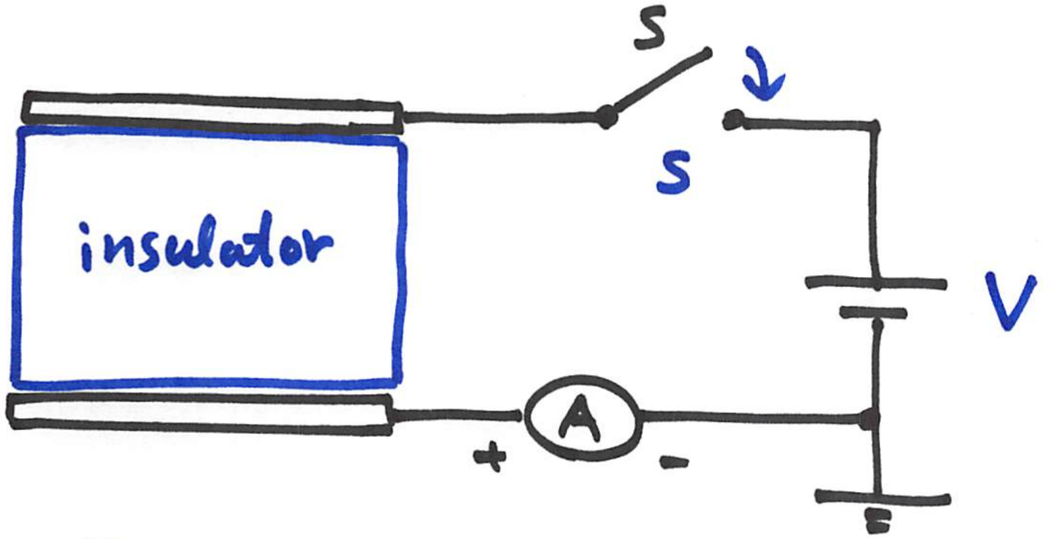
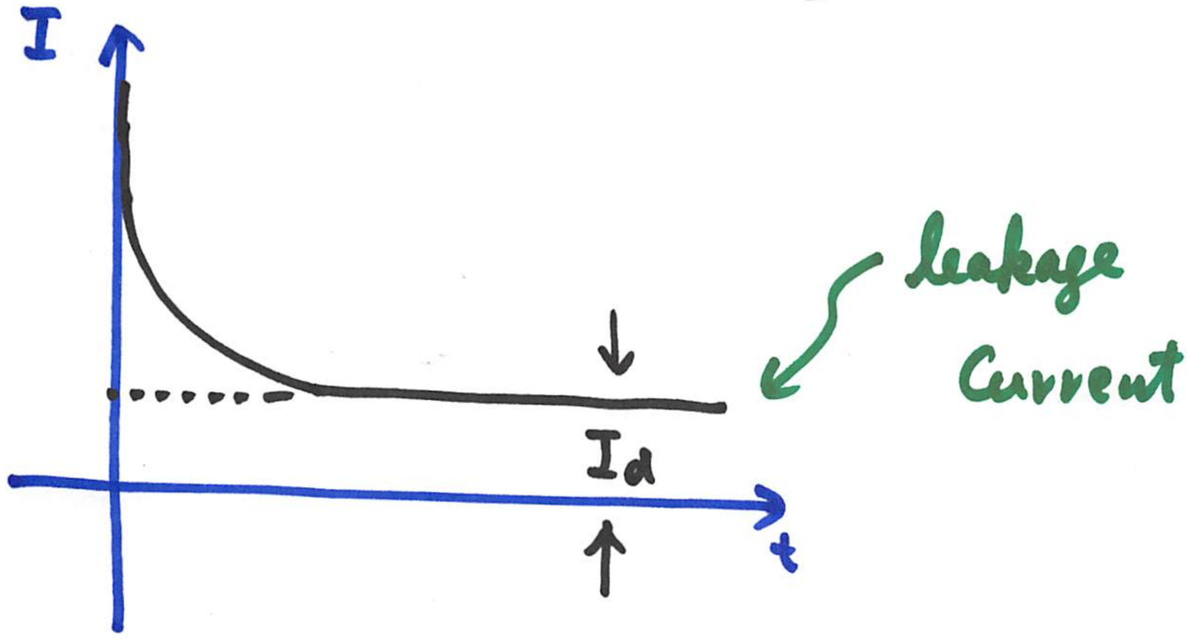
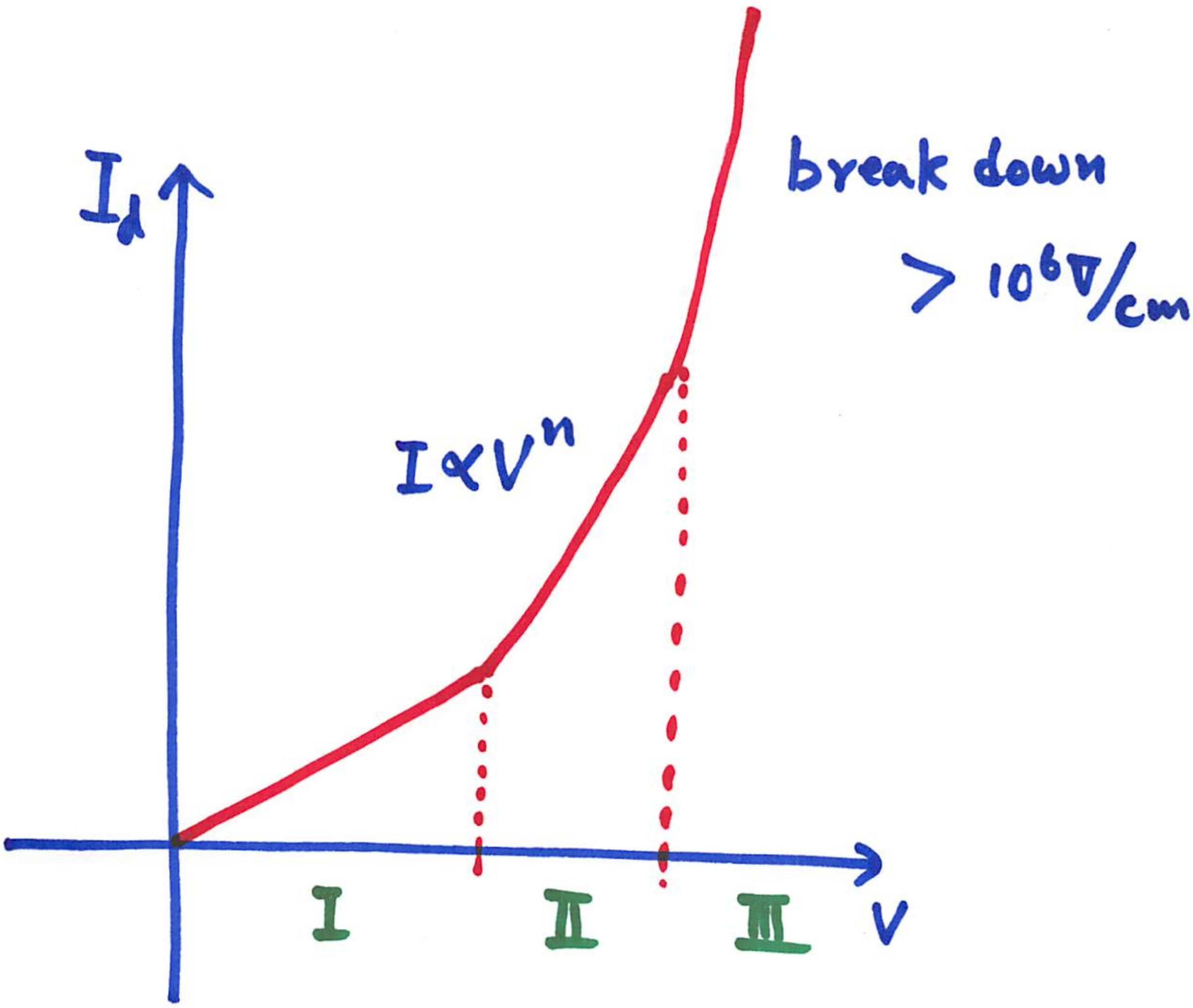
Conduction mehanism of insulator





I_d : ?

$$I_d = \underset{\sim}{e}\,\underset{\sim}{n}\,\underset{\sim}{v}$$



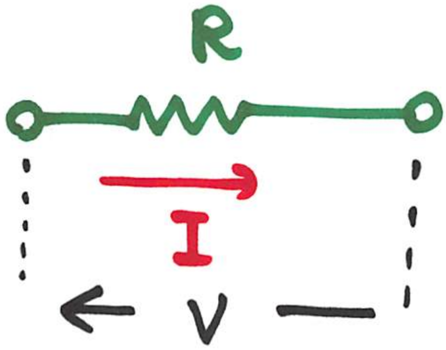
I Low electric field region

$$I \propto V$$

II High electric field region

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

Ohm law



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

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

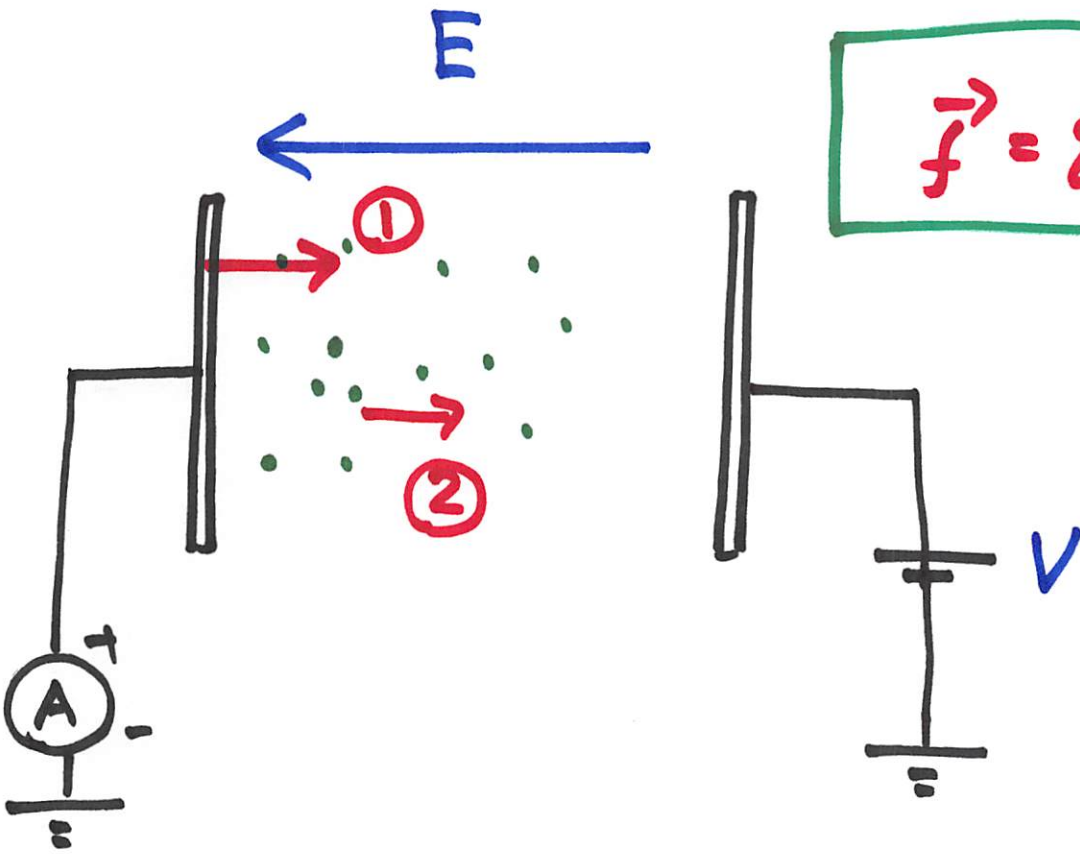
$$j = env$$

$$= en\mu E$$

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

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

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



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

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

$$J = en_0 v$$
$$= en_0 \mu E \; \left(= en_0 \mu \frac{V}{d}\right)$$

$I \propto V$

II) High electric field region

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

$$J = en_{inj} v$$

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

⊙ injection mehanism !!

