Optoelectronics is a practical and self-contained graduate-level textbook and reference, which will be of great value to both students and practising engineers in the field. Sophisticated concepts are introduced by the authors in a clear and coherent way, including such topics as quantum mechanics of electron–photon interaction, quantization of the electromagnetic field, semiconductor properties, quantum theory of heterostructures, and non-linear optics. The book builds on these concepts to describe the physics, properties, and performances of the main optoelectronic devices: light emitting diodes, quantum well lasers, photodetectors, optical parametric oscillators, and waveguides. Emphasis is placed on the unifying theoretical analogies of optoelectronics, such as equivalence of quantization in heterostructure wells and waveguide modes, entanglement of blackbody radiation and semiconductor statistics. The book concludes by presenting the latest devices, including vertical surface emitting lasers, quantum well infrared photodetectors, quantum cascade lasers, and optical frequency converters.
Optoelectronics

Emmanuel Rosencher
Research Director
French Aerospace Research Agency (ONERA, France)
Professor at the Ecole Polytechnique (Paris, France)

Borge Vinter
Senior Scientist
THALES Research and Technology

Translated by Dr Paul G. Piva
For Nadia, Anne, Julien, and Clara, for their patience with all my love.

For Nadia who understands so many other things.
Contents

Preface xv
Properties of common semiconductors xvii

1 Quantum mechanics of the electron 1

1.1 Introduction 1
1.2 The postulates of quantum mechanics 1
1.3 The time-independent Schrödinger equation 6
  1.3.1 Stationary states 6
  1.3.2 Calculation of stationary states in a one-dimensional potential 7
1.4 The quantum well 8
  1.4.1 The general case 8
  1.4.2 The infinite square well 14
1.5 Time-independent perturbation theory 15
1.6 Time-dependent perturbations and transition probabilities 18
  1.6.1 The general case 18
  1.6.2 Sinusoidal perturbation 20
1.7 The density matrix 23
  1.7.1 Pure quantum ensembles 24
  1.7.2 Mixed quantum ensembles 24
  1.7.3 Density matrix and relaxation time for a two-level system 26

Complement to Chapter 1 29

1.A Problems posed by continuums: the fictitious quantum box and the density of states 29
1.B Perturbation on a degenerate state 33
1.C The quantum confined Stark effect 37
1.D The harmonic oscillator 41
1.E Transition probabilities and Rabi oscillations 50
<table>
<thead>
<tr>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2 Quantum mechanics of the photon</strong></td>
</tr>
<tr>
<td>2.1 Introduction</td>
</tr>
<tr>
<td>2.2 Maxwell’s equations in reciprocal space</td>
</tr>
<tr>
<td>2.3 Properties of the Fourier transform</td>
</tr>
<tr>
<td>2.4 Quantization of electromagnetic waves</td>
</tr>
<tr>
<td>2.5 The photon</td>
</tr>
<tr>
<td>2.6 The coherent state</td>
</tr>
<tr>
<td>2.7 Blackbody radiation</td>
</tr>
<tr>
<td><strong>Complement to Chapter 2</strong></td>
</tr>
<tr>
<td>2.A Radiation field for an oscillating charge: the Lorentz gauge</td>
</tr>
<tr>
<td>2.B Thermography</td>
</tr>
<tr>
<td><strong>3 Quantum mechanics of electron–photon interaction</strong></td>
</tr>
<tr>
<td>3.1 Introduction</td>
</tr>
<tr>
<td>3.2 Dipolar interaction Hamiltonian for electrons and photons</td>
</tr>
<tr>
<td>3.3 Linear optical susceptibility obtained by the density matrix</td>
</tr>
<tr>
<td>3.4 Linear optical susceptibility: absorption and optical gain</td>
</tr>
<tr>
<td>3.5 The rate equations</td>
</tr>
<tr>
<td>3.5.1 Adiabatic approximation and corpuscular interpretation</td>
</tr>
<tr>
<td>3.5.2 Stimulated emission</td>
</tr>
<tr>
<td>3.5.3 Absorption saturation</td>
</tr>
<tr>
<td>3.6 Spontaneous emission and radiative lifetime</td>
</tr>
<tr>
<td>3.6.1 Spontaneous emission</td>
</tr>
<tr>
<td>3.6.2 The rate equations including spontaneous emission</td>
</tr>
<tr>
<td>3.7 Polychromatic transitions and Einstein’s equations</td>
</tr>
<tr>
<td>3.8 Rate equations revisited</td>
</tr>
<tr>
<td>3.8.1 Monochromatic single-mode waves</td>
</tr>
<tr>
<td>3.8.2 Multimode monochromatic waves</td>
</tr>
<tr>
<td>3.8.3 Polychromatic waves</td>
</tr>
<tr>
<td><strong>Complement to Chapter 3</strong></td>
</tr>
<tr>
<td>3.A Homogeneous and inhomogeneous broadening: coherence of light</td>
</tr>
<tr>
<td>3.A.1 Homogeneous broadening</td>
</tr>
<tr>
<td>3.A.2 Inhomogeneous broadening</td>
</tr>
<tr>
<td>3.B Second-order time-dependent perturbations</td>
</tr>
</tbody>
</table>
3.C Einstein coefficients in two limiting cases: quasi-monochromatic and broadband optical transitions

