The Wonder of Nanotechnology
Quantum Optoelectronic Devices and Applications
The Wonder of Nanotechnology
Quantum Optoelectronic Devices and Applications

Manijeh Razeghi
Leo Esaki
Klaus von Klitzing
Editors

SPIE PRESS
Bellingham, Washington USA
# Contents

Foreword by Leo Esaki  
Preface by Klaus von Klitzing  
Introduction by Manijeh Razeghi  
"An Imaging Perspective from the Nanometer Scale" by Nibir K. Dhar  
List of Contributors

## I Historic Overview

### 1 Role of Symmetry in Conductance, Capacitance, and Doping of Quantum Dots

*Raphael Tsu and Tim LaFave, Jr.*

1.1 Introduction  
1.2 Birth of the Superlattice  
1.2.1 Response of a time-dependent electric field and Bloch oscillation  
1.3 Resonant Tunneling in Manmade Quantum Wells  
1.3.1 Time-dependent resonant tunneling  
1.3.2 Quantum cascade laser with superlattice components  
1.3.3 Type-II superlattice  
1.3.4 Terahertz sound in Stark ladder superlattices  
1.3.5 Cold cathode  
1.4 Size-Dependent Dielectric Constant $\varepsilon(a)$  
1.5 Role of Symmetry in Capacitance of Few-Electron Quantum Dots  
1.5.1 A classical correspondence between quantum dots and atomic structure  
1.5.2 Toward a general solution of the Thomson problem and atomic structure  
1.5.3 The dielectric function and atomic dimension  
1.6 Symmetry: Key in Interaction with Nanotechnology  
1.7 A Few Important Considerations  
References
### Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 Introduction</td>
<td>106</td>
</tr>
<tr>
<td>5.2 Superlinear Electroluminescence in GaSb-based Narrow-Gap Heterostructures with High Conduction-Band Offsets</td>
<td>107</td>
</tr>
<tr>
<td>5.3 Superlinear Electroluminescence in GaSb-based Nanostructures with a Deep Al(As)Sb/InAsSb/Al(As)Sb QW</td>
<td>113</td>
</tr>
<tr>
<td>5.4 Theoretical Consideration of Radiative and Auger Recombination in Deep QWs</td>
<td>118</td>
</tr>
<tr>
<td>5.5 Conclusions</td>
<td>125</td>
</tr>
<tr>
<td>Acknowledgment</td>
<td>126</td>
</tr>
<tr>
<td>References</td>
<td>126</td>
</tr>
<tr>
<td>6 Antimonide Quantum Dot Nanostructures for Novel Photonic Device Applications</td>
<td>133</td>
</tr>
<tr>
<td>Anthony Krier, Peter J. Carrington, Qiandong Zhuang, Robert J. Young,</td>
<td></td>
</tr>
<tr>
<td>Manus Hayne, Lu Qi, Juanita James, Magnus C. Wagener, J. Reinhardt Botha, Paul Koenraad, and Erwin Smakman</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1 Introduction</td>
<td>133</td>
</tr>
<tr>
<td>6.2 Molecular Beam Epitaxy Growth of InSb Quantum Dots</td>
<td>134</td>
</tr>
<tr>
<td>6.3 Characterization of InSb Quantum Dots</td>
<td>135</td>
</tr>
<tr>
<td>6.4 MBE Growth of GaSb Quantum Dots</td>
<td>138</td>
</tr>
<tr>
<td>6.5 Solar Cells Containing Stacks of GaSb Quantum Rings</td>
<td>143</td>
</tr>
<tr>
<td>6.6 Summary</td>
<td>147</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>149</td>
</tr>
<tr>
<td>References</td>
<td>149</td>
</tr>
<tr>
<td>7 n-Type Doping in GaSb using Dimethyltellurium (DMTe) by Metalorganic Chemical Vapor Deposition (MOCVD)</td>
<td>157</td>
</tr>
<tr>
<td>Ari Handono Ramelan</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.1 Introduction</td>
<td>157</td>
</tr>
<tr>
<td>7.2 Review of Te-Doped GaSb Growth</td>
<td>158</td>
</tr>
<tr>
<td>7.3 Dopant Impurities</td>
<td>159</td>
</tr>
<tr>
<td>7.4 Growth of Te-Doped GaSb</td>
<td>161</td>
</tr>
<tr>
<td>7.4.1 Metalorganic sources</td>
<td>161</td>
</tr>
<tr>
<td>7.4.2 Growth condition</td>
<td>161</td>
</tr>
<tr>
<td>7.5 Characterization</td>
<td>163</td>
</tr>
<tr>
<td>7.6 Results and Discussion</td>
<td>163</td>
</tr>
<tr>
<td>7.6.1 Surface morphology and growth rate</td>
<td>163</td>
</tr>
<tr>
<td>7.6.2 Electrical properties</td>
<td>164</td>
</tr>
<tr>
<td>7.7 Conclusions</td>
<td>170</td>
</tr>
<tr>
<td>References</td>
<td>171</td>
</tr>
<tr>
<td>8 AlGaN-based Intersubband Device Technology</td>
<td>175</td>
</tr>
<tr>
<td>Can Bayram, Devendra K. Sadana, and Manijeh Razeghi</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Introduction to Terahertz Devices</td>
<td>176</td>
</tr>
<tr>
<td>8.1.1 Terahertz applications</td>
<td>176</td>
</tr>
</tbody>
</table>
8.1.2 Available terahertz sources 177
8.1.3 Conventional semiconductor and III-nitride terahertz sources 177
8.1.4 III-nitride material challenges 177
8.2 III-Nitride MOCVD 178
8.2.1 Effect of growth temperature 178
8.2.2 High-Al-content structures 179
  8.2.2.1 Overview of pulsed growth technique 179
  8.2.2.2 Tunability of AlN and GaN layers in the SL 181
  8.2.2.3 Effect of doping on optical and structural quality 182
  8.2.2.4 Effect of capping on optical and structural quality 182
8.2.3 Low-Al-content structures 183
8.3 Infrared Optical Devices 185
  8.3.1 Near-infrared devices 186
  8.3.2 Mid-infrared devices 186
  8.3.3 Toward terahertz 188
  8.3.4 Conclusion 189
8.4 Resonant Tunneling Diodes 189
  8.4.1 Introduction 189
  8.4.2 Device design 191
  8.4.3 Material growth 192
    8.4.3.1 Polar devices 192
    8.4.3.2 Nonpolar devices 193
  8.4.4 Device fabrication 193
  8.4.5 Electrical characterization 195
    8.4.5.1 Polar devices 196
    8.4.5.2 Nonpolar devices 196
8.5 Summary 197
8.6 Conclusions 198
References 199

