GaAs and Related Materials

Bulk Semiconducting and Superlattice Properties

Sadao Adachi
Department of Electronic Engineering
Gunma University
Kiryu-shi, Gunma 376, Japan

World Scientific
Singapore • New Jersey • London • Hong Kong
3 Thermal Properties

3.1 Phase Diagram, 26
   3.1.1 Ga-As and Al-As Binaries, 26
   3.1.2 GaAs-AlAs Pseudobinary System, 28

3.2 Specific Heat, 29
   3.2.1 GaAs and AlAs, 30
   3.2.2 AlGaAs Alloy, 33

3.3 Debye Temperature, 34
   3.3.1 GaAs and AlAs, 34
   3.3.2 AlGaAs Alloy, 36

3.4 Thermal Expansion Coefficient, 37
   3.4.1 GaAs and AlAs, 37
   3.4.2 AlGaAs Alloy, 39
   3.4.3 AlGaAs/GaAs Multilayers, 40

3.5 Thermal Conductivity, 41
   3.5.1 GaAs and AlAs, 41
      (a) Temperature Effects, 41
      (b) Impurity Doping Effects, 42
   3.5.2 InGaAs and AlGaAs Alloys, 43
   3.5.3 AlAs/GaAs Superlattices, 46
   3.5.4 Device Structures, 46

References, 46

4 Elasticity and Elastic Waves

4.1 Second-Order Elastic Constants, 49
   4.1.1 GaAs and AlAs: Room-Temperature Values, 50
   4.1.2 AlGaAs Alloy: Room-Temperature Values, 52
   4.1.3 AlAs/GaAs Superlattices, 55
   4.1.4 Temperature and Pressure Effects, 55

4.2 Third-Order Elastic Constants, 56

4.3 Young’s Modulus, Poisson’s Ratio, and Other Moduli, 57

4.4 Sound Velocities, 60
   4.4.1 Bulk Materials, 60
   4.4.2 AlGaAs/GaAs Superlattices, 63

4.5 Surface Acoustic Waves, 63
   4.5.1 Bulk Materials, 63
   4.5.2 AlGaAs/GaAs Heterostructures, 66

References, 67

5 Phonons and Lattice Vibronic Properties

5.1 Phonon Dispersion Relations, 70
   5.1.1 Bulk Materials, 70
      (a) GaAs, 70
      (b) AlAs, 73
      (c) AlGaAs Alloy, 74
CONTENTS

5.1.2 Al(Ga)As/GaAs(AlAs) Superlattices, 75
   (a) General Features, 75
   (b) Folded Acoustic Modes, 80
   (c) Optical Phonons, 84
   (d) AlAs/GaAs[011], [012], and [111] Superlattices, 89

5.2 Phonon Frequencies, 91
   5.2.1 GaAs and AlAs, 91
   5.2.2 AlGaAs Alloy: Two-Mode Behavior, 93
   5.2.3 Temperature and Pressure Effects, 95
      (a) Temperature, 95
      (b) Pressure, 97

5.3 Gruneisen Parameters, 99
   5.3.1 Mode Gruneisen Parameter, 99
      (a) GaAs and AlAs, 99
      (b) AlAs/GaAs Superlattices, 99
   5.3.2 Averaged Gruneisen Parameter, 101

5.4 Phonon Deformation Potentials, 103
   5.4.1 Formulation, 103
   5.4.2 Experimental Results, 105

References, 107

6 Collective Effects and Some Response Characteristics 112
   6.1 Static and High-Frequency Dielectric Constants, 112
      6.1.1 Bulk Materials: Room-Temperature Values, 112
         (a) GaAs and AlAs, 114
         (b) AlGaAs Alloy, 116
      6.1.2 Temperature and Pressure Effects, 116
         (a) Temperature, 116
         (b) Pressure, 117
   6.1.3 Al(Ga)As/GaAs Superlattices, 118