3.D Equivalence of the $\mathbf{A} \cdot \mathbf{p}$ and $\mathbf{D} \cdot \mathbf{E}$ Hamiltonians and the Thomas–Reiche–Kuhn sum rule

4 Laser oscillations

4.1 Introduction

4.2 Population inversion and optical amplification
  4.2.1 Population inversion
  4.2.2 Optical amplification and gain saturation

4.3 Three- and four-level systems

4.4 Optical resonators and laser threshold

4.5 Laser characteristics
  4.5.1 Internal laser characteristics and gain clamping
  4.5.2 Output power
  4.5.3 Spectral characteristics

4.6 Cavity rate equations and the dynamic behaviour of lasers
  4.6.1 Damped oscillations
  4.6.2 Laser cavity dumping by loss modulation ($Q$-switching)
  4.6.3 Mode locking

Complement to Chapter 4

4.A The effect of spontaneous emission and photon condensation

4.B Saturation in laser amplifiers

4.C Electrodynamic laser equations: electromagnetic foundations for mode locking

4.D The Schawlow–Townes limit and Langevin-noise force

4.E A case study: diode pumped lasers

5 Semiconductor band structure

5.1 Introduction

5.2 Crystal structures, Bloch functions, and the Brillouin zone

5.3 Energy bands

5.4 Effective mass and density of states

5.5 Dynamic interpretation of effective mass and the concept of holes
## Contents

5.6 Carrier statistics in semiconductors  
5.6.1 Fermi statistics and the Fermi level  
5.6.2 Intrinsic semiconductors  
5.6.3 Doped semiconductors  
5.6.4 Quasi-Fermi level in a non-equilibrium system

Complement to Chapter 5

5.A The nearly free electron model  
5.B Linear combination of atomic orbitals: the tight binding model  
5.C Kane's $k \cdot p$ method  
5.D Deep defects in semiconductors

6 Electronic properties of semiconductors

6.1 Introduction  
6.2 Boltzmann's equation  
6.3 Scattering mechanisms  
6.4 Hot electrons  
6.4.1 Warm electrons  
6.4.2 Hot electrons: saturation velocity  
6.4.3 Hot electrons: negative differential velocity  
6.5 Recombination  
6.6 Transport equations in a semiconductor

Complement to Chapter 6

6.A The Hall effect  
6.B Optical phonons and the Fröhlich interaction  
6.B.1 Phonons  
6.B.2 The Fröhlich interaction  
6.C Avalanche breakdown  
6.D Auger recombination

7 Optical properties of semiconductors

7.1 Introduction  
7.2 Dipolar elements in direct gap semiconductors  
7.3 Optical susceptibility of a semiconductor  
7.4 Absorption and spontaneous emission
### Contents

#### 7  
**Bimolecular recombination coefficient**  313  
**Conditions for optical amplification in semiconductors**  316