III Lasers 207

9 Advances in High-Power Quantum Cascade Lasers and Applications 209
Arkadiy Lyakh, Richard Maulini, Alexei Tsekoun, Boris Tadjikov, and
C. Kumar N. Patel
9.1 Introduction 209
9.2 MWIR Laser Design 211
9.3 Tapered-Waveguide Geometry 212
9.4 Silicon Carbide Submounts 213
9.5 MWIR QCL Experimental Data 214
9.6 LWIR QCL Design 217
9.7 LWIR QCL Experimental Data 218
9.8 Conclusion 219
References 220
10 High-Performance Quantum Cascade Lasers for Industrial Applications 225
Mariano Troccoli, Jenyu Fan, Gene Tsvid, and Xiaojun Wang

10.1 Introduction 225
10.2 Manufacturing of High-Performance QC Lasers 226
  10.2.1 Design 226
  10.2.2 Growth 227
  10.2.3 Fabrication 229
10.3 Results 230
  10.3.1 High-power multimode devices 230
  10.3.2 Low-power-consumption distributed-feedback-laser devices 232
  10.3.3 Power scaling: arrays 234
10.4 Conclusions 236
Acknowledgments 237
References 238

11 Mid-infrared Tunable Surface-Emitting Lasers for Gas Spectroscopy 243
Hans Zogg, Ferdinand Felder, and Matthias Fill

11.1 Introduction 244
11.2 Some Properties of Narrow-Gap Lead Chalcogenides (IV-VI Compound Semiconductors) 245
  11.2.1 Structure, binary compositions, alloying 245
  11.2.2 Band structure and Auger recombination 245
  11.2.3 Permittivities 246
  11.2.4 Defects and non–lattice-matched growth 246
  11.2.5 Growth on Si(111) and thermal-mismatch dislocation glide 246
11.3 Applications 247
  11.3.1 Broadband photovoltaic IV-VI mid-infrared detectors 247
  11.3.2 Resonant-cavity-enhanced detectors 247
  11.3.3 Edge-emitting laser diodes 248
  11.3.4 Monolithic vertical-cavity surface-emitting lasers (VCSELs) and microdisk lasers 248
11.4 VECSELs 248
  11.4.1 Principle and structure of the long cavity 248
  11.4.2 Optical and electronic simulation 251
  11.4.3 Short cavity and end pumping 253
11.5 Conclusions 255
References 256

