VE320 RC5

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Overview

Generation and Recombination in Thermal Equilibrium

- In thermal equilibrium, carrier concentrations are independent of time.
- Generation and recombination rates of electrons and holes are equal.
- Generation rate = Recombination rate:
  $G_{n0} = G_{p0} = R_{n0} = R_{p0}$, unit: $(cm^3 \cdot s)^{-1}$

Notation

Table 6.1 | Relevant notation used in Chapter 6

Symbol	Definition
n_0, p_0	Thermal-equilibrium electron and hole concentrations (independent of time and also usually position)
n, p	Total electron and hole concentrations (may be functions of time and/or position)
$\delta n = n - n_0$ $\delta p = p - p_0$	Excess electron and hole concentrations (may be functions of time and/or position)
g'_n, g'_p	Excess electron and hole generation rates
R'_n, R'_p	Excess electron and hole recombination rates
τ_{n0}, τ_{p0}	Excess minority carrier electron and hole lifetimes

Generation and Recombination in Nonequilibrium

- The semiconductor is affected by time-varying factors like light/current.
- A higher generation rate: total generation rate $= G_{n0} + g_n^{'} = G_{p0} + g_p^{'}$
- A higher amount of n and p: $n = n_0 + \delta n$, $p = p_0 + \delta p$
- In normal cases (direct generation): $g_n^{'} = g_p^{'}$
- Total recombination rate: $R_n = R_p = \alpha_r np$
- Please note that $np \neq n_0 p_0 = n_i^2$

Net Recombination Rate

- small injection: n-type: $n_0 \gg \delta p(t)$; p-type: $p_0 \gg \delta n(t)$
- $\tau_{n0} = (\alpha_r p_0)^{-1}$, $\tau_{p0} = (\alpha_r n_0)^{-1}$
- n-type: $R_n' = R_p' = \dfrac{\delta p}{\tau_{p_0}}$
- p-type: $R_n' = R_p' = \dfrac{\delta n}{\tau_{n_0}}$

Continuity Equation

- p-type: $D_n \frac{\mathrm{d}^2 n}{\mathrm{d}x^2} + \mu_n(E\frac{\mathrm{d}n}{\mathrm{d}x} + n\frac{\mathrm{d}E}{\mathrm{d}x}) + g_n^{'} - \frac{\delta n}{\tau_{n0}} = \frac{\mathrm{d}\delta n}{\mathrm{d}t}$
- n-type: $D_p \frac{\mathrm{d}^2 p}{\mathrm{d}x^2} - \mu_p(E\frac{\mathrm{d}p}{\mathrm{d}x} + p\frac{\mathrm{d}E}{\mathrm{d}x}) + g_p^{'} - \frac{\delta p}{\tau_{p0}} = \frac{\mathrm{d}\delta p}{\mathrm{d}t}$
- For homogeneous semiconductor, $n(x) = n_0 + \delta n(x)$, the equation can be simplified as

$$D_n \frac{\mathrm{d}^2 \delta n}{\mathrm{d}x^2} + \mu_n(E\frac{\mathrm{d}\delta n}{\mathrm{d}x} + n\frac{\mathrm{d}E}{\mathrm{d}x}) + g_n^{'} - \frac{\delta n}{\tau_{n0}} = \frac{\mathrm{d}\delta n}{\mathrm{d}t}$$

$$D_p \frac{\mathrm{d}^2 \delta p}{\mathrm{d}x^2} - \mu_p(E\frac{\mathrm{d}\delta p}{\mathrm{d}x} + p\frac{\mathrm{d}E}{\mathrm{d}x}) + g_p^{'} - \frac{\delta p}{\tau_{p0}} = \frac{\mathrm{d}\delta p}{\mathrm{d}t}$$

Continuity Equation

Table 6.2 |

Specification	**Effect**
Steady state	$\frac{\partial(\delta n)}{\partial t} = 0, \quad \frac{\partial(\delta p)}{\partial t} = 0$
Uniform distribution of excess carriers (uniform generation rate) + no boundary confinement	$D_n \frac{\partial^2(\delta n)}{\partial x^2} = 0, \quad D_p \frac{\partial^2(\delta n)}{\partial x^2} = 0$
Zero electric field	$\mathrm{E} \frac{\partial(\delta n)}{\partial x} = 0, \quad \mathrm{E} \frac{\partial(\delta p)}{\partial x} = 0$
No excess carrier generation	$g' = 0$
No excess carrier recombination (infinite lifetime)	$\frac{\delta n}{\tau_{n0}} = 0, \quad \frac{\delta p}{\tau_{p0}} = 0$

Model

Model 1: Uniform distribution of excess carriers, uniform doping, no electric field, n-type:
No excess carrier generation:

$$\frac{\mathrm{d}(\delta p)}{\mathrm{d}t} = -\frac{\delta p}{\tau_{p0}}$$

Solution: $\delta p(t) = \delta p(0)e^{-\frac{t}{\tau_{p0}}}$
Excess carrier generation, with no excess carrier at t = 0:

$$\frac{\mathrm{d}(\delta p)}{\mathrm{d}t} = -\frac{\delta p}{\tau_{p0}} + g'$$

Solution: $\delta p(t) = g'\tau_{p0}(1 - e^{-\frac{t}{\tau_{p0}}})$

Model 2: Steady state, non-uniform distribution of excess carriers, uniform doping, no electric field, n-type:
No excess carrier generation:

$$D_p \frac{\mathrm{d}^2(\delta p)}{\mathrm{d}x^2} - \frac{\delta p}{\tau_{p0}} = 0$$

Solution: $\delta p(x) = Ae^{-\frac{x}{L_p}} + Be^{\frac{x}{L_p}}$, $L_p = \sqrt{D_p \tau_{p0}}$.Remember to plug in the boundary condition to solve the coefficients.
Excess carrier generated uniformly at rate g:

$$D_p \frac{\mathrm{d}^2(\delta p)}{\mathrm{d}x^2} - \frac{\delta p}{\tau_{p0}} + g = 0$$

Solution: $\delta p(x) = Ae^{\lambda x} + g\tau_{p0}$ with $\lambda = \pm\frac{1}{\sqrt{D_p \tau}}$

Model

Model 3: Non-uniform distribution of excess carriers, uniform doping, uniform electric field E_0, n-type:
No excess carrier generation:

$$D_p \frac{\mathrm{d}^2(\delta p)}{\mathrm{d}x^2} - \mu_p E_0 \frac{\mathrm{d}(\delta p)}{\mathrm{d}x} - \frac{\delta p}{\tau_{p0}} = \frac{\mathrm{d}(\delta p)}{\mathrm{d}t}$$

Solution:

$$\delta p(x, t) = \frac{e^{-\frac{t}{\tau_{p0}}}}{\sqrt{4\pi D_p t}} \exp\left(\frac{-(x - \mu_p E_0 t)^2}{4 D_p t}\right)$$

Model

Model 4: Steady state, non-uniform distribution of excess carriers, uniform doping, uniform electric field E, n-type:
No excess carrier generation:

$$D_p \frac{\mathrm{d}^2(\delta p)}{\mathrm{d}x^2} - \mu_p E_0 \frac{\mathrm{d}(\delta p)}{\mathrm{d}x} - \frac{\delta p}{\tau_{p0}} = 0$$

Solution:

$$\delta p(x) = A\exp(\lambda x) + C$$

$$\lambda = \frac{L_p(E) \pm \sqrt{L_p^2(E) + 4L_p^2}}{2L_p^2}$$

$$L_p = \sqrt{\tau_{p0} D_p}$$

$$L_p(E) = \tau_{p0}\mu_p E$$

Quasi-Fermi Energy Level

Fermi energy level considering excess carriers:

$$n_0 + \delta n = n_i \exp(\frac{E_{Fn} - E_{Fi}}{kT})$$
$$p_0 + \delta p = n_i \exp(\frac{E_{Fi} - E_{Fp}}{kT})$$

Excess Carrier Lifetime

$$R_n = R_p = \frac{C_n C_p N_t (np - n_i^2)}{C_n(n + n') + C_p(p + p')}$$
$$= \frac{np - n_i^2}{\tau_{p0}(n + n') + \tau_{n0}(p + p')}$$

where

$$n' = N_c \exp[-\frac{E_c - E_t}{kT}], \; p' = N_v \exp[-\frac{E_t - E_v}{kT}]$$
$$\tau_{n0} = \frac{1}{C_n N_t}, \; \tau_{p0} = \frac{1}{C_p N_t}$$

Surface Effect

- Periodic potential wells break on the surface.
- Allowed energy levels appear inside forbidden band.
- A lot of traps in the middle of forbidden band.
- Lower excess carrier concentration on the surface.

Surface Effect

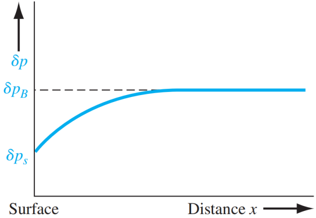

Figure 6.18 | Steady-state excess hole concentration versus distance from a semiconductor surface.

$$-D_p[\hat{n} \cdot \frac{\mathrm{d}(\delta p)}{\mathrm{d}x}]|_{\mathrm{surf}} = s\delta p|_{\mathrm{surf}}$$

s: surface recombination velocity

Reference

1. Semiconductor Physics and Devices: Basic Principles 4th ed. Donald A. Neamen.
2. 2023Summer Ve320Mid2_RC_part1, Qian Zhao
3. 2022Summer RC_Mid2_part1, Xingyuan Wang