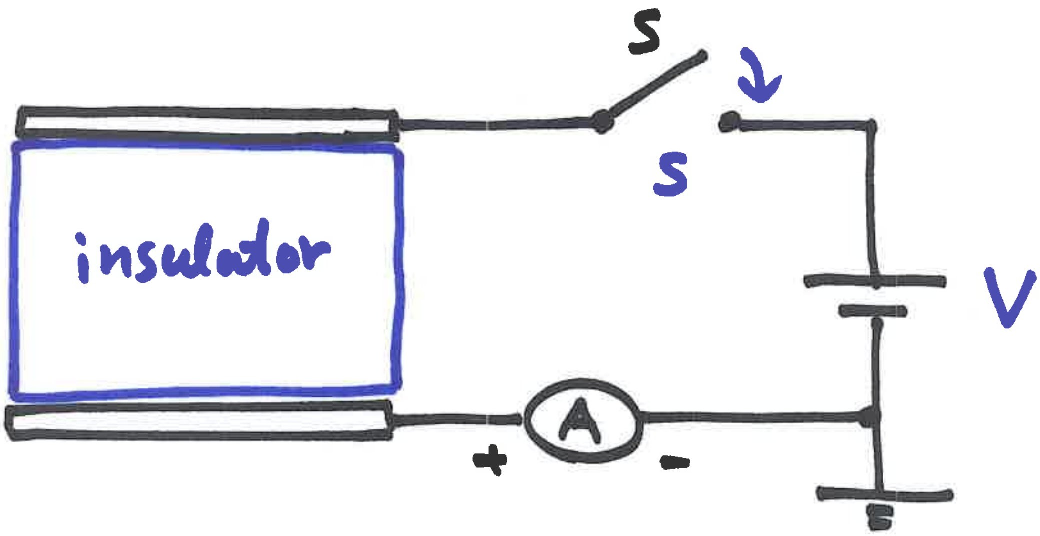
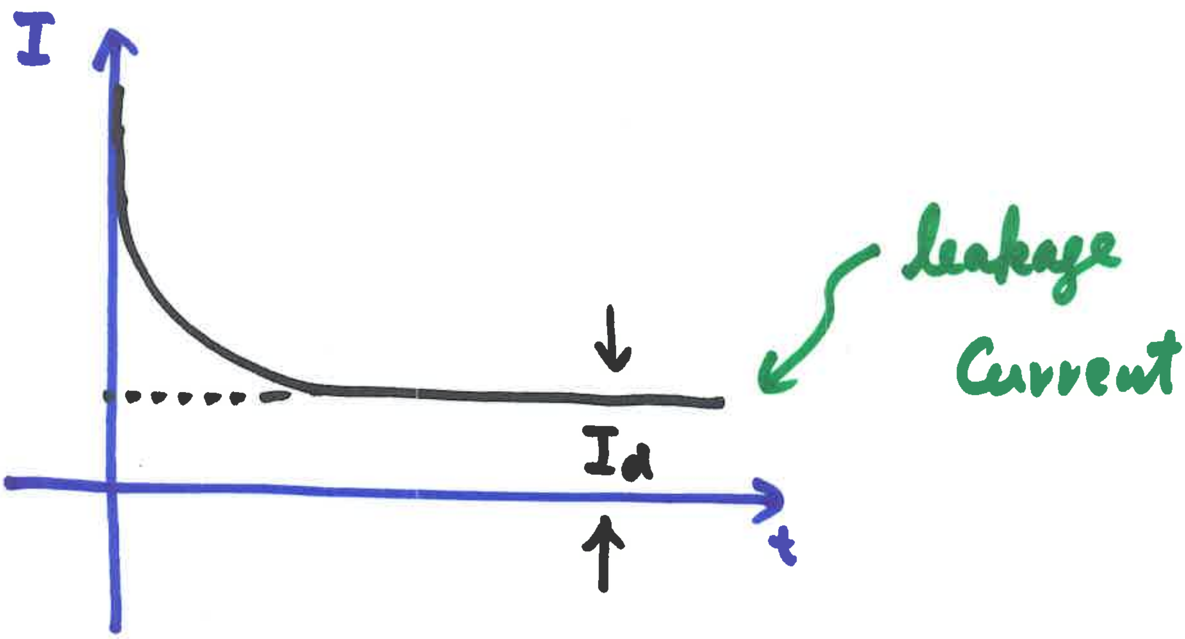
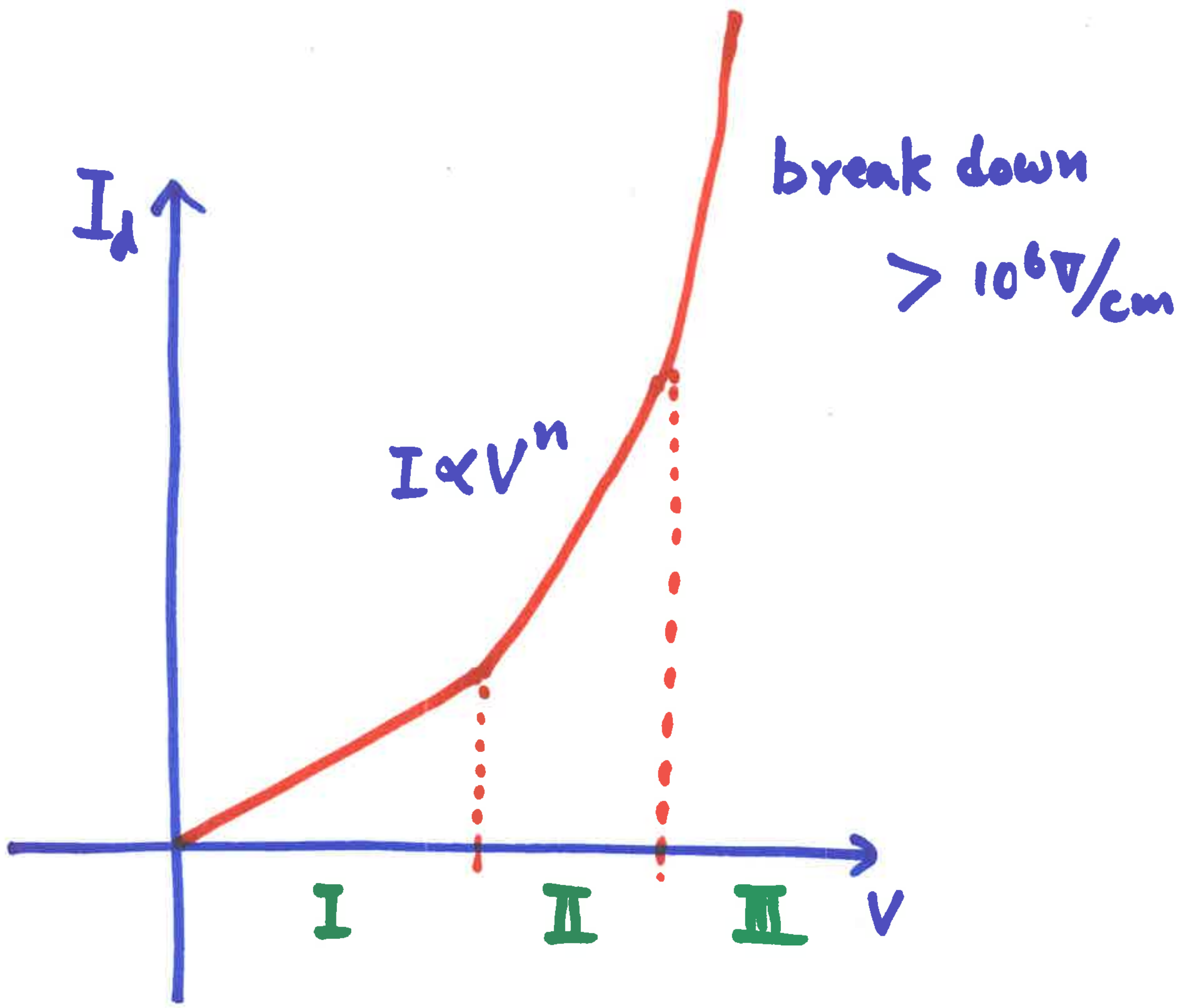
Conduction mehanism of insulator





I_d : ?

$$I_d = e n v$$



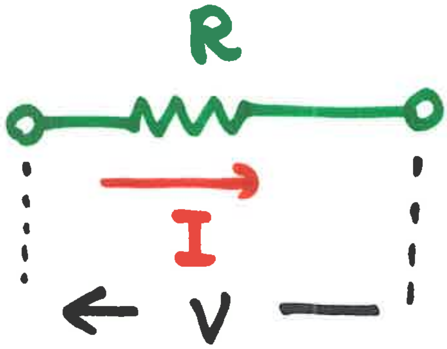
I Low electric field region

$$I \propto V$$

II High electric field region

$$I \propto V^n \qquad \text{e.g. } n = 2$$

ohm law



$$I = \frac{V}{R}$$

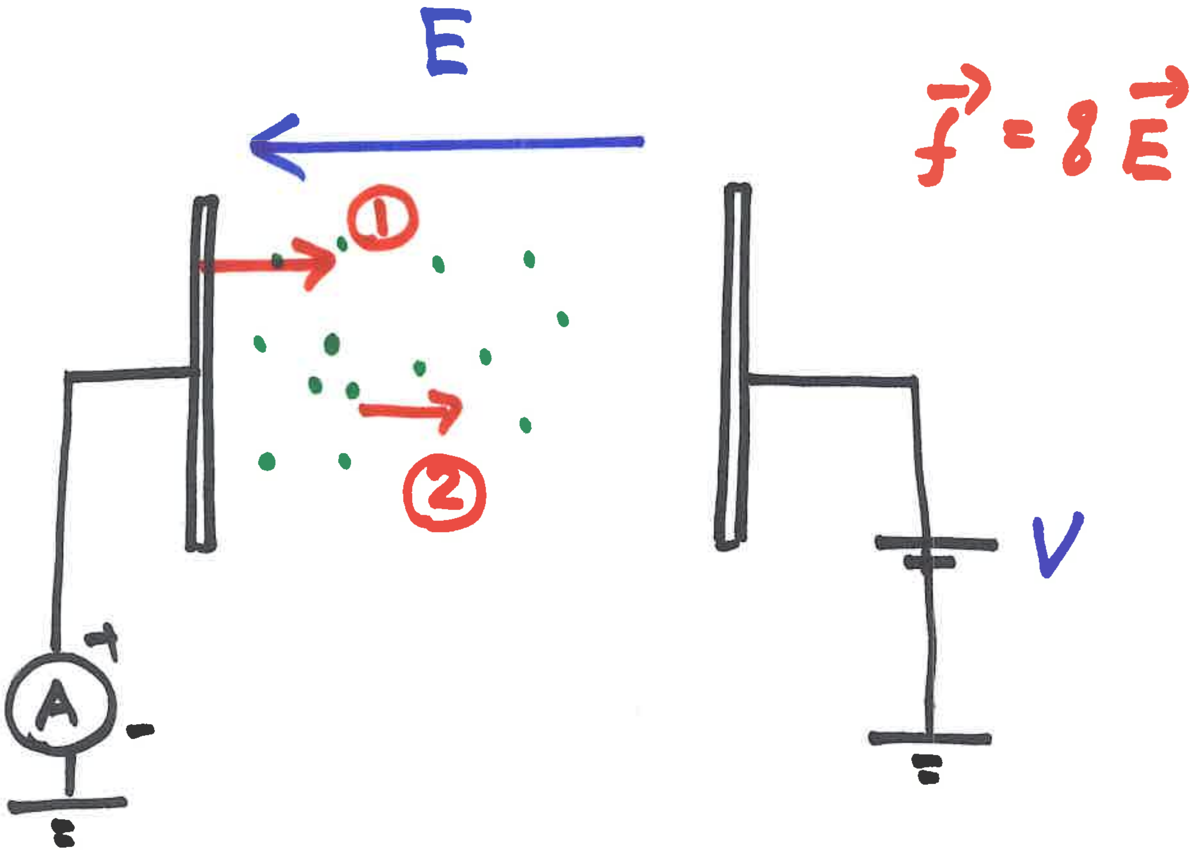
$$I = \frac{V}{R} = GV$$

$$j = env$$

$$= en\mu E$$

$$= en\mu \frac{V}{d}$$

$$en = \text{const} \;!!$$



① injected electrons en_j

(depend on V)

② excited electrons en_0

(not dependent on application voltage)

① injection from electrode

② already in insulator

I) Low electric field region

$$|en_0| > |en_{inj}|$$

$$J = en_0 v$$

$$= en_0 \mu E \quad \left(= en_0 \mu \frac{V}{d}\right)$$

$$I \propto V$$

II) High electric field region

$$|en_0| < |en_{inj}|$$

$$J = en_{inj} v$$

$$n_{inj} \propto f(V) \quad ?$$

⊙ injection mechanism !!