**Complement to Chapter 7**

- **7.A** The Franz–Keldysh-effect electromodulator  321  
- **7.B** Optical index of semiconductors  328  
  - **7.B.1** Mid- and far-infrared regions  329  
  - **7.B.2** Near gap regime  330  
- **7.C** Free-carrier absorption  333

#### 8  
**Semiconductor heterostructures and quantum wells**  342

- **8.1** Introduction  342  
- **8.2** Envelope function formalism  344  
- **8.3** The quantum well  350  
- **8.4** Density of states and statistics in a quantum well  354  
- **8.5** Optical interband transitions in a quantum well  358  
  - **8.5.1** Hole states in the valence bands  358  
  - **8.5.2** Optical transitions between the valence and conduction bands  359  
- **8.6** Optical intersubband transitions in a quantum well  365  
- **8.7** Optical absorption and angle of incidence  369  
  - **8.7.1** Summary for interband and intersubband transition rates  369  
  - **8.7.2** Influence of the angle of incidence  370

**Complement to Chapter 8**

- **8.A** Quantum wires and boxes  377  
- **8.B** Excitons  380  
  - **8.B.1** Three-dimensional excitons  381  
  - **8.B.2** Two-dimensional excitons  385  
- **8.C** Quantum confined Stark effect and the SEED electromodulator  388  
- **8.D** Valence subbands  392

#### 9  
**Waveguides**  396

- **9.1** Introduction  396  
- **9.2** A geometrical approach to waveguides  396  
- **9.3** An oscillatory approach to waveguides  400  
- **9.4** Optical confinement  407
## Contents

### Chapter 9

9.5 Interaction between guided modes: coupled mode theory 410

**Complement to Chapter 9**

9.A Optical coupling between guides: electro-optic switches 414
9.B Bragg waveguides 421
9.C Frequency conversion in non-linear waveguides 427
  9.C.1 TE mode in–TE mode out 427
  9.C.2 TE mode in–TM mode out 432
9.D Fabry–Pérot cavities and Bragg reflectors 434
  9.D.1 The Fabry–Pérot cavity 437
  9.D.2 Bragg mirrors 442

### Chapter 10

10 Elements of device physics 447

10.1 Introduction 447
10.2 Surface phenomena 448
10.3 The Schottky junction 451
10.4 The p–n junction 456

**Complement to Chapter 10**

10.A A few variants of the diode 466
  10.A.1 p–n heterojunction diode 466
  10.A.2 The p–i–n diode 467
10.B Diode leakage current 470

