

1 Introduction

The substances in which at $T = 0$ K the uppermost of the energy bands occupied by electrons (the valence band) and the lowermost of the unoccupied energy bands (the conduction band) do not overlap are referred to semiconductors or dielectrics. The dividing line between the two classes of substances is rather arbitrary. Unlike dielectrics, in semiconductors the energy gap between the conduction band and the valence band is not too large. This gives rise to the appearance of a noticeable number of free charge carriers in the bands at $T \neq 0$ K.

The electrical resistivity of semiconductors (at $T = 290$ K) lies usually in the range $10^{-3} \leq \rho \leq 10^{10}$ Ohm.cm (in metals $\rho = 10^{-6}$ – 10^{-4} Ohm.cm).

The characteristic features of this class of substances are an increase in electrical conduction with temperature, low (as compared with metals) densities of current carriers, a high sensitivity of the electrical properties to radiations and impurities as well as the nonohmic behavior of contacts.

The forbidden gap width E_g represents an energy gap between the absolute maximum of the valence band and the absolute minimum of the conduction band. It is determined from the temperature dependence of resistance or by optical methods (absorption edge, long-wave threshold of photoconductivity). The value of E_g depends on temperature and pressure; the dependence is governed by the coefficients

$$\alpha_T = \frac{\partial E_g}{\partial T}$$

and

$$\alpha_P = \frac{\partial E_g}{\partial P}.$$

Carrier mobility and conductivity. The drift mobility

$$\mu_d = \frac{v_d}{\mathcal{E}},$$

where v_d is the drift velocity of carriers in the electric field \mathcal{E} , is determined by direct experiments from the time of propagation of an injected pulse of minority carriers in a sample. The electrical conductivity σ is related to the drift mobilities of electrons and holes μ_n, μ_p and to their densities n and p by the formula

$$\sigma = e(n\mu_n + p\mu_p).$$

The measurement of the Hall effect allows one to determine the Hall mobility

$$\mu_H = |R\sigma|,$$

where R is the Hall coefficient.

Hall effect. In a semiconductor placed in a magnetic field perpendicular to a current flowing in the semiconductor, there occurs an electric field perpendicular to both the current and the magnetic field. This is a so-called Hall effect described by the relationship

$$E_H = RjH,$$

where E_H is the strength of the Hall electric field; j is the current density; H is the strength of the magnetic field; R is the Hall coefficient.

In the case of one sort of carriers (with a density n)

$$R = \pm \frac{r}{ne}.$$

Here R is in cm^3/C ; n in cm^{-3} ; $e = 1.6 \cdot 10^{-19} \text{ C}$; r is the numerical factor (so-called Hall-factor) whose value is determined by the mechanism of carrier momentum relaxation. The sign of R correlates with the sign of the carrier charge ($R < 0$ in n -type samples; $R > 0$ in p -type samples).

When two sorts of carriers (for example, electrons and holes) are present, R depends on the magnetic field strength:

$$R = \frac{R_n \sigma_n (1 + \sigma_p^2 H^2 R_p^2) + R_p \sigma_p (1 + \sigma_n^2 H^2 R_n^2)}{(\sigma_n + \sigma_p)^2 + \sigma_n \sigma_p (R_n + R_p) H^2}.$$

Here $\sigma_n = ne\mu_n$; $\sigma_p = pe\mu_p$; $R_n = -1/ne$; $R_p = 1/pe$.

For $H \rightarrow \infty$ $R \rightarrow [e(p - n)]^{-1}$, if $p \neq n$, and

$$R = \frac{1}{ne} \frac{\mu_p - \mu_n}{\mu_p + \mu_n}$$

if $n = p$.

The Hall mobility of carrier μ_H is defined by the relationship $\mu_H = |R\sigma|$.

The lifetime of carriers represents a time for which the nonequilibrium density of carriers decreases down to the equilibrium value through their recombination. The basic recombination mechanisms are a radiative one (the energy of recombining electron-hole pair is emitted, as a photon), a phonon one (the energy is transferred to the lattice), and a collisional one (the energy of the pair is transferred to a third particle).

More frequently the recombination occurs not directly, but through recombination centers (impurities, defects).

The theoretical estimation of the radiative recombination time τ_R yields the upper limit of the τ value. For $T = 300 \text{ K}$ and a near-intrinsic density the values of τ_R are given in Table 1 along with the real values of τ .

Table 1. The recombination time τ and the radiative recombination time τ_R for some semiconductors [162] (near-intrinsic carrier density, $T = 300 \text{ K}$)

Semiconductor	Si	Ge	InSb	InAs	PbS	PbSe	PbTe
$\tau_R, \text{ s}$	3	0.3	$3 \cdot 10^{-7}$	10^{-5}	10^{-5}	$3 \cdot 10^{-6}$	$2 \cdot 10^{-6}$
$\tau, \text{ s}$	$2 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-7}$	10^{-7}	10^{-5}	—	—

Surface recombination. Besides the recombination in the bulk of a semiconductor the carriers can recombine at its surface. The surface recombination rate s is defined as the velocity of particle flow from the bulk to the surface such that required to maintain an excess of nonequilibrium carriers. The rate s depends strongly on the method of surface treatment. For example, for germanium $s \approx 10 \text{ cm/s}$ upon etching its surface by boiling H_2O_2 and $s \approx 10^5 \text{ cm/s}$ and more upon lapping. Usually $s \approx 10^2 - 10^3 \text{ cm/s}$.

The diffusion length L_D is a distance characterizing the spatial decrease in the nonequilibrium carrier density down to the equilibrium value. The value of L_D is defined through the diffusion coefficient D and the lifetime τ by the relationship $L_D = \sqrt{D\tau}$. The diffusion coefficient and the mobility are related by the Einstein relation $D = kT\mu / e$ (in a nondegenerate semiconductor). The maximum diffusion length characterizes the degree of crystal perfection and purity. At $T = 300$ K, $L_D \approx 0.5$ cm in Ge, $L_D \approx 0.3$ cm in Si, and $L_D \approx 10^{-2} - 10^{-3}$ cm in InSb [162].

Band structure and effective masses. The effective mass of a carrier characterizes its motion in the crystal lattice. The reverse effective mass $(m^*)^{-1}$ is the tensor quantity defined by the dependence $E(p)$ of the energy of the carrier E on its quasimomentum p .

$$(m^*)_{ij}^{-1} = \frac{\partial^2 E(p)}{\partial p_i \partial p_j}$$

Usually it will suffice to know the behavior of $E(p)$ only in the vicinity of the extreme points: the energy minima or maxima. The isoenergetic surfaces near the extrema are often represented as spheres (with the effective mass, for example, for several subbands of the valence band m_{p1} , m_{p2} , etc.) or ellipsoids (with the effective masses for the conduction band $m_{n||}$, $m_{n\perp 1}$, $m_{n\perp 2}$ ¹).

To analyze experimental data the concept of a density-of-states effective mass (m_{dn} and m_{dp} for electrons and holes, respectively) is in frequent use. In the case of the ellipsoidal isoenergetic surfaces this quantity is determined from the relationship

$$m_d = N^{2/3} (m_{||} m_{\perp 1} m_{\perp 2})^{1/3}$$

where N is the number of extrema in the band.

For the energy bands having the degenerate spherical surfaces of constant energy with the effective masses m_{p1} , m_{p2} , etc. the density-of-states effective mass is defined as follows:

$$m_{dp} = (m_{p1}^{3/2} + m_{p2}^{3/2} + \dots)^{2/3}$$

The concepts of an ohmic effective mass m_σ and a cyclotron effective mass m_c are also introduced. They are defined by the relationships

$$\frac{1}{m_\sigma} = \frac{1}{3} \left(\frac{1}{m_{||}} + \frac{1}{m_{\perp 1}} + \frac{1}{m_{\perp 2}} \right)$$

(the ellipsoidal isoenergetic surfaces),

$$m_c = \frac{h}{2\pi} \frac{\partial S}{\partial E}$$

(S is the area of the section of the isoenergetic surface by a plane normal to the magnetic field).

The general expressions for m_d , m_σ , and m_c see, for example, in [84].

The cyclotron resonance is a direct method for determining $E(p)$ and the effective masses. The valuable data about the band structure and the effective masses can be obtained in measuring the anisotropy of magnetoresistance, the Shubnikov-de Haas type effects, and the magnetooptic effects.

The intrinsic carrier density n_i corresponds to an ideally pure material and can be calculated, if the band structure and the effective masses are known, by the formula:

$$n_i = 4,82 \cdot 10^{15} T^{3/2} \left(\frac{m_{dn} m_{dp}}{m_0^2} \right)^{3/4} \exp \left(\frac{E_g - \alpha_T T}{2kT} \right)$$

where m_{dn} and m_{dp} are the density-of-states effective masses of electron and holes, respectively; m_0 is the mass of a free electrons; k is the Boltzmann constant; α_T is the temperature coefficient of the energy gap width.

¹ Often $m_{\perp 1} = m_{\perp 2}$, then the symbol $m_{\perp} = m_{\perp 1} = m_{\perp 2}$ is used.

As a rule, n_i is determined experimentally from the data of measurements of the Hall effect and the conduction in the corresponding temperature range.

The **Debye temperature** T_D is defined through the limiting lattice vibration frequency ω_m by the relationship

$$kT_D = \hbar\omega_m$$

The different Debye temperatures correspond, generally speaking, to the different branches of vibrations. The values of T_D determined from thermal measurements are averaged over the vibration branches that are essential at the temperature of measurements. More comprehensive information can be obtained, for example, in measuring the elastic constants.

The **limiting frequency of optical phonons** ω_l , or ω_t , is the frequency of respective (longitudinal or transverse) optical lattice vibrations with wavelengths considerably longer than the interatomic distance. Determined from the infrared absorption and reflection spectra as well as by neutron spectroscopy. For elementary semiconductors (Ge, Si, etc.): $\omega_i = \omega_t = \omega_0$.

The **spectroscopic splitting factor** g in the conduction (or valence) band characterizes the splitting of the energy levels of carriers in a magnetic field due to their magnetic moments

$$E = (n + 1/2) \hbar\omega_H \pm 1/2 g \hbar\omega_h$$

$n = 1, 2, \dots$, where ω_H is the cyclotron frequency of charge carrier in the crystal which is determined from the measurement of the oscillation effects in the magnetic field by the para- and nuclear magnetic resonance methods.

Dielectric constant. The values of the dielectric constant ϵ_0 and ϵ_∞ are determined from static and high-frequency (or optical) measurements, respectively. In the tables everywhere, except as otherwise indicated, the presented values belong to $T = 290$ K.

The tables contain mainly the data on semiconductors with $E_g < 3$ eV. Ternary and more complex semiconducting compounds are not described². Data on the parameters of semiconductor devices are also absent.

2 Elementary semiconductors

2.1 Silicon and germanium

Silicon and germanium are the widely used and best-investigated semiconductors. They crystallize into a diamond lattice and have a complex band structure.

In Si six equivalent absolute minima of the conduction band are located on the [100] axes inside the Brillouin zone. In the vicinity of each of these minima the isoenergetic surfaces represent ellipsoids of revolution (six ellipsoids).

In Ge eight equivalent absolute minima of the conduction band are located on the [111] axes at the boundary of the Brillouin zone.

In the vicinity of each of these minima the isoenergetic surfaces represent ellipsoids of revolution (the equivalent number of the ellipsoids is four).

The valence bands in Si and Ge are split into three subbands: two of them are degenerate at $k = 0$ and the third subband is split off due to spin-orbit interaction.

The electronic band structures of Si and Ge (with the symbols used in the tables) are shown in Figs. 22 and 23, respectively.

The electrophysical properties of Si and Ge are presented in Tables 2-5 and Figs. 24-43.

²For the properties of some classes of ternary compounds, see [16, 121, 123, 145, 289, 290].