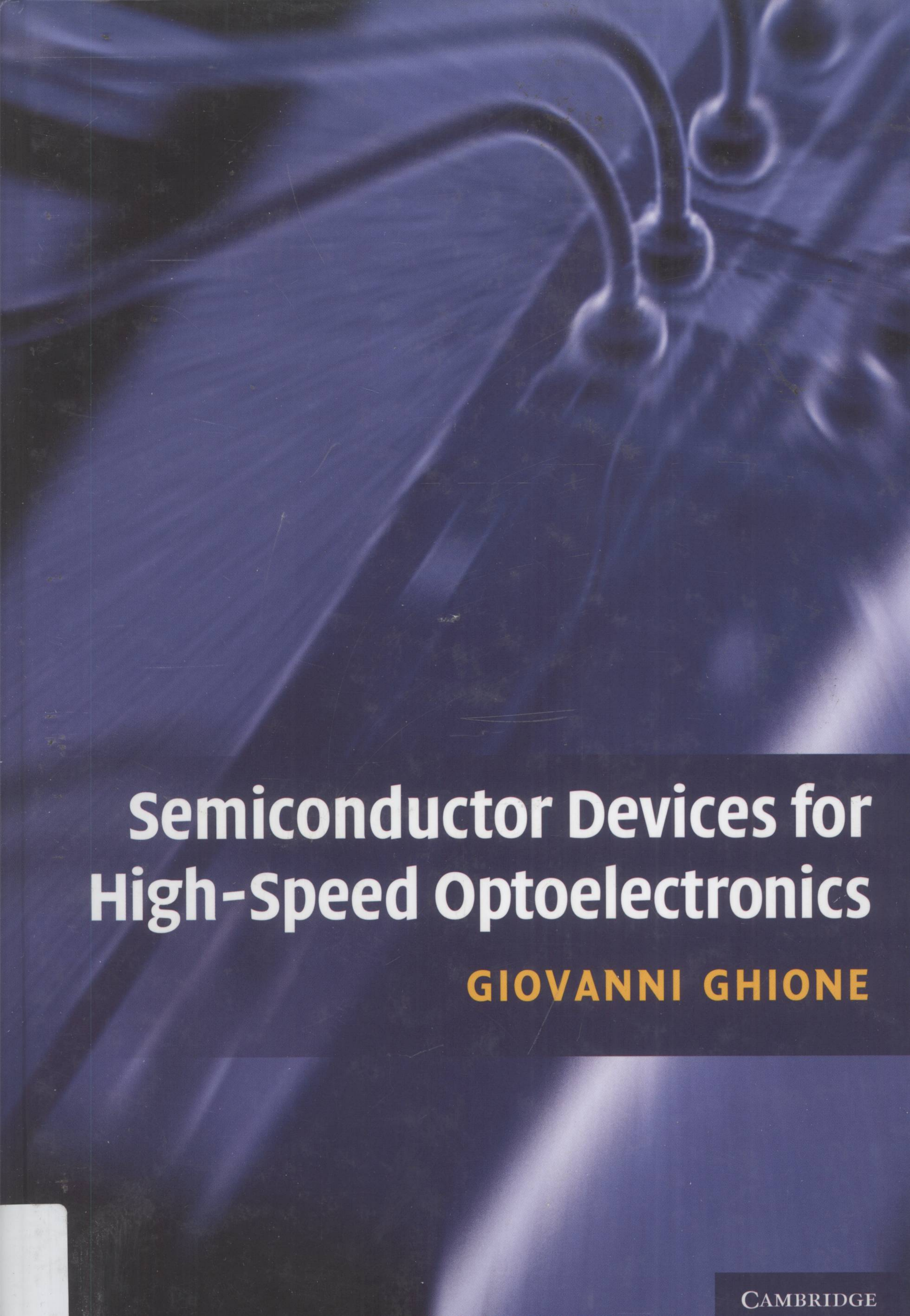

# Semiconductor Devices for High-Speed Optoelectronics

GIOVANNI GHIONE

CAMBRIDGE

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GIOVANNI GHIONE
Politecnico di Torino, Italy



CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521763448



First published 2009

Printed in the United Kingdom at the University Press, Cambridge

*A catalogue record for this publication is available from the British Library*

ISBN 978-0-521-76344-8 hardback

Additional resources for this publication at www.cambridge.org/Ghione

# Preface

The development of high-speed fiber-based optical communication systems that has taken place since the early 1970s can be really considered as a technological wonder. In a few years, key components were devised (such as the semiconductor laser) with the help of novel technological processes (such as epitaxial growth) and found immediate application thanks to the development of low-loss optical fibers. New compound semiconductor alloys (namely, InGaAsP) were ready to provide their potential to emit the right wavelengths needed for long-haul fiber propagation. When electronic repeaters seemed unable to provide a solution to long-haul propagation, fiber amplifiers were developed that allowed for all-optical signal regeneration. And the list could be continued. A miracle of ingenuity from a host of researchers made it possible to assemble this complex puzzle in a few years, thus bringing optoelectronic technology to a consumer electronics level.

Increasing the system capacity by increasing the transmission speed was, of course, a main concern from the early stages of optical system development. While optoelectronic devices behave, on the electronic side, in a rather conventional way up to speeds of the order of 1 Gbps, for larger speeds (up to 40 Gbps and beyond) RF wave propagation has to be accounted for in designing and modeling optoelectronic devices. When speed increases, the distributed interaction between RF and optical waves becomes a useful, sometimes indispensable, ingredient in many optoelectronic devices, like modulators and (to a lesser extent) detectors. Similarly, the electronic circuits that interface light sources, modulators, and detectors should provide broadband operation up to microwave or millimeter-wave frequencies, thus making it mandatory to exploit compound semiconductor electronics (GaAs- or InP-based) or advanced Si-based solutions (like SiGe HBT integrated circuits or nanometer MOS processes).

Increasing speed beyond the 10 Gbps limit by improving device performance, however interesting it is from the research and development side, may in practice be less appealing from the market standpoint. The ultimate destiny of optoelectronic devices (such as sources, modulators, and detectors) optimized for 40 Gbps (or even faster) systems after the post-2000 market downturn still is uncertain, and research in the field has followed alternative paths to the increase of system capacity. At the same time, new application fields have been developed, for instance in the area of integrated all-Si optical signal processing systems, and also for integrated circuit level high-capacity communications. However, the development of high-speed optoelectronic devices has raised a number of stimulating (and probably lasting) design issues. An example is the principle of the distributed interaction between optical and RF waves, which is common to a variety of high-speed components. Another relevant theme is the co-design and the (possibly monolithic) integration of the electronic and optoelectronic components of a system, not to mention the critical aspects concerning device packaging and interconnection in systems operating at 40 Gbps and beyond.

Taking the above into account, it is not surprising that the main purpose of the present book is to provide a kind of unified (or, perhaps, not too widely separated) treatment of high-speed electronics and optoelectronics, starting from compound semiconductor basics, down to high-speed transistors, ICs, detectors, sources and modulators. Part of the material was originally developed for a number of postgraduate and Master courses, and therefore has the ambition (but also the limitation) of providing a treatment starting from the very basics. It is hoped that this justifies both the presence of introductory material on semiconductors and semiconductor optical properties, and a treatment of high-speed electronics starting from a review of transmission lines and scattering parameters. From this standpoint, the text attempts to be as self-contained as possible. Of course, the choice of subjects is somewhat influenced by the author's personal tastes and previous research experience (not to mention the need to keep the page count below 500): some emphasis has been put on noise, again with an attempt to present a self-contained treatment of this rather difficult topic, and many important optoelectronic components have not been included (to mention one, semiconductor optical amplifiers). Yet another innovative subject that is missing is microwave photonics, where of course the RF and microwave and optoelectronic worlds meet. Nevertheless, the text is (in the author's opinion, at least) different enough from the many excellent textbooks on optoelectronics available on the market to justify the attempt to write it.

I wish to thank a number of colleagues (from Politecnico di Torino, unless otherwise stated) for their direct or indirect contribution to this book. Ivo Montrosset provided many useful suggestions on the treatment of optical sources. Incidentally, it was under the guidance of Ivo Montrosset and Carlo Naldi that (then an undergraduate student) I was introduced to the basics of passive and active optoelectronic devices, respectively; this happened, alas, almost 30 years ago. Helpful discussions with Gian Paolo Bava and Pierluigi Debernardi (Consiglio Nazionale delle Ricerche) on laser noise, with Simona Donati Guerrieri on the semiconductor optical properties and with Fabrizio Bonani and Marco Pirola on active and passive high-speed semiconductor electronic devices and circuits are gratefully acknowledged. Michele Goano kindly revised the sections on compound semiconductors and the numerical problems, and provided useful suggestions on III-N semiconductors. Federica Cappelluti prepared many figures (in particular in the section on photodetectors), initially exploited in lecture slides. Finally, Claudio Coriasso (Avago Turin Technology Center, Torino) kindly provided material on integrated electroabsorption modulators (EAL), including some figures. Additionally, I am indebted to a number of ME students who cooperated in research, mainly on lithium niobate modulators; among those, special mention goes to F. Carbonera, D. Frassati, G. Giarola, A. Mela, G. Omegna, L. Terlevich, P. Zandano. A number of PhD students also worked on subjects relevant to the present book: Francesco Bertazzi (now with Politecnico di Torino) on EM modeling of distributed electrooptic structures; Pietro Bianco,

on high-speed modulator drivers; Federica Cappelluti, on electroabsorption modulator modeling; Gloria Carvalho, on EAL modeling; Antonello Nespola (now with Istituto Superiore Mario Boella), on the modeling of distributed high-speed photodetectors. Part of the thesis work of Antonello Nespola and Federica Cappelluti was carried out within the framework of a cooperation with UCLA (Professor Ming Wu, now at University of California, Berkeley). Finally, I gratefully recall many helpful discussions with colleagues from the industry: among those, Marina Meliga, Roberto Paoletti, Marco Romagnoli, and Luciano Socci.

Giovanni Ghione
January 2009

# Contents

# 1 Semiconductors, alloys, heterostructures

## 1.1 Introducing semiconductors

Single-crystal semiconductors have a particularly important place in optoelectronics, since they are the starting material for high-quality sources, receivers and amplifiers. Other materials, however, can be relevant to some device classes: polycrystalline or amorphous semiconductors can be exploited in light-emitting diodes (LEDs) and solar cells; dielectrics (also amorphous) are the basis for passive devices (e.g., waveguides and optical fibers); and piezoelectric (ferroelectric) crystals such as lithium niobate are the enabling material for a class of electrooptic (EO) modulators. Moreover, polymers have been recently exploited in the development of active and passive optoelectronic devices, such as emitters, detectors, and waveguides (e.g., fibers). Nevertheless, the peculiar role of single-crystal semiconductors justifies the greater attention paid here to this material class with respect to other optoelectronic materials.

From the standpoint of electron properties, semiconductors are an intermediate step between insulators and conductors. The electronic structure of crystals generally includes a set of allowed energy bands, that electrons populate according to the rules of quantum mechanics. The two topmost energy bands are the *valence* and *conduction* band, respectively, see Fig. 1.1. At some energy above the conduction band, we find the *vacuum level*, i.e., the energy of an electron free to leave the crystal. In *insulators*, the valence band (which hosts the electrons participating to the chemical bonds) is separated from the conduction band by a large energy gap $E_g$, of the order of a few electronvolts (eV). Due to the large gap, an extremely small number of electrons have enough energy to be promoted to the conduction band, where they could take part into electrical conduction. In insulators, therefore, the conductivity is extremely small. In *metals*, on the other hand, the valence and conduction bands overlap (or the energy gap is *negative*), so that all carriers already belong to the conduction band, independent of their energy. Metals therefore have a large conductivity. In *semiconductors*, the energy gap is of the order of 1–2 eV, so that some electrons have enough energy to reach the conduction band, leaving *holes* in the valence band. Holes are pseudo-particles with positive charge, reacting to an external applied electric field and contributing, together with the electrons in the conduction band, to current conduction. In pure (*intrinsic*) semiconductors, therefore, charge transport is *bipolar* (through electrons and holes), and the conductivity is low, exponentially dependent on the gap (the larger the gap, the lower the conductivity). However, impurities can be added (*dopants*) to provide large numbers of electrons to

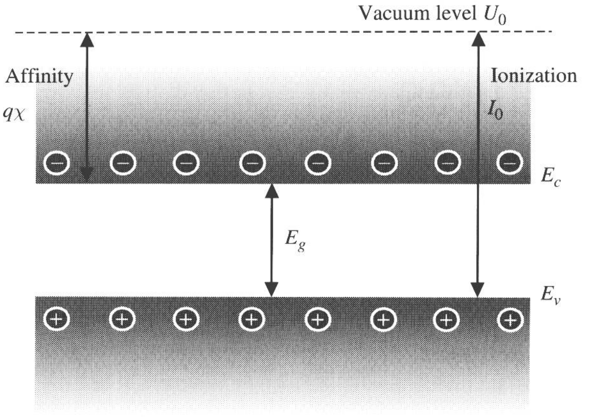


**Figure 1.1** Main features of semiconductor bandstructure. $E_g$ is the energy gap; $E_c$ is the conduction band edge; $E_v$ is the valence band edge.

the conduction band (*donors*) or of holes to the valence band (*acceptors*). The resulting doped semiconductors are denoted as $n$-type and $p$-type, respectively; their conductivity can be artificially modulated by changing the amount of dopants; moreover, the dual doping option allows for the development of $pn$ junctions, one of the basic building blocks of electronic and optoelectronic devices.

## 1.2 Semiconductor crystal structure

Crystals are regular, periodic arrangements of atoms in three dimensions. The point set $\underline{r}$ defining the crystal nodes, corresponding to the atomic positions (Bravais lattice) satisfies the condition $\underline{r} = k\underline{a}_1 + l\underline{a}_2 + m\underline{a}_3$, where $k, l, m$ are integer numbers and $\underline{a}_1$, $\underline{a}_2$, $\underline{a}_3$ are the *primitive vectors* denoting the *primitive cell*, see Fig. 1.2. Bravais lattices can be formed so as to fill the entire space only if the angles $\alpha_1, \alpha_2, \alpha_3$ assume values from a discrete set (60°, 90°, 120°, or the complementary value to 360°). According to the relative magnitudes of $a_1, a_2, a_3$ and to the angles $\alpha_1, \alpha_2, \alpha_3$, 14 basic lattices can be shown to exist, as in Table 1.1. In semiconductors, only two lattices are technologically important at present, i.e. the *cubic* and the *hexagonal*. Most semiconductors are cubic (examples are Si, Ge, GaAs, InP...), but some are hexagonal (SiC, GaN). Both the cubic and the hexagonal structure can be found in carbon (C), where they are the diamond and graphite crystal structures, respectively.

Three kinds of Bravais cubic lattices exist, the simple cubic (sc), the face-centered cubic (fcc) and the body-centered cubic (bcc), see Fig. 1.3. The cubic semiconductor crystal structure can be interpreted as two *shifted* and *compenetrated* fcc Bravais lattices.

Let us consider first an elementary semiconductor (e.g., Si) where all atoms are equal. The relevant cubic lattice is the *diamond lattice*, consisting of two interpenetrating

**Table 1.1** The 14 Bravais lattices.

| Name | Bravais lattices | Conditions on primitive vectors |
|---|---|---|
| Triclinic | 1 | $a_1 \neq a_2 \neq a_3, \alpha_1 \neq \alpha_2 \neq \alpha_3$ |
| Monoclinic | 2 | $a_1 \neq a_2 \neq a_3, \alpha_1 = \alpha_2 = 90^\circ \neq \alpha_3$ |
| Orthorhombic | 4 | $a_1 \neq a_2 \neq a_3, \alpha_1 = \alpha_2 = \alpha_3 = 90^\circ$ |
| Tetragonal | 2 | $a_1 = a_2 \neq a_3, \alpha_1 = \alpha_2 = \alpha_3 = 90^\circ$ |
| Cubic | 3 | $a_1 = a_2 = a_3, \alpha_1 = \alpha_2 = \alpha_3 = 90^\circ$ |
| Trigonal | 1 | $a_1 = a_2 = a_3, \alpha_1 = \alpha_2 = \alpha_3 < 120^\circ \neq 90^\circ$ |
| Hexagonal | 1 | $a_1 = a_2 \neq a_3, \alpha_1 = \alpha_2 = 90^\circ, \alpha_3 = 120^\circ$ |

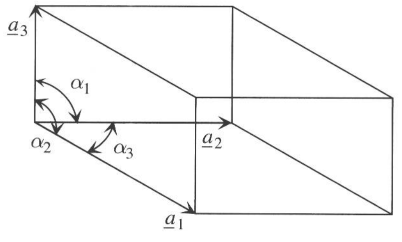


**Figure 1.2** Semiconductor crystal structure: definition of the primitive cell.

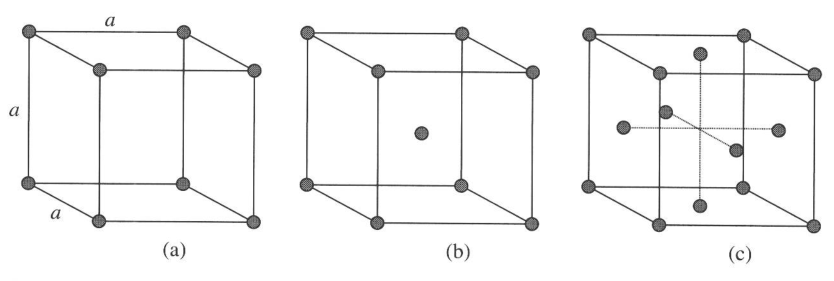


**Figure 1.3** Cubic Bravais lattices: (a) simple, (b) body-centered, (c) face-centered.

fcc Bravais lattices, displaced along the body diagonal of the cubic cell by one-quarter the length of the diagonal, see Fig. 1.4. Since the length of the diagonal is $d = a\left|\hat{x} + \hat{y} + \hat{z}\right| = a\sqrt{3}$, the displacement of the second lattice is described by the vector

$$\underline{s} = \frac{a\sqrt{3}}{4}\frac{\hat{x} + \hat{y} + \hat{z}}{\sqrt{3}} = \frac{a}{4}\left(\hat{x} + \hat{y} + \hat{z}\right).$$

## 1.2.1 The Miller index notation

The Miller indices are a useful notation to denote planes and reference directions within a lattice. The notation $(h, k, l)$, where $h$, $k$, $l$ are integers, denotes the set of parallel planes that intercepts the three points $\underline{a}_1/h$, $\underline{a}_2/k$ and $\underline{a}_3/l$, or some multiple thereof, while $[h, k, l]$ in square brackets is the direction orthogonal to plane $(h, k, l)$.

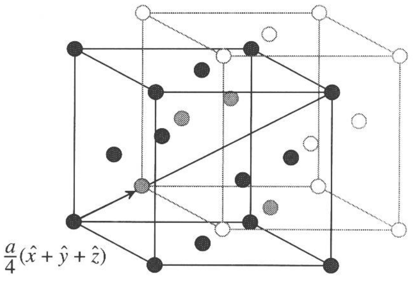


**Figure 1.4** The diamond lattice as two cubic face-centered interpenetrating lattices. The pale and dark gray points represent the atoms falling in the basic cell.

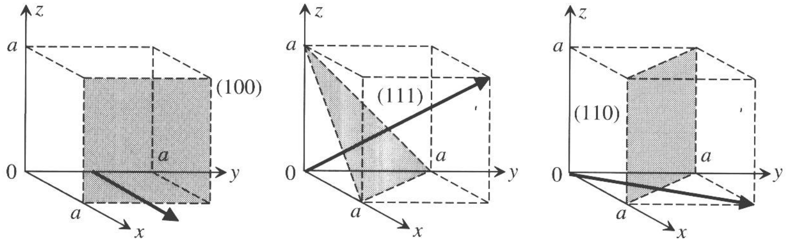


**Figure 1.5** Examples of planes and directions according to the Miller notation.

Additionally, $\{h, k, l\}$ is a family of planes with symmetries and $\langle h, k, l\rangle$ is the related direction set. In cubic lattices, the primitive vectors coincide with the Cartesian axes and $a_1 = a_2 = a_3 = a$, where $a$ is the lattice constant; in this case, we simply have $[h, k, l] \equiv h\widehat{x} + k\widehat{y} + l\widehat{z}$ where $\widehat{x}$, $\widehat{y}$ and $\widehat{z}$ are the Cartesian unit vectors.

To derive the Miller indices from the plane intercepts in a cubic lattice, we normalize with respect to the lattice constant (thus obtaining a set of integers $(H, K, L)$), take the reciprocal $(H^{-1}, K^{-1}, L^{-1})$ and finally multiply by a minimum common multiplier so as to obtain a set $(h, k, l)$ such as $h : k : l = H^{-1} : K^{-1} : L^{-1}$. Notice that a zero index corresponds to an intercept point at infinity. Examples of important planes and directions are shown in Fig. 1.5.

**Example 1.1:** Identify the Miller indices of the following planes, intersecting the coordinate axes in points (normalized to the lattice constant): (a) $x = 4$, $y = 2$, $z = 1$; (b) $x = 10$, $y = 5$, $z = \infty$; (c) $x = 3.5$, $y = \infty$, $z = \infty$; (d) $x = -4$, $y = -2$, $z = 1$.

We take the reciprocal of the intercept, and then we multiply by the minimum common multiplier, so as to obtain an integer set with minimum module. In case (a), the reciprocal set is $(1/4, 1/2, 1)$, with minimum common multiplier 4, leading to the Miller indices $(1, 2, 4)$. In case (b), the reciprocals are $(1/10, 1/5, 0)$ with Miller indices $(1, 2, 0)$. In case (c), the plane is orthogonal to the $z$ axis, and the Miller indices simply are $(1, 0, 0)$. Finally, case (d) is similar to case (a) but with negative intercepts; according to the Miller notation we overline the indices rather than using a minus sign; we thus have $(\overline{1}, \overline{2}, 4)$.

### 1.2.2 The diamond, zinc-blende, and wurtzite semiconductor cells

The cubic diamond cell includes 8 atoms; in fact, if we consider Fig. 1.6, the corner atoms each contribute to eight adjacent cells, so that only $8/8 = 1$ atom belongs to the main cell. The atoms lying on the faces belong half to the main cell, half to the nearby ones, so that only $6/2 = 3$ atoms belong to the main cell. Finally, the other (internal) 4 atoms belong entirely to the cell. Therefore, the total number of atoms in a cell is $1 + 3 + 4 = 8$. In the diamond cell, each atom is connected to the neighbours through a tetrahedral bond. All atoms are the same (C, Si, Ge...) in the diamond lattice, while in the so-called *zinc-blende lattice* the atoms in the two fcc constituent lattices are different (GaAs, InP, SiC...). In particular, the corner and face atoms are metals (e.g., Ga) and the internal atoms are nonmetals (e.g., As), or vice versa.

In the diamond or zinc-blende lattices the Miller indices are conventionally defined with respect to the cubic cell of side $a$. Due to the symmetry of the tetrahedral atom bonds, planes (100) and (110), etc. have two bonds per side, while planes (111) have three bonds on the one side, two on the other. Moreover, the surface atom density is different, leading, for example, to different etch velocities.

Some semiconductors, such as SiC and GaN, have the hexagonal *wurtzite* crystal structure. Hexagonal lattices admit many *polytypes* according to the stacking of successive atom layers; a large number of polytypes exists, but only a few have interesting semiconductor properties (e.g. 4H and 6H for SiC). The wurtzite cell is shown in Fig. 1.7, including 12 equivalent atoms. In the ideal lattice, one has

$$|\underline{a}_3| = c, \quad |\underline{a}_1| = |\underline{a}_2| = a, \quad \frac{c}{a} = \sqrt{\frac{8}{3}} \approx 1.633.$$

Some properties of semiconductor lattices are shown in Table 1.2.[1] It can be noted that wurtzite-based semiconductors are often anisotropic (uniaxial) and have two dielectric constants, one parallel to the $c$-axis, the other orthogonal to it.

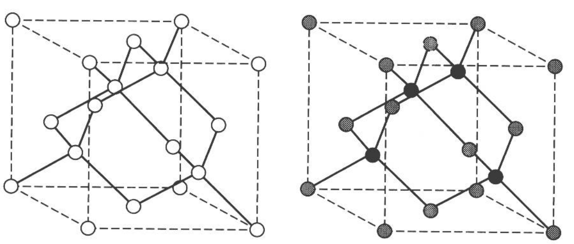

**Figure 1.6** The diamond (left) and zinc-blende (right) lattices.

[1] Semiconductor properties are well documented in many textbooks; an excellent online resource is provided by the Ioffe Institute of the Russian Academy of Sciences at the web site [1].