### Chapter 11

11 Semiconductor photodetectors 475

11.1 Introduction 475
11.2 Distribution of carriers in a photoexcited semiconductor 475
11.3 Photoconductors 481
  11.3.1 Photoconduction gain 481
  11.3.2 Photoconductor detectivity 484
  11.3.3 Time response of a photoconductor 486
11.4 Photovoltaic detectors 488
  11.4.1 Photodiode detectivity 492
  11.4.2 Time response of a photodiode 494
11.5 Internal emission photodetector 497
11.6 Quantum well photodetectors (QWIPs) 500
11.7 Avalanche photodetectors 509
<table>
<thead>
<tr>
<th>Chapter 11: Detector noise</th>
<th>513</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.A Detector noise</td>
<td>513</td>
</tr>
<tr>
<td>11.A.1 Fluctuations</td>
<td>514</td>
</tr>
<tr>
<td>11.A.2 Physical origin of noise</td>
<td>518</td>
</tr>
<tr>
<td>11.A.3 Thermal noise</td>
<td>518</td>
</tr>
<tr>
<td>11.A.4 Generation–recombination noise</td>
<td>521</td>
</tr>
<tr>
<td>11.A.5 Multiplication noise</td>
<td>525</td>
</tr>
<tr>
<td>11.B Detectivity limits: performance limits due to background (BLIP)</td>
<td>530</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 12: Optical frequency conversion</th>
<th>538</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.1 Introduction</td>
<td>538</td>
</tr>
<tr>
<td>12.2 A mechanical description for second harmonic frequency generation</td>
<td>538</td>
</tr>
<tr>
<td>12.3 An electromagnetic description of quadratic non-linear optical interaction</td>
<td>543</td>
</tr>
<tr>
<td>12.4 Optical second harmonic generation</td>
<td>546</td>
</tr>
<tr>
<td>12.5 Manley–Rowe relations</td>
<td>550</td>
</tr>
<tr>
<td>12.6 Parametric amplification</td>
<td>551</td>
</tr>
<tr>
<td>12.7 Optical parametric oscillators (OPOs)</td>
<td>554</td>
</tr>
<tr>
<td>12.7.1 Simply resonant optical parametric oscillators (SROPOs)</td>
<td>554</td>
</tr>
<tr>
<td>12.7.2 Doubly resonant optical parametric oscillator (DROPO)</td>
<td>557</td>
</tr>
<tr>
<td>12.8 Sum frequency, difference frequency, and parametric oscillation</td>
<td>560</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Complement to Chapter 11</th>
<th>565</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.A A quantum model for quadratic non-linear susceptibility</td>
<td>565</td>
</tr>
<tr>
<td>12.B Methods for achieving phase matching in semiconductors</td>
<td>572</td>
</tr>
<tr>
<td>12.B.1 Birefringent phase matching</td>
<td>573</td>
</tr>
<tr>
<td>12.B.2 Quasi-phase matching</td>
<td>579</td>
</tr>
<tr>
<td>12.C Pump depletion in parametric interactions</td>
<td>582</td>
</tr>
<tr>
<td>12.D Spectral and temporal characteristics of optical parametric oscillators</td>
<td>587</td>
</tr>
<tr>
<td>12.E Parametric interactions in laser cavities</td>
<td>596</td>
</tr>
<tr>
<td>12.F Continuous wave optical parametric oscillator characteristics</td>
<td>602</td>
</tr>
<tr>
<td>12.F.1 Singly resonant OPO</td>
<td>603</td>
</tr>
<tr>
<td>12.F.2 Doubly resonant OPO: the balanced DROPO</td>
<td>608</td>
</tr>
<tr>
<td>12.F.3 Doubly resonant OPO: the general case</td>
<td>610</td>
</tr>
</tbody>
</table>
13 Light emitting diodes and laser diodes

13.1 Introduction 613
13.2 Electrical injection and non-equilibrium carrier densities 613
13.3 Electroluminescent diodes 617
13.3.1 Electroluminescence 617
13.3.2 Internal and external efficiencies for LEDs 619
13.3.3 A few device issues 623
13.4 Optical amplification in heterojunction diodes 624
13.5 Double heterojunction laser diodes 629
13.5.1 Laser threshold 629
13.5.2 Output power 634
13.6 Quantum well laser diodes 637
13.6.1 Optical amplification in a quantum well structure: general case 637
13.6.2 Transparency threshold 641
13.6.3 Laser threshold for a quantum well laser 647
13.6.4 Scaling rule for multi-quantum well lasers 649
13.7 Dynamic aspects of laser diodes 652
13.8 Characteristics of laser diode emission 655
13.8.1 Spectral distribution 655
13.8.2 Spatial distribution 656

Complement to Chapter 13 660

13.A Distributed feedback (DFB) lasers 660
13.B Strained quantum well lasers 665
13.C Vertical cavity surface emitting lasers (VCSELs) 671
13.C.1 Conditions for achieving threshold in a VCSEL 671
13.C.2 VCSEL performance 675
13.D Thermal aspects of laser diodes and high power devices 676
13.E Spontaneous emission in semiconductor lasers 683
13.F Gain saturation and the $K$ factor 690
13.G Laser diode noise and linewidth 696
13.G.1 Linewidth broadening 700
13.G.2 Relative intensity noise (RIN) and optical link budget 701
13.H Unipolar quantum cascade lasers 704
13.I Mode competition: cross gain modulators 708

Index 713
Preface

The field of optoelectronics is currently in full expansion, drawing to its classrooms and laboratories numerous science and engineering students eager to master the discipline. From the lecturer's perspective, optoelectronics is a considerable challenge to teach as it emerges from a complex interplay of separate and often seemingly disjointed subjects such as quantum optics, semiconductor band structure, or the physics of carrier transport in electronic devices. As a result, the student (or lecturer) is left to navigate through a vast literature, often found to be confusing and incoherent.