Conduction Mechanism of Insulator

$$I_d = \underbrace{en}\ \underbrace{v_d}$$

en : carrier

v_d : velocity

$$\mu = \frac{\partial v_d}{\partial E}$$

mobility [$cm^2/V \cdot s$]

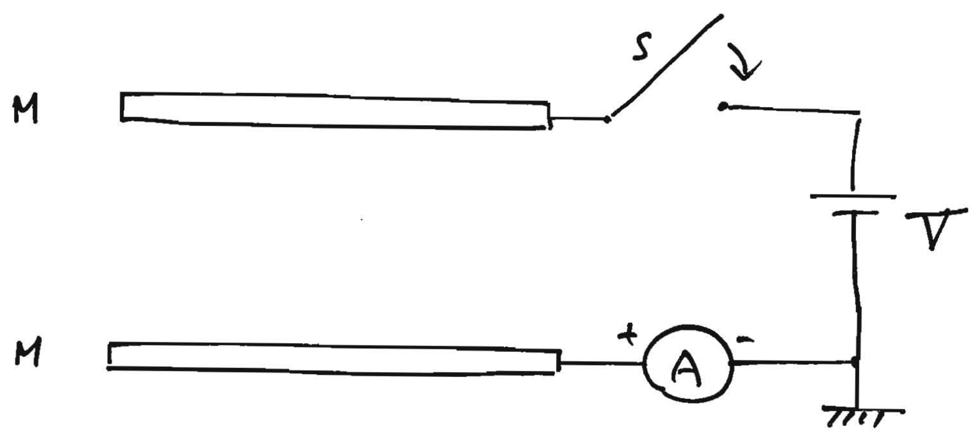
(1.) what is en ?

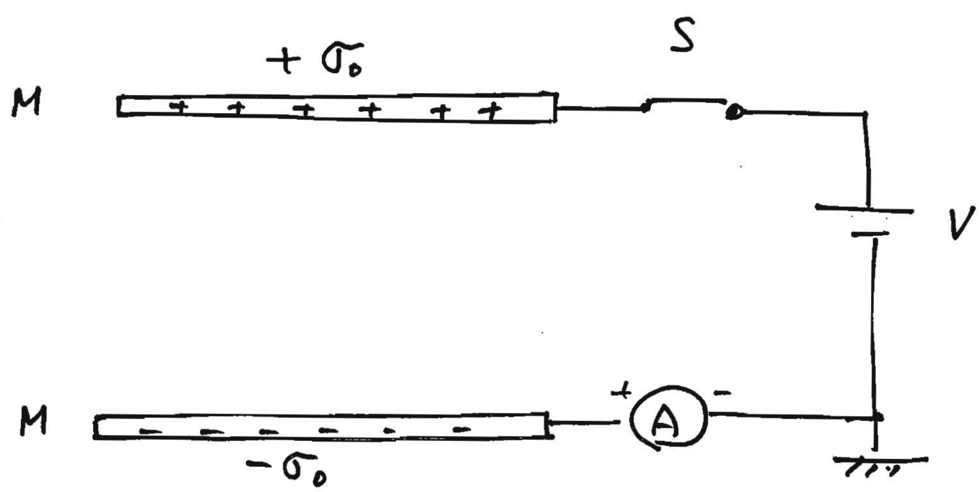
(2.) How μ is determined

. Band Conduction ?

. Hopping Conduction ?

⋮

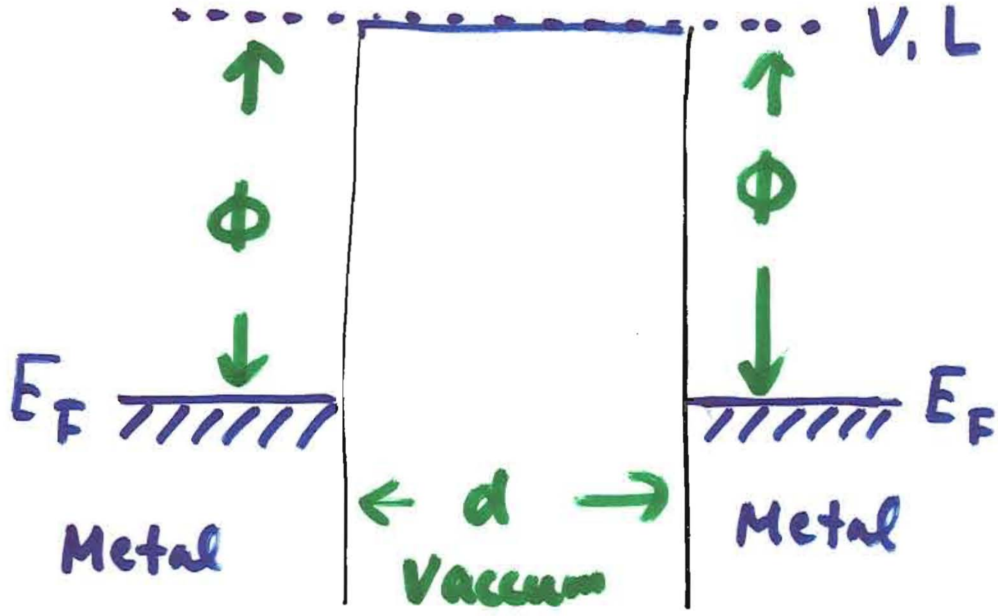




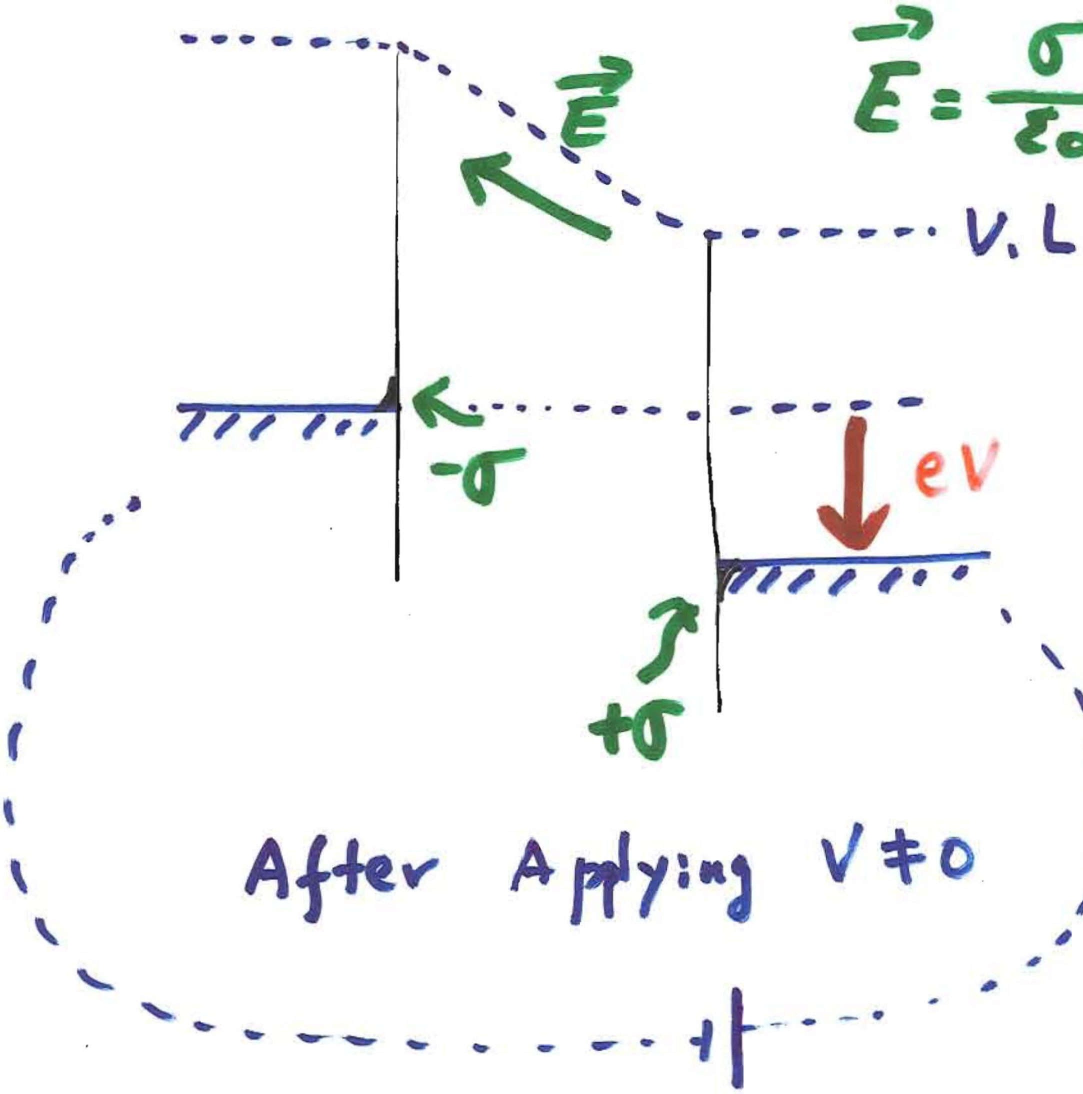
Question.

How we can describe the above situation using energ diagram?

What is metal?



