Transport and non equilibrium behaviour in semiconductors.

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Nonequilibrium excess carriers in semiconductors

Characteristic of excess carriers

$$F_{px}^{+}(x+dx) = F_{px}^{+}(x) + \frac{\partial F_{px}^{+}}{\partial x} \cdot dx$$

$$\frac{\partial p}{\partial t} dxdydz = \left[F_{px}^{+}(x+dx)\right] dydz = -\frac{\partial F_{px}^{+}}{\partial x} dxdyxz$$

$$\frac{\partial p}{\partial t} dxdydz = -\frac{\partial F_{px}^{+}}{\partial x} dxdyxz + g_p dxdydz - \frac{p}{\tau_{pt}} dxdydz$$

p is the density of holes, τ_{pt} thermal-equilibrium and excess carriar lifetimes

$$\frac{\partial p}{\partial t} = -\frac{\partial F_p^{+}}{\partial x} + g_p - \frac{p}{\tau_{pt}}$$

$$J_p = e\mu_p pE - eD_p \frac{\partial p}{\partial x}$$

$$\frac{J_p}{+e} = F_p^{+} = \mu_p pE - D_p \frac{\partial p}{\partial x}$$

$$\frac{\partial p}{\partial t} = -\mu_p \frac{\partial (pE)}{\partial x} + D_p \frac{\partial^2 p}{\partial x^2} + g_p - \frac{p}{\tau_{pt}}$$

With one dimensionality in mind

$$\frac{\partial (pE)}{\partial x} = E\frac{\partial p}{\partial x} + p\frac{\partial E}{\partial x}$$

In the 3d case:

$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - \mu_p \left(E\frac{\partial p}{\partial x} + p\frac{\partial E}{\partial x}\right) + g_p - \frac{p}{\tau_{pt}}$$

For a homogeneous semiconductor:

$$\frac{\partial \delta p}{\partial t} = D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p \left(E\frac{\partial \delta p}{\partial x} + p\frac{\partial E}{\partial x}\right) + g_p - \frac{p}{\tau_{pt}}$$

Quasi Fermi energy levels

When excess carriers are present there's no thermal equilibrium, so the Fermi level is not defined, but one can define quasi Fermi levels.

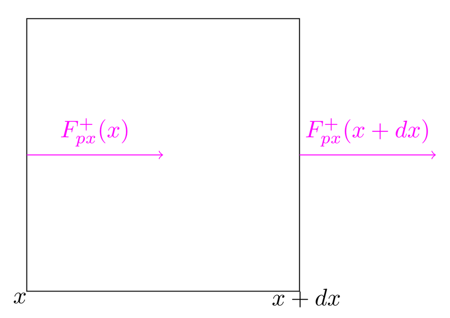
$$n_0 = n_i \exp\left(\frac{E_F - E_{Fi}}{kT}\right)$$

$$p_0 = n_i \exp\left(\frac{E_{Fi} - E_F}{kT}\right)$$

$$n_0 + \delta n = n_i \exp\left(\frac{E_{Fn} - E_{Fi}}{kT}\right)$$

$$p_0 + \delta p = n_i \exp\left(\frac{E_{Fi} - E_{Fp}}{kT}\right)$$

Figure



Excess carrier lifetime

It's important the speed at which generation and recombination occurs a state in the energy within the bandgap is called a trap, and can act as a recombination center. 4 processes can hapen there 1: Electrons jump from conducting band to the trap

$$R_{cn} = C_n N_t \left[1 - f_F(E_t)\right] n$$

R_{cn} is the capture rate, C_n ta constant proportional to the electron-capture cross section, N_t the concentration of traps, n the electron concentration in the conducting band and $f_F(E_t)$ the fermi function at the trap energy:

$$f_F(E_t) = \frac{1}{1 + \exp\left(\frac{E_t - E_F}{kT}\right)}$$

Process 2 describes electrons escaping from a negatively charged hole:

$$R_{en} = E_n N_t f_F(E_t)$$

R_{en} is the emmision rate, E_n a constant and $f_{F(E_t)}$ the probability that the trap is occupied. At thermal equilibrium:

$$R_{en} = R_{cn}$$

$$E_n N_t f_{F0(E_t)} = C_n N_t \left[1 - f_{F0}(E_t)\right] n_0$$

$$E_n = n' C_n$$

$$n' = N_c \exp\left[-\frac{E_c - E_t}{kT}\right]$$

n' corrosponds to the electron concentration in the conducting band if $E_t = E_F$, outside equilibrium:

$$\begin{aligned} R_n &= R_{cn} - R_{en} \\ &= \left[C_n N_t (1 - f_F(E_t)) n\right] - \left[E_n N_t f_F(E_t)\right] \\ &= C_n N_t \left[n(1 - f_F(E_t)) - n' f_F(E_t)\right] \end{aligned}$$

The same two processes exists for the holes:

$$R_p = C_p N_t \left[p(1 - f_F(E_t)) - p'(1 - f_F(E_t))\right]$$

$$p' = N_c \exp\left[-\frac{E_t - E_v}{kT}\right]$$

$$f_F(E_t) = \frac{C_n n + C_p p'}{C_n(n + n') + C_p(p + p')} \qquad \text{By } R_p = R_n$$

$$R_n = R_p \equiv R = \frac{C_n C_p N_t (np - n_i^2)}{C_n(n + n') + C_p(p + p')} =$$

$$fracδnτ$$

Now apllying the conditions of extrinsic doping and low injection, for an n type:

$$n_0 \gg p_0, \quad n_0 \gg \delta p, \quad n_0 \gg n', n_0 \gg p'$$

$$R = C_p N_t \delta p$$

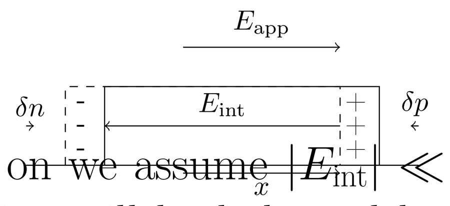
$$\frac{\delta n}{\tau} = C_p N_t \delta p \equiv \frac{\delta p}{\tau_{p0}}$$

$$\tau_{p0} = \frac{1}{C_p N_t}$$

The fewer the number of excess carriers the longer the lifetime.

Ambipolar transport

$$\nabla \cdot E_{\text{int}} = \frac{e(\delta p - \delta n}{\epsilon_s} = \frac{\partial E_{\text{int}}}{\partial x}$$



´ϵ_s is the permittivity of the semi conductor, form here on we assume $|E_{\text{int}}| \ll |E_{\text{app}}|$, and charge neutrality, the excess hole concentration will be balanced by an equal excesss hole conentration. now define:

$$g_n = g_p \equiv g$$

$$R_n = \frac{n}{\tau_{nt}} = R_p = \frac{p}{\tau_{pt}} = R$$

$$\frac{\partial \delta p}{\partial t} = D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p \left(E\frac{\partial \delta p}{\partial x} + p\frac{\partial E}{\partial x}\right) + g_p - R$$

$$\frac{\partial \delta n}{\partial t} = D_n \frac{\partial^2 \delta n}{\partial x^2} - \mu_n \left(E\frac{\partial \delta n}{\partial x} + n\frac{\partial E}{\partial x}\right) + g_n - R$$

$$(\mu_n n + \mu_p p)\frac{\partial \delta n}{\partial t} = (\mu_n n D_p + \mu_p p D_n)\frac{\partial^2 \delta n}{\partial x^2} + (\mu_n \mu_p)(p - n)E\frac{\partial \delta n}{\partial x} + (\mu_n n + \mu_p p)(g - R)$$

$$D' \frac{\partial^2 \delta n}{\partial x} + \mu' E \frac{\partial \delta n}{\partial x} + g - R = \frac{\partial \delta n}{\partial t}$$

$$D' = \frac{\mu_n n D_p + \mu_p p D_n}{\mu_n n + \mu_p p}$$

$$\mu' = \frac{\mu_n \mu_p (p - n)}{\mu_n n + \mu_p p}$$

´The three above equations are the "ambipolar transport equation", "ambipolar diffusion coefficient" and the "ambipolar mobility", The einstein releation holds:

$$\frac{\mu_n}{D_n} = \frac{\mu_p}{D_p} = \frac{e}{kT}$$

$$D' = \frac{D_n D_p (n + p)}{D_n n + D_p p}$$

´now with low-level injection:

$$= \frac{D_n D_p (n_0 + \delta n + p_0 + \delta n)}{D_n (n_0 + deltan + D_p (p_0 + \delta n)}$$

$$D' = D_n$$

$$\mu' = \mu_n$$

´Thus the minority carrier becomes the most important for ambipolar transport under low level injection. Now fr generation/recombination

$$R_n = R_p = \frac{n}{\tau_{nt}} = \frac{p}{\tau_{pt}} = R$$

´For the minority carrier $\tau_{it} = \tau_t$ where i is either n or p

$$g - R = g_n - R = (G_{n0} + g_n') - (R_{n0} + R_n')$$

$$G_{n0} = R_{n0}$$

$$g - R = g_n - R = g_n' - R_n' = g_n' - \frac{\delta n}{\tau_n}$$

´same for hole generation

$$D_n \frac{\partial^2 \delta n}{\partial x^2} - \mu_n E \frac{\partial \delta n}{\partial x} + g' - \frac{n}{\tau_{n0}} = \frac{\partial \delta n}{\partial t}$$

$$D_p \frac{\partial^2 \delta p}{\partial x^2} - \mu_p E \frac{\partial \delta p}{\partial x} + g' - \frac{p}{\tau_{p0}} = \frac{\partial \delta p}{\partial t}$$

´The dielectric relaxation time constant

$$\nabla \cdot E = \frac{\rho}{\epsilon}$$

$$J = \sigma E$$

$$\nabla \cdot J = -\frac{\partial \rho}{\partial t} = \sigma \nabla \cdot E = \frac{\sigma \rho}{\epsilon}$$

$$= -\frac{\partial \rho}{\partial t} = -\frac{d\rho}{dt}$$

$$\frac{d\rho}{dt} + \frac{\sigma}{\epsilon}\rho = 0$$

$$\rho(t) = \rho(0) e^{-\frac{t}{\tau_d}} \quad \tau_d = \frac{\epsilon}{\sigma}$$

´Haynes–Shockley: A field of v_1 is applied to a semiconductor, a pulse is sent through the semiconductor and travels a distance d inside it:

$$x - \mu_p E_0 t = 0 \qquad x = d$$

$$\mu_p = \frac{d}{E_0 t_0}$$

$$(d - \mu_p E_0 t)^2 = 4 D_p t$$

$$D_p = \frac{(\mu_p E_0 \Delta t)^2}{16 t_0}$$

$$\Delta t = t_2 - t_1$$

$$S = K \exp\left(-\frac{t_0}{\tau_{p0}}\right) = K \exp\left(-\frac{d}{\mu_p E_0 \tau_{pd}}\right)$$

is the area under the curve.