6.2 Piezoelectricity, 122
   6.2.1 Piezoelectric Constant, 122
      (a) Piezoelectric Stress Constant, 122
      (b) Piezoelectric Strain Constant, 123
   6.2.2 Electromechanical Coupling Constant, 124
   6.2.3 Al(Ga)As/GaAs Superlattices, 124
      (a) Elastic Strains and Piezoelectric Tensor Elements, 124
      (b) Strain-Induced Polarization Fields, 126

6.3 Frohlich Coupling Constant, 129
   6.3.1 Bulk Materials, 129
   6.3.2 Al(Ga)As/GaAs Multilayers, 132

References, 132

7 Energy-Band Structure: Energy-Band Gaps of Bulk Materials 135
   7.1 General Remarks, 135
      7.1.1 Energy-Band Structure and Density of States, 135
7.1.2 Bowing Parameter, 142
7.2 Energy-Band Gaps, 144
  7.2.1 $E_0$ and $E_0+\Delta_0$ Gaps, 144
  7.2.2 Indirect Gaps, 148
  7.2.3 $E_1$ and $E_1+\Delta_1$ Gaps, 154
  7.2.4 $E_2$ and $E_2$ Regions, 154
7.3 Temperature, Pressure, and Doping Effects, 157
  7.3.1 Temperature, 157
  7.3.2 Pressure, 164
  7.3.3 Doping, 170
References, 174

8 Energy-Band Structure: Band Lineups and Heterojunction Energy-Band Diagrams
  8.1 Band Lineups, 179
  8.2 Conduction- and Valence-Band Offsets, 180
    8.2.1 An Overview, 180
      (a) Electron Affinity Rule, 181
      (b) Transition-Metal Level Approach, 183
    8.2.2 Measurement Techniques and GaAs-AlGaAs Values, 184
      (a) Optical Techniques, 184
      (b) Electrical Techniques, 186
    8.2.3 Concluding Remarks, 188
  8.3 Subband Energy Levels and Density of States, 191
    8.3.1 Quantum Wells and Superlattices, 191
    8.3.2 Triangular Wells, 196
  8.4 Optical Transition Energies in Al(Ga)As/GaAs Quantum Structures, 200
    8.4.1 Lowest-Gap Region, 200
      (a) Wider-Well Samples, 200
      (b) Narrow Quantum Wells and Short-Period Superlattices, 203
    8.4.2 Higher-Lying-Gap Regions, 208
      (a) $E_0+\Delta_0$ Region, 208
      (b) $E_1$ and $E_1+\Delta_1$ Regions, 211
      (c) $E_2$ Region, 215
    8.4.3 Orientation Effects, 216
  8.5 External Perturbation Effects, 217
    8.5.1 Temperature, 217
    8.5.2 Hydrostatic Pressure, 219
    8.5.3 Uniaxial Stress, 222
    8.5.4 Electric Field, 222
    8.5.5 Doping, 225
References, 225

9 Energy-Band Structure: Electron and Hole Effective Masses
  9.1 Electron Effective Mass, 231
9.1.1 Γ-Band Minimum, 232
   (a) GaAs and AlAs, 232
   (b) AlGaAs Alloy, 235
   (c) Polaron Effect, 238

9.1.2 X- and L-Band Minima, 238

9.1.3 Temperature, Pressure, and Carrier-Concentration Effects, 240
   (a) Temperature, 240
   (b) Pressure, 241
   (c) Carrier-Concentration Effect: Nonparabolicity and Anisotropy, 243

9.1.4 AlGaAs/GaAs Heterostructures, 246
   (a) Low-Dimensional Effects, 246
   (b) Temperature and Pressure Effects, 250

9.2 Hole Effective Mass, 251

9.2.1 Heavy- and Light-Hole Effective Mass, 251
   (a) GaAs and AlAs, 251
   (b) AlGaAs Alloy, 255
   (c) Polaron Effect, 257

9.2.2 Spin-Orbid-Splitoff Hole Effective Mass, 257

9.2.3 Temperature, Pressure, and Carrier-Concentration Effects, 257
   (a) Temperature, 257
   (b) Pressure, 259
   (c) Carrier-Concentration Effect: Nonparabolicity, 260

