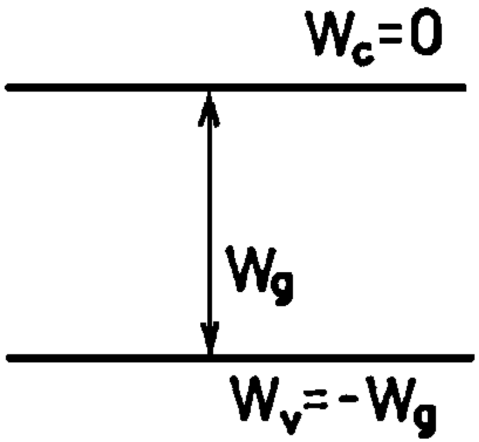
Basic properties of Semiconductors



Free charge carriers

- **electrons** -e $m_{n,}$ ***n***
- **holes** +e m_p ***p***

In thermodynamic equilibrium

$$n.p = N_c N_v \exp(-W_g/kT) = n_i^2$$

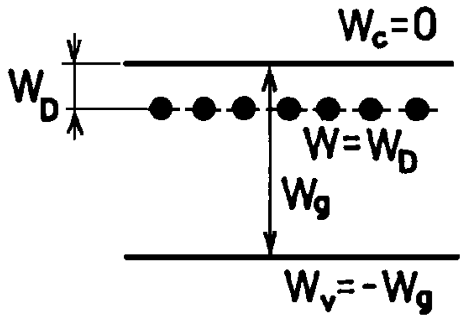
Carrier concentrations can be expressed using of Fermi energy $\boldsymbol{W_F}$

$$n = N_c \exp(W_F/kT)$$

$$p = N_v \exp[(-W_g - W_F)/kT]$$

Donor doping

N- type

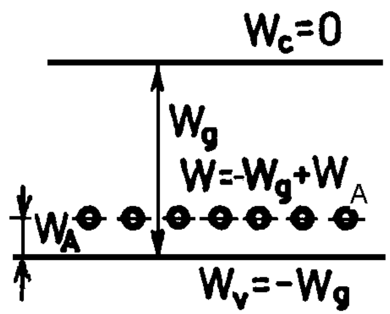


$$n = N_D$$

$$p_N = n_i^2/N_D$$

Aceptor doping

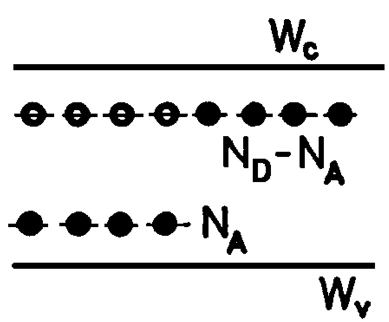
P- type



$$p = N_A$$

$$n_P = n_i^2/N_A$$

Real semiconductor

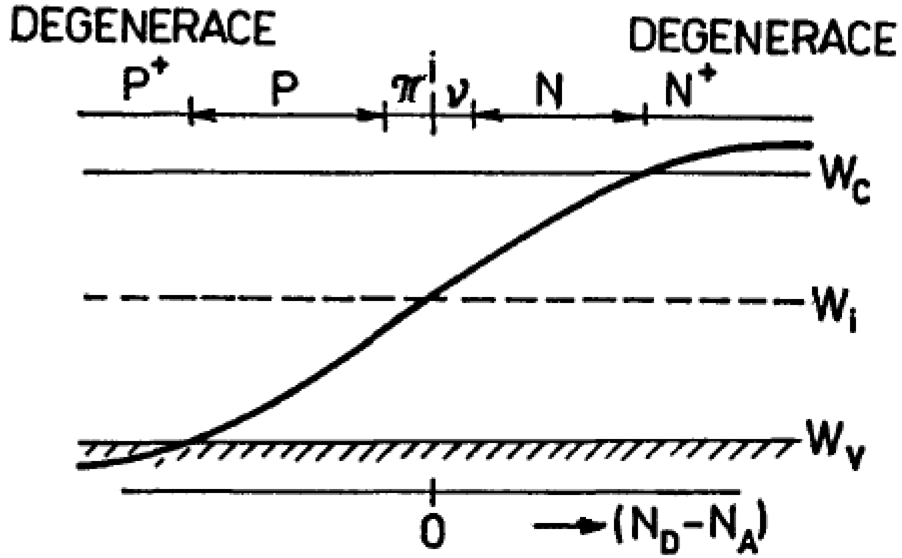


N -type

$$n = N_D - N_A$$

P-type

$$p = N_A - N_D$$



N^+	heavily doped (degenerate) n-type semiconductor
N	normally doped (non-degenerate) n-type semiconductor
ν	lightly doped n-type semiconductor (sometimes shown as N^-)
I	intrinsic (fully compensated) semiconductor
π	lightly doped p-type semiconductor (sometimes shown as P^-)
P	normally doped (non-degenerate) p-type semiconductor
P^+	heavily doped (degenerate) p-type semiconductor

The Conductivity of Semiconductors

the thermal carrier velocity $\boldsymbol{v_{th}}$

$$W_{kin} = \frac{3}{2}kT = \frac{1}{2}m^* \ v_{th}^2$$

In electric field, a drift velocity is superimposed

$$\vec{v}_{dn} = \mu_n \vec{E}, \qquad \vec{v}_{dp} = \mu_p \vec{E},$$

The current density that results from the transport of the carriers

$$\vec{J} = \vec{J}_p + \vec{J}_n = e(n\mu_n + p\mu_p)\vec{E} = \gamma \vec{E}$$

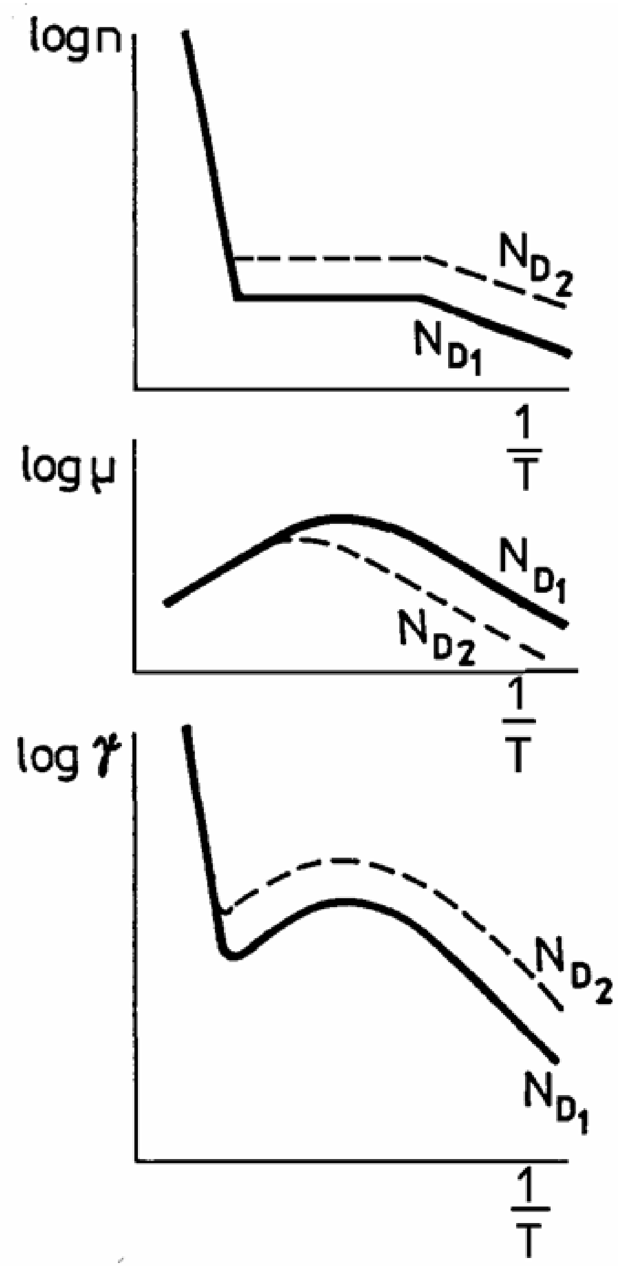
the electrical conductivity γ is given by

$$\gamma = e(n\mu_n + p\mu_p)$$

the mobility varies with temperature

$$\mu \sim T^{-r}$$

In the case of Si $3/2 < \boldsymbol{r} < 5/2$



Under conditions of thermodynamic equilibrium

- electron concentration $\boldsymbol{n_0}$
- hole concentration $\boldsymbol{p_0}$

$$n_0 p_0 = n_i^2$$

Under external influence, the increased concentrations of carriers may be expressed as

$$n = n_o + \Delta n, \quad p = p_o + \Delta p$$

$\Delta\boldsymbol{n}$, $\Delta\boldsymbol{p}$ excess carrier concentration

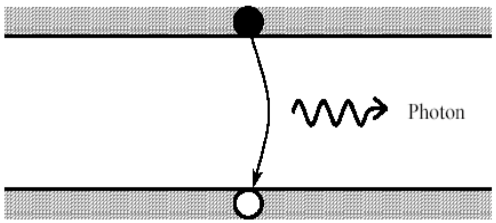
usually $\Delta n = \Delta p$

$$np = \left(n_0 + \Delta n(0)\right)\left(p_0 + \Delta p(0)\right) = n_{\mathrm{i}}^2 \exp\left(\frac{\Delta W}{kT}\right)$$

Excess carrier recombination

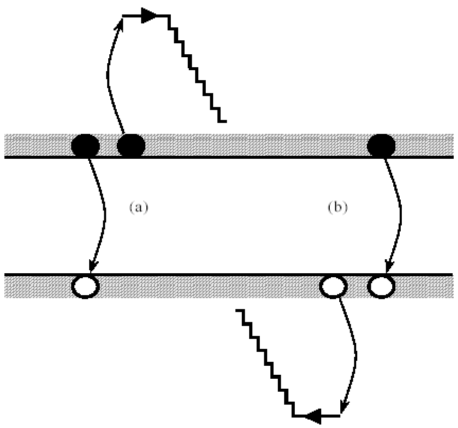
$$\left(\frac{d\Delta n}{dt}\right)_{rec} = -\frac{\Delta n}{\tau}$$

τ carrier liftime



Irradiative recombination

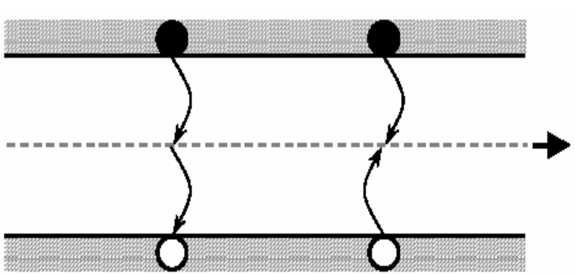
$$\tau_r = \frac{1}{C_r N}$$



Auger recombination

$$\tau_A = \frac{1}{C_{An} N_D^2}$$

$$\tau_A = \frac{1}{C_{Au} \Delta n^2}$$



Recombination via local centres

$$\tau_t = \frac{1}{C_t N_t}$$

N_t is trap concentration

Resulting carrier lifetime

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_A} + \frac{1}{\tau_t}$$

Diffusion and Drift of Charge Carriers

Whenever the carrier concentration varies with position , diffusion occurs. With carrier diffusion is connected electrical current with density

$$\vec{J}_{ndif} = e.D_n \, grad \, n, \quad \vec{J}_{pdif} = -e.D_p \, grad \, p$$

The diffusion coefficients $D_n = \frac{kT}{e}\mu_n, \quad D_p = \frac{kT}{e}\mu_p$

When both an electric field and a concentration gradient are present simultaneously, the total current density is the sum of the diffusion and drift current densities and can be expressed for each carrier as .

$$\vec{J}_n = e(n\mu_n \vec{E} + D_n \, grad \, n) \qquad \vec{J}_p = e(p\mu_p E - D_p \, grad \, p)$$

The total current density $\vec{J} = \vec{J}_n + \vec{J}_p$

Continuity equations

The concentration profiles may vary with time. The overall effect is determined by the processes of diffusion and drift, and by the generation and recombination of the excess carriers. It is described by Fick's second law

$$\frac{\partial n}{\partial t} = G_n - \frac{\Delta n}{\tau_n} + \frac{1}{e}\, div\, \vec{J}_n$$

$$\frac{\partial p}{\partial t} = G_p - \frac{\Delta p}{\tau_p} - \frac{1}{e}\, div\, \vec{J}_p$$

Considering carrier flow in the *x*-direction, when there is zero carrier generation in the region under discussion

$$\frac{\partial n}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial \Delta n}{\partial x}\right) + \frac{\partial}{\partial x}\left(en\mu_n E\right) - \frac{\Delta n}{\tau}$$

Often it is used in a simplified form $$\frac{\partial n}{\partial t} = D\frac{\partial^2 n}{\partial x^2} - \frac{\Delta n}{\tau}$$

Multiplying through by the electronic charge, *e*, and integrating over all or part of the device volume, it can be put in the form:

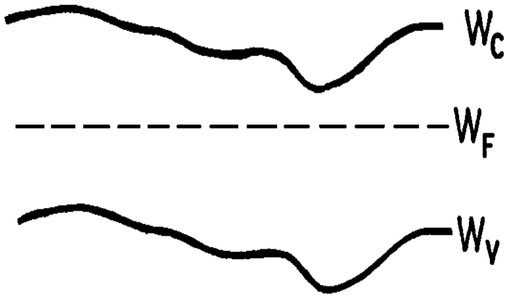
(the charge-control model) $$\frac{dQ}{dt} = I(t) - \frac{Q}{\tau_{ef}}$$

Effects of Non-Uniform Doping

The position of the Fermi level in the band-gap, in thermal equilibrium, is given (for N-type semiconductor) by

$$W_F - W_c = kT \ln \frac{N_D}{N_c}$$

When the difference between the concentration of donors and the concentration of acceptors (N_D - N_A) is a function of position, the energy difference between the Fermi level and the bottom of the conduction band, (W_F - W_c), is also a function of position. Because, in thermal equilibrium, the Fermi energy is uniform throughout the volume of the semiconductor, the value of W_c, which represents the potential energy of the free electrons, now varies with position. The resulting potential gradient gives rise to an internal electric field, the so-called ***built-in field***



$$\vec{E} = -grad\ \varphi = \frac{1}{e} grad\,(W_F - W_c) = -\frac{kT}{e}\frac{1}{n}\ grad\ n$$

In the case of P-type semiconductor $\vec{E} = \frac{kT}{e}\frac{1}{p}\ grad\ p$

Whenever electrical neutrality is not maintained and regions of space charge occur

$$div\ \vec{E} = -div\ grad\ V = e(p - n + N_D - N_A)/\varepsilon_r \varepsilon_o$$

With non-uniform doping, the superposition of the internal and external electric fields may invalidate Ohm's law