Conduction Mechanism of Insulator

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

en: carrier

v_d: velocity

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

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

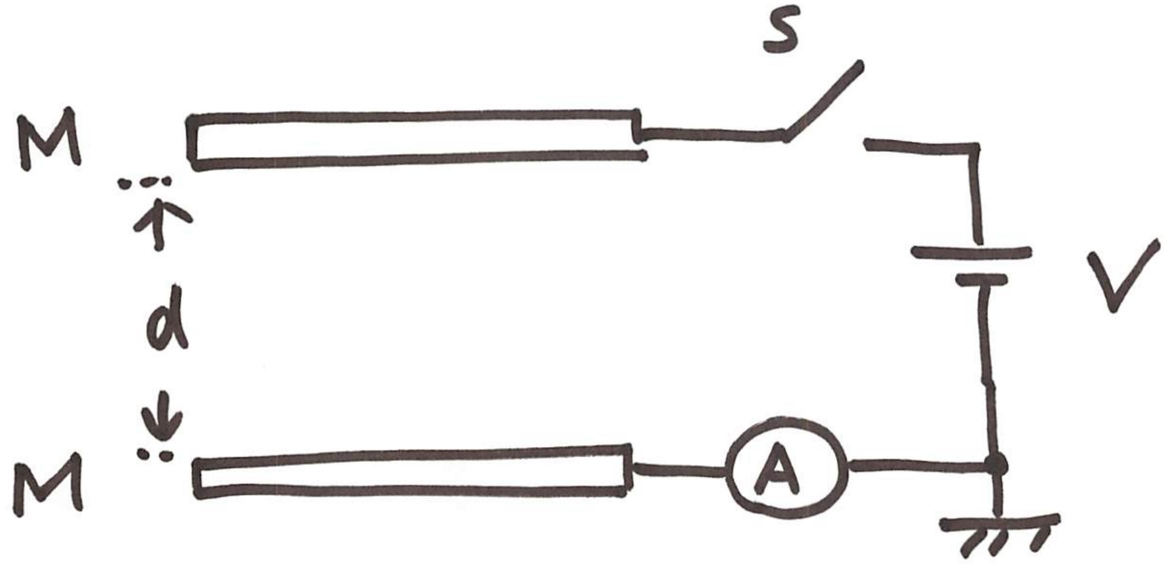
(1.) What is en ?

(2.) How μ is determined

. Band Conduction ?

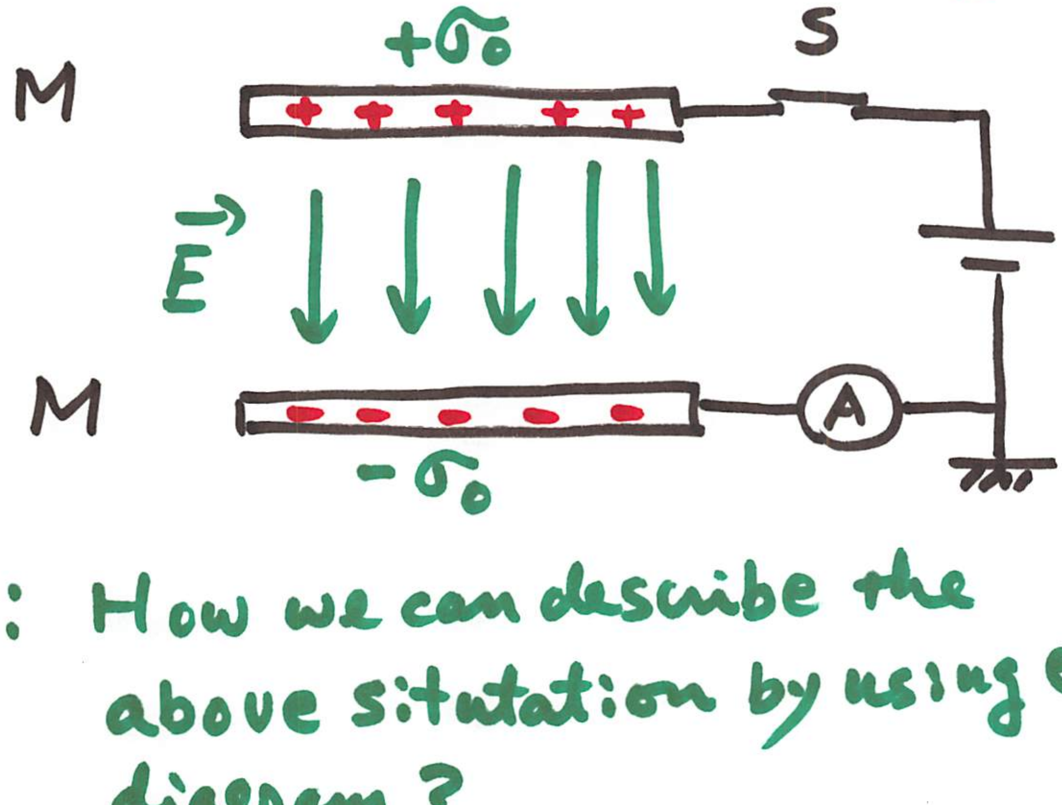
. Hopping Conduction ?

⋮



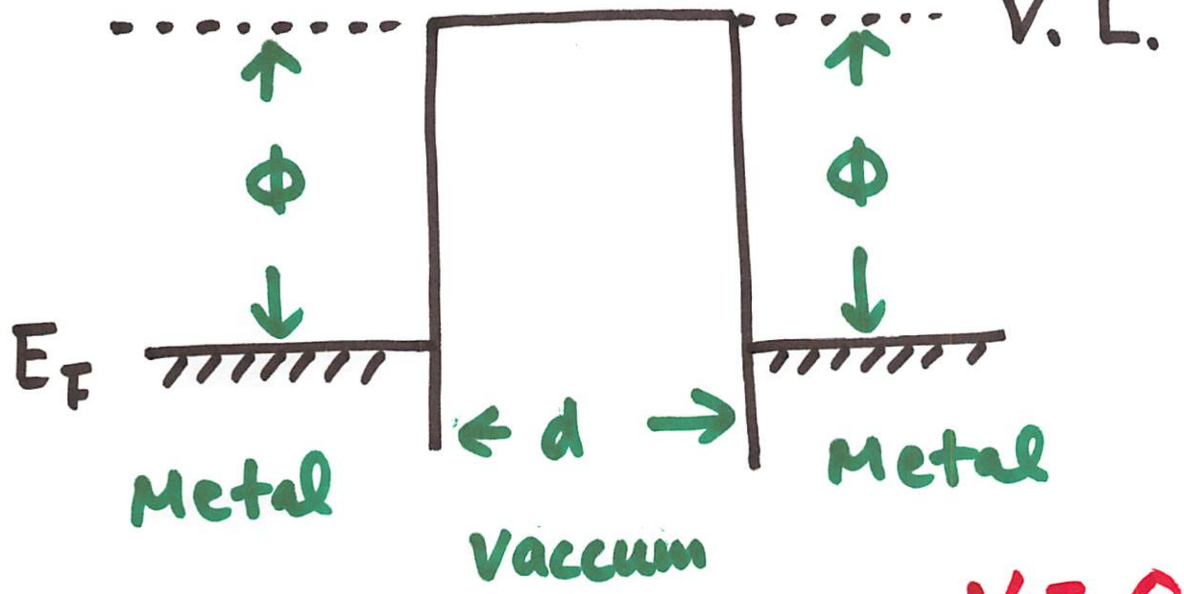
in vaccum

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



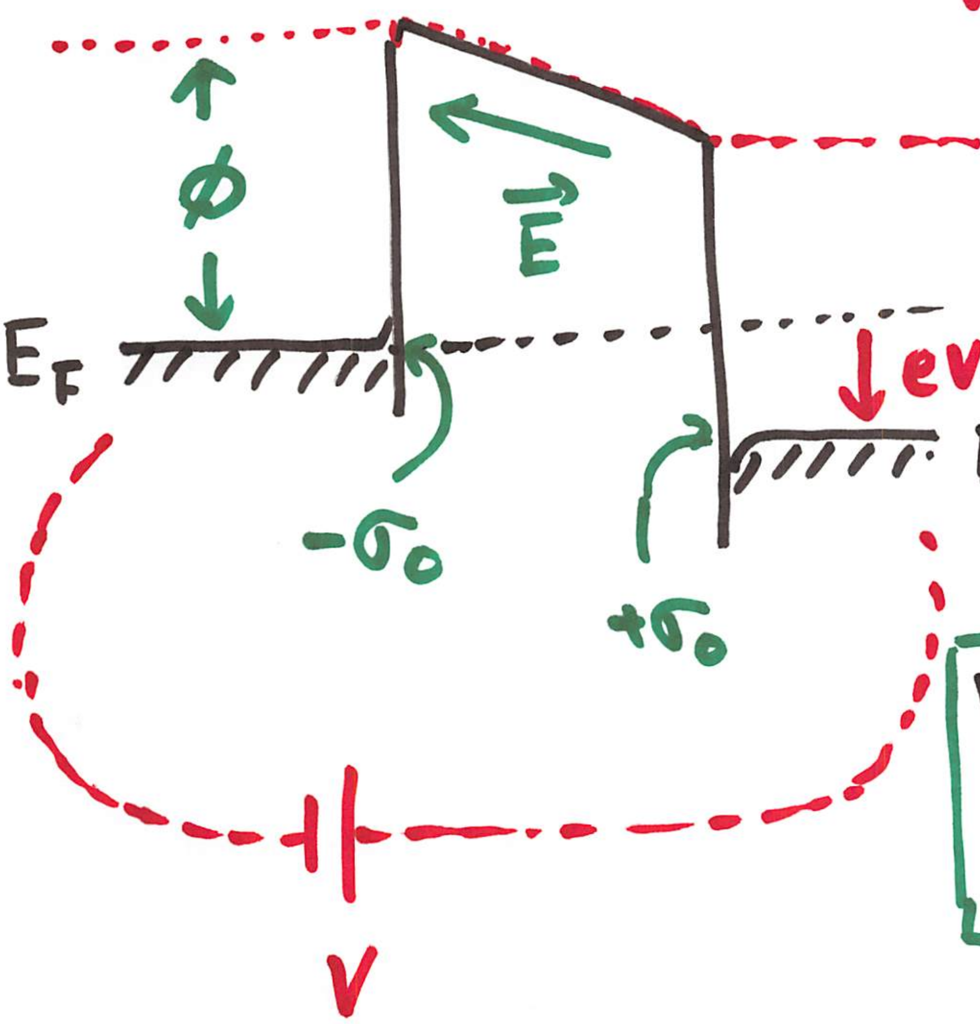
Q: How we can describe the above situation by using energy diagram?

Q: what is metal "M"?



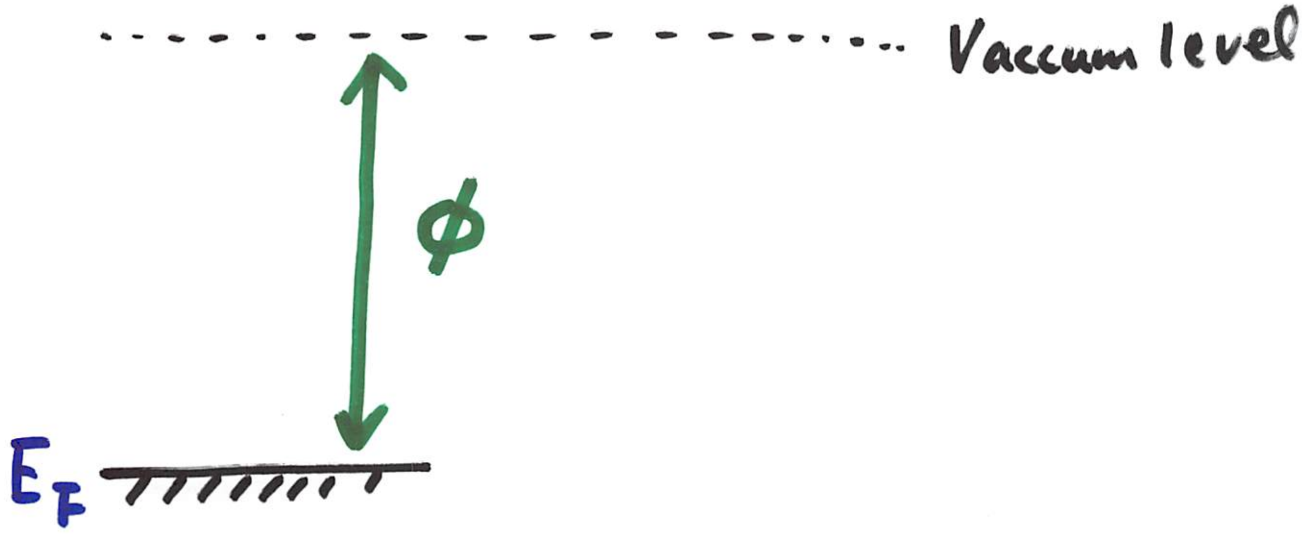
$V = 0$

$V = V$



$$\boxed{E = \frac{\sigma_0}{\varepsilon_0}}$$

$$\boxed{\begin{aligned} V &= E d \\ &= \frac{\sigma_0}{\varepsilon_0} d \end{aligned}}$$