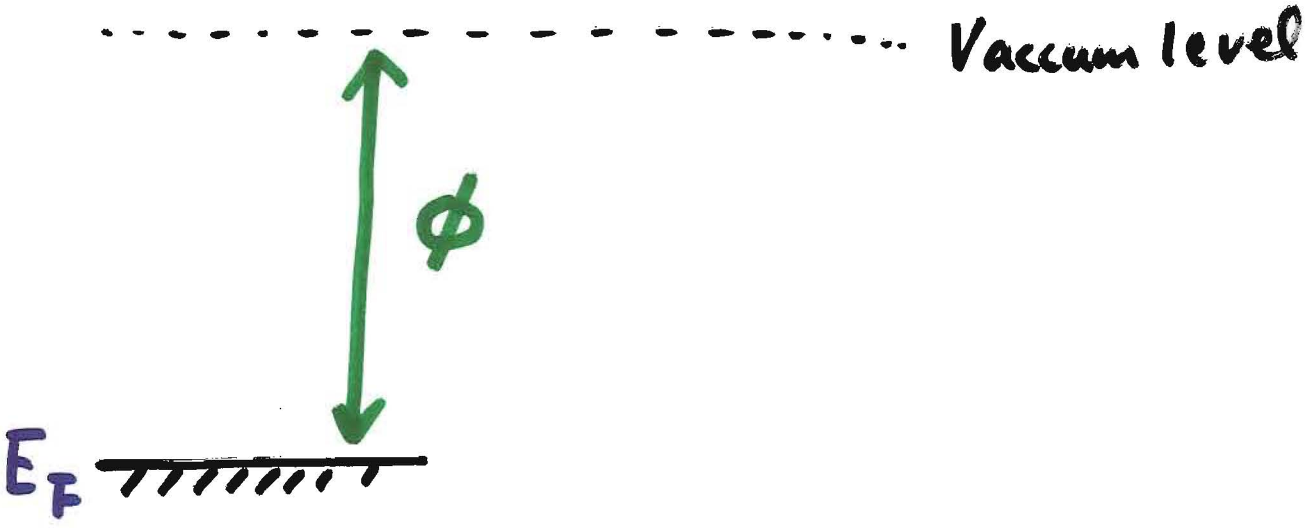
before Applying $V \neq 0$



$$\vec{E} = \frac{\sigma}{\varepsilon_0} \quad \cdots\cdots (1)$$

$$V = E \cdot d$$
$$= \frac{\sigma}{\varepsilon_0} d \quad \cdots (2)$$

After Applying $V \neq 0$



ϕ : Work function

$$M \longrightarrow M^+ + e$$

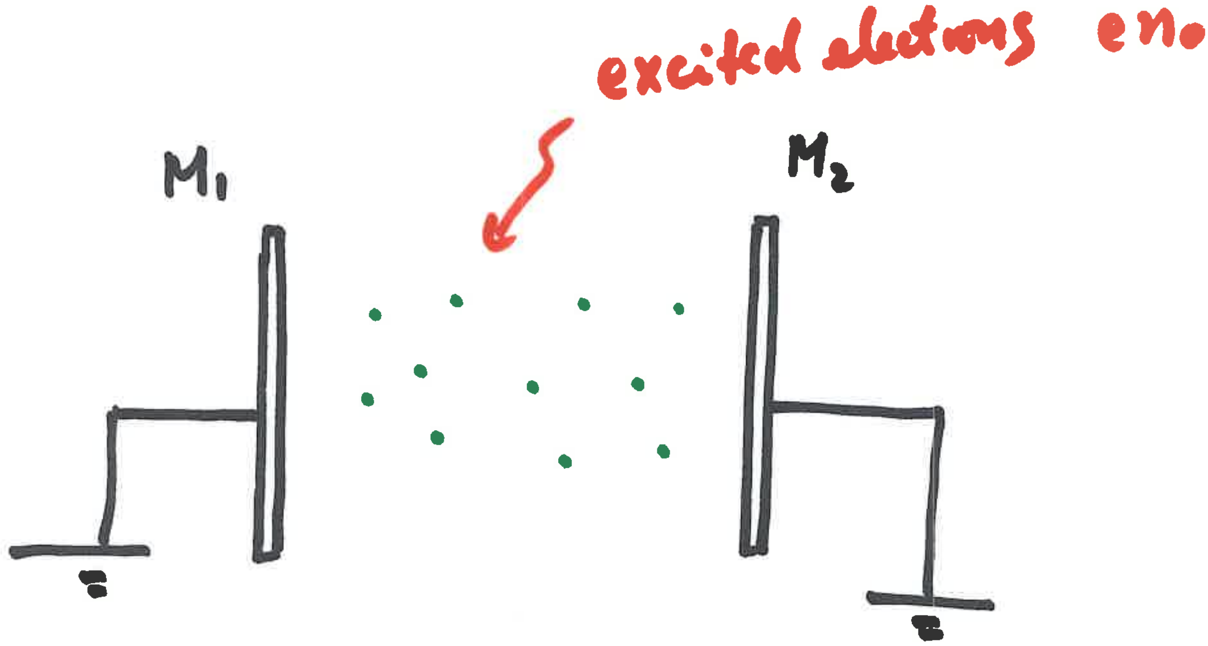
e.g.

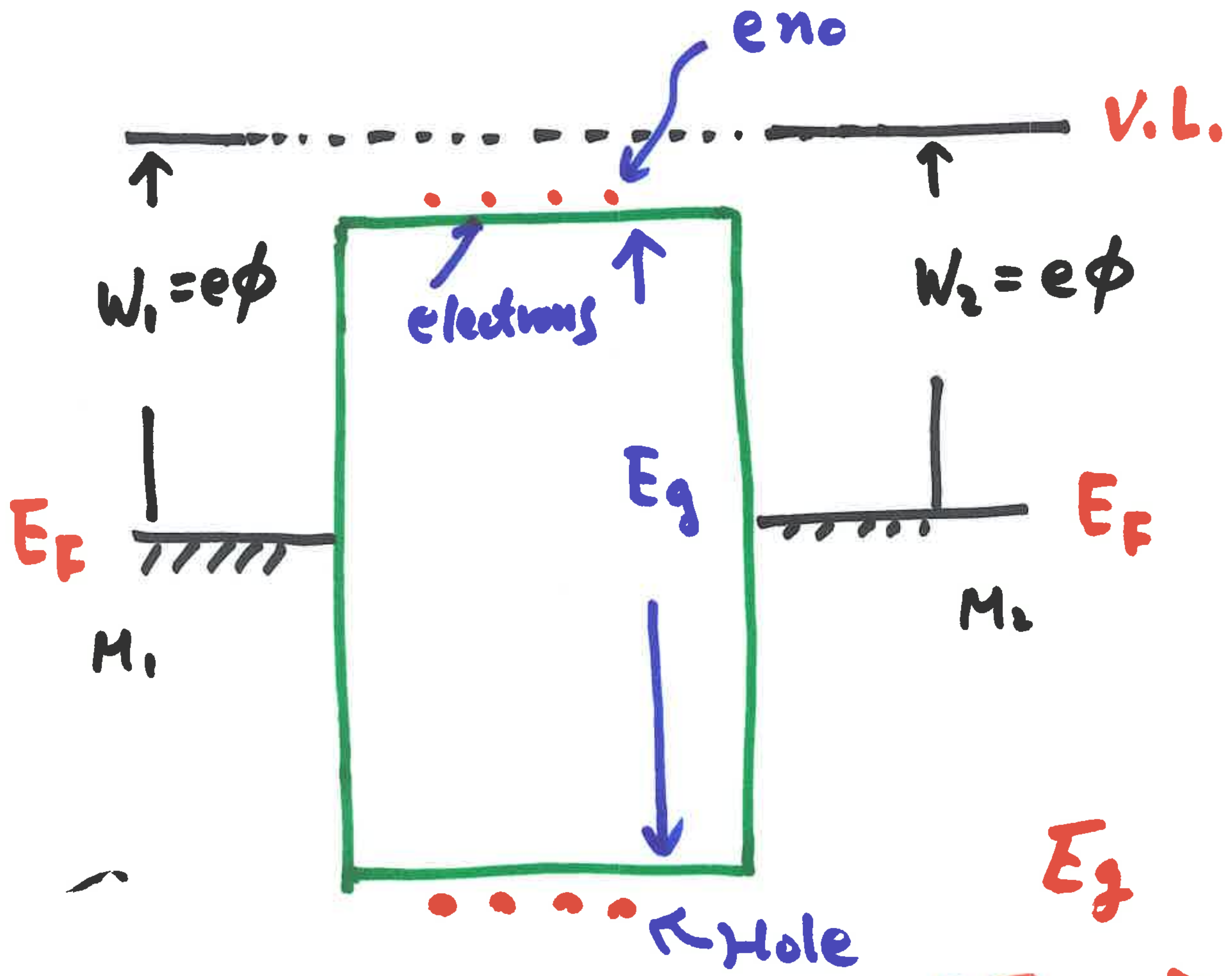
Au : 4.9 eV

Al : 4.0 ev

Cs : 1.94 ev

K : 1.6 ~ 2.3 ev





E_g

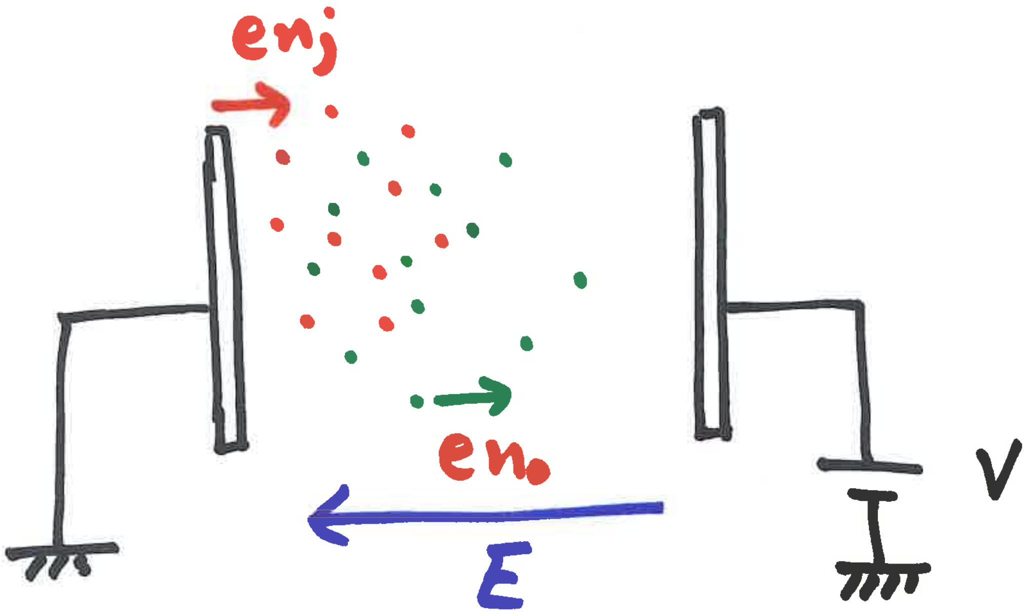
P.E. $> 7eV$

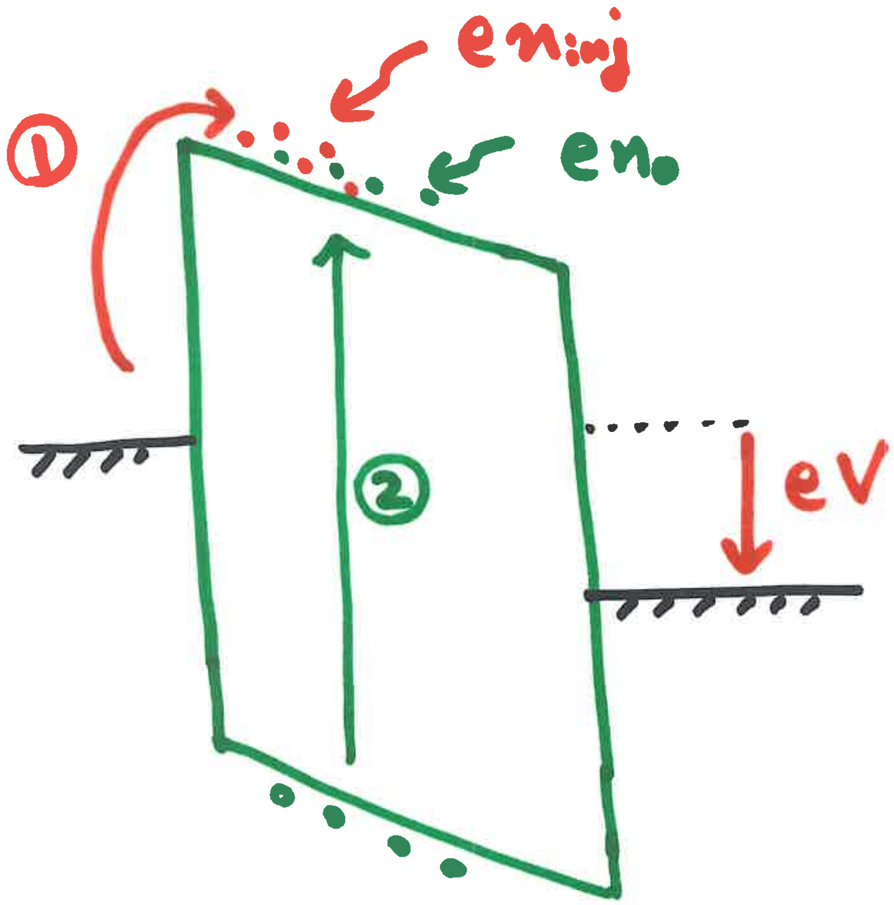
diamond $\sim 5.0eV$

Si $\sim 1.1eV$

$$en_0 \propto \exp\left(-\frac{E_g}{2kT}\right)$$

(excited electron density)





$$\nabla\cdot\vec{E} = \frac{e n_{inj}}{\varepsilon_0 \varepsilon_r}$$

space charge field

① injection of electrons (excess electrons)

② excited electrons at equilibrium

Low electric field region

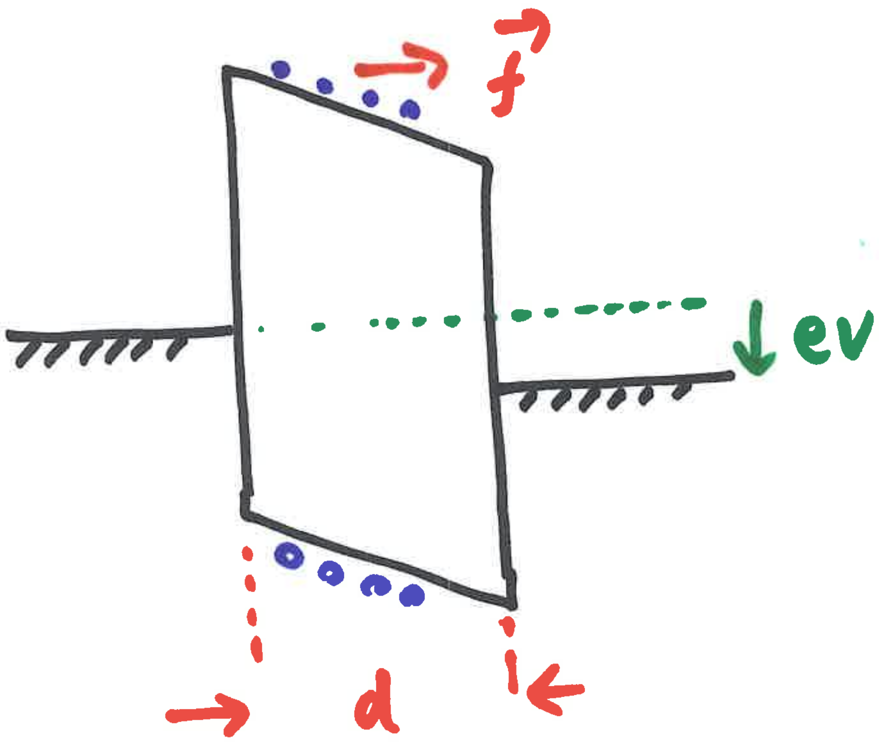
$\simeq$ thermodynamic equilibrium is established

$$I_d \simeq e n v_d$$

$$en \simeq e n_0$$

$$\vec{f} = q\vec{E}$$

$$\bar{E} = \frac{V}{d}$$



$$I_d \simeq e n_0 \mu E = \left(e n_0 \mu \frac{1}{d}\right) V$$
$$= KV$$

ohmic current!!

"Electric field" is working to move excited electrons.

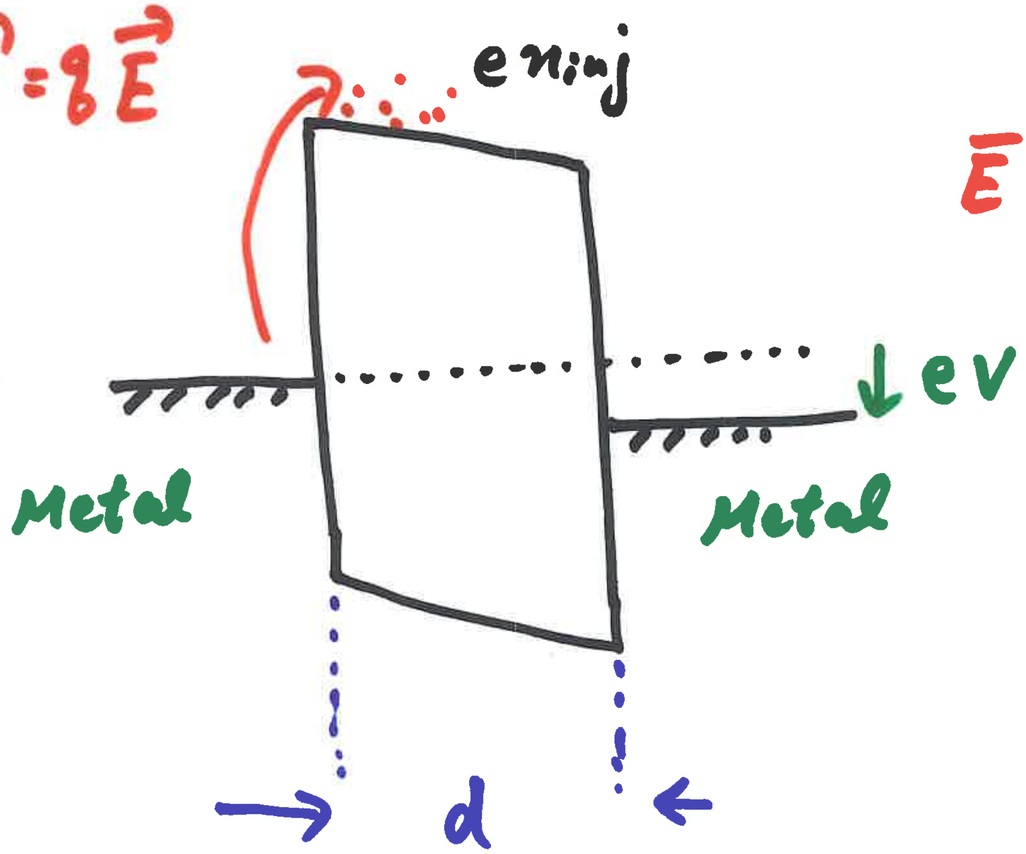
High Electric Field Region

Main carriers are injected electrons

$$I_d = e n v_d$$

$$en \simeq e n_{inj}$$ (injected electrons)

$\vec{f} = q\vec{E}$



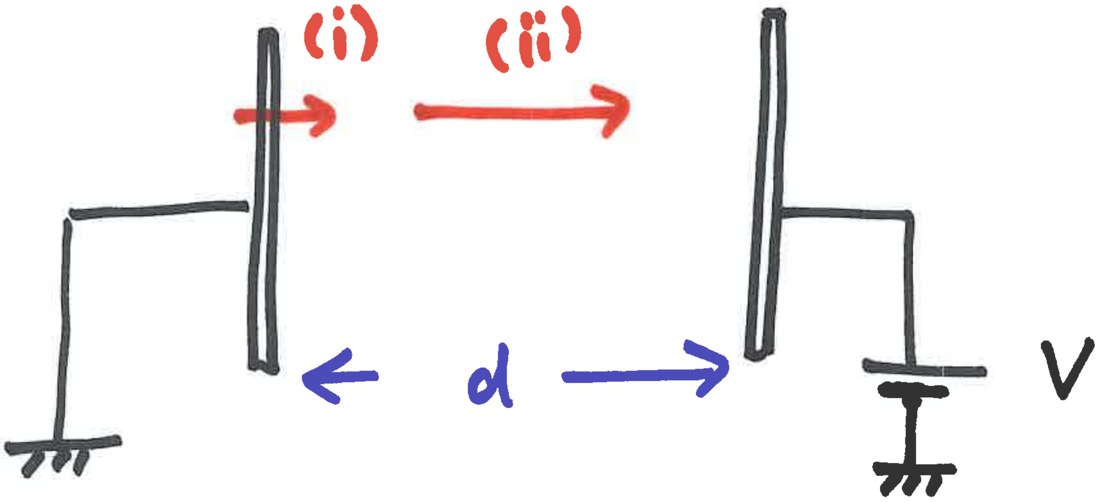
$\bar{E} = \frac{V}{d}$

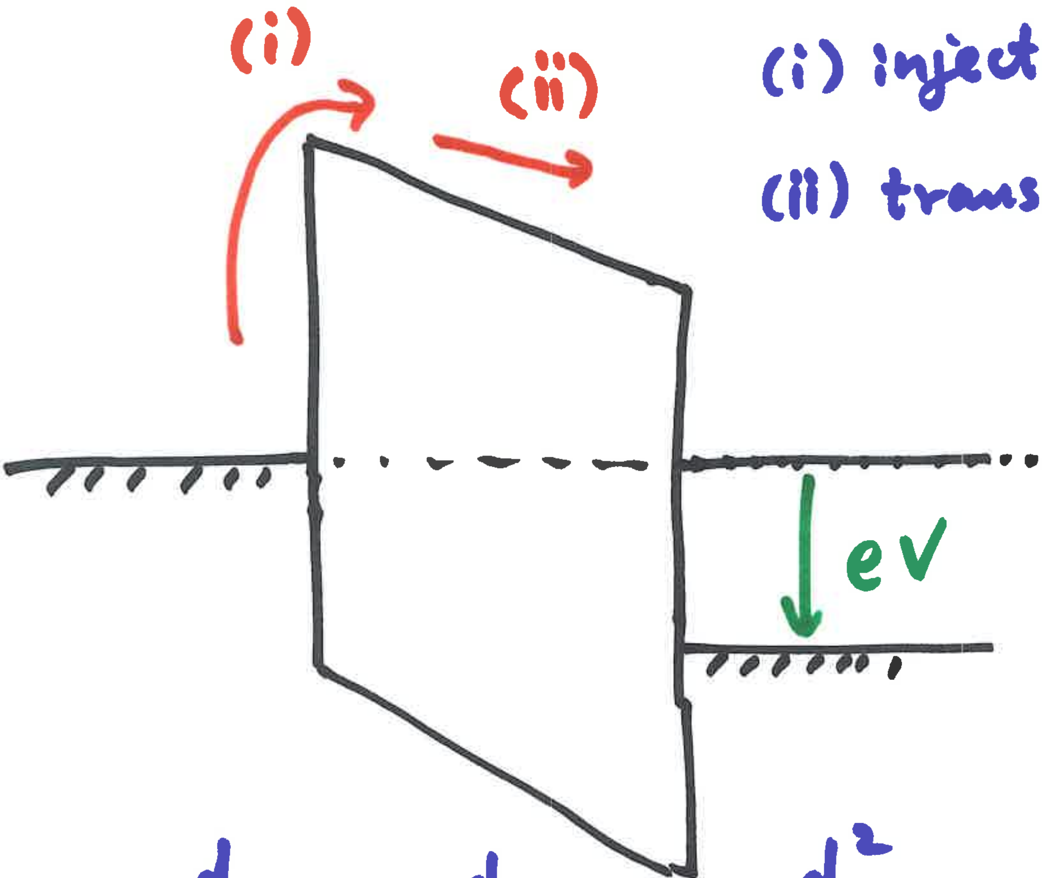
$$I_d \simeq e n_{inj} v_d \qquad v_d = \mu E_{loc}$$

