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Physique des Semi-conducteurs et Composants Électroniques

Niveaux : Licence + Master

Spécialités :
- Physique des Matériaux
- Physique Appliquée
- Physique Fondamentale
- Physique Énergétique
- Énergétique et Énergies Renouvelables

Références :

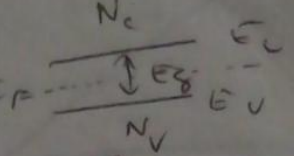
- Introduction à la Φ du Solide (E. Mooser)
- Physique des 1/2 Cdts et Composants Élec (H. Mathieu)
- Physique du Solide : Propriétés Élec (M. Brousseau)
- Traité des Matériaux : 8 : Physique des Matériaux (M. Gerl et al)
- Initiation à la Φ des Solides (Cazaux)
- 1/2 Cdt Material and Devices Characteriz (Schroder)
- Devices (Sze)

- 1/2 Cdt intrinsèque
- 1/2 Cdt extrinsèque
- Phénomènes de transport et équation de continuité
  - Conduction Électron — m^*
  - Courant de diffusion → relation d'Einstein
  - Équation de Poisson
- Génération + recombinaison + Durée de vie des porteurs
- Équation de continuité + Application $\begin{cases} L_n \\ \tau_n \end{cases}$
- Jonction PN
  - $\rho(x)$
  - $V(x)$
  - $E(x)$
  - V_d
  - Largeur ZCE, longueur de Debye
  - Capacité
  - Courant dans la jonction $J(V)$
- Contact Métal - 1/2 Cdt → Diode de Schottky
  - Métal - Vide
  - Métal - 1/2 Cdt
  - 1/2 Cdt - 1/2 Cdt
  - Courant thermoélectronique
  - Contact Schottky < ZCE, V_d, $\rho(x)$ $E(x)$ / $V(x)$; Polarisation Direct / inverse

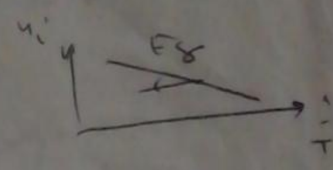
Master – Physique Appliquée – 1ère Année

Matière : Composants à 1/2 Cdt. ①

- 1/2 Cdt intrinsèque



$n = N_c \exp -\frac{(E_c - E_F)}{kT}$; $f(E) = \frac{1}{1+\exp\frac{E-E_F}{kT}}$



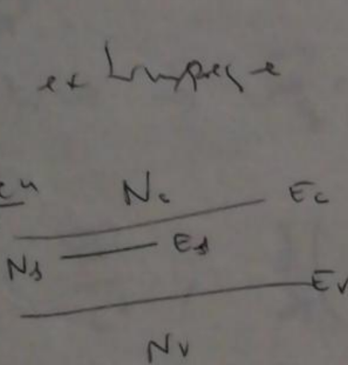
$p = N_v \exp -\frac{(E_F - E_v)}{kT}$;

$np = n_i^2 \rightarrow n_i = p_i = \sqrt{N_v N_c} \exp -\frac{(E_g)}{kT}$

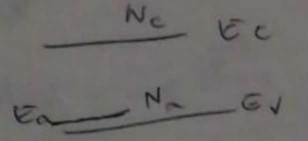
$E_F = \frac{E_g}{2} \quad \forall T$; $f_t = 1 - f(E)$

$\sigma = n e \mu$; $\vec{v} = \mu \vec{E}$

- 1/2 Cdt extrinsèque



$E_d = \frac{e^4}{2(4\pi\varepsilon_0)^2} \cdot \frac{m^*}{\varepsilon_r^2}$ (~qq meV)



$$\begin{cases} D(E) = \frac{V}{2\pi^2}\left(\frac{2m}{\hbar^2}\right)^{3/2} E^{1/2} \\ \int_0^\infty x^{1/2} e^{-x}\, dx = \frac{\sqrt{\pi}}{2} \\ N_{c,v} = 2\left(\frac{2\pi m_{e,h} kT}{h^2}\right)^{3/2} \end{cases}$$

$N_d^0 = N_d \frac{1}{1+\frac{1}{2}\exp\frac{E_d-E_F}{kT}}$ ②

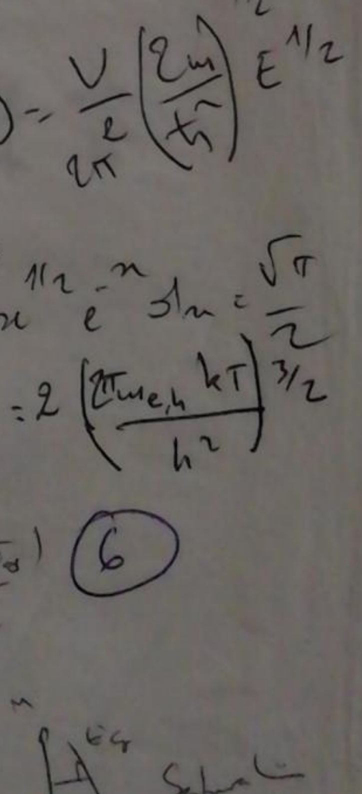
$N_d^+ = N_d - N_d^0$ ③

$n = N_d^+ + p$ ①

$n = N_c \exp -\frac{(E_c - E_F)}{kT}$ ④

$n = \left(\frac{N_c N_d}{2}\right)^{1/2} \exp -\frac{(E_c - E_d)}{2kT}$ ⑥

$E_{F_n} = \frac{E_c + E_d}{2} + \frac{kT}{2} \ln\left(\frac{1}{2}\frac{N_d}{N_c}\right)$



$(n-p)\,n = \frac{N_c}{2}(N_d - n + p) \exp\frac{E_d - E_c}{kT}$ ⑤

- Phénomènes de Transport et équation de Continuité

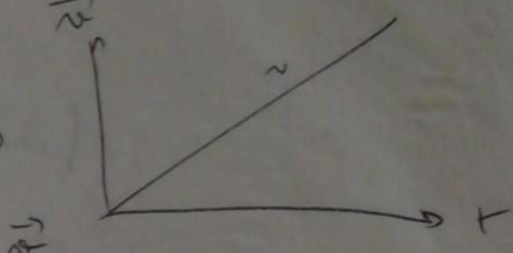
- Conduction Électrique

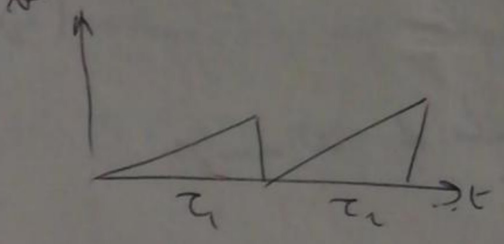
$$\vec{J} = \sigma \vec{E} = n(-e)\,\vec{v} = \sigma(-\vec{\nabla} V) \quad \text{(Modèle de Drude)}$$

$$\vec{v}_e = -\mu_e \vec{E}$$

$$m^* \frac{d\vec{v}_g}{dt} = -e\vec{E} \quad \longrightarrow$$

$$\vec{v} = -\frac{e\vec{E}}{m^*}\, t$$





$$\vec{v}_e = -\frac{e\vec{E}}{m^*}\,\tau$$

$$\vec{f}_f = -m^* \frac{\vec{v}}{\tau}$$

$$m^* \frac{d\vec{v}_g}{dt} = -e\vec{E} - m^* \frac{\vec{v}}{\tau}$$

$$\boxed{\tau \simeq 10^{-13}\,\text{s}}$$

$$E = \hbar\omega \quad \rightarrow \quad \vec{v}_g = \vec{\nabla}\omega = \frac{1}{\hbar}\vec{\nabla} E$$

