9. Drift Current and Diffusion Current

【Key Points】

To learn two current conduction mechanisms of drift current and diffusion current, and Einstein relation (the relationship between diffusion constant and mobility in thermal equilibrium).

Conduction systems in semiconductor

- Drift current
- Diffusion current

・ **Drift current: Carriers drift by electric field**

In low electric field

n-type : $j_e = qnv = qn\mu_e F$

p-type : $j_h = qpv = qp\mu_h F$

※ In high electric field, the carrier velocity cannot follow the relationship $v = \mu F$ because of lattice vibration.(Velocity is saturated)

・ **Diffusion current: Carriers diffuse to the area at lower carrier concentration**

Not doped semiconductor: $pn = n_i^2$、 $p = n$

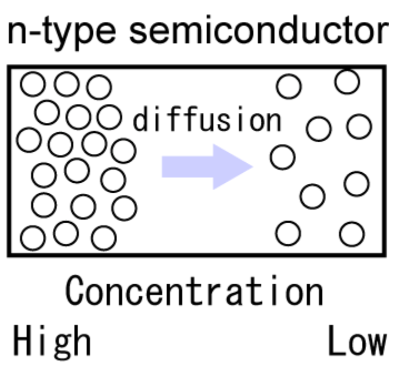
Carrier density n_i～10^{10} cm^{-3}

Doped semiconductor:

Carrier density 10^{16}～$10^{19\sim20}$ cm^{-3}

Carrier concentration gradient exists in semiconductor.

(Huge number of free electron exists in metal. Therefore, the gradient does not exist)



Holes diffuse from higher concentration area to lower one.

Electrical current: the amount of charge through in unit time ([A] = [C/s])

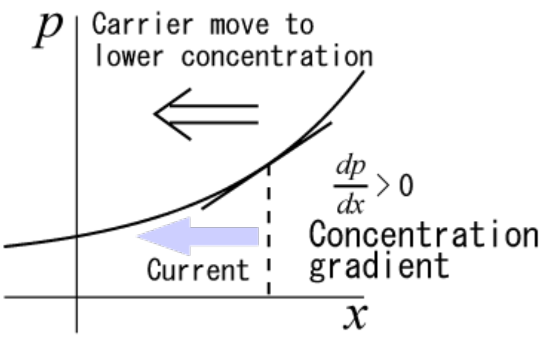
Diffusion moves carrier. ← Diffusion current

・Hole diffusion

(the number of diffused hole) ∝ (hole concentration gradient)

Let proportionality coefficient D_h, (D_h : diffusion constant [cm^2/s])

$$j_h = -qD_h \frac{dp}{dx}$$

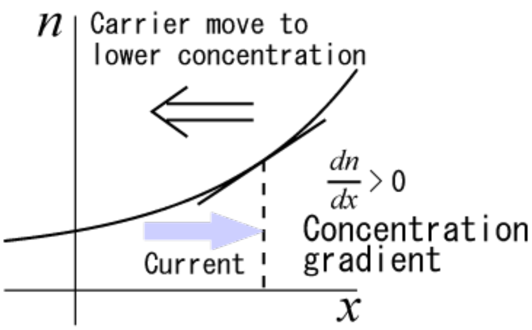


・Electron diffusion

※ Current direction is opposite to the direction which electrons move in.

Let electron proportionality coefficient D_e,

$$j_e = qD_e \frac{dn}{dx}$$



Total electrical current in semiconductor is the sum of drift current and diffusion current.

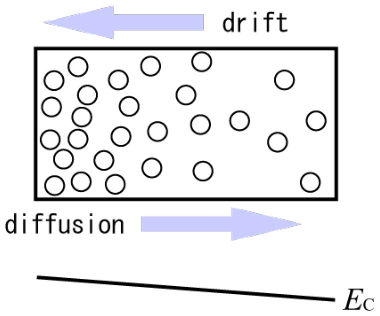
electron current : $j_e = q\left(n\mu_e F + D_e \frac{dn}{dx}\right)$

hole current : $j_h = q\left(p\mu_h F - D_h \frac{dp}{dx}\right)$

Einstein relation (Relationship between diffusion constant and mobility)

Diffusion constant: the parameter that shows how easy the carrier moves.

→related to the carrier mobility.



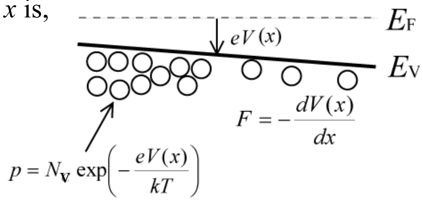
Considering the case that the carrier is hole.

The electric field at the position x is,

$$F = -\frac{dV(x)}{dx}$$

(Fermi level E_F is the base of energy level)

Suppose the Maxwell-Boltzmann distribution is available, the carrier density at the position x is,



$$p = N_V \exp\left(-\frac{qV(x)}{kT}\right)$$

Therefore,

$$\frac{dp}{dx} = \frac{dp}{dV}\frac{dV}{dx} = -\frac{q}{kT}p\frac{dV}{dx} = \frac{qp}{kT}F$$

In thermal equilibrium state, no electrical current flows in semiconductor.

$$j_h = q\left(p\mu_h F - D_h \frac{dp}{dx}\right) = 0$$

As a result, the Einstein relation can be derived.

$$D_h = \frac{kT}{q}\mu_h$$

In the case that the carrier is electron, the Einstein relation can be derived in the same manner as hole.

$$D_e = \frac{kT}{q}\mu_e$$

In inorganic semiconductor, diffusion constant D is proportional to mobility μ

Majority carrier injection

Carrier injection: To increase the carrier density from thermal equilibrium state

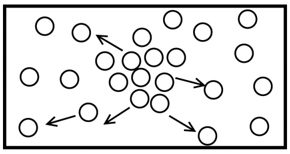
(Thermal diffusion, ion injection etc.)

・In the case of majority carrier (hole) injection.

Inject hole in *p*-type semiconductor

(the amount of injected hole is less than that of initial density)

Excess holes are spread in a short period of time (~ 1 ps [10^{-12} s]).



Dielectric relaxation phenomena

(Supplement: the derivation of dielectric relaxation phenomena by using vector formula)

Time variation of excess carrier density Δp can be written as

$$q\frac{\partial \Delta p}{\partial t} = -\mathrm{div}\,\mathbf{i} \qquad (\boldsymbol{i}\text{: current density})$$

Suppose V is the potential by excess carrier, current density $\boldsymbol{i}$ derived from Ohm's law is,

$$\boldsymbol{i} = -\sigma\,\mathrm{grad}V \qquad \left(\text{In one dimensional } x\text{: } i = -\sigma\frac{dV}{dx} = \sigma F\right)$$

The potential V can be written from Poisson's equation as

$$\nabla^2 V = -\frac{q\Delta p}{\varepsilon_r \varepsilon_0}$$

By using vector formula $\nabla^2 V = \mathrm{div}\cdot(\mathrm{grad}V)$,

$$\frac{\partial \Delta p}{\partial t} = -\frac{\sigma \Delta p}{\varepsilon_r \varepsilon_0}$$

Δp can be written as a time-dependent function,

$$\Delta p(t) = \Delta p(0)\exp\left(-\frac{t}{\tau'}\right), \quad \tau' = \frac{\varepsilon_r \varepsilon_0}{\sigma}$$

(τ': **dielectric relaxation time**)

Suppose *p*-type Si carrier density is 10^{18} cm^{-3}, τ is calculated as below.

(ε_r =11.7、σ=10 S/cm =1000 S/m)

$$\tau' = \frac{11.7\times 8.854\times 10^{-12}}{1000} = 1.04\times 10^{-13}\,\mathrm{s}$$