"Electric field" makes a contribution to inject electrons into the insulator

High electric field region

$\begin{cases} \text{carrier injection process} & \text{(i)} \\ \text{carrier transport process} & \text{(ii)} \end{cases}$

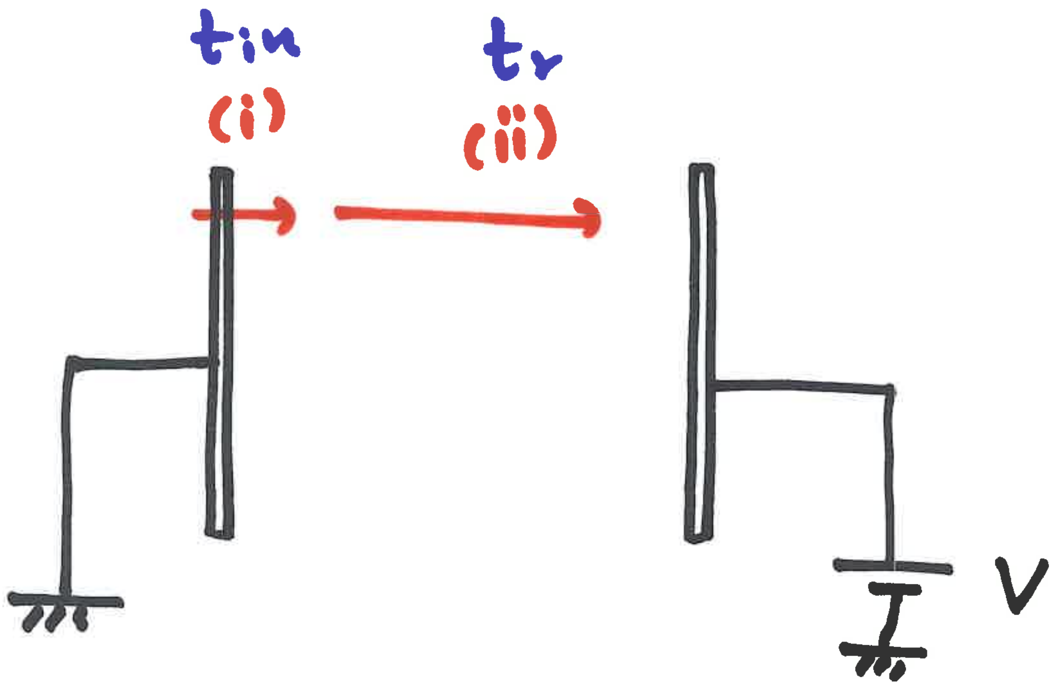




(i) injection t_{in}

(ii) transport t_r

$$t_r = \frac{d}{v} = \frac{d}{\mu E} = \frac{d^2}{\mu V}$$



$t_{in} \gg t_r$ injection limited process

$t_{in} \ll t_r$
- bulk limited
- transport limited

typical Conduction mechanism

(I) Space charge limited Current

$t_{in} \ll t_r$ (transport limited)

(II) Schottky Conduction

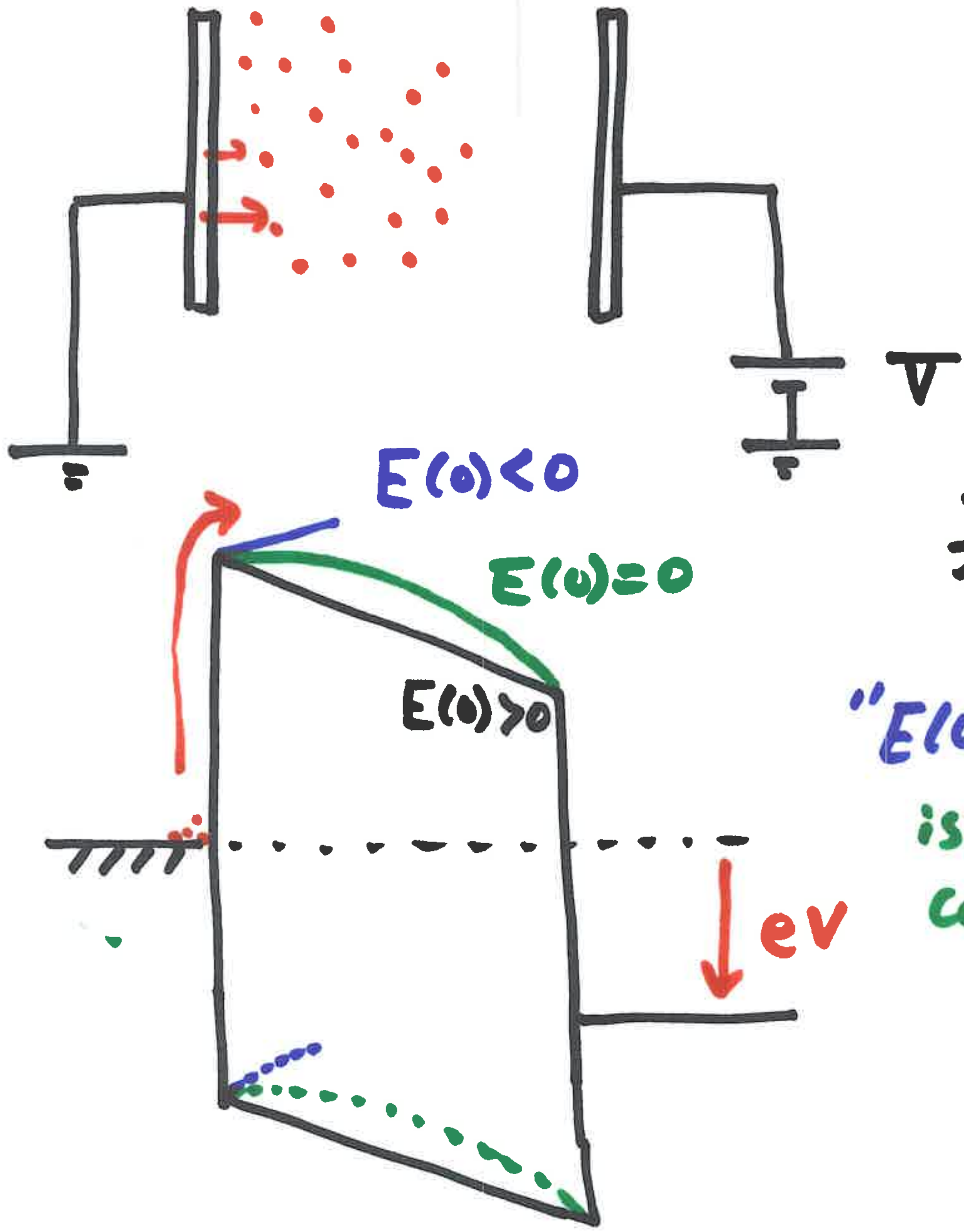
$t_{in} \gg t_r$ (injection limited)

(I) space charge limitted Current

SCLC

" Carrier injection is smooth, but carrier transport is slow"

→ carriers are accumulated in a insulator.

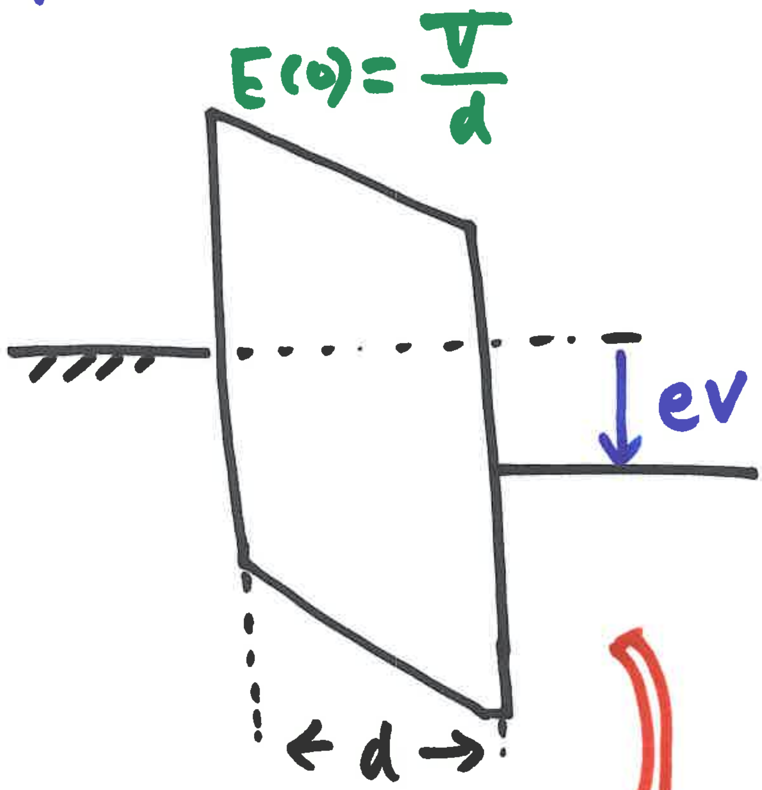


$\vec{f} = q\vec{E}$

"E(0)=0" is the boundary condition.

Sapace Charge limitted Current

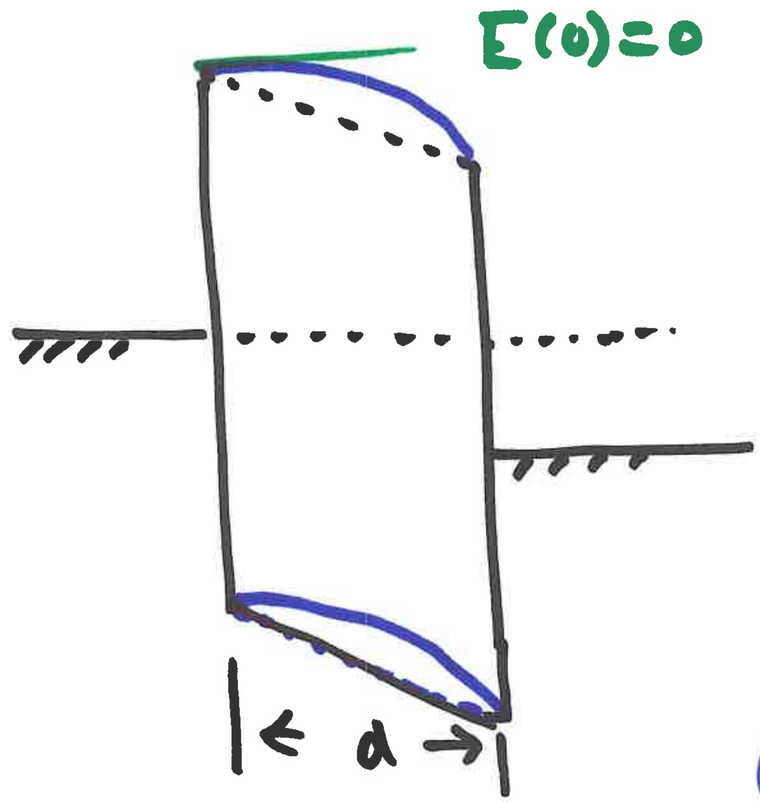
$t=0$



$$\Delta E(0) = 0 - \frac{V}{d}$$

$$= -\frac{V}{d}$$

$t \to \infty$



$\Downarrow$

electron injection

$$Q_{inj} \propto \varepsilon_0 \varepsilon_s \Delta E(0)$$

$$Q_{inj} \simeq -\frac{\varepsilon_0 \varepsilon_s}{d} V$$

$$I = -e\bar{n}\,\bar{v}$$

$$-e\bar{n} \simeq \frac{Q_{inj}}{d} = \left(+\varepsilon_0\varepsilon_s\frac{V}{d}\right)\cdot\frac{1}{d}$$

