Physics of
Semiconductor Devices
Physics of
Semiconductor Devices

Third Edition

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A scanning electron micrograph of an array of the floating-gate nonvolatile semiconductor memory (NVSM) magnified 100,000 times. NVSM was invented at Bell Telephone Laboratories in 1967. There are more NVSM cells produced annually in the world than any other semiconductor device and, for that matter, any other human-made item. For a discussion of this device, see Chapter 6. Photo courtesy of Macronix International Company, Hsinchu, Taiwan, ROC.
Preface

Since the mid-20th Century the electronics industry has enjoyed phenomenal growth and is now the largest industry in the world. The foundation of the electronics industry is the semiconductor device. To meet the tremendous demand of this industry, the semiconductor-device field has also grown rapidly. Coincident with this growth, the semiconductor-device literature has expanded and diversified. For access to this massive amount of information, there is a need for a book giving a comprehensive introductory account of device physics and operational principles.

With the intention of meeting such a need, the First Edition and the Second Edition of Physics of Semiconductor Devices were published in 1969 and 1981, respectively. It is perhaps somewhat surprising that the book has so long held its place as one of the main textbooks for advanced undergraduate and graduate students in applied physics, electrical and electronics engineering, and materials science. Because the book includes much useful information on material parameters and device physics, it is also a major reference for engineers and scientists in semiconductor-device research and development. To date, the book is one of the most, if not the most, cited works in contemporary engineering and applied science, with over 15,000 citations (ISI, Thomson Scientific).

Since 1981, more than 250,000 papers on semiconductor devices have been published, with numerous breakthroughs in device concepts and performances. The book clearly needed another major revision if it were to continue to serve its purpose. In this Third Edition of Physics of Semiconductor Devices, over 50% of the material has been revised or updated, and the material has been totally reorganized. We have retained the basic physics of classic devices and added many sections that are of contemporary interest such as the three-dimensional MOSFETs, nonvolatile memory, modulation-doped field-effect transistor, single-electron transistor, resonant-tunneling diode, insulated-gate bipolar transistor, quantum cascade laser, semiconductor sensors, and so on. On the other hand, we have omitted or reduced sections of less-important topics to maintain the overall book length.

We have added a problem set at the end of each chapter. The problem set forms an integral part of the development of the topics, and some problems can be used as worked examples in the classroom. A complete set of detailed solutions to all end-of-chapter problems has been prepared. The solution manuals are available free to all adopting faculties. The figures and tables used in the text are also available in electronic format, to instructors from the publisher. Instructors can find out more information at the publisher's website at http://www.wiley.com/interscience/sze.
In the course of writing this text, we had the fortune of help and support of many people. First we express our gratitude to the management of our academic and industrial institutions: the National Chiao Tung University, the National Nano Device Laboratories, Agere Systems, and MVC, without whose support this book could not have been written. We wish to thank the Spring Foundation of the National Chiao Tung University for the financial support. One of us (K. Ng) would like to thank J. Hwang and B. Leung for their continued encouragement and personal help.

We have benefited greatly from suggestions made by our reviewers who took their time from their busy schedule. Credits are due to the following scholars: A. Alam, W. Anderson, S. Banerjee, J. Brews, H. C. Casey, Jr., P. Chow, N. de Rooij, H. Eisele, E. Kasper, S. Luryi, D. Monroe, P. Panayotatos, S. Pearton, E. F. Schubert, A. Seabaugh, M. Shur, Y. Taur, M. Teich, Y. Tsividis, R. Tung, E. Yang, and A. Zaslavsky. We also appreciate the permission granted to us from the respective journals and authors to reproduce their original figures cited in this work.

