Semiconductor Materials

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演習1
Exercise1

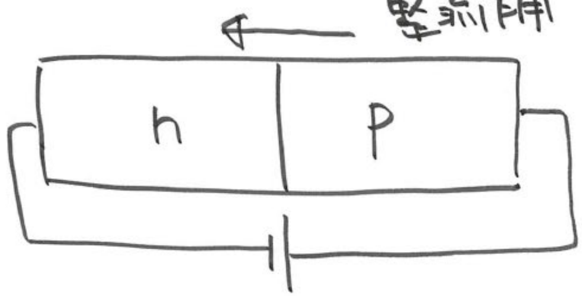
アクセプター濃度 $N_A = 1\times10^{19}/cm^3$ の p-Si と
ドナー濃度 $N_D = 1\times10^{16}/cm^3$ の n-Si
の pn接合における内蔵電位を求めよ。(300K).

$E_g = E_c - E_v = 1.1\,eV$
$N_c = 2.86\times10^{19}/cm^3$
$N_v = 2.66\times10^{19}/cm^3$
$kT = 0.026\,eV$
$q = 1.6\times10^{-19}\,C$

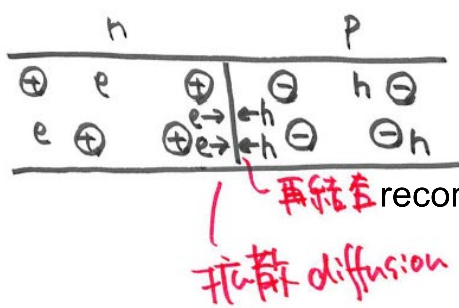
Evaluate the built-in potential for the pn junction where the acceptor density and donor density in Si are N_A=1 x 10^{19} cm^{-3} and N_D=1 x 10^{16} cm^{-3}, respectively.

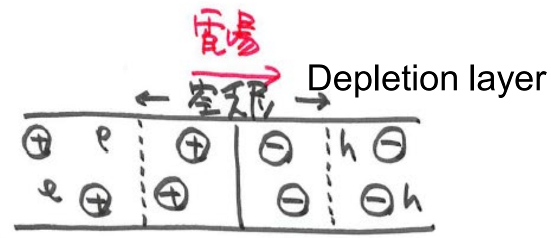
pn接合 pn junction

整流作用 Rectifying effect



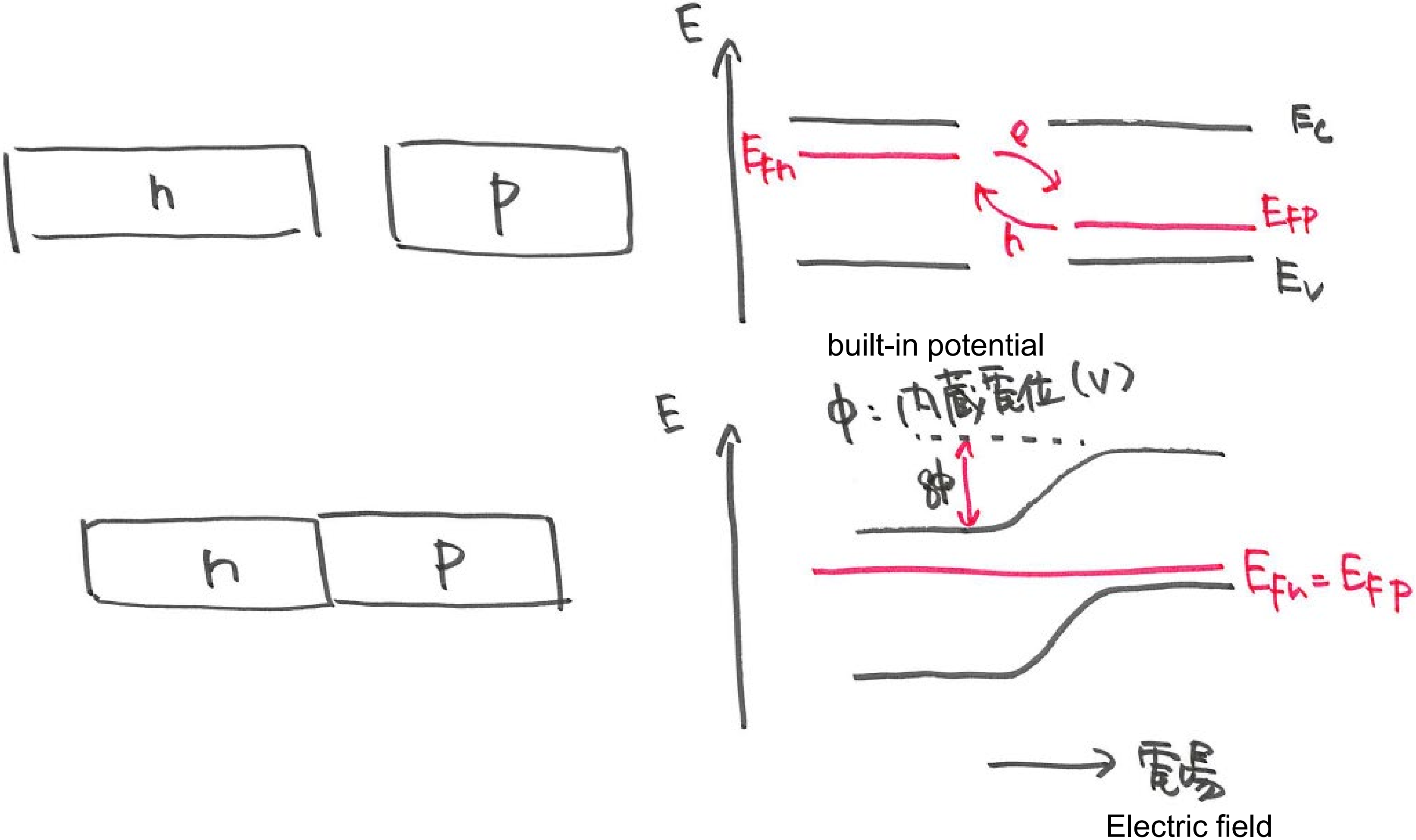
ダイオード diode、LED (Light Emitting Diode)



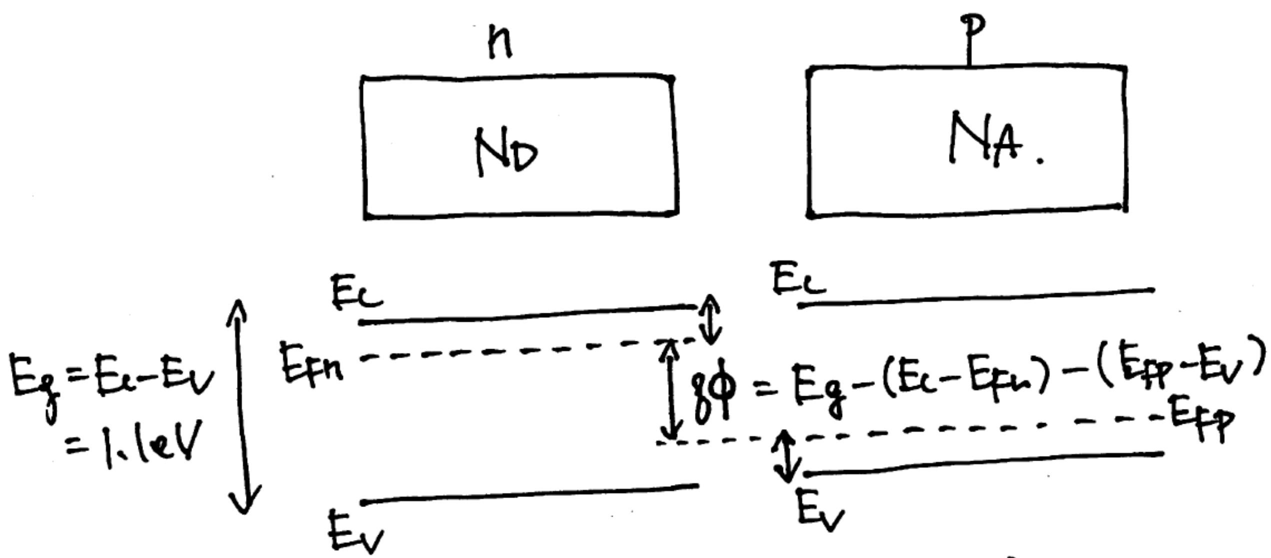


(ホール hole: $\longrightarrow$ drift $=$ $\longleftarrow$ diffusion)

(電子 electron: $\longleftarrow$ drift $=$ $\longrightarrow$ diffusion)


n
p
E
Efn
e
h
Ec
Efp
Ev
n
p
built-in potential
φ：内蔵電位(V)
E
qφ
Efn = Efp
電場
Electric field

演習1
Exercise1
(solution)



内蔵電位.

$\phi(V)$ = built-in potential.

$1\times10^{16}/cm^3$

$N_D \sim n = N_c \exp\left(-\frac{E_c - E_{fn}}{kT}\right)$

$\downarrow$

$E_c - E_{fn} = 0.207$

$1\times10^{19}/cm^3$

$N_A \sim p = N_v \exp\left(-\frac{E_{fp} - E_v}{kT}\right)$

$\downarrow$

$E_{fp} - E_v = 0.025$

電気素量 (elementary charge).

$$q\phi = 0.87\,(\mathrm{eV}) = 0.87 \times q\,(\mathrm{J}).$$

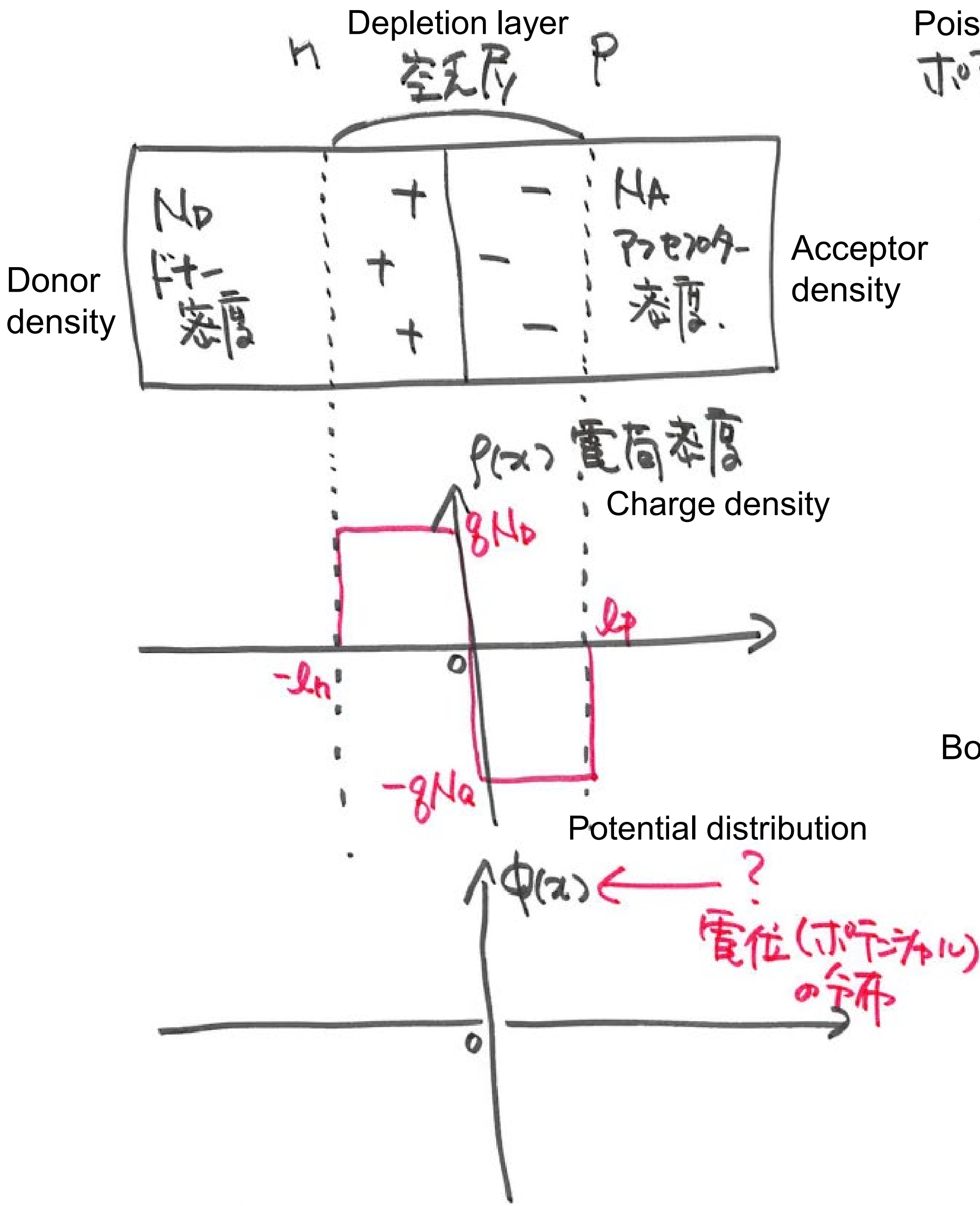
$$\therefore \phi = \frac{0.87 \times q\,(\mathrm{J})}{q\,(\mathrm{C})} = 0.87\,(\mathrm{V}).$$

$\boxed{\mathrm{eV}}$

1eV: $+q$ (C) の電荷を 1 (V) だけ電位の高いところへ運ぶのに必要な仕事

Energy necessary to carry a particle ($+q$) to a position where the position is 1 (V) higher.

$$1\,\mathrm{eV} = q\,(\mathrm{C}) \times 1\,(\mathrm{V})$$
$$= 1.6 \times 10^{-19}\,(\mathrm{J}).$$



Poisson's equation
ポアソン方程式

$$\frac{d^2\phi(x)}{dx^2} = -\frac{\rho(x)}{\varepsilon_s}$$

Permittivity of Si
Siの誘電率

$11.7 \times 8.854 \times 10^{-12}\ \mathrm{F/m}$

Siの比誘電率
relative permittivity of Si

Permittivity of vacuum
真空の誘電率

$\rho(x) \rightarrow \phi(x)$を求めるための方程式
Differential equation

境界条件
Boundary condition

$$E(-l_n) = E(l_p) = 0$$

$$\phi(0) = 0$$

中性条件
Neutral condition

$$N_D l_n = N_A l_p$$

(i) $0 \leq x \leq l_p$, $\rho(x) = -qN_A$

$$\frac{d^2\phi(x)}{dx^2} = \frac{qN_A}{\varepsilon_s}$$

$$\Big\downarrow$$

$E(l_p)=0$

$$-E(x) = \frac{d\phi(x)}{dx} = \frac{qN_A}{\varepsilon_s}x + A = \frac{qN_A}{\varepsilon_s}(x - l_p)$$

Electric field
電場

$$\Big\downarrow$$

$$\phi(x) = \frac{qN_A}{\varepsilon_s}\frac{(x-l_p)^2}{2} + B = \frac{qN_A}{2\varepsilon_s}\left\{(x-l_p)^2 - l_p^2\right\}$$

$\phi(0)=0$

(ii) $-l_n \leq x \leq 0$, $\rho(x) = qN_D$

$$\phi(x) = -\frac{qN_D}{2\varepsilon_s}\left\{(x+l_n)^2 - l_n^2\right\}$$

$-l_n \leq x \leq 0$ のとき.　　$\rho(x) = qN_D$

$$\frac{d^2\phi(x)}{dx^2} = -\frac{qN_D}{\varepsilon_s}$$

$$\downarrow$$

$E(-l_n)=0.$

$$-E(x) = \frac{d\phi(x)}{dx} = -\frac{qN_D}{\varepsilon_s}x + A = -\frac{qN_D}{\varepsilon_s}(x+l_n)$$

$$\downarrow$$

$$\phi(x) = -\frac{qN_D}{\varepsilon_s}\frac{(x+l_n)^2}{2} + B = -\frac{qN_D}{2\varepsilon_s}\left\{(x+l_n)^2 - l_n^2\right\}.$$

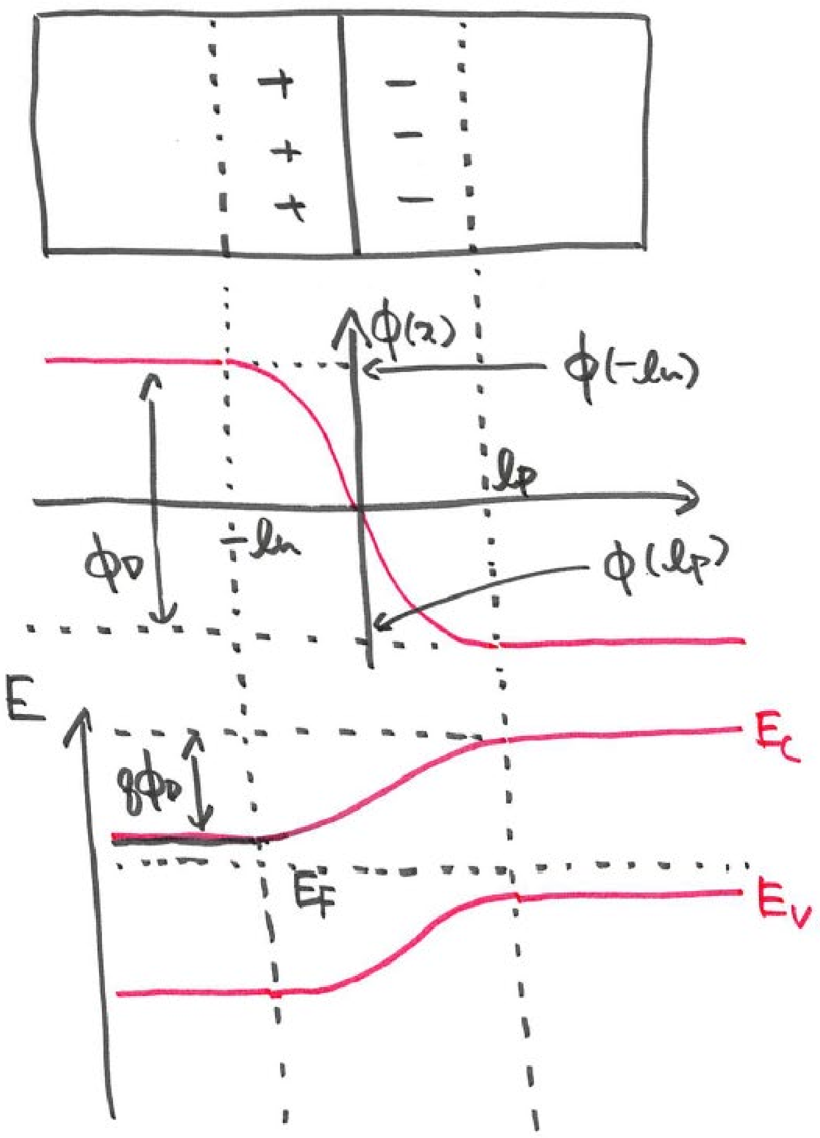
$\phi(0)=0$

Built-in potential

内蔵電位

$$\phi_D = \phi(-l_n) - \phi(l_p)$$

$$= \frac{qN_D}{2\varepsilon_s} l_n^2 + \frac{qN_A}{2\varepsilon_s} l_p^2$$



Derivation of depletion layer width
空乏層幅の導出

$$\phi_D = \frac{q}{2\varepsilon_s}\left(N_D l_n^2 + N_A l_p^2\right)$$

$$= \frac{q}{2\varepsilon_s}\left(N_D l_n^2 + (N_A l_p) l_p\right).$$

$N_D l_n.$

$$= \frac{q}{2\varepsilon_s} N_D l_n \underbrace{(l_n + l_p)}_{= W}.$$

W (空乏層の巾).

$$\begin{cases} l_n + l_p = W. \\ N_D l_n = N_A l_p. \end{cases}$$

$$\downarrow$$

$$l_n = \frac{N_A}{N_A + N_D} W$$

$\therefore$

$$W = l_n + l_p$$

$$= \sqrt{\frac{2\varepsilon_s}{q} \cdot \frac{N_A + N_D}{N_A N_D} \phi_D}$$

演習
Exercise

$N_A = 1\times10^{19}/\mathrm{cm}^3$, $N_D = 1\times10^{16}/\mathrm{cm}^3$ のとき、
空乏層の巾と $x=0$ での電場 $E(0)$ を求めよ。

Derive the depletion layer width and electric field at the junction, E(0), for the pn junction where the acceptor density and donor density in Si are N_A=1 x 10^{19} cm^{-3} and N_D=1 x 10^{16} cm^{-3}, respectively.

$q = 1.6\times10^{-19}\,(\mathrm{C})$, $\varepsilon_s = 11.7\times8.854\times10^{-12}\,(\mathrm{F/m})$