The aim of this text is to teach optoelectronics as a science in itself. To do so, a tailored presentation of its various sub-disciplines is required, emphasizing within each of these, those concepts which are key to the study of optoelectronics. Also, we were determined to offer a partial description of quantum mechanics oriented towards its application in optoelectronics. We have therefore limited ourselves to a utilitarian treatment without elaborating on many fundamental concepts such as electron spin or spherical harmonic solutions to the hydrogen atom. On the other hand, we have placed emphasis on developing formalisms such as those involved in the quantization of the electromagnetic field (well suited to a discussion of spontaneous emission), or the density matrix formalism (of value in treating problems in non-linear optics).

Similarly, our treatment of semiconductor physics ignores any discussion of the effect of the crystallographic structure in these materials. Rather, a priori use is made of the semiconductor band structures which implicitly incorporate these effects on the electrical and optical properties of these materials. In carrying out our rather utilitarian-minded presentation of these disciplines, we have claimed as ours Erwin Schrödinger's maxim that it mattered little whether his theory be an exact description of reality insofar as it proved itself useful.

We have sought in this work to underline wherever possible the coherence of the concepts touched on in each of these different areas of physics, as it is from this vantage point that optoelectronics may be seen as a science in its own right. There exists, for instance, a profound parallel between the behaviour of an electron in a quantum well and that of an electromagnetic wave in an optical waveguide. As well, one finds between the photon statistics of black bodies, the mechanics of quantum transitions within semiconductor band structures and the statistics of...
charge carriers in these materials, an entanglement of concepts comprising the basis for infrared detection. In the same spirit, this work does not pretend to present an exhaustive list of all known optoelectronic devices. Such an effort could only come at the cost of the overall coherence aimed at in this work, and add to the type of confusion we have claimed as our enemy. The goal is rather to present those optoelectronic concepts which will allow an overall understanding of principles necessary in solving problems of a general or device-specific nature. Thus, only the analysis of generic classes of optoelectronic components will be undertaken here without entering into the labyrinth offered by more particular applications.

Lastly, regarding the problem of notation (a problem inherent to any multidisciplinary study), we have chosen simply to follow the lead of standard physics notation in any given chapter. Thus, the symbol \( \varepsilon \) may be used indiscriminately to represent the permittivity, the quantum confinement energy, or the saturation coefficient of a semiconductor laser. We could have attempted the introduction of various notations for each of these different uses based on the Latin, Greek, and Hebrew character sets, but we realized that even these would have soon been exhausted. We have thus chosen merely to redefine in each chapter the correspondence between the symbols and their respective notions.

The authors wish to thank all those having assisted with the preparation of this manuscript, such as Erwan LeCohec, Andrea Fiore, Arnaud Fily, Jean-Yves Duboz, Eric Costard, Florence Binet, Eric Herniou, Jean-Dominique Orwen, Anna Rakovska, and Anne Rosencher among many others. This work could never have seen the light of day without the support of ONERA and THALES (ex THOMSON-CSF) and most particularly the encouragement of Mr Pierre Tournois, formerly scientific director of THOMSON-CSF. Finally, the authors are deeply indebted to Paul Piva, whose translation from French to English reflects his competence, intelligence, and culture.
## Properties of common semiconductors