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Introduction

The book is organized into five parts:

- **Part I**: Semiconductor Physics
- **Part II**: Device Building Blocks
- **Part III**: Transistors
- **Part IV**: Negative-Resistance and Power Devices
- **Part V**: Photonic Devices and Sensors

Part I, Chapter 1, is a summary of semiconductor properties that are used throughout the book as a basis for understanding and calculating device characteristics. Energy band, carrier concentration, and transport properties are briefly surveyed, with emphasis on the two most important semiconductors: silicon (Si) and gallium arsenide (GaAs). A compilation of the recommended or most-accurate values for these semiconductors is given in the illustrations of Chapter 1 and in the Appendices for convenient reference.

Part II, Chapters 2 through 4, treat the basic device building blocks from which all semiconductor devices can be constructed. Chapter 2 considers the p-n junction characteristics. Because the p-n junction is the building block of most semiconductor devices, p-n junction theory serves as the foundation of the physics of semiconductor devices. Chapter 2 also considers the heterojunction, that is a junction formed between two dissimilar semiconductors. For example, we can use gallium arsenide (GaAs) and aluminum arsenide (AlAs) to form a heterojunction. The heterojunction is a key building block for high-speed and photonic devices. Chapter 3 treats the metal-semiconductor contact, which is an intimate contact between a metal and a semiconductor. The contact can be rectifying similar to a p-n junction if the semiconductor is moderately doped and becomes ohmic if the semiconductor is very heavily doped. An ohmic contact can pass current in either direction with a negligible voltage drop and can provide the necessary connections between devices and the outside world. Chapter 4 considers the metal-insulator-semiconductor (MIS) capacitor of which the Si-based metal-oxide-semiconductor (MOS) structure is the dominant member. Knowledge of the surface physics associated with the MOS capacitor is important, not only for understanding MOS-related devices such as the MOSFET and the floating-gate nonvolatile memory but also because of its relevance to the stability and reliability of all other semiconductor devices in their surface and isolation areas.
Part III, Chapters 5 through 7, deals with the transistor family. Chapter 5 treats the bipolar transistor, that is, the interaction between two closely coupled p-n junctions. Chapter 6 considers the MOSFET (MOS field-effect transistor). The distinction between a field-effect transistor and a potential-effect transistor (such as the bipolar transistor) is that in the former, the channel is modulated by the gate through a capacitor whereas in the latter, the channel is controlled by a direct contact to the channel region. The MOSFET is the most-important device for advanced integrated circuits, and is used extensively in microprocessors and DRAMS (dynamic random access memories). Chapter 6 also treats the nonvolatile semiconductor memory which is the dominant memory for portable electronic systems such as the cellular phone, notebook computer, digital camera, audio and video players, and global positioning system (GPS). Chapter 7 considers three other field-effect transistors; the JFET (junction field-effect-transistor), MESFET (metal-semiconductor field-effect transistor), and MODFET (modulation-doped field-effect transistor). The JFET is an older member and now used mainly as power devices, whereas the MESFET and MODFET are used in high-speed, high-input-impedance amplifiers and monolithic microwave integrated circuits.

