1. 2nd order.

$\frac{d^2y}{dx^2} = \beta^2 y \quad y = A_1 e^{\beta x} + A_2 e^{-\beta x}$;

$\frac{d^2y}{dx^2} = -\beta^2 y \quad y = A_1 e^{i\beta x} + A_2 e^{-i\beta x}$. $\beta = \frac{2\pi}{\lambda}$ λ : wavelength. β : wave number.

2. Wave Particle. Matter particle.

$E = h\overset{mu}{\nu} = \hbar\omega$. $\omega = 2\pi\overset{mu}{\nu}$ $\quad E = \frac{1}{2}mv^2$

$p = \frac{h}{\lambda} = \hbar k \quad k = \beta = \frac{2\pi}{\lambda}$. $\quad p = mv$. Light is a wave and a particle.

$h = 6.626\times10^{-34}$ J.s. $\hbar = \frac{h}{2\pi} = 1.054\times10^{-34}$ J.s.

3. Schrodinger Equation. Wave function $\varphi(x,t)$

$-\frac{\hbar^2}{2m}\frac{d^2\varphi}{dx^2} = E\varphi \quad -\frac{\hbar^2}{2m}\frac{d^2\varphi}{dx^2} + V(x)\varphi = E\varphi$ $\quad |\varphi(x,t)|^2 = \varphi(x)\varphi^*(x)$ probability density function. independent of time

Boundary Condition. $\int_{-\infty}^{\infty}|\varphi(x)|dx = 1$

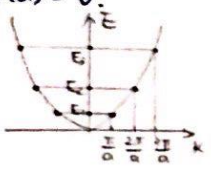
$\varphi(x)$ and $\frac{d\varphi(x)}{dx}$ finite, single-valued, continuous.

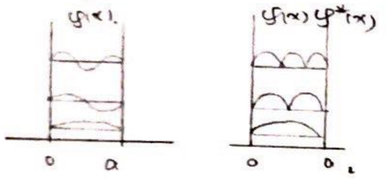
4. Infinite Quantum Well.

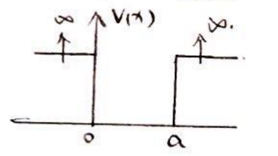
$\begin{cases} 0 \le x \le a & V(x) = 0 \\ x<0 \text{ or } x>a. & V(x) = \infty. \quad \varphi(x) = 0. \end{cases}$ $\quad -\frac{\hbar^2}{2m}\frac{d^2\varphi}{dx^2} = E\varphi$. $\varphi(x) = Ae^{-ikx} + Be^{ikx}$

$k = \sqrt{\frac{2mE}{\hbar^2}} \quad E = \frac{k^2\hbar^2}{2m} = \frac{n^2\pi^2\hbar^2}{2ma^2}$

$\begin{cases} \int_{-\infty}^{\infty}\varphi(x)\varphi^*(x) = 1 \\ \varphi(0) = A + B = 0. \Rightarrow \\ \varphi(a) = 0. \end{cases}$ $\quad \sin(ka) = 0.$ $\quad k = \frac{n\pi}{a} \quad n = 0, \pm1, \pm2, \cdots$







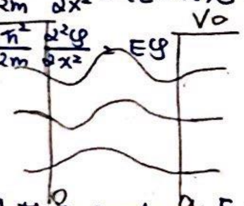
$k_1 = i\sqrt{\frac{2m(V_0-E)}{\hbar^2}}$ if $E < V_0$.

$k_1 = \sqrt{\frac{2m(E-V_0)}{\hbar^2}}$ if $E > V_0$.

Finite Quantum Well.

$\begin{cases} x<0 \text{ or } x>a. & V(x) = V_0 \\ 0 \le x \le a. & V(x) = 0. \end{cases}$ $\quad -\frac{\hbar^2}{2m}\frac{d^2\varphi}{dx^2} = (E - V_0)\varphi$. $\varphi_1 = Ae^{-ik_1x} + Be^{ik_1x}$.

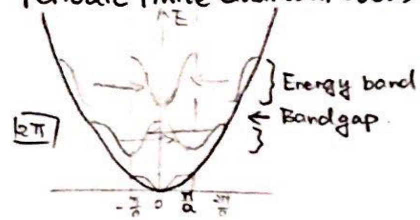
$-\frac{\hbar^2}{2m}\frac{d^2\varphi}{dx^2} = E\varphi \quad \varphi_2 = Ce^{-ik_2x} + De^{ik_2x}$.



$k_2 = \sqrt{\frac{2mE}{\hbar^2}} \quad B = 0.$

$\begin{cases} \varphi(x)|_{x=0,a} \text{ continuous} \\ \varphi'(x)|_{x=0,a} \\ \int_{-\infty}^{\infty}\varphi(x)\varphi^*(x)dx = 1 \end{cases}$

Periodic Finite Quantum Wells. Infinite number. E continuous.



$\frac{mV_0ba}{\hbar^2}\frac{\sin(\alpha a)}{\alpha a} + \cos(\alpha a) = \cos(ka)$

$-\frac{\pi}{a} \sim \frac{\pi}{a}$: 1st Brillouin Zone perpendicular bisector.

Reduced k space

5. Band structures of Metals, Semiconductors and Insulators

	Conduction band	Valence band	T = 0K	T = 300K.
Metal	Partially filled.	Completely filled	conductive	
Semi-conductors.	Empty	Completely filled.	nonconductive	conductive.
Insulator.	Empty	Completely filled.	nonconductive. (large bandgap)	

Electric field ← propagating speed. ac → dc

Doping in semiconductors.

① n-type. e right below conduction band

② p-type hole right above valence band.

6. Crystal Lattice.

Reciprocal Lattice. a in real space → $\frac{2\pi}{a}$ in k space.

Miller index. intercept of the plane along 3 axes, ~~int~~ their reciprocals, int.

Any parallel plane is entirely equivalent to any other.

Location of origin is entirely arbitrary.

7. $\begin{cases} \text{Direct Bandgap. same } k. \text{ GaAs} \\ \text{Indirect Bandgap. } P(\text{absorbing photon}) * P(\text{phonon scattering}) \text{ Si. Ge.} \end{cases}$

wave + particle.

8. Effective mass of electrons.

In conduction band. $\quad$ In valence band.

$E = E_c + \frac{\hbar^2}{2m_n^*}k^2 \quad m_n^* > 0 \quad E = E_v - \frac{\hbar^2}{2m_p^*}k^2 \quad m_p^* > 0.$

$E - E_c = C_1k^2 \quad C_1 > 0. \quad E - E_v = -C_2k^2 \quad C_2 > 0.$

$\frac{1}{m_n^*} = \frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{2C_1}{\hbar^2} \quad \frac{1}{m_p^*} = -\frac{1}{\hbar^2}\frac{d^2E}{dk^2} = \frac{+2C_2}{\hbar^2}$

$E = E_c + \frac{\hbar^2}{2}\left(\frac{k_x^2}{m_{nx}^*} + \frac{k_y^2}{m_{ny}^*} + \frac{k_z^2}{m_{nz}^*}\right)$

$m_e^* = \sqrt{m_{ex}^{*2} + m_{ey}^{*2} + m_{ez}^{*2}}$

9. Density of States. $g(E) = \frac{dV_k}{dE} = \frac{d(\frac{4}{3}\pi k^3)}{dE} = \frac{4\pi(2m_n^*)^{\frac{3}{2}}}{h^3}\sqrt{E - E_c}$ (k space)

$k = \frac{\sqrt{2m_n^*(E - E_c)}}{\hbar} \quad g_c(E) = \frac{4\pi(2m_n^*)^{\frac{3}{2}}}{h^3}\sqrt{E - E_c} \quad g_v(E) = \frac{4\pi(2m_p^*)^{\frac{3}{2}}}{h^3}\sqrt{E_v - E}$ (real space).

$E_v < E < E_c \quad g(E) = 0.$

10. Fermi Energy Level and Fermi-Dirac Distribution.

$f_F(E) = \frac{1}{1 + \exp(\frac{E - E_F}{kT})}$ $\quad T = 0K. \; f_F(E > E_F) = 0. \; f_F(E < E_F) = 1.$

$T > 0K \quad f_F(E = E_F) = \frac{1}{2}.$

$T_2 > T_1 \quad f_F(E > E_F): T_2 > T_1 \quad f_F(E < E_F): T_2 < T_1$

Boltzmann distribution

when $\exp(\frac{E - E_F}{kT}) >> 1 \Rightarrow E - E_F > 2kT \quad f_F(E) \approx \exp(-\frac{E - E_F}{kT})$.

10. Charge carrier concentration.

$$n_0 = \int_{E_c}^{\infty} g_c(E) f_F(E)\, dE = 2\frac{(2\pi m_n^* kT)^{\frac{3}{2}}}{h^3}\exp\left(\frac{E_F-E_c}{kT}\right) = N_c \exp\left(\frac{E_F-E_c}{kT}\right).$$

$N_c = 2.8\times10^{19}\ cm^{-3}$ at $T=300K$. $k = 1.38\times10^{-23} J/K$

$$P_0 = \int_{-\infty}^{E_v} g_v(E)[1-f_F(E)]\, dE = 2\frac{(2\pi m_p^* kT)^{\frac{3}{2}}}{h^3}\exp\left(\frac{E_v-E_F}{kT}\right) = N_v \exp\left(\frac{E_v-E_F}{kT}\right)$$

$N_v = 1.04\times10^{19} cm^{-3}$ at $T=300K$. $kT = 0.0259 eV$ at $T=300K$.

① Intrinsic. $E-E_F > 3kT$

$E_F = E_{Fi}$ $\quad n_0 = n_i = N_c\exp\left(\frac{E_{Fi}-E_c}{kT}\right)$ $\quad p_0 = p_i = n_i = N_v\exp\left(\frac{E_v-E_{Fi}}{kT}\right)$.

$n_0 p_0 = n_i^2 = N_c N_v \exp\left(-\frac{E_c-E_v}{kT}\right)$ $\quad E_g = E_c - E_v = 1.12eV$ for Si at 300K.

$n_i = 1.5\times10^{10} cm^{-3}$

$$n_i = n_0 = p_0 \quad E_F = \underbrace{\frac{E_c+E_v}{2}}_{E_{midgap}} - kT\ln\left(\frac{N_c}{N_v}\right)^{\frac{1}{2}} = \frac{E_c+E_v}{2} + \frac{3}{4}kT\ln\left(\frac{m_p^*}{m_n^*}\right) = E_{Fi}$$

$$\approx \frac{E_c+E_v}{2} = E_i.$$

② Extrinsic.

$$n_0 = N_c\exp\left(\frac{E_F-E_c}{kT}\right) = n_i\exp\left(\frac{E_F-E_{Fi}}{kT}\right) \overset{100\%\ ionized}{\approx} N_D. \quad E_F = E_c - kT\ln\left(\frac{N_c}{N_D}\right) = E_{Fi} + kT\ln\left(\frac{N_D}{n_i}\right)$$

n-type $E_F > E_{Fi}$

$$p_0 = N_v\exp\left(\frac{E_v-E_F}{kT}\right) = n_i\exp\left(\frac{E_{Fi}-E_F}{kT}\right) \approx N_A \quad E_F = E_v + kT\ln\left(\frac{N_v}{N_A}\right) = E_{Fi} - kT\ln\left(\frac{N_A}{n_i}\right)$$

p-type $E_F < E_{Fi}$

$\begin{cases} \text{n-type } N_D > N_A & n_0 = N_D - N_A \\ \text{p-type } N_D < N_A. & p_0 = N_A - N_D. \end{cases}$

11. Ionization of dopants.

① Probability of electrons occupying dopant energy level. $f_D(E) = \dfrac{1}{1+\frac{1}{g}\exp\left(\frac{E_D-E_F}{kT}\right)}$ $\quad$ g: degenerating factor.

② Ionization rate $1-f_D(E) = \dfrac{1}{1+2\exp\left(\frac{E_F-E_D}{kT}\right)} = \begin{cases} \frac{1}{3} & E_D = E_F \\ 1 & E_D >> E_F \\ 0 & E_D << E_F. \end{cases}$ $= \frac{n_0}{N_D}$

③ Charge neutrality.

$n_0 + N_A^- = N_D^+ + p_0$.

$n_0 = N_D^+ - N_A^- + p_0$.

n-type doping.

$\begin{cases} n_0 = N_D^+ + p_0. \\ n_0 p_0 = n_i^2 \end{cases}$

$$n_0 = \frac{N_D^+ + \sqrt{N_D^{+2} + 4n_i^2}}{2}$$

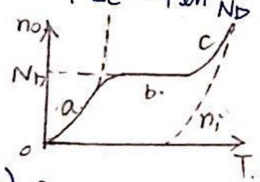
① $n_i >> N_D^+ \Rightarrow T$ very high.

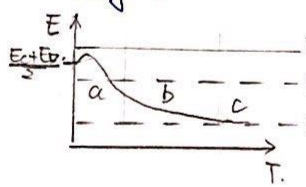
$n_0 = p_0 = n_i = \sqrt{N_c N_v}\exp\left(-\frac{E_g}{2kT}\right)$. c

② $n_i << N_D^+$

$$E_F = E_c + kT\ln\frac{\sqrt{1+\frac{8N_D}{N_c}\exp\left(\frac{E_A}{kT}\right)}-1}{4\exp\left(\frac{E_A}{kT}\right)}$$

$$= \begin{cases} \frac{E_c+E_D}{2} + \frac{kT}{2}\ln\frac{N_D}{2N_c} & T\text{small. a } T\to 0\ E_F \to \frac{E_c+E_D}{2} \\ E_c - kT\ln\frac{N_c}{N_D} & T\text{big b.} \end{cases}$$





④ $n_i << N_D^+ \Rightarrow T$ not very high.

$$n_0 = N_D^+ = N_c\frac{-1+\sqrt{1+\frac{8N_D}{N_c}\exp\left(\frac{E_A}{kT}\right)}}{4\exp\left(\frac{E_A}{kT}\right)} = \begin{cases} \sqrt{\frac{N_D N_c}{2}}\exp\left(-\frac{E_A}{2kT}\right) & T\text{small. a.} \\ N_D & T\text{ big} \end{cases}$$

$$n_0 = \frac{N_D}{1+2\exp\left(\frac{E_c-E_D}{kT}\right)\cdot\exp\frac{E_F-E_c}{kT}}$$

$E_A = E_c - E_D$. ionization energy

12. Carrier Transport

Conductivity $\sigma = q(\mu_n n + \mu_p p)$

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

n-type $I = \frac{\Delta Q}{\Delta t} = \frac{nqA_c\Delta L}{\Delta t} = nqA_c v = nqA_c\frac{\mu V}{L}$.

$= nqA_c\sqrt{\frac{2qV}{m}} = nqA_c\mu E = \frac{V}{R}$.

$V = I\cdot R = I\left(\frac{\rho L}{A}\right) = I\cdot\frac{L}{A\cdot\sigma}$ $\quad$ μ mobility.

13. Generation and Recombination.

$\downarrow R = rnp$. $\quad \uparrow G$ only a function of T intrinsic. equilibrium $G_0 = R = rn_0p_0 = rn_i^2$

non-equilibrium ① Light illumination ②. Current injection. $n = n_0 + \Delta n$ $\quad p = p_0 + \Delta p$.

$R = r(n_0+\Delta n)(p_0+\Delta p)$ $\quad G = G_0 = rn_i^2$ $\quad np > n_i^2$

Net recombination $U = R - G_0 = r\Delta n(n_0+p_0) + r(\Delta n)^2$ $\quad$ neutrality $\Delta n \approx \Delta p$.

Minority carrier lifetime $\tau = \frac{\Delta n}{U} = \frac{1}{r(n_0+p_0)+r\Delta n}$

small injection condition $\Delta n << n_0 + p_0$ $\quad \tau = \frac{1}{r(n_0+p_0)}$ = constant

N-type $\tau = \frac{1}{rn_0}$ $\quad$ P-type $\tau = \frac{1}{rp_0}$

$\begin{cases} \text{Direct recombination} \\ \text{Indirect : Recombination center, trap states. } E_t. \end{cases}$

$$U = \frac{np - n_i^2}{\tau_p\left[n + n_i\exp\left(\frac{E_t-E_i}{kT}\right)\right] + \tau_n\left[p + n_i\exp\left(\frac{E_i-E_t}{kT}\right)\right]} \qquad \tau_p = \frac{1}{N_t r_p} \quad \tau_n = \frac{1}{N_t r_n}$$

Bulk recombination (in a unit volume) $\tau_b = \frac{\Delta n}{U_b} \Rightarrow U_b = \Delta n\frac{1}{\tau_b}$

Surface recombination rate (in a unit surface area) $U_s = U\cdot(\Delta x)_s = \Delta n\frac{\Delta x}{\tau} = \Delta n S$ $\quad$ surface velocity

Total $U = U_b + \frac{U_s}{(\Delta x)_s} \Rightarrow \frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \boxed{\frac{S}{(\Delta x)_s}} = \frac{1}{\tau_s}$

14. Carrier Concentration at non-equilibrium.

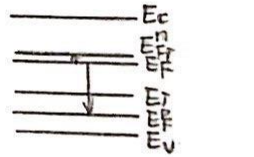
time dependent $\frac{d\Delta p(t)}{dt} = -\frac{\Delta p(t)}{\tau}$

15. Quasi Fermi Level.

$(n_0+\Delta n)\times(p_0+\Delta p) = n_i^2\exp\left(\frac{E_F^n - E_F^p}{kT}\right)$.

$n_0 + \Delta n = N_c\exp\left(\frac{E_F^n - E_c}{kT}\right) = n_i\exp\left(\frac{E_F^n - E_i}{kT}\right)$

$p_0 + \Delta p = N_v\exp\left(\frac{E_v - E_F^p}{kT}\right) = n_i\exp\left(\frac{E_i - E_F^p}{kT}\right)$



16. Carrier drift $E \neq 0$. driving force.

flux (# charges) $J = qnv = qn\mu_n E$. $\quad n = n_0 + \Delta n$.

drift current $J_1 = J_2 = q(n_0+\Delta n)\mu_n E$.

Carrier diffusion. $E = 0$. driving force: thermal dynamics.

flux (# carriers) $S_p = -D_p\frac{d\Delta p(x)}{dx}$.

$D_p\frac{d^2\Delta p}{dx^2} = \frac{\Delta p}{\tau}$. $\quad \Delta p(x) = Ae^{-x/L_p} + Be^{x/L_p}$. $\quad L_p = \sqrt{D_p\tau}$.

	for holes	for electrons	
Diffusion Current Density	$J_p = qS_p = -qD_p\frac{d\Delta p}{dx}$	$J_n = -qS_n = qD_n\frac{d\Delta n}{dx}$	$J = J_p + J_n$.
Drift Current Density	$J_p = qp\mu_p E$.	$J_n = -qn\mu_n E$.	$J_p = (J_p)_{diff} + (J_p)_{drift}$ $J_n = (J_n)_{diff} + (J_n)_{drift}$

$J = qn\mu_n E_x + qp\mu_p E_x + qD_n\frac{dn}{dx} - qD_p\frac{dp}{dx}$

17. Einstein Relation. $D_n = \frac{\mu_n kT}{q}$.

μ_p. μ_n decided by T. impurity concentration & material.

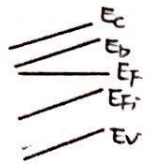
$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = \frac{kT}{q}$$

18. Induced Electric field.

nonuniformly doped with donor impurity atoms.

$\phi = +\frac{1}{e}(E_F - E_{Fi})$ $\quad E_F - E_{Fi} = kT\ln\left(\frac{n}{n_i}\right)$.

$E_x = -\frac{d\phi}{dx} = \frac{1}{e}\frac{dE_{Fi}}{dx} = -\frac{kT}{e}\frac{1}{n(x)}\frac{dn(x)}{dx}$.



19. Reflection Coefficient.

$R = \frac{v_r \cdot B_1 \cdot B_1^*}{v_i \cdot A_1 \cdot A_1^*}$ $\quad v_i$: incident $\quad v_r$: reflected. $\quad [V=0]\ \varphi_1(x) = A_1 e^{jk_1x} + B_1 e^{-jk_1x}$ $\quad k_1 = \frac{mv}{\hbar}$. $\quad v_i = v_r = \frac{\hbar}{m}k$,

Transmission coefficient.

$T = \frac{v_t \cdot A_3 \cdot A_3^*}{v_i \cdot A_1 \cdot A_1^*}$ $\quad v_t$: transmitted. $\quad [V=0]\ \varphi_1(x) = A_1 e^{jk_1x} + B_1 e^{-jk_1x}$

$\varphi_3(x) = A_3 e^{jk_3x} + B_3 e^{-jk_3x}$

$v_t = v_i$

20. Continuity Equation.

Pure diffusion. $\quad D_p \frac{d^2\Delta p(x)}{dx^2} = \frac{\Delta p}{\tau}$

Drift + Diffusion $\quad -D_p \frac{d^2 \Delta p(x)}{dx^2} + \frac{d}{dx}(\mu_p p E) = -\frac{\Delta p(x)}{\tau}$.

Drift + Diffusion + Light illumination

$-D_p \frac{d^2\Delta p(x)}{dx^2} + \frac{d}{dx}(\mu_p p E) = -\frac{\Delta p(x)}{\tau} + G_{ex}$

Accumulation over time

$\frac{\partial \Delta p}{\partial t} = D_p \frac{d^2\Delta p(x)}{dx^2} - \frac{d}{dx}(p\mu_p E) - \frac{\Delta p}{\tau} + G_{ex}$. $\quad \Delta p = Ae^{-\lambda x} + C$.

$\frac{\partial \Delta n}{\partial t} = D_n \frac{d^2\Delta n}{dx^2} + n\mu_n \frac{dE}{dx} + \mu_n E \frac{dn}{dx} - \frac{\Delta n}{\tau} + G_{ex}$.

*. Steady state $\frac{\partial n}{\partial t}, \frac{\partial p}{\partial t} = 0$.

Uniform distribution of excess carrier $D_p\frac{d^2p}{dx^2}, D_n\frac{d^2n}{dx^2} = 0$.

Zero electric field $E=0$. $\quad$ constant E $\frac{dE}{dx} = 0$.

No excess carrier generation $G_{ex} = 0$.

No excess carrier recombination $\frac{\Delta n}{\tau_n}, \frac{\Delta p}{\tau_p} = 0\ (\tau_n, \tau_p \to \infty)$

*. Centrifugal force $F = m^*\omega^2 r$ $\quad \omega = \frac{v}{r} = 2\pi f$

Magnetic force $F = evB$.

*. Conductivity $\sigma = q(\mu_n n + \mu_p p) = \begin{cases} q\mu_p p = q\mu_p N_A & \text{p-type} \\ q\mu_n n = q\mu_n N_D & \text{n-type.} \end{cases}$

*. Ambipolar mobility $\quad$ Ambipolar diffusion coefficient

$\mu' = \frac{\mu_n\mu_p(p-n)}{\mu_n n + \mu_p p}$. $\quad D' = \frac{D_n D_p(n+p)}{D_n n + D_p p}$.

$k = 1.38\times10^{-23}$ J/K. $\quad q = 1.6\times10^{-19}$ C $\quad m_0 = 9.1\times10^{-31}$ kg $\quad kT = 0.0259$ eV.

	N_c (cm^{-3})	N_v	m_n^*/m_0	m_p^*/m_0	n_i
Si	2.8×10^{19}	1.04×10^{19}	1.08	0.56	1.5×10^{10}
GaAs	4.7×10^{17}	7×10^{18}	0.067	0.48	1.8×10^{6}
Ge.	1.04×10^{19}	6×10^{18}	0.55	0.37	2.4×10^{13}.

$\mu_n = 1350$ cm^2/(V·s)

$\mu_p = 480$ cm^2/(V·s).

21. Continuity

①. $\frac{ds}{dx} = -\frac{\Delta p}{\tau} \Rightarrow D_p \cdot \frac{d^2\Delta p}{dx^2} = \frac{\Delta p}{\tau}$ $\quad \Delta p(x) = Ae^{-x/L_p} + Be^{x/L_p}$ $\quad L_p = \sqrt{D_p \tau}$.

② Δp uniform, no electric field, light is cut off when $t=0$, $\Delta p(0) = \Delta p_0$

$\frac{\partial \Delta p}{\partial t} = -\frac{\Delta p}{\tau}$ $\quad \Delta p = \Delta p_0 e^{-t/\tau}$

③. At equilibrium, no electric field. $x \in [0, \infty)$. At $x=0$, surface velocity S.

$D_p \cdot \frac{d^2\Delta p}{dx^2} - \frac{\Delta p}{\tau} + g = 0$. $\Rightarrow \Delta p(x) = Ae^{-x/L_p} + Be^{x/L_p} + C$ $\quad C = g\cdot\tau$ $\quad B = 0$.

$x=0$. $-S_p = S\cdot\Delta p(0) \Rightarrow D_p \cdot \frac{d\Delta p}{dx} = S\cdot\Delta p(0) \Rightarrow A = -\frac{g\cdot\tau\cdot S}{S + D_p/L_p}$

④ At equilibrium, constant E. no g. $\Delta p(0) = \Delta p_0$.

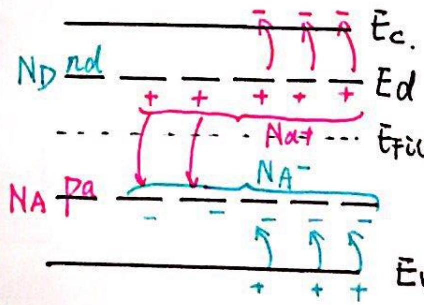
$D_p \cdot \frac{\partial^2 \Delta p}{\partial x^2} - \mu_p E \cdot \frac{\partial \Delta p}{\partial x} - \frac{\Delta p}{\tau} = 0$. $\Rightarrow \Delta p = \Delta p_0 \exp\left[\frac{L_p(E) - \sqrt{L_p^2(E) + 4L_p^2}}{2L_p^2}x\right]$

$L_p = \sqrt{\tau \cdot D_p}$ $\quad L_p(E) = \mu_p \cdot \tau \cdot E$.

⑤. $\frac{\partial \Delta p}{\partial t} = G_{ex} - \underbrace{\frac{\partial S}{\partial x}}_{\text{gradient}} - U$ $\nearrow \frac{\Delta p}{\tau}$.

*. n-type. P. As. Te.

p-type. B. Ga



$N_D = nd + Nd^+$

$N_A = pa + N_A^-$