$$\bar{v} = \mu\bar{E} = \mu\frac{V}{d}$$

$$I \simeq \left(\varepsilon_0\varepsilon_s\frac{V}{d}\right)\cdot\frac{1}{d}\cdot\left(\mu\frac{V}{d}\right)$$

$$\simeq \frac{\varepsilon_0\varepsilon_s\mu}{d^3}V^2$$

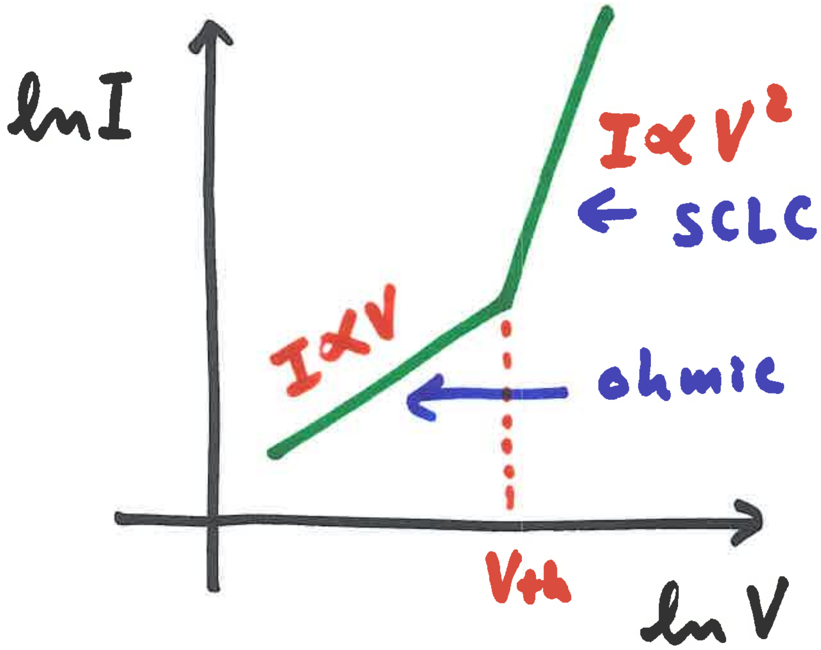
$$I \propto V^2$$

Space Charge limited Current

$$\begin{cases} I = env & v = \mu E \quad \cdots ① \\ \dfrac{dE}{dx} = -\dfrac{en}{\varepsilon_0 \varepsilon_s} & \cdots ② \\ E(0) = 0 & \cdots ③ \end{cases}$$

$$I = \frac{9}{8} \varepsilon_s \varepsilon_0 \mu \frac{V^2}{d^3}$$

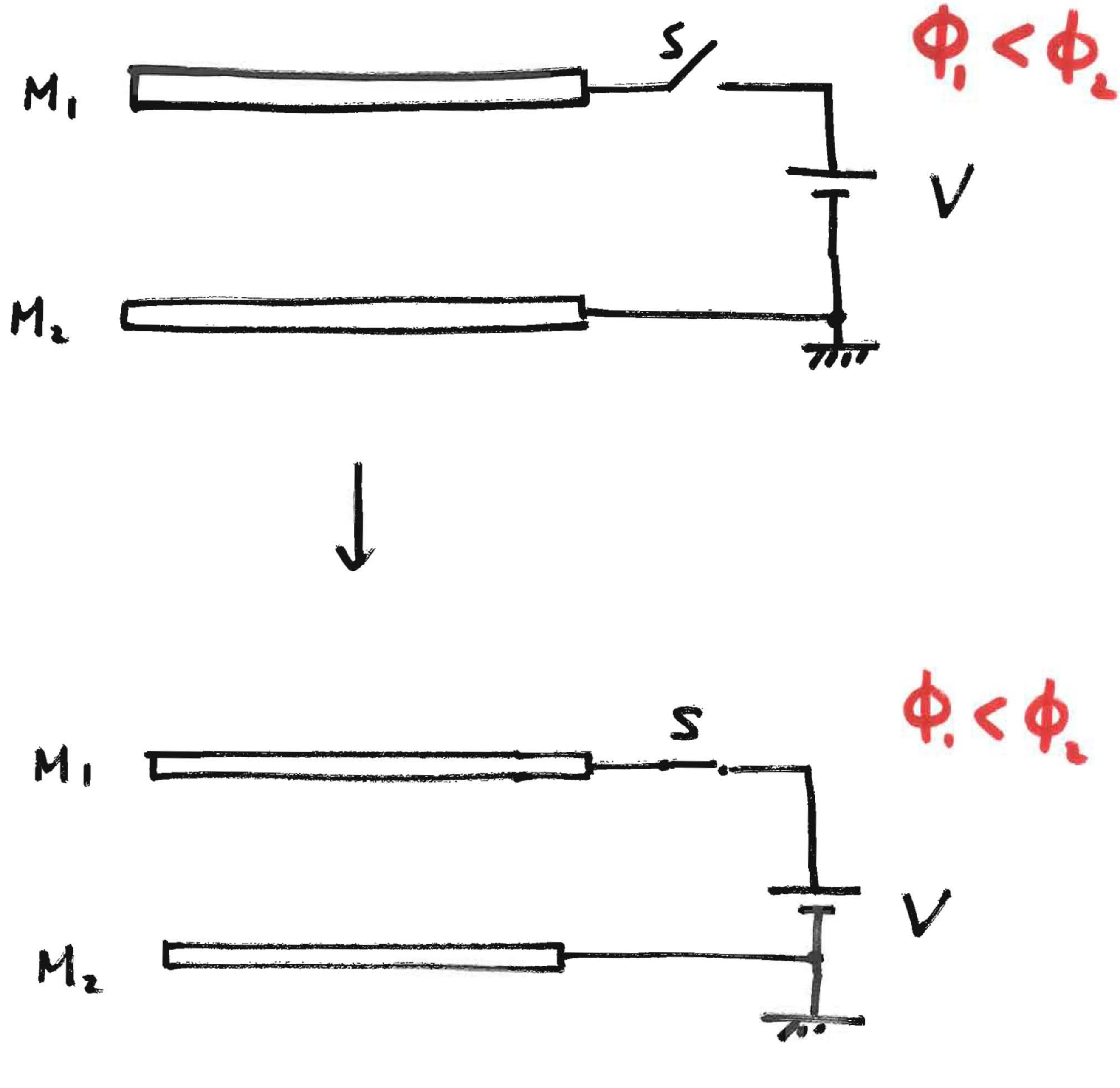
(in the text book).



at $V = V_{th}$

$$\frac{9}{8}\varepsilon_0\varepsilon_s\mu\frac{V_{th}^2}{d^3} = \frac{e n_0 \mu}{d} V_{th}$$

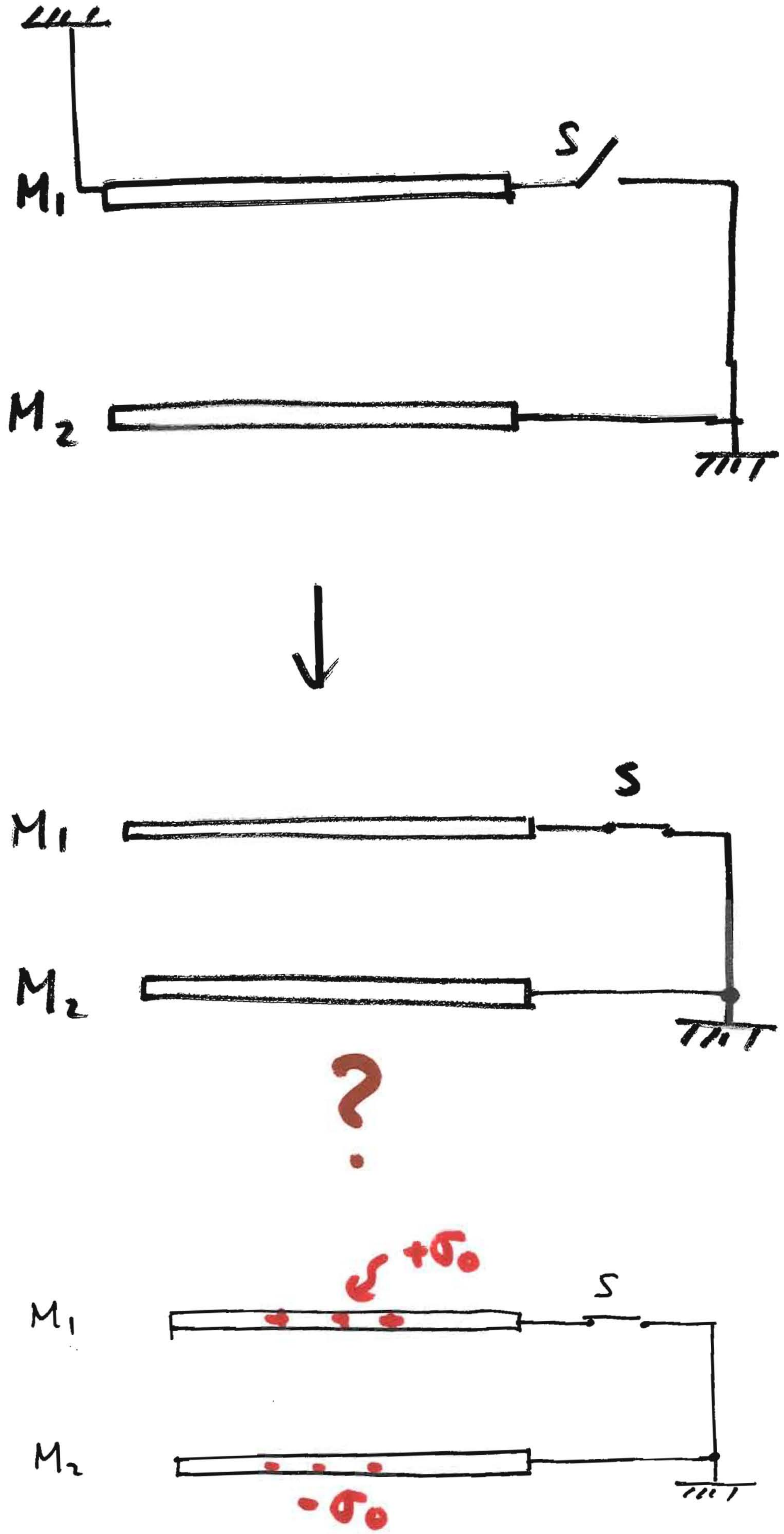
$$\therefore \quad \underbrace{\frac{9}{8}\left(\varepsilon_0\varepsilon_s\frac{1}{d}\right)V_{th}}_{\text{injected charge}} = \underbrace{e n_0 d}_{\text{excited electrons at the equilibrium state}}$$



?