Part IV, Chapters 8 through 11, considers negative-resistance and power devices. In Chapter 8, we discuss the tunnel diode (a heavily doped p-n junction) and the resonant-tunneling diode (double-barrier structure formed by multiple heterojunctions). These devices show negative differential resistance due to quantum-mechanical tunneling. They can generate microwaves or serve as functional devices, that is, they can perform a given circuit function with a greatly reduced number of components. Chapter 9 discusses the transit-time devices. When a p-n junction or a metal-semiconductor junction is operated in avalanche breakdown, under proper conditions we have an IMPATT diode that can generate the highest CW (continuous wave) power output of all solid-state devices at millimeter-wave frequencies (i.e., above 30 GHz). The operational characteristics of the related BARITT and TUNNETT diodes are also presented. The transferred-electron device (TED) is considered in Chapter 10. Microwave oscillation can be generated by the mechanism of electron transfer from a high-mobility lower-energy valley in the conduction band to a low-mobility higher-energy valley (in momentum space), the transferred-electron effect. Also presented are the real-space-transfer devices which are similar to TED but the electron transfer occurs between a narrow-bandgap material to an adjacent wide-bandgap material in real space as opposed to momentum space. The thyristor, which is basically three closely coupled p-n junctions in the form of a p-n-p-n structure, is discussed in Chapter 11. Also considered are the MOS controlled thyristors (a combination of MOSFET with a conventional thyristor) and the insulated-gate bipolar transistor (IGBT, a combination of MOSFET with a conventional bipolar transistor). These devices have a wide range of power-handling and switching capability; they can handle currents from a few milliamperes to thousands of amperes and voltages above 5000 V.
Part V, Chapters 12 through 14, treats photonic devices and sensors. Photonic devices can detect, generate, and convert optical energy to electric energy, or vice versa. The semiconductor light sources, light-emitting diode (LED) and laser, are discussed in Chapter 12. The LEDs have a multitude of applications as display devices such as in electronic equipment and traffic lights, and as illuminating devices such as flashlights and automobile headlights. Semiconductor lasers are used in optical-fiber communication, video players, and high-speed laser printers. Various photodetectors with high quantum efficiency and high response speed are discussed in Chapter 13. The chapter also considers the solar cell which converts optical energy to electrical energy similar to a photodetector but with different emphasis and device configuration. As the worldwide energy demand increases and the fossil-fuel supply will be exhausted soon, there is an urgent need to develop alternative energy sources. The solar cell is considered a major candidate because it can convert sunlight directly to electricity with good conversion efficiency, can provide practically everlasting power at low operating cost, and is virtually nonpolluting. Chapter 14 considers important semiconductor sensors. A sensor is defined as a device that can detect or measure an external signal. There are basically six types of signals: electrical, optical, thermal, mechanical, magnetic, and chemical. The sensors can provide us with information about these signals which could not otherwise be directly perceived by our senses. Based on the definition of sensors, all traditional semiconductor devices are sensors since they have inputs and outputs and both are in electrical forms. We have considered the sensors for electrical signals in Chapters 2 through 11, and the sensors for optical signals in Chapters 12 and 13. In Chapter 14, we are concerned with sensors for the remaining four types of signals, i.e., thermal, mechanical, magnetic, and chemical.

We recommend that readers first study semiconductor physics (Part I) and the device building blocks (Part II) before moving to subsequent parts of the book. Each chapter in Parts III through V deals with a major device or a related device family, and is more or less independent of the other chapters. So, readers can use the book as a reference and instructors can select chapters appropriate for their classes and to their order of preference. We have a vast literature on semiconductor devices. To date, more than 300,000 papers have been published in this field, and the grand total may reach one million in the next decade. In this book, each chapter is presented in a clear and coherent fashion without heavy reliance on the original literature. However, we have an extensive listing of key papers at the end of each chapter for reference and for further reading.

REFERENCE

PART I

SEMICONDUCTOR PHYSICS

• Chapter 1  Physics and Properties of Semiconductors
  —A Review
1

Physics and Properties of Semiconductors—A Review

1.1 INTRODUCTION

The physics of semiconductor devices is naturally dependent on the physics of semiconductors themselves. This chapter presents a summary and review of the basic physics and properties of semiconductors. It represents only a small cross section of the vast literature on semiconductors; only those subjects pertinent to device operations are included here. For detailed consideration of semiconductor physics, the reader should consult the standard textbooks or reference works by Dunlap, Madelung, Moll, Moss, Smith, Boer, Seeger, and Wang, to name a few.

To condense a large amount of information into a single chapter, four tables (some in appendices) and over 30 illustrations drawn from experimental data are compiled and presented here. This chapter emphasizes the two most-important semiconductors: silicon (Si) and gallium arsenide (GaAs). Silicon has been studied extensively and widely used in commercial electronics products. Gallium arsenide has been intensively investigated in recent years. Particular properties studied are its direct bandgap...
CHAPTER 1. PHYSICS AND PROPERTIES OF SEMICONDUCTORS—A REVIEW

for photonic applications and its intervalley-carrier transport and higher mobility for generating microwaves.

1.2 CRYSTAL STRUCTURE

1.2.1 Primitive Cell and Crystal Plane

A crystal is characterized by having a well-structured periodic placement of atoms. The smallest assembly of atoms that can be repeated to form the entire crystal is called a primitive cell, with a dimension of lattice constant \( a \). Figure 1 shows some important primitive cells.

Many important semiconductors have diamond or zincblende lattice structures which belong to the tetrahedral phases; that is, each atom is surrounded by four equidistant nearest neighbors which lie at the corners of a tetrahedron. The bond between two nearest neighbors is formed by two electrons with opposite spins. The diamond and the zincblende lattices can be considered as two interpenetrating face-centered cubic (fcc) lattices. For the diamond lattice, such as silicon (Fig. 1d), all the atoms are the same; whereas in a zincblende lattice, such as gallium arsenide (Fig. 1e), one sublattice is gallium and the other is arsenic. Gallium arsenide is a III-V compound, since it is formed from elements of groups III and V of the periodic table.

Most III-V compounds crystallize in the zincblende structure; however, many semiconductors (including some III-V compounds) crystallize in the rock-salt or wurtzite structures. Figure 1f shows the rock-salt lattice, which again can be considered as two interpenetrating face-centered cubic lattices. In this rock-salt structure, each atom has six nearest neighbors. Figure 1g shows the wurtzite lattice, which can be considered as two interpenetrating hexagonal close-packed lattices (e.g., the sublattices of cadmium and sulfur). In this picture, for each sublattice (Cd or S), the two planes of adjacent layers are displaced horizontally such that the distance between these two planes is at a minimum (for a fixed distance between centers of two atoms), hence the name close-packed. The wurtzite structure has a tetrahedral arrangement of four equidistant nearest neighbors, similar to a zincblende structure.

Appendix F gives a summary of the lattice constants of important semiconductors, together with their crystal structures. Note that some compounds, such as zinc sulfide and cadmium sulfide, can crystallize in either zincblende or wurtzite structures.

Since semiconductor devices are built on or near the semiconductor surface, the orientations and properties of the surface crystal planes are important. A convenient method of defining the various planes in a crystal is to use Miller indices. These indices are determined by first finding the intercepts of the plane with the three basis axes in terms of the lattice constants (or primitive cells), and then taking the reciprocals of these numbers and reducing them to the smallest three integers having the same ratio. The result is enclosed in parentheses \((hkl)\) called the Miller indices for a single plane or a set of parallel planes \(\{hkl\}\). Figure 2 shows the Miller indices of important planes in a cubic crystal. Some other conventions are given in Table 1.
Fig. 1 Some important primitive cells (direct lattice) and their representative elements; $a$ is the lattice constant.
1.2.2 Reciprocal Lattice

For a given set of the direct basis vectors, a set of reciprocal lattice basis vectors $a^*,$ $b^*,$ and $c^*$ can be defined as

$$a^* = 2\pi \frac{b \times c}{a \cdot b \times c},$$

$$b^* = 2\pi \frac{c \times a}{a \cdot b \times c}$$

Table 1  Miller Indices and Their Represented Plane or Direction of a Crystal Surface

<table>
<thead>
<tr>
<th>Miller Indices</th>
<th>Description of plane or direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(hkl)</td>
<td>For a plane that intercepts $hk,$ $lk,$ $l$ on the $x,$ $y,$ and $z$-axis, respectively.</td>
</tr>
<tr>
<td>(hkl)</td>
<td>For a plane that intercepts the negative $x$-axis.</td>
</tr>
<tr>
<td>(hklm)</td>
<td>For a full set of planes of equivalent symmetry, such as ${100}$ for $(100),$ $(311),$ $(011),$ $(110),$ $(110)$ in cubic symmetry.</td>
</tr>
<tr>
<td>(hklm)</td>
<td>For a direction of a crystal such as $[100]$ for the $x$-axis.</td>
</tr>
<tr>
<td>(hklm)</td>
<td>For a full set of equivalent directions.</td>
</tr>
<tr>
<td>(hklm)</td>
<td>For a plane in a hexagonal lattice (such as wurtzite) that intercepts $hk,$ $lk,$ $l,$ and $m$ on the $a_1,$ $a_2,$ $a_3,$ and $z$-axis, respectively (Fig. 1g).</td>
</tr>
</tbody>
</table>
\[ \epsilon^2 = \frac{u \cdot b}{a \cdot b \cdot c} \]

such that \( a \cdot u^* = 2\pi, u \cdot b^* = 0 \), and so on. The denominators are identical due to the equality that \( a \cdot b \cdot c = b \cdot c \cdot a \cdot a \cdot b \) which is the volume enclosed by these vectors. The general reciprocal lattice vector is given by

\[ G = h\mathbf{a}^* + k\mathbf{b}^* + l\mathbf{c}^* \]

where \( h, k, \) and \( l \) are integers. It follows that one important relationship between the direct lattice and the reciprocal lattice is

\[ G \cdot R = 2\pi \cdot \text{integer} \]

and therefore each vector of the reciprocal lattice is normal to a set of planes in the direct lattice. The volume \( V_r \) of a primitive cell of the reciprocal lattice is inversely proportional to that \( V_d \) of the direct lattice; that is,

\[ V_r = \frac{(2\pi)^3 V_d}{3} \]

where \( V_r = a \cdot b \cdot c \).

The primitive cell of a reciprocal lattice can be represented by a Wigner-Seitz cell. The Wigner-Seitz cell is constructed by drawing perpendicular bisector planes in the reciprocal lattice from the chosen center to the nearest equivalent reciprocal lattice sites. This technique can also be applied to a direct lattice. The Wigner-Seitz cell in the reciprocal lattice is called the first Brillouin zone. Figure 3a shows a typical example for a body-centered cubic (bcc) reciprocal lattice. If one first draws lines from the center point \( \mathbf{R} \) to the eight corners of the cube, then forms the bivector.

Fig. 3 Brillouin zones for (a) fcc, diamond, and zincblende lattices, (b) bcc lattice, and (c) wurtzite lattice.
planes, the result is the truncated octahedron within the cube—a Wigner-Seitz cell. It can be shown that a face-centered cubic (fcc) direct lattice with lattice constant \( a \) has a bcc reciprocal lattice with spacing \( 4\pi a \). Thus the Wigner-Seitz cell shown in Fig. 3a is the primitive cell of the fcc reciprocal (bcc) lattice for an fcc direct lattice. The Wigner-Seitz cells for fcc and hexagonal direct lattices can be similarly constructed and shown in Figs. 3b and 3c. It will be shown that the reciprocal lattice is useful to visualize the \( E-k \) relationship when the coordinates of the wave vectors \( k \) \((k \cdot k = 2\pi)\) are mapped into the coordinates of the reciprocal lattice. In particular, the Brillouin zone for the fcc lattice is important because it is relevant to most semiconductor materials of interest here. The symbols used in Fig. 3a will be discussed in more details.

1.3 ENERGY BANDS AND ENERGY GAP

The energy-momentum \( (E-k) \) relationship for carriers in a lattice is important, for example, in the interactions with photons and phonons where energy and momentum have to be conserved, and with each other (electrons and holes) which leads to the concept of energy gap. This relationship also characterizes the effective mass and the group velocity, as will be discussed later.

The band structure of a crystalline solid, that is, the energy-momentum \( (E-k) \) relationship, is usually obtained by solving the Schrödinger equation of an approximate one-electron problem. The Bloch theorem, one of the most important theorems basic to band structure, states that if a potential energy \( V(r) \) is periodic in the direct lattice space, then the solutions for the wavefunction \( \psi_0(r, k) \) of the Schrödinger equation:

\[
\frac{-\hbar^2}{2m^*} \nabla^2 \psi_0(r) - V(r) \psi_0(r, k) = E(k) \psi_0(r, k)
\]

are of the form of a Bloch function:

\[
\psi_0(r, k) = \exp(j k \cdot r) \varphi_0(r, k).
\]

Here \( b \) is the band index, \( \varphi_0(r, k) \) and \( \varphi_0(r, k) \) are periodic in \( R \) of the direct lattice. Since

\[
\psi_0(r + R, k) = \exp(j k \cdot (r + R)) \varphi_0(r + R, k) = \exp(j k \cdot r) \exp(j k \cdot R) \varphi_0(r, k),
\]

and is equal to \( \psi_0(r, k) \), it is necessary that \( k \cdot R \) is a multiple of \( 2\pi \). It is the property of Eq. 4 that the reciprocal lattice can be used when \( G \) is replaced with \( R \) for visualizing the \( E-k \) relationship.

From the Bloch theorem one can also show that the energy \( E(k) \) is periodic in the reciprocal lattice, that is, \( E(k) = E(k + \mathbf{G}) \), where \( \mathbf{G} \) is given by Eq. 3. For a given band index, to label the energy uniquely, it is sufficient to use only \( k \)'s in a primitive cell of the reciprocal lattice. The standard convention is to use the Wigner-Seitz cell of the reciprocal lattice (Fig. 3). This cell is the Brillouin zone or the first Brillouin zone. It is thus evident that we can reduce any momentum \( k \) in the reciprocal space to a
point inside the Brillouin zone, where any energy state can be given a label in the reduced zone schemes.

The Brillouin zone for the diamond and the zincblende lattices is the same as that of the fcc and is shown in Fig. 3a. Table 2 summarizes its most important symmetry points and symmetry lines, such as the center of the zone, the zone edges and their corresponding k axes.

The energy bands of solids have been studied theoretically using a variety of numerical methods. For semiconductors the three methods most frequently used are the orthogonalized plane-wave method, the pseudopotential method, and the k·p method. Figure 4 shows results of studies of the energy-band structures of Si and GaAs. Notice that for any semiconductor there is a forbidden energy range in which allowed states cannot exist. Energy regions or energy bands are permitted above and below this energy gap. The upper bands are called the conduction bands; the lower bands, the valence bands. The separation between the energy of the lowest conduction band and that of the highest valence band is called the bandgap or energy gap, which is one of the most important parameters in semiconductor physics. In this figure the bottom of the conduction band is designated $E_c$, and the top of the valence band $E_v$. Within the bands, the electron energy is conventionally defined to be positive when measured upward from $E_c$, and the hole energy is positive when measured downward from $E_v$. The bandgaps of some important semiconductors are listed in Appendix F.

The valence band in the zincblende structure, such as that for GaAs in Fig. 4b, consists of four subbands when spin is neglected in the Schrödinger equation, and each band is doubled when spin is taken into account. Three of the four bands are degenerate at $k = 0$ point, and form the upper edge of the band, and the fourth band forms the bottom (not shown). Furthermore, the spin-orbit interaction causes a splitting of the band at $k = 0$.

Near the band edges, i.e., bottom of $E_c$ and top of $E_v$, the $E$-k relationship can be approximated by a quadratic equation

$$E(k) = \frac{n^2 k^2}{2m^*},$$

where $m^*$ is the associated effective mass. But as shown in Fig. 4, along a given direction the two top valence bands can be approximated by two parabolic bands with different curvatures, the heavy-hole band (the wider band in k-axis with smaller $\frac{d^2E}{dk^2}$)
and the light-hole band (the narrower band with larger $\frac{\partial^2 E}{\partial k^2}$). The effective mass in general is tensorial with components $m_i^e$ defined as

$$\frac{1}{m_i^e} = \frac{1}{\hbar^2} \left( \frac{\partial^2 E}{\partial k_i \partial k_j} \right).$$

(9)

The effective masses are listed in Appendix F for important semiconductors.