12 Frequency Noise and Linewidth of Mid-infrared Continuous-Wave Quantum Cascade Lasers: An Overview 261
Stéphane Schilt, Lionel Tombez, Gianni Di Domenico, and Daniel Hofstetter

12.1 Introduction 261
12.2 Frequency Noise and Laser Linewidth in QCLs: Experimental Methods
12.2.1 Relation between frequency noise and laser linewidth 263
12.2.2 Frequency noise measurement methods 265
12.3 Intrinsic Linewidth in QCLs 268
12.4 Impact of Technical Noise on the QCL Experimental Linewidth 269
12.5 Overview of Reported Frequency Noise Spectra in 4- to 5-μm QCLs 272
12.5.1 Free-running QCLs 272
12.5.2 Frequency-stabilized QCLs 275
12.6 Temperature Dependence of the Frequency Noise in a QCL 276
12.7 The Origin of Frequency Noise in QCLs 278
12.8 Conclusion and Outlook 279
References 280

13 Wide-Bandgap Semiconductor Quantum Cascade Lasers Operating at Terahertz Frequencies 289
Hung Chi Chou, John Zeller, Anas Mazady, and Mehdi Anwar
13.1 Introduction 290
13.1.1 Motivation 290
13.1.2 Terahertz QCLs: background and recent developments 290
13.1.3 Terahertz QCLs: challenges 292
13.2 Terahertz QCLs: Structure and Design 293
13.2.1 Lasing in terahertz QCLs 293
13.2.2 Rate equations of a three-level QCL 297
13.2.3 Electron transmission in QCLs 298
13.3 Simulation and Analysis 300
13.3.1 Absorption and optical gain 300
13.3.2 Terahertz output power and wall-plug efficiency 304
13.3.3 Polar versus nonpolar cases 311
13.4 Conclusion 313
References 314

14 HgCdTe versus Other Material Systems: A Historical Look 323
Antoni Rogalski
14.1 Introduction 323
14.2 The HgCdTe Era 325
14.3 Alternative-Material Systems 331
14.3.1 PbSnTe 331
14.3.2 InSb and InGaAs 333
14.3.3 GaAs/AlGaAs QW SLs 335
14.3.4 InAs/GaInSb strained-layer SLs 337
14.3.5 Hg-based alternatives to HgCdTe 340
15 Type-II Superlattices: Status and Trends
Elena A. Plis and Sanjay Krishna

15.1 Introduction
15.2 Limitations of T2SLS Technology
  15.2.1 Short carrier lifetime
  15.2.2 Passivation
  15.2.3 Heterostructure engineering
  15.2.4 Nonuniformity and reproducibility issues
  15.2.5 Spectral crosstalk in multicolor T2SLS imagers
15.3 Proposed Solutions
  15.3.1 Ga-free type-II InAs/InAsSb superlattice detectors
  15.3.2 Interband cascade infrared photodetector (ICIP) architecture
  15.3.3 InAs/GaSb T2SLS MWIR detectors grown on (111) GaSb substrates
15.4 Summary
Acknowledgments
References

16 MWIR Detectors: A Comparison of Strained-Layer Superlattice Photodiodes with HgCdTe
William E. Tennant

16.1 Introduction: Why This Comparison?
16.2 Some Diode Basics
  16.2.1 Diode architecture
  16.2.2 The key metric: background-limited performance (BLIP)
16.3 Real MWIR Devices at 150 K
  16.3.1 HgCdTe
  16.3.2 Strained-layer superlattice (SLS)
16.4 Performance Assessment and Comparison
16.5 Summary and Conclusions
References

17 Mid- and Long-Wavelength Barrier Infrared Detectors
David Z. Ting, Alexander Soibel, Sam A. Keo, Cory J. Hill,
Jason M. Mumolo, Linda Höglund, Jean Nguyen, Arezou Khoshakhlagh,
Sir B. Rafol, John K. Liu, and Sarath D. Gunapala

17.1 Introduction
17.2 The Complementary-Barrier Infrared Detector (CBIRD)
  17.2.1 CBIRD structure and characterization
  17.2.2 CBIRD contact designs
18 Modulation Transfer Function Measurements of Infrared Focal Plane Arrays

