Semiconductor Materials

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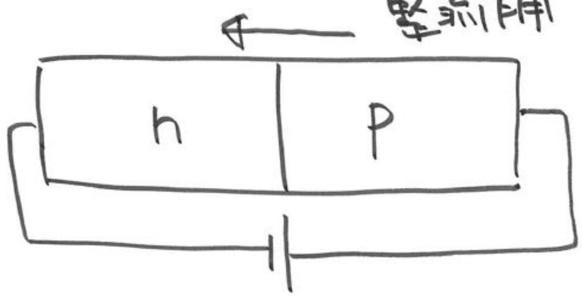
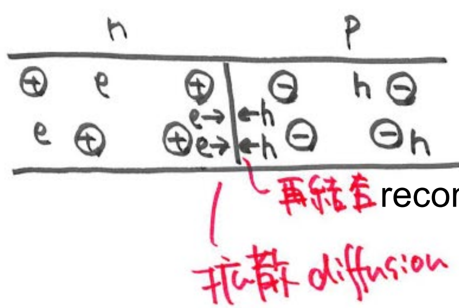
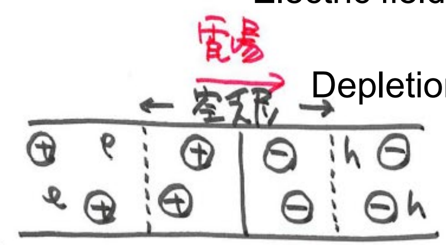
pn接合 pn junction

整流作用 Rectifying effect



ダイオード diode 、LED (Light Emitting Diode)



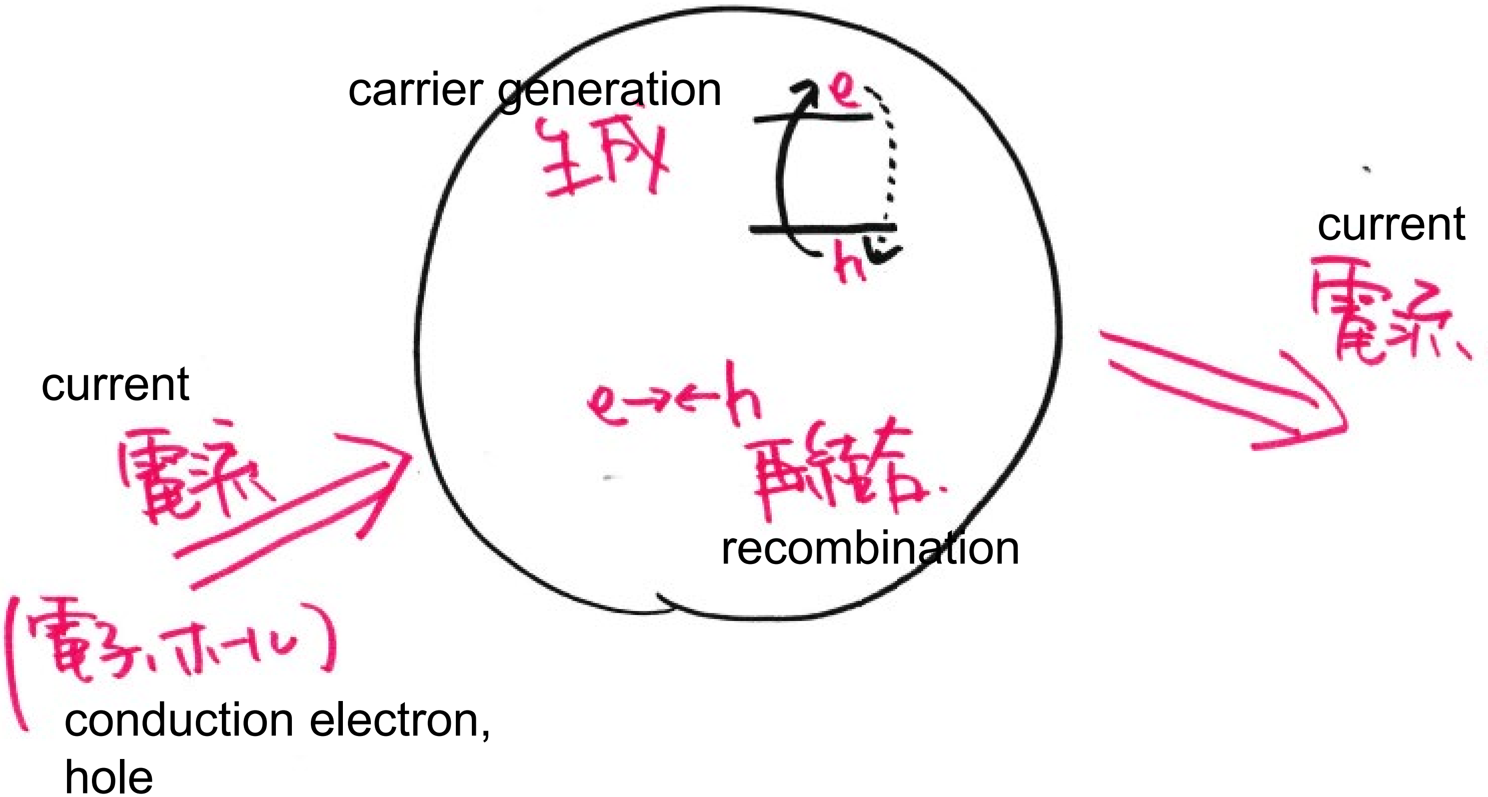


(ホール hole: → drift = ← diffusion)

(電子 electron: ← drift = → diffusion)

Continuity equation

(電流) 連続の式



Continuity equation for holes

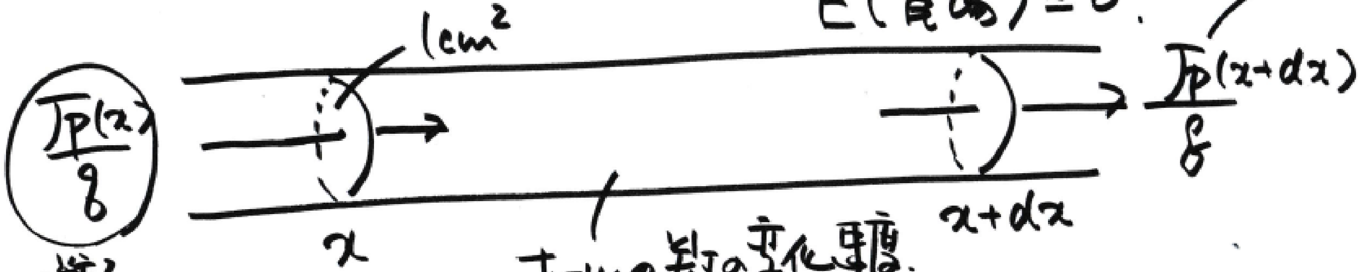
連続の式（ホール）

Current density of holes

ホールの電流密度.

Electric field

E(電場)$=0$.



ホールの粒子の流れ.

Flow of holes

ホールの数の変化速度.

Change rate of holes

$$\frac{\partial p(x,t)}{\partial t} \times dx$$

$$(g-r) = -\frac{p-p_0}{\tau}$$

$$\frac{\partial p}{\partial t}dx = \frac{J_p(x)}{q} - \frac{J_p(x+dx)}{q} + (g-r)dx$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{J_p(x+dx)-J_p(x)}{dx} - \frac{p-p_0}{\tau}$$

$$= -\frac{1}{q}\frac{\partial J_p(x)}{\partial x} - \frac{p-p_0}{\tau}$$

$$J_p(x) = -qD_p\frac{\partial p}{\partial x}$$

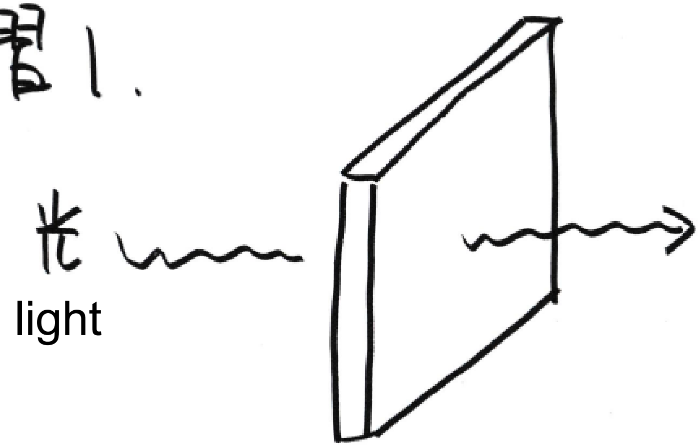
$$= D_p\frac{\partial^2 p}{\partial x^2} - \frac{p-p_0}{\tau}$$

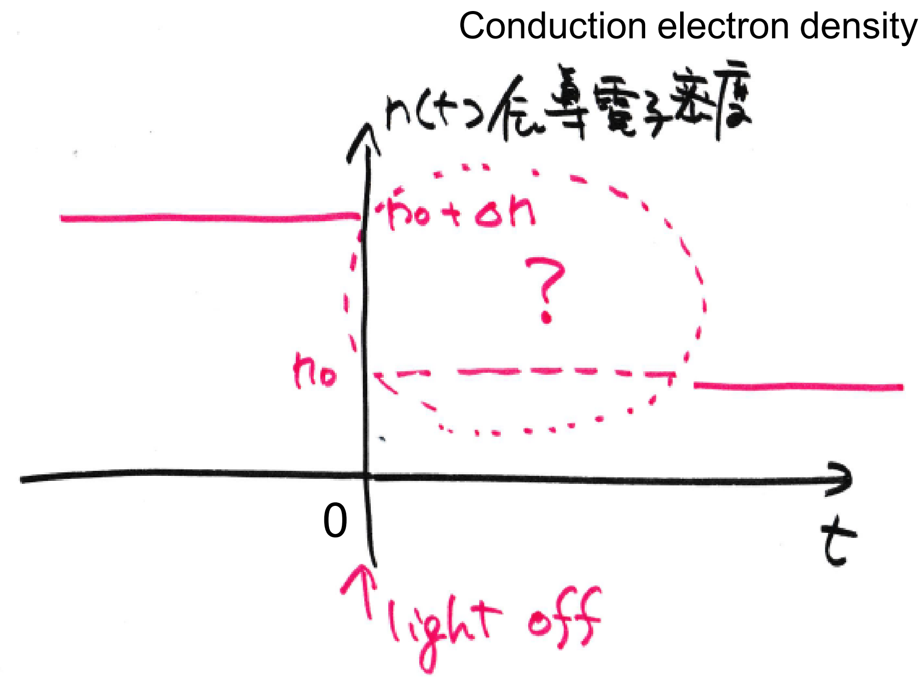
(電子) $$\frac{\partial n}{\partial t} = D_n\frac{\partial^2 n}{\partial x^2} - \frac{n-n_0}{\tau}$$

Continuity equation for conduction electrons

Exercise 1

演習1.





$t>0$ での $n(t)$ を求めよ.

($n(x,t)$ の x 依存性はないものとする)

Derive n(t) for t > 0.
The x dependence of n can be neglected.

$$\frac{\partial n}{\partial t} = \cancel{D_n \frac{\partial^2 n}{\partial x^2}} - \frac{n-n_0}{\tau}$$

$$\frac{dn(t)}{dt} = -\frac{n(t)-n_0}{\tau}$$

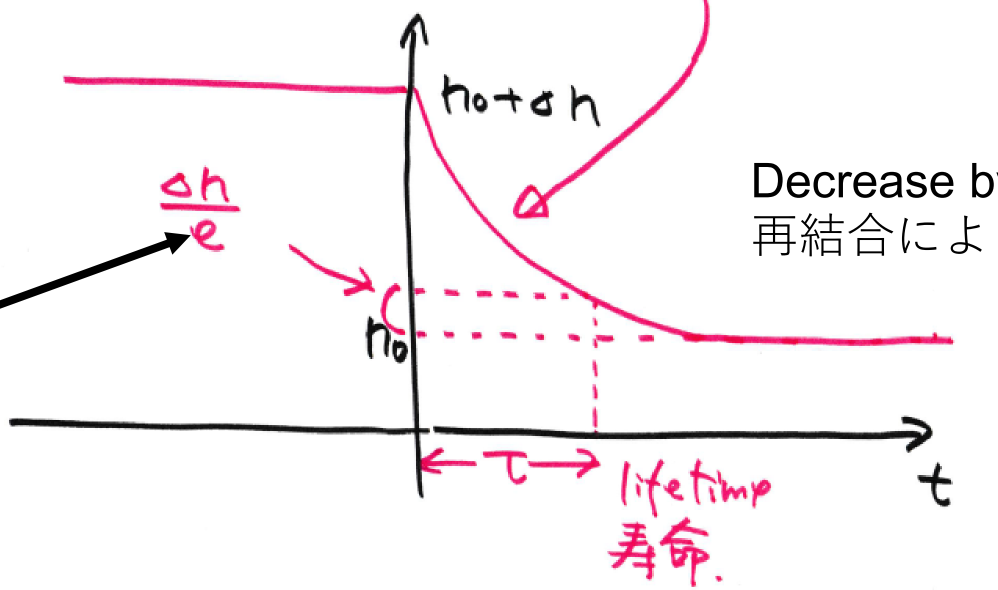
Exercise 1 (solution)