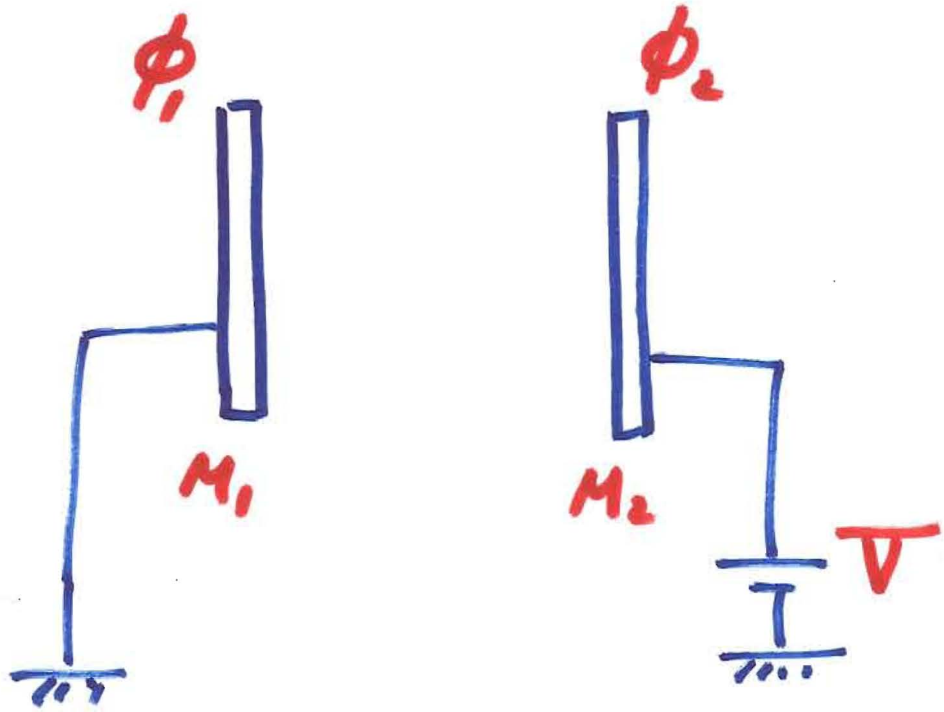
Work function of metal M1, M2
is different

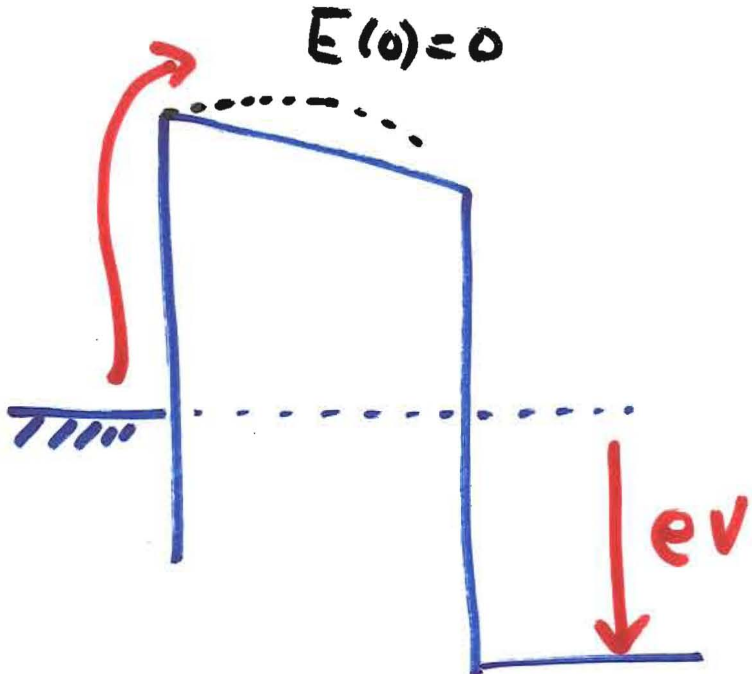
$\phi_1 < \phi_2$



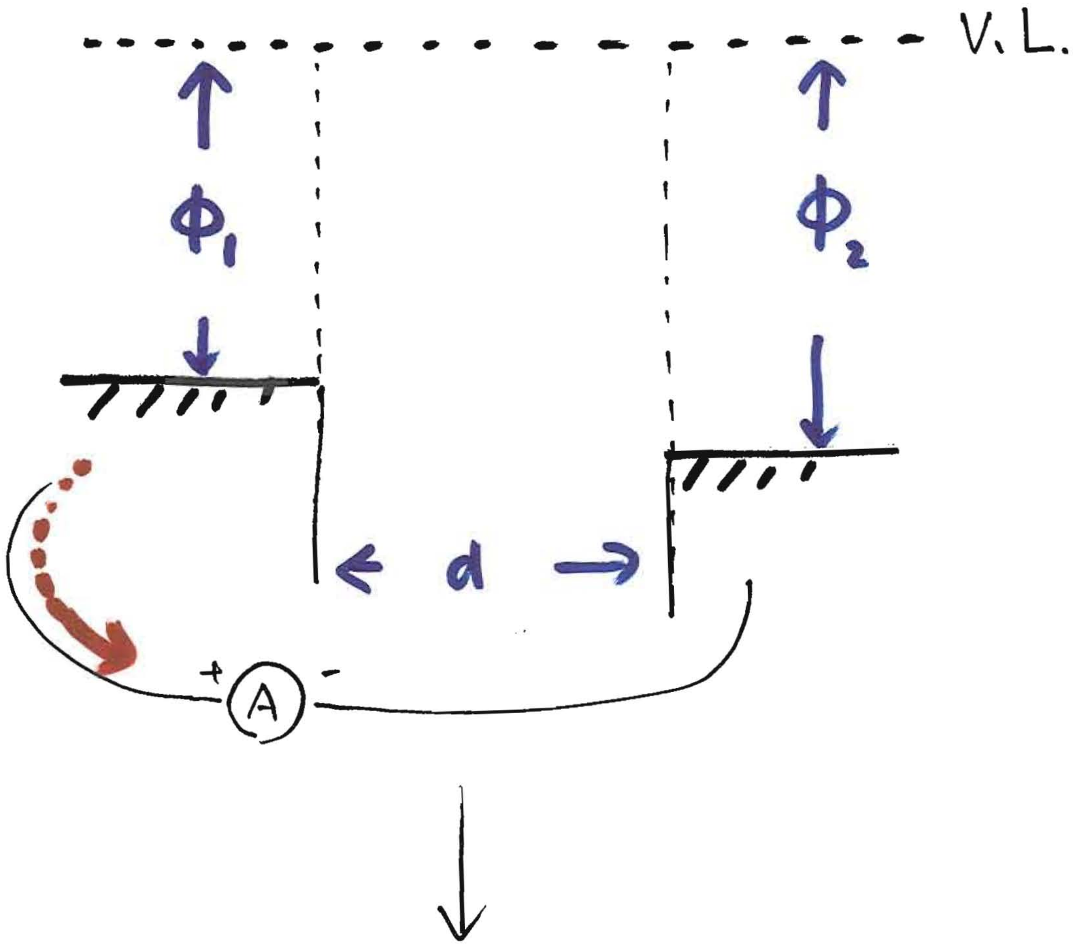
Space charge Limited Current

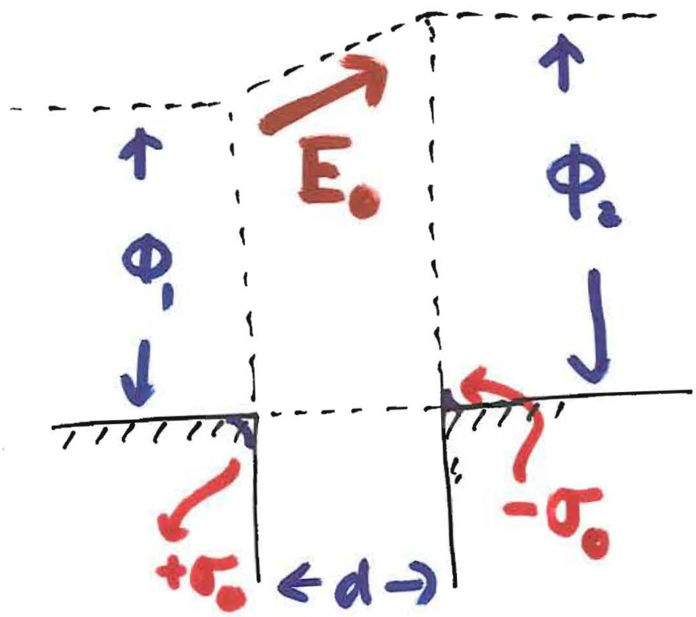
SCLC





$$\boxed{\Delta E(0) = 0 - \frac{V}{d} + \frac{\Delta\phi}{d}}$$





$$E_0 = \frac{\sigma_0}{\varepsilon_0} \left(= \frac{\Delta\phi}{d} \right)$$

$\vec{E_0}$: internal electric field

$$E_0 \cdot d = \phi_2 - \phi_1 = \Delta\phi$$

$$\Delta\phi = \frac{\sigma_0}{\varepsilon_0} d \quad //$$

$$I = -e\bar{n}\,\bar{v}$$

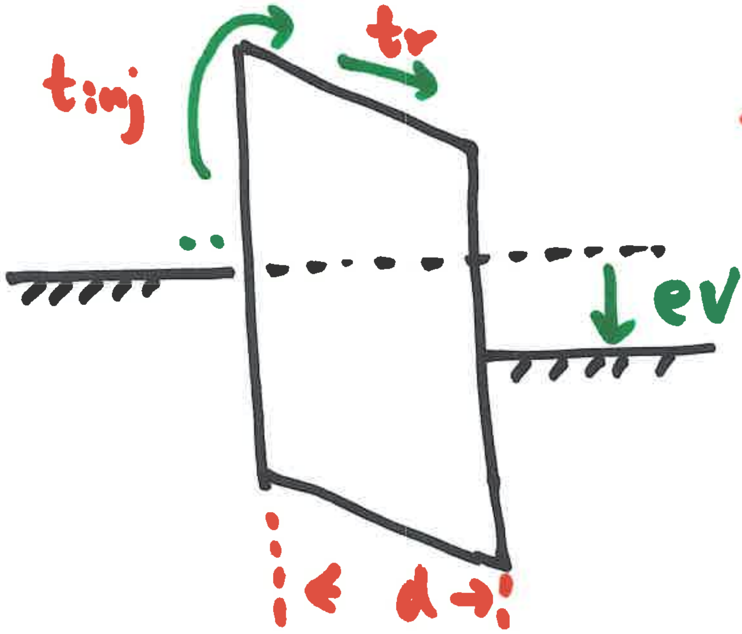
$$-e\bar{n} = \frac{Q_{inj}}{d} = \left(\varepsilon_0 \varepsilon_s \frac{\Delta\phi + V}{d}\right) \cdot \frac{1}{d}$$

$$\bar{v} = \mu \bar{E} = \mu \frac{V}{d}$$

$$I \simeq \left(\varepsilon_0 \varepsilon_s \frac{V + \Delta\phi}{d}\right) \cdot \frac{1}{d} \cdot \left(\mu \frac{V}{d}\right)$$

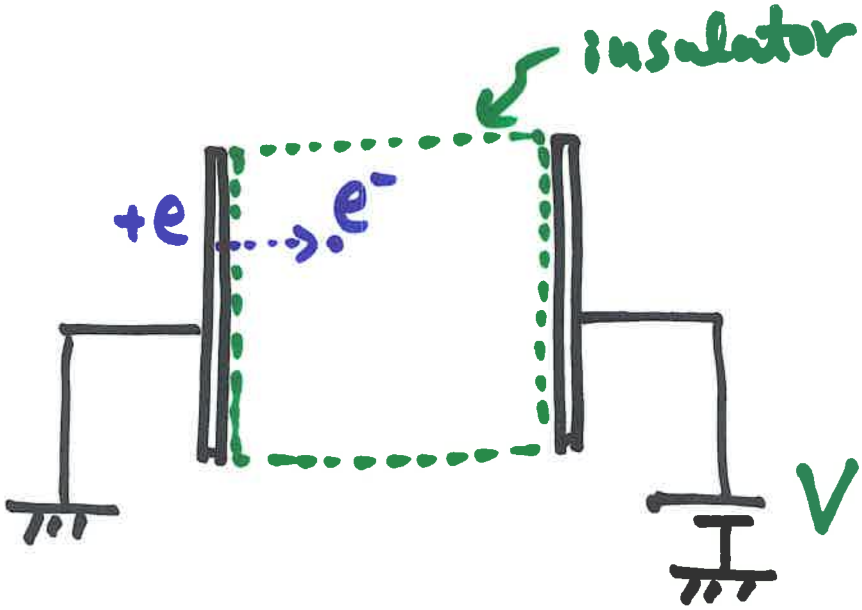
$$\simeq \frac{\varepsilon_0 \varepsilon_s \mu}{d^3} V (V + \Delta\phi) \quad //$$

Schottky Current ⟶ Schottky effect



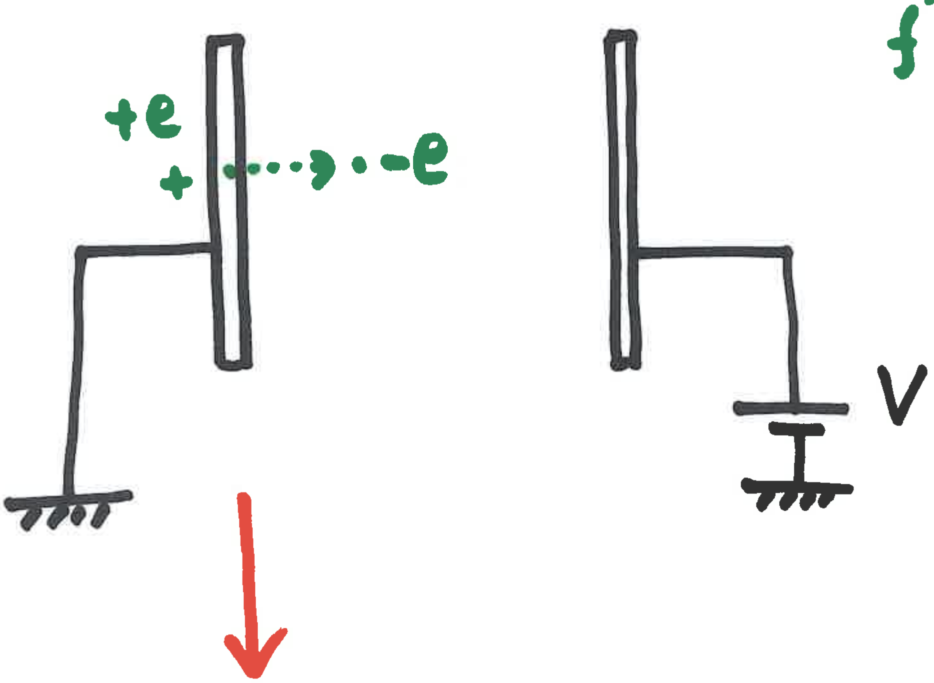
$t_{inj} > t_r$

" no accumulation of injected electrons in insulator "



what happens when electron-e inject into the insulator

$$\vec{f} = q\vec{E}$$



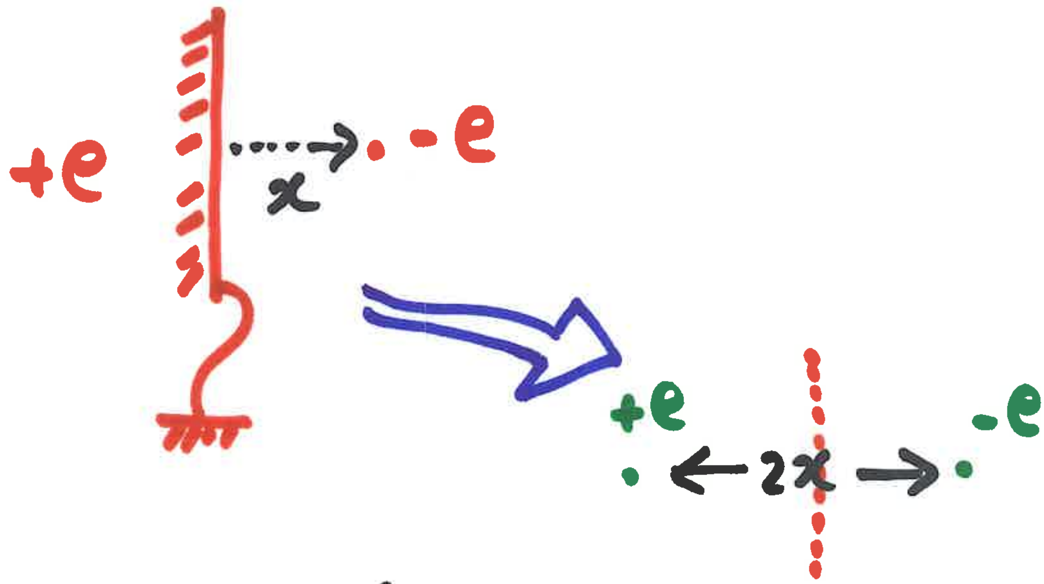


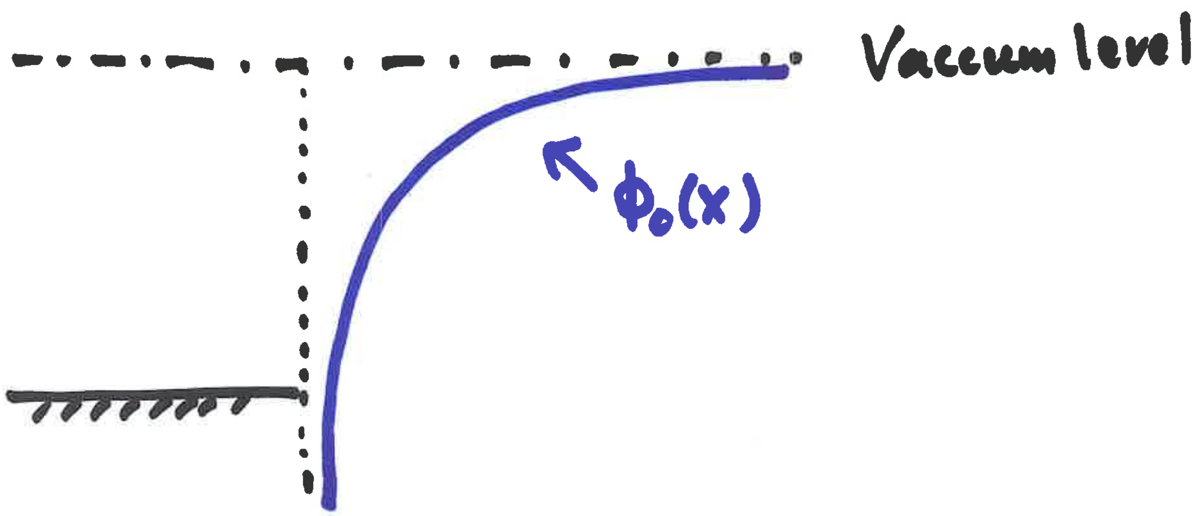
image force

$$f = \frac{1}{4\pi\varepsilon_0\varepsilon_s}\frac{e^2}{(2x)^2} = \frac{e^2}{16\pi\varepsilon_0\varepsilon_s x^2}$$

Coulomb force

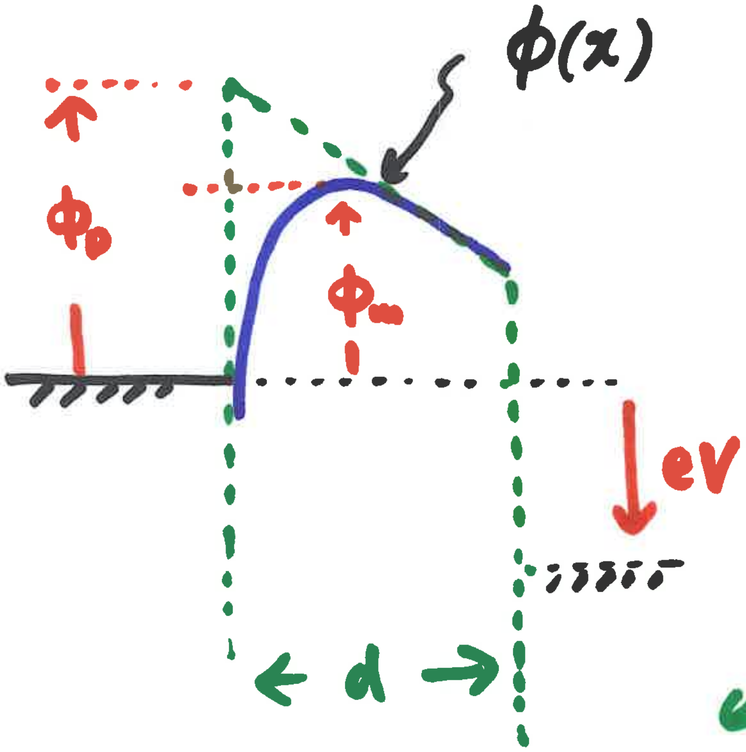
$$f = -\frac{\partial \phi_o(x)}{\partial x}$$

$$\phi_o(x) = -\int_{\infty}^{x} -f\,dx = -\frac{1}{16\pi\varepsilon_o\varepsilon_s}\frac{e^2}{x}$$



Injected electrons experience potential field $\phi_o(x)$

" If we define $\phi_o(x)$, we do not need to consider interaction between electrode and injected electrons "



$E = \frac{V}{d}$

Potential distribution changes

$$\phi(x) = \phi_0(x) - eEx$$

$$\phi_0(x) = -\frac{1}{16\pi\varepsilon_0\varepsilon_s}\frac{e^2}{x}$$

effective barrier height

$$\phi_0 \longrightarrow \phi_m$$

$$\Delta = \phi_0 - \phi_m$$

Results of Schottky effect.

Calculation

$$\frac{d\phi(x)}{dx} = 0$$

at $x = x_m$

$$\phi(x_m) = \left(\frac{e^3 E}{4\pi\varepsilon_s\varepsilon_0}\right)^{\frac{1}{2}}$$

Current

$$I = env$$

$$\propto e n_{inj} \exp\left(-\frac{H}{kT}\right)$$

at $E = 0$ $\quad H = \Phi_0$

$E \neq 0$ $\quad H \rightarrow \Phi_0 - \phi(x_m)$

$$I \propto e n_{inj} \exp\left(-\frac{\Phi_0}{kT}\right) \cdot \exp\left(-\frac{\phi(x_m)}{kT}\right)$$

$$\ln I \propto \sqrt{E}$$