

Contents

Part I Materials and Device Design Considerations

Theory of Mid-wavelength Infrared Laser Active Regions: Intrinsic Properties and Design Strategies

<i>J.T. Olesberg and M.E. Flatté</i>	3
1 Challenges and Opportunities in MWIR Laser Active Region Design.....	3
1.1 Intrinsic Material Properties Dominate Device Performance	4
1.2 Opportunities Provided by Heterostructure Design	5
2 Metrics for Material Comparison and Device Design	6
2.1 Single-stage Active Regions	8
2.1.1 Threshold Figure of Merit for Bulk GaAs	12
2.2 Choice of Active Region Thickness.....	14
2.2.1 Optimal Thickness of Bulk GaAs	14
2.3 Maximizing the Slope Efficiency	16
2.3.1 Maximising Efficiency for a specific Optical Power.....	16
2.4 Cascaded Active Regions.....	17
3 Band-edge Optimization of Active Region Materials.....	21
3.1 Density of States Imbalance.....	21
3.2 The Effects of Density of States Imbalance	25
3.3 Reducing Density of States Imbalance Using Strain	30
3.4 Reducing Density of States Imbalance Using Quantum Confinement	30
3.5 Development of 2–3 μm GaInAsSb Diodes.....	32
3.6 Optimizing Band Edge Properties Using InAs/GaSb/AlSb Materials.....	40
4 Final State Optimization of Active Region Materials	47
4.1 Suppression of Intersubband Absorption	48
4.2 Suppression of Auger Recombination	50
5 Cavity-integrated Active Region Design for Optimal Laser Performance.....	53
5.1 Optimization of the Active Region	53
5.2 Transport and Optical Cladding	56
6 Calculating the Electronic and Optical Properties of Semiconductors	59
6.1 Electronic Structure and Momentum Matrix Elements.....	59
6.1.1 k,p methods for Bulk Materials.....	61
6.1.2 k,p Methods for Heterostructures.....	63
6.1.3 Influence of Interface Bonds	68

6.2	Comparison with Experiment	70
6.2.1	Non-equilibrium Absorption	70
6.2.2	Auger Recombination.....	73
7	Concluding Remarks.....	75
Appendix.	Derivation of Expressions for the Electronic and Optical Properties of Semiconductors.....	76
A1	Density of States.....	77
A2	Optical Properties	77
A3	Carrier Recombination Rates.....	80
A4	Carrier Mobilities	82
References	84

Bandstructure and High-pressure Measurements

<i>B.N. Murdin, A.R. Adams and S.J. Sweeney</i>	93	
1	Bandstructure Calculation by the k.p Method.....	93
1.1	Bulk Bandstructure	94
1.1.1	Zinc-blende Crystals.....	96
1.1.2	Lead-salts.....	99
1.2	Quantum Well Structures	101
1.3	Temperature Dependence of the Bandstructure	103
1.4	Hydrostatic Pressure and Strained Layer Quantum Wells	103
2	Transition Rates.....	105
2.1	Interband Optical Transition Rates	106
2.2	Auger Recombination.....	106
2.3	Auger Rates in Bulk Zinc Blende Materials	109
2.4	Auger Suppression in Bulk Materials: Pb-salts.....	110
2.5	Auger Suppression in Bulk Materials: Dilute III-V Nitrides	111
2.6	Auger Suppression in Quantum Wells.....	112
3	High Pressure.....	114
3.1	Near-infrared Applications	114
3.1.1	Radiative Recombination.....	114
3.1.2	Non-radiative Recombination.....	118
3.2	Determination of Mid-IR Material Pressure Coefficients.....	120
3.3	Interband Mid-IR Devices.....	121
3.3.1	InAs LEDs	121
3.3.2	Comparison of Near-IR and 2.37 μ m InGaAsSb Lasers	122
4	Conclusion.....	125
References	126

Part II Lasers

III-Sb-based Type-I QW Diode Lasers

<i>M. Rattunde, J. Schmitz, C. Mermelstein, R. Kiefer and J. Wagner</i>	131	
1	Introduction	131
2	III-Sb-based Material System	132
2.1	AlGaAsSb.....	132

2.2 Strained GaInAsSb Layers.....	132
2.3 Laser Structure.....	134
3 Fabrication of (AlGaIn)(AsSb)-based Diode Lasers.....	136
3.1 Growth.....	136
3.2 Epitaxial Layer Characterization.....	137
3.3 Device Processing.....	139
4 Gain and Loss Mechanisms in III-Sb-based Lasers Emitting at Around 2 μm	140
4.1 Optical Gain and Electric Loss in the QW Active Region.....	140
4.2 Optical Losses in the Laser Structure.....	143
5 High-power Performance of 2 μm III-Sb-based Diode Lasers.....	146
6 Long-wavelength III-Sb-based Type-I QW Lasers.....	150
7 Outlook.....	151
Acknowledgments.....	153
References.....	153

VCSELs Emitting in the 2 – 3 μm Wavelength Range

<i>F. Genty, A. Garnache and L. Cerutti</i>	159
1 Introduction.....	159
2 A Short Description of Vertical-cavity Lasers.....	160
2.1 Conventional Microcavity VCSELs.....	160
2.2 External-cavity VCSELs (VECSELs).....	163
2.2.1 Structure Description.....	163
2.2.2 Geometrical Stability of a Concave/plane Laser Cavity.....	165
3 VCSELs Emitting in the 2–3 μm Range.....	168
3.1 CdHgTe-based Structures – CEA, Grenoble (France).....	169
3.2 InP-based Structures – Walter Schottky Institute, University of Munich, Garching (Germany).....	171
3.3 GaSb-based Structures I – Naval Research Laboratory/ Hughes Research Laboratory (USA).....	173
3.4 GaSb-based Structures II – University of Montpellier 2 (France).....	176
3.4.1 Electrically-pumped Microcavity VCSEL Emitting Near 2.2 μm	176
3.4.2 Optically-pumped GaSb-based VCSEL Structures.....	177
4 Conclusion.....	184
Acknowledgments.....	185
References.....	185

Antimonide Type-II “W” Lasers

<i>I. Vurgaftman, W.W. Bewley, C.L. Canedy, C.S. Kim, J. R. Lindle, M. Kim, and J.R. Meyer</i>	189
1 Introduction.....	189
2 Advances in the MBE Growth of “W” Laser Structures.....	191
3 Optically Pumped “W” Lasers.....	196
4 Single-stage “W” Diode Lasers.....	199
5 Interband Cascade “W” Lasers.....	201
6 “W” VCSELs and PCDFB Lasers.....	203
7 Critical Issues in Improving the Performance of “W” Lasers.....	208

8 Conclusions..... 212
 References 213

Interface Lasers with Asymmetric Band Offset Confinement

K.D. Moiseev and Y.P. Yakovlev 219

1 Introduction..... 219

2 The 2D-Electron Channel in a Type II Broken-gap p-GaInAsSb/p-InAs Heterointerface..... 220

3 Interface Luminescence Properties of the Type II Broken-gap Single p-GaInAsSb/p-InAs Heterojunction 220

3.1 Interface EL in a Single p-GaInAsSb/p-InAs Heterojunction..... 220

3.2 Tunnelling-injection Laser Based on the Type II p-GaIn_{0.17}AsSb/p-In_{0.83}GaAsSb Heterojunction..... 224

3.3 Suppression of Auger-recombination Processes at the Type II Heterointerface..... 226

4 Interface Laser with Improved Temperature Dependence 228

4.1 Electroluminescence in a Single p-GaIn_{0.17}AsSb/n-In_{0.83}GaAsSb Heterostructure..... 228

4.2 Advanced Tunnel-injection Heterostructure Laser 230

4.3 Prospects for High-temperature Luminescence in Type II Broken-gap Heterojunctions 233

5 Conclusions..... 235
 References 235

IV-VI Semiconductors for Mid-infrared Optoelectronic Devices

P. J. McCann 237

1 Introduction..... 237

2 Spectroscopy with IV-VI Semiconductor Lasers..... 237

3 IV-VI Semiconductor Growth and Characterization 241

3.1 IV-VI Layers on BaF₂..... 242

3.2 IV-VI Layers on Silicon..... 245

4 Self-heating Effects in IV-VI Mid-IR Lasers..... 248

5 Electrophonon Resonance in PbSe QWs 249

6 Progress in Laser Fabrication Using Substrate Removal 254

7 Summary 259

Acknowledgements 260
 References 260

Mid-infrared Vertical Cavity Surface Emitting Lasers Based on the Lead Salt Compounds

G. Springholz, T. Schwarzl and W. Heiss 265

1 Introduction..... 265

2 Vertical Surface Emitting Lasers 266

3 Lead Salt-based Bragg Interference Mirrors..... 268

3.1 Mirror Materials..... 268

3.2 Examples and Results 270

4 Lead Salt Vertical Cavity Surface Emitting Lasers 272

4.1 Design Issues and Resonator Structure 272

4.2	PbTe/EuTe Quantum Well VCSELs.....	274
4.2.1	Structure and Optical Characterization.....	274
4.2.2	Threshold and Laser Emission.....	275
4.2.3	Temperature Dependence of Emission.....	276
4.3	Room Temperature PbTe QW VCSELs.....	277
4.4	PbSe/PbSrSe VCSELs.....	280
5	Self-assembled Infrared Quantum Dot Lasers.....	281
5.1	Self-assembled PbSe Quantum Dots.....	281
5.2	Quantum Dot VCSELs: Growth and Characterization.....	284
5.3	Quantum Dot Laser Emission.....	286
6	Lead Salt VCSELs with Different Active Regions.....	288
6.1	VCSEL Structures and Optical Properties.....	288
6.2	Laser Emission.....	289
6.2.1	Bulk-like PbTe VCSEL.....	289
6.2.2	PbTe/PbEuTe Quantum Well VCSEL.....	291
6.2.3	Lasing Properties of the Quantum Dot VCSEL.....	292
6.2.4	Tuning Properties.....	292
7	CW-VCSELs Emitting at 6-8 μm	293
7.1	Structure and Optical Properties.....	293
7.2	Laser Emission.....	294
8	Conclusions.....	298
	Acknowledgements.....	298
	References.....	299

Optically Pumped MIR Lasers

	<i>R. Kaspi, G.C. Dente and A.P. Ongstad</i>	303
1	Introduction.....	303
2	Optically Pumped Laser Design.....	303
2.1	Guidelines for Optical Pumping and the MIR-OPSL.....	303
2.2	Type-II Quantum Wells.....	306
2.3	Dielectric Waveguide Design for the MIR-OPSL.....	309
2.3.1	Connection Between Confinement Factor and Beam Quality.....	309
2.3.2	Ghost Modes in the MIR-OPSL.....	313
3	Laser Characteristics.....	315
3.1	Spectral Power and Loss Measurements.....	315
3.2	Beam Quality.....	319
4	Conclusion.....	321
	References.....	321

Mid-infrared Quantum Cascade Lasers

	<i>J. Cockburn</i>	323
1	Introduction.....	323
1.1	General QCL Concepts and Current Status.....	323
2	QCL Active Region Design.....	326
2.1	Intersubband Population Inversion.....	327
2.2	Two-well and Three-well Active Regions.....	328
2.3	Double Phonon Resonance Active Region.....	330

