Semiconductor Physics Documentation

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CHAPTER

ONE

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1.1 Basic physics of semiconductors

1.1.1 Carrier density

In this page, we derive the classical and quantum mechanical carrier densities.

Classical carrier densities cannot deal with quantum effects, such as enegy quantization, and carrier leakage into a barrier.

Classical carrier density

Quantum mechanical carrier density

In quantum mechanics, the carrier density can be obtained by solving Schrödinger equation.

1.1.2 Strain calculation

1.1.3 Band theory

1.1.4 Generation and recombination rates

1.2 Basic equations

In this section, we introduce some basic equations related to semiconductor devices.

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1.2.1 Poisson equation

The electrostatic potential can be calculated with the corresponding charge distribution ρ with Poisson equation.

$$\nabla \cdot (\varepsilon_s \nabla \Psi) = -\rho, \tag{1.2.1}$$

where ε_s is the dielectric permittivity and $\varepsilon_s = 11.9\varepsilon_0$ for Si. Ψ is the electrostatic potential. The electric charge density in a semiconductor is given by the summation of the electron charge density n, the hole charge density p, and the ionized impurity doping density D. Therefore,

$$\rho = q(n - p + D), \tag{1.2.2}$$

where q is the elementary charge. Note that D consists of the ionized acceptor and donor type impurity densities, which mean $D = N_A - N_D$.

Thus, (1.2.1) can be expressed as following,

$$\nabla^2 \Psi = -\frac{q(n - p + N_A - N_D)}{\varepsilon_s}. \tag{1.2.3}$$

The left side can be rewritten in the orthogonal coordinate system,

$$\nabla^2 \Psi(x, y, z) = \frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2}. \tag{1.2.4}$$

For a 1D problem, (1.2.4) can be reduced to

$$\frac{d^2 \Psi_i}{dx^2} = -\frac{d\xi}{dx} = -\frac{\rho}{\varepsilon_s} = -\frac{q(n - p + N_A - N_D)}{\varepsilon_s}, \tag{1.2.5}$$

Of course, $\xi = -\nabla \Psi$ holds in (1.2.5).

Poisson equation is often used to determine the distributions of electrostatic potential and electric field caused by a charge density ρ.

1.2.2 Current-density equations

The common current equation consists of the drift component, caused by the electric field, and the diffusion component, caused by the gradient of the carrier concentration. The current density equations are below,

$$\mathbf{J_n} = q\mu_n n\xi + qD_n \nabla n, \tag{1.2.6}$$

$$\mathbf{J_p} = q\mu_p p\xi - qD_p \nabla p \tag{1.2.7}$$

and

$$\mathbf{J_{conduction}} = \mathbf{J_n} + \mathbf{J_p}, \tag{1.2.8}$$

where $\mathbf{J_n}$ and $\mathbf{J_p}$ are the electron and hole current densities, respectively. μ_n and μ_p are the electron and hole mobilities. For nondegenerate semiconductors, the carrier diffusion constants (D_n and D_p) and the mobilities are given by the Einstein relation,

$$D_n = \frac{kT}{q}\mu_n, \tag{1.2.9}$$

$$D_p = \frac{kT}{q}\mu_p. \tag{1.2.10}$$

Therefore, for a 1D case, (1.2.6) and (1.2.7) can be reduced to

$$J_n = q\mu_n n\xi + qD_n \frac{dn}{dx} = q\mu_n \left(n\xi + \frac{kT}{q}\frac{dn}{dx} \right) = \mu_n n \frac{dE_{Fn}}{dx}, \tag{1.2.11}$$

and

$$J_p = q\mu_p p\xi - qD_p \frac{dp}{dx} = q\mu_p \left(p\xi - \frac{kT}{q}\frac{dp}{dx} \right) = \mu_p p \frac{dE_{Fp}}{dx}, \tag{1.2.12}$$

where E_{Fn} and E_{Fp} are quasi Fermi levels for electrons and holes, respectively.

These equations indicate that no electron or hole current run in the region where the quasi Fermi level is constant over x. Note that these equations are valid for low electric field ξ. If the electric field is sufficiently high, the term $\mu_n \xi$ or $\mu_p \xi$ should be replaced by the saturation velocity v_s. The last equalities about E_{Fn} and E_{Fp} do not hold any more either.

1.2.3 Continuity equations

While the above current-density equations hold for steady-state conditions, the continuity equations deal with time-dependent states such as low-level injection, generation, and recombination. You can see *Generation and recombination rates* for further information about recombination and generation. The net change of carrier concentration is the difference between generation and recombination, plus the net current flowing in and out of the region of interest.

$$\frac{\partial n}{\partial t} = G_n - U_n + \frac{1}{q}\nabla \cdot \mathbf{J_n}, \tag{1.2.13}$$

$$\frac{\partial n}{\partial t} = G_n - U_n + \frac{1}{q}\nabla \cdot \mathbf{J_n}, \tag{1.2.14}$$

where G_n and G_p are the electron and hole generation rate $(\mathrm{cm^{-3}s^{-1}})$, respectively. U_n and U_p are the electron and hole recombination rate $(\mathrm{cm^{-3}s^{-1}})$, which have the following relations,

$$U_n = \frac{\Delta n}{\tau_n}, \tag{1.2.15}$$

$$U_p = \frac{\Delta p}{\tau_p}. \tag{1.2.16}$$

For more details, refer to [1].

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1.3 MIS structure

This document is in progress

1.4 MIS capacitor

This document is in progress.

1.5 Bipolar transistor

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1.6 MOSFET

This document is in progress

This documentation explains semiconuctor physics. There will be updates soon!! Stay tuned.

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BIBLIOGRAPHY

[1] S. M. Sze and Kwok K. Ng. *Physics of Semiconductor Devices*. Wiley-Interscience, 3rd edition, 2006. URL: https://onlinelibrary.wiley.com/doi/book/10.1002/0470068329.