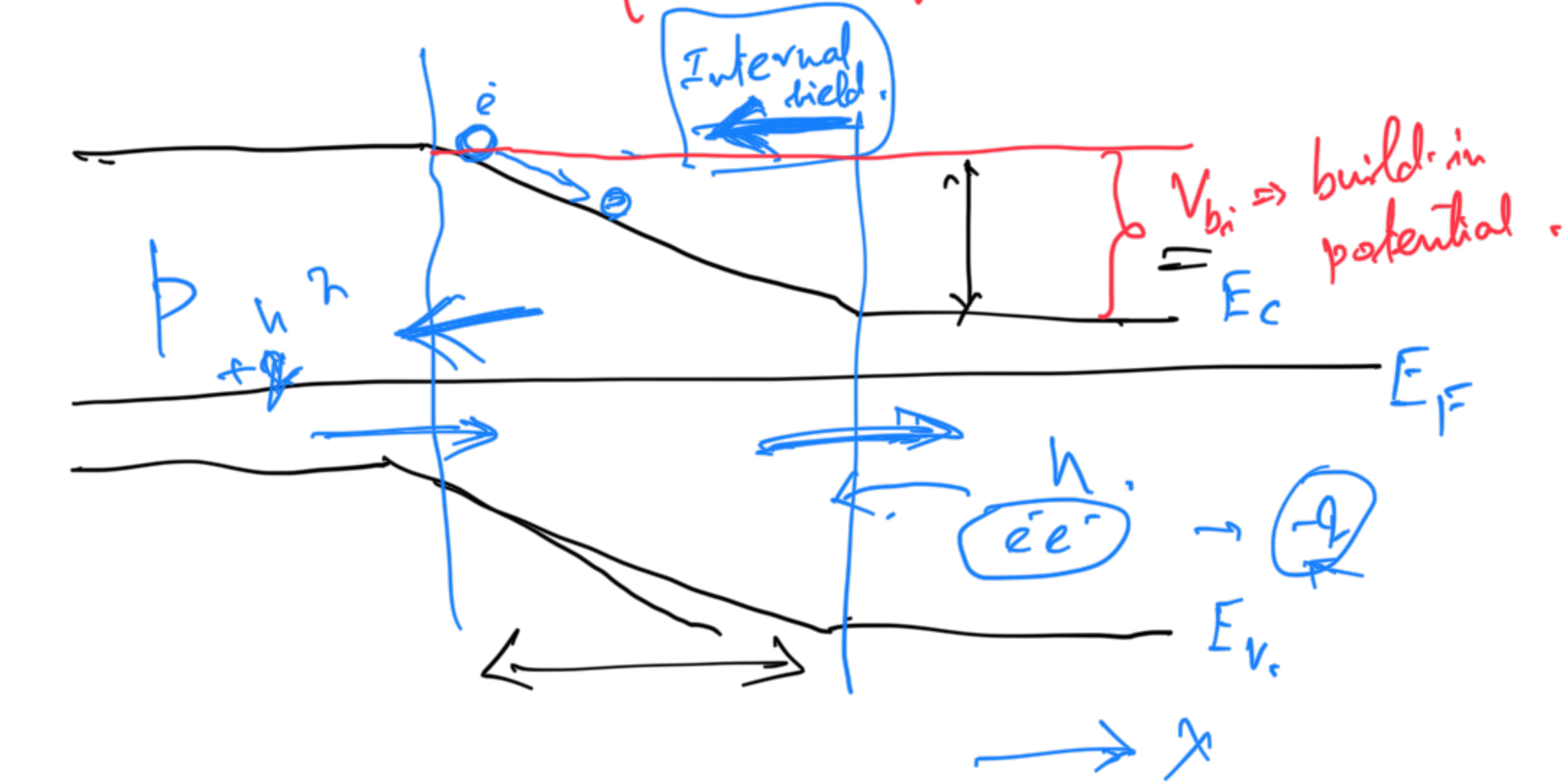
E → K.

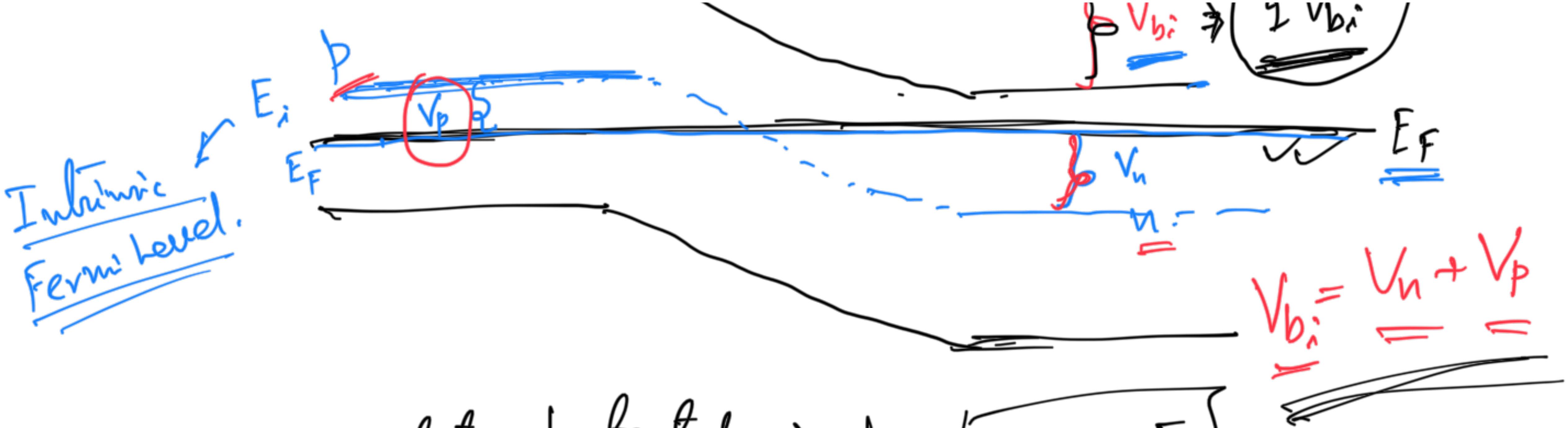
Si


Internal field.
h →
E_c
E_g
← e

$E_F - E_V$ → p type carrier concentration





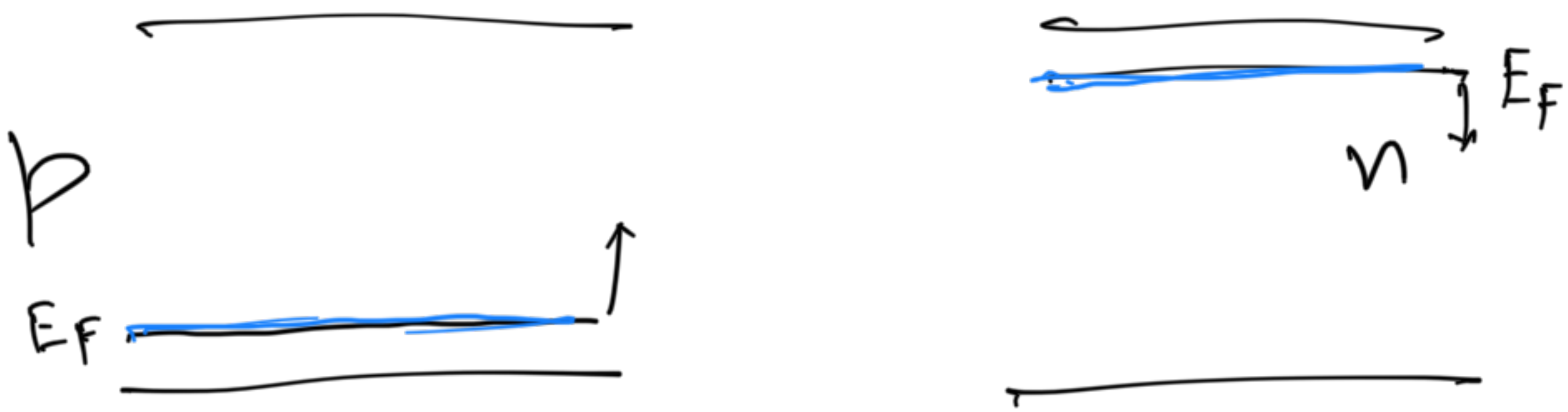


$$V_{bi} = V_n + V_p$$

$V \Rightarrow$ Electric potential

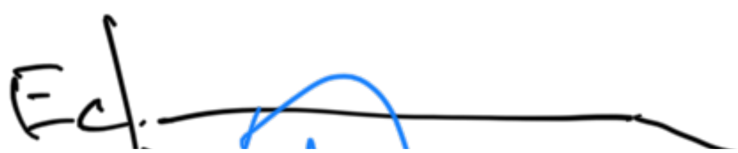
$E \rightarrow$ potential energy

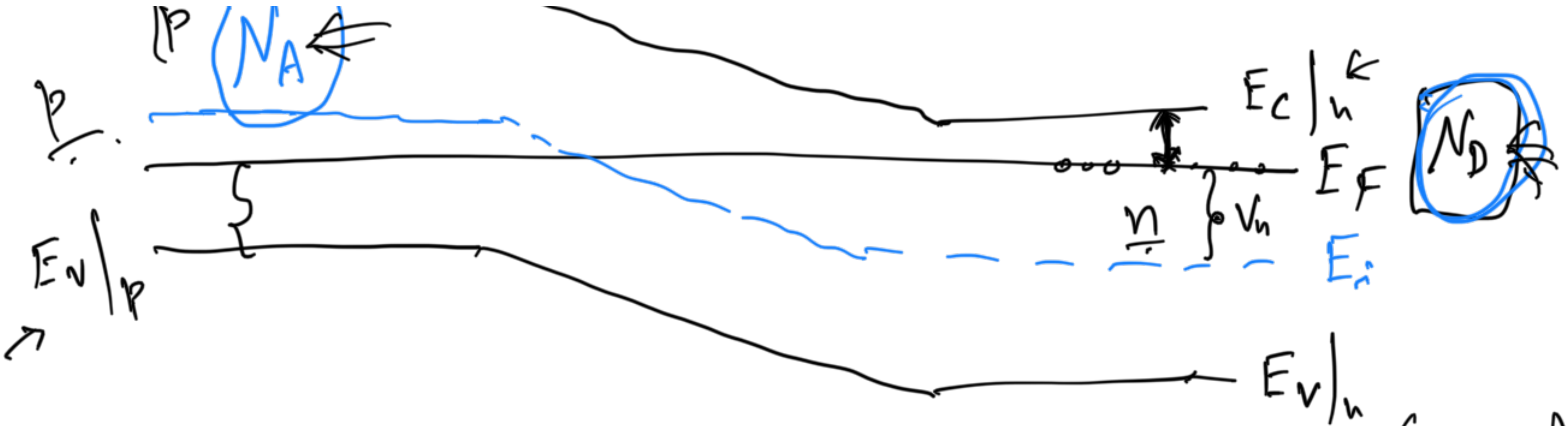
$$\boxed{qV = E}$$



① $T = 300$ K.

② $10^{15} \Rightarrow 10^{15}$





$$-q(V_n) = E_C|_n - E_F$$
$$= -KT \ln \frac{N_D}{n_i}.$$

$$V_n = \frac{KT}{q} \ln\left(\frac{N_D}{n_i}\right)$$

$$p = n_i \exp\left(\frac{E_i - E_F}{KT}\right)$$
$$N_A = n_i \exp\left(\frac{E_i - E_F}{KT}\right)$$
$$n = n_i \exp\left(\frac{E_F - E_i}{KT}\right)$$
$$N_D = n_i \exp\left(\frac{E_F - E_i}{KT}\right)$$
$$(E_F - E_i) = KT \ln\left(\frac{N_D}{n_i}\right)$$

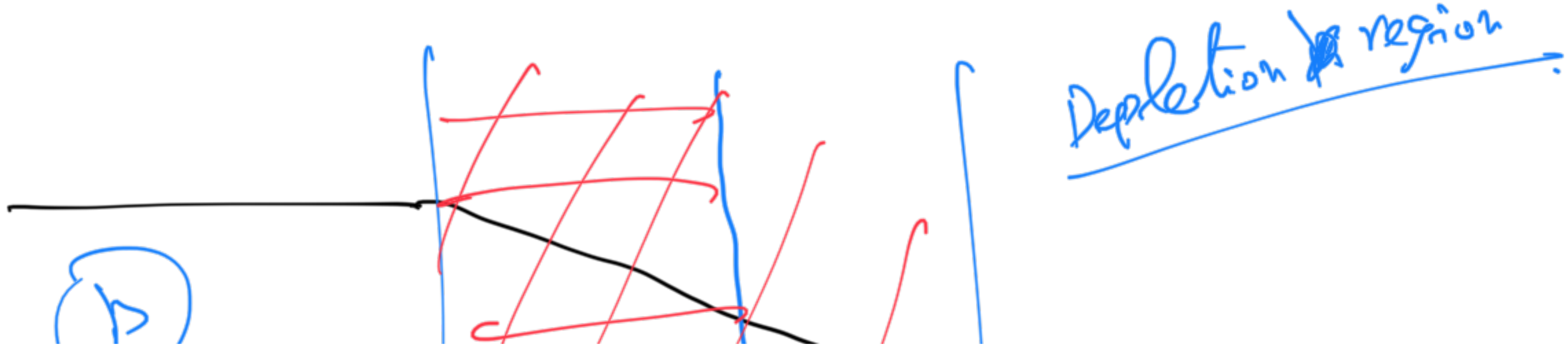
$$q(V_p) = E_F - E_V|_p$$

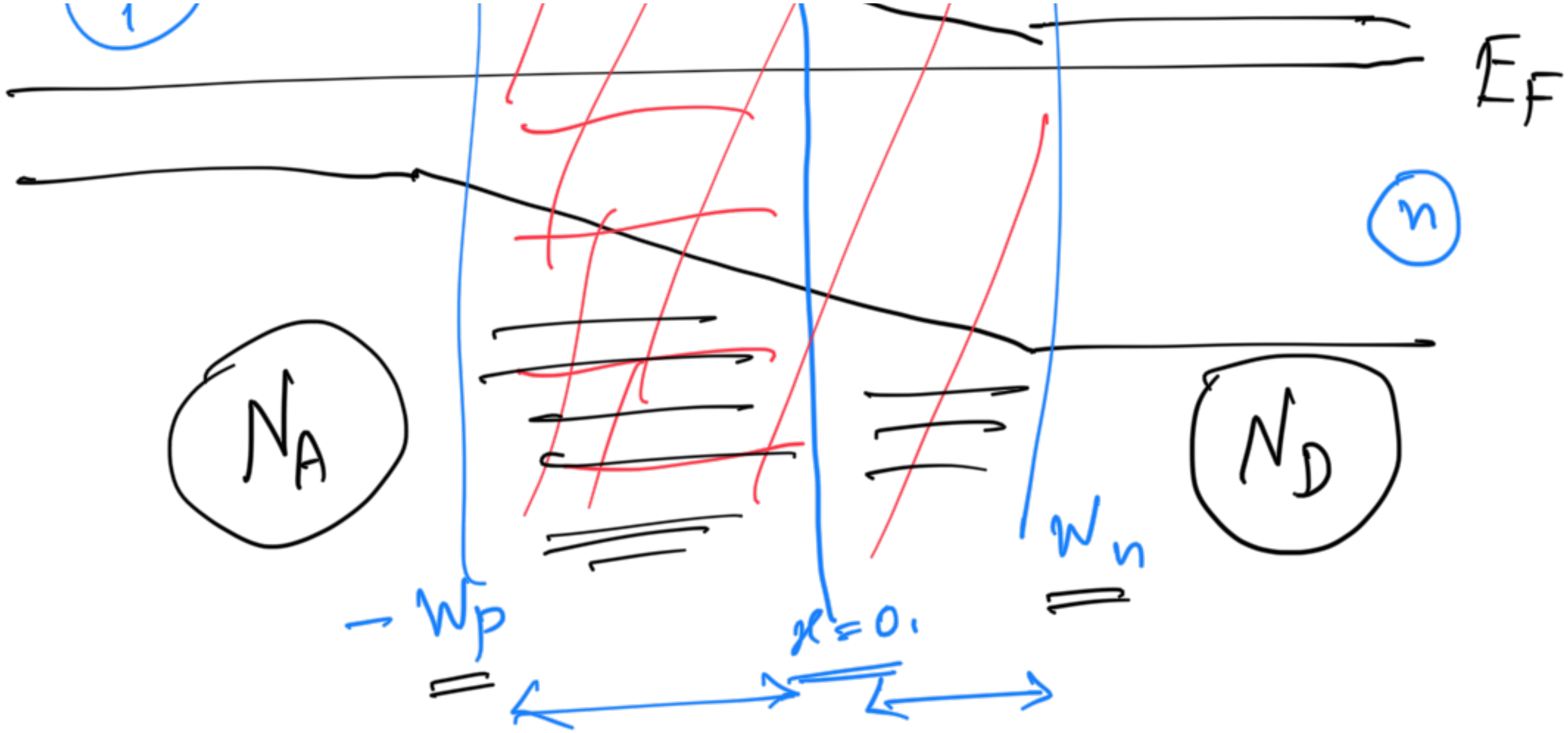
$$= \frac{KT}{q} \ln\left(\frac{N_A}{n_i}\right)$$

$$V_{bi} = V_n + V_p = \frac{KT}{q} \ln\left(\frac{N_D}{n_i}\right) + \frac{KT}{q} \ln\left(\frac{N_A}{n_i}\right)$$

$$\boxed{V_{bi} = \frac{KT}{q} \ln\left(\frac{\overset{n}{N_D}\,\overset{p}{N_A}}{n_i^2}\right)}$$

Si

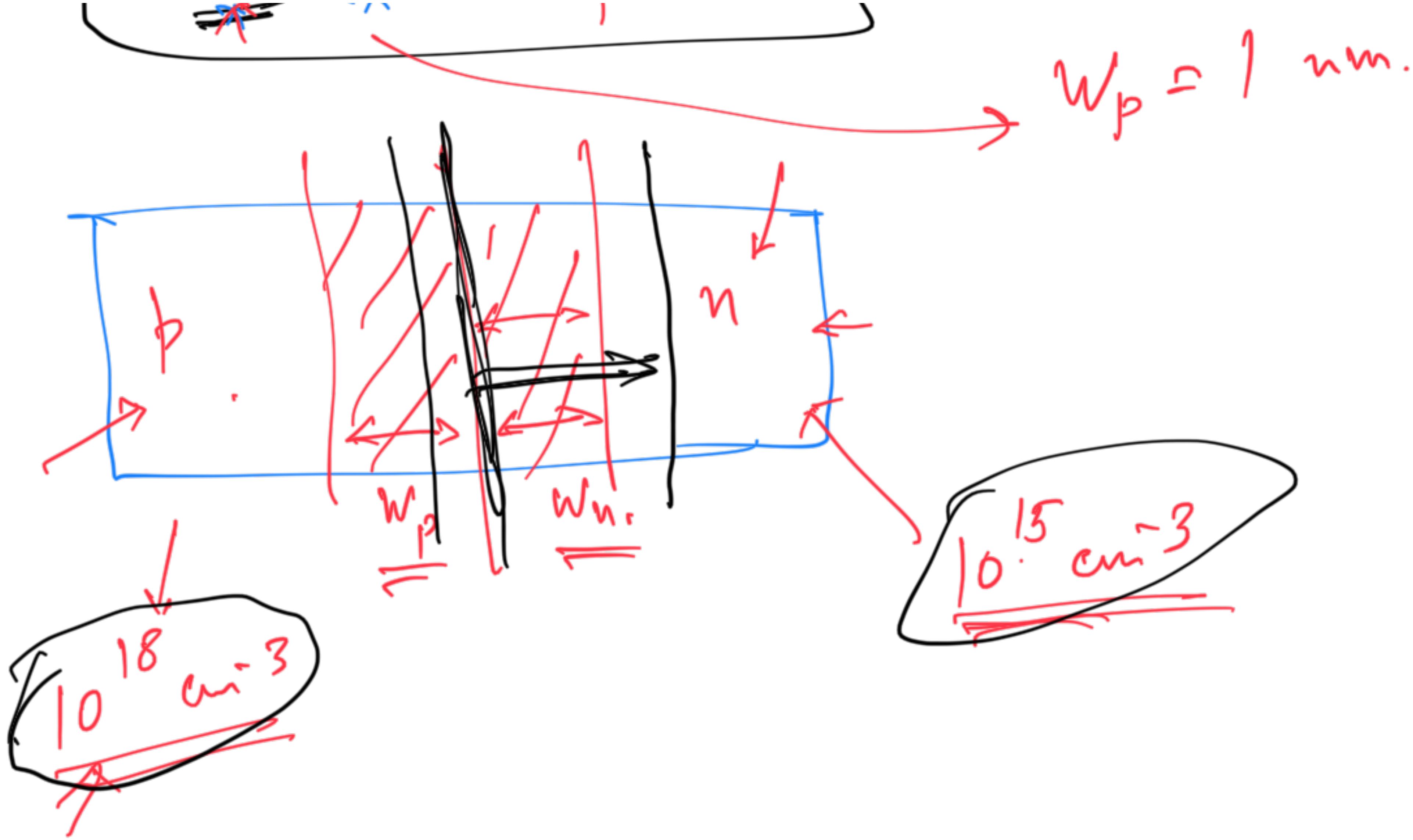




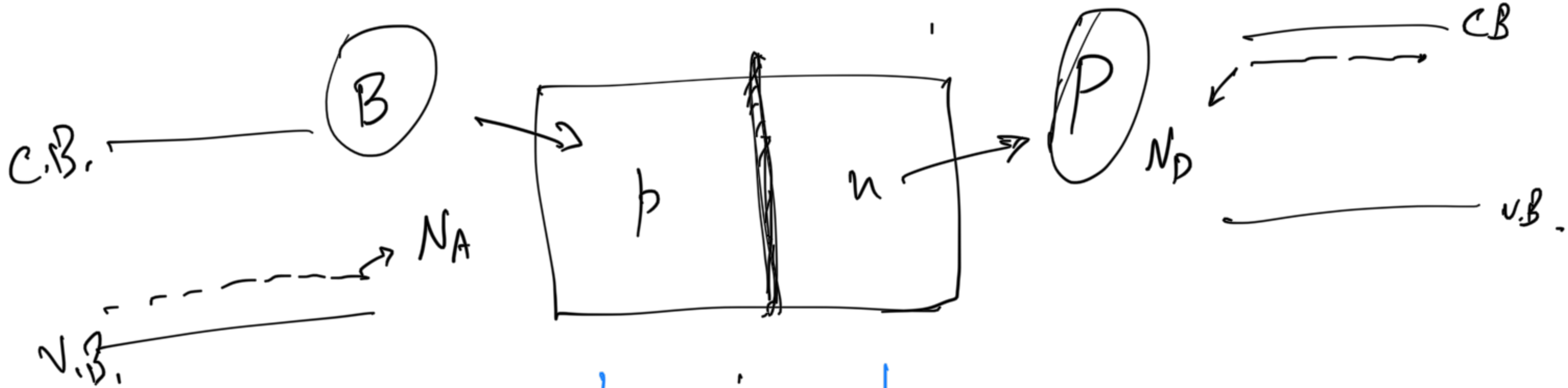
Under eq^m $\Rightarrow$ Areal charge density $\Rightarrow$ Same in both side of p-n junction

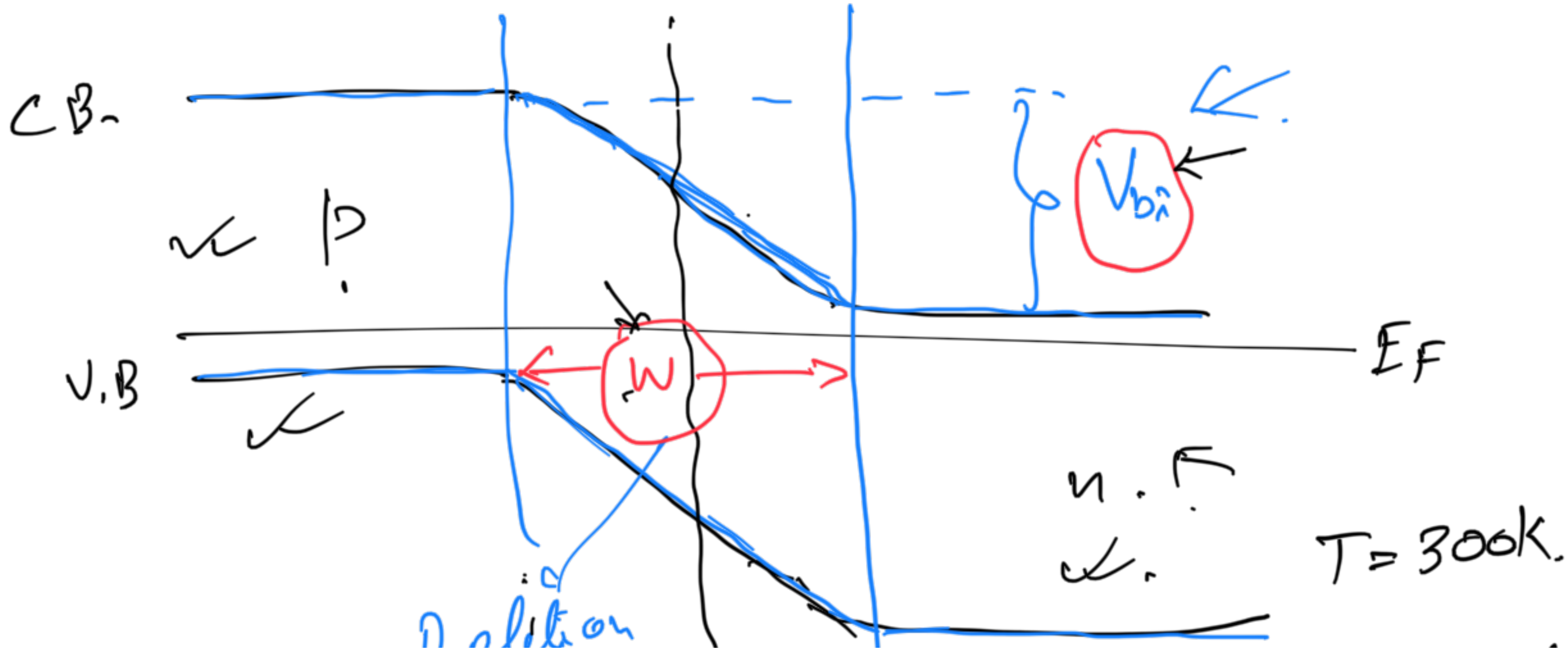
$N_A W_p \Rightarrow$ Areal charge density $\Rightarrow N_D W_n$.

$$\boxed{N_A W_p = N_D W_n} \rightarrow W_n \Rightarrow 1000 \text{ nm}.$$


$W_p = 1$ nm.
p
n
W_p
W_n
10^{18} cm^{-3}
10^{15} cm^{-3}

p-n junction - bias

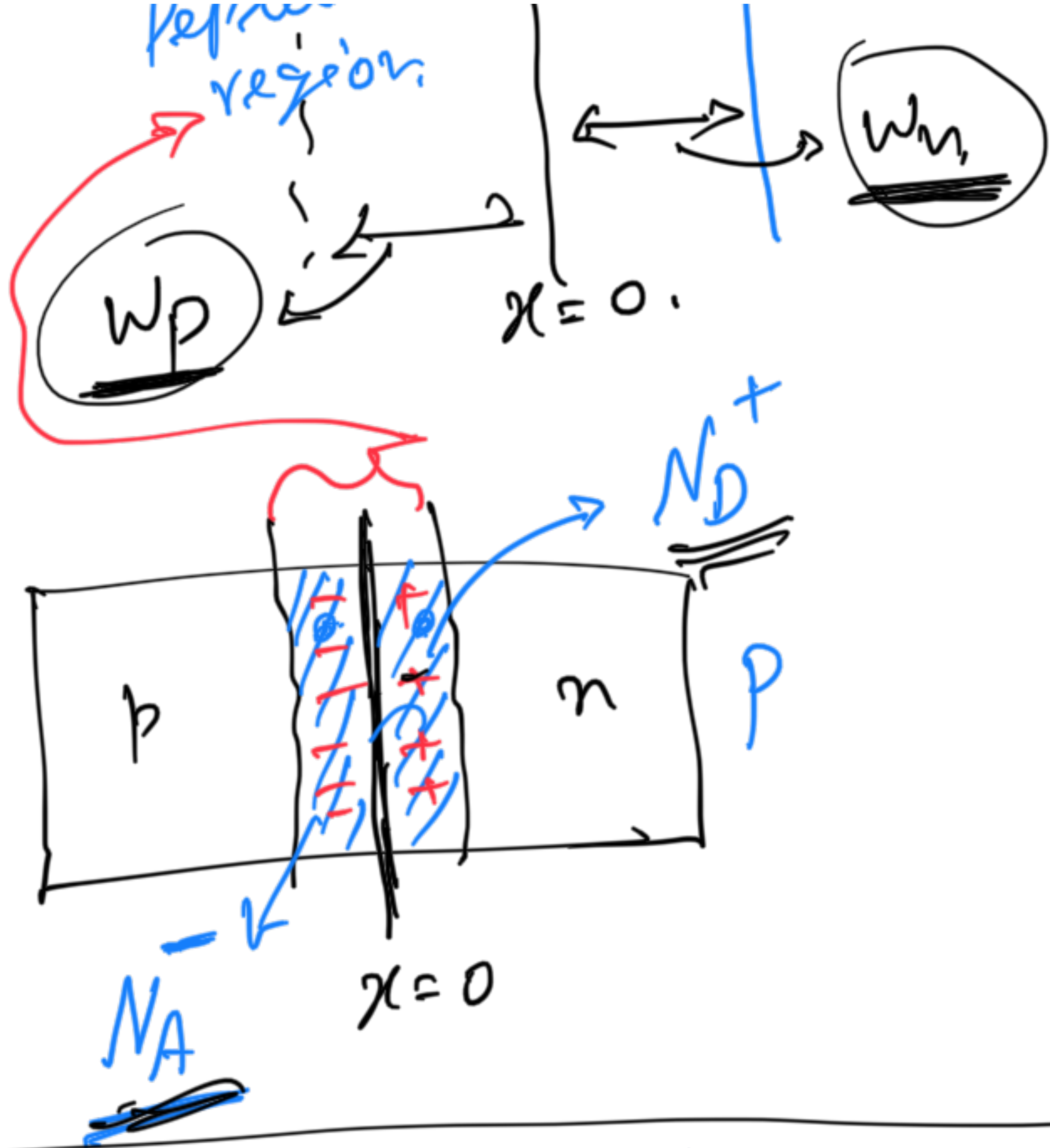




$KT = 0.026\ eV$

$\Rightarrow 26\ meV.$

$10^{18} \quad 10^{18}$



$$\boxed{W = \sqrt{\frac{2\epsilon_0 \epsilon_{Si}}{q} V_{bi}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)}}$$

$N_A / N_D.$

$\Rightarrow 10^{15}$

10^{18}

Total depletion

built-in potential of p-n junction.

width.

$\epsilon_0 = 8.854 \times 10^{-14}$ F/cm ← cgs.

$= 8.854 \times 10^{-12}$ F/m → S.I.

ϵ_{Si} = relative permittivity of Si

$= 11.9$

q = charge $= 1.6 \times 10^{-19}$ C

$$\boxed{V_{bi} = \frac{KT}{q} \ln\left(\frac{N_A N_D}{n_i^2}\right)}.$$

$n_i \Rightarrow 1.4 \times 10^{10}\ cm^{-3}$

$T = 300K$.

$KT = 26$ meV.

$W_n N_D = W_p N_A$ → $W_p = \dfrac{W_n N_D}{N_A}$

$$W = W_n + W_p$$

$$W_n = \frac{N_A W_p}{N_D}$$

$$= W_n + \frac{W_n N_D}{N_A}$$

$$\boxed{W = W_n \left[1 + \frac{N_D}{N_A}\right]} \longrightarrow \frac{N_A + N_D}{N_A}$$

$$\boxed{W_n = \frac{W N_A}{N_A + N_D}}, \quad \boxed{W_p = \frac{W \cdot N_D}{N_A + N_D}}$$

What is the effect of doping ??

$10^{18} \longrightarrow 10^{15}$

10^{15}

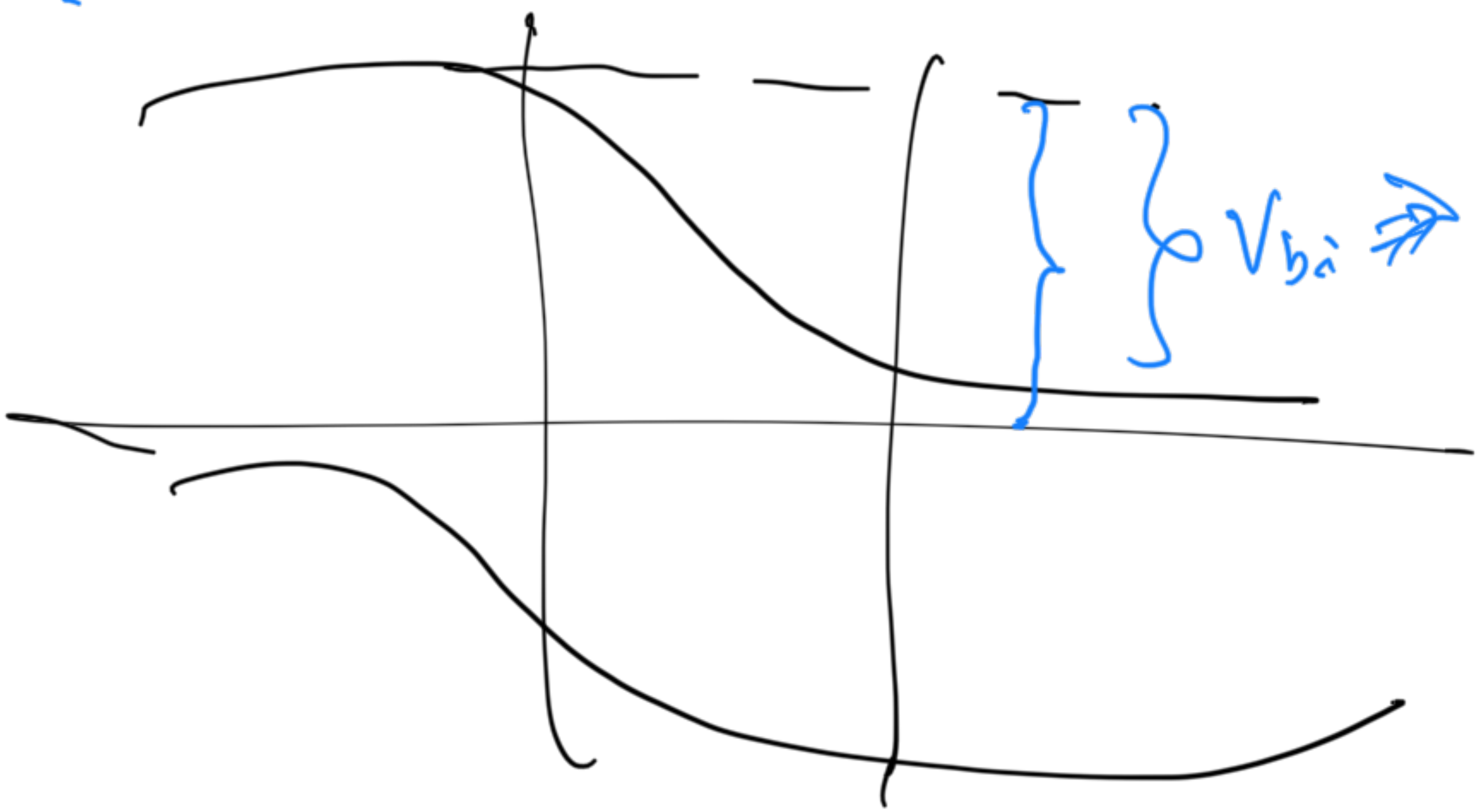
10^{10}

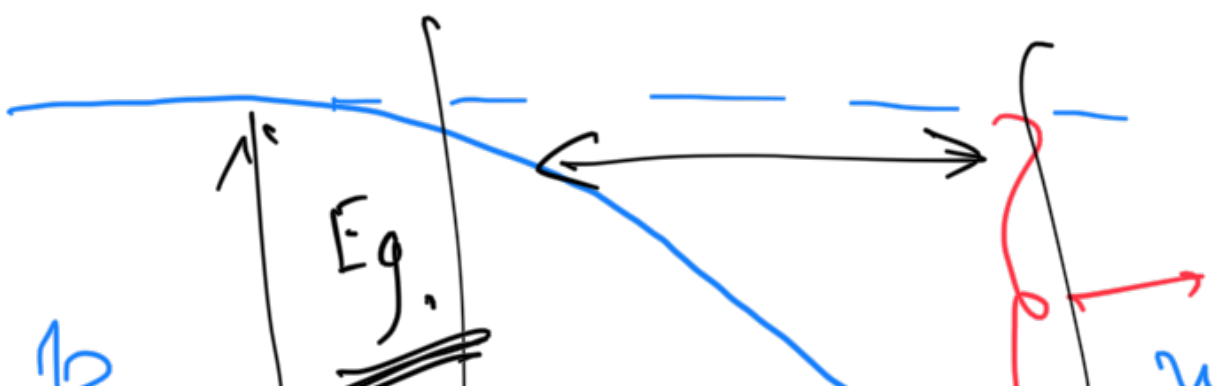
$n_i \to 10^{15}$

$e \to 10^{10}$

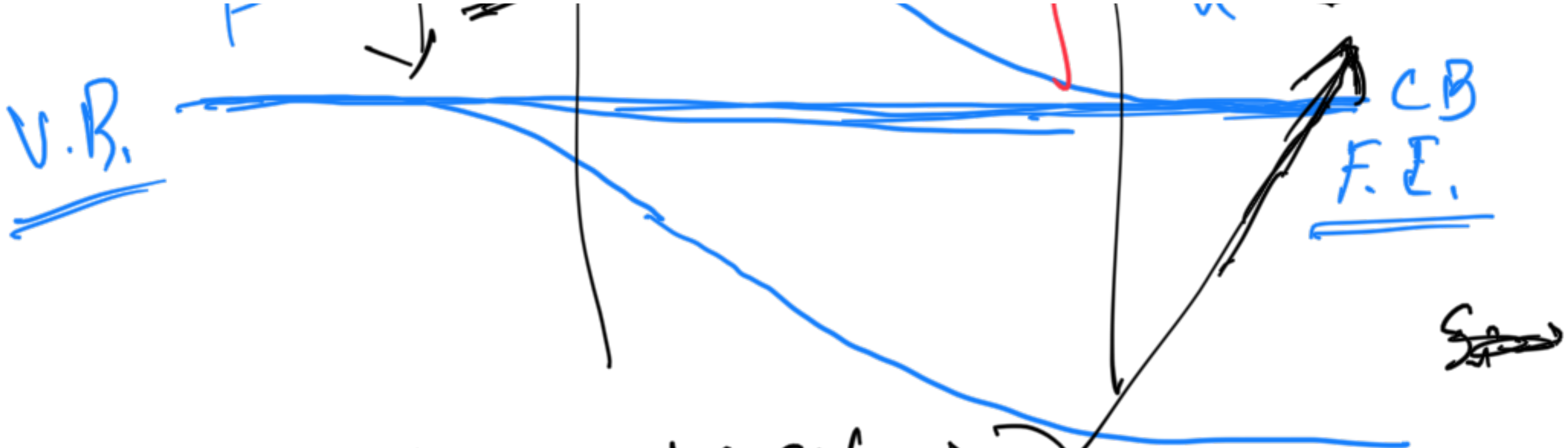
$$10^{15} > N_A \text{ or } N_D > 10^{18}$$

$$N_A \text{ or } N_D \to 10^{15} \longrightarrow V_{bi} \Rightarrow$$



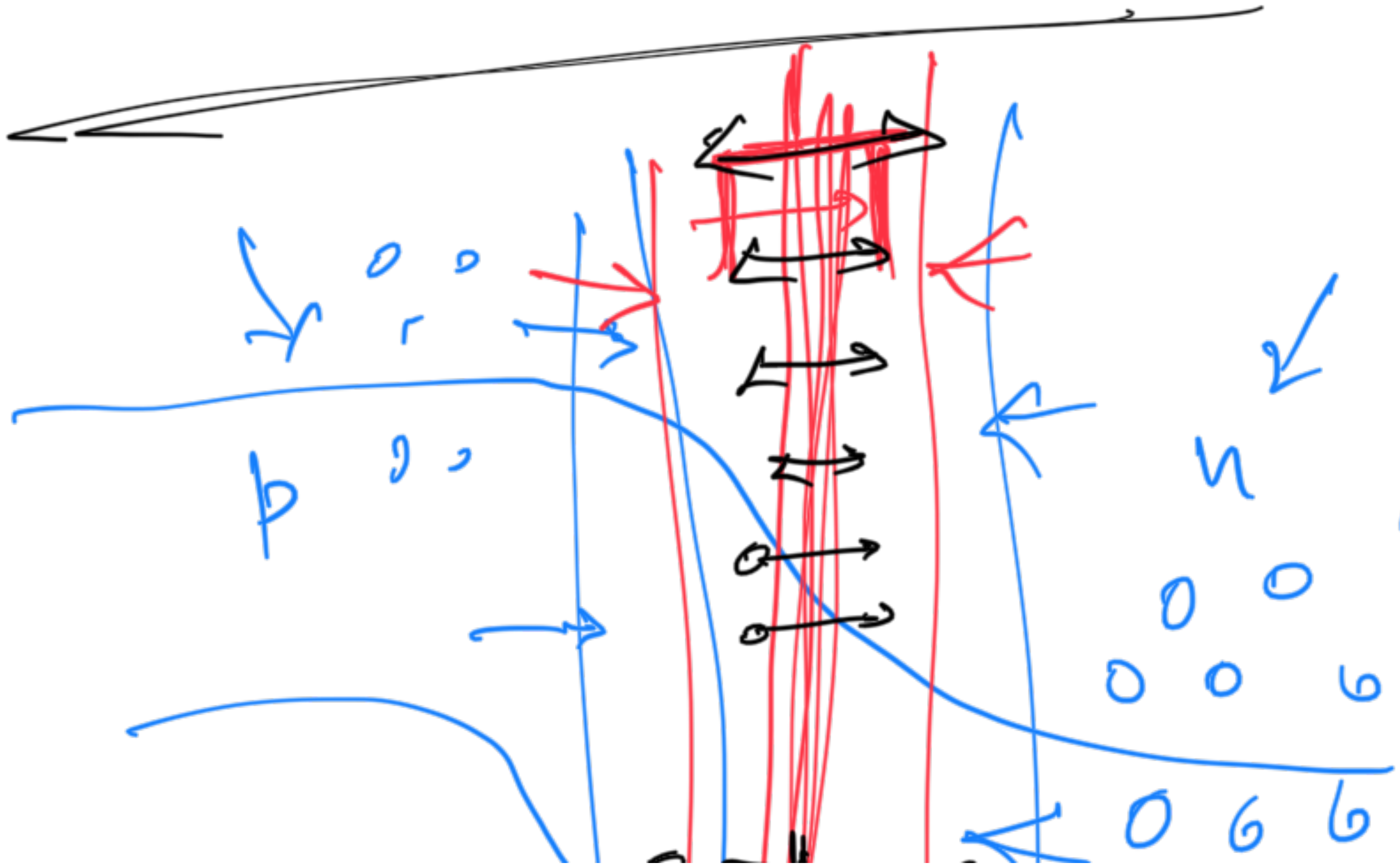


$$V_{bi}\big|_{max} = V_{F.E.}$$

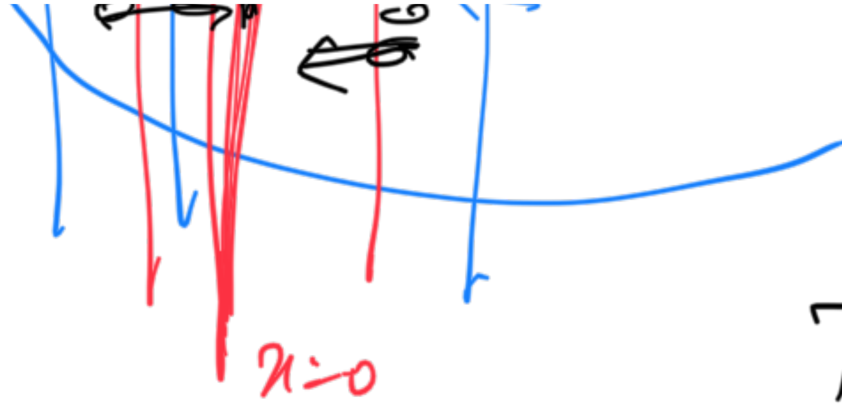


$E_g \Rightarrow$

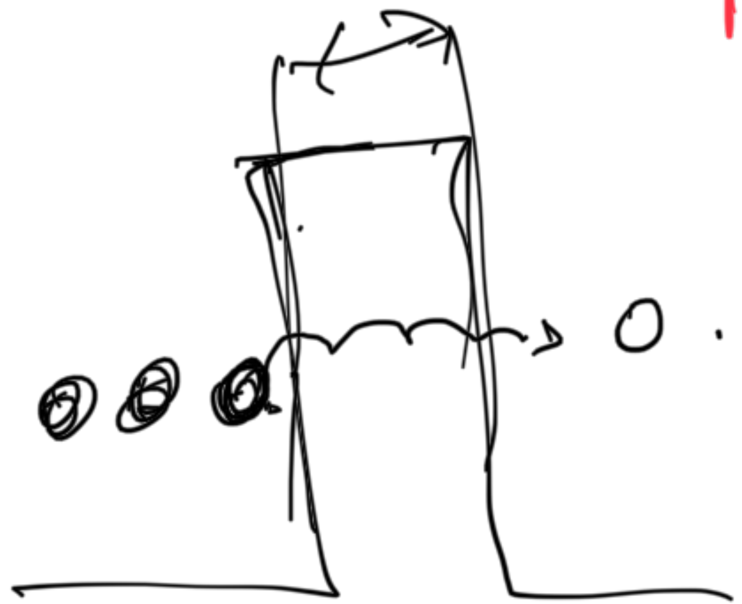
- $Si \rightarrow 1.1$ eV.
- $Ge \rightarrow 0.7$ eV.
- $GaN \rightarrow 3.4$ eV.
- $GaAs \rightarrow 1.43$ eV.



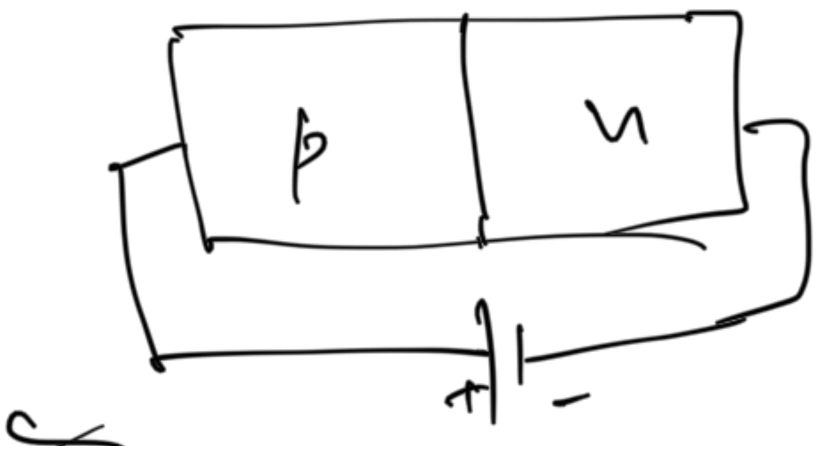
$10^{15} > 10^{18} > 10^{20}$

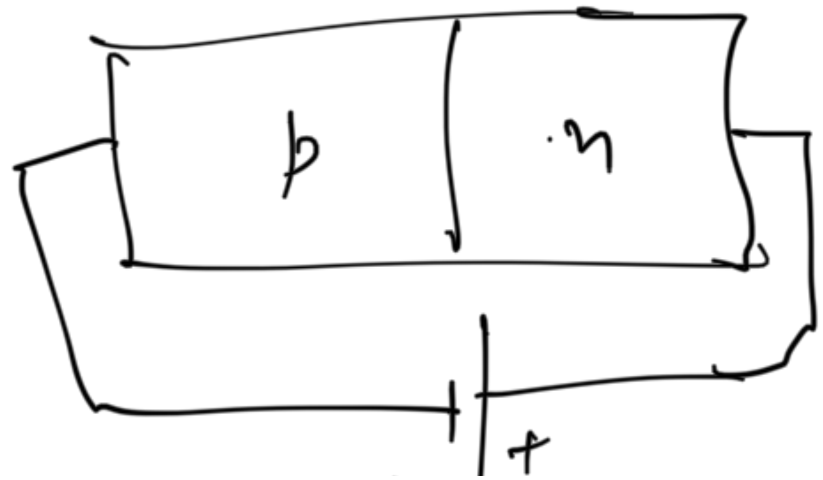


Tunneling diode.



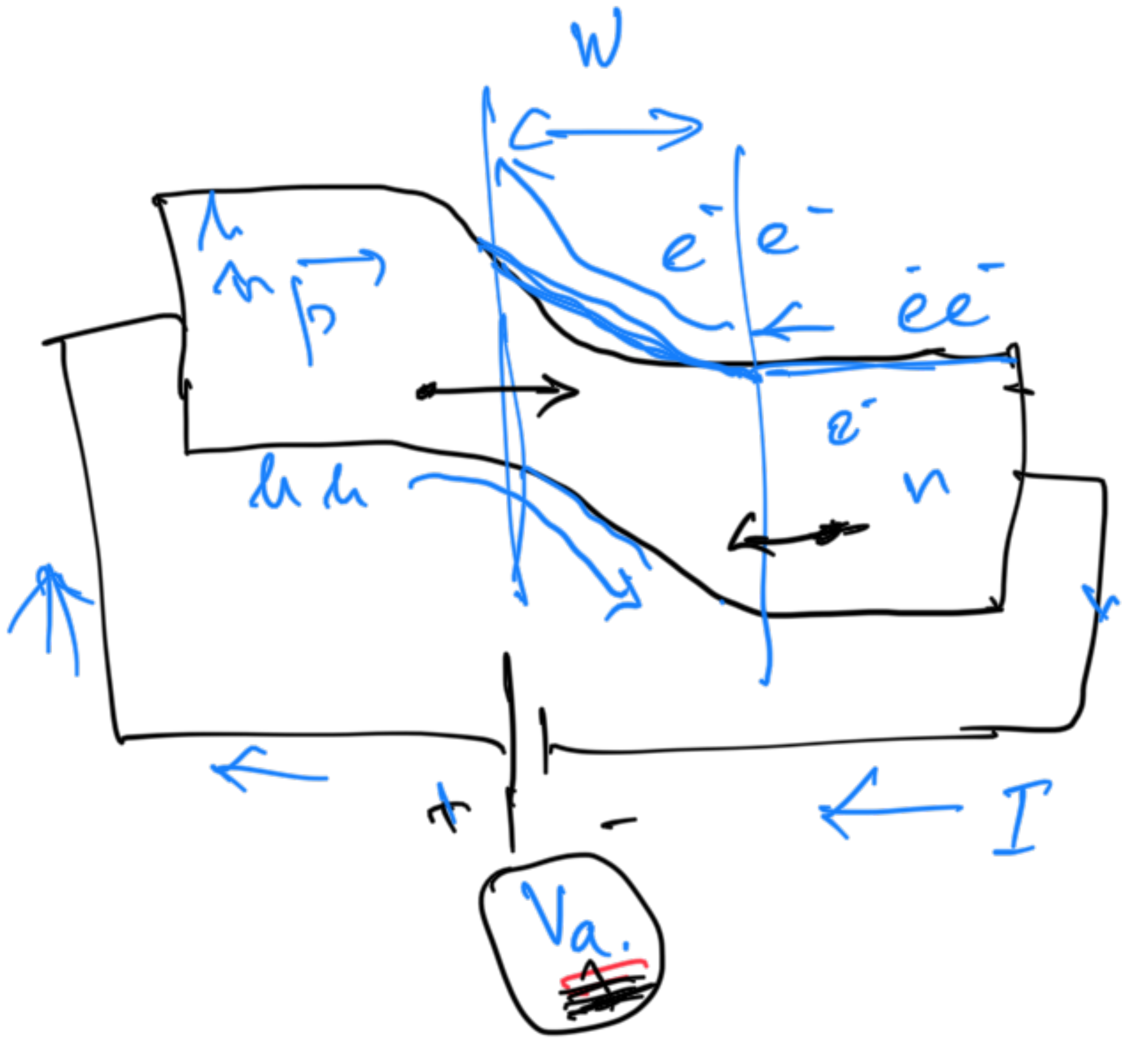
p-n junction under bias

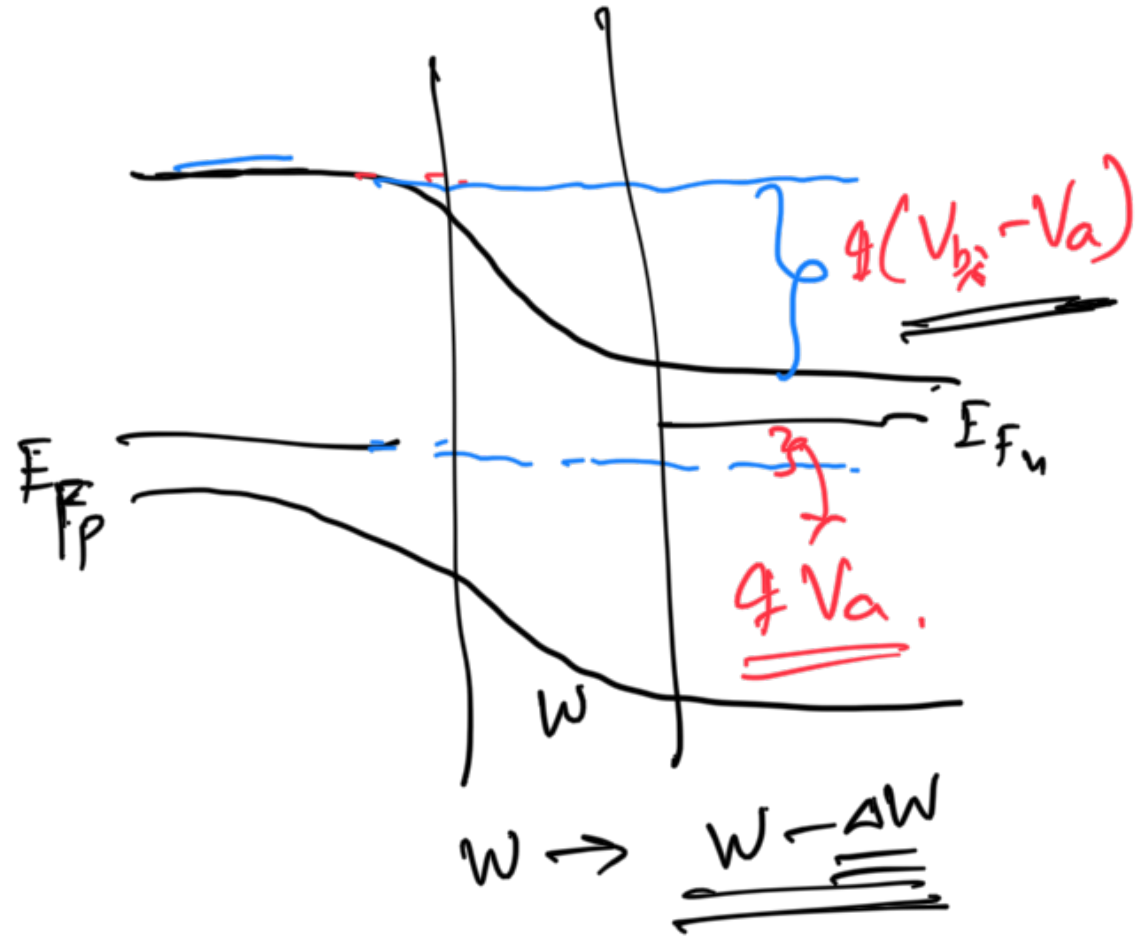




forward bias.

reverse bias.



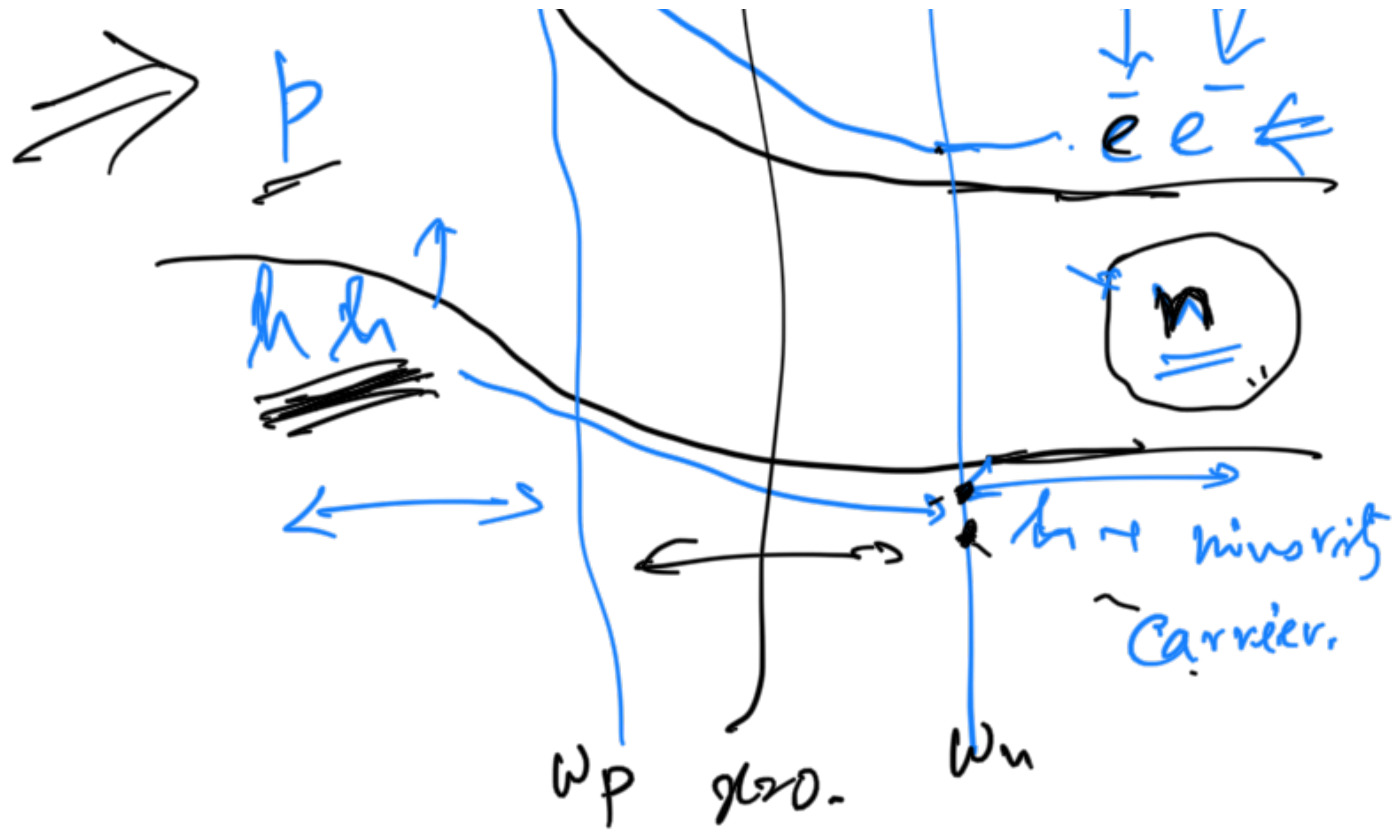


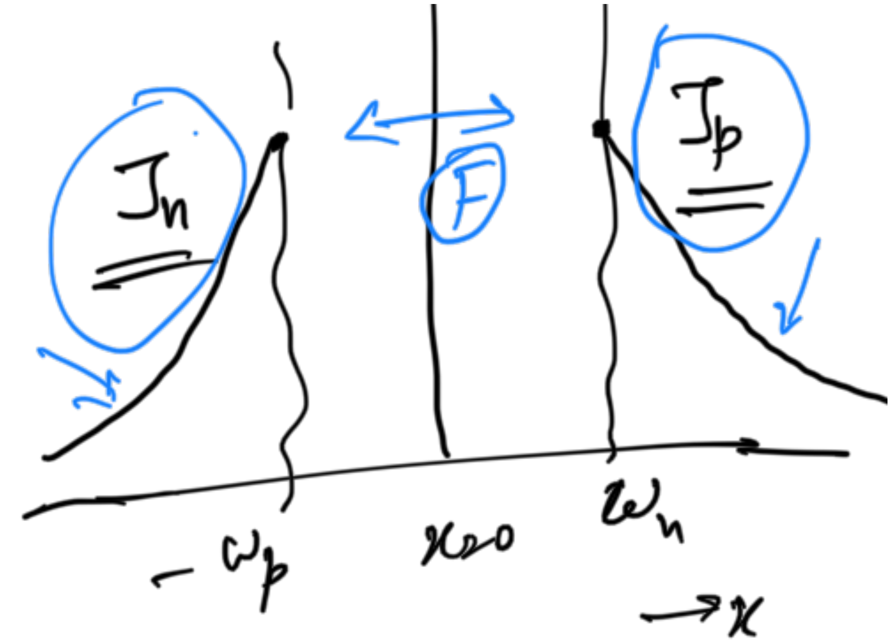
$V_{bi} = 1\,V.$

$V_a = 0.6\,V.$

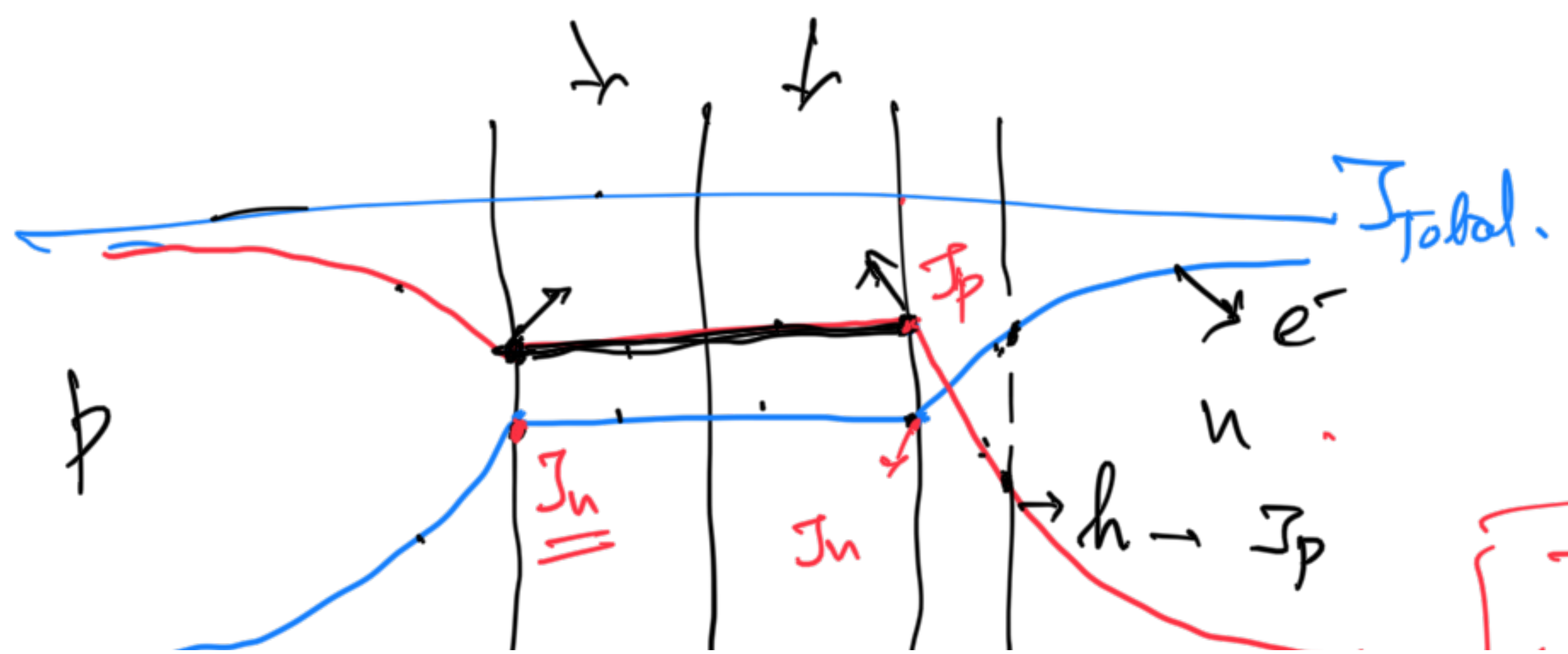
$\gg$

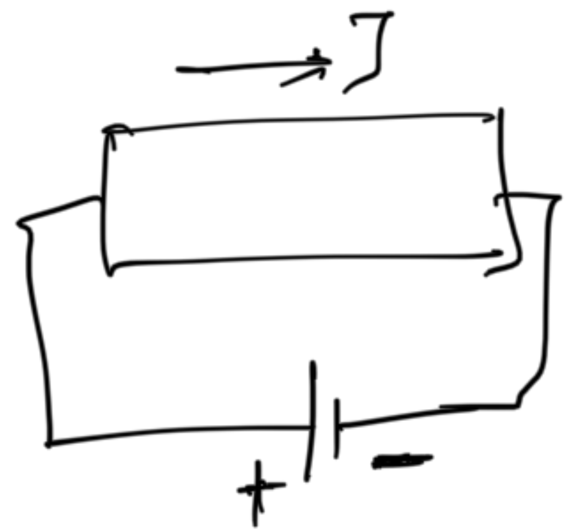
$V_{bi}\big|_{net} = 1 - 0.6 = 0.4\,V.$



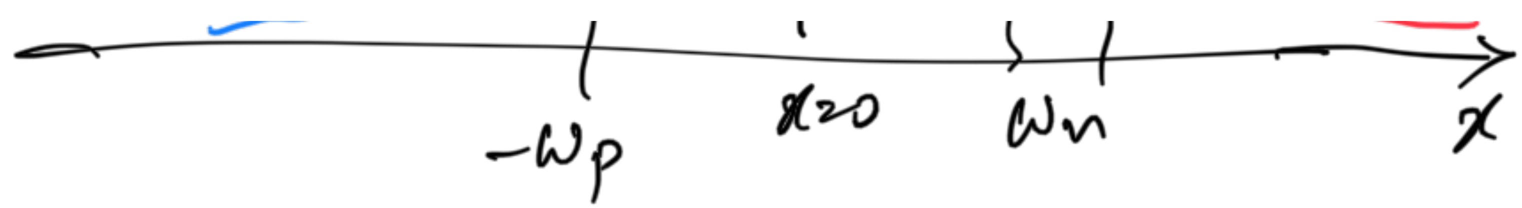


J_n & J_p → diffusion current of the respective minority carriers.

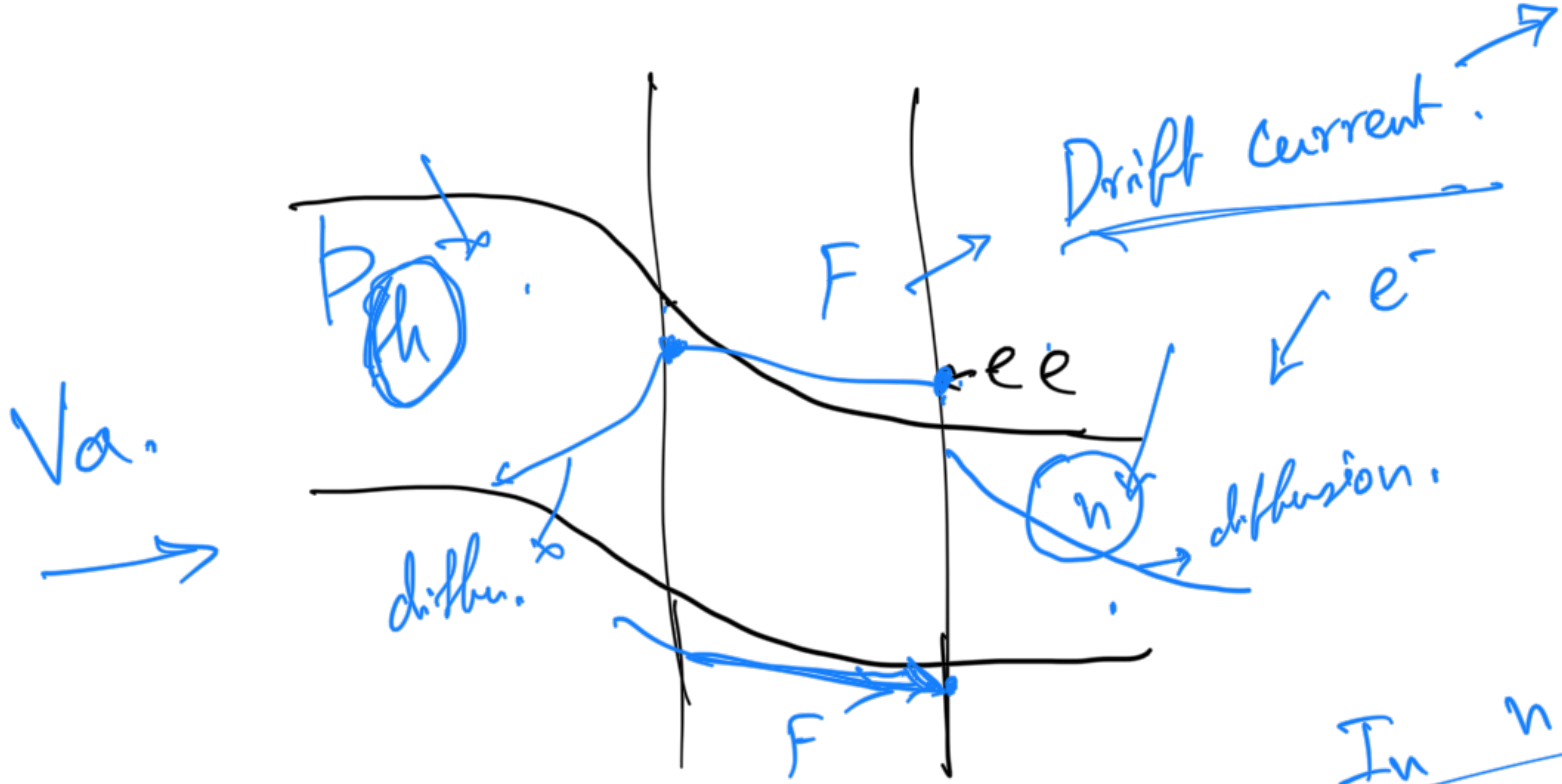




$$\boxed{J_{Total} = J_p + J_n}$$



Total



In n side →

majority → e^- → drift current

minority h → diffusion current

p side →

e^- → diffusion

drift.

$h \rightarrow$

$$\boxed{J_{Total} = J_p + J_n}$$

$h \swarrow$ $J_p \rightarrow$ minority carriers current in n side

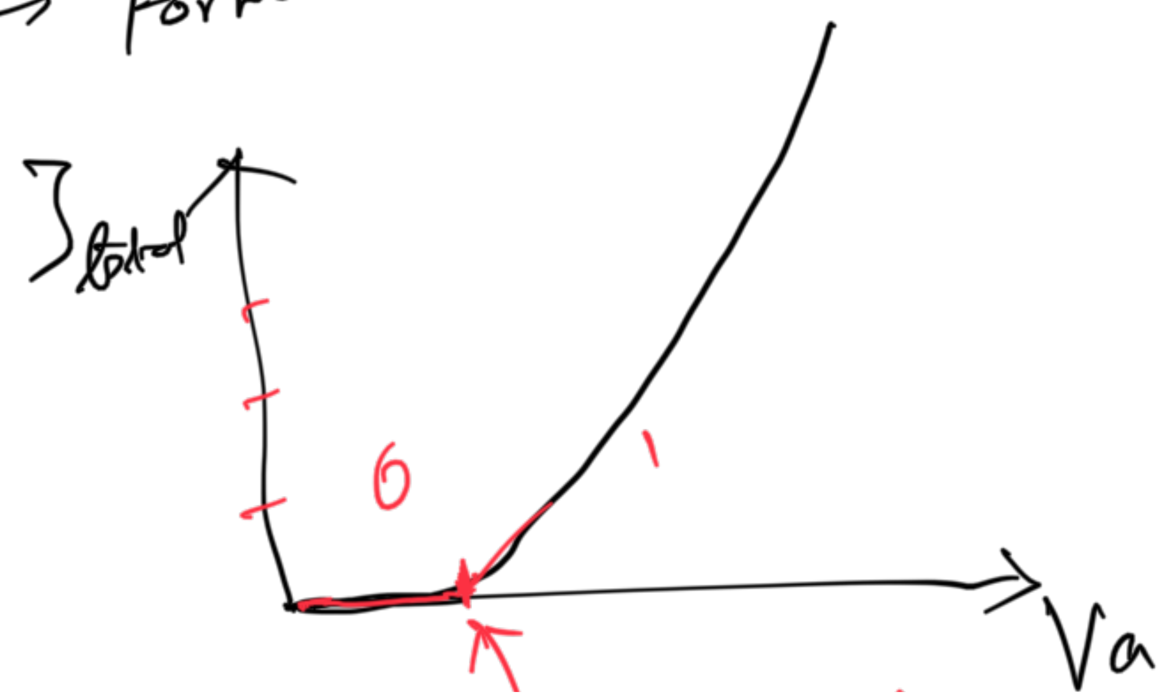
$J_n \rightarrow$ " in p side.

$\swarrow$ e^-

$$\boxed{J_{Total} = J_0\left(e^{\frac{qV_a}{KT}} - 1\right)}$$

Prefactor ← material specific parameter.

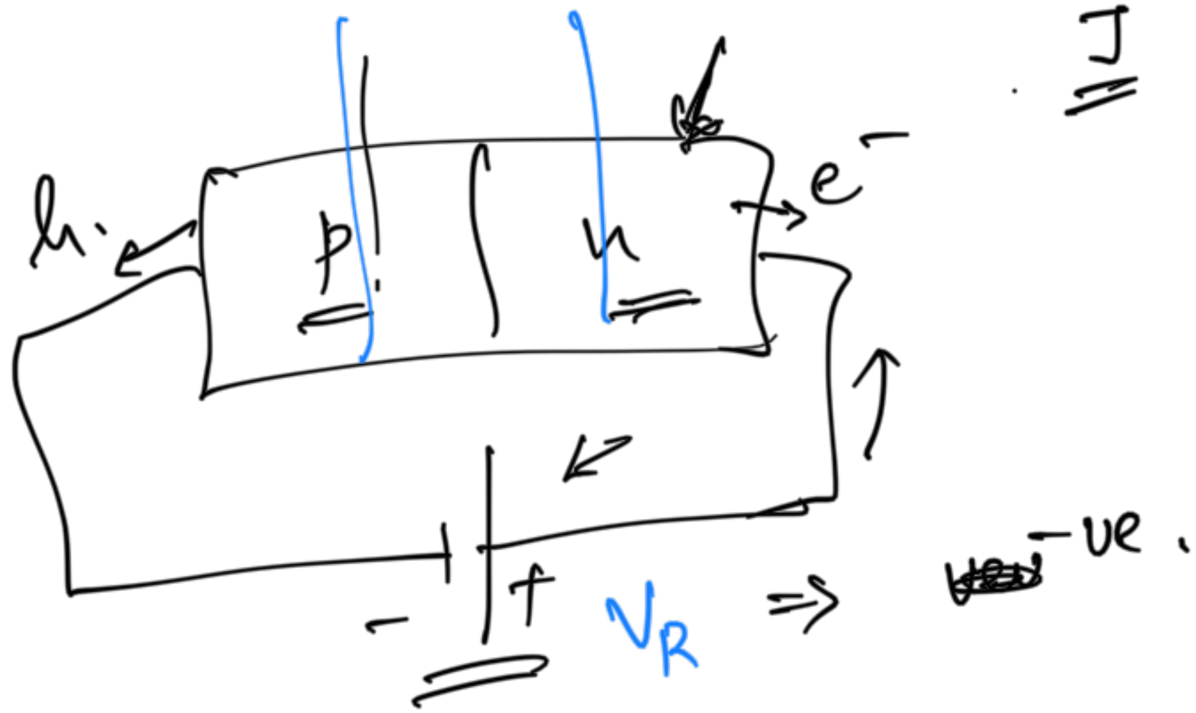
$V_a \rightarrow$ Forward bias voltage.



turn-on voltage.

$\approx qV_{bi} \rightarrow E_g \Rightarrow$ band gap.

Reverse bias.



$W \Rightarrow W + \Delta W$

$V_{bi} \Rightarrow V_{bi} + V_R.$

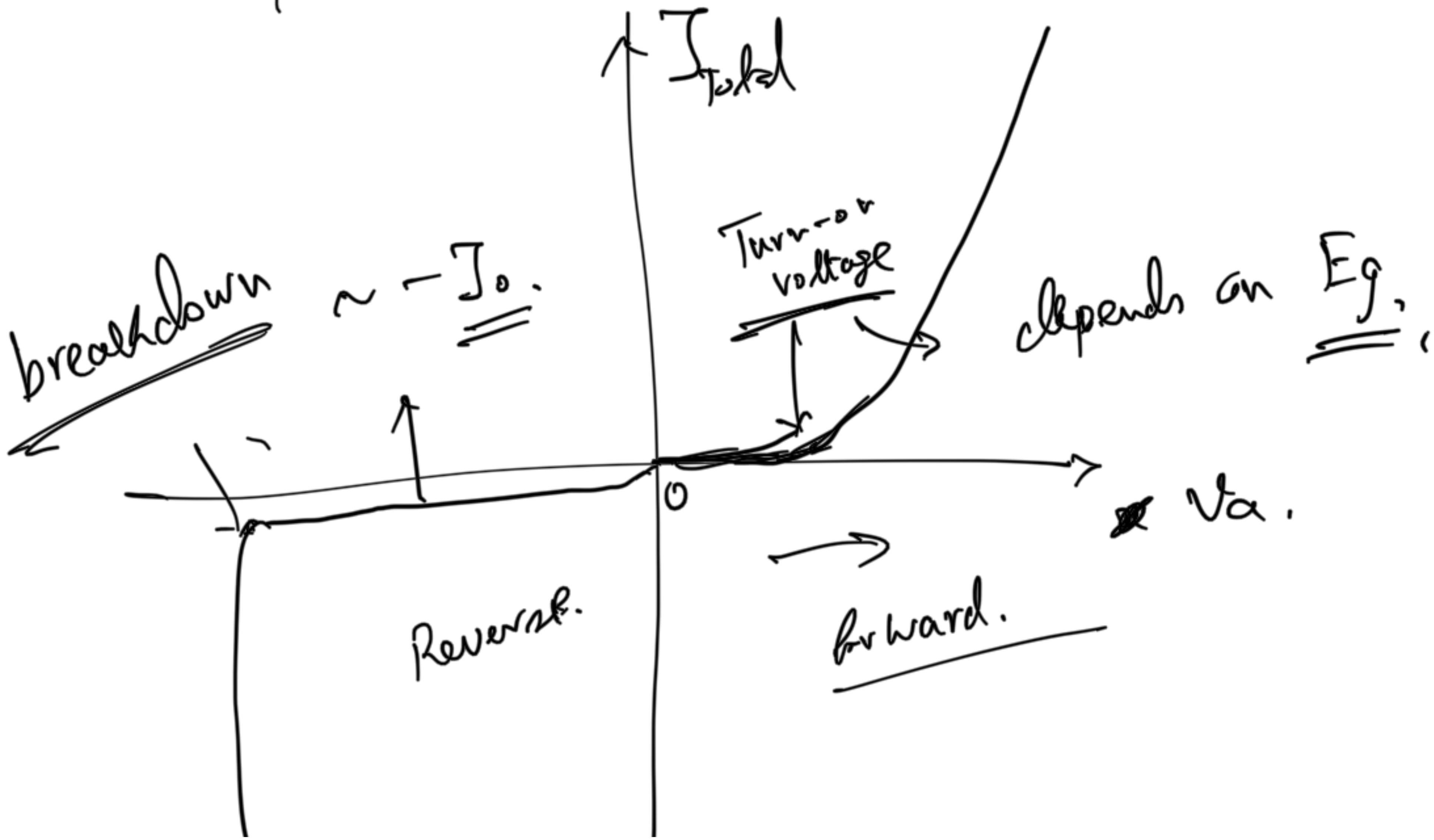
$$J_{Total} = J_0 \left[e^{\frac{qV_a}{kT}} - 1 \right]$$

$e^{(-)} \rightarrow$

very small quantity

Reverse bias $\rightarrow$ $V_a \longrightarrow -ve.$

$$I_{Total}\Big|_R = I_0(-1) \simeq -I_0.$$



PYL - 102 Manisha Thakurathi
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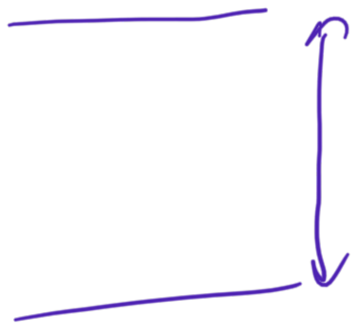
→ Dielectric Materials :- 3-4

→ Magnetic Materials :- 3-4

Dielectric materials



$E_g > 4eV$ Large Band gap

⇒ High resistivity

Dielectric :- Which resist electricity

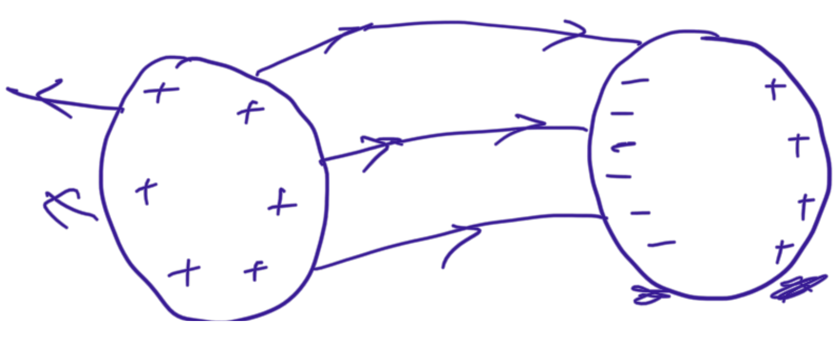
→ High Electric field
[To Behave like a semi-conductor or metal

Exa. :- Ceramic or Plastic

An electric insulator :- High Breakdown field

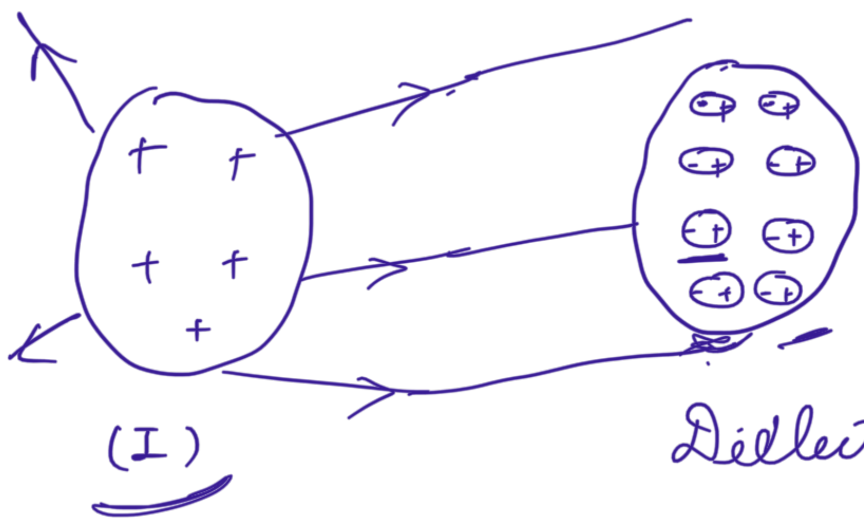
Properties of Dielectric :-

→



Charged Insulator (I)   Conductor (C)

Electrostatic Induction



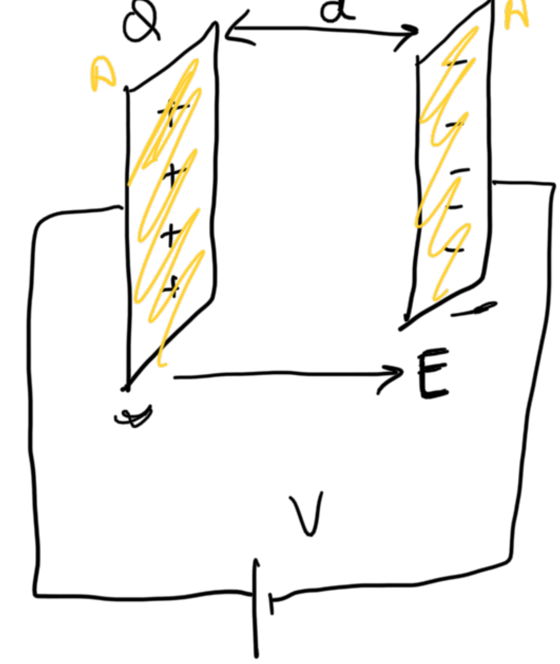
If one removes the charged insulator the induced dipole moments fade out because of the thermal energy.

Capacitance & Dielectric constant :

① → Parallel - plate capacitor : Vaccume

② → Parallel - ——— " : Dielectric

① : PPC with vaccume :



Capacitor is a device that stores electrical charge

Area : A

Charge Q creats a potential diff. V

$$Q \propto V$$

$$Q = \underbrace{C}_{\text{Capacitance}} V \qquad 1F = \frac{\text{Coulomb}}{\text{Volt}}$$

$$1F = C/V$$

The SI unit of capacitance is Farad

$\mu F \sim 10^{-6} F$ $\quad$ $nF \sim 10^{-9} F$

$$C = \frac{Q}{V} \quad \text{——} \ (1)$$

Q :- surface charge density σ_s

$$\sigma_s = \frac{Q}{A} \quad \text{charge per unit area}$$

$$Q = \sigma_s A \quad \text{——} \ (2)$$

V :- $\quad V = Ed \quad \text{——} \ (3)$ $\quad \overset{d}{\longleftrightarrow}$ $\quad \vec{E}$

(1), (2) & (3) :-

$$\boxed{C = \frac{Q}{V} = \frac{\sigma_s A}{Ed}} \quad \text{——} \ (4)$$

Geometrical factors

Dielectric permittivity (ε)

$$\varepsilon = \frac{\sigma_s}{E} \quad \text{--- (5)}$$

Eq^n (4) becomes :-

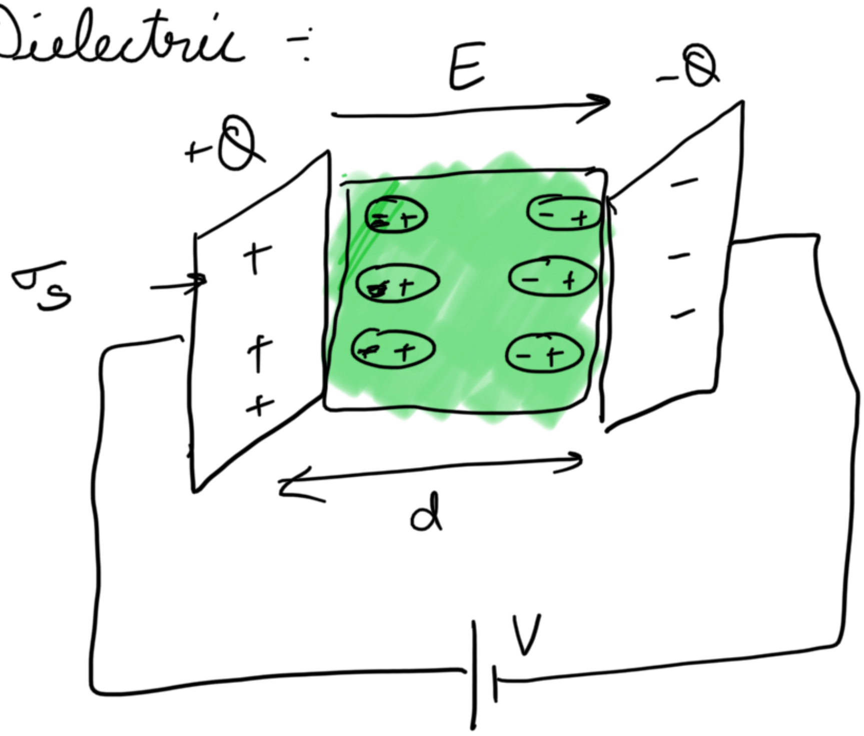
$$\boxed{C = \varepsilon \frac{A}{d}}$$

Vacuume :- $\boxed{C_0 = \varepsilon_0 \frac{A}{d}}$ $\qquad \varepsilon_0 = \frac{\sigma_{s0}}{E_0}$

C_0 :- capacitance of a capacitor filled with a vacuum

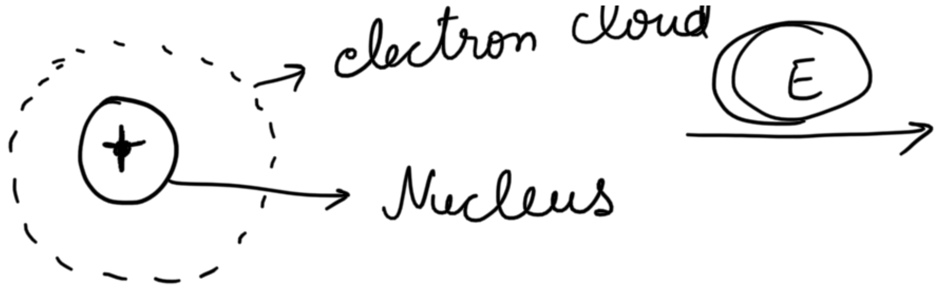
ε_0 :- Permittivity of vacuum or free space

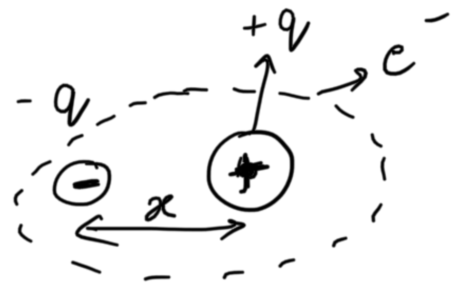
(2) Parallel plate capacitor filled with Dielectric :-



Ideal Dielectrics :- no energy loss

Polarization :-



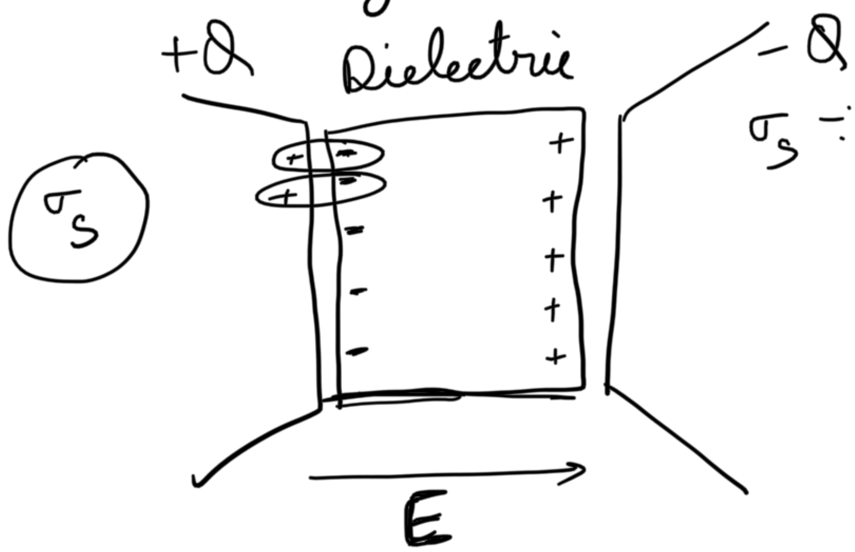


Dipole moment

$$\boxed{\mu = q \times x}$$

The SI unit of μ :- Cm   Debye (D)

$$1 \text{ Debye} = 3.3356 \times 10^{-30} \text{ Cm}$$



σ_S :- Surface charge density
Plates

Reduced Surface charge density

$$= \sigma_S - \sigma_b$$

σ_b → Bound charge density

free Charge density gets reduced

⇓

Voltage across the plate is also reduced $\boxed{Q \propto V}$

$\Downarrow$

Electric field also is smaller compared to the vacuume case (E_0)

$$\boxed{E < E_0}$$

~~Def~~ Dielectric constant (K) / Relative dielectric permittivity (ϵ_r)

$$K = \epsilon_r = \frac{E_0}{E} \quad \text{— (6)}$$

E_0 → In vacuume

E → In the presence of dielectric

Vacuume → Dielectric

$Q \longrightarrow Q$

$$Q = C_0 V_0 = C V$$

$$\boxed{V = Ed}$$

$$V_0 = E_0 d$$

$$= C_0 E_0 = C E \quad \text{— (7)}$$

From (6) & (7) :-

$$R = \epsilon_r = \frac{E_0}{E} = \frac{C}{C_0} = \frac{\epsilon A/d}{\epsilon_0 \frac{A}{d}}$$

ϵ :- Dielectric permittivity

ϵ_0 :- Permittivity of the vacuume

$$\boxed{R = \epsilon_r = \frac{\epsilon}{\epsilon_0}} \quad \text{— (8)}$$

Definition :- Ratio of the capacitor filled with a dielectric to that of an identical capacitor with a vacuum.

Dimensionless -: K

Si -: 11 $\qquad$ Al_2O_3 -: 9.9

Air = 1

Physically K tells us -: the ability of different material to store charge

$$C = \epsilon \frac{A}{d} \qquad \epsilon = \epsilon_0 K$$

$$\boxed{C = \epsilon_0 K \frac{A}{d}}$$

Easily polarized

$\Downarrow$

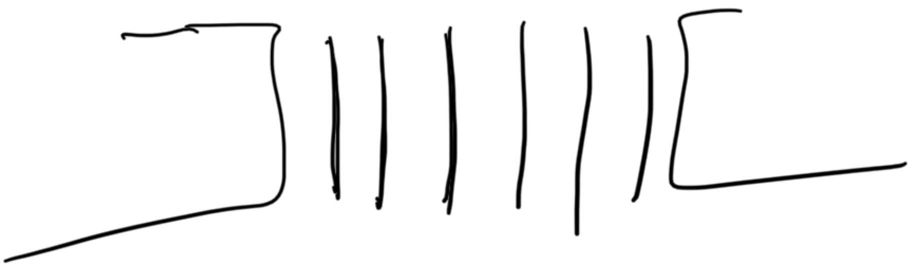
Influenced by E easily

$\Downarrow$

K will be higher

Goal

→ Minimize the overall size of the capacitor while enhancing the total capacitance



$$C = C_1 + C_2 + \cdots$$

Volumetric efficiency (VE)

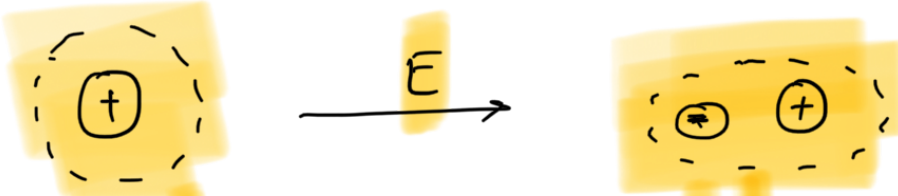
Each singl layer has an area A & thickness d

$$\boxed{VE = \frac{\epsilon_0 K \frac{A}{d}}{A d}}$$

Lec. 2

Dielectric Materials

Recap :-



$Q \propto V \Rightarrow Q = CV$

C ↓ Capacitance

$C = \dfrac{\varepsilon A}{d}$

ε ↓ Permittivity

$R = \epsilon_r = \dfrac{C}{C_0} = \dfrac{\varepsilon}{\varepsilon_0}$

R ↓ Dielectric constant / Relative Permittivity

Volumetric efficiency (VD)

Dielectric Polarization :- (P)

σ_s :- Surface charge density

→ σ_b :- Bound charge density

$(\sigma_s - \sigma_b)$:- Effective free charge

→ Magnitude of σ_b

⇛ Stress (Cause) → Strain (Effect)

Related by Young's modulus

Electric field (Cause) → Polarization P (Effect)

Related by dielectric constant (R) ϵ_r

→ N - number of small dipoles

$\overleftrightarrow{x}$

(− +)

$-q_d$ q_d

dipole moment $= q_d x$

polarization of individual atom

P ÷ Total dipole moment per unit volume of the material

average of dipole moment $\langle q_d x \rangle$

$$P = \sigma_b = N \underbrace{\langle q_d x \rangle}_{\mu}$$

μ ÷ average dipole moment

$$\boxed{P = N\mu} \quad \text{——} \quad (1)$$

Lets define α as polarizability

$$\boxed{\mu = \alpha E} \quad \text{——} \quad (2)$$

$E \rightarrow$ local Electric field

SI Unit of α ÷ $C.m$ ÷ $[\mu]$

$\frac{V}{m}$ ÷ $[E]$

$$\alpha = C\,V^{-1}.m^2 \text{ or } F\,m^2$$

$$\boxed{\alpha_{volume} = \frac{10^6}{4\pi\epsilon_0} \times \alpha}$$

(cm^3 or $\mathring{A}^3$)

volume Polarizability

From (1) & (2)

$$\boxed{P = N\alpha E} \quad \text{——} \quad (3)$$

$P = N\alpha E$

Dielectric flux Density (D)

$$D = P + \epsilon_0 E \quad — (4)$$

Sources of D $\equiv$ Bound charge + Free charge density

$$D = \epsilon E \quad — (5) \text{ (Dielectric displacement)}$$

$$P = (\epsilon - \epsilon_0) E \quad — (5)$$

From Eq^n (3) & (5)

$$\alpha = \frac{(\epsilon - \epsilon_0)}{N}$$

$$\boxed{\underset{(K)}{\epsilon_r} = \frac{\epsilon}{\epsilon_0} = 1 + \frac{N\alpha}{\epsilon_0}} \quad — (6)$$

Importance of (6) :- Dielectric constant of the material to the polarizibility of the atom (α) & the concentration of atom (N)

Dielectric Susceptibility (χ_e)

$$\underset{\text{Effect}}{P} = \chi_e \epsilon_0 \underset{\text{Cause}}{E} \quad — (7)$$

magnetic Sus. : χ_m

Eq ⑤ : $P = (\epsilon - \epsilon_0) E$

$$\boxed{\chi_e = (R-1) = (\epsilon_r - 1)} \quad — ⑧$$

For <u>Vacuum</u> $R : 1$

$\Rightarrow \chi_e = 0$

χ_e describes : How much the material is susceptible / Polarizable

For more polarizable atoms, χ_e would be higher

$\boxed{P, \alpha, \chi_e}$ → Introduced

Local Electric field :

E :

For a solid or liquid (in the presence of E), the actual field experienced by the atoms / ions / molecules is different from the E (external field) is called as internal / local electric field (E_{local}).

More polar the material

$\Downarrow$

larger the local electric field

For a cubic-structured isotropic material / an amorphous material

the $\boxed{E_{local} = E + \frac{P}{3\epsilon_0}}$ — (9)

$\downarrow$

local field approximation

$P = N\alpha E_{local}$

$N\alpha = \frac{P}{E_{local}} = \frac{P}{E + \frac{P}{3\epsilon_0}}$ — (10)

$P = (\epsilon - \epsilon_0)E$ — (11)

Eq^n (10) & (11) :-

$$N\alpha = \frac{(\epsilon - \epsilon_0)E}{E - \frac{(\epsilon - \epsilon_0)E}{3\epsilon_0}}$$

$\frac{\epsilon}{\epsilon_0} = \epsilon_r$ = Dielectric contt.

$$\boxed{\frac{\epsilon_r - 1}{\epsilon_r + 2} = \frac{1}{3\epsilon_0} N\alpha} \quad \text{—} (12)$$

Macroscopic   Microscopic quantities

Eq^n (12) is known as Clausius-Mossotti Equation.

* Not valid for polar materials with permanent dipoles

N = The concentration of dipoles

= No. of molecules/volume

$$N = N_{AV} \times \frac{\rho}{M}$$

$N_{av} = 6.023 \times 10^{23}$ molecules/mole

ρ : Density (kg/m^3)

M : Molecular weight (kg/mol)

Eq^n (12) :

$$\boxed{\left(\frac{\epsilon_r - 1}{\epsilon_r + 2}\right)\frac{M}{\rho} = \frac{N_{AV} \times \alpha}{3\epsilon_0}}$$

$$\frac{N_{AV}\,\alpha}{3\epsilon_0} = P_m = \text{Molar Polarization}$$

$$\alpha = \alpha_e + \alpha_{ionic}$$

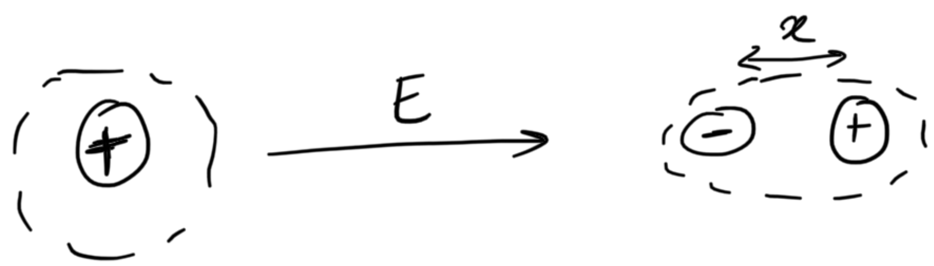
electronic   Ionic

Polarization Mechanisms :-

1. Electronic Polarization
2. Ionic, atomic or vibrational Polarization
3. Dipolar or orientational Polarization
4. Interfacial Polarization
5. Spontaneous ferroelectric Polarization

1. Electronic Polarization / optical

All materials have this



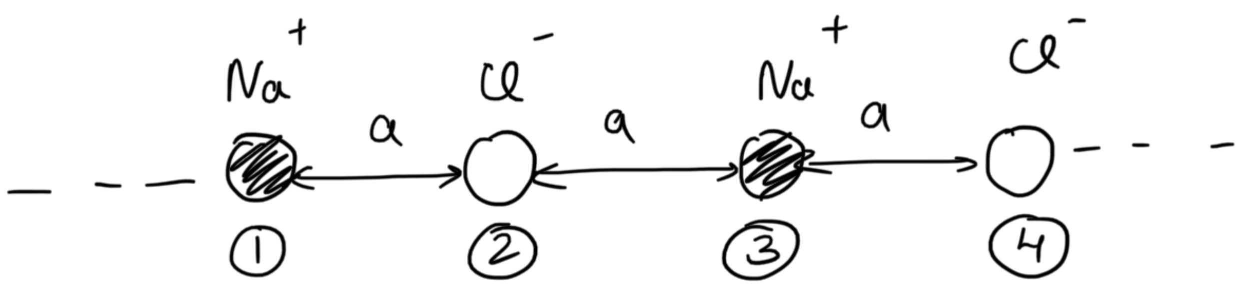
Time $\sim 10^{-14}$ Seconds

Fre. $\sim 10^{14}$ Hz (EM wave)

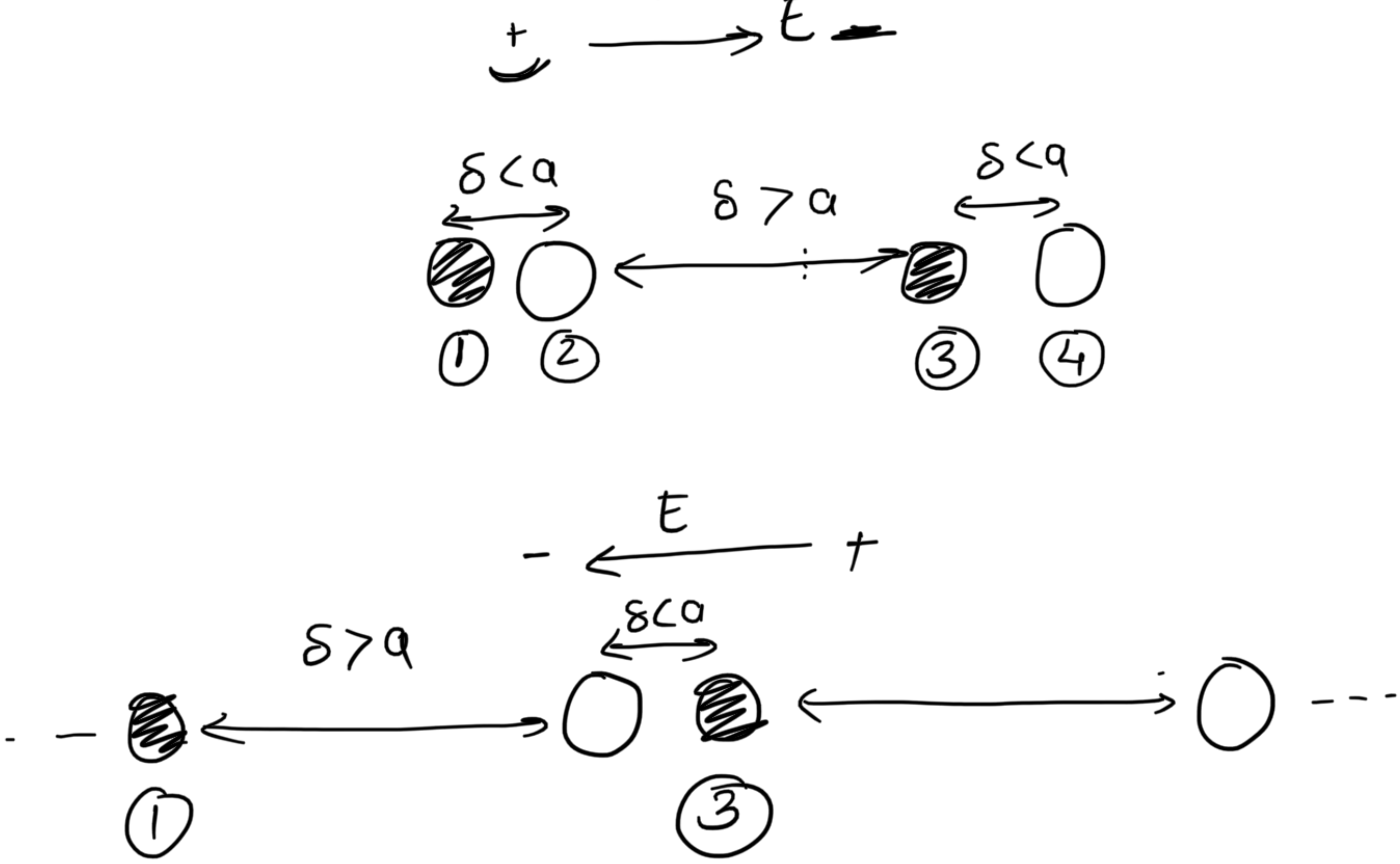
This field interacts with dielectric material & causes electronic polarization

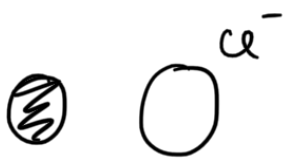
② Ionic, atomic or vibrational Polarization :-

Ⓐ



Ⓑ





→ Electronic

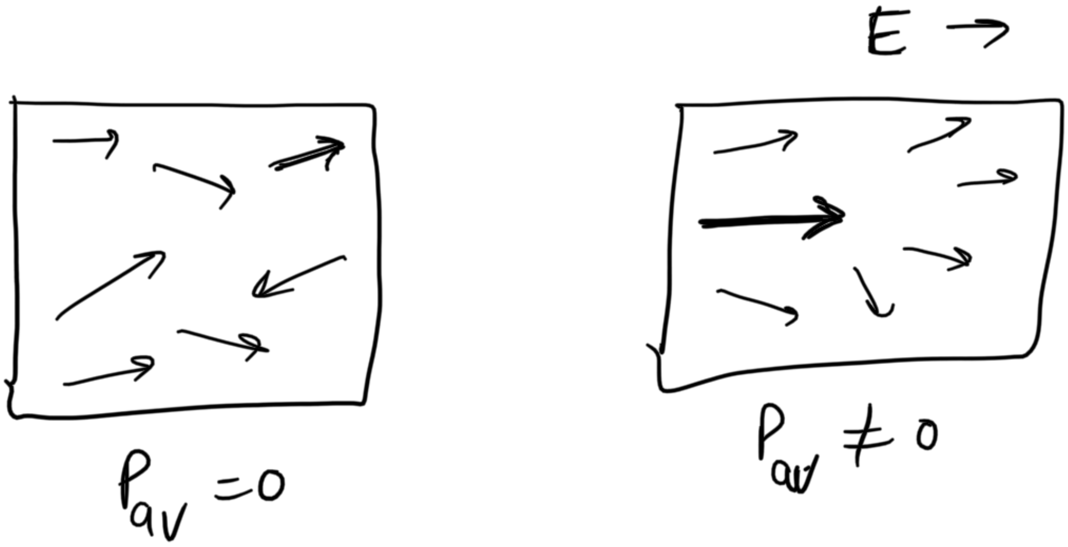
Time ~ 10^{-13} Sec.

Fre. ~ 10^{13} Hz.

③ Dipolar or orientational Polarization

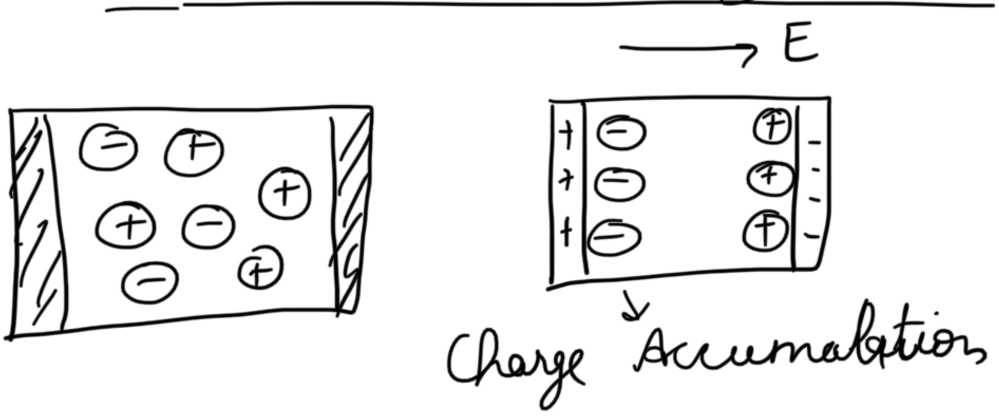
Molecules known as polar molecules have a permanent dipole moment

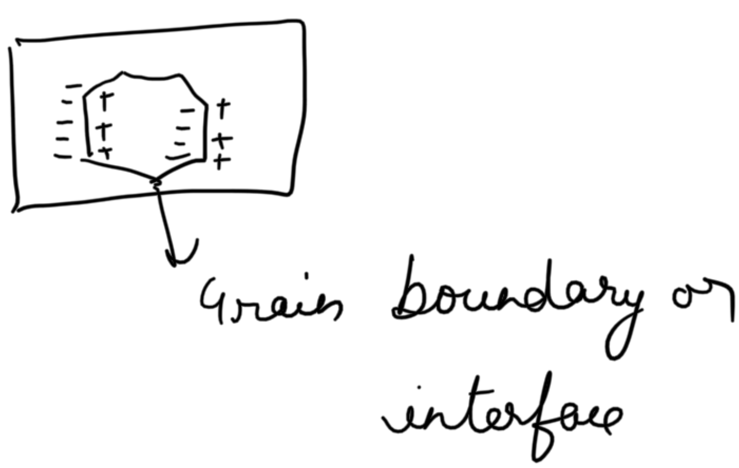
For exa. – H_2O



Dielectri constant in the Nitrobenzene ($C_6H_5CO_3$) decreases with increasing temperature

(4) Interfacial Polarization :-





Exa.:- CCTO

Calcium Copper Titanium Oxide

(5) Spontaneous or Ferroelectric Polarization

A Ferroelectric material which is defind as a system having Spontaneous polarization

Exa.:- $BaTiO_3$

Lecture 5

Ferroelectrics, Piezoelectrics & Pyroelectrics

Ferroelectric materials :- (FEM)

Spotaneous polarisation
(Present in the material

$\downarrow$ Apply electric field

Reorient the polarisation

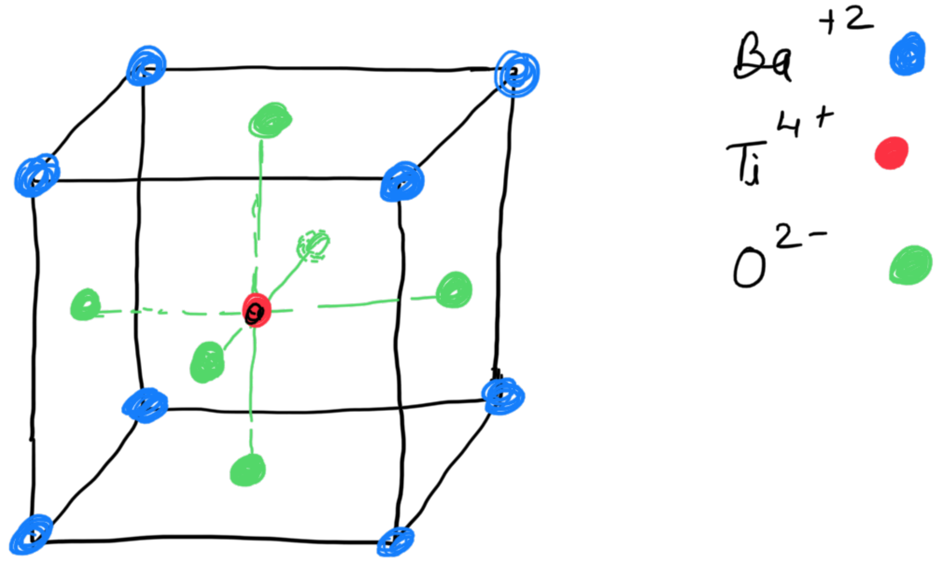
→ Polarization in the FEM can exist in the absence of E under certain range of Temperature & pressure
However, in dielectric the polarization gets generated after the application of E & once the electric ~~ft~~ field is removed the polarisation disappears

Why? :- Crystal structure without inversion symmetry

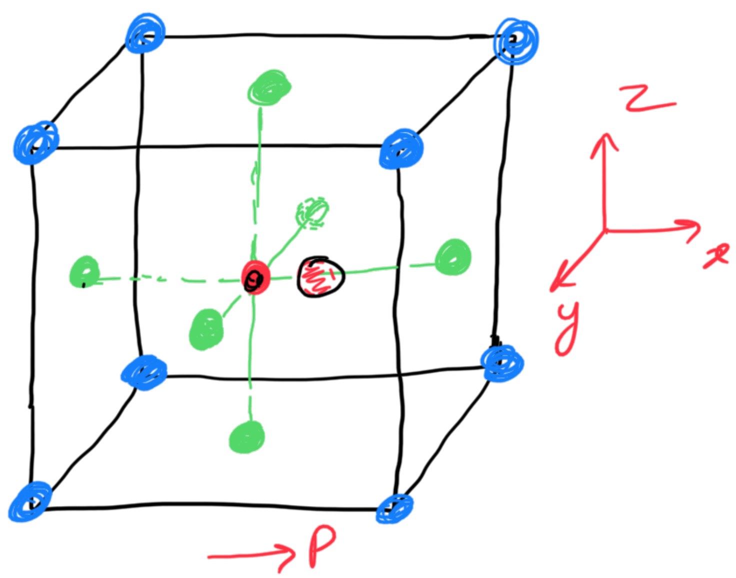
Inversion symmetry :- $r \to -r$

the system remains invarient

Exa.:- $BaTiO_3$



At high temp.: Paraelectric phase
inversion symmetric, non polar



Six configurations

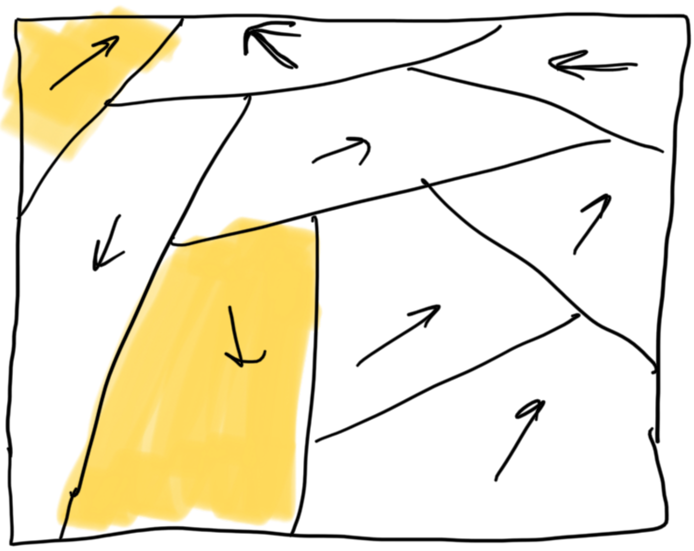
Lower the temp. ⇒ Ferroelectric Phase

→ Inversion symmetry is broken

→ The point where the transforma-tion from paraelectric to ferroelectric phase appears, is called Curie Temperature (T_c)

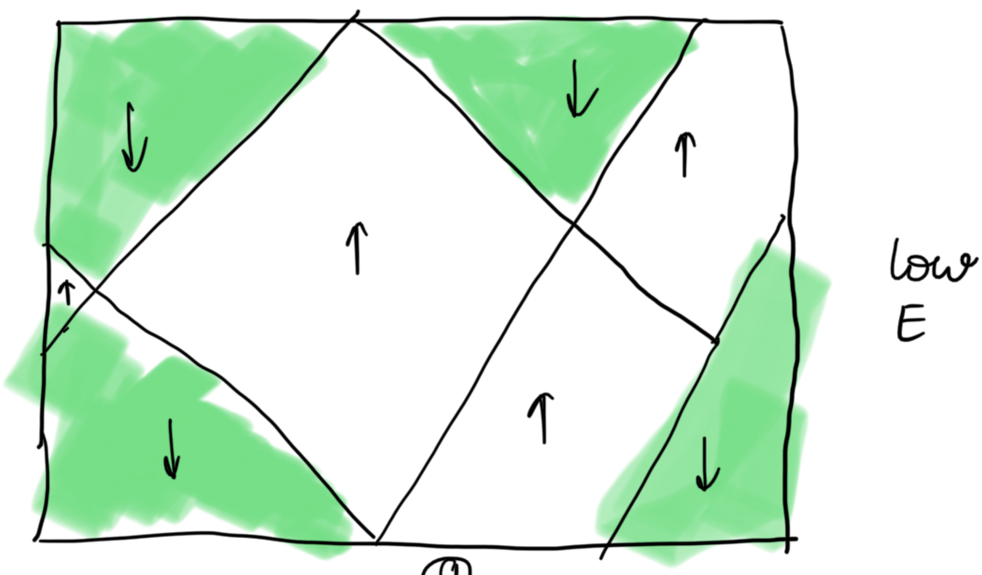
<u>Ferroelectric Domains :-</u>

The region of FEM, in which the $\bar{P}$ is in a given direction, is known as ferroelectric domain or a Weiss domain.

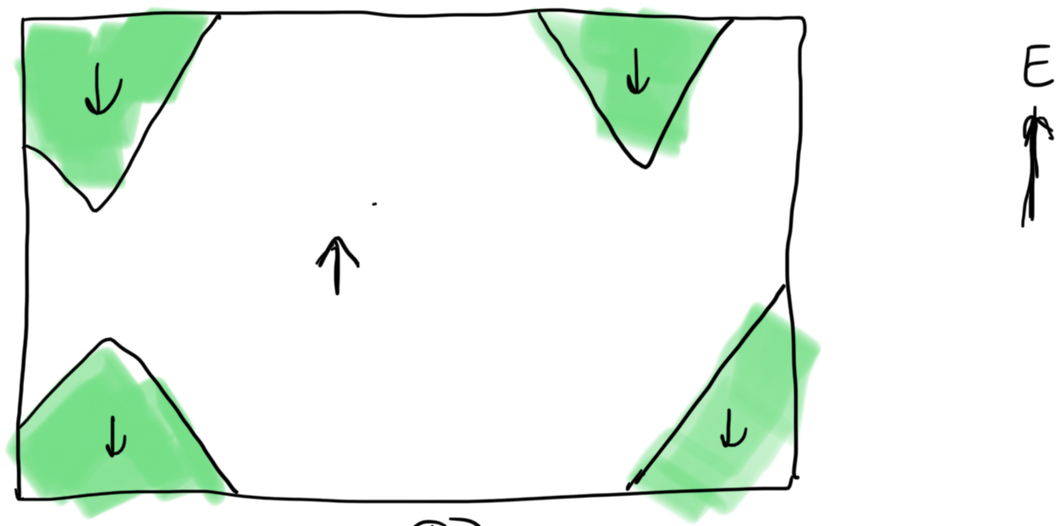


Size of domain ~ 100 nm to 1 mm

Domain wall :- Seperates different domain
↓
(Domain boundary)



(a)



(b)

→ The application of E helps to align the domains or polar regions

Dependence of dielectric constant on temperature :-

$$\epsilon = \frac{C}{(T - T_c)} \qquad (T > T_c)$$

T_c : Curie Temperature
C : Curie-Weiss coefficient / Curie Constant

Ferroelectric Hysteresis Loop :

Tells us how the ϵ_r / P / D depends on the strength of the electric field.

→ Saturation Polarization (P_s)

When we apply relatively high E, the material becomes single domain.
⇒ Polarization is said to be saturated

→ Poling : Process of applying an electric field in order to align a substantial fraction of domains

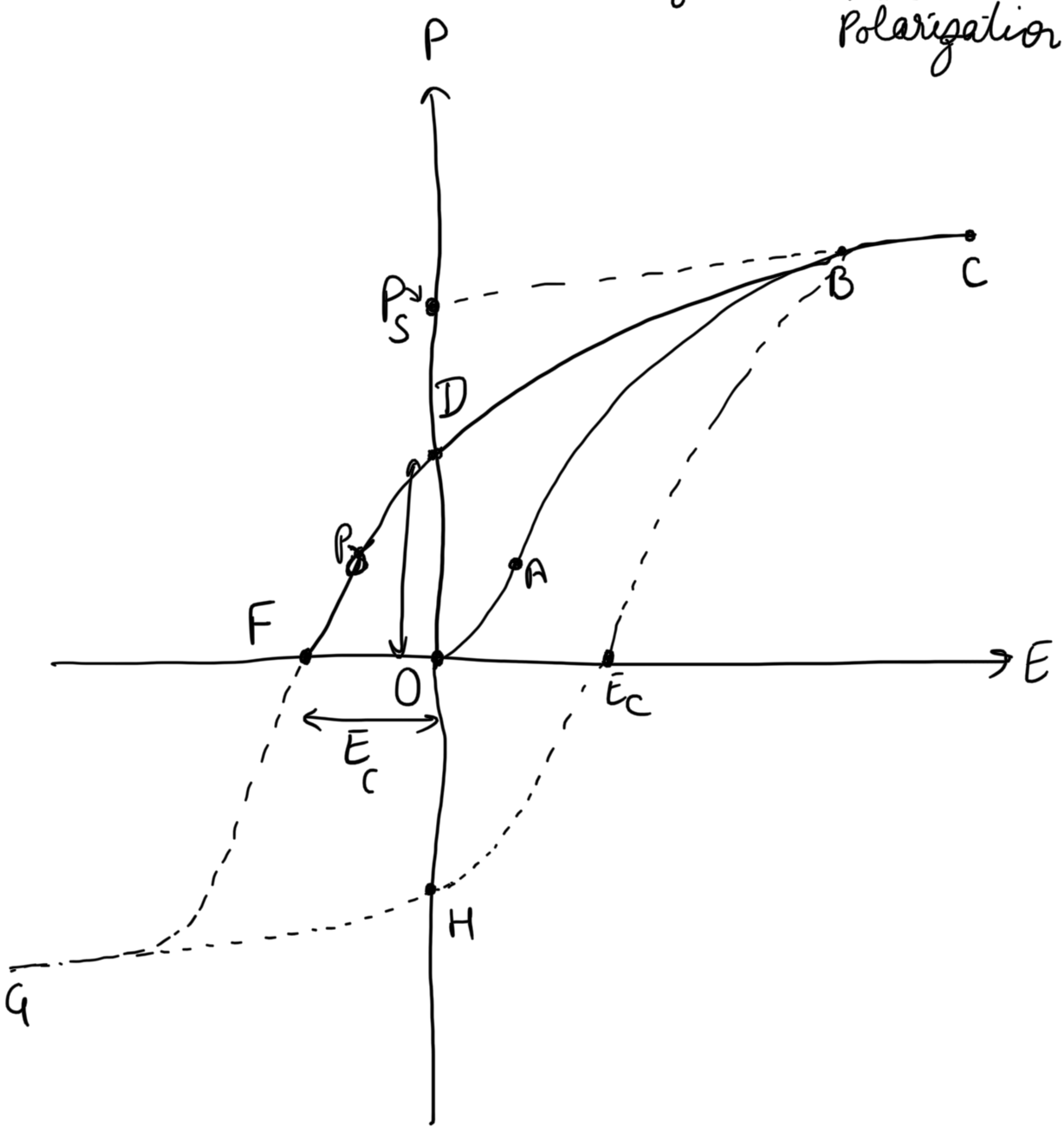
→ Depoling: Where domains undergo randomization

⇒ Hysteresis Loop describes : How D/P varies as a function of E

... as a function of E

$$D = \epsilon_0 E + P$$

P_r : Remnant Polarization



E_c : Coercive field

P-E Hysteresis loop

<u>Piezoelectricity :</u>

Poled ferroelectric material

If we a connect a wire : There will be no current we apply stress ⇒ the dipole moment

⇓

Polarization

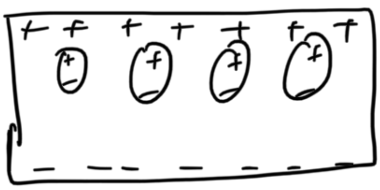
⇓

Bound charge density changes

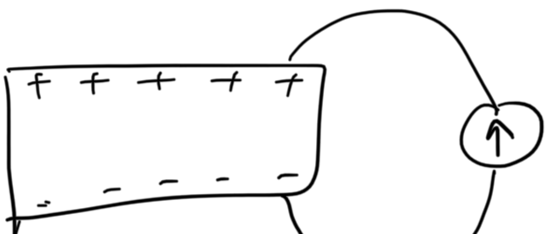
⇓

Current in system

Pyroelectricity : (Effect of temperature)

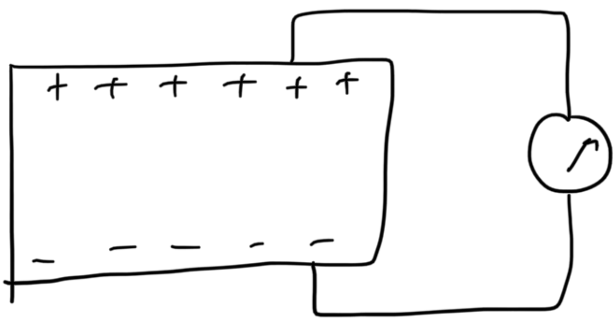


$\frac{dT}{dt} = 0$



current = 0

$\frac{dT}{dt} > 0$



Finite current

Lecture :- 4

Magnetic Materials

magnet has its origin in a magnetic material known as "magnetite"

Iron oxide / Lodestone

$\Downarrow$

used in Magnetic Compass

Magnetite is probably the first materials known to be magnetic

Magneticc means :- They respond to magnetic field in some fashion.

Physical origin of magnetic & dielectric behaviour are quite different.

Magnetic → Spin motion of electrons

Dielectric → Non uniform distribution of electric charge

Origin of Magnetism :-

wire (current carryin)

Magnetic moment $\mu = I A$

Magnetic moment by a current loop

Magnetic moment : Building block of the magnet

similar to dipole moment of dielectric materials

The unit of μ : Am^2 (Ampere meter^2)

①: e^- orbiting the nucleus (Orbital angular momentum of e^-)

Nucleus (orbital motion)

②: Electron spin (Spin angular momentum of e^-)

own axis

(spin motion)

③: Nuclear spin (small contribution in general)

A charged particle rotating in an orbit creates μ (angular magnetic moment)

$$\mu = \frac{qL}{2m}$$

q - charge

L : Angular momentum

m : mass of the charged particle

$L = mvr$

v → Velocity

r → Radius of the orbit

Basic unit of magnetic ~~magt~~ moment is Bohr magneton (μ_B)

$$\mu_B = \frac{h}{2\pi}\frac{q_e}{2m_e} = 9.274 \times 10^{-24}\ A\,m^2$$

q_e : electronic charge

m_e : Mass of e^-

Gyromagnetic ratio (γ) $\quad \gamma = \frac{q}{2m}$

$\mu_S = -\frac{e}{m} S$ $\quad$ S : Spin angular momentum

Magnetisation (M) :- Total magnetic dipole moment per unit volume.

<u>unit of M :-</u> $\left[A m^2 / m^3 \right] \equiv \left[A / \text{meter} \right]$

* Magnetic moment of nuclear spin will be $\sim 10^{-3} \mu_B$, can be ignored when we will calculate the total μ of an atom or an ion

Manganese (M_n) $Z = 25$

<u>Free M_n atom :-</u>

$\underline{1s^2\, 2s^2\, 2p^6\, 3s^2\, 3p^6\, 4s^2}\; \underbrace{3d^5}$

5 - unpaired e^- $\quad \boxed{\uparrow}\boxed{\uparrow}\boxed{\uparrow}\boxed{\uparrow}\boxed{\uparrow}$

$$\mu = \sqrt{n(n+2)} \text{ B.M.}$$
$$= \sqrt{5 \times 7}\ \mu_B = \sqrt{35}\ \mu_B$$

$\uparrow \nearrow \downarrow \nearrow \searrow$:- Paramagnet

↑ ↑ ↑ ↑ ↑ : Ferromagnet

↑ ↓ ↑ ↓ ↑ ... : Antiferromagnet

↑ ↓ ↑ ↓ ↑ : Ferrimagnets

Eletric	Magntic
* Electric field (E)	Magnetizing field (H)
* Polarization (P)	Magnetization (M)
* Dielectric Displacement (D)	Magnetic induction or Flux density (B)
* Dielectric Susceptibility (χ_e)	Magnetic Sus.. (χ_m)
* Dielectric constant (k/ϵ_r)	Relative magnetic permeability (μ_r)
* Ferroelectric, Paraelectric	Ferromagnetic, Paramagnetic ..
* Piezoelectricity	Piezomagnetism

Applied externally to the material : (H) (Cause)

creates M (magnetisation)

Magnetic Induction / Flux density (B) :

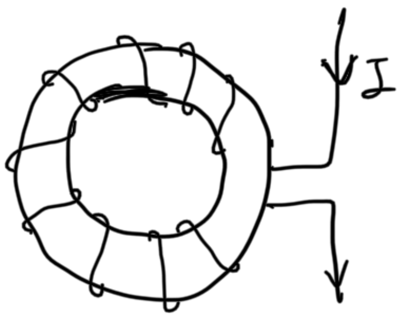
Number of flux lines per unit area

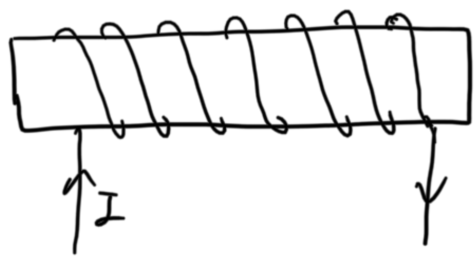
Unit of flux density Weber/m^2 $\equiv$ Wb/m^2

$\equiv$ Tesla

How to create magnetizing field (H)

Toroidal Solenoid





Solenoid using a current carrying coil

Consider a coil of length l with n turns

$$H = N \times I$$

$$N = \frac{n}{l}$$

Unit of H is Amperes/meters (A/m)

Lecture 5 + 6

Origin of Magnetism -

orbit motion + spin

Magnetic moment μ, unit μ_B (Bohr magnetron)

H - (Magnetizing field)

M - Magnetization

B - Magnetic flux density/induction (Tesla)

$$D = \epsilon_0 E + P$$

$\downarrow$

Dielectric Displacement

$$B_{int} = \mu_0 H + \mu_0 M$$

$\downarrow$

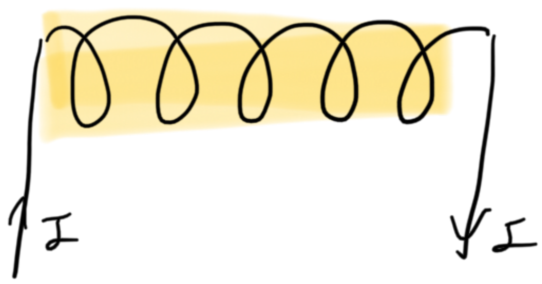
Magnetic induction created inside the material

μ_0 = Magnetic permeability of the free space $= 4\pi \times 10^{-7}$ W/A m

Henry/m

In Vacuume

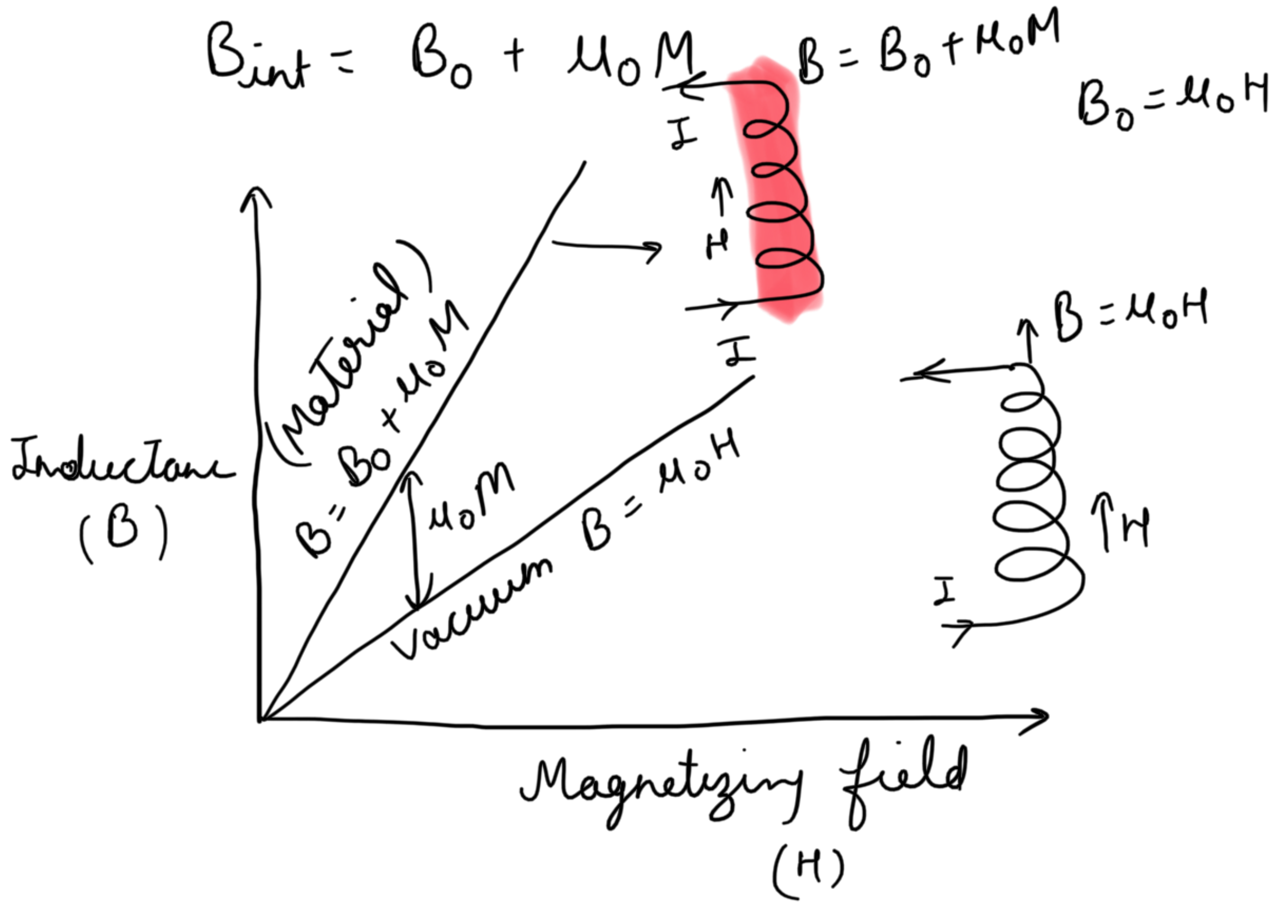
(No material)



$\mu_0 M = 0$

$$B_{int} = \mu_0 H = B_0$$

$$B_{int} = B_0 + \mu_0 M$$



→ In case of superconductors -

$$B_{int} = 0 \Rightarrow \underline{B_0} = \underline{-\mu_0 M}$$

* Entire magnetic flux is excluded from inside the superconductor

→ <u>Silver (Material)</u> $B_{int} < B_0$

⇒ some of the flux gets excluded from inside the material

$\Rightarrow$ These kind of material $\div$ Diamagnetic material

$\rightarrow$ Coppor / Aluminum $\div$ $B_{int} > B_0$

Flux lines concentrated inside the material (Paramagnetic material)

$\rightarrow$ Fe (Iron) $B_{int} >> B_0$

(Ferromag. / Ferrimag.)

Magnetic Susceptibility (χ_M)
Magnetic Permeability (μ)

$\underline{\chi_M} = \dfrac{M}{H}$ (A Property that relates M & H)

$B_{int} = \mu H$ (For diamagnetic & paramagnetic)

μ = Magnetic permeability

$B_{int} = \underbrace{B_0} + \mu_0 M = \mu H$

$B_{int} = \mu_0 \mu_r H = \underbrace{\mu_0 H} + \mu_0 M$

$M = (\mu_r - 1) H$

$\chi_M = \dfrac{M}{H}$

$$\Rightarrow \boxed{\chi_M = \mu_r - 1} \Leftrightarrow \boxed{\mu_r = 1 + \chi_m}$$

It relates permeability to susceptibility

Demagnetizing fields :-

The magnetizing field inside (H_{int}) the ferromagnetic / ferrimagnetic is different than the magnetizing field (H)

$\Downarrow$ why

Because M is large

$$B_{int} = \mu_0 H + \mu_0 M \quad \text{(last section)}$$

$$\boxed{B_{int} = \mu_0 H + \mu_0 (1 - N_d) M}$$

$N_d M \equiv H_d$ demagnetizing field

$\downarrow$

Demagnetizing factor

N_d Depends on the geometry of the magnetic material varies from 0 to 1

Classification of the magnetic materials :-

① Diamagnetic materials :-

When an external Magnetic field is applied, the material excludes the magnetic flux

Exa -: Metals, inert gases & organic compounds

* Diamagnetism $\Leftrightarrow$ comes from orbital motion of the electron

* $\mu_r < 1 \Rightarrow \chi_m$ will be negative

* Susceptibility is independent of temperature

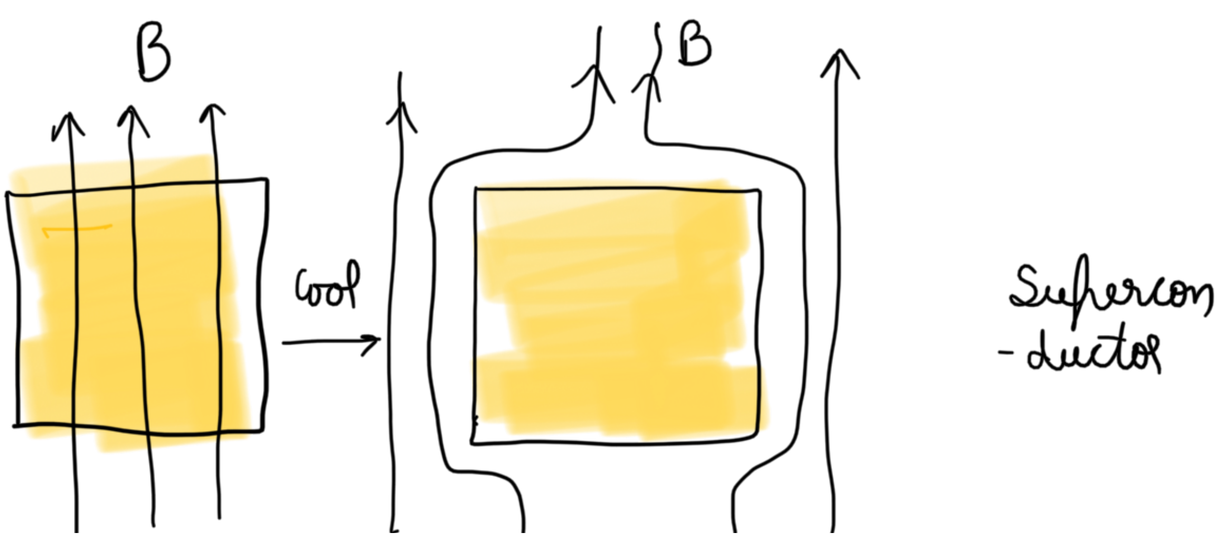
Perfect Diamagnetic material -:

* Below critical Temperature (T_c) the resistance goes to zero $\Rightarrow$ supercon-ducting state

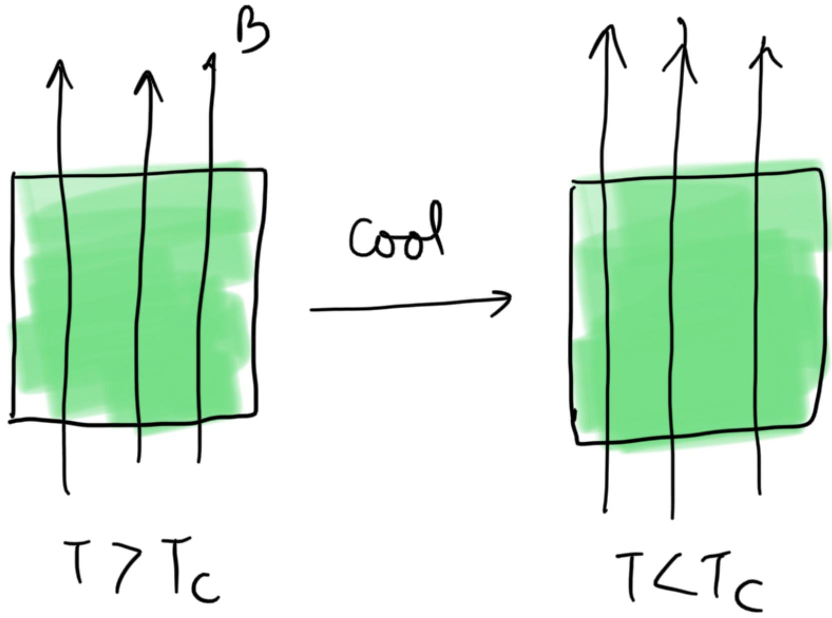
$\boxed{\text{Curie Temperature} - T_c}$

* $\chi_m = -1$

Meissner effect -: Expulsion of magnetic flux lines due to diamagnetic behaviour of a superconductor



$T > T_c$ $\quad$ $T < T_c$



Perfect Conductor

② Paramagnetic Materials :-

Effects originates from the unpaired electron, this leads to a net magnetic moment for the atom / ion.

- * The susceptibility is very small ($\chi_m \sim 10^{-3} - 10^{-6}$) but Positive
- * As T increases, χ_m decreases
- * Paramagnetic material show slight attraction in the presence of permanent magnet
- * Curie Temperature (T_c) :- Ferromag material to Paramagnetic

③ Antiferromagnetic material -

$$- - \uparrow \downarrow \uparrow \downarrow \uparrow \downarrow - -$$

* Individual atom/ion has a net spin mag. moment, however the mag. moments are aligned in an antiparallel way

Exa.: Cr, α-Mn, MnO

* χ_m is slightly larger than 0
* If we heat an antife. material, the coupling gets destroyed & material becomes paramagnetic. The temp. at which this phase transition happens "Neel" temperature (T_N or θ_N)

④ Ferromagnetic & Ferrimagnetic materials:

$$- - \uparrow \uparrow \uparrow \uparrow - - - \quad \text{Ferro mag.}$$

$$- - - - \uparrow \downarrow \uparrow \downarrow - - - - \quad \text{Ferri mag.}$$

* Important Feature: there is a net magnetization even without the magnetizing field $\Rightarrow$ Due to the spontaneous alignment of mag. moment

Curie - Weiss law :-

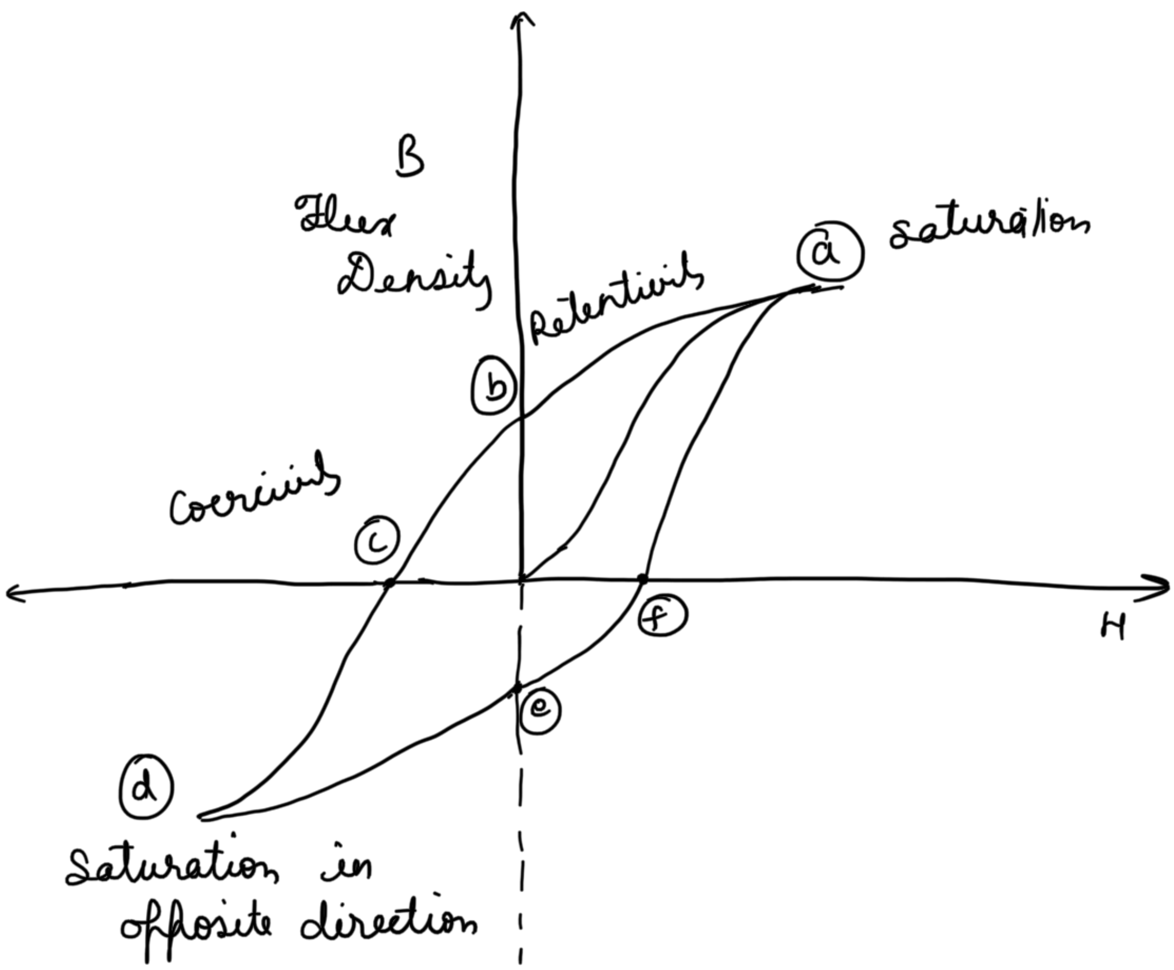
$$\chi_m = \frac{C}{T-\theta_p}$$

Variation of χ_m with temperature

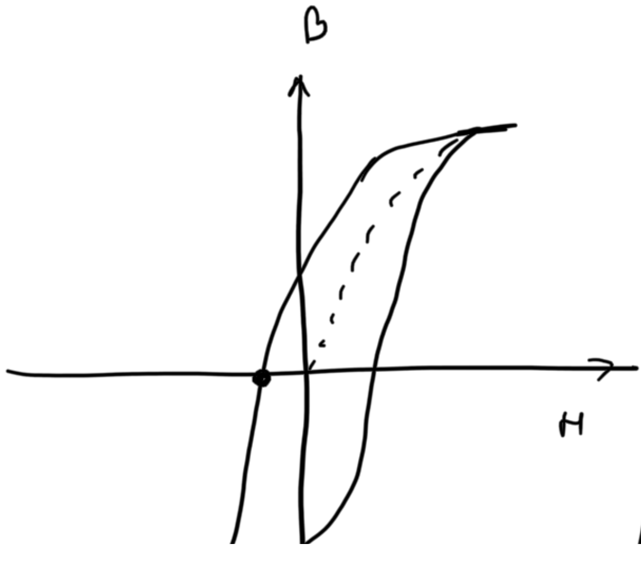
θ_p :- Curie Temperature

C :- Curie Constant

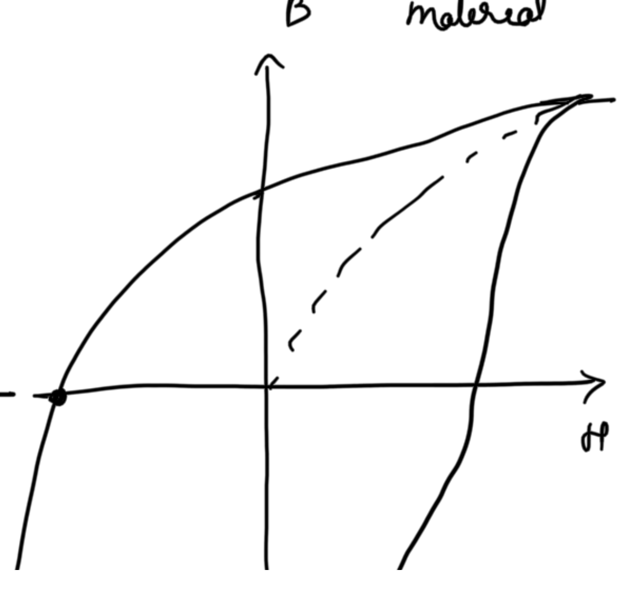
The Hysteresis Loop for ferro- & ferri materials :-



Soft magnetic material



Hard magnetic material



__Easy Axis__ :- Along which small magnetic field gives saturation magnetization

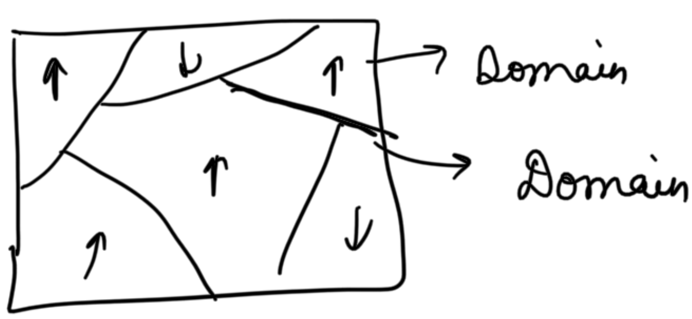
__Hard Axis__ :- Along this large magnetic field to reach saturation

__Magnetic Anisotropy__ :- It means that the magnetic properties are dependent on the crystallographic direction

1:- Magnetocrystalline anisotropy :-
The energy needed to rotate from the easy axis is known as magnetocrystalline anisotropy energy

2:- Magnetoshape anisotropy :- Depending upon the shape of the material, the coercivity changes

__Magnetic Domain walls__ :-



Two factors :-

① Anisotrophy energy E_1

② Exchange energy E_2

If $E_1 > E_2$

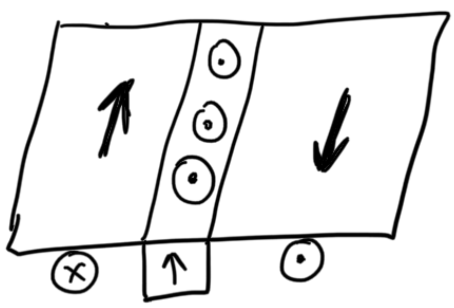
Domain wall will be Thin

$E_1 < E_2$

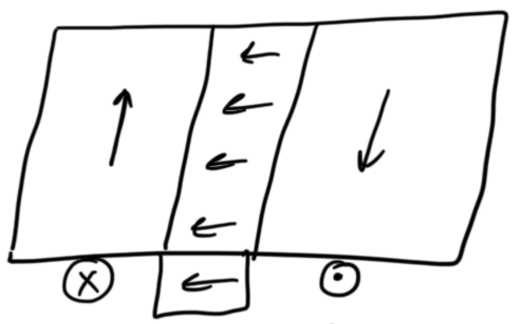
Domain wall will be thicker

Bloch wall & Neel wall

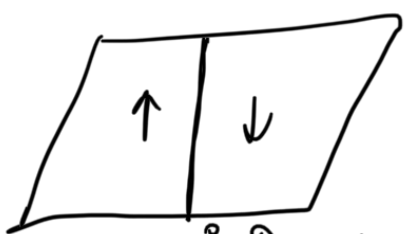
For Magnetic thin films



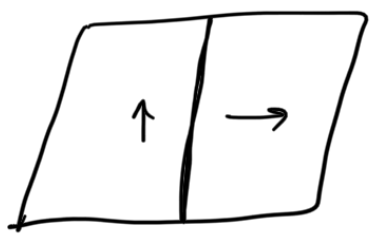
Bloch wall



Neel wall



180° Domain wall



90° Domain wall