<table>
<thead>
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<th>Si</th>
<th>Ge</th>
<th>GaAs</th>
<th>AlAs</th>
<th>InAs</th>
<th>GaP</th>
<th>InP</th>
<th>GaSb</th>
<th>InSb</th>
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<tbody>
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<td><strong>Bandgap</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$E_g$ (eV) @ $T = 0$ K</td>
<td>indirect</td>
<td>indirect</td>
<td>direct</td>
<td>indirect</td>
<td>direct</td>
<td>indirect</td>
<td>direct</td>
<td>direct</td>
<td>direct</td>
</tr>
<tr>
<td>@ $T = 300$ K</td>
<td>1.170</td>
<td>0.744</td>
<td>1.519</td>
<td>2.229</td>
<td>0.418</td>
<td>2.350</td>
<td>1.424</td>
<td>0.236</td>
<td>0.18</td>
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<td>Lattice constant, $a_0$ Å</td>
<td>5.43095</td>
<td>5.64613</td>
<td>5.6533</td>
<td>5.6600</td>
<td>6.0583</td>
<td>5.4505</td>
<td>5.8688</td>
<td>6.096</td>
<td>6.4794</td>
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<tr>
<td>Relative permittivity, $\varepsilon_r/\varepsilon_0$</td>
<td>11.9</td>
<td>16.2</td>
<td>13.1</td>
<td>10.06</td>
<td>15.15</td>
<td>11.1</td>
<td>12.56</td>
<td>15.69</td>
<td>16.8</td>
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<tr>
<td><strong>Effective mass</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Electron longitudinal, $m_e/m_0$</td>
<td>0.9163</td>
<td>1.59</td>
<td>0.067</td>
<td>0.15(Γ)</td>
<td>0.023</td>
<td>0.254</td>
<td>0.073</td>
<td>0.047</td>
<td>0.014</td>
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<tr>
<td>Electron traverse, $m_\parallel/m_0$</td>
<td>0.1905</td>
<td>0.0823</td>
<td>4.8</td>
<td></td>
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<tr>
<td>Heavy hole, $m_{hh}/m_0$</td>
<td>0.537</td>
<td>0.284</td>
<td>0.50</td>
<td>0.79</td>
<td>0.40</td>
<td>0.67</td>
<td>0.60</td>
<td>0.8</td>
<td>0.42</td>
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<td>Light hole, $m_{lh}/m_0$</td>
<td>0.153</td>
<td>0.043</td>
<td>0.087</td>
<td>0.15</td>
<td>0.026</td>
<td>0.17</td>
<td>0.12</td>
<td>0.05</td>
<td>0.016</td>
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<td><strong>Luttinger parameters</strong></td>
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<tr>
<td>$g_1$</td>
<td>4.25</td>
<td>13.4</td>
<td>7.0</td>
<td>3.45</td>
<td>20.4</td>
<td>4.05</td>
<td>5.04</td>
<td>13.3</td>
<td>40.1</td>
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<tr>
<td>$g_2$</td>
<td>0.32</td>
<td>4.3</td>
<td>2.3</td>
<td>0.68</td>
<td>8.3</td>
<td>0.49</td>
<td>1.6</td>
<td>4.4</td>
<td>18.1</td>
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<td>$g_3$</td>
<td>1.45</td>
<td>5.7</td>
<td>2.9</td>
<td>1.3</td>
<td>9.1</td>
<td>1.25</td>
<td>2.4</td>
<td>6.2</td>
<td>19.2</td>
</tr>
<tr>
<td><strong>Intrinsic density</strong>, $n_i$ (cm$^{-3}$)</td>
<td>$1.5 \times 10^{10}$</td>
<td>$2.4 \times 10^{13}$</td>
<td>$1.8 \times 10^6$</td>
<td>$1.3 \times 10^{15}$</td>
<td>$3.0 \times 10^{6}$</td>
<td>$1.2 \times 10^{8}$</td>
<td>$4.3 \times 10^{12}$</td>
<td>$2.0 \times 10^{16}$</td>
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<tr>
<td><strong>Mobility</strong></td>
<td></td>
<td></td>
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<tr>
<td>Electron, $\mu_e$ (cm$^2$ Vs$^{-1}$)</td>
<td>1450</td>
<td>3900</td>
<td>8000</td>
<td>400</td>
<td>30 000</td>
<td>200</td>
<td>5000</td>
<td>5000</td>
<td>80 000</td>
</tr>
<tr>
<td>Hole, $\mu_h$ (cm$^2$ V$^{-1}$ s$^{-1}$)</td>
<td>370</td>
<td>1800</td>
<td>400</td>
<td>100</td>
<td>480</td>
<td>150</td>
<td>180</td>
<td>1500</td>
<td>1500</td>
</tr>
</tbody>
</table>

### Further reading

General references useful in obtaining values for semiconductor properties:


Recent review works: