Semiconductor physics: basics

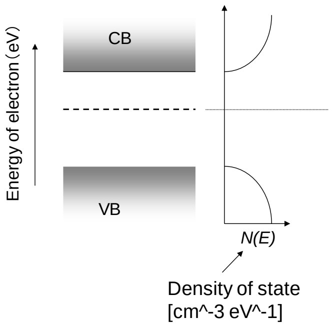
Google ➔Power Kyutech

Pw = ISPSD

Diagram of theories

Solid-state physics | Semiconductor (Device) physics | Semiconductor Device Design

Band structure



Fermi-Dirac distribution,
Density of state and electron density

Boltzmann Approximation

Carrier concentration

N_C

N_V

$$n = n_i \cdot e^{(E_F - E_i)/kT}$$

$$p = n_i \cdot e^{(E_i - E_F)/kT}$$

Thermal equilibrium condition

Energy → Potential

Carrier and potential (Voltage)

$$n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi)}$$

$$p = n_i \cdot e^{\frac{q}{kT}(\phi - \varphi)}$$

Boltzmann Distribution

Ideal gas

Drift – Diffusion Model

$$J_n = -q\mu_n n \frac{d\varphi}{dx} + qD_n \frac{dn}{dx}$$

$$J_p = -q\mu_p p \frac{d\varphi}{dx} - qD_p \frac{dp}{dx}$$

Models in Other Fields

Current continuity equation

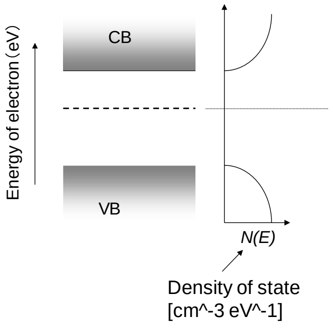
Gauss' divergence theorem

Poisson Eq

Diagram of theories (today)

Solid-state physics | Semiconductor (Device) physics | Semiconductor Device Design

Band structure



Fermi-Dirac distribution,
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Boltzmann Approximation

Carrier and potential (Voltage)

$$n = n_i \cdot e^{(E_F - E_i)/kT}$$

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Energy ➔ Potential

$$n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi)}$$

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Boltzmann Distribution

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Models in Other Fields

Current continuity equation

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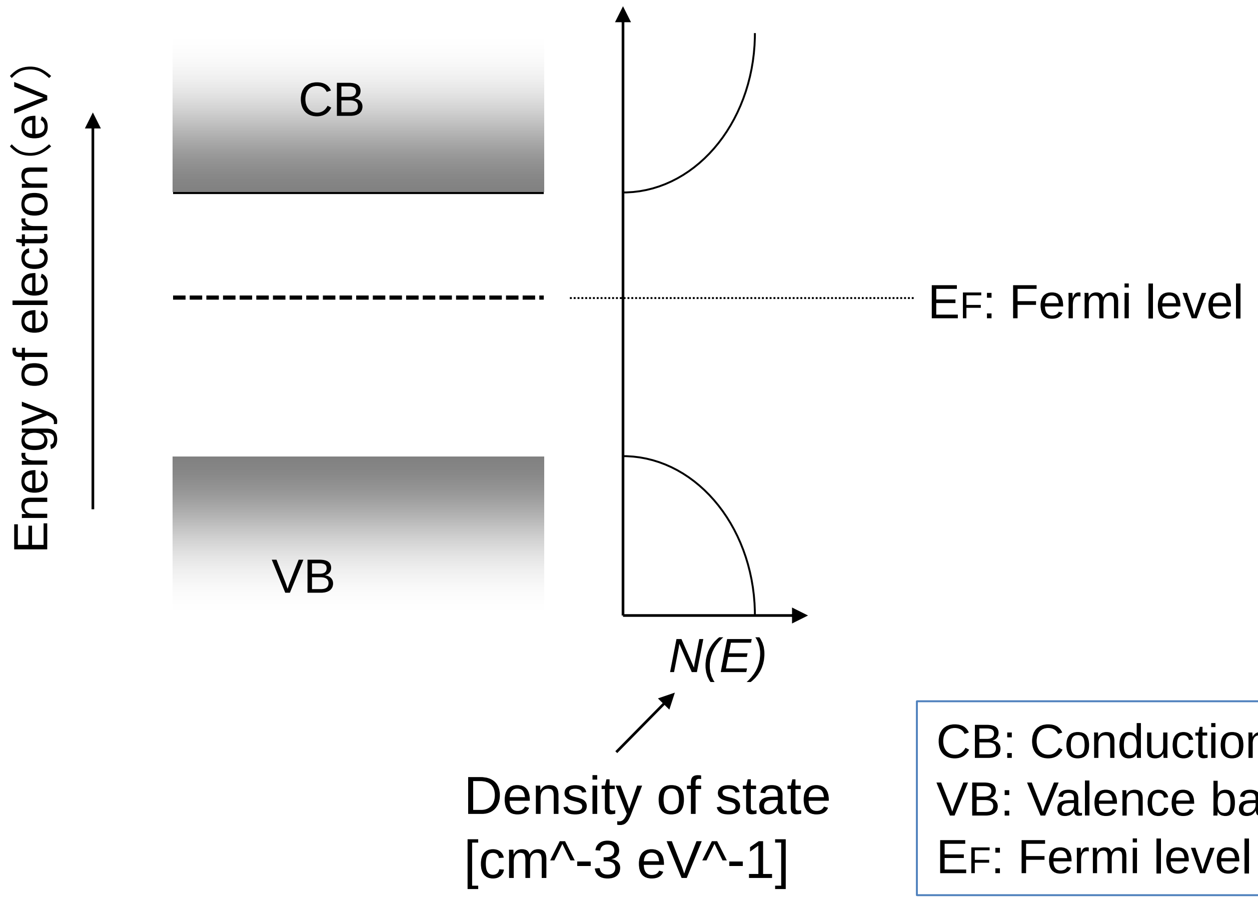
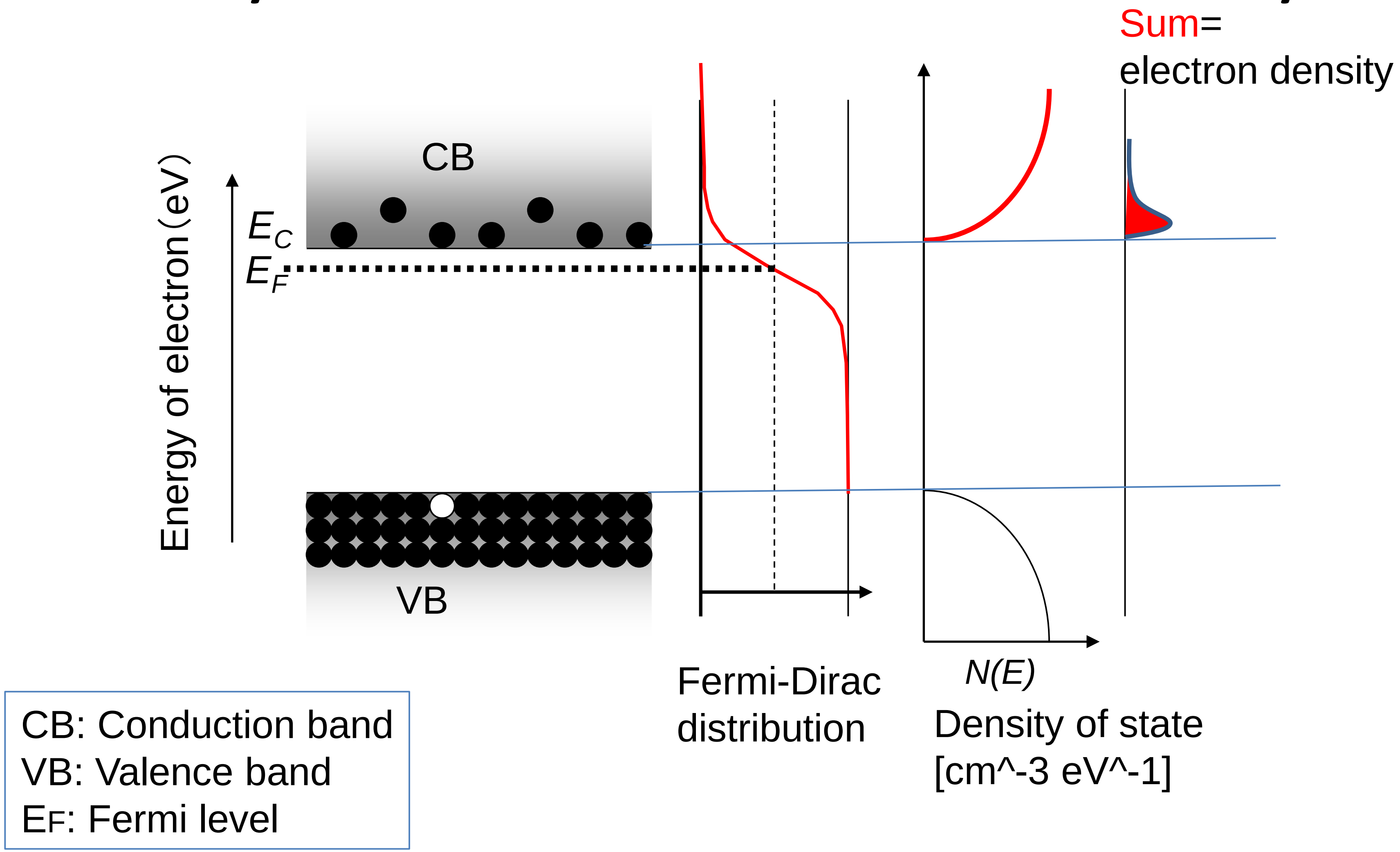
Semiconductor physics basics

Band gap of semiconductor

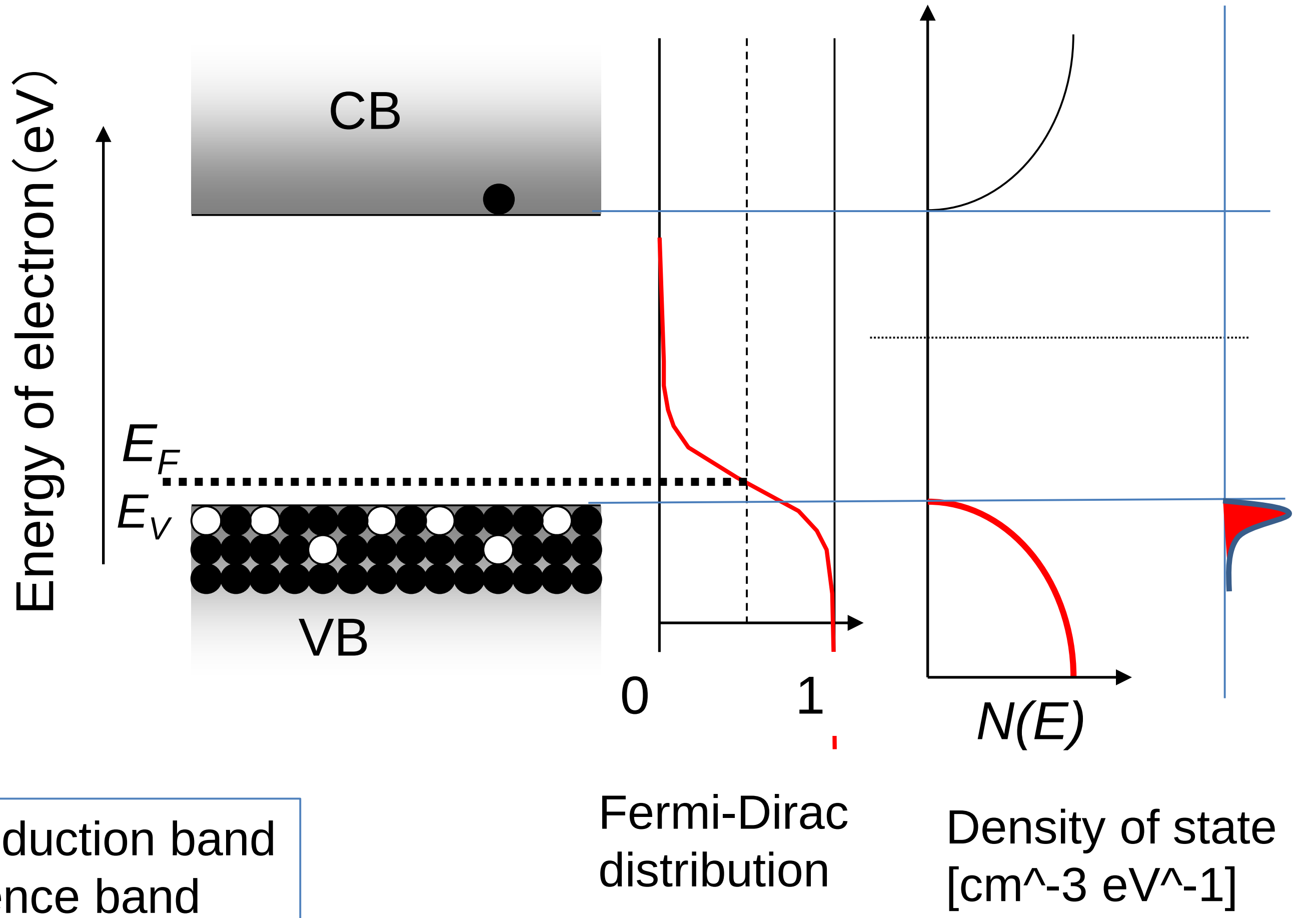


CB: Conduction band
VB: Valence band
E_F: Fermi level

Fermi-Dirac distribution,
Density of state and electron density

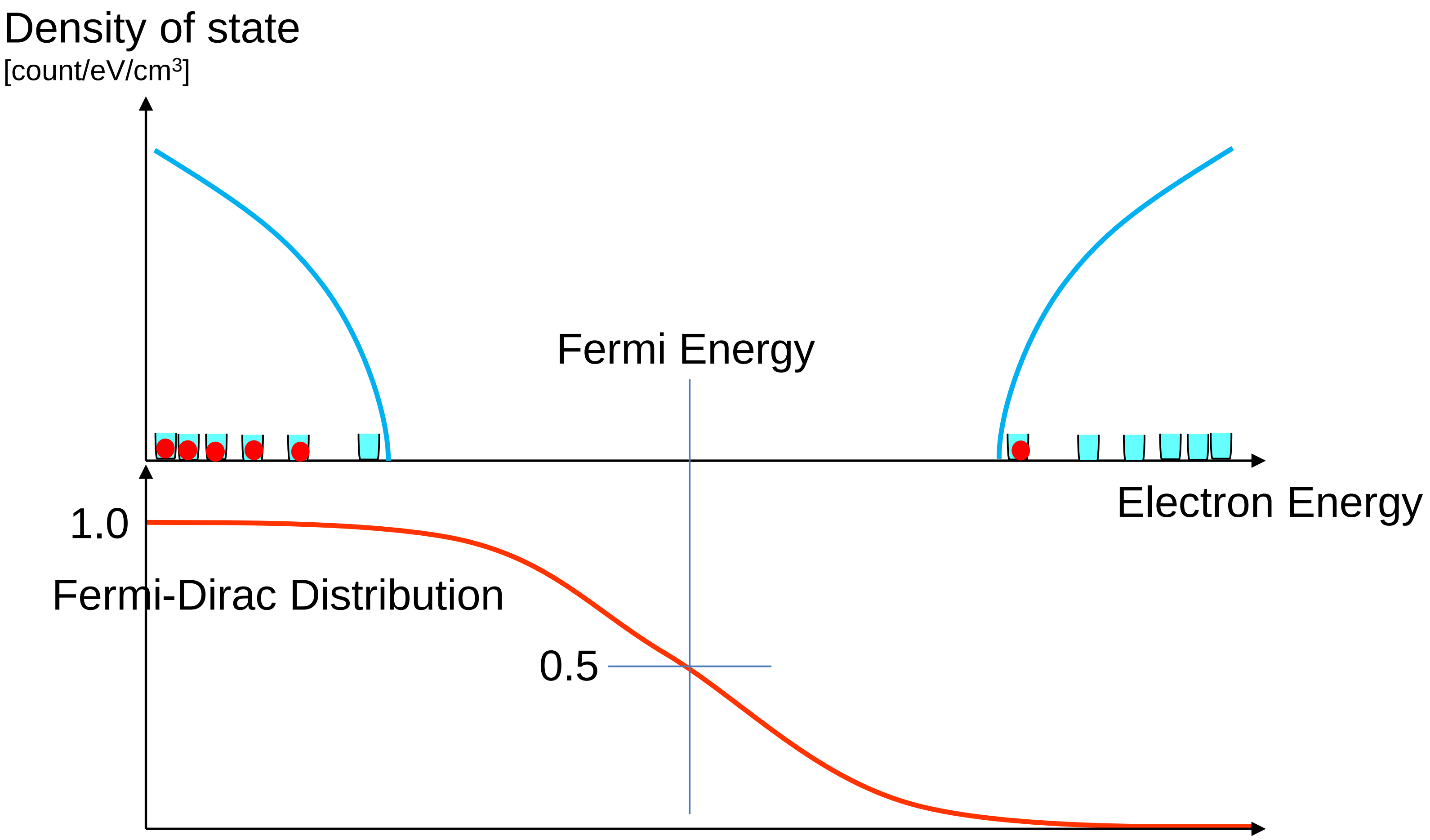


Fermi-Dirac distribution, Density of state and hole density

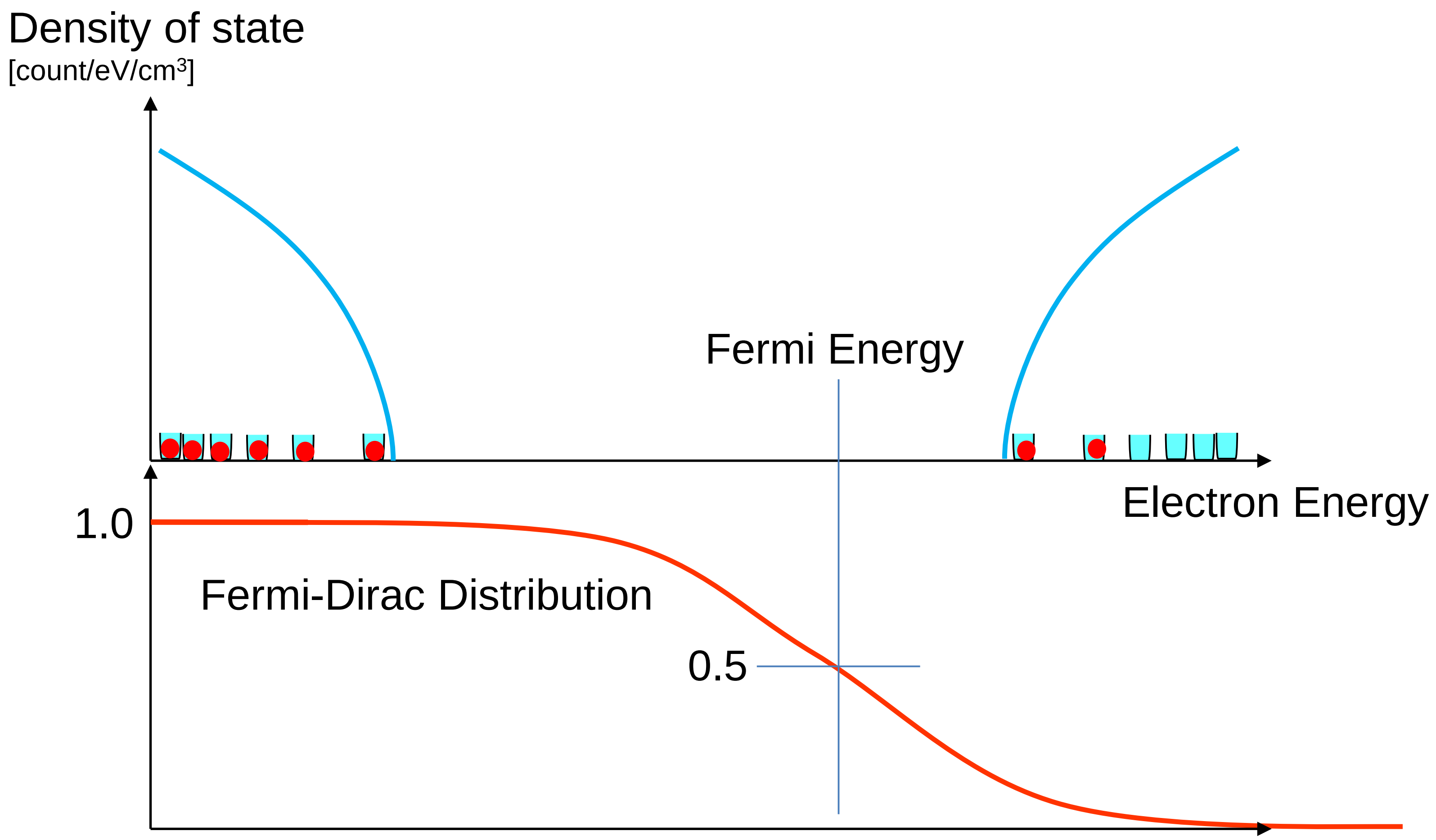


CB: Conduction band
VB: Valence band
E_F: Fermi level

Remark: Density of state and Fermi energy



Remark: Density of state and Fermi energy



Boltzmann Approximation

Electron

Fermi-Dirac distribution

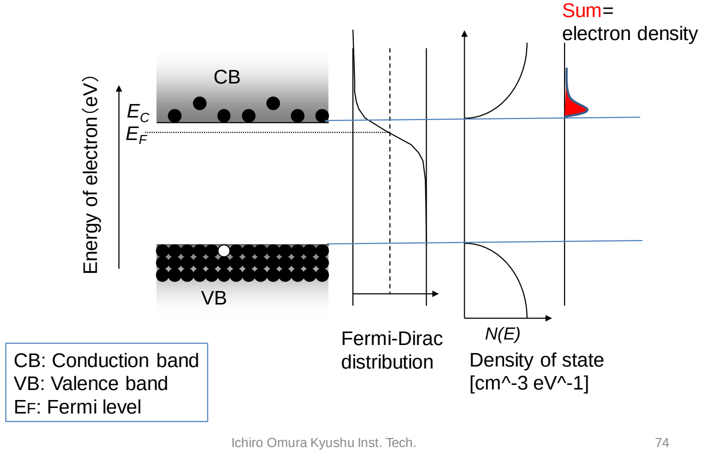
Density of state

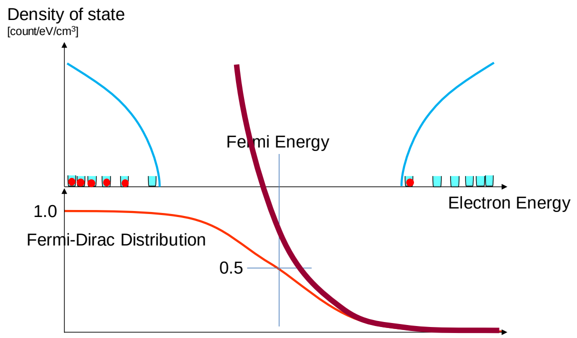
$$n = \int_{E_c}^{\infty} \frac{1}{1+e^{(E-E_F)/kT}} N(E)dE$$

$$\frac{1}{1+e^{(E-E_F)/kT}} \approx e^{-(E-E_F)/kT}$$

>>1

$$n = \int_{E_F}^{\infty} e^{-(E-E_F)/kT} N(E)dE$$





Boltzmann Approximation

Hole

Fermi-Dirac distribution

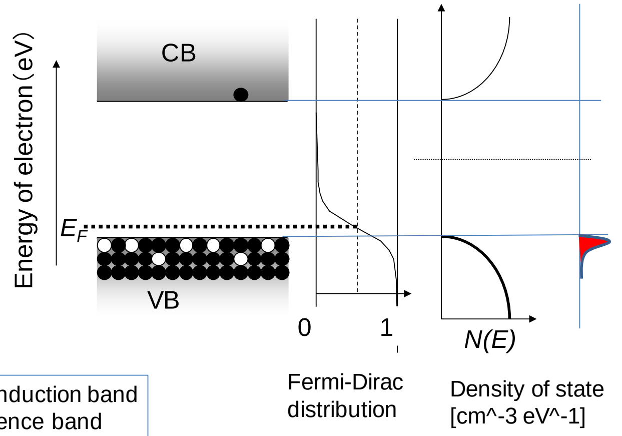
Density of state

$$p = \int_{-\infty}^{E_V} \left\{ 1 - \frac{1}{1+e^{(E-E_F)/kT}} \right\} N(E)dE$$

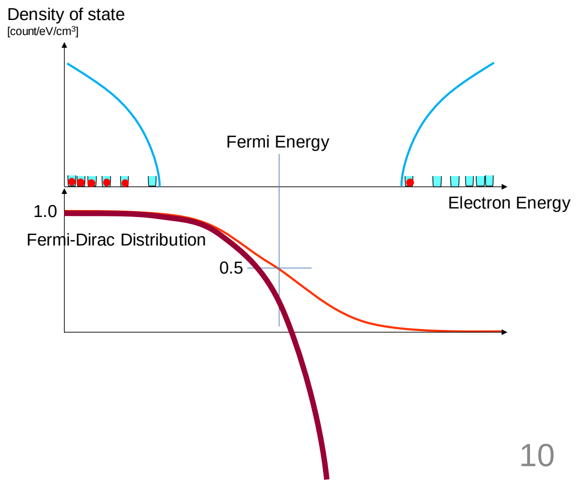
$$1 - \frac{1}{1+e^{(E-E_F)/kT}} = \frac{e^{(E-E_F)/kT}}{1+e^{(E-E_F)/kT}} \approx e^{(E-E_F)/kT}$$

$e^{(E-E_F)/kT}$ <<1

$$p = \int_{-\infty}^{E_F} e^{(E-E_F)/kT} N(E)dE$$



CB: Conduction band
VB: Valence band
EF: Fermi level



Boltzmann Approximation (Thermal Equilibrium)

Electron $n(E_F) = \int_{E_F}^{\infty} e^{-(E-E_F)/kT} N(E) dE$

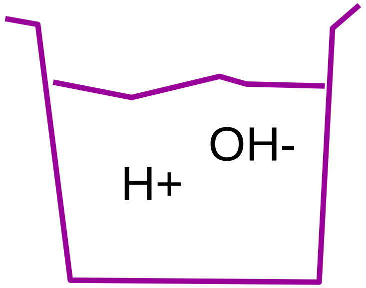
Hole $p(E_F) = \int_{-\infty}^{E_F} e^{(E-E_F)/kT} N(E) dE$

$$\underline{p(E_F) \times n(E_F)} = \int_{E_F}^{\infty} e^{-(E-E_F)/kT} N(E) dE \times \int_{-\infty}^{E_F} e^{(E-E_F)/kT} N(E) dE$$

= Constant for any E_F

Define **intrinsic carrier density n$_i$** as,

$$n_i = \sqrt{p(E_F) \times n(E_F)} \longrightarrow \boxed{p \cdot n = n_i^2}$$



$[H^+] \times [OH^-] = 1 \times 10^{-14} (mol/L)^2$

Boltzmann Approximation (Thermal Equilibrium)

Ideal semiconductor crystal under thermal equilibrium

➔ electric field =0

➔ No space charge

➔ $n = p$ is satisfied in the crystal and they are equal to n_i

Intrinsic Fermi energy $\boldsymbol{E_i}$ is defined as Fermi energy satisfying,

$$n(E_i) = p(E_i) = n_i$$

$$\boxed{n = n_i \cdot e^{(E_F - E_i)/kT} \qquad p = n_i \cdot e^{(E_i - E_F)/kT}}$$

Boltzmann Approximation to carrier density and potential

$$n = n_i \cdot e^{(E_F - E_i)/kT} \qquad p = n_i \cdot e^{(E_i - E_F)/kT}$$

Potential $\varphi = -\dfrac{E_i}{q}$ Fermi Potential $\phi = -\dfrac{E_F}{q}$

$$n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi)} \qquad p = n_i \cdot e^{\frac{q}{kT}(\phi - \varphi)}$$

Good bye "Band theory", "electron energy", Density of state, Fermi-Dirac distribution!!

Drift velocity

Electric field (V/cm)

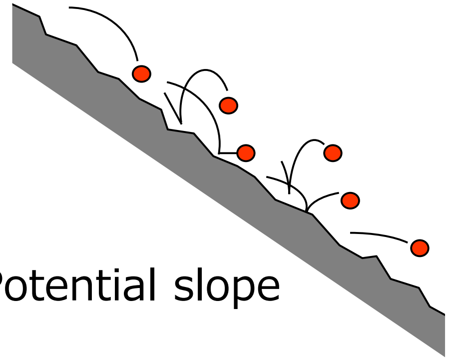
Velocity of electron $$v_n = -\mu_n \cdot E$$

Velocity of hole $$v_p = \mu_p \cdot E$$

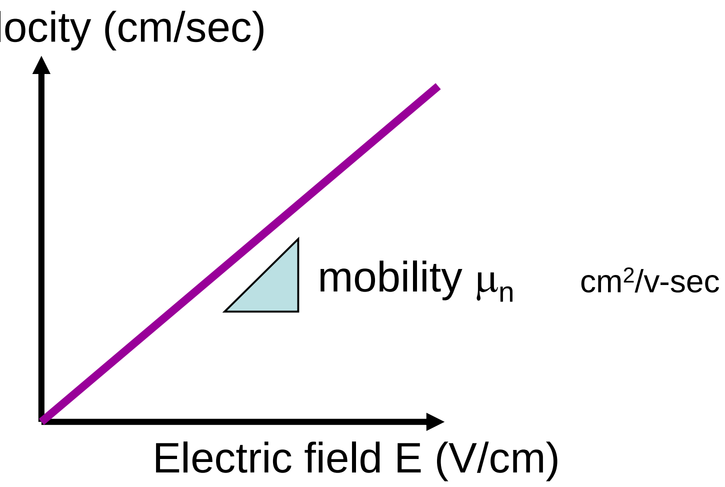
Electric field

Potential[V]

$$E = -\frac{d\varphi}{dx}$$



Potential slope

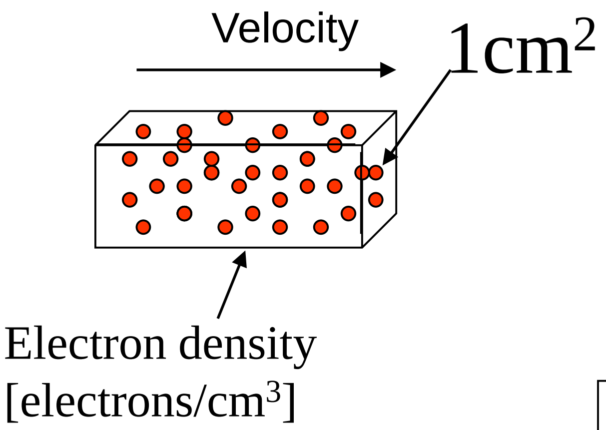


Drift current density

Flux: count/cm^2*sec

Drift current = Electron charge X Drift carrier flux

Drift carrier flux [carriers/cm^2/sec]
= Carrier density [carriers/cm^3] X velocity[cm/sec]



Electron drift current density[A/cm^2]

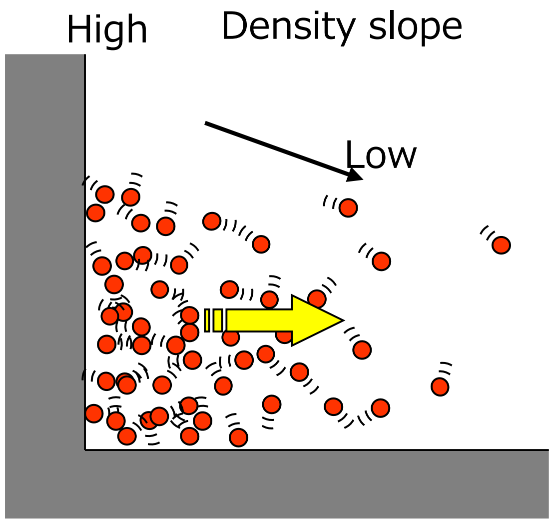
$$J_n = -q v_n n \longrightarrow J_n = q \mu_n n E$$

Hole drift current density[A/cm^2]

$$J_p = q v_p p \longrightarrow J_p = q \mu_p p E$$

Diffusion current density

Diffusion current: Current by carrier diffusion with density difference



Electron diffusion flux $= -D_n \dfrac{dn}{dx}$

Hole diffusion flux $= -D_p \dfrac{dp}{dx}$

Electron diffusion current density $\boxed{J_n = qD_n \dfrac{dn}{dx}}$

Hole diffusion current density $\boxed{J_p = -qD_p \dfrac{dp}{dx}}$

Drift-diffusion model
= Current equation

Electron and hole current density (Drift + diffusion)

$$J_n = -q\,\mu_n\, n\frac{d\varphi}{dx} + qD_n\frac{dn}{dx}$$

$$J_p = -q\,\mu_p\, p\frac{d\varphi}{dx} - qD_p\frac{dp}{dx}$$

Einstein relationship

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

Current in semiconductor

Electron and hole current density (Drift + diffusion)

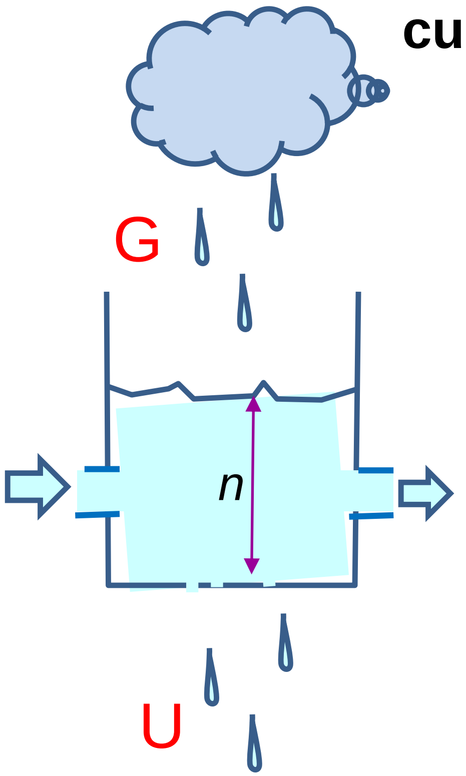
$$J_n = -q\,\mu_n\, n\frac{d\varphi}{dx} + qD_n\frac{dn}{dx} \qquad J_p = -q\,\mu_p\, p\frac{d\varphi}{dx} - qD_p\frac{dp}{dx}$$

Total current in semiconductor

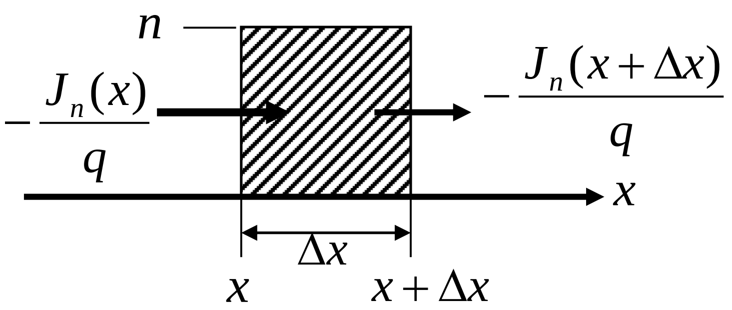
$$\boxed{J = J_n + J_p + J_{disp}} \qquad J_{disp} = \frac{d\varepsilon E}{dt}$$

Displacement current

Current continuity equation



Continuity equations for electron current and hole current



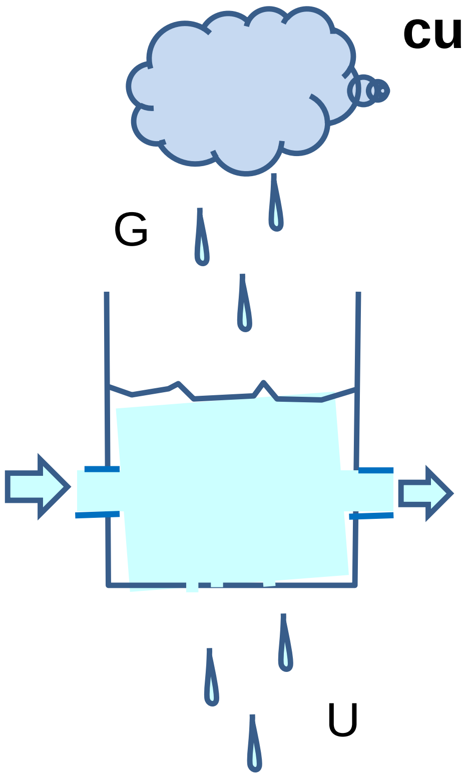
$$\frac{dn}{dt}\Delta x = -\frac{J_n(x)}{q} + \frac{J_n(x+\Delta x)}{q} + G_n \cdot \Delta x - U_n \cdot \Delta x$$

Gauss' Theorem

G_p, G_n: carrier generation rate [Carriers/cm^3/sec]
U_n, U_p: carrier recombination rate [Carriers/cm^3/sec]

Current continuity equation

Continuity equations for electron current and hole current



$$\frac{dn}{dt}\Delta x = -\frac{J_n(x)}{q} + \frac{J_n(x+\Delta x)}{q} + G_n \cdot \Delta x - U_n \cdot \Delta x$$

Δt➔zero

$$\frac{dn}{dt} = \frac{1}{q}\frac{dJ_n}{dx} + G_n - U_n$$

$$\frac{dp}{dt} = -\frac{1}{q}\frac{dJ_p}{dx} + G_p - U_p$$

G_p, G_n: carrier generation rate [Carriers/cm^3/sec]
U_n, U_p: carrier recombination rate [Carriers/cm^3/sec]

Poisson eq. and Donor / acceptor

Poisson equation:
Equation to obtain electric field

$$\frac{d\,\varepsilon \cdot E}{dx} = \rho$$

Poisson eq.

Donor concentration

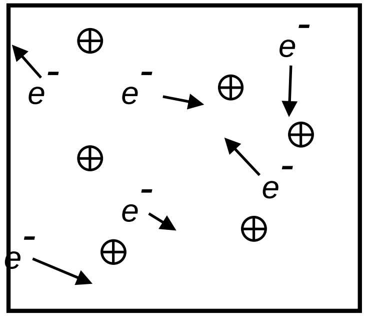
Acceptor concentration

$$\boxed{\frac{d\,\varepsilon \cdot E}{dx} = \underbrace{q(N_D - N_A + p - n)}_{\text{Charge density[C/cm}^3\text{]}}}$$

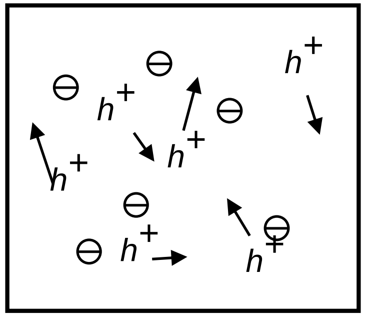
where

$$E = -\frac{d\varphi}{dx}$$

Free electron and fixed positive charge (Donor)（N_D）



Free hole and fixed negative charge (Acceptor)（N_A）



…..under equilibrium condition

Quasi Fermi Potentials

Expand the Fermi Potential to Non-thermal-equilibrium conditions

Electron quasi Fermi potential ϕ_n

$$\boxed{n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi_n)}}$$

Hole quasi Fermi potential ϕ_p

$$\boxed{p = n_i \cdot e^{\frac{q}{kT}(\phi_p - \varphi)}}$$

Under thermal equilibrium condition $\phi_n = \phi_p$

Current equation for electron and hole can be expressed by quasi Fermi potentials (Problem ➔ prove this, use "Einstein relationship", see next page)

$$J_n = -q\,\mu_n\,n\frac{d\phi_n}{dx} \qquad J_p = -q\,\mu_p\,p\frac{d\phi_p}{dx}$$

Problem

$$n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi_n)} \qquad p = n_i \cdot e^{\frac{q}{kT}(\phi_p - \varphi)}$$

$$J_n = -q\mu_n n \frac{d\varphi}{dx} + qD_n \frac{dn}{dx} \qquad J_p = -q\mu_p p \frac{d\varphi}{dx} - qD_p \frac{dp}{dx}$$

Einstein relationship $\dfrac{D_n}{\mu_n} = \dfrac{kT}{q}, \quad \dfrac{D_p}{\mu_p} = \dfrac{kT}{q}$

Prove following eq.

$$\boxed{J_n = -q\mu_n n \frac{d\phi_n}{dx} \qquad J_p = -q\mu_p p \frac{d\phi_p}{dx}}$$

Summary of basic equations

Equations used in power semiconductor device design

Current equations

$$\boxed{J_n = -q\mu_n n \frac{d\varphi}{dx} + qD_n \frac{dn}{dx}} \qquad \boxed{J_p = -q\mu_p p \frac{d\varphi}{dx} - qD_p \frac{dp}{dx}}$$

Current continuity equations

$$\boxed{\frac{dn}{dt} = \frac{1}{q}\frac{dJ_n}{dx} + G_n - U_n} \qquad \boxed{\frac{dp}{dt} = -\frac{1}{q}\frac{dJ_p}{dx} + G_p - U_p}$$

Poisson equation

$$\boxed{\frac{d\varepsilon \cdot E}{dx} = q(N_D - N_A + p - n)}$$ where $E = -\frac{d\varphi}{dx}$

No band theory, no electron energy=>For device design use

Problem: Where is bandgap parameter in the equations??

Related equations

Einstein relationship

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

Displacement current and total current

$$\boxed{J_{disp} = \frac{d\varepsilon E}{dt}} \qquad \boxed{J = J_n + J_p + J_{disp}}$$

Carrier density and current density by quasi Fermi potential

$$\boxed{n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi_n)}} \qquad \boxed{p = n_i \cdot e^{\frac{q}{kT}(\phi_p - \varphi)}}$$

$$\boxed{J_n = -q\,\mu_n\,n\frac{d\phi_n}{dx}} \qquad \boxed{J_p = -q\,\mu_p\,p\frac{d\phi_p}{dx}}$$

Potentials at Ohmic contact

Metal contact (Ohmic)

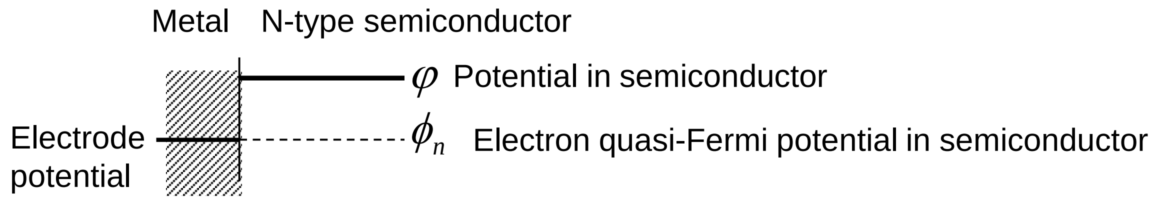
Built-in potential

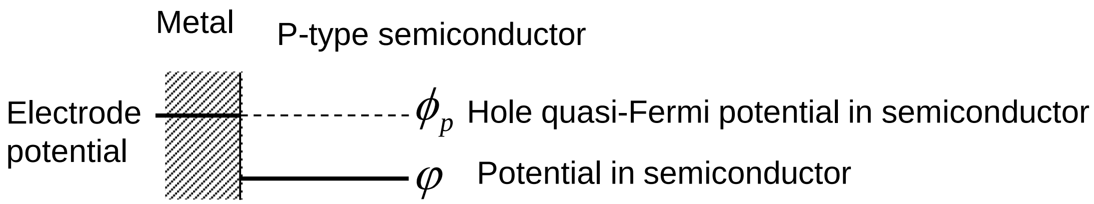
$$N_D \approx n = n_i e^{\frac{q}{kT}(\varphi - \phi_n)}$$

$$V_{built-in} = \frac{kT}{q} \log \frac{N_D}{n_i}$$

$$N_A \approx p = n_i e^{\frac{q}{kT}(\phi_p - \varphi)}$$

$$V_{built-in} = -\frac{kT}{q} \log \frac{N_A}{n_i}$$





Rem.

Under thermal equilibrium condition,

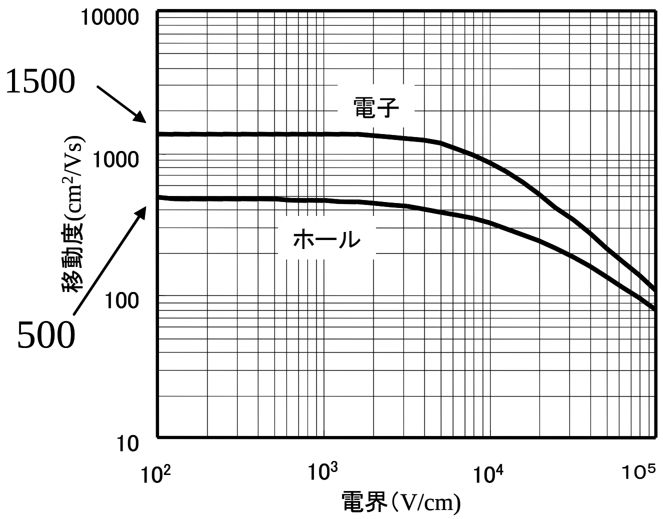
$$\frac{d\,\varepsilon \cdot E}{dx} = q(N_D - N_A + p - n) = 0$$

$$\begin{cases} N_D - N_A + p - n = 0 \\ p \cdot n = n_i^2 \end{cases}$$

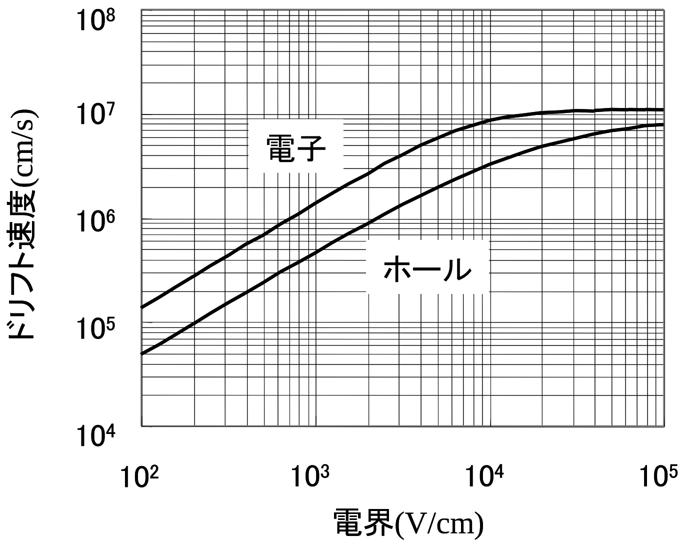
Need to solve equations for accurate hole, electron concentration and built-in potentials

Electron and hole mobility for silicon

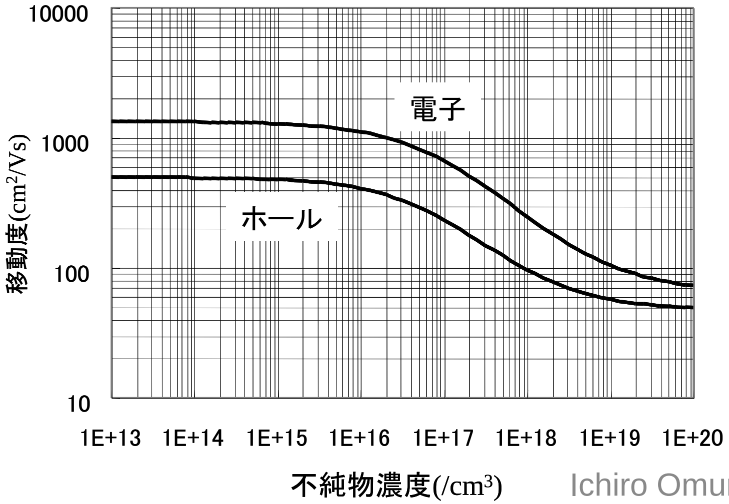
Electron and hole mobility for silicon



Electron and hole velocity for silicon



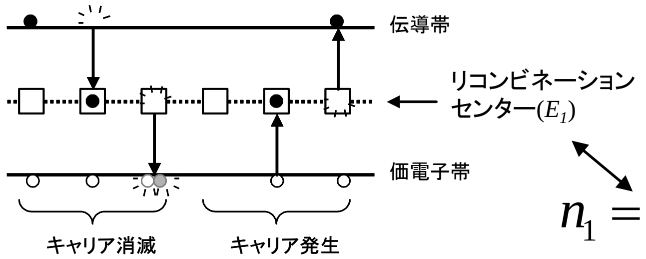
Mobilities as functions of impurity concentration



Recombination (SRH)

Recombination rate U_n ,U_p

SRH type recombination



$$n_1 = n_i e^{(E_1 - E_i)/kT}$$

$$p_1 = n_i e^{(E_i - E_1)/kT}$$

$$\frac{dn}{dt} = -\frac{1}{q}\frac{dJ_n}{dx} + G_n - \boxed{U_n}$$

$$\frac{dp}{dt} = \frac{1}{q}\frac{dJ_p}{dx} + G_p - \boxed{U_p}$$

Electron and hole lifetime

$$\boxed{U_n^{SRH} = U_p^{SRH} = \frac{pn - n_i^2}{\tau_p(n + n_1) + \tau_n(p + p_1)}}$$

In N-type semiconductor（*$n=N_D$>>p*）

$$U_n^{SRH} = U_p^{SRH} = \boxed{\frac{p - p_{n0}}{\tau_p}}$$

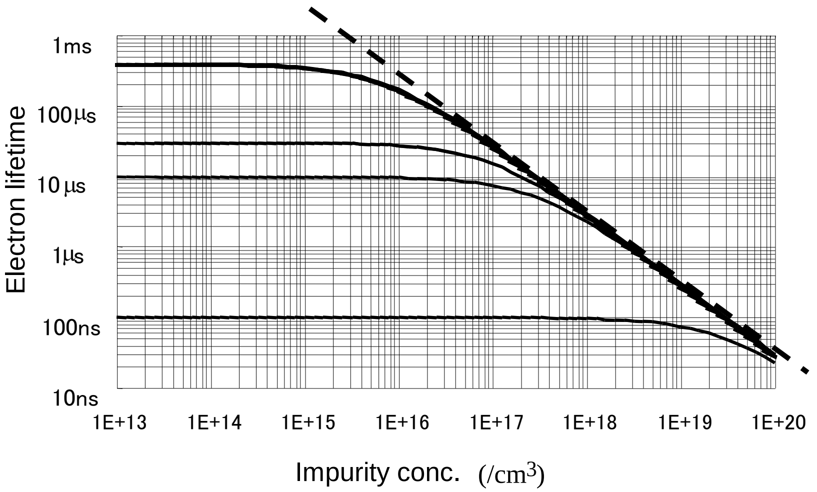
In P-type semiconductor（*$p=N_A$>>n*）

$$U_n^{SRH} = U_p^{SRH} \cong \boxed{\frac{n - n_{p0}}{\tau_n}}$$

p_{n0} : hole density in N-type semiconductor

n_{p0} : electron density in P-type semiconductor

Carrier lifetime lowering by impurity



Impact ionization

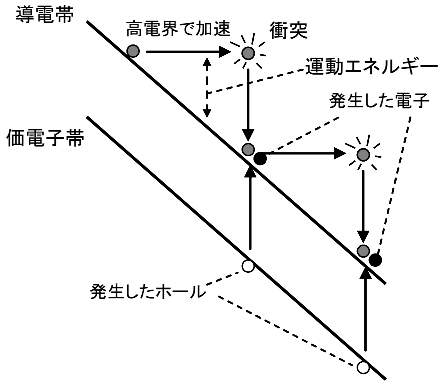
Carrier generation / impact ionization

Ionization rate

$$\alpha_n(E) = A_n e^{-b_n/|E|}$$
$$\alpha_p(E) = A_p e^{-b_p/|E|}$$

Carrier generation rate by impact ionization

$$G_n^{imp} = G_p^{imp} = \frac{1}{q}\left(\alpha_n |J_n| + \alpha_p |J_p|\right)$$



Example of parameters

$$A_n = 7.03\times10^5[\mathrm{cm}^{-1}]$$
$$A_p = 1.582\times10^6[\mathrm{cm}^{-1}]$$
$$b_n = 1.23\times10^6[\mathrm{V/cm}]$$
$$b_p = 2.036\times10^6[\mathrm{V/cm}]$$

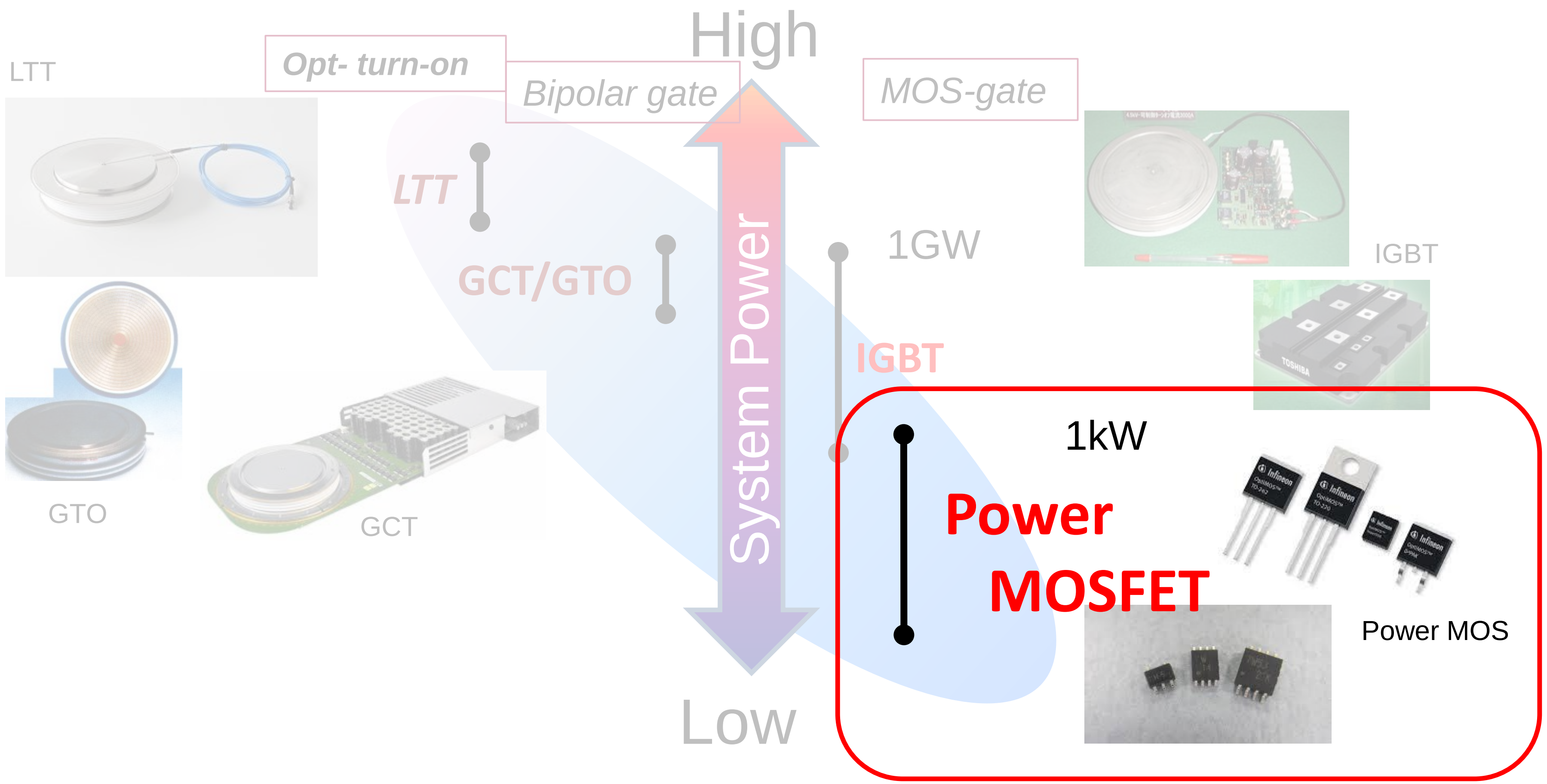
$$\frac{dn}{dt} = -\frac{1}{q}\frac{dJ_n}{dx} + \boxed{G_n} - U_n$$

$$\frac{dp}{dt} = \frac{1}{q}\frac{dJ_p}{dx} + \boxed{G_p} - U_p$$

Ionization rate: number of electron-hole pairs generated by moving electron or holes for 1cm

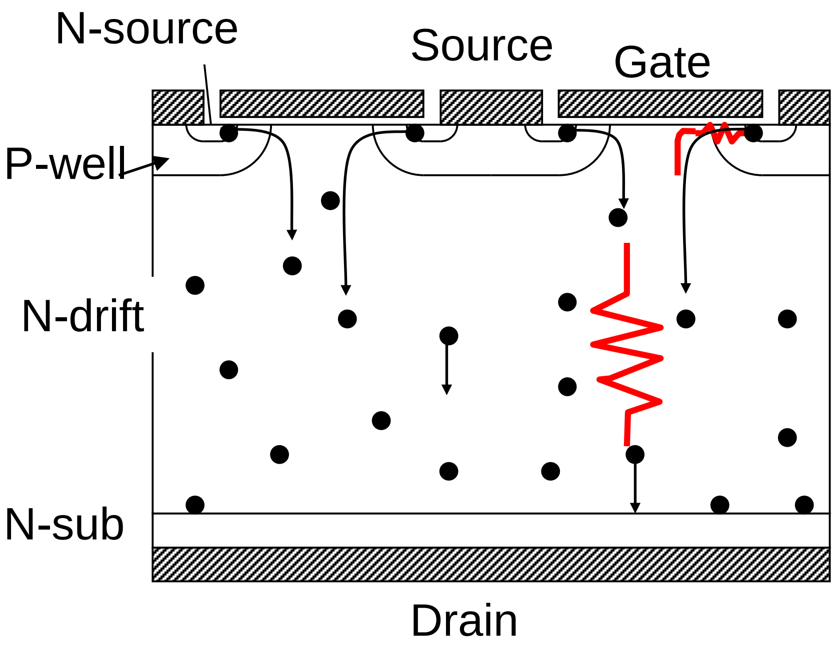
Carrier generation rate: number of electron-hole pairs generated in 1 cm3 for 1 sec.

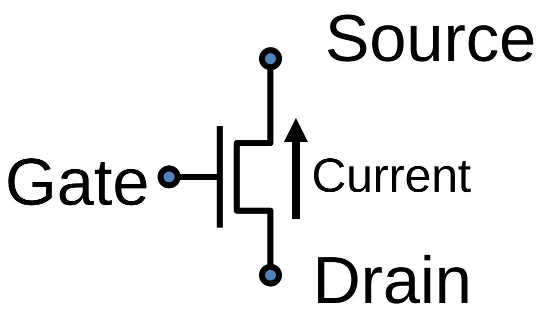
Power MOSFET

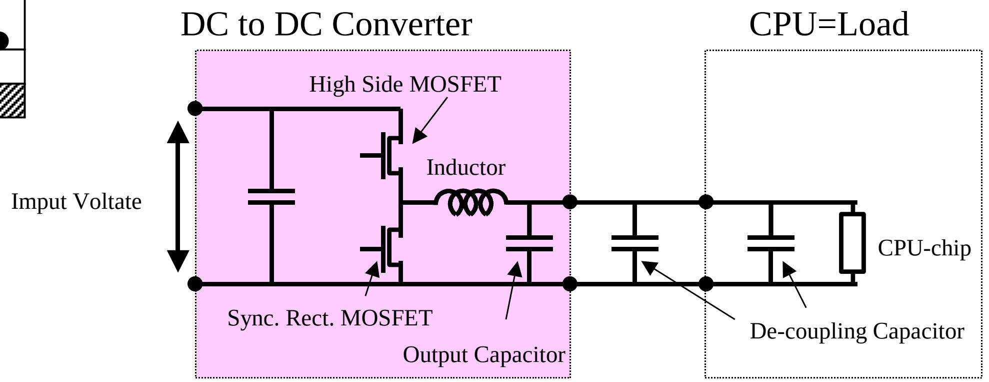


Photos:
Infineon
Toshiba
ABB
TMEIC

Power MOSFET





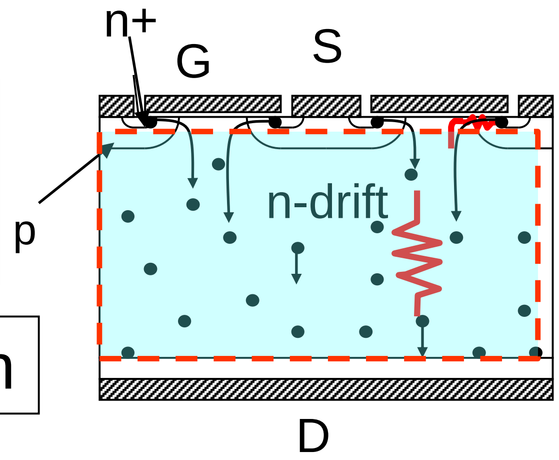


Conduction carrier…… *Electron or hole*
Switching control ……. *MOS-gate*
Switching Freq. ………. *High*

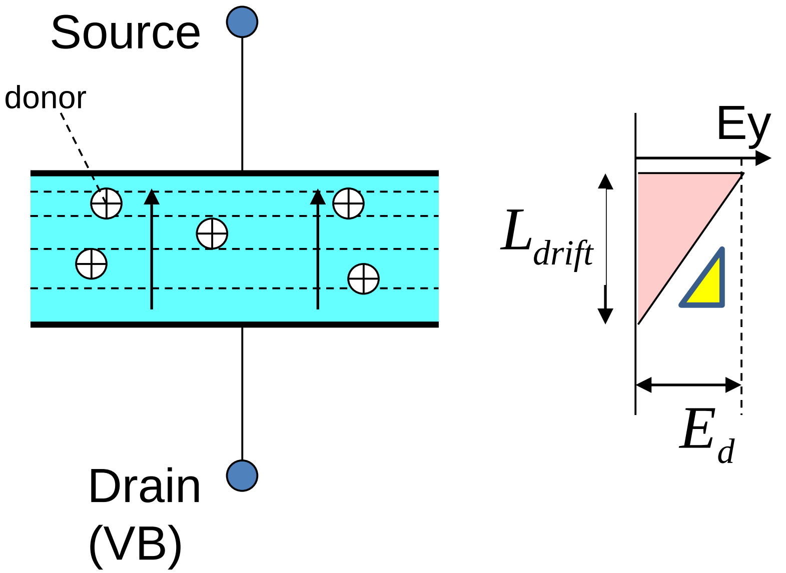
Function of N-drift layer

Function of N-drift layer:

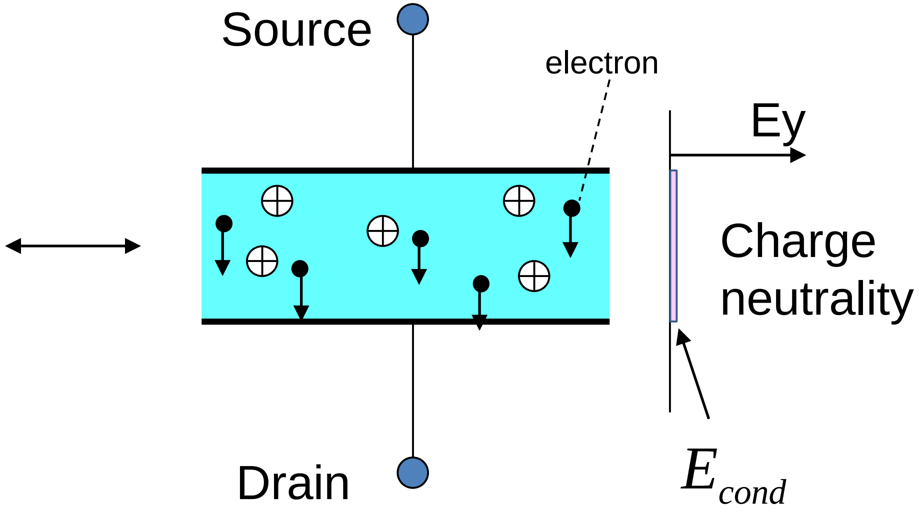
1. **Voltage blocking (higher breakdown voltage)**
2. **Current conduction (lower resistivity)**



Voltage Blocking



Conduction



Blocking state (Poisson eq.)

$$qN_D = -\varepsilon \frac{dE_y}{dy} = \varepsilon \cdot \frac{E_d}{L_{drift}}$$

Conduction state (current eq.)

$$J_n = q\mu_n N_D E_{cond} = q\mu_n N_D \frac{V_{cond}}{L_{drift}}$$

μ_n: electron mobility

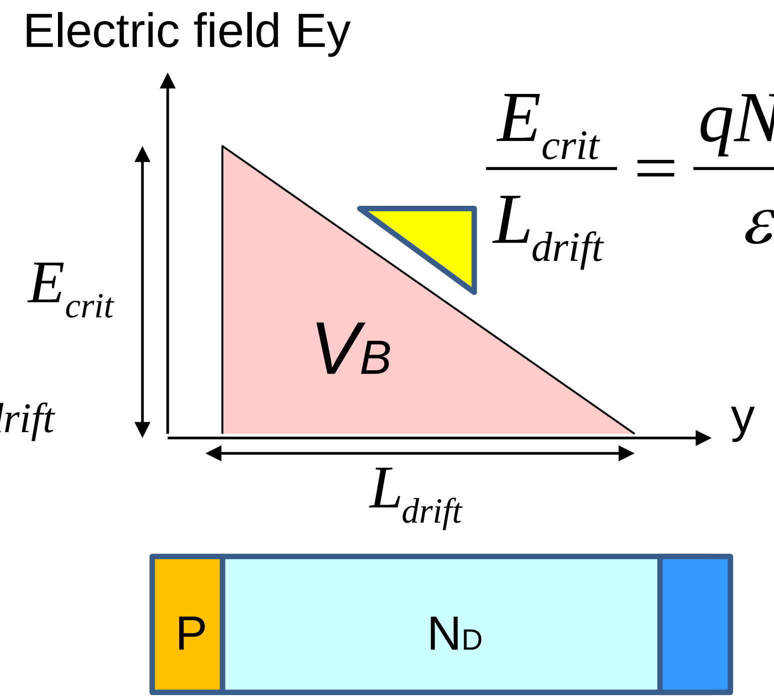
Breakdown voltage calculation

Poisson Eq.

$$\frac{d\,\varepsilon \cdot E}{dx} = q(N_D - N_A + p - n)$$

$$\frac{E_{crit}}{L_{drift}} = \frac{qN_D}{\varepsilon}$$

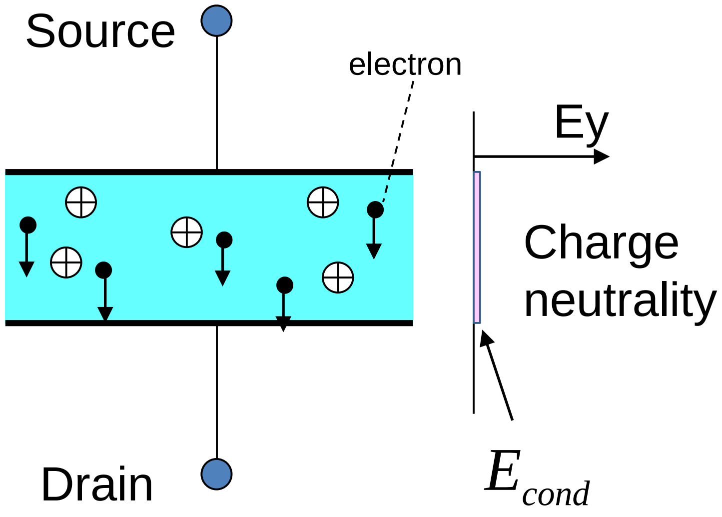
$$V_B = \frac{1}{2} E_{crit} \times L_{drift}$$



Drift layer doping $\quad N_D = \varepsilon \cdot \dfrac{E_{crit}^2}{2qV_B}$

Drift layer length $\quad L_{drift} = \dfrac{2V_B}{E_{crit}}$

Conduction resistance calculation



Conduction resistance

$$J_n = q\mu_n N_D E_{cond} = q\mu_n N_D \frac{V_{cond}}{L_{drift}}$$

$$R_{on}A = \frac{L_{drift}}{q\mu_n N_D}$$

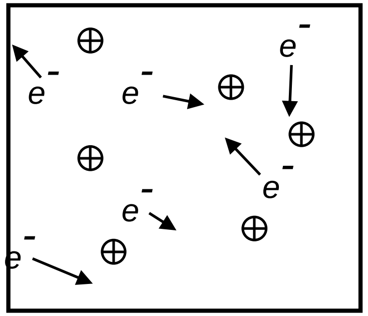
Resistance for unit area

$$\frac{d\,\varepsilon \cdot E}{dx} = q(N_D - N_A + p - n) \approx 0$$

$$\Downarrow$$

$$\boxed{n \approx N_D}$$

Free electron and fixed positive charge (Donor)（N_D）



Problem

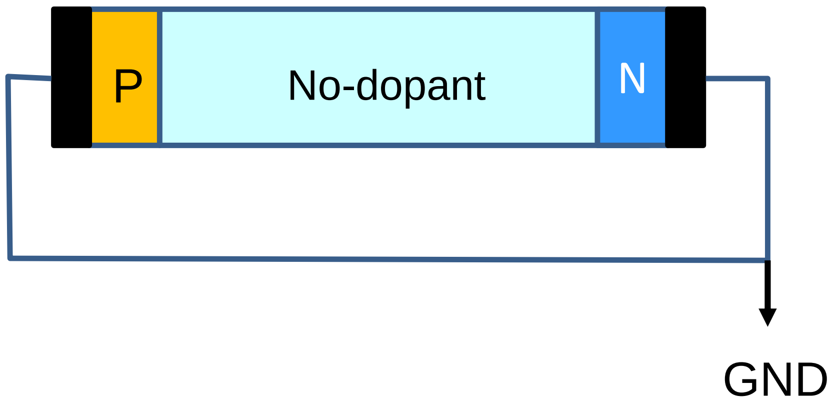
1.Calculate required drift length for breakdown voltage 1200V.
(Ecrit=2.0E5 V/cm)

2. Calculate donor concentration for drift layer
(q=1.6E-19 C, ε=1.0e-12 [F/cm](silicon)

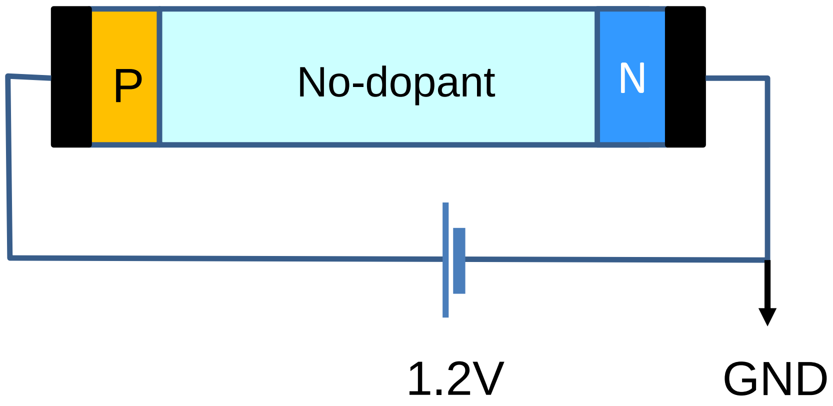
3. Calculate drift resistance (mobility of electron 1500 cm^2/V-s)

4. Calculate 1~3 for 600V, 1700V,

Problem: Draw potential distribution in PiN diode and electrode



Problem: Draw potential distribution in PiN diode, assume constant stored carrier n_{store}



Not to be used in the lecture

Boltzmann Approximation

Electron

$$n = \int_{E_c}^{\infty} e^{-(E-E_F)/kT} N(E) dE$$

$$= e^{-(E_C-E_F)/kT} \underbrace{\int_{E_c}^{\infty} e^{-(E-E_C)/kT} N(E) dE}_{\boxed{N_C}}$$

N_C Effective Density of State

$\Downarrow$

$$\boxed{n = N_C \cdot e^{-(E_C-E_F)/kT}}$$

Boltzmann Approximation

Hole

Fermi-Dirac distribution

Density of state

$$p=\int_{-\infty}^{E_V}\left\{1-\frac{1}{1+e^{(E-E_F)/kT}}\right\}N(E)dE$$

$$1-\frac{1}{1+e^{(E-E_F)/kT}}\approx e^{(E-E_F)/kT}$$

$$\boxed{p=N_V\cdot e^{-(E_F-E_V)/kT}}$$

$$p=\int_{-\infty}^{E_V}\left\{1-\frac{1}{1+e^{(E-E_F)/kT}}\right\}N(E)dE$$

$$\cong\int_{-\infty}^{E_V}e^{(E-E_F)/kT}N(E)dE$$

$$=e^{(E_V-E_F)/kT}\underbrace{\int_{-\infty}^{E_V}e^{(E-E_V)/kT}N(E)dE}_{N_V}$$

Effective Density of State N_V

Intrinsic carrier density, n_i

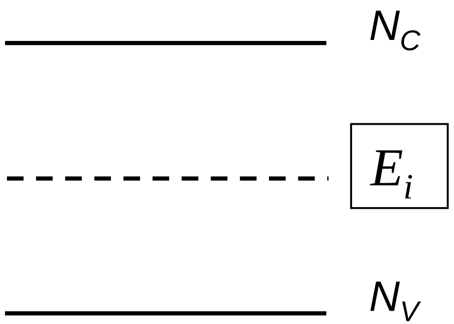
Pure semiconductor without impurity = Intrinsic semiconductor

Charge neutrality under thermal equilibrium➔$p = n = n_i$

$$n_i = N_C \cdot e^{-(E_C - E_i)/kT}$$ Electron density

$$n_i = N_V \cdot e^{-(E_i - E_V)/kT}$$ Hole density

$$n_i = \sqrt{N_C \cdot N_V} e^{-(E_C - E_V)/2kT}$$
$$= \sqrt{N_C \cdot N_V} e^{-E_g/2kT}$$



Problem: Calculate intrinsic Fermi level, *E_i*

Intrinsic carrier density and potentials

$$n = N_C \cdot e^{-(E_C - E_F)/kT}$$

$$p = N_V \cdot e^{-(E_F - E_V)/kT}$$

$$n_i = N_C \cdot e^{-(E_C - E_i)/kT}$$

$$n_i = N_V \cdot e^{-(E_i - E_V)/kT}$$

$$\boxed{n = n_i \cdot e^{(E_F - E_i)/kT}}$$

$$\boxed{p = n_i \cdot e^{(E_i - E_F)/kT}}$$

Potential $\varphi = -\dfrac{E_i}{q}$ Fermi Potential $\phi = -\dfrac{E_F}{q}$

$$\boxed{n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi)}}$$

$$\boxed{p = n_i \cdot e^{\frac{q}{kT}(\phi - \varphi)}}$$

Thermal equilibrium condition

Potential[V] $\varphi = -\frac{E_i}{q}$ Fermi Potential[V] $\phi = -\frac{E_F}{q}$

$$n = n_i \cdot e^{\frac{q}{kT}(\varphi - \phi)} \qquad p = n_i \cdot e^{\frac{q}{kT}(\phi - \varphi)}$$

$$p \cdot n = n_i^2$$

$[H^+] \times [OH^-] = 1 \times 10^{-14} (\mathrm{mol/L})^2$

Boltzmann Approximation (Appdx)

Electron $$n = \int_{E_c}^{\infty} e^{-(E-E_F)/kT} N(E)dE$$

Hole $$p = \int_{-\infty}^{E_V} e^{(E-E_F)/kT} N(E)dE$$

$$pn = \int_{E_c}^{\infty} e^{-(E-E_F)/kT} N(E)dE \times \int_{-\infty}^{E_V} e^{(E-E_F)/kT} N(E)dE$$ = Constant for any $\boldsymbol{E_F}$

Define intrinsic carrier density n_i as,

$$n_i = \sqrt{\int_{E_c}^{\infty} e^{-(E-E_F)/kT} N(E)dE \times \int_{-\infty}^{E_V} e^{(E-E_F)/kT} N(E)dE} \longrightarrow p \cdot n = n_i^2$$

$\boldsymbol{E_i}$ is defined so that following equation is satisfied (p=n=n_i for pure crystal from Poisson Eq.).

$$n_i = \int_{E_c}^{\infty} e^{-(E-E_i)/kT} N(E)dE = \int_{-\infty}^{E_V} e^{(E-E_i)/kT} N(E)dE$$

$$n = n_i \cdot e^{(E_F-E_i)/kT} \qquad p = n_i \cdot e^{(E_i-E_F)/kT}$$