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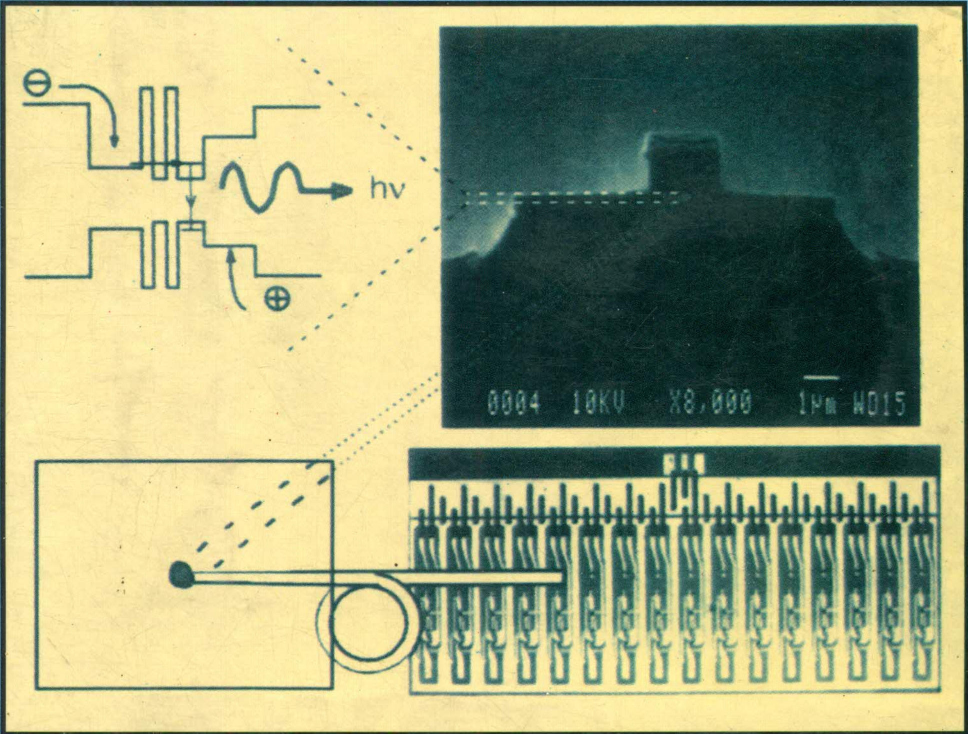
Semiconductor Optoelectronic Devices

Second Edition



PALLAB BHATTACHARYA

Semiconductor Optoelectronic Devices

Second Edition

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Dedicated to the cherished memory of my parents.

Preface

SCOPE AND PURPOSE

Knowledge of the relation between light and electricity has existed since the nineteenth century. However, widespread use of the interaction of light with electricity has become practical only within the last two decades. The advent and use of optoelectronic devices has occurred primarily due to the development of advanced semiconductor materials technology and the development of low-loss optical fibers. Optoelectronic devices convert light to electricity (detectors and solar cells) and electricity to light (emitters). These devices, together with optical fibers and light modulators, have helped to usher us into the information age. Optoelectronics, which combines the properties of light with the capabilities of microelectronics, is an essential enabling technology for the information age. In fact, it is said that optoelectronics may be the most significant new technology since semiconductors. Optoelectronic devices and circuits have unobtrusively and efficiently made their way into our daily lives. Telephone networks, laptop computers, remote controls, photography, imaging, bar code readers, compact discs, high-definition television, flat-panel displays, health care, and transportation are just a few examples. Stated differently, optoelectronics helps in the collection, transmission, storage, and display of information in the information age. It is hoped that this text, dedicated to the enormous progress in the field, will serve two main purposes:

1. to formally introduce senior-level undergraduate and graduate students to optoelectronics, thereby helping them to guide their studies and career developments; and

2. to provide, in an accessible textbook format, a good and well-focused reference/tutorial book for practicing engineers and physicists.

CHANGES IN THE SECOND EDITION

Even in the short time since the first edition was published, continued and rapid progress has been made in the field of optoelectronics. Vertical-cavity surface emitting lasers have near-zero threshold current, monolithically integrated photoreceivers now operate at bit rates higher than 20 Gbits/s, blue-emitting lasers using nitride-based heterostructures have been reported, true microcavity emitters are being made and tested, and lightwave networks operating at 10 Gbits/s or higher data rates are within reach. These rapid changes and the encouraging feedback received from students, fellow-scientists and reviewers of the first edition have motivated me to work on the second edition.

The present edition differs essentially from the first in the following respects.

Problems and Examples. The number of worked out examples and problems has been enhanced in every chapter to help the readers and instructors.

Additions in the Text. Two types of additions have been made in the present edition, to enhance readability and to enhance depth and breadth. Thus, in many instances explanations of materials and device phenomena have been expanded. At the same time new subjects have been added. Examples are nitrides and visible light emitters, a more detailed treatment of transient phenomena and linewidth of lasers, description of new types of modulators, more detailed treatment of distributed feedback lasers, surface-emitting lasers, avalanche and metal- semiconductor-metal photodiodes, photoreceivers and phototransistors, and description of new devices such as the quantum cascade laser and the tunneling injection laser.

Additional Appendices. A feature in the first edition that was viewed favorably was the use of Appendices as a vehicle for more rigorous treatment of selected subjects. This makes the text less intimidating to undergraduate students. Therefore, many of the additions mentioned previously have found their way into an expanded list of appendices in the present edition. There are 20 appendices in all.

New Chapter on Lightwave Networks. A new chapter on lightwave networks has been added to reflect the enormous progress in the field of fiber-optic communication and the use of optoelectronic devices for this application. The chapter begins with a brief description of optical fibers and describes components used in analog and digital transmission systems and wavelength division multiplexed networks.

Chapter Highlights. This feature has been added at the end of each chapter, not to serve as a table of contents, but to highlight new and attractive portions of the chapter.

Reading List. The list of reference texts has been updated and enhanced in almost every chapter.

List of Tables. This has been added in the beginning of the text.

PRESENTATION

The text has been developed at two levels to benefit both the seniors and graduate students. The book is intended to be self-sufficient and extensive reference work should not be necessary. A background of a first course in semiconductors is assumed.

The first four chapters lay the foundations for the optoelectronic devices. The first chapter describes compound semiconductor materials and their epitaxy. Much of the present-day device concepts would not be realized without sophisticated and matured epitaxial techniques. Semiconductor statistics and carrier transport properties are described in Chapter 2. The basic optical processes of absorption and recombination in bulk and quantum well structures are analyzed and described in Chapter 3. Here, detailed quantum mechanical calculations are excluded, since these are found in at least half-a-dozen texts. However, appropriate references are provided as footnotes. Chapter 4 describes junction theory, including metal-semiconductor junctions and heterojunctions. The case of high-level injection, which becomes important for laser operation, is emphasized in this chapter.

The devices themselves are described in Chapters 5–11 in the following order: light-emitting diodes, lasers, photodetectors, solar cells, and light-modulators. Lasers and photodetectors, which are perhaps the more important and common optoelectronic devices, are each described in two chapters. Optoelectronic integrated circuits (OEICs) are described in Chapter 12. Finally, the text is concluded in Chapter 13 with a review of lightwave networks, an emerging and important subject.

The principles of the devices and circuits are presented with appropriate analyses and derivations. Measurement techniques and recent experimental results are also included to give the reader a feel for real parameter values.

The organization of these chapters should provide the instructor the flexibility to present material to both undergraduate and graduate students. In discussing the different devices, I have introduced new concepts, within the scope of the text. For example, pseudomorphic materials, quantum wells, distributed-feedback, surface-emitting, visible and tunneling-based lasers, modulated barrier photodiodes, coherent and wavelength selective detection, quantum well modulation devices, and monolithically integrated transmitters and receivers are all described and analyzed in various levels of detail.

HOW TO USE THIS BOOK

This book is flexible and can be adapted to your local curriculum and course needs. An example of a one-term senior undergraduate course that could be taught from the book would cover Chapters 1, 2, and 4 as review; Chapters 3, 5, 6, part of 7, 8, and parts of 11 and 12 should be treated as essential; and Chapter 10 could be treated as optional. The rest of Chapters 7, 11, and 12, and Chapters 9 and 13 I consider advanced material that you can teach in a graduate level course or material that you can choose from selectively to tailor the course to your desired emphasis and objectives. Again, the appendices enhance the flexibility in the use of this text. For example, an undergraduate course could omit the use of most of the appendices while graduate and research students would benefit from the rigorous derivations therein.

READING LIST AND PROBLEMS

Suggested texts for more extensive reading and key articles from journals and periodicals are listed at the end of each chapter and as footnotes. These will help the more inquisitive students to go beyond the confines of the text and course and to enhance their knowledge and understanding. Also included are a set of problems at the end of each chapter, in addition to worked-out examples. The purpose of these problems is twofold:

1. to enhance the understanding of the different devices and underlying concepts; and
2. to get a feel for practical values of different device and material parameters and their units.

UNITS

The rationalized MKS system of units has been mostly followed, with convenient changes. For example, cm is more often used as the unit of length, and the electron volt (eV) is used in place of joule (J) as the unit of energy. The cgs system is sometimes used to keep in line with common use.

ACKNOWLEDGMENTS

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I would like to thank again my professional colleagues who have generously contributed data and photographs. They are J. Goldman (RIBER SA) and Drs. G. A. Antypas (Crystacomm Inc.), S. N. G. Chu (AT&T Bell Laboratories), I. Hayashi (Optoelectronics Technology Research Laboratory), J. L. Jewell (Photonics Research Incorporated), J. Loehr (Wright Laboratories, WPAFB), D. A. B. Miller (AT&T Bell Laboratories), D. Pooladdej (Laser Diode, Inc.), R. Sahai (Rockwell International), J. Singh (University of Michigan), S. Swirhun (Bandgap Technology Corporation), W. T. Tsang (AT&T Bell Laboratories), O. Wada (Fujitsu Limited), I. Weinberg (NASA, Lewis Research Center), and E. Woelk (AIXTRON GmbH).

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Ultimately, it is the encouragement, understanding, and support of my family which provided me the courage to embark on this project.

Pallab Bhattacharya
Ann Arbor, Michigan

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About the Author

PALLAB BHATTACHARYA is Professor of Electrical Engineering and Computer Science and Director of the Solid State Electronics Laboratory at the University of Michigan, Ann Arbor. His teaching and research interests include liquid-phase and molecular beam epitaxy of elemental and III-V compound semiconductors, materials characterization, electronic and optoelectronic devices and optoelectronic integrated circuits. He received the Ph.D. degree from the University of Sheffield, United Kingdom (1978) and was on the faculty of Oregon State University (1978–1983). Since 1983 he has been at the University of Michigan. He was Invited Professor at the Ecole Polytechnique Federale de Lausanne, Switzerland, during 1981–1982. He has published over 250 technical articles in archival journals. He received the Parker Rhodes Scholarship at the University of Sheffield, the L.L. Stewart Faculty Development Award at Oregon State University and the Research Excellence Award at the University of Michigan. He was elected Fellow of IEEE in 1988. He is Editor of *IEEE Transactions of Electron Devices* and has edited *Properties of Lattice-Matched and Strained InGaAs* (INSPEC, UK, 1993) and *Properties of III-V Quantum Wells and Superlattices* (INSPEC, UK, 1996). He has served on the Advisory Board of the Electrical and Communications Systems Division at the National Science Foundation. He has also served on several other committees and panels in academia, government, industry and technical conferences.

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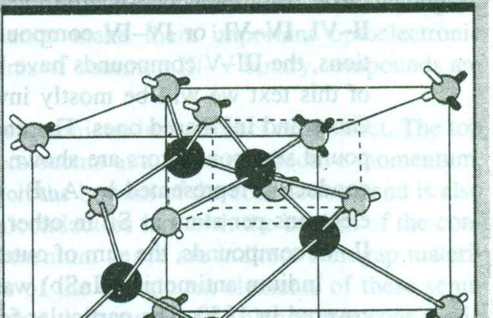
Elemental and Compound Semiconductors

Chapter Contents



1.1 INTRODUCTION

Optoelectronics deals with the interaction of electronic processes with light and optical processes. Devices in which such interaction can suitably take place, usually accompanied by an energy conversion process (e.g., from electrical to optical, and vice versa), are called optoelectronic devices. Such devices are conveniently made with semiconductors, and this text is devoted to the understanding of the principles of semiconductor optoelectronic devices and the properties of materials with which they can be made. Research and development of optoelectronic devices and optoelectronic integrated circuits have received a tremendous boost with the development of low-loss optical fibers for long distance communication. These devices and circuits now play an important role in our daily lives. The optoelectronics market is projected to grow at an annual rate of 9–10%.

Although the elemental semiconductors, and in particular Si, have been very useful for the development of microelectronics, they have some important drawbacks. The fundamental bandgap of these semiconductors is indirect. This implies that they emit light very poorly and their absorption coefficients are low. As a solar energy converter Si is technologically good, but because of its small energy gap the conversion efficiency is low. It became clear that Si, considered by many as a universal semiconductor material, cannot perform many important functions. For optoelectronic applications, in particular, it was natural then to turn to other materials. It turned out that compound semiconductor materials offered many of the desired properties and could be synthesized without much difficulty. Compound semiconductors, as the name suggests, are made from elements of different columns of the periodic table. Examples are III–V, II–VI, IV–VI, or IV–IV compounds. Historically, for optoelectronic device applications, the III–V compounds have been the first and most widely used. For the purpose of this text we will be mostly involved with III–V compounds, and in particular the GaAs and InP-based ones. The energy band diagrams of common elemental and compound semiconductors are shown in Fig. 1.1. It may be noted that a compound semiconductor, represented by $A_{III}B_{V}$ or $C_{II}D_{VI}$, has the same average number of valence electrons per atom as Si. In other words Si has four valence electrons and in III–V or II–VI compounds, the sum of outer electrons is eight.

Indium antimonide (InSb) was the first III–V compound semiconductor to be discovered in 1950. The particular features of this compound that attracted interest were the ease with which it could be synthesized, the electron mobility, and the ionic component in the crystal binding. These properties are still of immense interest, and as advanced epitaxial techniques are being developed, the purity of the crystals continues to improve. Furthermore, because of its low bandgap, $\mathcal{E}_g = 0.17$ eV, InSb has become important for the development of far infrared detector technology. Two important events, the invention of the semiconductor laser and the discovery of the Gunn effect, turned the interest to other III–V compounds such as GaAs ($\mathcal{E}_g = 1.43$ eV) and InP ($\mathcal{E}_g = 1.35$ eV). The next in order of importance is GaP, which has its bandgap (2.1 eV) in the visible part of the spectrum and therefore became important for the development of the light-emitting diode (LED). It may be noted that the bandgap of GaP is indirect, but by certain doping techniques, which we shall learn about in Chapter 5, it is possible to improve the radiative efficiency. Compared to Si and Ge, GaAs

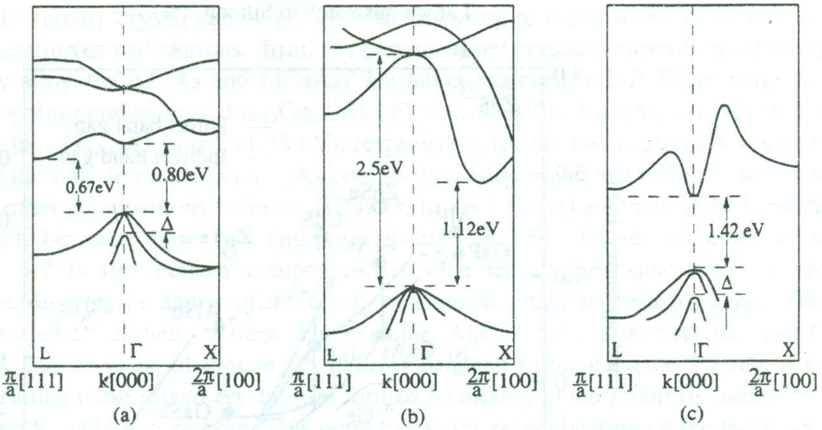


Figure 1.1 Diagrams showing the variations of electron energy with wave number (momentum) in (a) Ge, (b) Si, and (c) GaAs along the [100] and [111] directions in *k* space. Electrons are located near the minimum of the conduction band, whereas holes are located near the maximum of the valence band. The band structures of Ge and Si are examples of indirect-gap semiconductors, whereas that of GaAs represents a direct bandgap semiconductor. Δ is the spin-orbit splitting (from S. Wang, *Fundamentals of Semiconductor Theory and Device Physics*, Prentice Hall, Englewood Cliffs, NJ, 1989).

and InP have high electron mobilities and velocities, properties that are extremely important for the development of high-speed electronic devices. Their direct bandgaps and the consequent high radiative efficiency make them important optoelectronic materials. The bandgaps and lattice constants of common III–V binary compounds are depicted in Fig. 1.2.

It is instructive to find out what makes a semiconductor direct or indirect. The top of the valence band of most semiconductors occurs at a value of effective momentum, or *k*, equal to zero. Semiconductors in which the bottom of the conduction band is also at $k = 0$ are direct bandgap materials. Semiconductors in which the bottom of the conduction band occurs at other points in momentum space are indirect bandgap materials. It is evident from the atomic structure of the constituent elements of these semiconductors, described in the next section, that their outermost valence electrons are in s- or p-type orbitals. Although true only for elements in their atomic form, the s- or p-like character is also retained in the crystalline semiconductors. The bands of a semiconductor are a result of the crystal potential that originates from the equilibrium arrangement of atoms in the lattice. If the edge of the conduction band is made up of s-type states, the semiconductor is direct bandgap. If, on the other hand, the lowest conduction band edge is made up of p-type states, then the semiconductor is indirect bandgap.

An attractive feature of the binary compounds is that they can be combined or *alloyed* to form *ternary* or *quaternary* compounds, or *mixed crystals*. These compounds are made up of three or four group III and group V atoms and are indicated by the tie lines between the binary compounds in Fig. 1.2. Note that by choosing different binary compounds, it is possible to select different bandgaps, and therefore varying

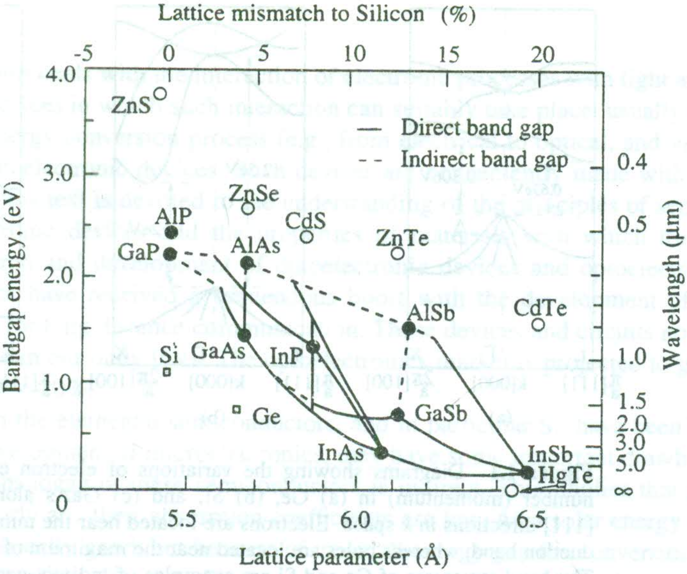


Figure 1.2 Energy bandgap versus lattice constant for common elemental and compound semiconductors. The tie lines joining the binaries represent ternary compositions. The dashed lines represent indirect bandgap material. The vertical dashed line passing through the point representing InP contains the bandgaps for the lattice-matched InGaAlAs and InGaAsP quaternary systems.

emission energies for light sources. However, by alloying it is possible to vary the bandgap *continuously* and monotonically, and together with it the bandstructure, electronic, and optical properties. The formation of ternary and quaternary compounds of varying bandgaps also enables the formation of heterojunctions, which have become essential for the design of high-performance electronic and optoelectronic devices. As an example, the bandgap of the ternary compound $Al_xGa_{1-x}As$ $(0 \leq x \leq 1)$ depends on the mole fraction x of AlAs in the solid solution and changes continuously from 1.43 eV (GaAs, $x = 0$) to 2.1 eV (AlAs, $x = 1$). As we shall see later, the bandstructure, electronic, and optical properties of the mixed crystal also change with change in alloy composition, and these are exploited in the design of electronic and optoelectronic devices. Among the common GaAs and InP-based ternary and quaternary compounds, the properties of $Al_xGa_{1-x}As$ have been most thoroughly investigated. Other important ternary and quaternary compounds are $GaAs_{1-x}P_x$, $In_{1-x}Ga_xP$, $In_xGa_yAl_{1-x-y}As$, and $In_{1-x}Ga_xAs_yP_{1-y}$. The last two are usually grown on InP substrates. The bandgaps and lattice constants of these compounds can be found from the tie lines in Fig. 1.2. The quaternary compounds mentioned above have emerged as being extremely important for optical communication, since their bandgaps correspond to the spectral window in which silica fibers have their lowest loss and dispersion. Several important observations may be made from Fig. 1.2. First, it may be noted that the lattice constants of GaAs (5.6532 Å) and AlAs (5.6611 Å) are almost identical. This implies that all the mixed crystal compositions of $Al_xGa_{1-x}As$ can be grown *lattice-matched* on GaAs substrates. We shall soon see in Sec. 1.5 that this is very useful because any thickness of the ternary crystal can be grown without having to worry about strain effects or the generation of dislocations. Similarly certain mixed crystal compositions of the quaternary alloys InGaAlAs and InGaAsP are lattice-matched to InP. These range from the end-point compositions $In_{0.53}Ga_{0.47}As$ ($\mathcal{E}_g = 0.74$ eV) to $In_{0.52}Al_{0.48}As$ ($\mathcal{E}_g = 1.45$ eV) and $In_{0.53}Ga_{0.47}As$ to InP (1.35 eV), respectively, for the two quaternary systems. Note that the only ternary $In_xGa_{1-x}As$ composition lattice-matched to InP is with $x = 0.53$. All other compositions from $x = 0$ (GaAs) to $x = 1$ (InAs) are mismatched and the mismatch between these two end-point binaries is 7%. The second point to note in Fig. 1.2 is that certain compositions of the ternary and quaternary compounds, depending on the nature of the binary constituents, have indirect bandgaps. These are indicated by dashed tie lines. For example, $Al_xGa_{1-x}As$ is indirect bandgap for $x \geq 0.43$ and AlAs is, of course, an indirect bandgap semiconductor. Finally, it may be noted that these mixed crystals are formed by mixing in the group III sublattice, or the group V sublattice, or both. This point has an important bearing on the techniques used to grow them.

Many physical parameters of ternary compounds are determined by the parameters of the constituent binaries and vary roughly linearly with composition. For example, the lattice constant, a, of $In_xGa_{1-x}As$ is given by Vegard's law as

$$a_{In_xGa_{1-x}As} = xa_{InAs} + (1-x)a_{GaAs} \tag{1.1}$$

Similarly, for a quarternary compound $A_{1-x}B_xC_yD_{1-y}$, a material parameter Q can be expressed as

$$\begin{aligned} Q(x,y) = \{&x(1-x)[(1-y)T_{12}(x) + yT_{43}(x)] \\ &+ y(1-y)[(1-x)T_{14}(y) + xT_{23}(y)]\} \\ &[x(1-x) + y(1-y)]^{-1} \end{aligned} \tag{1.2}$$

where T_{ij} is the material parameter for the ternary alloy formed by binaries i and j. The relevant parameters of GaAs and $In_{0.53}Ga_{0.47}As$ together with those for Si, for the purpose of comparison, are listed in Appendix 1.

1.2 BONDING IN SOLIDS

In the *solid state*, also referred to as *condensed matter*, the atoms forming the solid are held together by bonding forces. The atoms also maintain a finite, fixed distance from each other. If the array of atoms have long-range order or *periodicity*, the resulting solid is crystalline, and we will study the properties of crystals in the next section. The periodic array of atoms leads the way to the energy band models and conduction properties. However, before going into all that, we should understand the nature of the forces that hold the atoms together in their equilibrium positions. There are in general two types of forces, attractive and repulsive, which are both functions of the interatomic distance z. At large distances the attractive forces dominate, and therefore the atoms are drawn nearer to each other. At small interatomic distances the repulsive forces dominate, and the atoms are pushed further apart. In equilibrium the forces of attraction $F_A(z)$, and repulsion, $F_R(z)$, must balance to establish the equilibrium atomic spacing. In other words: