

# Contents

|  |              |
|--|--------------|
| <b>PREFACE</b>                                   | <b>xx</b>    |
| <b>INTRODUCTION</b>                              | <b>xxiii</b> |
| I.1 THE INFORMATION AGE                          | xxiii        |
| .2 DEMANDS OF THE INFORMATION AGE                | xxiv         |
| .3 OPTOELECTRONICS: AN ENABLING TECHNOLOGY       | xxvii        |
| I.4 ELECTRONIC DEVICES: SOME CRACKS IN THE ARMOR | xxviii       |
| .5 THE PROMISE OF OPTICAL INFORMATION PROCESSING | xxix         |
| I.6 ROLE OF THIS BOOK                            | xxx          |

## 1 MATERIALS FOR OPTOELECTRONICS: STRUCTURAL PROPERTIES

|   |    |
|---|----|
| INTRODUCTION  | 2  |
| .2 STATES OF MATTER: ORDER  | 2  |
| 3 CRYSTALLINE MATERIALS   | 4  |
| 1.3.1 Periodicity of a crystal  | 6  |
| 1.3.2 Basic lattice types   | 7  |
| 1.3.3 The diamond and zinc blende structures                            | 9  |
| 1.3.4 Ferroelectric crystals  | 10 |
| 1.3.5 Notation to denote planes and points in a lattice: Miller indices | 12 |
| 1.3.6 Artificial structures: Superlattices and quantum wells            | 16 |

|      |                                   |    |
|------|-----------------------------------|----|
| 1.4  | INTERFACES                        | 18 |
| 1.5  | POLYCRYSTALLINE MATERIALS         | 19 |
| 1.6  | AMORPHOUS AND GLASSY MATERIALS    | 20 |
| 1.7  | LIQUID CRYSTALS                   | 23 |
| 1.8  | DEFECTS IN MATERIALS              | 27 |
| .9   | SCIENCE AND TECHNOLOGY CHALLENGES | 31 |
| 1.10 | CHAPTER SUMMARY                   | 33 |
|      | PROBLEMS                          | 34 |
|      | REFERENCES                        | 39 |

## 2 LIGHT PROPAGATION IN MEDIA 41

|       |   |    |
|-------|---|----|
| 2.1   | INTRODUCTION  | 42 |
| 2.2   | MAXWELL EQUATIONS AND THE WAVE EQUATION                 | 42 |
| 2.3   | POLARIZATION OF LIGHT                                   | 48 |
| 2.4   | FRESNEL FORMULAE: PROPAGATION ACROSS MEDIA              | 52 |
| 2.4.1 | Electric vector perpendicular to the plane of incidence | 52 |
| 2.4.2 | Magnetic vector perpendicular to the plane of incidence | 54 |
| 2.4.3 | Polarization effects: Brewster's law                    | 56 |
| 2.4.4 | Total internal reflection and evanescent fields         | 58 |
| 2.5   | WAVE PROPAGATION IN CRYSTALS                            | 62 |
| 2.6   | LIGHT MODULATION THROUGH POLARIZATION CONTROL           | 66 |
| 2.7   | CHAPTER SUMMARY   | 72 |
| 2.8   | PROBLEMS  | 75 |
| 2.9   | REFERENCES  | 77 |

|          |  |           |
|----------|--|-----------|
| <b>3</b> | <b>LIGHT PROPAGATION IN WAVEGUIDES</b>                     | <b>78</b> |
| 3.1      | INTRODUCTION   | 79        |
| 3.2      | WAVEGUIDES: SOME PHYSICAL PROPERTIES                       | 79        |
|          | 3.2.1 Some properties of optical fibers                    | 81        |
| 3.3      | PLANAR WAVEGUIDES: A GEOMETRICAL OPTICS STUDY              | 81        |
|          | 3.3.1 Guided modes in a planar waveguide                   | 86        |
| 3.4      | OPTICAL FIBERS: GEOMETRICAL OPTICS                         | 90        |
| 3.5      | POLARIZATION CONSTRAINTS IN WAVEGUIDES                     | 92        |
| 3.6      | GUIDED OPTICAL MODES IN PLANAR WAVEGUIDES                  | 94        |
|          | 3.6.1 Optical confinement factor                           | 99        |
| 3.7      | OPTICAL FIBERS: WAVE OPTICS                                | 101       |
| 3.8      | WAVEPACKET PROPAGATION:<br>DISPERSION AND GROUP VELOCITY   | 107       |
|          | 3.8.1 Motion of a wavepacket                               | 109       |
|          | 3.8.2 Waveguide dispersion                                 | 113       |
| 3.9      | LIGHT COUPLING DEVICES:<br>WAVEGUIDE-TO-WAVEGUIDE COUPLERS | 115       |
|          | 3.9.1 Coupled mode theory and the directional coupler      | 115       |
|          | 3.9.2 Planar-to-planar guide couplers                      | 118       |
|          | 3.9.3 Planar-to-linear guide couplers                      | 120       |
|          | 3.9.4 Waveguide to fiber couplers                          | 121       |
| 3.10     | BEAM-WAVEGUIDE COUPLERS                                    | 122       |
|          | 3.10.1 Transverse coupler                                  | 122       |
|          | 3.10.2 The prism coupler                                   | 122       |
|          | 3.10.3 The grating coupler                                 | 125       |
| 3.11     | CHAPTER SUMMARY  | 126       |
| 3.12     | PROBLEMS   | 126       |
| 3.13     | REFERENCES   | 130       |

|  |            |
|--|------------|
| <b>4 ELECTRONIC PROPERTIES<br/>OF SEMICONDUCTORS</b>                 | <b>131</b> |
| 4.1 INTRODUCTION   | 132        |
| 4.2 ELECTRONS IN A PERIODIC POTENTIAL:<br>BLOCH THEOREM              | 132        |
| 4.2.1 From atomic levels to bands                                    | 133        |
| 4.2.2 The crystal momentum   | 135        |
| 4.3 CONDUCTION AND VALENCE BANDEDGES<br>IN SEMICONDUCTORS            | 136        |
| 4.3.1 Density of states  | 141        |
| 4.4 HOLES IN SEMICONDUCTORS  | 145        |
| 4.5 BANDSTRUCTURES OF SOME SEMICONDUCTORS                            | 146        |
| 4.6 MODIFICATION OF BANDSTRUCTURE BY ALLOYING                        | 148        |
| 4.7 BANDSTRUCTURE MODIFICATION BY HETEROSTRUCTURES:<br>QUANTUM WELLS | 151        |
| INTRINSIC CARRIER CONCENTRATION                                      | 155        |
| 4.9 DEFECT LEVELS IN SEMICONDUCTORS                                  | 158        |
| DOPING IN SEMICONDUCTORS   | 161        |
| 4.10.1 Heavily-doped semiconductors                                  | 164        |
| 4.10.2 Modulation doping   | 165        |
| BANDSTRUCTURE OF AMORPHOUS SEMICONDUCTORS                            | 166        |
| 4.11.1 Extended and localized states: Mobility edges                 | 167        |
| 4.12 CHAPTER SUMMARY   | 169        |
| 4.14 PROBLEMS  | 173        |
| REFERENCES   | 176        |

|          |   |            |
|----------|---|------------|
| <b>5</b> | <b>TRANSPORT AND OPTICAL PROPERTIES OF SEMICONDUCTORS</b>             | <b>177</b> |
| 5.1      | INTRODUCTION  | 178        |
| 5.2      | QUANTUM MECHANICS OF SCATTERING PROCESSES                             | 178        |
| 5.2.1    | The perturbation  | 180        |
| 5.3      | TRANSPORT PROPERTIES OF SEMICONDUCTORS:<br>DRIFT IN AN ELECTRIC FIELD | 187        |
| 5.3.1    | Velocity-electric field relations in semiconductors                   | 188        |
| 5.3.2    | Very high field transport: Breakdown phenomenon                       | 192        |
| 5.4      | CARRIER TRANSPORT BY DIFFUSION  | 198        |
| 5.4.1    | Transport by drift and diffusion                                      | 199        |
| 5.5      | OPTICAL PROPERTIES OF SEMICONDUCTORS                                  | 200        |
| 5.6      | CHARGE INJECTION AND QUASI-FERMI LEVELS                               | 208        |
| 5.6.1    | Quasi-Fermi levels  | 209        |
| 5.7      | CHARGE INJECTION AND RADIATIVE RECOMBINATION                          | 211        |
| 5.7.1    | Phosphors and fluorescence  | 216        |
| 5.8      | CHARGE INJECTION NON-RADIATIVE EFFECTS                                | 218        |
| 5.8.1    | Defect-related non-radiative processes                                | 219        |
| 5.8.2    | Auger recombination   | 220        |
| 5.9      | THE CONTINUITY EQUATION: DIFFUSION LENGTH                             | 220        |
|          | MODULATION OF OPTICAL PROPERTIES BY<br>ELECTRIC FIELDS                | 224        |
| 5.10.1   | The electro-optic effect  | 224        |
| 5.11     | CHAPTER SUMMARY   | 228        |
|          | PROBLEMS  | 232        |
|          | REFERENCES  | 235        |

# 6 LIGHT DETECTION AND IMAGING 236

|       |  |     |
|-------|--|-----|
| 6.1   | INTRODUCTION   | 237 |
| 6.2   | OPTICAL ABSORPTION IN A SEMICONDUCTOR                      |     |
| 6.3   | PHOTOCURRENT IN A P-N DIODE                                | 244 |
| 6.3.1 | Application to a solar cell                                | 248 |
| 6.4   | THE PHOTOCONDUCTIVE DETECTOR                               | 253 |
| 6.5   | THE P-I-N PHOTODETECTOR                                    | 257 |
| 6.5.1 | Material choice and frequency response of a p-i-n detector | 258 |
| 6.6   | THE AVALANCHE PHOTODETECTOR                                | 261 |
| 6.6.1 | APD design issues  | 262 |
| 6.7   | THE PHOTOTRANSISTOR  | 266 |
| 6.8   | METAL-SEMICONDUCTOR DETECTORS                              |     |
| 6.9   | NOISE AND DETECTION LIMITS                                 | 272 |
| 6.10  | THE RECEIVER AMPLIFIER                                     | 278 |
| 6.11  | THE CHARGED COUPLED DEVICE                                 | 281 |
| 6.12  | ADVANCED DETECTORS   | 283 |
| 6.13  | CHAPTER SUMMARY  | 286 |
| 6.14  | PROBLEMS   | 290 |
| 6.15  | REFERENCES   | 293 |

# 7 THE LIGHT EMITTING DIODE

|     |                              |     |
|-----|------------------------------|-----|
| 7.1 | INTRODUCTION                 | 295 |
| 7.2 | MATERIAL SYSTEMS FOR THE LED | 295 |

|             |  |     |
|-------------|--|-----|
| <b>7.3</b>  | <b>OPERATION OF THE LED</b>                | 298 |
| 7.3.1       | Carrier injection and spontaneous emission | 300 |
| <b>7.4</b>  | <b>EXTERNAL QUANTUM EFFICIENCY</b>         | 309 |
| <b>7.5</b>  | <b>ADVANCED LED STRUCTURES</b>             | 313 |
| 7.5.1       | Heterojunction LED                         | 313 |
| 7.5.2       | Edge-emitting LED                          | 314 |
| 7.5.3       | Surface-emitting LED                       | 316 |
| <b>7.6</b>  | <b>LED PERFORMANCE ISSUES</b>              | 316 |
| 7.6.1       | Light-current characteristics              | 317 |
| 7.6.2       | Spectral purity of LEDs                    | 318 |
| 7.6.3       | LED temporal response                      | 320 |
| 7.6.4       | Temperature dependence of LED emission     | 324 |
| <b>7.7</b>  | <b>APPLICATION OF LEDS</b>                 | 327 |
| <b>7.8</b>  | <b>LED RELIABILITY ISSUES</b>              | 330 |
| <b>7.9</b>  | <b>CHAPTER SUMMARY</b>                     |     |
| <b>7.10</b> | <b>PROBLEMS</b>                            | 335 |
| <b>7.11</b> | <b>REFERENCES</b>                          |     |

## 8 THE LASER DIODE

|            |  |     |
|------------|--|-----|
| <b>8.1</b> | <b>INTRODUCTION</b>                            | 339 |
| <b>8.2</b> | <b>SPONTANEOUS AND STIMULATED EMISSION</b>     |     |
| <b>8.3</b> | <b>THE LASER STRUCTURE: THE OPTICAL CAVITY</b> | 342 |
| 8.3.1      | Optical absorption, loss and gain              | 344 |
| <b>8.4</b> | <b>THE LASER BELOW AND ABOVE THRESHOLD</b>     | 350 |
| <b>8.5</b> | <b>THE TIME RESPONSE OF A LASER</b>            | 356 |
| 8.5.1      | Large-signal switching of a laser              | 359 |
| 8.5.2      | Small-signal response of a laser               | 360 |

|       |  |     |
|-------|--|-----|
| 8.6   | <b>SEMICONDUCTOR LASER DESIGN:</b>               |     |
|       | ELECTRONIC STRUCTURE DESIGN                      | 365 |
| 8.6.1 | Low threshold current                            | 366 |
| 8.7   | <b>ADVANCED STRUCTURES: TAILORING THE CAVITY</b> | 369 |
| 8.7.1 | Issues in a Fabry-Perot cavity                   | 369 |
| 8.7.2 | The distributed feedback lasers                  | 373 |
| 8.7.3 | The surface-emitting laser                       | 376 |
| 8.7.4 | The DBR laser                                    | 379 |
| 8.8   | <b>TEMPERATURE DEPENDENCE OF LASER OUTPUT</b>    | 380 |
| 8.8.1 | Temperature dependence of the threshold current  | 380 |
| 8.8.2 | Temperature dependence of the emission frequency | 381 |
| 8.9   | <b>CHAPTER SUMMARY</b>                           | 383 |
| 8.10  | <b>PROBLEMS</b>                                  | 385 |
| 8.11  | <b>REFERENCES</b>                                | 387 |

## **9 MODULATION AND DISPLAY DEVICES** 388

|       |  |     |
|-------|--|-----|
| 9.1   | <b>INTRODUCTION</b>                                    | 389 |
| 9.2   | <b>LIQUID CRYSTAL CELLS: THE UNDERLYING PRINCIPLES</b> | 390 |
| 9.3   | <b>CHALLENGES IN SCALING TO A DISPLAY SCREEN</b>       | 397 |
| 9.3.1 | The pixel addressing challenge                         | 397 |
| 9.3.2 | The switch solution                                    | 404 |
| 9.4   | <b>PASSIVE MATRIX LIQUID CRYSTAL DISPLAY</b>           | 406 |
| 9.5   | <b>ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS</b>           | 407 |
| 9.5.1 | The thin film transistor                               | 408 |
| 9.6   | <b>CHALLENGES FOR DISPLAY TECHNOLOGY</b>               | 411 |
| 9.6.1 | Field emission displays                                | 413 |
| 9.7   | <b>NEEDS FOR HIGH SPEED LIGHT MODULATION</b>           | 414 |
| 9.7.1 | Figures of merit for modulators                        | 416 |

## CONTENTS

|        |   |     |
|--------|---|-----|
| 9.8    | ELECTRO-OPTIC MODULATORS                  |     |
| 9.9    | INTERFEROMETRIC MODULATORS                | 423 |
| 9.9.1  | Fabry-Perot modulators                    | 423 |
| 9.9.2  | Mach-Zender modulators                    | 424 |
| 9.10   | THE DIRECTIONAL COUPLER                   | 425 |
| 9.11   | ADVANCED MODULATION AND SWITCHING DEVICES | 427 |
| 9.11.1 | Motivations for quantum well devices      | 428 |
| 9.11.2 | Electro-absorption modulators             | 429 |
| 9.12   | CHAPTER SUMMARY                           | 431 |
| 9.13   | PROBLEMS                                  | 435 |
| 9.14   | REFERENCES                                | 437 |

## 10 OPTICAL COMMUNICATION SYSTEMS DEVICE NEEDS

|        |   |     |
|--------|---|-----|
| 10.1   | INTRODUCTION  |     |
| 10.2   | A CONCEPTUAL PICTURE OF THE OPTICAL<br>COMMUNICATION SYSTEM |     |
| 10.3   | INFORMATION CONTENT AND CHANNEL CAPACITY                    |     |
| 10.4   | MODULATION AND DETECTION SCHEMES                            | 445 |
| 10.4.1 | Amplitude modulation  | 445 |
| 10.4.2 | Frequency modulation  | 446 |
| 10.4.3 | Intensity modulation  | 448 |
| 10.5   | SOME PROPERTIES OF OPTICAL FIBERS                           | 448 |
| 10.5.1 | Fiber losses  | 449 |
| 10.5.2 | Multipath dispersion  | 450 |
| 10.5.3 | Material dispersion   | 452 |
| 10.5.4 | Signal attenuation and detector demands                     | 456 |
| 10.5.5 | Fiber amplifier   | 458 |

|       |   |     |
|-------|---|-----|
|       | SUMMARY OF DEVICE REQUIREMENTS                                  | 461 |
| 10.7  | ADVANCED DEVICES: OPTOELECTRONIC<br>INTEGRATED CIRCUITS (OEICS) | 462 |
|       | CHAPTER SUMMARY   | 463 |
|       | PROBLEMS  | 466 |
| 10.10 | REFERENCES  | 467 |

# 11 FABRICATION AND PROCESSING OF DEVICES 468

|       |   |     |
|-------|---|-----|
|       | INTRODUCTION                                    | 469 |
|       | SEMICONDUCTORS: BULK CRYSTAL GROWTH             | 469 |
|       | EPITAXIAL CRYSTAL GROWTH                        | 471 |
|       | LITHOGRAPHY                                     | 478 |
|       | 11.4.1 Photoresist coating                      | 478 |
|       | 11.4.2 Mask generation and image transfer       | 481 |
|       | ETCHING   | 482 |
|       | 11.5.1 Wet chemical etching                     | 482 |
|       | 11.5.2 Plasma etching                           | 484 |
|       | 11.5.3 Reactive ion beam etching (RIBE)         | 485 |
|       | 11.5.4 Ion beam milling                         | 485 |
|       | EPITAXIAL REGROWTH                              | 487 |
|       | FABRICATION OF OPTICAL FIBERS                   | 489 |
|       | 11.7.1 The preform production and fiber pulling | 489 |
| 11.8  | FIBER COUPLING AND SPLICING                     | 493 |
|       | CHAPTER SUMMARY                                 | 496 |
|       | PROBLEMS  | 496 |
| 11.11 | REFERENCES                                      | 499 |

**A****LIST OF SYMBOLS**

500

**IMPORTANT PROPERTIES OF  
SEMICONDUCTORS**

506

**C****DENSITY OF STATES**

511

C.1    **INTRODUCTION**

511

C.2    **THE ELECTRON WAVEFUNCTION AND THE  
DENSITY OF STATES**

511

C.2.1 Density of states for a 3-dimensional system

513

C.2.2 Density of states in sub-3-dimensional systems

515

**THE P-N DIODE: A SUMMARY**

518

D.1    **INTRODUCTION**

518

D.2    **THE P-N JUNCTION**

518

D.2.1 The unbiased p-n junction

519

D.2.2 P-N junction under bias

524

D.2.3 Charge injection and current flow

525

D.2.4 The real diode: Effects of defects

528

**INDEX**

530