Metal

ϕ : Work function

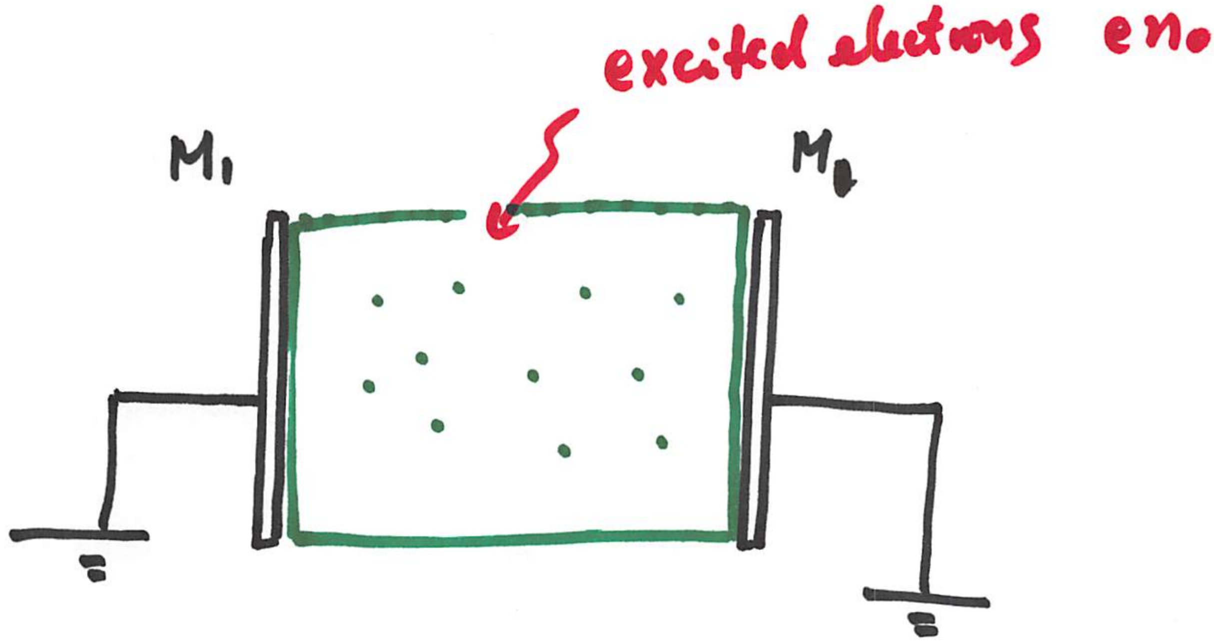
$$M \longrightarrow M^+ + e$$

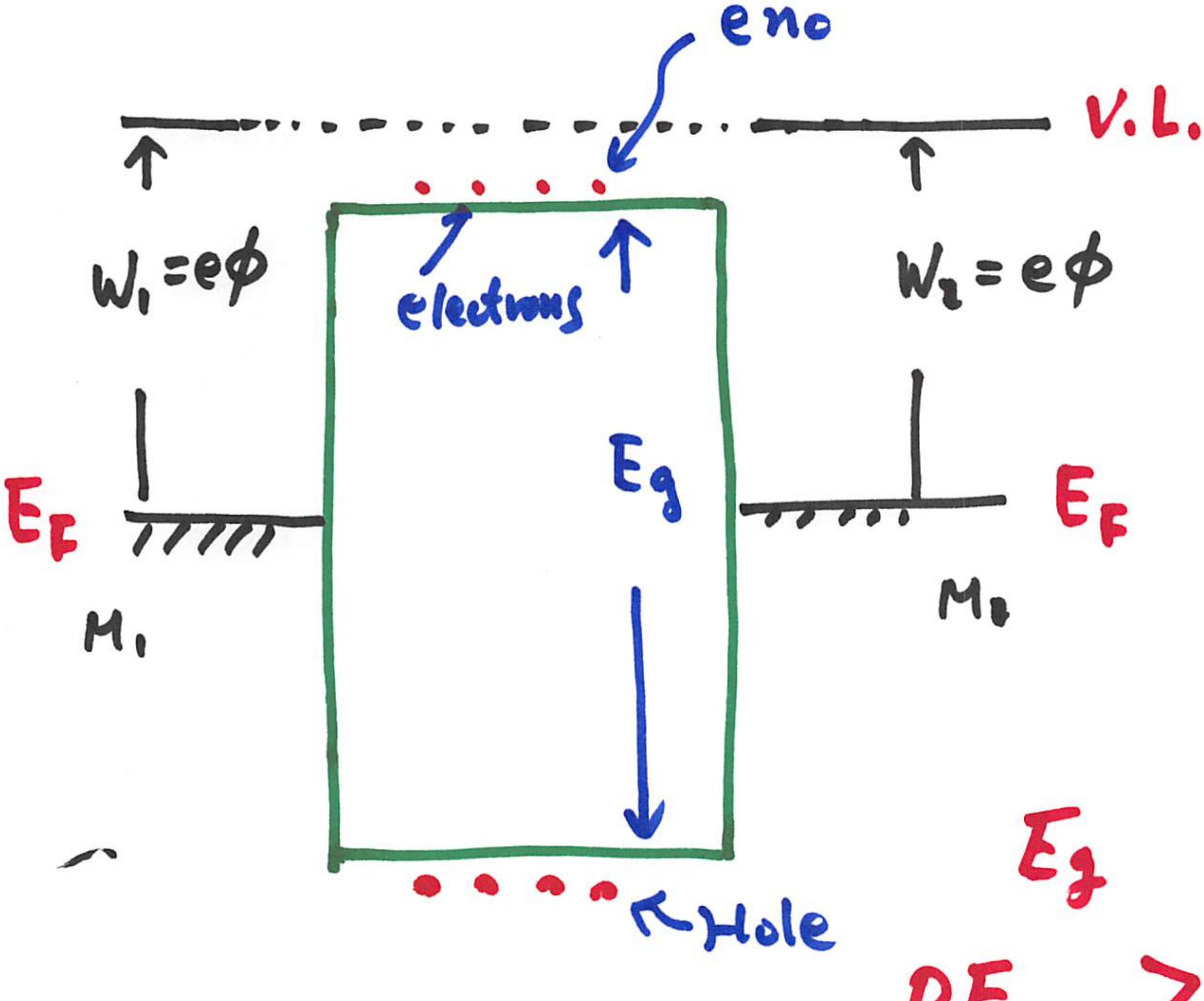
e.g. Au : 4.9 eV

Al : 4.0 eV

Cs : 1.94 eV

K : 1.6 ~ 2.3 eV





E_g

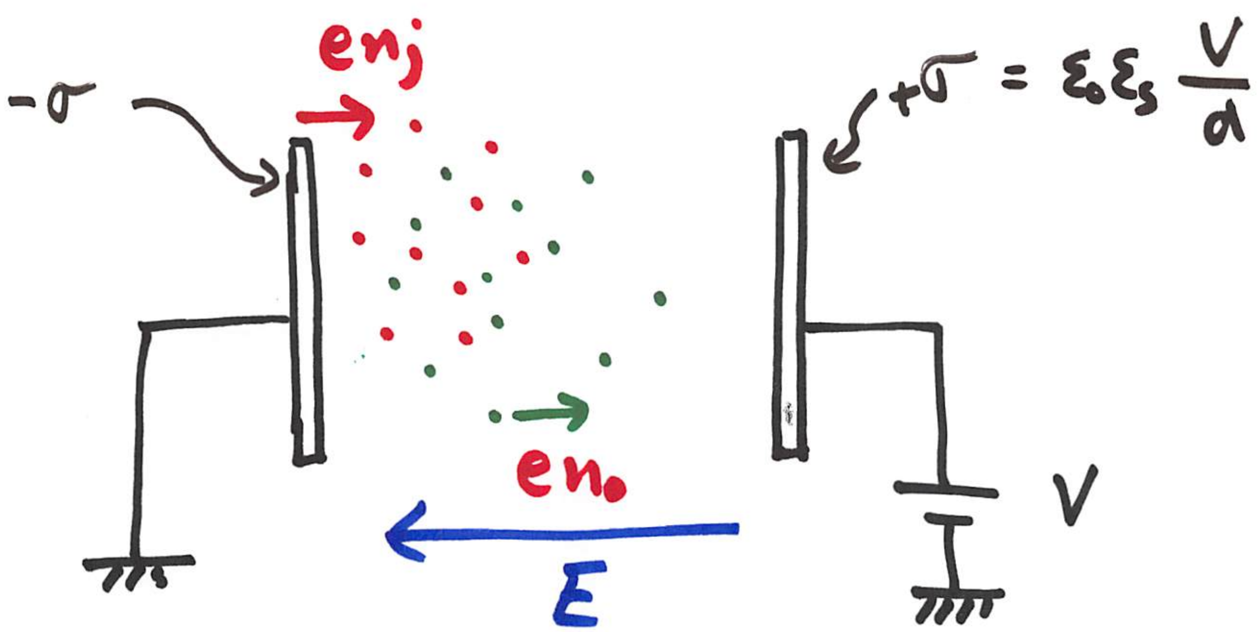
PE. $> 7eV$

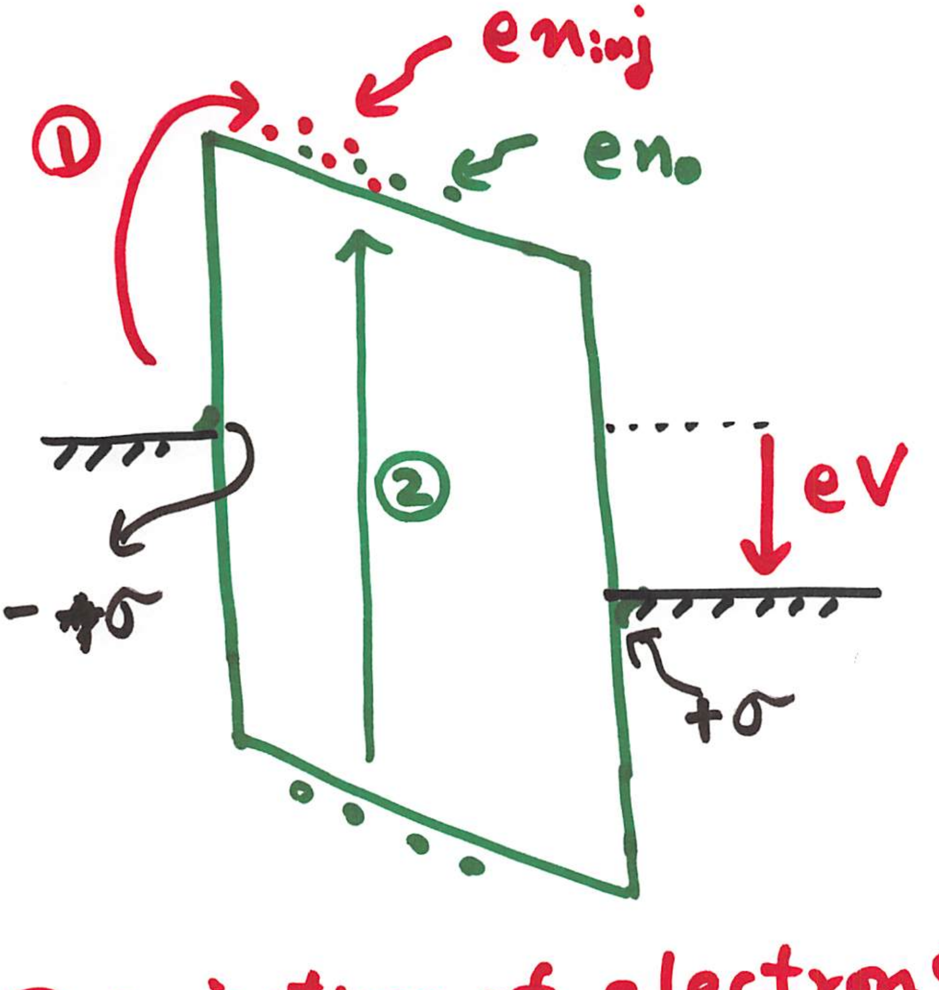
diamond $\sim 5.0eV$

$S_i \sim 1.1eV$

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

(excited electron density)





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

space charge field

① injection of electrons (excess electrons)

② excited electrons at equilibrium

Low electric field region

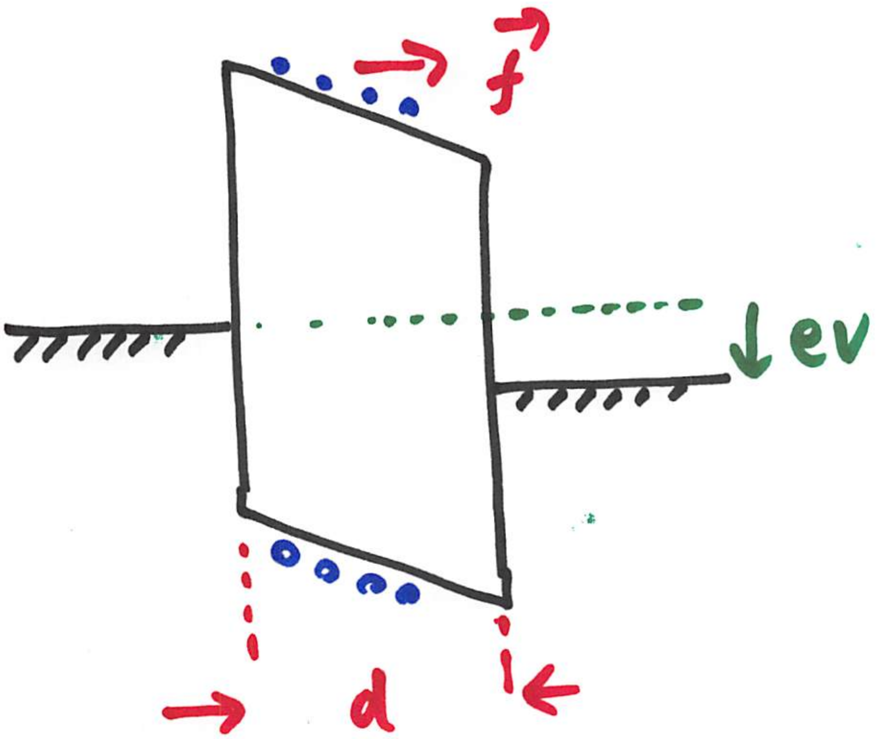
$\simeq$ thermodynamic equilibrium is established

$$I_d \simeq e n v_d$$

$$en \simeq en_0$$

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

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



$$I_d \simeq en_0 \mu E = \left(en_0 \mu \frac{1}{d}\right) V$$

$$= KV$$

ohmic current!!

"Electric field" is working to move excited electrons.

