Semiconductor Devices and Integrated Electronics

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Preface

For some time there has been a need for a semiconductor device book that carries diode and transistor theory beyond an introductory level and yet has space to touch on a wider range of semiconductor device principles and applications. Such topics are covered in specialized monographs numbering many hundreds, but the voluminous nature of this literature limits access for students. This book is the outcome of attempts to develop a broad course on devices and integrated electronics for university students at about senior-year level. The educational prerequisites are an introductory course in semiconductor junction and transistor concepts, and a course on analog and digital circuits that has introduced the concepts of rectification, amplification, oscillators, modulation and logic and switching circuits. The book should also be of value to professional engineers and physicists because of both, the information included and the detailed guide to the literature given by the references. The aim has been to bring some measure of order into the subject area examined and to provide a basic structure from which teachers may develop themes that are of most interest to students and themselves.

Semiconductor devices and integrated circuits are reviewed and fundamental factors that control power levels, frequency, speed, size and cost are discussed. The text also briefly mentions how devices are used and presents circuits and comments on representative applications. Thus, the book seeks a balance between the extremes of device physics and circuit design.

Study questions and further reading references are offered at the end of each chapter. An instructor can maintain the integrated-electronics balance by his choice of questions and further reading matter. Where the needs of the curriculum require it, either device physics or circuit technology may be emphasized by appropriate selection of the assigned reading and study questions. Many of the questions are numerical and can be answered from treatment of the appropriate subject matter in the text; others require extensive use of a library. To avoid pressure on particular issues of journals it is recommended that classes be divided into groups to study five or six different questions. Such work may then form the basis for general class discussion each week.

The topics that are covered include junction *pn* diodes, Schottky barrier diodes, varactors, bipolar transistors, JFETs, MOSFETs, integrated circuit fundamentals and applications, charge-coupled devices, Impatt oscillators, Gunn oscillators, solar cells, light detecting devices, electron emission devices, light emitting devices, injection lasers, and semiconductor sensors. For a one-semester course the material covered may be limited to Chaps. 1-10. If two semesters are available, a suitable division is Chaps. 1-9 and 10-15.

No attempt has been made to cover topics such as thermoelectrics, cryogenics, bulk or surface wave acoustic devices, and gas or dye lasers. Neither has there been space for description of semiconductor processing, crystal growing, epitaxy methods and thin- and thick-film circuit fabrication technologies and display systems.

Some sections of the book have been reviewed for content and emphasis by authorities in various fields. Their comments have eliminated some errors and misunderstandings and I offer them my thanks. Carnegie-Mellon University provided a short leave of absence in 1975 in order that progress could be made and I am grateful for this, and to the University of California, Berkeley, for receiving me during this time. The library and editorial assistance of M. Shure and B. Smith, and the drafting assistance of E. Lipanovich, have contributed substantially to the outcome and I am greatly in their debt. I am also indebted to students for problems and comments.

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A great deal of important and interesting advanced material is discussed in this book. Some introductory material is included in each chapter to set the stage but there is no space to consider in detail elementary concepts of semiconductors or circuits. Some familiarity is therefore assumed with analog and digital circuits, amplifiers, oscillators, modulators and gates; and with semiconductor concepts of bandgaps, mobilities, density of states, Fermi levels, doping, minority carrier diffusion and lifetime, the simple *pn* junction model and general ideas about bipolar and field-effect transistors. We begin, therefore, with a list of some standard equations of semiconductors. If the form and notation are not familiar some time should be spent with the introductory semiconductor books that are included in the reference list at the end of the volume.

1.1 INTRODUCTORY SEMICONDUCTOR EQUATIONS AND CONCEPTS

Three important semiconductors are silicon (Si), germanium (Ge), and gallium arsenide (GaAs).

The bandgaps of Si, Ge and GaAs are 1.1, 0.66 and 1.43 eV at 300°K and their respective electron mobilities are 1350, 3600 and about 5000 $cm^2V^{-1}sec^{-1}$. If perfectly pure they would have intrinsic resistivities of about 2.5×10^3, 50 and 10^8 ohm-cm, respectively, corresponding to intrinsic carrier densities of 1.5×10^{10}, 2.5×10^{13} and 1.7×10^6 cm^{-3} at 300°K. Semiconductors of Si and Ge may be doped n type by group V impurities such as P, As and Sb, and p type by group III impurities such as B, Al, Ga and In. Gallium arsenide is doped n type by group VI impurities such as S, Se and Te, and p type by group II impurities such as Zn and Cd. Group IV impurities such as Si, Ge, and Sn have doping effects in GaAs that depend on the lattice site occupied by the impurity. For instance, Ge in liquid-phase epitaxially grown material tends to be on the As site and be a p type dopant whereas Sn is on the Ga site and is an n type dopant.

Nowadays, Si has almost completely replaced Ge for diodes and transistors because the larger energy gap allows higher temperature operation, the raw material is lower in cost, the oxide is favorable to masking operations and the dopant properties in Si are good (low segregation coefficients, good solubilities, shallow energy levels and easily controlled diffusion conditions).

An important semiconductor is GaAs because the electron mobility and saturation drift velocity is high so it is suited to high frequency operation for microwave transistors and diodes. Also, GaAs has a band structure that allows transferred-electron (Gunn) oscillations (see Chap. 11) and good solar cell performance (see Chap. 12) and efficient light emission (see Chap. 14). On the other hand, GaAs is much more expensive than Si because of higher raw material costs and extra difficulties of preparation.

Tables of the physical properties of Si, Ge and GaAs and curves of resistivity, mobility and other properties such as diffusion coefficients, energy levels and solubilities for impurities are found in various books. Many other semiconductors in the III-V group and the II-VI group are also of great value in special applications. Some data for these are given in Chaps. 12, 13 and 14.

Now let us review briefly some of the simple equations of semiconductor bulk and transport theory.

- Thermal energy $= kT/q = 0.026$ eV at 300°K where $q = 1.6 \times 10^{-19}$ coulombs per electron.
- Photon energy of light $E = hc/\lambda = 1.24/\lambda$ eV. Wavelength range of visible light is about 0.40-0.72 μm corresponding to an energy range 3.0-1.7 eV.
- The resistivity, at low field strengths, is given by

$$\rho = 1/(qn\mu_n + qp\mu_p) \tag{1.1}$$

and

$$J = q(n\mu_n + p\mu_p)\mathcal{E} \tag{1.2}$$

- The intrinsic concentration in a semiconductor varies with temperature as

$$n_i^2 = AT^3 e^{-E_g/kT} \tag{1.3}$$

- Mobility varies with temperature as T^{-m} where m is 2.5 for electrons and 2.7 for holes in Si. The mobility concept begins to be modified at drift velocities in excess of 10^6 cm sec^{-1} ($\mathcal{E} > 10^3$ V cm^{-1}).
- The concepts of doping and Fermi levels lead to the following expressions

$$n = N_c e^{-(E_c - E_F)/kT} \tag{1.4}$$

$$p = N_v e^{-(E_F - E_v)/kT} \tag{1.5}$$

or

$$n = n_i e^{(E_F - E_i)/kT} \tag{1.6}$$

$$p = n_i e^{(E_i - E_F)/kT} \tag{1.7}$$

where

$$N_{c,v} = 2\left(\frac{2\mu m^* kT}{h^2}\right)^{3/2} \tag{1.8}$$

For Si at 300°K, $N_c = 2.8 \times 10^{19}$ cm^{-3} and $N_v = 1.04 \times 10^{19}$ cm^{-3} (these are the effective density of energy states imagined to be concentrated at the band edges E_c and E_v). For GaAs the values are $N_c = 4.7 \times 10^{17}$ cm^{-3} and $N_v = 7.0 \times 10^{18}$ cm^{-3}.

If the Fermi level approaches within a few kT of the band edge because the doping is heavy, these equations may not be used and account must be taken of the variation of the energy state density with distance from the band edge--typically this variation is proportional to $(E - E_c)^{1/2}$.

- The product of Eqs. (1.4) and (1.5) gives

$$np = N_c N_v e^{-(E_c - E_v)/kT} \tag{1.9}$$

or

$$np = n_i^2 \tag{1.10}$$

Thus if n_i^2 for Si at 300°K is 2.25×10^{20} cm^{-3} and if the doping is 10^{15} atoms cm^{-3} of As the value of n is 10^{15} cm^{-3} and the density p is 2.25×10^5 cm^{-3}.

The product np is a constant only in equilibrium. This condition is not valid if carriers are being injected into the semiconductor by light or from a junction.

- Minority carriers in a condition of disturbed equilibrium diffuse by a random walk process and so in density gradients the net flow is given by

$$\text{Flow cm}^{-2}\,\text{sec}^{-1} = -D_{n,p}\frac{d(n,p)}{dx} \qquad (1.11)$$

- The Einstein relationship shows that mobility and the diffusion coefficient are related by

$$D = \mu\frac{kT}{q} \qquad (1.12)$$

Thus, if μ_n is 1350 $\text{cm}^2\,\text{V}^{-1}\,\text{sec}^{-1}$ for Si the value of D_n is 35 $\text{cm}^2\,\text{sec}^{-1}$ at 300°K.

- The transport equations for a bulk semiconductor containing both density gradients and electric fields are

$$J_n = q\mu_n n\mathcal{E} + qD_n\frac{dn}{dx} \qquad (1.13)$$

and

$$J_p = q\mu_p p\mathcal{E} - qD_p\frac{dp}{dx} \qquad (1.14)$$

- If the minority carrier average lifetime in a semiconductor is τ, the effect of a pulse of light is to cause a conductivity increase that returns to the equilibrium conductivity with an exponential time constant expression

$$\Delta\sigma = \Delta\sigma_0 e^{-t/\tau} \qquad (1.15)$$

- Consideration of the net balance of recombination and generation of minority carriers in a semiconductor leads to expressions of the form

$$\frac{dp}{dt} = -\frac{p - p_0}{\tau_p} \qquad (1.16)$$

where p_0 is the equilibrium hole density.

- In a spatial element of an n-type semiconductor with a hole density gradient present and recombination present the expression becomes

$$\frac{\partial p}{\partial t} = -\frac{p - p_0}{\tau_p} + D_p\frac{d^2p}{dx^2} \qquad (1.17)$$

- In an n type semiconductor with an injected carrier density of $p_{x=0}$ sus-