$$\frac{d\vec{v}_g}{dt} = \frac{\vec{F}}{m^*} \; ; \quad \frac{d}{dt}\left(\frac{1}{\hbar}\vec{\nabla}_k E\right) = \frac{d\vec{v}_g}{dt} = \frac{dv_g}{dk}\cdot\frac{dk}{dt}$$

$$dW = -e\vec{E}\cdot\vec{v}\,dt = \frac{dE}{dt}\,dt = \frac{\partial E}{\partial k}\cdot\frac{dk}{dt}$$

$$-e\vec{E}\cdot\frac{1}{\hbar}\nabla_k E = \nabla_k E\cdot\frac{dk}{dt}$$

$$-e\vec{E} = \hbar\frac{d\vec{k}}{dt} = F$$

$$\frac{d\vec{v}_g}{dt} = \frac{dv}{dk}\cdot\frac{dk}{dt} = \vec{\nabla}_k v\cdot\frac{dk}{dt} = \nabla_k\left(\frac{1}{\hbar}\nabla_k E\right)\cdot\frac{\vec{F}}{\hbar}$$

$$\vdots$$

$$\frac{d\vec{v}_g}{dt} = \nabla_k(\nabla_k E)\,\frac{1}{\hbar^2}\,\vec{F}$$

$$\frac{d\vec{v}_g}{dt} = \left(\frac{1}{m^*}\right)_{ij}\vec{F} \; ; \quad \left(\frac{1}{m^*}\right)_{ij} = \frac{1}{\hbar^2}\frac{\partial^2 E}{\partial k_i\,\partial k_j}$$

$\mu = \frac{e\tau}{m^*}$, plusieurs collisions (mécanismes) $\frac{1}{\tau} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_3}$

- Notion de diffusion

$$\vec{J}_{par} = -D\vec{\nabla}n \quad \text{(particules)}$$

$$\vec{J}_{ch} = (-e)(-D\vec{\nabla}n) \quad \text{(charge)}$$
$$= eD_n\vec{\nabla}n$$

équation de diffusion

$$\frac{\partial n}{\partial t} = -\vec{\nabla}\cdot\vec{J}_p = D\frac{\partial^2 n}{\partial x^2}$$

Conservation du nombre

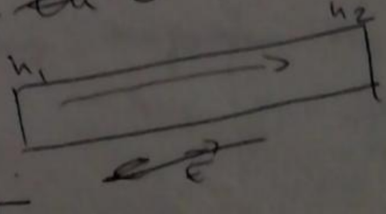
- Relation d'Einstein

$$D \rightleftarrows \mu$$

$$n = N_c \exp -\frac{(E_c - E_F)}{kT} \quad \text{(homogène)}$$

$$n(x) = N_c \exp -\frac{(E_c(x) - E_F)}{kT} \quad \text{(non homogène)}$$

Inhomogénéité $\Rightarrow \exists$ diffusion + ~~Ch~~ $\vec{E}$



Courant Total = 0

Courant électr $\rightleftarrows$ Courant de diff

$$\underbrace{n(x)\,e\mu_n E_x}_{\text{Courant Élec}} + \underbrace{eD_n\frac{dn}{dx}}_{\text{diffusion}} = 0$$

$$E_x = -\frac{dV(x)}{dx} = \frac{1}{e}\frac{dE_c(x)}{dx} \quad ; \quad \frac{dE_c(x)}{dx} = \frac{dE_c(x)}{dn(x)}\frac{dn(x)}{dx}$$

$$\frac{dn(x)}{dE_c(x)} = -\frac{1}{kT}n(x)$$

$$E_x = -\frac{kT}{e}\frac{1}{n(x)}\frac{dn(x)}{dx}$$

$-\ \mu_n kT + e D_n = 0 \Rightarrow \frac{D_n}{\mu_n} = \frac{kT}{e}$ relation d'Einstein

- Équation de Poisson

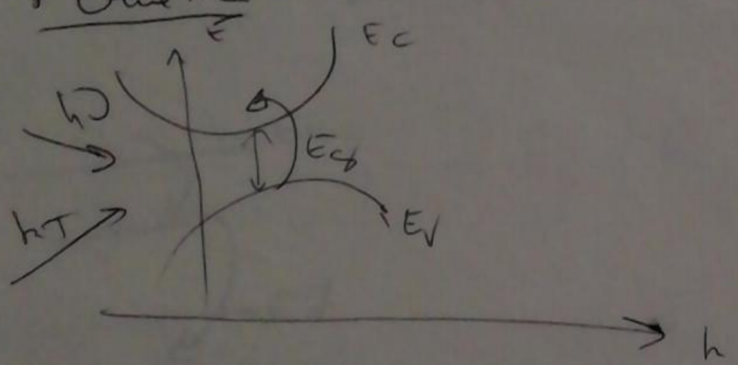
$\rho(x,y,z) \longrightarrow \vec{E}$; théo Gauss $\Rightarrow \mathrm{div}\,\vec{E} = \rho/\varepsilon$

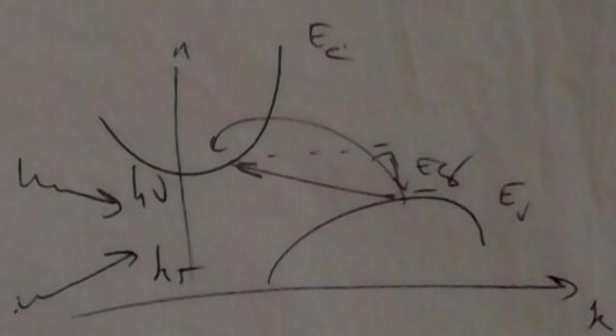
$\vec{E} = -\vec{\nabla} V \longrightarrow \Delta V = -\rho/\varepsilon$

$(\rho = e\,[(N_d^+ + p) - (n + N_a^-)]$

- Génération + Recombinaison de Porteurs

+ Génération





Génération de paire e-t

$n = n_0 + \Delta n$

$p = p_0 + \Delta p$

$\Delta n = \Delta p$

$n_0 p_0 = n_i^2$

$p \cdot n \neq n_i^2$

type n $\rightarrow$ - majoritaire n_0 ($10^{16}\,cm^{-3}$)

- minoritaire $p_0 = \frac{n_i^2}{n_0}$ ($\frac{10^{10} \cdot 10^{10}}{10^{16}}$ ...

Faible injection $\Delta n = \Delta p \ll n_0$

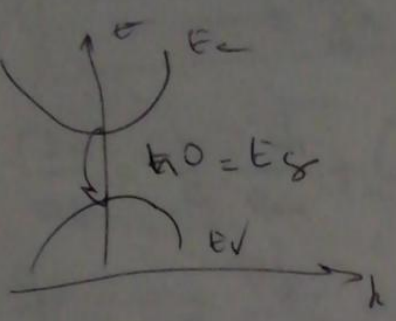
$n \simeq n_0$

$p \simeq \Delta p$

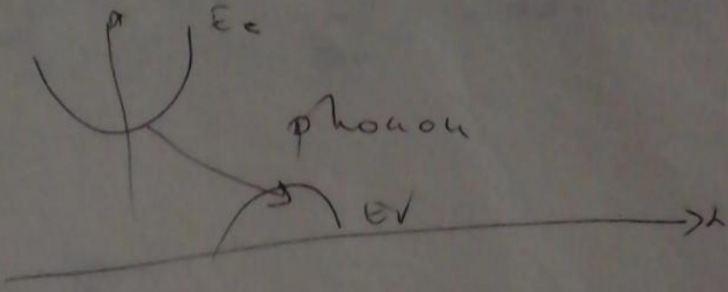
- Recombinaison

suppression de l'excitation (kT ou $h\nu$) → retour à l'équilibre

- Recombinaison directe

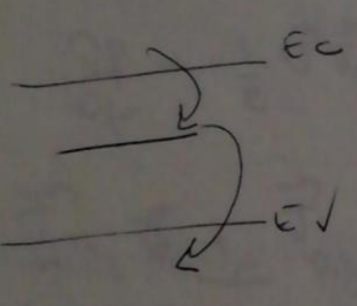


radiative



non radiative

- Recombinaison indirecte



- Durée de vie des porteurs minoritaires

type n → N_d

$n = n_0 + \Delta n \simeq N_d$

$p = p_0 + \Delta p \simeq \Delta p$

$$\frac{d}{dt} p = \frac{d}{dt} \Delta p = \underset{\text{génération}}{G} - \underset{\text{recom}}{R} = G - \frac{\Delta p}{\tau_p}$$