2.4	Bound to Continuum Active Region.....	330
2.5	Comparison of InP-based and GaAs-based QCLs	333
3	Quantum Cascade Lasers for 3-5 μ m Operation.....	336
3.1	Strain Compensated InGaAs-AlInAs-InP	338
3.2	InGaAs-AlAsSb-InP	340
3.3	InAs-AlSb	344
4	Quantum Cascade Lasers Grown by Metal-Organic Vapour Phase Epitaxy	347
5	Conclusions.....	351
	Acknowledgements	351
	References	351

Part III LEDs and Detectors

Mid-infrared Electroluminescence in LEDs Based on InAs and Related Alloys

	<i>A. Krier, X.L. Huang and V.V. Sherstnev</i>	359
1	Introduction.....	359
1.1	Background.....	360
2	Limitations to LED Performance	362
2.1	Internal Quantum Efficiency.....	362
2.2	Purification Using Rare Earth Gettering and Pb Neutral Solvent Epitaxy.....	363
2.3	Purification of Epitaxial InAs Using Gd Gettering	364
2.4	Fabrication of InAsSb LEDs at 4.6 μ m.....	366
2.5	InAs LEDs for Methane Detection at 3.3 μ m	368
2.6	Neutral Solvent Epitaxy	370
3	High-pressure Measurements.....	374
4	Optical Extraction	377
5	Comparison of Devices.....	379
6	InAsSb Quantum Dot Light Emitting Diodes Grown by Liquid Phase Epitaxy	381
7	Superluminescence and Ring Lasers.....	386
8	Conclusion	389
	Acknowledgements	390
	References	390

LED-Photodiode Opto-pairs

	<i>B.A. Matveev</i>	395
1	Introduction.....	395
2	Device Configuration and Fabrication.....	396
2.1	Substrate and Buffer Layers.....	397
2.2	Active Layer Properties	400
2.2.1	Layer Doping	400
2.2.2	Layer Thickness.....	401
2.2.3	Active Layer Mesa Diameter	402
2.3	Contacts	403
3	Choice of the Operating Mode.....	408

4	Out-coupling of Radiation in Mid-IR Devices.....	415
5	The Use of Diode Opto-pairs for Chemical Sensing.....	419
6	Summary.....	424
	Acknowledgements.....	424
	References.....	425

QWIP Detectors for the MWIR

	<i>S. Haywood, K.T. Lai and M. Missous</i>	429
1	Introduction.....	429
1.1	QWIPs vs Interband Detectors.....	429
2	MWIR Transitions in QWs.....	431
2.1	Square QW Structures.....	431
2.1.1	(In)GaAs/AlGaAs on GaAs.....	432
2.1.2	InGaAs/AlInAs on InP.....	433
2.2	Double-barrier QWs.....	433
2.2.1	DBQWs on GaAs Substrates.....	434
2.2.2	DBQWs on InP Substrates.....	435
3	Strain-balanced QWIPs for High-temperature Operation.....	436
3.1	Materials Growth and Characterisation.....	436
3.2	Stoichiometric Growth Conditions.....	437
3.3	Structural and Electrical Properties.....	438
3.4	Modelling the Intersubband Transitions.....	441
3.5	Measured Transitions.....	442
3.6	Predicted Temperature Performance.....	443
4	Enhanced Detector Performance and Functionality.....	444
4.1	Asymmetric Wells.....	445
4.1.1	Normal Incidence Absorption.....	445
4.1.2	Voltage Tuning via the Stark Effect.....	445
4.2	Photovoltaic Operation.....	446
4.3	High-speed Operation.....	447
5	Conclusions.....	447
	Acknowledgements.....	448
	References.....	448

Negative Luminescence

	<i>T. Ashley and G.R. Nash</i>	453
1	Introduction.....	453
2	Negative Luminescent Parameters.....	455
2.1	Key Parameters.....	455
2.2	Optical Concentrators.....	456
3	The Magnetoconcentration Effect.....	458
3.1	Principle of Operation.....	458
3.2	Indium Antimonide and Cadmium Mercury Telluride Devices.....	459
3.3	Other Material Systems.....	461
3.4	Conclusions.....	462
4	Photodiodes.....	462
4.1	Principle of Operation.....	462
4.2	Indium Antimonide Devices.....	464

4.3	Cadmium Mercury Telluride Devices.....	467
4.4	Other Device Structures and Material Systems.....	471
4.5	Conclusions.....	472
5	Applications of Negative Luminescence	473
5.1	IR Sources for Gas Sensing	473
5.1.1	Temperature Stabilisation.....	474
5.1.2	Efficient Long Wavelength IR Sources	474
5.2	Dynamic Infrared Scene Projection	476
5.3	Radiative Cooling	477
5.4	Uncooled IR Radiation Shields for BLIP IR Detectors	478
5.5	Radiometric Reference Planes for Thermal Imagers	479
5.5.1	DC Restoration in Scanned Thermal Imagers	479
5.5.2	Non-uniformity Correction in Staring Arrays.....	481
5.6	Camouflage.....	482
6	Summary.....	482
	References	483

Mid-infrared Quantum Dot Photodetectors

	<i>P. Bhattacharya, A. D. Stiff-Roberts and S. Chakrabarti</i>	487
1	Introduction.....	487
1.1	Quantum Dot Photodetectors in the Mid-Infrared	487
1.2	Comparison of HgCdTe Photodiodes and InAs/GaAs Quantum Dot Infrared Photodetectors	490
2	Infrared Detection with Quantum Dots.....	491
2.1	Bound-state Energy Levels in QDs.....	492
2.2	Density of States and Carrier Distribution in QDs.....	494
2.3	Intraband Absorption in QDs.....	495
2.4	Phonon Bottleneck and Effective Carrier Lifetime in QDs	497
3	Self-assembly of Quantum Dots by the Stranski-Krastanow Growth Mode.....	498
4	Characterization of Mid-infrared Quantum Dot Photodetectors	500
4.1	QDIP Heterostructure Designs.....	500
4.2	Dark Current	501
4.3	Mid-infrared Spectral Response in QDIPs.....	502
4.4	State-of-the-art Performance in MIR QDIPs at High Operating Temperatures	503
5	Conclusions.....	506
	Appendix. Infrared Photodetector Figures of Merit	507
A1	Photocurrent.....	507
A2	Dark Current	507
A3	Noise Current.....	507
A4	Normalized Spectral Response and Peak Responsivity	508
A5	Peak Specific Detectivity	508
A6	Photoconductive Gain and Quantum Efficiency	509
	Acknowledgements	510
	References	510

Quantum Photovoltaic Devices Based on Antimony Compound Semiconductors

<i>Y. Wei, A. Gin and M. Razeghi</i>	515
1 Introduction.....	515
2 Theoretical Modeling.....	516
2.1 The Type-II InAs/GaSb Superlattice	516
2.2 Nanopillar Structures	521
3 Material Growth and Characterization.....	526
4 Photodiodes with Cut-off Wavelength $\sim 8 \mu\text{m}$	531
5 Type II Focal Plane Arrays	533
6 Nanopillar Fabrication	535
6.1 Electron Beam Lithography.....	535
6.2 Nanopillar Device Fabrication Process.....	535
6.3 Nanopillars in GaSb Material	537
6.4 Nanopillars in InAs/GaSb Superlattice Material.....	538
6.5 Reactive Ion Etching Using $\text{BCl}_3:\text{Ar}$ and $\text{CH}_4:\text{H}_2:\text{Ar}$	538
6.6 Reactive Ion Etching Using Cyclic $\text{CH}_4:\text{H}_2:\text{Ar} / \text{O}_2$	539
6.7 Device Fabrication.....	540
6.7.1 Polyimide Planarization.....	540
6.7.2 Polyimide Etchback.....	540
6.7.3 Top Contact Deposition.....	541
6.7.4 Dark Current Measurements.....	542
7 Conclusion	543
Acknowledgement.....	543
Appendix. Superlattice Hamiltonian Matrix	543
References	545

High-speed Avalanche Photodiodes for the 2-5 μm Spectral Range

<i>M.P. Mikhailova and I.A. Andreev</i>	547
1 Introduction.....	547
2 Impact Ionization in III-V Semiconductors	548
2.1 Interband Ionization in Semiconductors	548
2.2 Threshold Energy of Impact Ionization	549
2.3 The Dependence of the Ionization Coefficients on the Electric Field.....	551
2.4 Two-valley Model.....	552
2.5 Inter-relationship Between Multiplication Coefficients and Ionization Coefficients of Electrons and Holes.....	553
2.6 Noise and Response Speed of APDs.....	554
3 Ionization Coefficients in III-V Semiconductors and their Alloys	557
3.1 Electron Impact Ionization.....	557
3.1.1 Anisotropy of Ionization Coefficients in Multi-valley Semiconductors of GaAs, InP Type	557
3.1.2 Anisotropy of Ionization Coefficients in Multi-valley Semiconductors of GaSb and their Alloys.....	558
3.2 Electron Impact Ionization in Semiconductors of InAs, InSb Type	560
3.3 Hole Impact Ionization	561
3.4 Hole Impact Ionization in Semiconductors with Band Gap "Resonance", $E_g = \Delta(\text{InAs, GaSb})$	562
4 Avalanche Photodiodes for the 2-2.5 μm Spectral Range.....	564

4.1	Experimental Ionization Coefficients in Solid Solutions Based on GaSb.....	565
4.1.1	Ionization Coefficients in GaSb, GaAlSb and GaAlAsSb.....	565
4.1.2	Experimental Ionization Coefficients in GaInAsSb.....	567
4.2	Dark Current in APDs with a ‘Resonant’ GaAl(As)Sb Composition	570
4.3	GaInAsSb/GaAlAsSb Avalanche Photodiode with Separate Absorption and Multiplication Region (SAM APD)	572
4.4	Noise and Response Speed of GaInAsSb/GaAlAsSb APDs.....	576
5	Avalanche Photodiodes for the 3-5 μm Spectral Range.....	581
5.1	Experimental Investigation of Ionization Coefficients in InAs, InGaAs and InAsSb.....	582
5.2	Noise and Response Speed of Long Wavelength APDs.....	585
6	Methods of Separating Ionization Coefficients Using Quantum Structures	586
7	Conclusion	588
	References	589

Part IV Applications

Infrared Methods for Gas Detection

	<i>J.G. Crowder, S.D. Smith, A. Vass and J. Keddie</i>	595
1	Introduction.....	595
2	Gas Absorption Spectra	595
3	Methods of Gas Detection	597
4	Infrared Sources for Gas Detection.....	598
4.1	Thermal Sources	599
4.2	Semiconductor Sources.....	600
5	Infrared Detectors for Gas Detection	601
5.1	Optical Immersion	602
6	Design of Optical and Gas Sampling Systems.....	604
6.1	A Non-imaging Gas Sensor with Thermal Source and Detector	606
6.2	A Long-path, Imaging Gas Sensor with Semiconductor Source and Detector.....	608
7	Laser Techniques	609
8	Conclusions.....	610
	References	610

Mid-infrared Biomedical Applications

	<i>I.K. Ilev and R.W. Waynant</i>	615
1	Introduction.....	615
2	Mid-IR Biophotonics	616
2.1	Biophotonics	616
2.2	Fundamentals of Mid-IR Biophotonics Applications	617
2.3	Mid-IR Biophotonics Delivery Systems	619
2.3.1	Basic Mid-IR Biophotonics Delivery System.....	619
2.3.2	Mid-IR Biomedical Lasers	620
2.3.3	Mid-IR Incoherent Light Sources	621

2.3.4	Mid-IR Bio-medical Delivery Fibers.....	622
2.3.5	All-Hollow-Waveguide Mid-IR Laser Delivery System.....	624
3	Mid-IR Bio-photonics Applications.....	625
3.1	Mid-IR Laser Surgery and Tissue Ablation.....	625
3.2	Mid-IR Bioimaging.....	627
3.3	Mid-IR Spectroscopy and Biosensors in Biomedicine.....	628
3.3.1	Non-invasive Blood Glucose Monitoring.....	628
3.3.2	Breath Analysis for Medical Applications.....	629
3.3.3	Summary of Mid-IR Spectroscopy and Biosensors.....	630
4	Conclusion.....	631
	References.....	631

Development of Infrared Countermeasure Technology and Systems

	<i>D.H. Titterton</i>	635
1	Introduction.....	635
2	Historical Development.....	637
3	Propagation and Atmospheric Windows.....	639
3.1	Humidity.....	640
3.2	Haze, Fog, Cloud and Rain.....	641
3.3	Turbulence.....	641
3.4	Extinction.....	643
3.5	Thermal Blooming.....	643
3.6	Ionisation.....	643
3.7	Wakes and Plumes.....	644
3.8	Aero-optical Effects.....	644
4	Defeat Mechanisms.....	645
4.1	Denial.....	645
4.1.1	Smokes and Obscurants.....	646
4.1.2	Pyrotechnic Smoke.....	647
4.1.3	Rapid-bloom Obscurant.....	647
4.1.4	Large-area Smoke Screening Systems.....	647
4.2	Deception.....	647
4.2.1	Expendables (Flares).....	649
4.2.2	On-board Techniques (Jammers).....	651
4.3	Dazzle.....	653
4.4	Damage.....	654
4.4.1	In-band Damage Route.....	655
4.4.2	Out-of-band Damage.....	657
4.5	Destruction.....	659
5	The Evolution of IR-jammer Systems.....	661
5.1	Incoherent IR Sources.....	662
5.2	Arc Lamps.....	664
5.3	Coherent Sources.....	666
5.4	DIRCM Systems.....	667
6	Characteristics of Laser-based Jammers.....	669
7	Future Developments of Laser-based Systems.....	670
	References.....	671

Survey of Thermophotovoltaic (TPV) Devices

<i>M.G. Mauk</i>	673
1 Introduction and Overview	673
2 TPV Literature and Other Sources of Information.....	679
3 Basic Operation of TPV Cells.....	680
4 TPV System Thermodynamic Limits and Modeling	684
5 TPV Cell Modeling.....	689
5.1 TPV Device Structure and Delineation.....	690
5.2 Minority Carrier Recombination and Limits to Open-circuit Voltage.....	692
6 Survey of TPV Materials and Devices.....	697
6.1 Silicon, Germanium, and Si-Ge Alloy TPV Cells	697
6.2 GaSb TPV Cells.....	699
6.3 TPV Cells Based on Bulk III-V Alloy Ternary Crystals.....	701
6.4 InGaAs and InAsP/InP TPV Cells and MIMs	703
6.5 Low-bandgap (< 0.5 eV) InAs and InAsSbP TPV Cells.....	706
6.6 TPV Cells Based on Other Semiconductors	710
6.7 Quantum Well TPV Cells	710
6.8 Isolation for Series Interconnection, Integrated Reflectors, and Wafer-bonding for TPV Cells	713
6.9 Tandem TPV Cells.....	714
6.10 Micron-gap TPV Cells.....	717
6.11 Spectral Control, Microstructured Emitters, Filters and Photonic Crystals	720
6.12 Thermophotonics	720
7 Concluding Remarks and Outlook for TPV Technology.....	721
Appendix. Modeling of InGaAsSb TPV Cells	723
A1 Materials Properties	723
A2 TPV Device Model	728
References	731
Index	739