9.2.4 AlGaAs/GaAs Heterostructures, 261
   (a) In-Plane and Perpendicular Masses, 261
   (b) Hole Dispersion Curves, 263

References, 265

10 Other Major Properties Related to the Energy-Band Structure 271
10.1 Intravalley Deformation Potentials: Γ Point, 271
10.1.1 Electrons, 271
10.1.2 Holes, 274
   (a) a, b, and d, 274
   (b) Optical-Phonon Deformation Potential d, 283
   (c) Acoustic-Mode Deformation Potentials, 287

10.2 Intravalley Deformation Potentials: L and X Points, 288
10.2.1 L Point, 288
   (a) Electrons, 288
   (b) Holes, 291
   (c) \(E_1\) and \(E_1+\Delta_1\) Transitions, 293

10.2.2 X Point, 294
   (a) Electrons, 294
   (b) \(E_2\) Transitions, 297

10.3 Intervalley Deformation Potentials for Electrons, 298
10.3.1 Theoretical Results, 298
10.3.2 Experimental Results, 300
   (a) GaAs, 300
   (b) AlGaAs Alloy, 303
10.4 Schottky-Barrier Height, 305
   10.4.1 GaAs, 305
   10.4.2 AlAs and AlGaAs Alloy, 312
10.5 Impact-Ionization Coefficient, 314
   10.5.1 Bulk Materials, 314
      (a) GaAs, 314
      (b) AlGaAs Alloy, 322
   10.5.2 AlGaAs/GaAs Heterostructures, 325
References, 328

11 Optical Properties: Bulk GaAs and Related Materials 336
11.1 Optical Dispersion Relations, 336
11.2 The Reststrahlen Region, 337
   11.2.1 GaAs and AlAs, 337
   11.2.2 AlGaAs Alloy, 345
11.3 The Interband Transition Region, 351
   11.3.1 Theoretical Model, 351
      (a) Harmonic Oscillator Approximation, 351
      (b) Standard Critical-Point Model, 353
      (c) Model Dielectric Function, 356
         1. \( E_0 \) and \( E_0+\Delta_0 \) Transitions, 357
         2. \( E_1 \) and \( E_1+\Delta_1 \) Transitions, 361
         3. \( E_0' \) and \( E_2 \) Transitions, 364
         4. Indirect-Band-Gap Transitions, 364
   11.3.2 Experimental Results: Room-Temperature Values, 366
      (a) GaAs and AlAs, 366
         1. \( \epsilon_1 \) and \( \epsilon_2 \), 366
         2. \( n, k, \alpha, \) and \( R \), 370
      (b) AlGaAs Alloy, 372
         1. \( \epsilon_1 \) and \( \epsilon_2 \), 372
         2. \( n, k, \alpha, \) and \( R \), 382
   11.3.3 Temperature, Pressure, and Radiation-Damage Effects, 388
      (a) Temperature and Pressure, 388
      (b) Radiation Damage: Partially Amorphized GaAs, 400
11.4 Near or Below the Fundamental Absorption Edge, 407
   11.4.1 Optical Absorption, 407
      (a) Theoretical Consideration, 407
         1. Optical Transitions and Their Selection Rules, 407
         2. Exciton Interactions, 409
      (b) Experimental Results, 411
         1. Optical Absorption Spectra, 411
         2. Exciton Parameter, 419
11.4.2 Refractive Index, 423
   (a) Theoretical Model, 423
   1. Sellmeier Equation, 423
   2. Single-Oscillator Model, 423
   3. Modified Single-Oscillator Model, 424
   4. Exponential Band-Edge Model, 424
   5. Simplified Interband-Transition Model, 425
   6. Quantum-Density-Matrix Formulation, 426
   (b) Experimental Results, 426
      1. GaAs and AlAs: Room-Temperature Values, 426
      2. GaAs and AlAs: Temperature, Pressure, and Doping Effects, 429
      3. AlGaAs Alloy, 434

11.4.3 Indirect Stimulated Emission in AlGaAs Alloy, 437

11.5 Free-Carrier Infrared Absorption and Related Phenomena, 439
   11.5.1 Free-Carrier and Interband Absorption, 439
      (a) n-GaAs, 439
      (b) p-GaAs, 441
   11.5.2 Carrier-Induced Change in Refractive Index, 445

References, 448

12 Optical Properties: Quantum Wells and Superlattices
   453
   12.1 The Reststrahlen Region, 453
   12.2 The Interband Transition Region, 458
      12.2.1 (001)-Oriented Superlattices and Quantum Wells, 458
      12.2.2 (110)-Oriented Superlattices and Quantum Wells, 461
   12.3 Near or Below the Fundamental Absorption Edge, 463
      12.3.1 Symmetry and Optical-Transition Selection Rules, 463
      12.3.2 Excitons and Optical Absorption, 466
         (a) Interband Absorption, 466
         (b) Exciton Parameters, 472
         (c) Intersubband Absorption, 476
      12.3.3 Refractive Index, 482
         (a) Theoretical Results, 482
         (b) Experimental Results, 486

References, 489

13 Elastooptic and Electrooptic Effects
   495
   13.1 Elastooptic Effect, 495
      13.1.1 Theoretical Model, 495
      13.1.2 Experimental Results, 498
         (a) Bulk Materials, 498
            1. GaAs and AlAs, 498
            2. AlGaAs Alloy, 504
         (b) AlAs/GaAs Superlattices, 507
   13.2 Linear and Quadratic Electrooptic Effects, 507
CONTENTS

13.2.1 Theoretical Model, 507
13.2.2 Experimental Results, 513
  (a) Bulk Materials, 513
    1. Linear Electrooptic Constant, 513
    2. Quadratic Electrooptic Constant, 517
  (b) Multiple Quantum Wells and Superlattices, 518
    1. Linear Electrooptic Constant, 518
    2. Quadratic Electrooptic Constant, 520
13.3 Franz-Keldysh and Stark Effects, 521
  13.3.1 Bulk Materials, 521
    (a) Franz-Keldysh Effect, 521
    (b) Stark Effect, 526
  13.3.2 AlGaAs/GaAs Quantum-Well Structures, 529
    (a) Quantum-Confinement Stark Effect, 529
    (b) Wannier-Stark Localization and Ladder, 533

References, 540

14 Carrier Transport Properties: Bulk GaAs and Related Materials 546
  14.1 Low-Field Mobility, 546
    14.1.1 Electrons, 546
      (a) GaAs and AlAs, 546
      (b) AlGaAs Alloy, 556
        1. Alloy Scattering Potential, 556
        2. Three-Valley Model, 558
        3. Experimental and Theoretical Results, 560
    14.1.2 Holes, 566
      (a) GaAs and AlAs, 566
      (b) AlGaAs Alloy, 575
  14.2 High-Field Transport, 579
    14.2.1 Velocity-Field Characteristics, 579
      (a) Electrons, 579
      (b) Holes, 595
    14.2.2 Gunn Effect, 599
  14.3 Minority-Carrier Transport, 600
    14.3.1 Electrons in p-Type Materials, 600
      (a) Mobility, 600
      (b) Drift Velocity, 603
    14.3.2 Holes in n-Type Materials, 605
  14.4 Superconductivity, 607
    14.4.1 Metallic Properties at High Pressures, 607
    14.4.2 As-Rich and In-Diffused GaAs Samples, 608

References, 608

15 Carrier Transport Properties: AlGaAs/GaAs Heterostructures 616
  15.1 Low-Field Mobility, 616
15.1.1 Electrons, 616
   (a) Quasi-Triangular Wells, 616
   (b) Square Wells, 626
15.1.2 Holes, 631
   (a) Quasi-Triangular Wells, 631
   (b) Square Wells, 637
15.2 Hot-Carrier Transport, 638
15.2.1 Parallel Transport, 638
   (a) Quasi-Triangular Wells, 638
   (b) Square Wells, 646
   (c) Minority Carriers, 648
15.2.2 Perpendicular Transport, 651
   (a) Hot Electrons and Tunneling, 651
   (b) Miniband Bloch Conduction, 654
15.3 Real-Space Transfer, 656

References, 658

Index to Tables of Physical Constants and Properties 663

Subject Index 667