τ_p = durée de vie des porteurs minoritaires

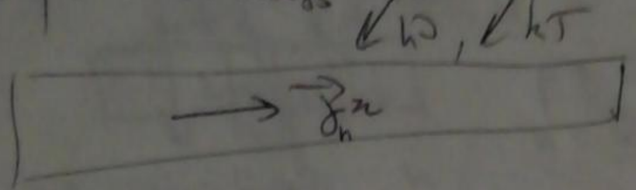
$$\tau_p = (10^{-3} - 10^{-9})\,s$$

Plusieurs mécanismes de recombinaison

$$\frac{1}{\tau_p} = \frac{1}{\tau_{p_1}} + \frac{1}{\tau_{p_2}} + \frac{1}{\tau_{p_3}} + \dots$$

Équation de Continuité

équations de continuité régissant les conditions de la dynamique des porteurs de charges:



$$\frac{\partial c}{\partial t} = -\operatorname{div}\vec{J} + G - R$$

$$\frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial J_n}{\partial x} + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{e}\frac{\partial J_p}{\partial x} + G_p - R_p$$

3 Dimensions:

$$\frac{\partial n}{\partial t} = \frac{1}{e}\vec{\nabla}\vec{J}_n + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{e}\vec{\nabla}\vec{J}_p + G_p - R_p$$

$$\vec{J}_n = \vec{J}_{Cond} + \vec{J}_{Diff} = ne\mu\vec{E} + eD_n\frac{\partial n}{\partial x}$$

Faible Injection: $R_n = \frac{\Delta n}{\tau_n} = \frac{n-n_0}{\tau_n}$

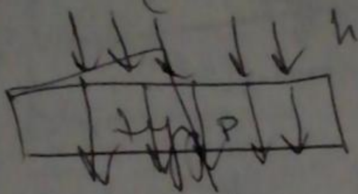
$$\frac{\partial n}{\partial t} = \mu_n\vec{E}\frac{\partial n}{\partial x} + \mu_n n\frac{\partial E}{\partial x} + D_n\frac{\partial^2 n}{\partial x^2} + G_n - \frac{n-n_0}{\tau_n}$$

$$\frac{\partial n}{\partial t} = D_n\frac{\partial^2 n}{\partial x^2} + \mu_n n\frac{\partial E}{\partial x} + \mu_n E\frac{\partial n}{\partial x} + G_n - \frac{n-n_0}{\tau_n}$$

$$\frac{\partial p}{\partial t} = D_p\frac{\partial^2 p}{\partial x^2} - \mu_p p\frac{\partial E}{\partial x} - \mu_p E\frac{\partial p}{\partial x} + G_p - \frac{p-p_0}{\tau_p}$$

- Applications

. Retour à $\rightleftarrows$ matériau excité



$$p = p_0 + \Delta p \simeq p_0$$
$$n = n_0 + \Delta n \simeq \Delta n = \Delta p$$

minoritaire n

$$\frac{\partial n}{\partial t} = G_n - R_n$$

$$\frac{\partial n}{\partial t} = G_n - \frac{n - n_0}{\tau_n}$$

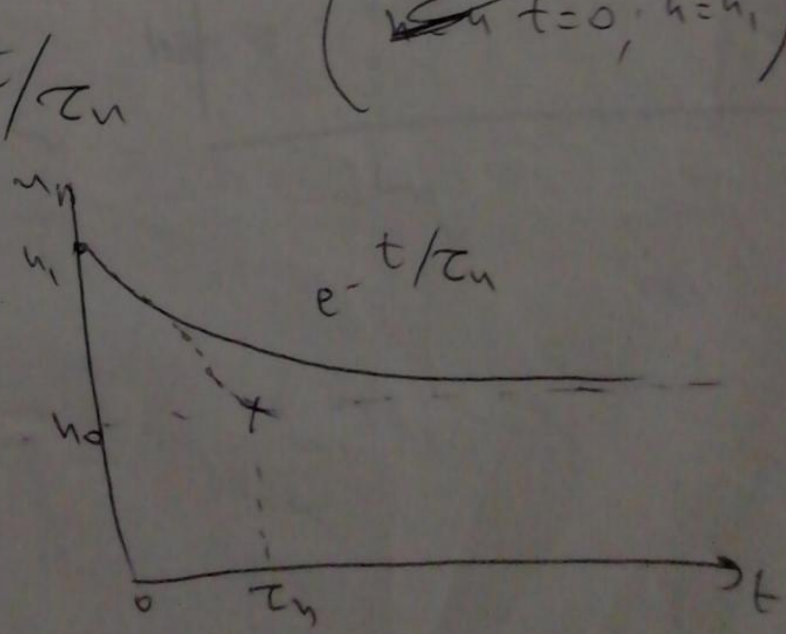
. Régime stationnaire $\rightarrow$ éclairement permanent $\left(\frac{dn}{dt} = 0\right)$

$$n = n_1 = C^{te}$$
$$n_1 - n_0 = G_n \cdot \tau_n$$

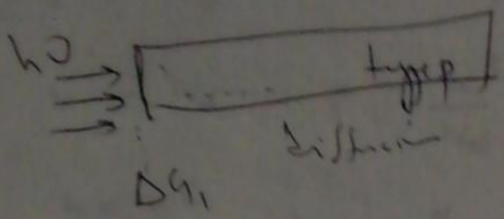
. Régime transitoire $\rightarrow$ suppression de la Génération $(G_n = 0)$

$$\frac{dn}{dt} = -\frac{n - n_0}{\tau_n} \qquad (t = 0,\ n = n_1)$$

$$(n - n_0) = (n_1 - n_0)\exp^{-t/\tau_n}$$



• longueur de Diffusion



n : minoritaire

Courant de diffusion : $J_{n} = e D_n \frac{\partial n}{\partial x}$

$$\frac{\partial n}{\partial t} = D_n \frac{\partial^2 n}{\partial x^2} + G_n - \frac{n - n_0}{\tau_n}$$

Rayonnement ~~peu~~ pénétrant $\Leftrightarrow$ G_n ds le volume $= 0$

et si l'éclairement est permanent : $\frac{\partial n}{\partial t} = 0$

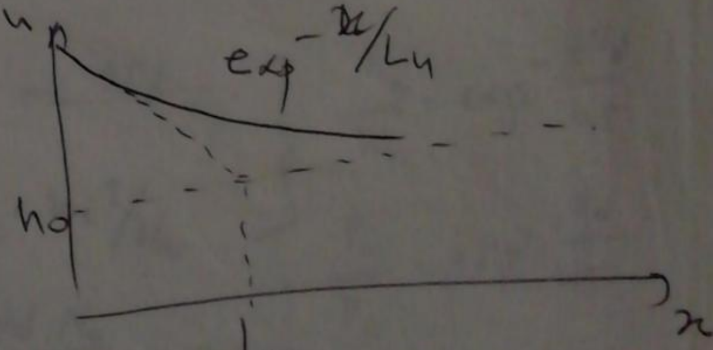
$$\frac{d^2(n - n_0)}{dx^2} - \frac{(n - n_0)}{L_n^2} = 0$$

$$L_n^2 = D_n \tau_n$$

$$\begin{cases} n(x=0) = n_1 \\ n(x=\infty) = n_0 \end{cases}$$

$$(n - n_0) = (n_1 - n_0) \exp^{-x/L_n}$$

$$D_n = D_{n\,sur} \exp^{-x/L_n}$$



L_n = longueur de diffusion

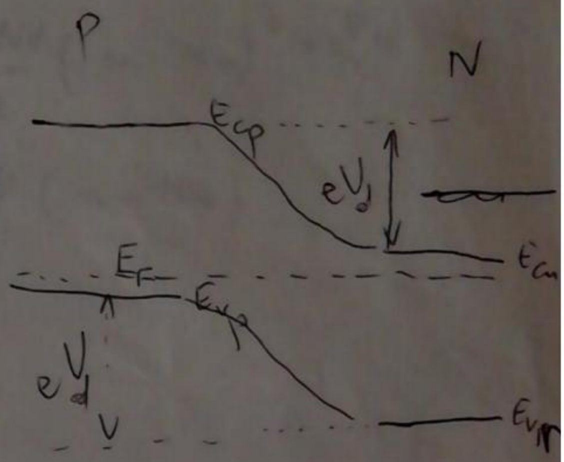
Jonction PN

. Charge d'espace

$n = N_d \quad p = \frac{n_i^2}{N_d}$ type n

$n = \frac{n_i^2}{N_a}$; $p = N_a$ type p

$$\rho(x) = e\left[\left(N_d + p_{(x)}\right) - \left(N_a + n_{(x)}\right)\right]$$



$\rho(x) = 0 \qquad x < x_p \; ; \; x > x_n$

$\rho(x) = -eN_a \qquad x_p < x < 0$

$\rho(x) = eN_d \qquad 0 < x < x_n$

. Tension de Diffusion

$V_d = \cancel{V_p - V_n} \; V_n - V_p$

$n_n = N_c \exp -(E_{c_n} - E_F)/kT = N_d$

$n_p = N_c \exp -(E_{cp} - E_F)/kT = n_i^2/N_a$

$\frac{n_p}{n_n} = \exp -\frac{eV_d}{kT}$

$\frac{p_n}{p_p} = \exp -\frac{eV_d}{kT}$

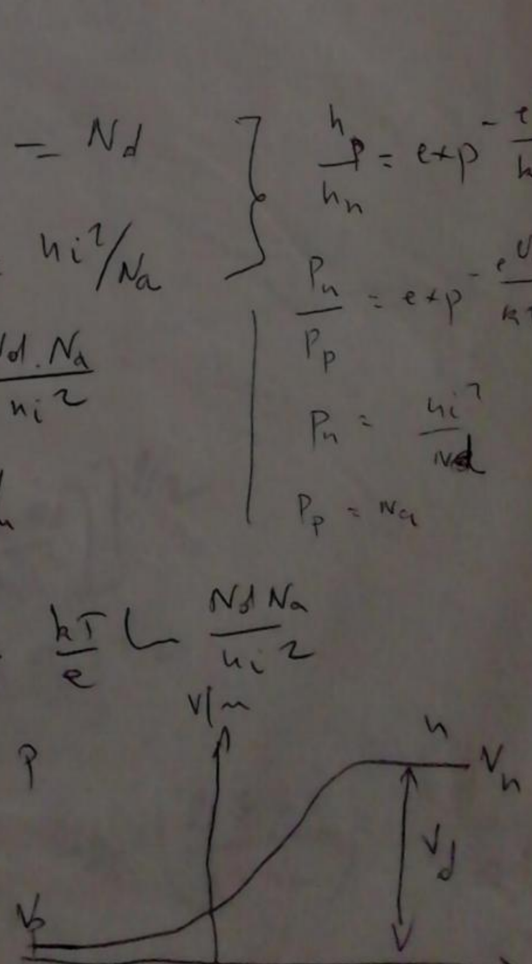
$p_n = \frac{n_i^2}{N_d}$

$p_p = N_a$

$E_{cp} - E_{c_n} = kT \ln \frac{n_n}{n_p} = kT \ln \frac{N_d . N_a}{n_i^2}$

$E_{cp} = -eV_p$; $E_{cn} = -eV_n$

$V_d = V_n - V_p = \frac{1}{e}\left[E_{cp} - E_{cn}\right] = \frac{kT}{e} \ln \frac{N_d N_a}{n_i^2}$



$E_{vp} = -eV_p \qquad E_{vn} = -eV_n$

$V_d = V_n - V_p = \frac{1}{e}\left(E_{vp} - E_{vn}\right)$

. Potentiel et Champ électrique de Zone de Charge d'espace

$$\Delta V = \frac{-\rho(x)}{\varepsilon}$$

- $x_p < x < 0$

$$\frac{d^2V}{dx^2} = \frac{eN_a}{\varepsilon} \Rightarrow V(x) = \frac{eN_a}{2\varepsilon}(x - x_p)^2 + V_p$$

$$E(x) = -\frac{eN_a}{\varepsilon}(x - x_p)$$

- $0 < x < x_n$

$$\frac{d^2V}{dx^2} = -\frac{eN_d}{\varepsilon} \Rightarrow V(x) = -\frac{eN_d}{2\varepsilon}(x - x_n)^2 + V_n$$

$$E(x) = \frac{eN_d}{\varepsilon}(x - x_n)$$

. Largeur de la Zone de charge d'espace

$$e N_a x_p = -e N_d x_n$$

$$W_p = |x_p| = -x_p \quad W_n = |x_n| \Rightarrow N_a W_p = N_d W_n$$

$$V_d = \frac{e}{2\varepsilon}\left[N_d W_n^2 + N_a W_p^2\right]$$

$$W_n^2 = \frac{2\varepsilon}{eN_d}\left[\frac{1}{1 + N_d/N_a}\right] V_d$$

$$W_p^2 = \frac{2\varepsilon}{eN_a}\left[\frac{1}{1 + N_a/N_d}\right] V_d$$

$$W_n = L_{Dn}\left[\frac{1}{1 + \frac{N_d}{N_a}} \cdot \ln\left[\frac{N_a N_d}{n_i^2}\right]\right]^{1/2}$$

$$W_p = L_{Dp}\left[\frac{1}{1 + N_a/N_d} \ln \frac{N_d N_a}{n_i^2}\right]^{1/2}$$

$$L_{Dn} = \left(\frac{2\varepsilon kT}{e^2 N_d}\right)^{1/2}, \quad L_{Dp} = \left(\frac{2\varepsilon kT}{e^2 N_a}\right)^{1/2}$$ longueur de Debye

$W = W_n + W_p$

Si $N_a \gg N_d$

$$W \simeq W_n \simeq L_{Dn}\left[\ln \frac{N_a N_d}{n_i^2}\right]^{1/2} = \left(\frac{2\varepsilon V_d}{e N_d}\right)^{1/2}$$

$N_a = 10^{18}\ \text{cm}^{-3}$, $N_d = 10^{17}\ \text{cm}^{-3}$ $\Rightarrow W = 4 L_{Dn}$ (0,1 et 1 µm)

• Capacité

Polarisation inverse $V_e < 0$

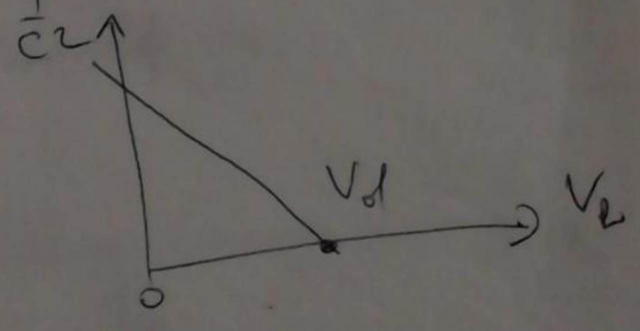
$V_d \longrightarrow V_d - V_e$

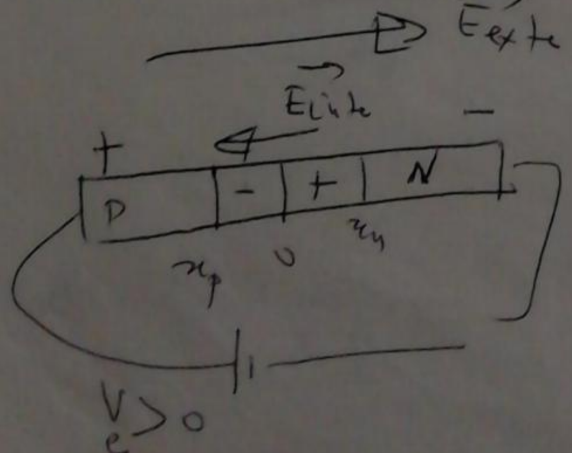
$$W(V) = \left(\frac{2\varepsilon(V_d - V_e)}{e N_d}\right)^{1/2}$$

la charge d'espace $= Q = e N_d \cdot W = \left(2\varepsilon e N_d (V_d - V_e)\right)^{1/2}$

$$C(V) = \left|\frac{dQ}{dV}\right| = \left(\frac{\varepsilon e N_d}{2}\right)^{1/2} (V_d - V_e)^{-1/2} =$$

$$\frac{1}{C^2} = \frac{2}{\varepsilon e N_d}(V_d - V_e)$$





. Courant dans la jonction

$$J_e = ne\mu E + eD\nabla n$$

$J_e <<$ devant les 2 termes qui le consti

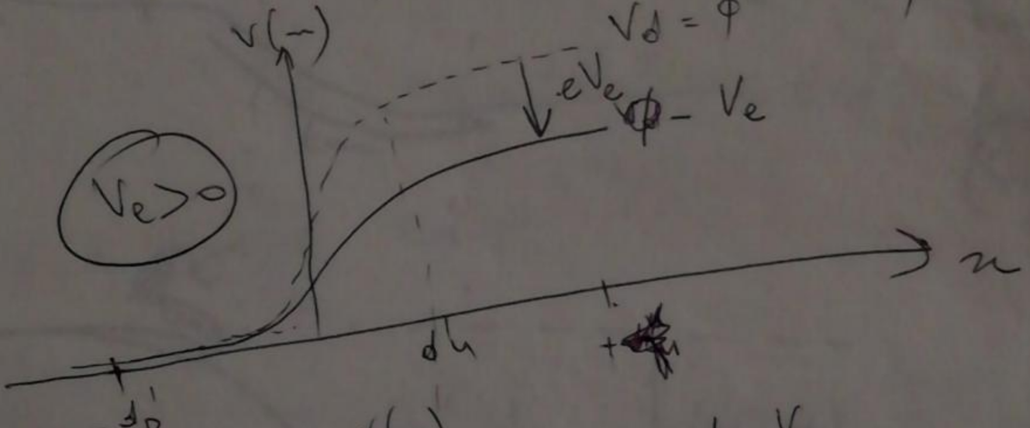
↓

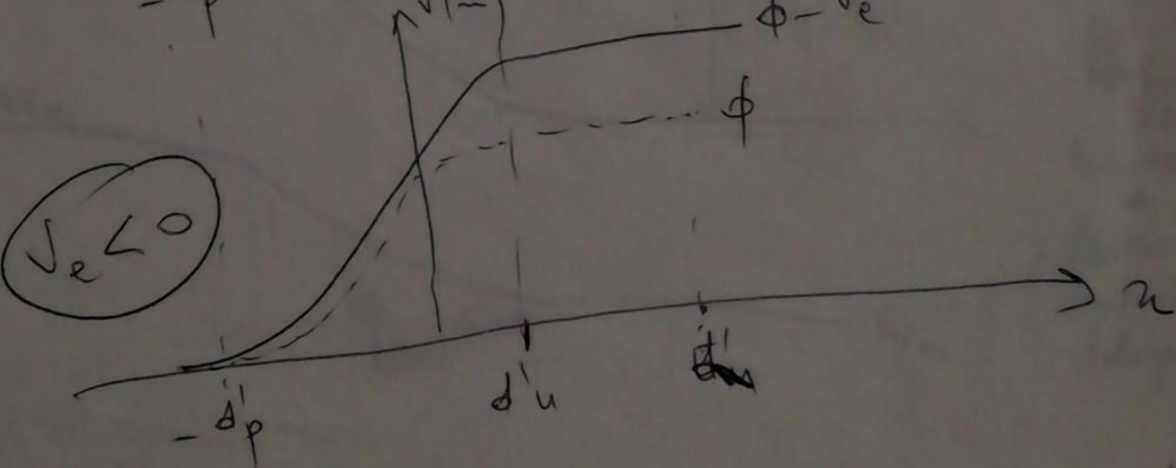
en presence de la polarisa°

$$ne\mu\vec{E} \# -eD\nabla n$$

$$n(x) \simeq A \exp \frac{eV(x)}{kT}$$

(relat° d'Einstein $\frac{D}{\mu} = \frac{kT}{e}$)





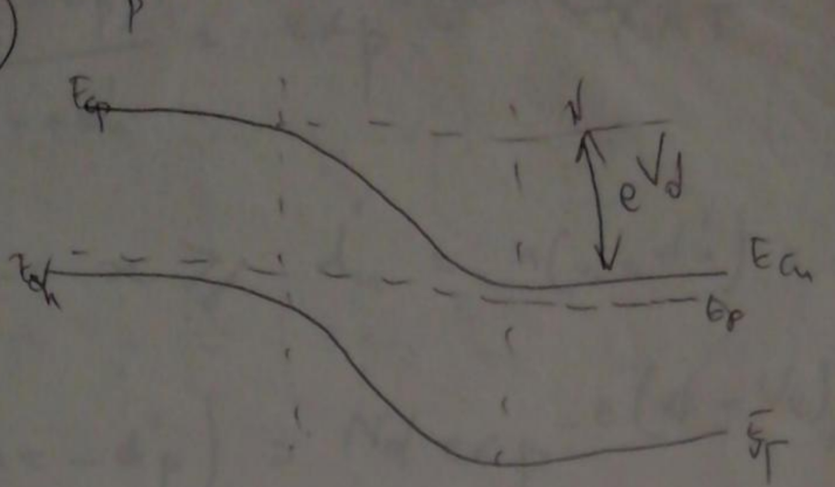
$$\phi - V_e = \frac{e}{2\varepsilon}\left[N_a d_p'^2 + N_d d_n'^2\right]$$

$W_n = d_n'$

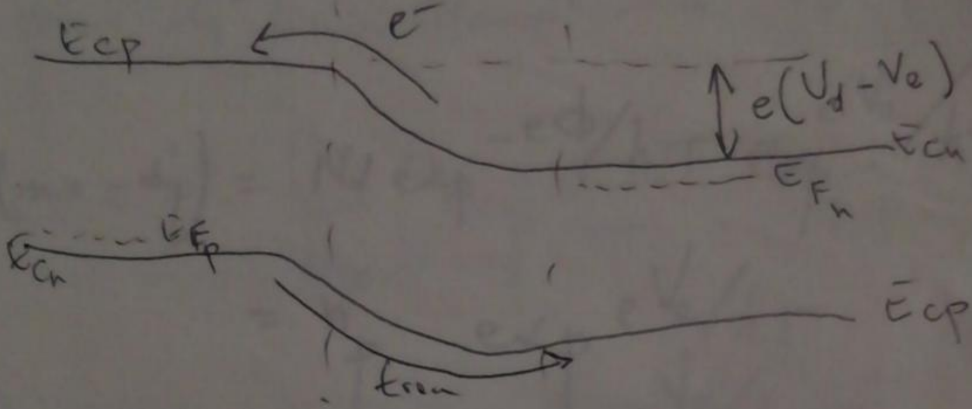
$W_p = d_p'$

$$N_a d_p' = N_d d_n'$$

$V_e = 0$



$V_e > 0$



Diminution de la hauteur de Barrière (Courant passe)

$V_e < 0$

Augmentation de la hauteur de Barrière (Courant bloqué)

$$\frac{n(x=-d'_p)}{n(x=+d'_n)} = \exp^{-e[\phi - V_e]/kT}$$

* pour $x \geq d'_n$ $= n(x=d'_n) = N_d$

$$n(x=-d'_p) = N_d \exp^{-e(\phi - V_e)/kT}$$

$$n(x=-d'_p) = N_d \exp^{-e\phi/kT} \exp^{eV_e/kT}$$

$$= n_p^0 \exp^{eV_e/kT}$$

$$n(x=-d'_p) = \frac{n_i^2}{N_a} \exp^{eV_e/kT}$$

Donc l'application de V_e modifie les minoritaires à la limite de la zone de charge d'espace

$$\Delta n(x=-d'_p) = n(x=-d'_p) - n_p^0 = n_p^0 \left[\exp^{\frac{eV_e}{kT}} - 1\right]$$

injection ou extraction $\Leftrightarrow$ $V_e > 0$ ou $V_e < 0$
(augmenté) (diminue les min)

Cette injection ou extraction provient de la région des porteurs qui sont majoritaires (dans le cas de la région n) diffusion des n dans p

$$J_e = e\,\Delta n(x=-d_p)\,\frac{D_e}{L_e} \qquad \left(j = nev \quad v = \frac{L}{\tau}\ ;\ L = \sqrt{D\tau} \right.$$

$$J_e = e\,n_p^0\,\frac{D_n}{L_n}\left[\exp\frac{eV_e}{kT} - 1\right]$$

De même pour les trous dans le n ($x = +d_n$)

$$J_t = e\,p_n^0\,\frac{D_t}{L_t}\left[\exp\frac{eV_e}{kT} - 1\right]$$

si pas de recombinaison dans la zone désertée

$$J = J_e + J_t$$

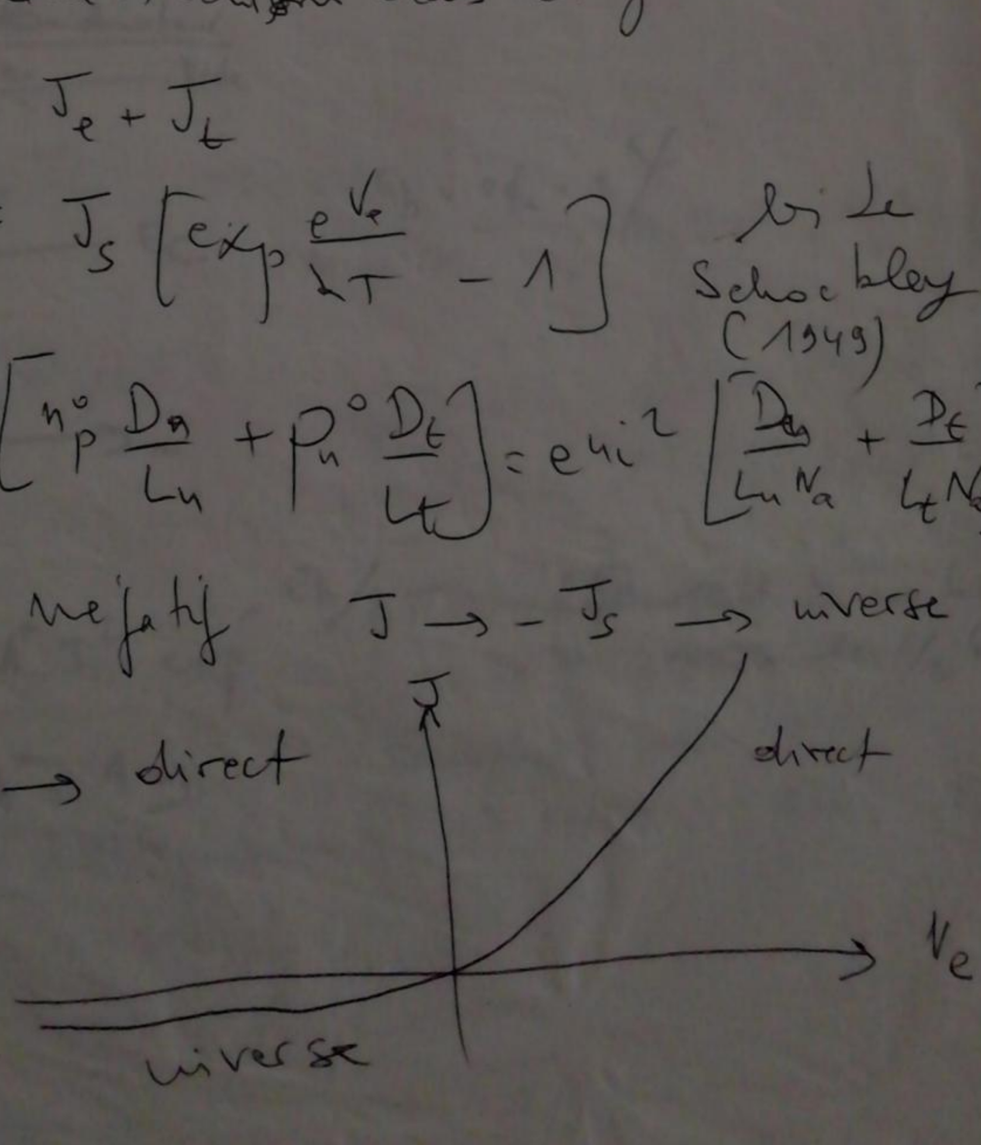
$$J = J_s\left[\exp\frac{eV_e}{kT} - 1\right]$$

loi de Schockley (1949)

$$J_s = e\left[n_p^0\,\frac{D_n}{L_n} + p_n^0\,\frac{D_t}{L_t}\right] = e\,n_i^2\left[\frac{D_n}{L_n N_a} + \frac{D_t}{L_t N_d}\right]$$

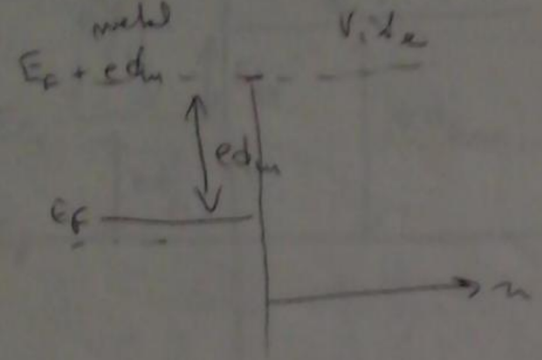
$V_e \gg$ et négatif $J \to -J_s \to$ inverse

$V_e > 0 \to$ direct



- Contact Métal - Semiconducteur : diode Schottky

• Métal - Vide



$e\phi_m$ = travail de sortie

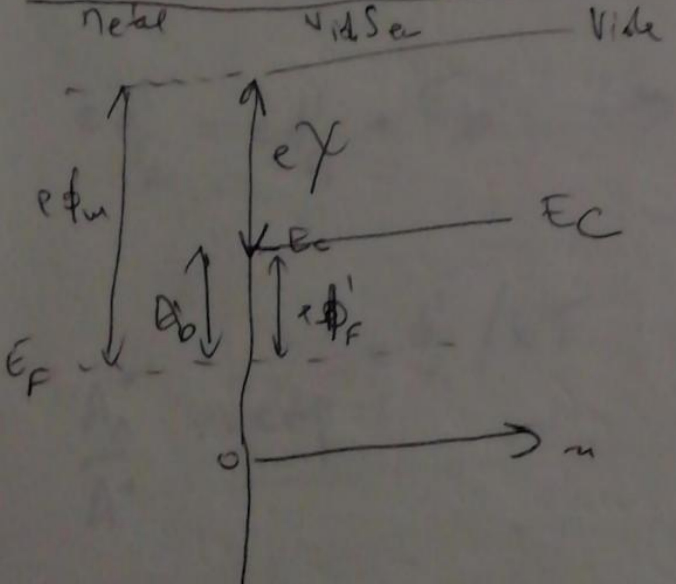
(émission Thermoélectronique)

$$J_x = -AT^2 \exp^{-e\phi_m/kT}$$

A - cte Richardson = $\frac{4\pi e m k^2}{h^3}$

(le signe - traduit le fait que lorsqu'1 e part du métal dans la direction x positif, il crée 1 courant dans le sens inverse)

• Métal - Semiconducteur



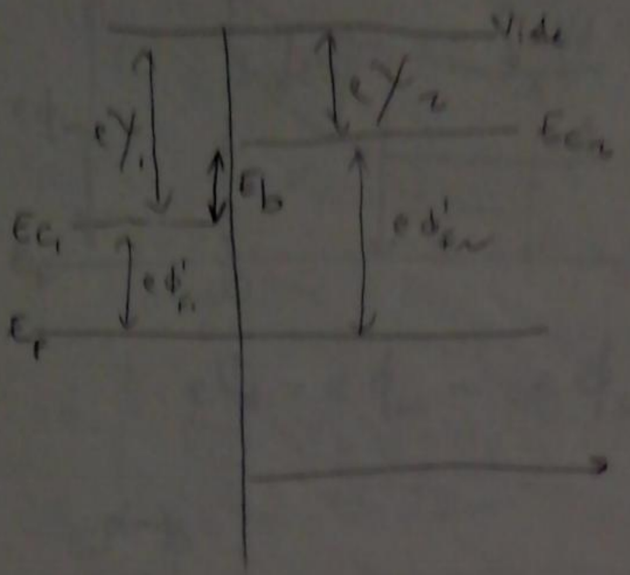
$$E_b = e\phi_m - e\chi$$

$$J_x = -A^* T^2 \exp^{-E_b/kT}$$

(courant du métal vers le 1/2 cdt

$$A^* = A \frac{m_e}{m}$$

• ½ Cdt – ½ Conducteur



$$E_b = e\chi_1 - e\chi_2$$

$$J_n = -A^* T^2 \exp^{-e\phi'_{F2}/kT} \quad , \quad A^* = A\,\frac{m_2}{m_1}$$

$$(e\phi'_0 = e\phi_m - e\chi)$$

$$e\phi'_{F2} = e\phi'_{F1} + E_b \longrightarrow J_n = -A_1^* T^2 \exp^{-E_b/kT}$$

$$A_1^* = A^* \exp^{-e\phi'_{F1}/kT} = A\,\frac{m_2}{m_1} \exp^{-e\phi'_{F1}/kT}$$

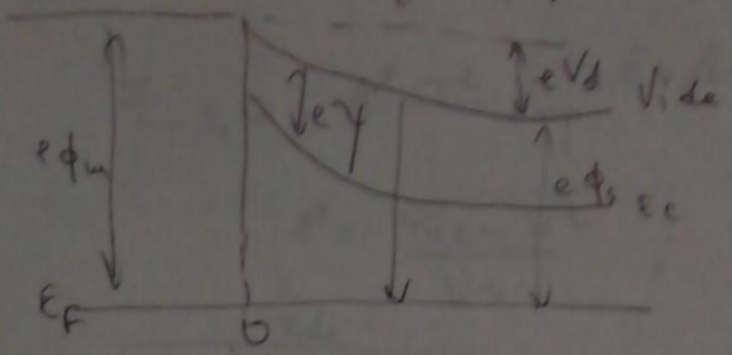
$$\frac{A_1^*}{A^*} = \exp^{-e\phi'_{F1}/kT}$$

= probabilité de trouver 1 é du ½ Cdt 1 proche de l'interface ½ Cdt 2

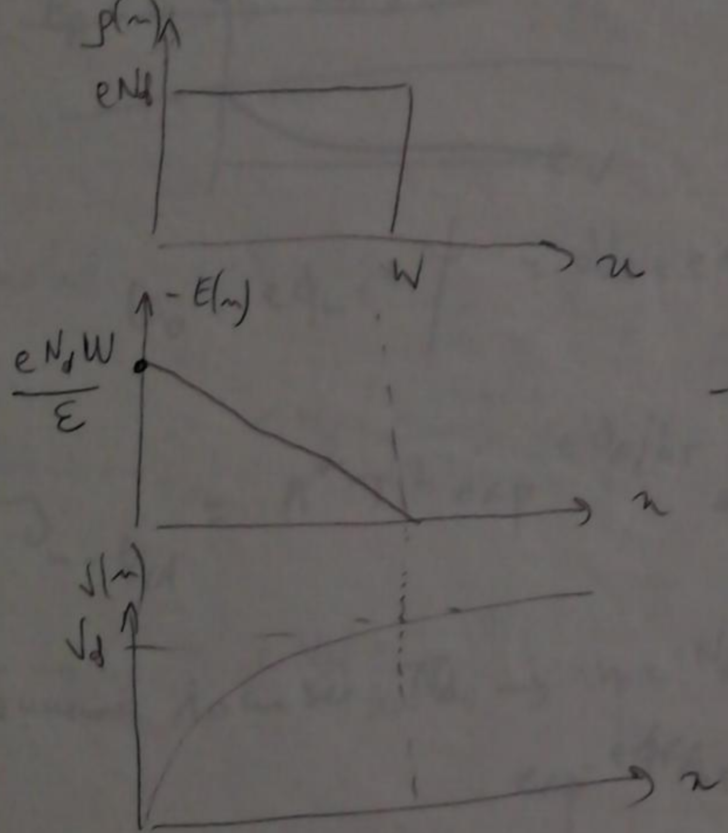
= probabilité pour que l'e⁻ soit dans E_{C1} au moment de franchir la barrière