$$\int \frac{dn}{n(t)-n_0} = -\int \frac{dt}{\tau}$$

$$\log(n-n_0) = -\frac{t}{\tau} + A$$

$$n - n_0 = A' e^{-\frac{t}{\tau}} \qquad n(0) = n_0 + \Delta n \text{ より } A' = \Delta n$$

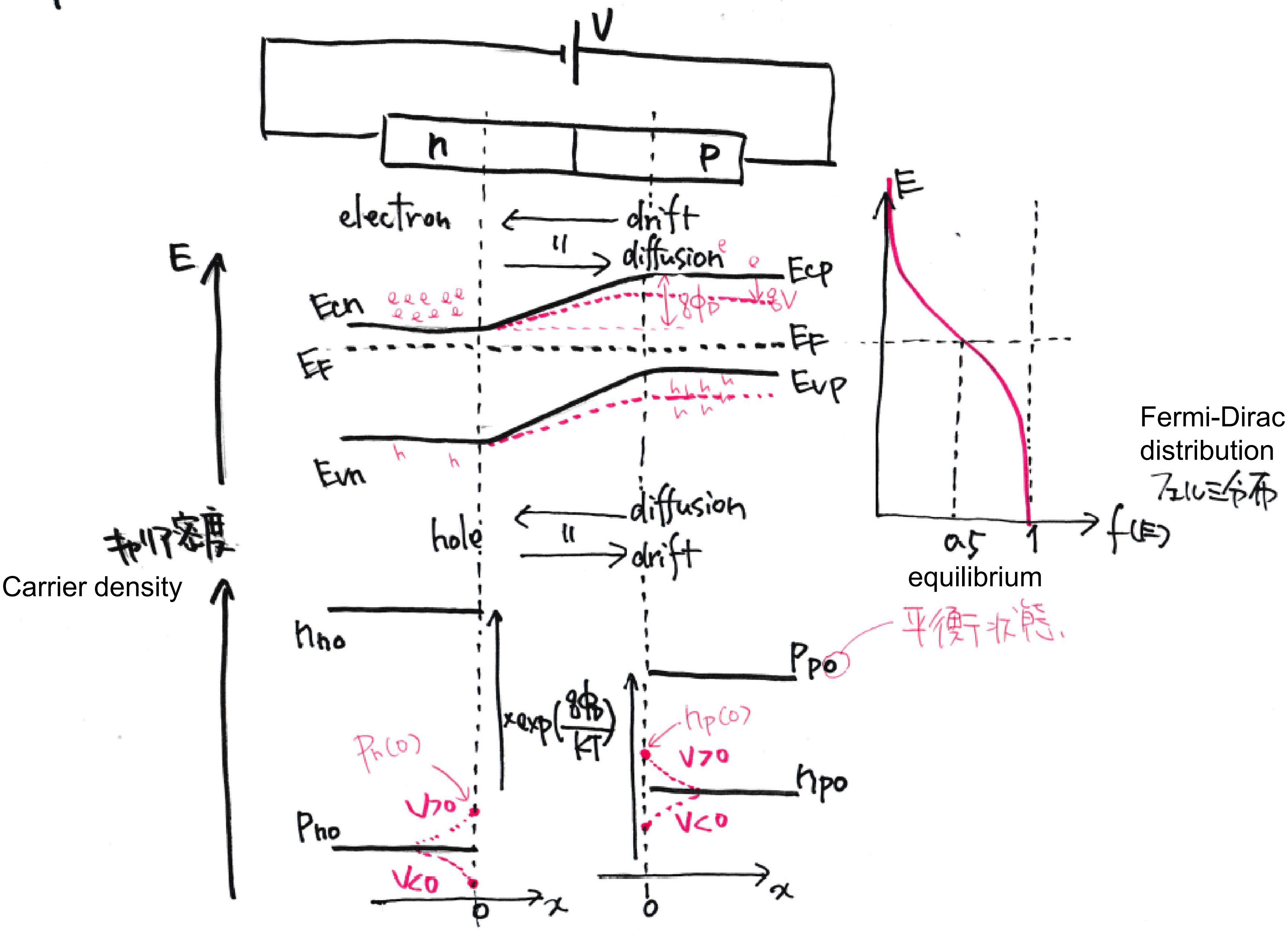
$$\therefore\ n(t) = n_0 + \Delta n\, e^{-\frac{t}{\tau}}$$



~2.718

Decrease by recombination
再結合によるキャリア数の減少

pn接合における電気伝導 Electrical current through the pn junction



Conduction electron density

電子密度

$$n_{no} = N_c \exp\left(-\frac{E_{cn}-E_F}{kT}\right)$$

$$n_{po} = N_c \exp\left(-\frac{E_{cp}-E_F}{kT}\right)$$

$$\frac{n_{no}}{n_{po}} = \exp\left(-\frac{E_{cn}-\cancel{E_F}-E_{cp}+\cancel{E_F}}{kT}\right) = \exp\left(\frac{q\Phi_D}{kT}\right)$$

Hole density

ホール密度

$$p_{no} = N_v \exp\left(-\frac{E_F-E_{vn}}{kT}\right)$$

$$p_{po} = N_v \exp\left(-\frac{E_F-E_{vp}}{kT}\right)$$

$$\frac{p_{po}}{p_{no}} = \exp\left(-\frac{\cancel{E_F}-E_{vp}-\cancel{E_F}+E_{vn}}{kT}\right) = \exp\left(\frac{q\Phi_D}{kT}\right)$$

when
V=0.2Vのとき
～2200

$\phi_D - V$

$$n_{p0} = n_{n0} \times \exp\left(-\frac{q\phi_D}{kT}\right)$$

$\downarrow$

$$n_p(0) = n_{p0} \times \exp\left(\frac{qV}{kT}\right)$$ ← p型内の空乏層端における電子密度

Conduction electron density in the p-type material at the depletion layer edge

$\phi_D - V$

$$p_{n0} = p_{p0} \times \exp\left(-\frac{q\phi_D}{kT}\right)$$

$\downarrow$

$$p_n(0) = p_{n0} \times \exp\left(\frac{qV}{kT}\right)$$ ← n型内の空乏層端におけるホール密度.

Hole density in the n-type material at the depletion layer edge

Conduction electron density in the p-type material
p型半導体中の伝導電子密度

$$\frac{\partial n_p}{\partial t} = D_n \frac{\partial^2 n_p}{\partial x^2} - \frac{n_p - n_{po}}{\tau_n} = 0 \longrightarrow D_n \frac{d^2 n_p(x)\overset{-n_{po}}{\vee}}{dx^2} = \frac{n_p - n_{po}}{\tau_n}$$

$$n_p(x) - n_{po} = A\exp\left(-\frac{x}{\sqrt{D_n\tau_n}}\right) + B\exp\left(\frac{x}{\sqrt{D_p\tau_p}}\right)$$

境界条件 $$n_p(0) = n_{po}\exp\left(\frac{qV}{kT}\right) = n_{po} + A$$

Boundary condition

$$\therefore A = n_{po}\left\{\exp\left(\frac{qV}{kT}\right) - 1\right\}$$

$$\therefore n_p(x) = n_{po} + n_{po}\left\{\exp\left(\frac{qV}{kT}\right) - 1\right\}\exp\left(-\frac{x}{\sqrt{D_n\tau_n}}\right)$$

Hole density in the n-type material
n型半導体中のホール密度

Steady-state condition　定常状態

$$\frac{\partial p_n}{\partial t} = D_p \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{\tau_p} = 0 \longrightarrow D_p \frac{d^2 p_n(x) \overset{-p_{n0}}{\vee}}{dx^2} = \frac{p_n - p_{n0}}{\tau_p}$$

$$p_n(x) - p_{n0} = A \exp\left(-\frac{x}{\sqrt{D_p \tau_p}}\right) + B \exp\left(\frac{x}{\sqrt{D_p \tau_p}}\right)$$

境界条件
Boundary condition

$$p_n(0) = p_{n0} \times \exp\left(\frac{qV}{kT}\right) = p_{n0} + B$$

$$\therefore B = p_{n0} \left\{ \exp\left(\frac{qV}{kT}\right) - 1 \right\}$$

$$\therefore p_n(x) = p_{n0} + p_{n0} \left\{ \exp\left(\frac{qV}{kT}\right) - 1 \right\} \exp\left(\frac{x}{\sqrt{D_p \tau_p}}\right)$$

Diffusion current by holes

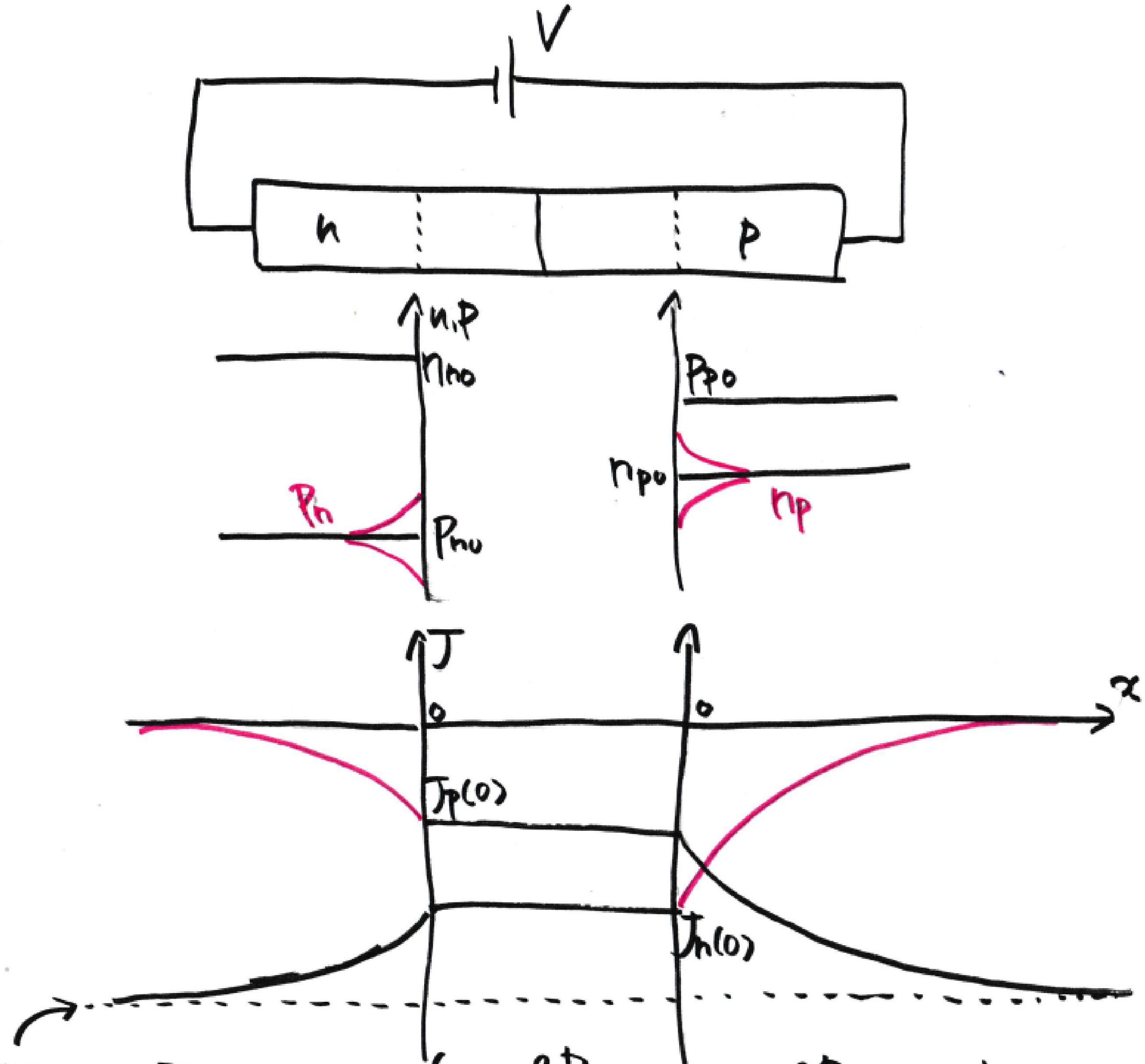
ホールによる電流

$$J_p(x) = -qD_p \frac{dp_n(x)}{dx}$$

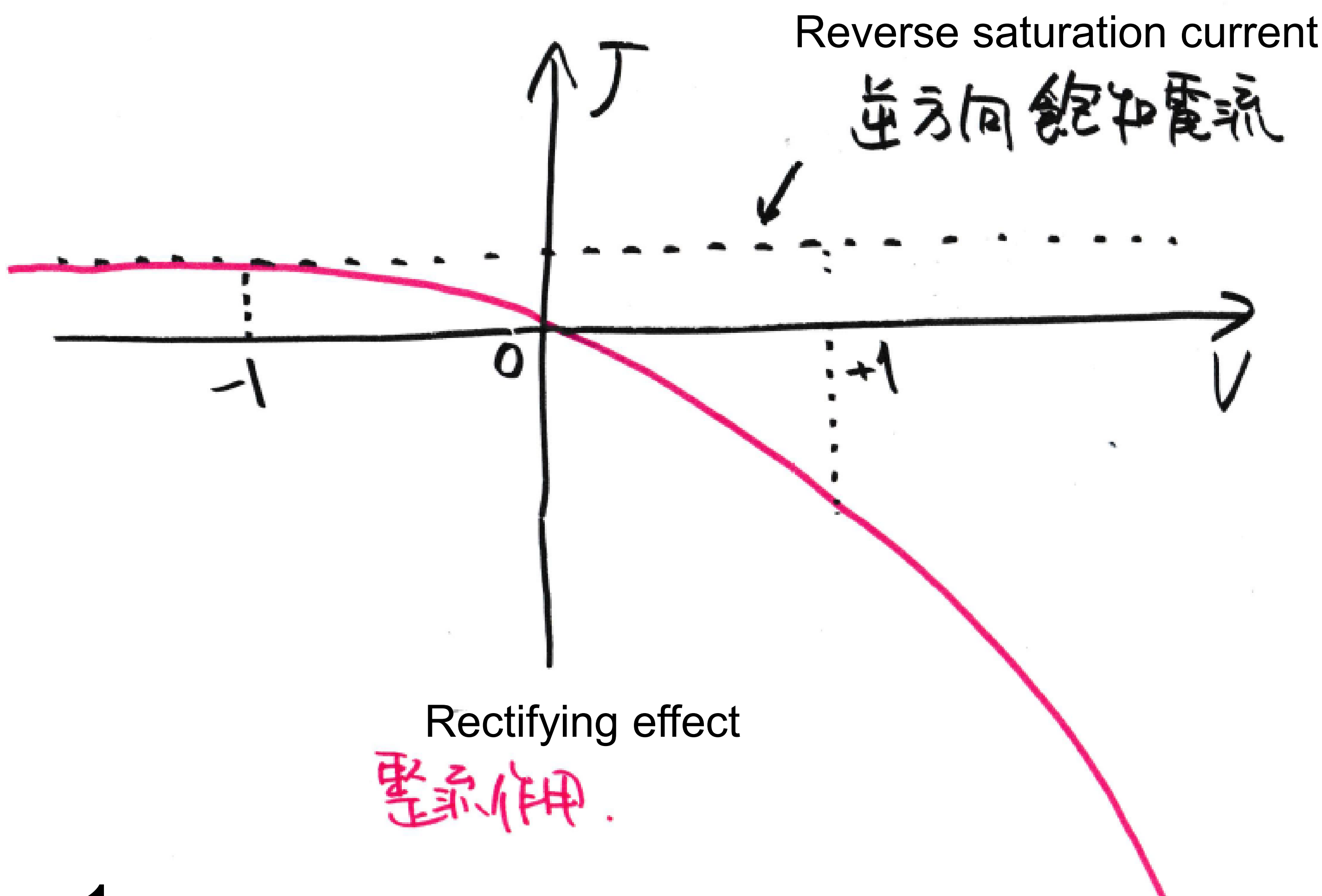
Diffusion current by conduction electrons

伝導電子による電流

$$J_n(x) = qD_n \frac{dn_p(x)}{dx}$$



$$J_{total} = J_n(0) + J_p(0) = \left(-\frac{qD_n}{\sqrt{D_n\tau_n}} n_{p0} - \frac{qD_p}{\sqrt{D_p\tau_p}} p_{n0} \right) \left\{ \exp\left(\frac{qV}{kT}\right) - 1 \right\} \quad \cdots\cdots (1)$$



Exercise 1

pn接合（室温）において、バイアスが+1(V)、-1(V)のときの電流値の比を求めよ。

Evaluate the ratio of current across a pn junction at V=+1(V) and -1(V) at room temperature.