Carriers in motion are also characterized by a group velocity

$$v_g = \frac{1}{\hbar} \frac{\partial^2 E}{\partial k_i}$$

(10)

and with momentum

$$p = \hbar k.$$  

(11)

The conduction band consists of a number of subbands (Fig. 4). The bottom of the conduction band can appear at the center $k = 0$ (1) or off center along different $k$ axes. Symmetry considerations alone do not determine the location of the bottom of the conduction band. Experimental results show, however, that in Si it is off center and
along the [100] axis (A), and in GaAs the bottom is at \( k = 0 \) (r). Considering that the valence-band maximum \( (E_v) \) occurs at \( \Gamma \), the conduction-band minimum can be aligned or misaligned in \( k \)-space in determining the bandgap. This results in direct bandgap for GaAs and indirect bandgap for Si. This bears significant consequences when carriers transfer between this minimum gap in that momentum (or \( k \)) is conserved for direct bandgap but changed for indirect bandgap.

Figure 5 shows the shapes of the constant-energy surfaces. For Si there are six ellipsoids along the (100)-axes, with the centers of the ellipsoids located at about three-fourths of the distance from the Brillouin zone center. For GaAs the constant energy surface is a sphere at the zone center. By fitting experimental results to parabolic bands, we obtain the electron effective mass: one for GaAs and two for Si, \( m_e \) along the symmetry axes and \( m_t \) transverse to the symmetry axes. Appendix G also includes these values.

At room temperature and under normal atmospheric pressure, the values of the bandgap are 1.12 eV for Si and 1.42 eV for GaAs. These values are for high-purity materials. For highly doped materials the bandgaps become smaller. Experimental results show that the bandgaps of most semiconductors decrease with increasing temperature. Figure 6 shows variations of bandgap as a function of temperature for Si and GaAs. The bandgap approaches 1.17 and 1.52 eV respectively for these two semiconductors at 0 K. The variation of bandgap with temperature can be expressed approximately by a universal function

\[
E_g(T) = E_g(0) - \frac{a T^2}{T + B}
\]

where \( E_g(0) \), \( a \), and \( B \) are given in the inset of Fig. 6. The temperature coefficients \( \frac{dE_g}{dT} \) for example, the bandgap of PbS (Appendix F) increases from 0.286 eV at 0 K to 0.41 eV at 300 K. Near room temperature, the bandgap of GaAs increases with pressure \( P \), and \( \frac{dE_g}{dP} \) is about \(-2.6 \times 10^{-4} \) eV-cm\(^2\)/N, while the Si bandgap decreases with pressure, with \( \frac{dE_g}{dP} = -2.4 \times 10^{-4} \) eV-cm\(^2\)/N.

![Fig. 5. Shapes of constant-energy surfaces for electrons in Si and GaAs. For Si there are six ellipsoids along the (100)-axes with the centers of the ellipsoids located at about three-fourths of the distance from the Brillouin zone center. For GaAs the constant-energy surface is a sphere at zone center. (After Ref. 21.)](image-url)
CHAPTER 1. PHYSICS AND PROPERTIES OF SEMICONDUCTORS—A REVIEW

1.169 4.9×10⁻⁶ 655

Fig. 6 Energy bandgaps of Si and GaAs as a function of temperature. (After Refs. 22–23.)

1.4 CARRIER CONCENTRATION AT THERMAL EQUILIBRIUM

One of the most important properties of a semiconductor is that it can be doped with different types and concentrations of impurities to vary its resistivity. Also, when these impurities are ionized and the carriers are depleted, they leave behind a charge density that results in an electric field and sometimes a potential barrier inside the semiconductor. Such properties are absent in a metal or an insulator.

Figure 7 shows three basic bond representations of a semiconductor. Figure 7a shows intrinsic silicon, which is very pure and contains a negligibly small amount of impurities. Each silicon atom shares its four valence electrons with the four neigh-

![Fig. 7 Three basic bond pictures of a semiconductor. (a) Intrinsic Si with no impurity. (b) n-type Si with donor (phosphorus). (c) p-type Si with acceptor (boron).]
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