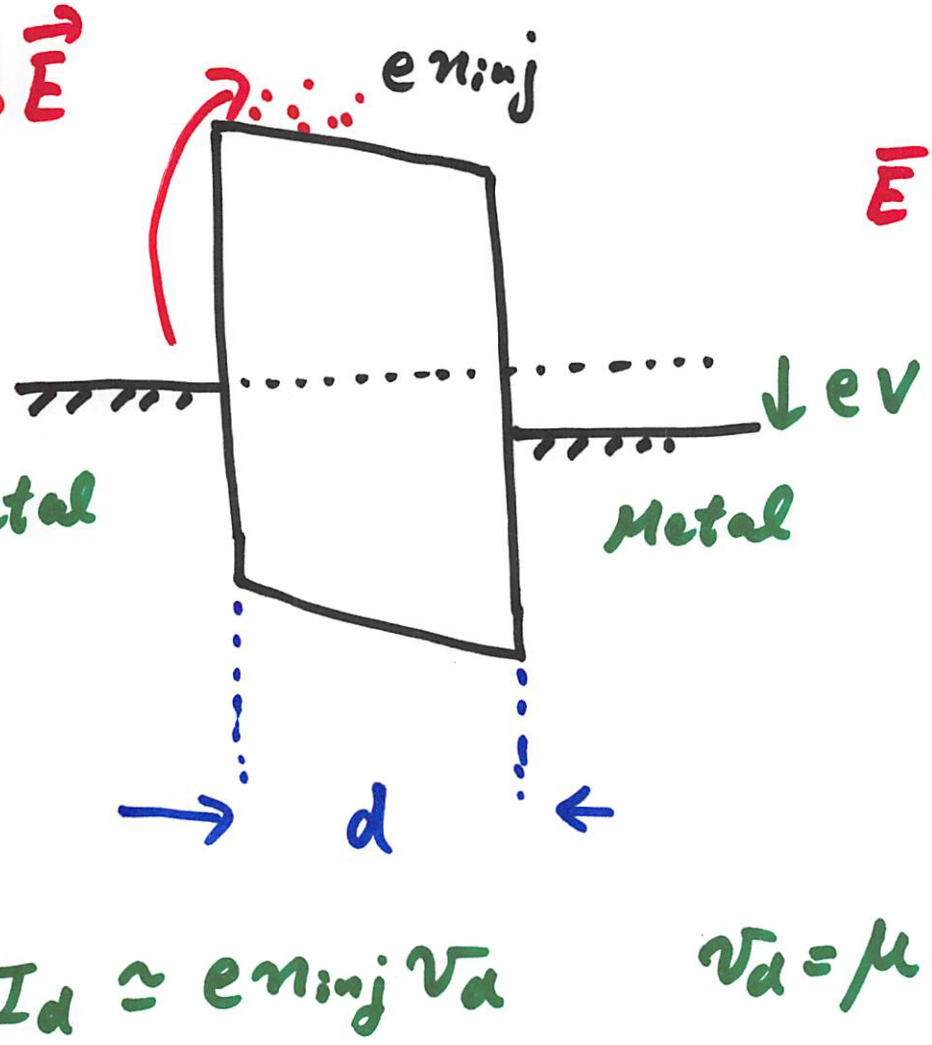
High Electric Field Region

Main carriers are injected electrons

$I_d = e n v_d$

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

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



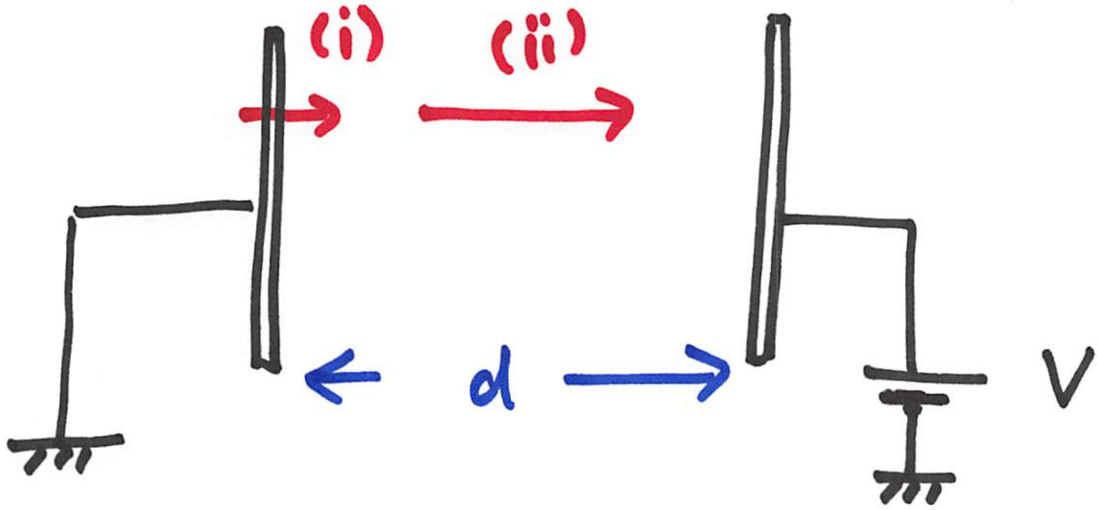
$E = \frac{V}{d}$

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

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

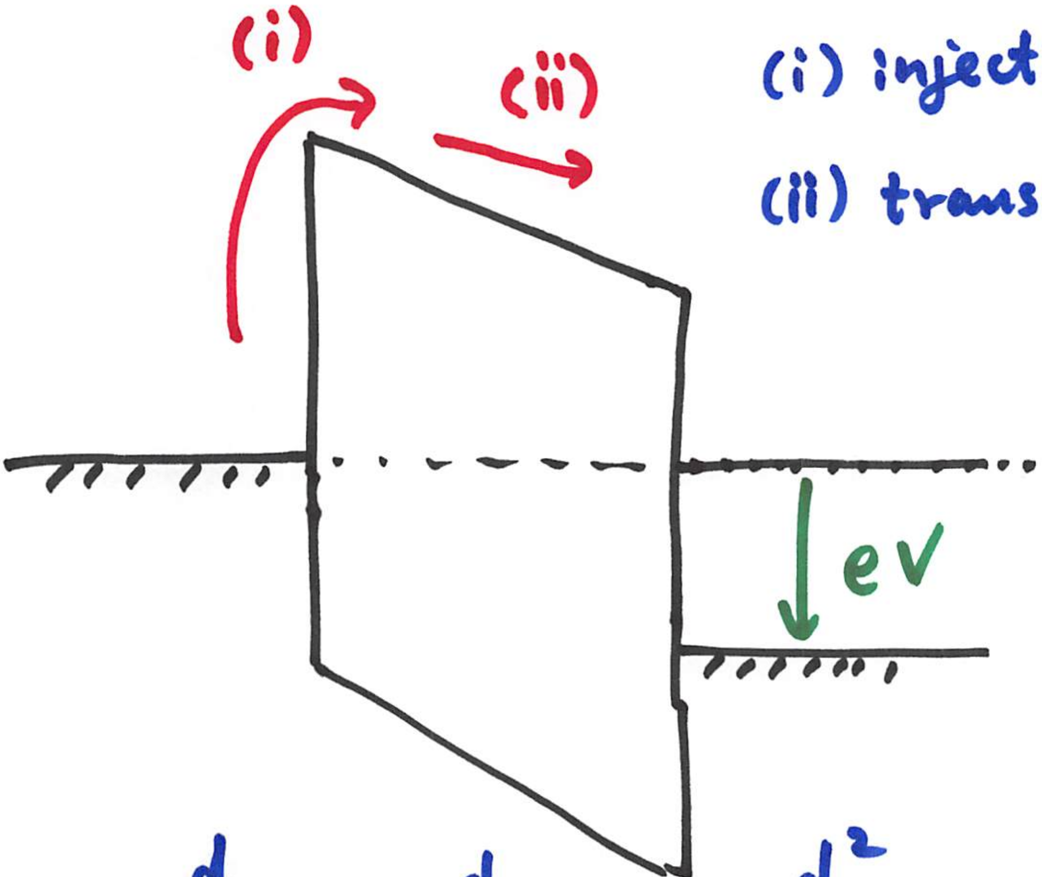
High electric field region

- carrier injection process (i)
- carrier transport process (ii)

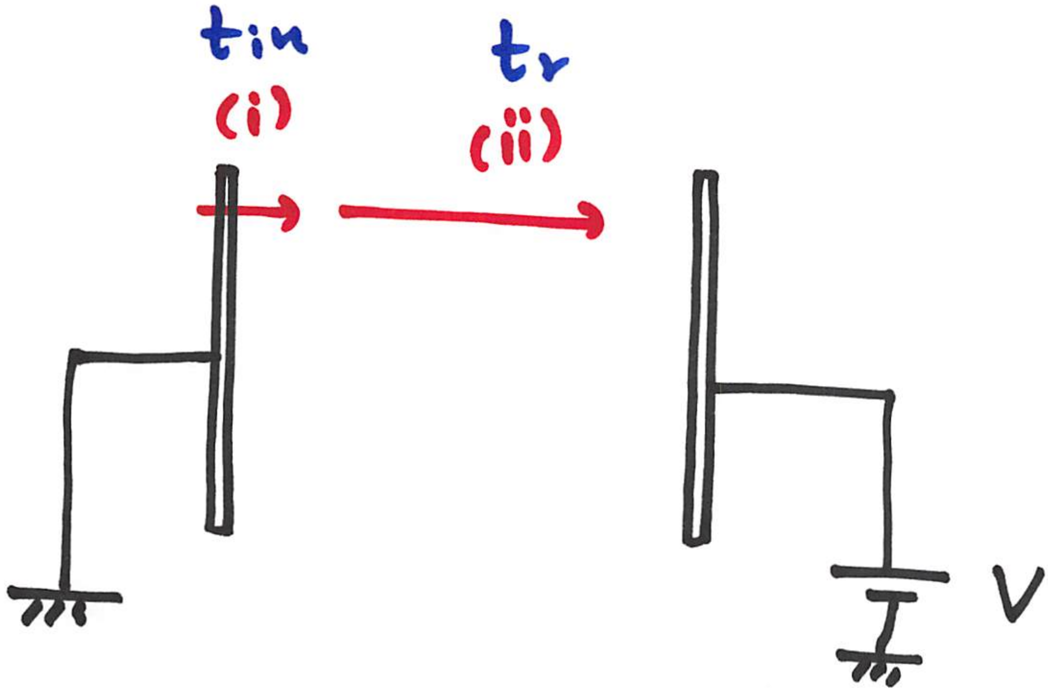


(i) injection t_{in}

(ii) transport t_r



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



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

$t_{in} \ll t_r$

- bulk limitted
- transport limitted

typical Conduction mechanism

(I) Space charge limitted Current

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

(II) Schottky Conduction

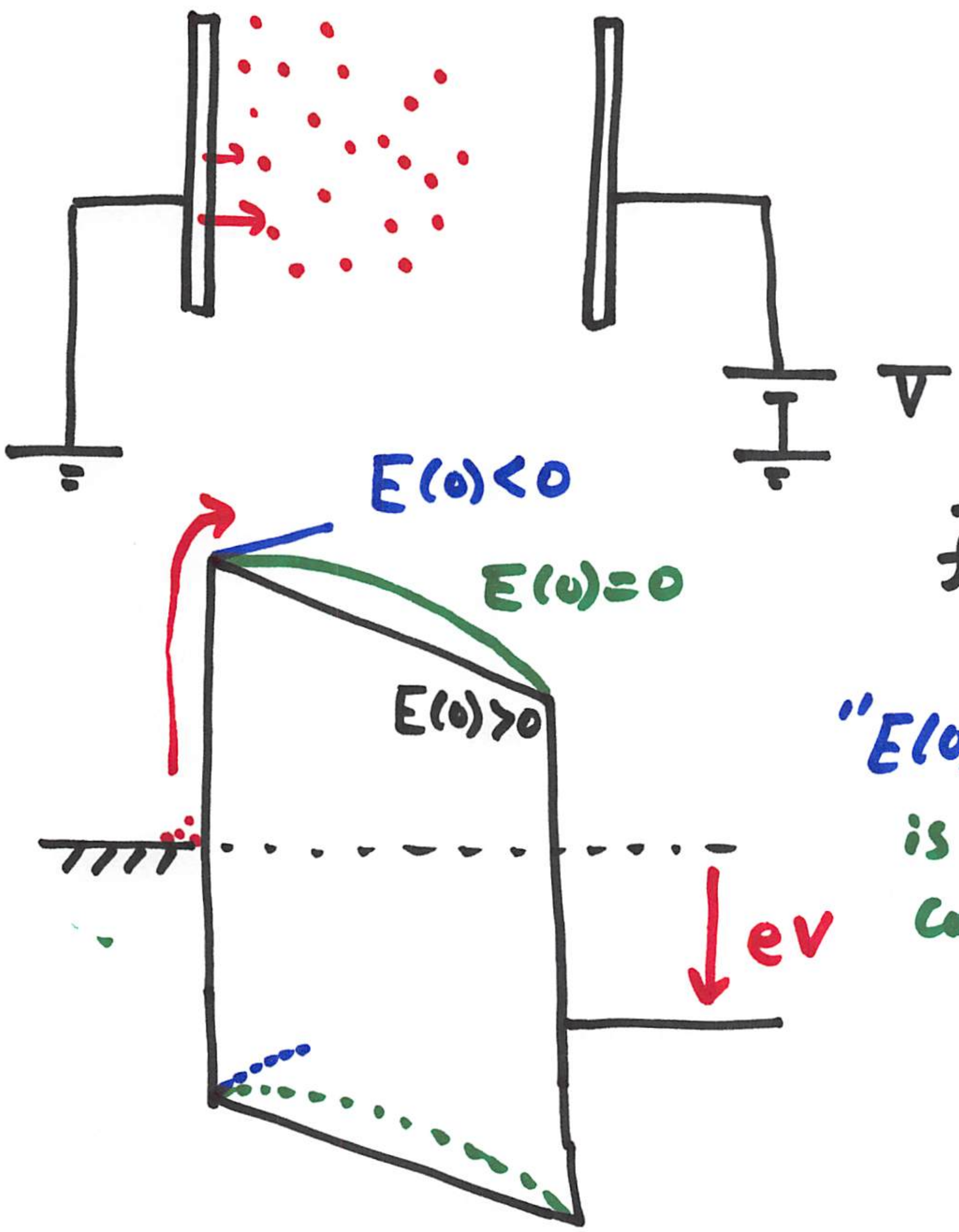
$t_{in} \gg t_r$ (injection limitted)

(I) space charge limited Current

SCLC

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

→ carriers are accumulated in a insulator.

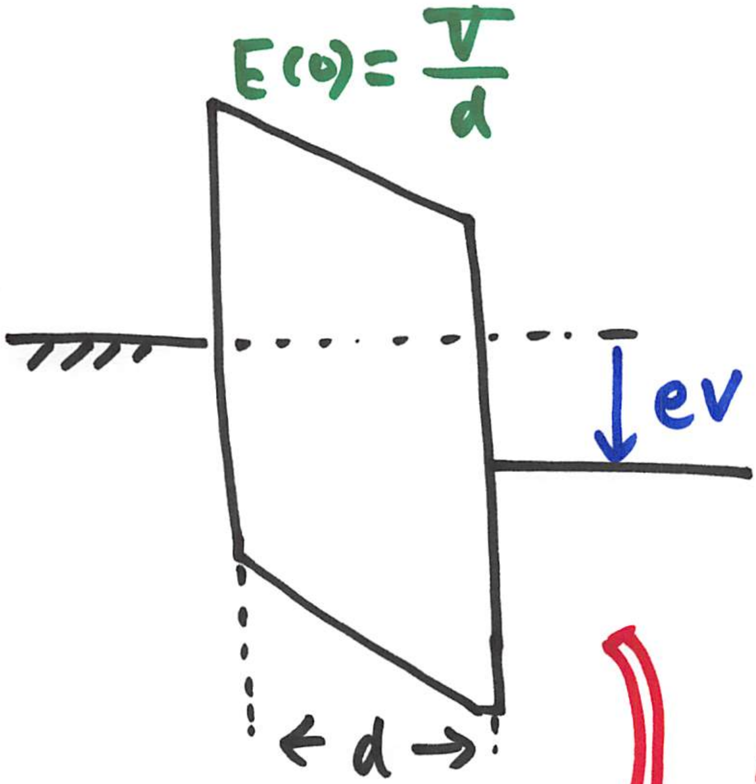


$\vec{f} = q\vec{E}$

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

Sapace Charge limitted Current

$t=0$



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

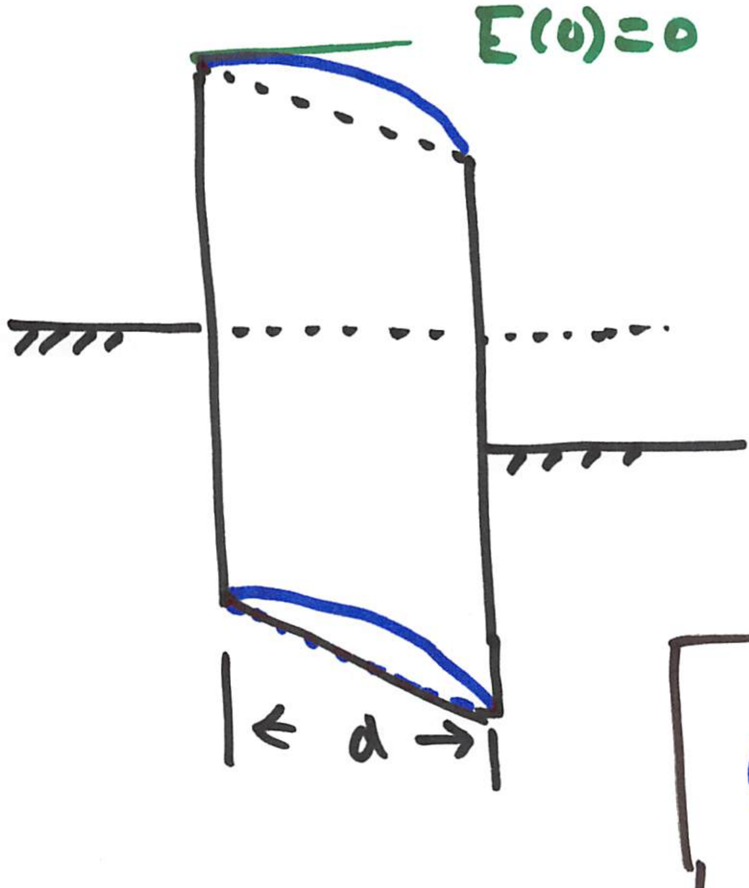
$= -\frac{V}{d}$

$\Downarrow$

electron injection

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

$t \to \infty$



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

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

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

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

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

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

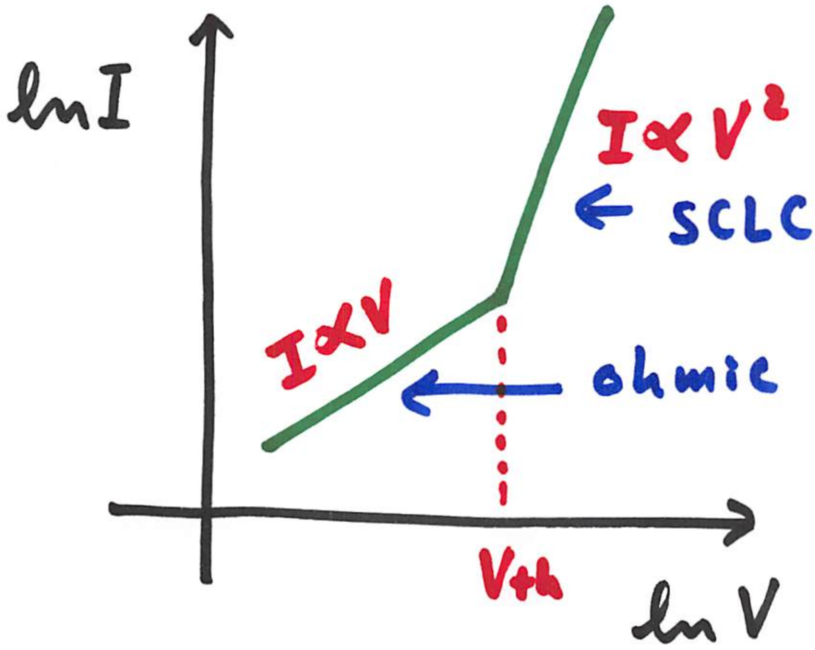
$$I \propto V^2$$

Space Charge limitted Current

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

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

(in the text book).



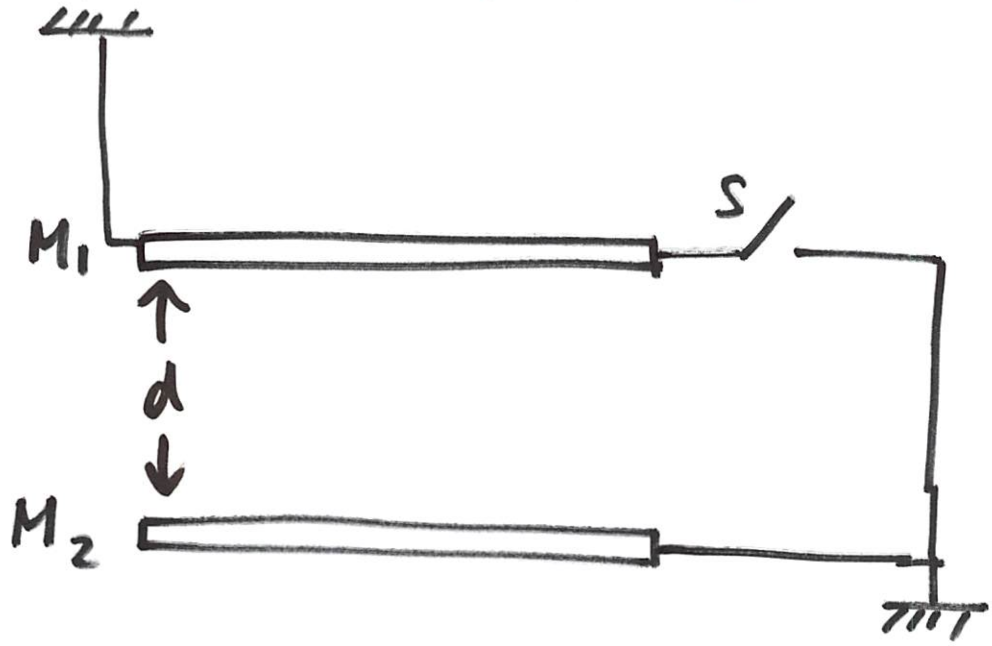
at $V = V_{th}$

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

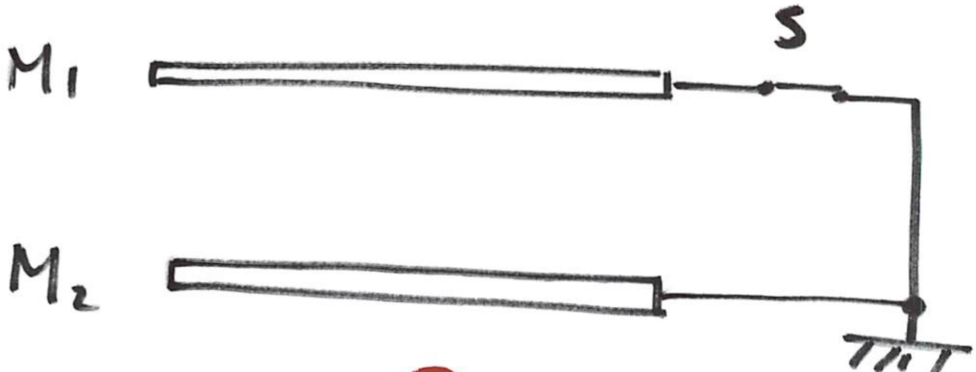
$$\therefore \quad \underbrace{\frac{9}{8}\left(\varepsilon_0\varepsilon_s\frac{1}{d}\right)V_{th}}_{\text{injected charge}} = \underbrace{e n_0 d}_{\text{excited electrons at the equilibrium state}}$$

⊡ dissimilar electrodes

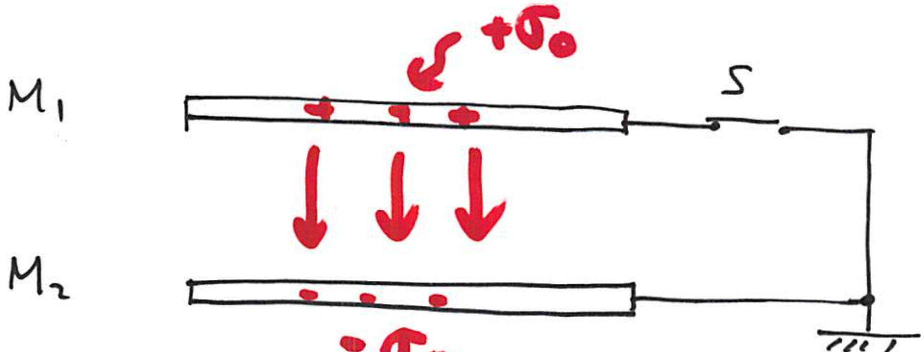
$\phi_1 < \phi_2$



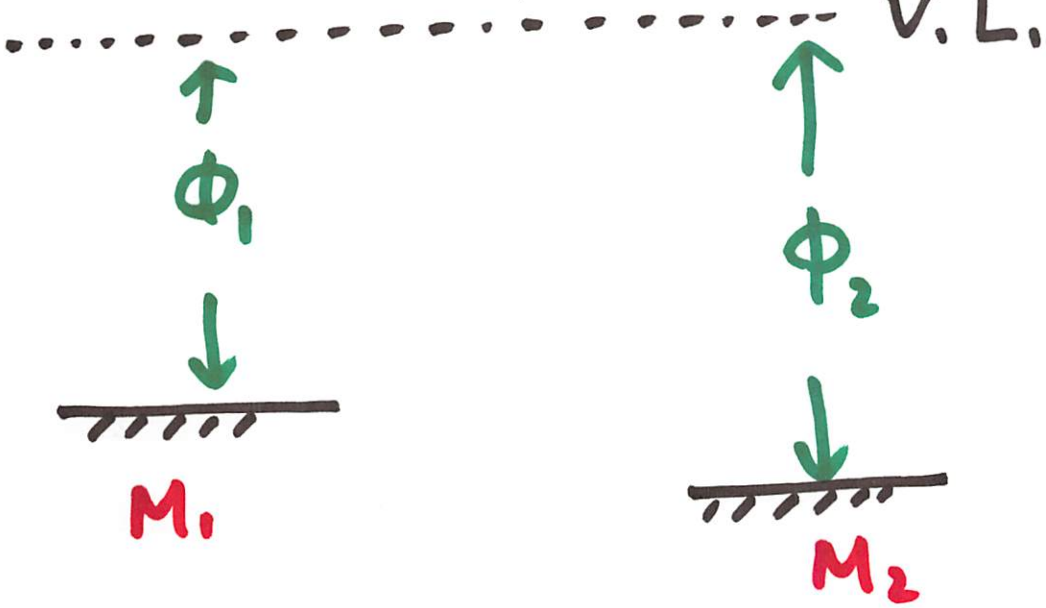
$\downarrow$



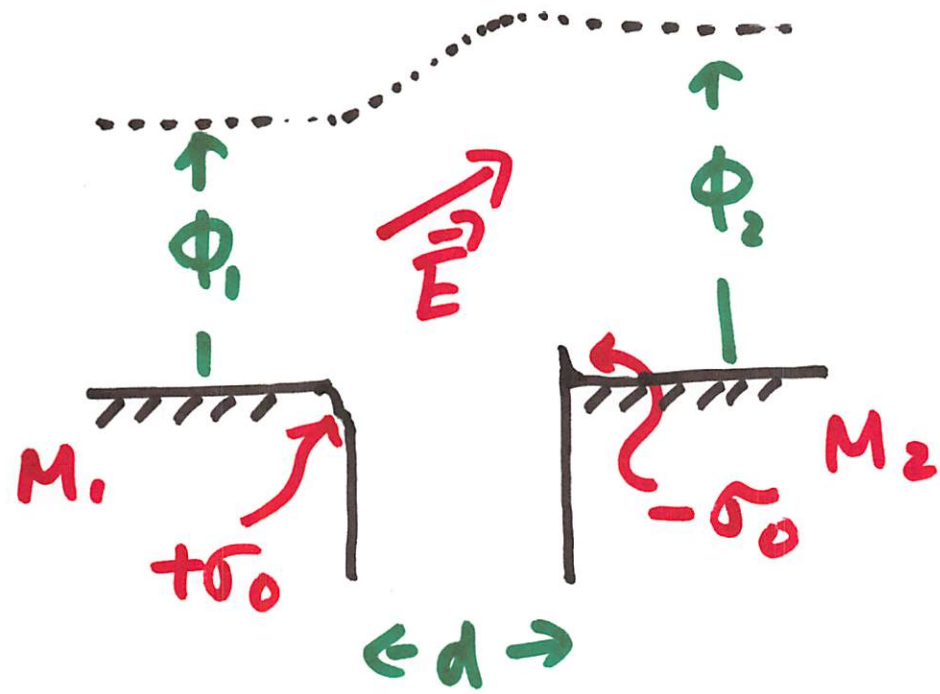
?



$$\boxed{E_0 = \frac{\sigma_0}{d}}$$

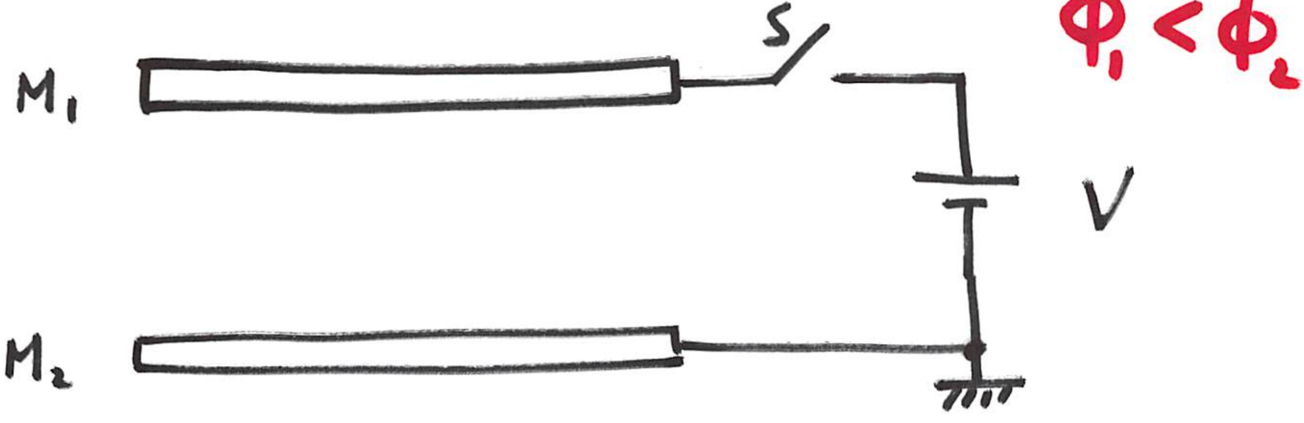


before connected



$$E = \frac{\sigma_0}{\varepsilon_0}$$

⊡ dissimilar electrodes



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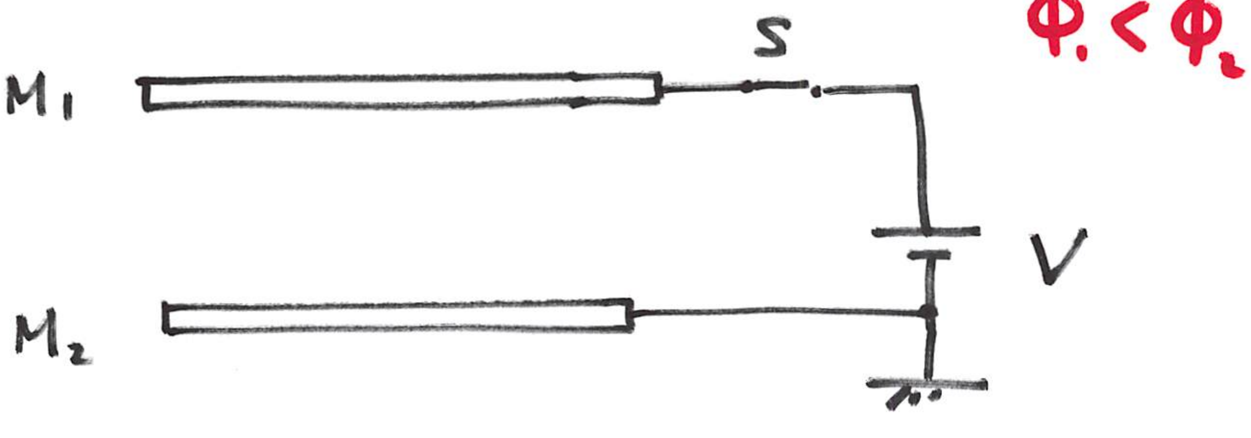
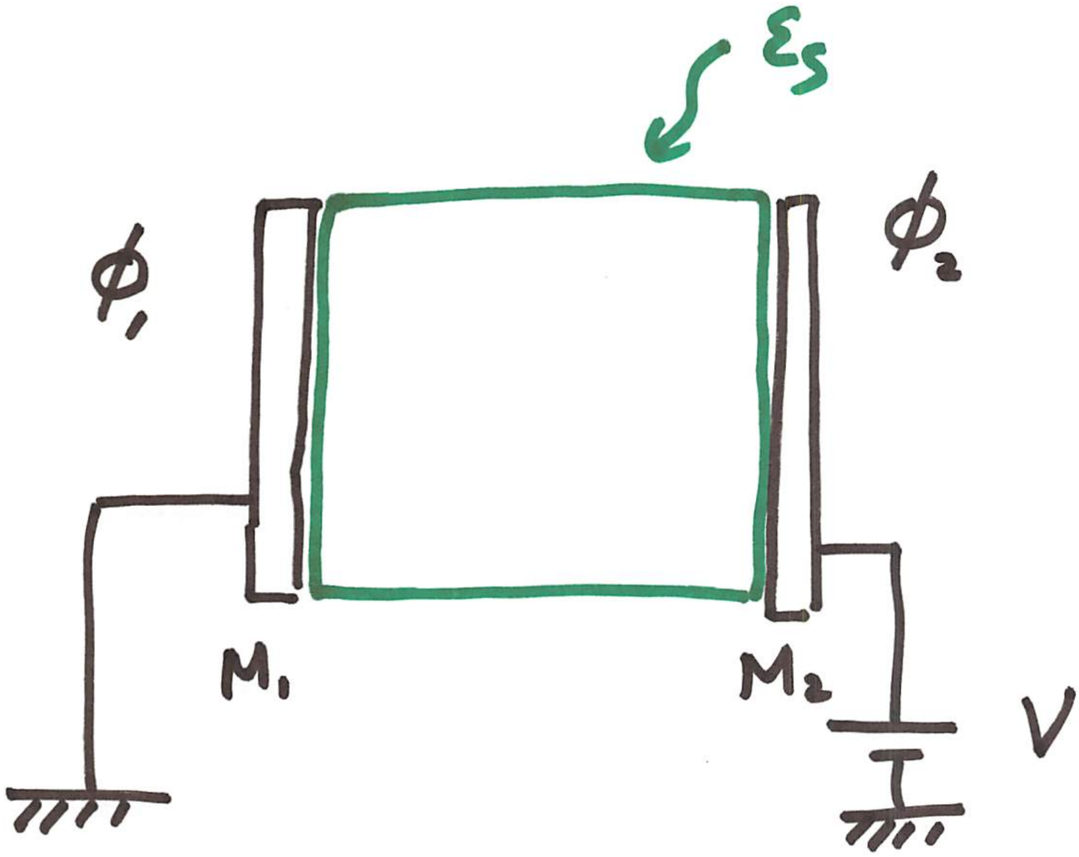


?

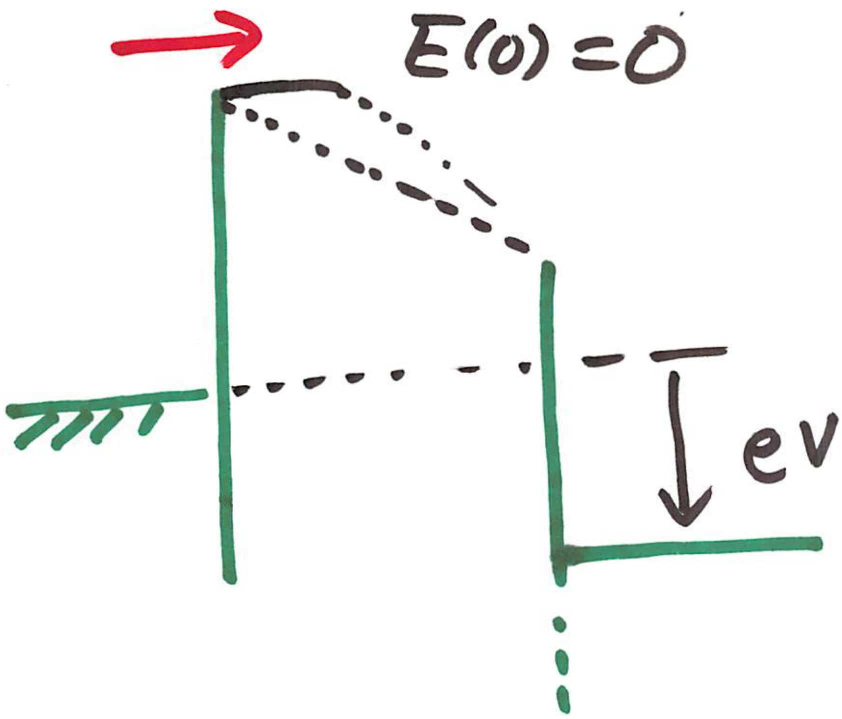
Work function of metal M_1, M_2
is different

Space charge Limitted Current



$\phi_2 > \phi_1$

Space charge Limitted Current



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

SCLC

$$I \simeq \frac{\varepsilon_0 \varepsilon_s}{d^3} \mu \, (V + \Delta\phi)^2 \quad ?$$