Ce coefficient (cette probabilité) est égal à 1 dans le cas du métal – ½ Cdt –

• Contact Metal - 1/2 Cdt (n)



$$eV_d = e\phi_m - e\phi_{sortie}$$



$$-E(x) = -\frac{eN_d}{\varepsilon}(x - W)$$

$$V(x) = -\frac{eN_d}{\varepsilon}\left(\frac{x^2}{2} - Wx\right)$$

$$V_d = \frac{eN_d}{2\varepsilon}W^2$$

$$W = \left(\frac{2\varepsilon}{eN_d}V_d\right)^{1/2}$$

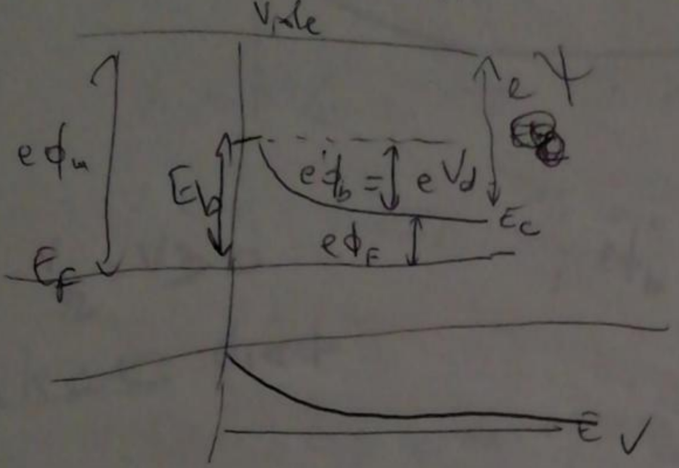
$$Q = eN_dW = \left[2\varepsilon eN_d(V_d - V)\right]^{1/2}$$

$$C(V) = dQ/dV \rightarrow \frac{1}{C^2} = \frac{2}{\varepsilon eN_d}(V_d - V)$$

• Courant d'émission thermoélectrique ($e\phi_m > e\chi$) (17)

$$J_{m \to 1/2 Cd} = A^* T^2 \exp^{-E_b/kT}$$

$$A^* = \frac{4\pi e m k^2}{h^3} \quad ; \quad E_b = e\phi_m - e\chi$$



Contact : Metal - 1/2 Cd

$\boxed{V = 0}$

$$E_b = e\phi_m - e\chi = eV_d + e\phi_F = e\phi_b + e\phi_F \ ; \ e\phi_F = E_c - E_F$$

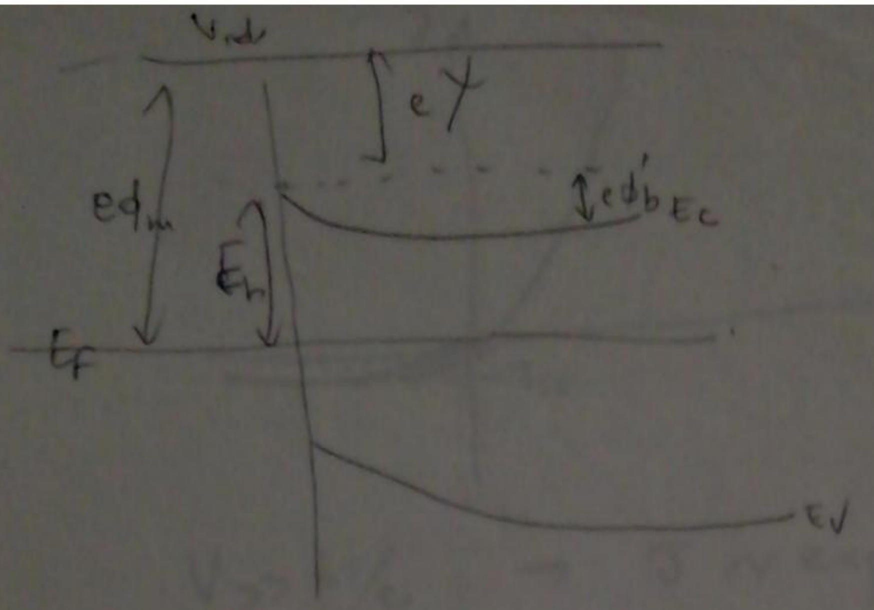
$$J_{m \to 1/2 Cd} = A^* T^2 \exp^{-e\phi_F/kT} \exp^{-e\phi_b/kT}$$

Donneurs ionisés $N_d \to n = N_c \exp^{-e\phi_F/kT} = N_d$

$$\exp^{-e\phi_F/kT} = N_d/N_c$$

$$J_{m \to 1/2 Cd} = A^* T^2 \frac{N_d}{N_c} \exp^{-e\phi_b/kT}$$

$$J_{m \to 1/2 Cd} = J_{1/2 Cd \to m} = e N_d \left(\frac{kT}{2\pi m_e}\right)^{1/2} \exp^{-eV_d/kT} \quad (N_c =$$



$V_d \longrightarrow V_d - V$

$V_m - V_{sc} = V > 0$; $e\phi'_b = e\phi_b - eV = eV_d - eV$

polarisation directe

- métal inchangé ; 1/2 Cdt : abaissement de la barrière

$$J_{1/2 C \to m} = e N_d \left(\frac{kT}{2\pi m^*}\right)^{1/2} \exp^{-e[V_d - V]/kT}$$

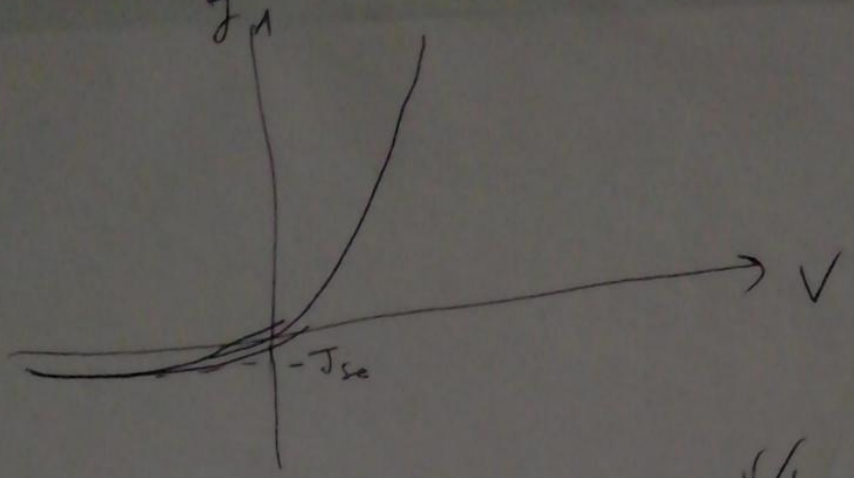
$\downarrow$ $e\phi'_b$

$$J_{m \to 1/2 C} = e N_d \left(\frac{kT}{2\pi m^*}\right)^{1/2} \exp^{-eV_d/kT}$$

Courant résultant $= J_{1/2 C \to m} - J_{m \to 1/2 C} = J$

$$J = J_{se}\left[\exp^{eV/kT} - 1\right]$$

$$J_{se} = e N_d \left(\frac{kT}{2\pi m^*}\right)^{1/2} \exp^{-eV_d/kT} = \text{Courant saturation}$$



$V \gg kT/e \rightarrow J \sim \exp^{eV/kT}$

$V < 0 \longrightarrow J \rightarrow -J_{se}$

Remarques

m - 1/2 Cdte de type p avec $e\phi_m < e\chi$, in Calcul

• m - 1/2 Cdt (n) avec $e\phi_m < e\chi$ → contact ohmique (pas de barrier)

=

• m - 1/2 Cdt (p) avec $e\phi_m > e\chi$ →