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

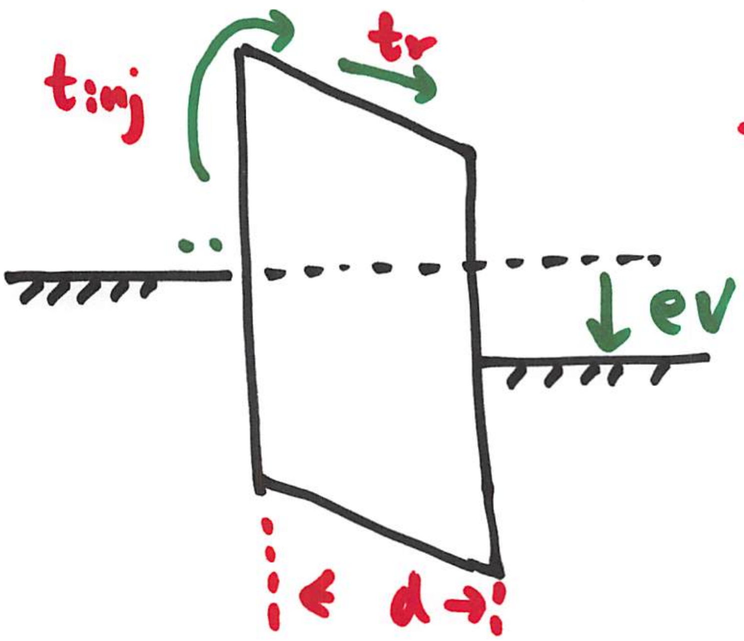
$$-e\bar{n} = \frac{Q_{inj}}{d} = \left(\varepsilon_0 \varepsilon_s \frac{\Delta\phi + V}{d}\right) \cdot \frac{1}{d}$$

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

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

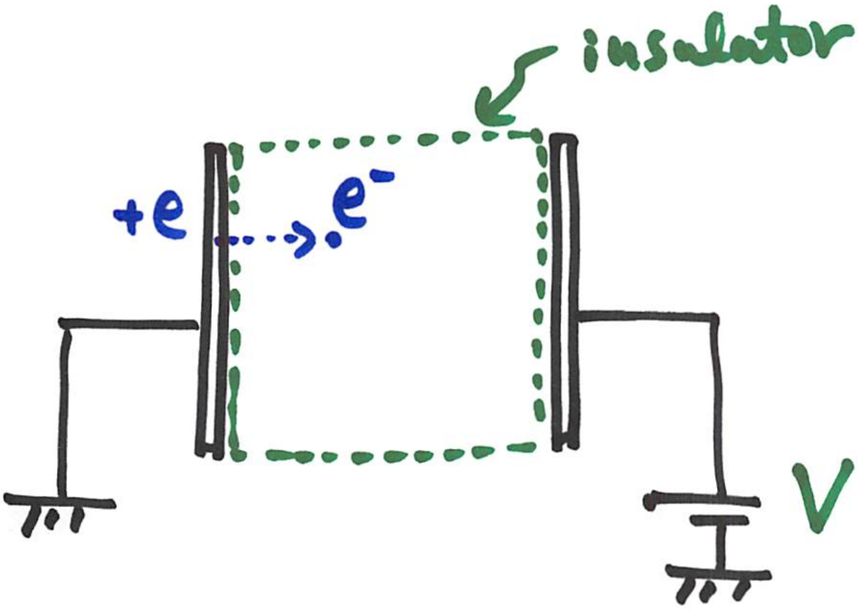
$$\simeq \frac{\varepsilon_0 \varepsilon_s \mu}{d^3} V (V + \Delta\phi) \quad //$$

Schottky Current ⟶ Schottky effect



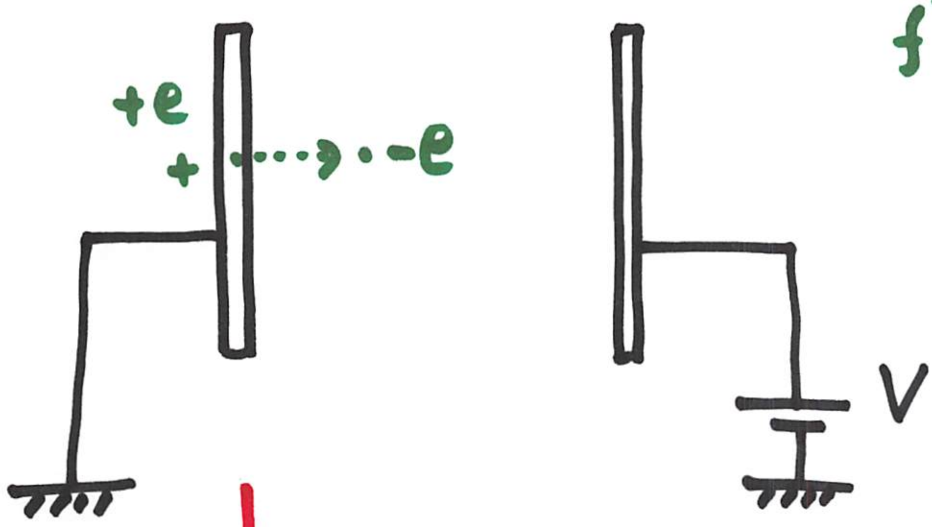
$t_{inj} > t_r$

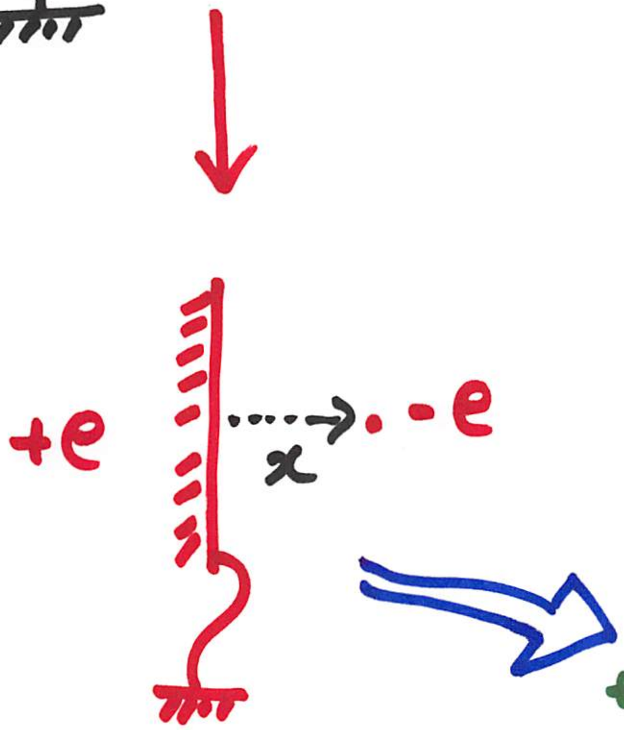
" no accumulation of injected electrons in insulator "



what happens when electron-e inject into the insulator

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





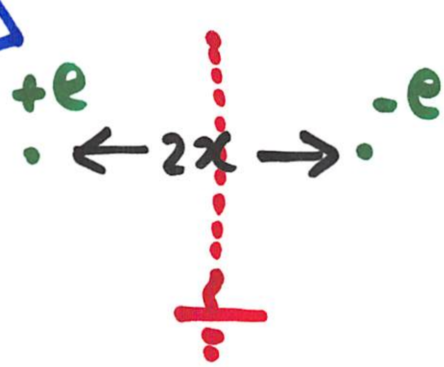


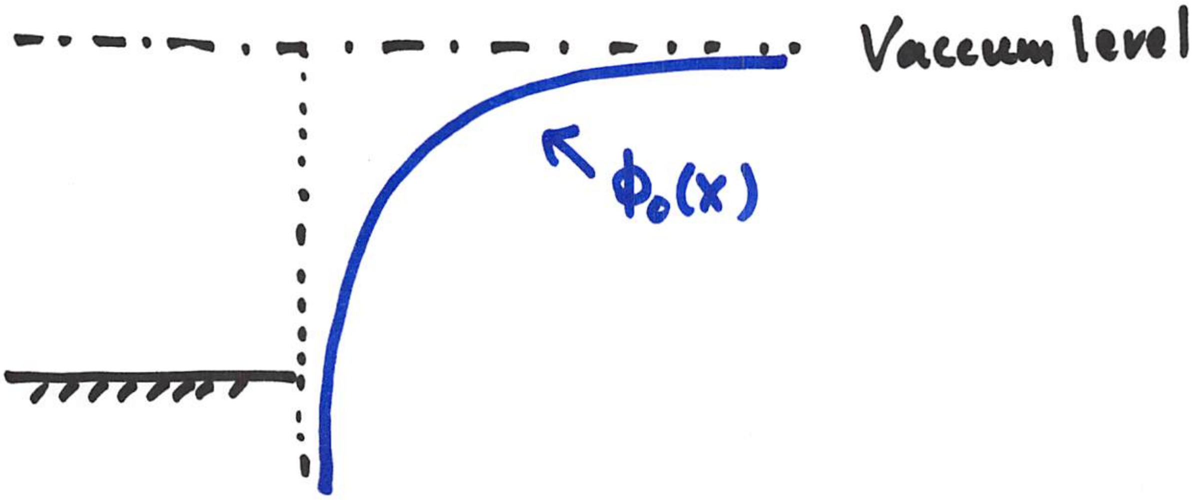
image force

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

Coulomb force

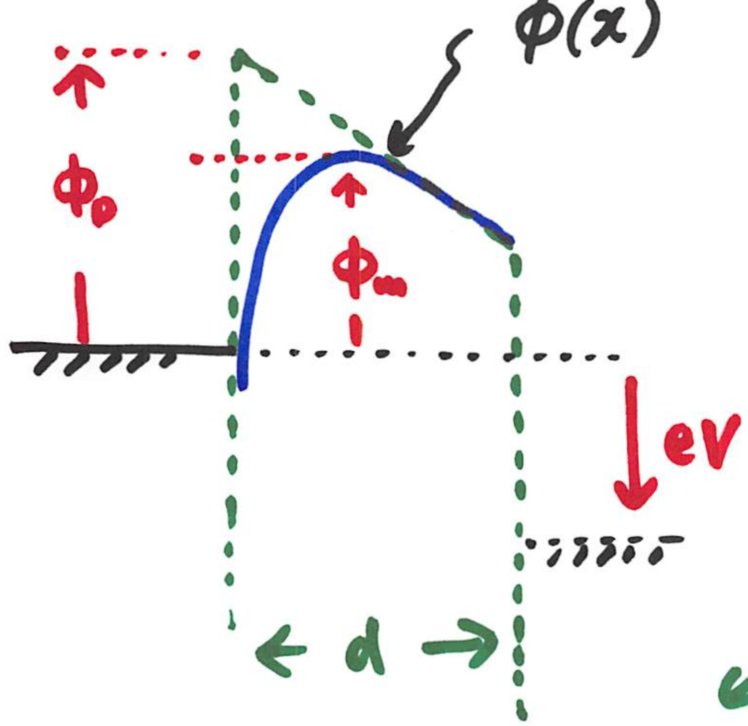
$$f = -\frac{\partial \phi_0(x)}{\partial x}$$

$$\phi_0(x) = -\int_{\infty}^{x} f\,dx = -\frac{1}{16\pi\varepsilon_0\varepsilon_s}\frac{e^2}{x}$$



Injected electrons experience potential field $\phi_0(x)$

" If we define $\phi_0(x)$,
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

$$I = e n v$$

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

at $E = 0$ $H = \phi_D$

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

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

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