Sarath D. Gunapala, Sir B. Rafol, David Z. Ting, Alexander Soibel, John K. Liu, Arezou Khoshakhlagh, Sam A. Keo, Jason M. Mumolo, Linda Höglund, and Jean Nguyen

18.1 Introduction 407
18.2 Mid-wavelength Infrared QWIP Device 411
18.3 MTF of Megapixel MWIR QWIP FPA 412
18.4 Long-Wavelength Infrared QWIP Device 416
18.5 MTF of Megapixel LWIR QWIP FPA 417
18.6 Dual-Band QWIP Device Structure 419
18.7 Testing and Characterization of Multiband QWIP FPA 420
18.8 NE\(\Delta\)T and MTF of Megapixel Multiband QWIP FPA 421
18.9 Complementary-Barrier Infrared Detector (CBIRD) Device Structure 424
18.10 Testing and Characterization of CBIRD FPA 425
18.11 MR\(\Delta\)T and MTF of CBIRD FPA 426
18.12 Conclusion 429
Acknowledgment 430
References 430

19 Quantum Dots for Infrared Focal Plane Arrays Grown by MOCVD

Manijeh Razeghi and Stanley Tsao

19.1 Introduction 436
19.1.1 Infrared detection basics 438
19.1.1.1 Photocurrent 439
19.1.1.2 Dark current 440
19.1.1.3 Detector metrics 441

19.2 QDs for Infrared Detection 442
19.2.1 Benefits of QDs for ISB detectors 443
19.2.1.1 High gain and the phonon bottleneck 444
19.2.1.2 Low dark current 445
19.2.1.3 Normal-incidence absorption 445
19.2.1.4 Versatility 446
19.2.2 The potential of QDIPs 446

19.3 QD Growth 447
19.3.1 The formation of QDs in the SK growth mode 447
19.3.2 Properties of SK-grown dots and their effect on QDIP performance

19.3.2.1 QD size

19.3.2.2 QD shape

19.3.2.3 QD density

19.3.2.4 QD uniformity

19.4 Device Fabrication and Measurement Procedures

19.5 Gallium-Arsenide-based QD Detectors

19.5.1 InGaAs/InGaP QDIP

19.5.2 First QDIP FPA

19.5.3 Two-temperature barrier growth for morphology improvement

19.6 Indium-Phosphide-based QD Detectors

19.6.1 InAs/InP QDIP

19.6.2 Detection wavelength tuning using QD engineering

19.6.3 High-operating-temperature QD detector and FPA

19.6.4 High-operating-temperature FPA

19.7 Conclusion

References

20 Near-Infrared Light Detection using CMOS Silicon Avalanche Photodiodes (SiAPDs)

Ehsan Kamrani, Frédéric Lesage, and Mohamad Sawan

20.1 Introduction

20.2 Background Theory: How SiAPDs Work

20.3 Design Challenges of NIR Detectors

20.3.1 Modeling and simulation

20.3.2 Fabrication: standard and dedicated CMOS process

20.3.3 Premature-edge-breakdown (PEB) effects

20.3.4 APD structure

20.4 SiAPD Circuitry Design

20.4.1 Circuitry required for SiAPD-based front ends

20.4.2 Linear-mode SiAPD front end

20.4.3 Geiger-mode SiAPD front end

20.5 Optimally Adaptive Control for Low-Noise, Low-Power, and Fast Photodetection

20.6 Conclusion

Acknowledgment

References

21 Modulation-Doped AlGaAs/InGaAs Thermopiles (H-PILEs) for an Uncooled IR FPA Utilizing Integrated HEMT-MEMS Technology

Masayuki Abe, Kian Siong Ang, Hong Wang, and Geok Ing Ng

21.1 Introduction
21.2 Seebeck Effect Consideration 535
  21.2.1 Seebeck-coefficient diffusion component 535
  21.2.2 Seebeck-coefficient phonon-drag component 535
21.3 Device Design Consideration 536
  21.3.1 Performance of a thermoelectric sensor 536
  21.3.2 AlGaAs/InGaAs thermopile design 537
    21.3.2.1 H-PILE structure 537
    21.3.2.2 High-sensitivity performance design (type-A) 538
    21.3.2.3 High-speed performance design (type-C) 539
  21.3.3 Scaled-down approach 540
21.4 Sensor Fabrication Technology 541
21.5 Measured Sensor Performance and Discussion 542
21.6 Conclusion and Future Prospects 545
Acknowledgments 547
References 547

22 Spin–Orbit Engineering of Semiconductor Heterostructures 551
Henri-Jean Drouhin, Federico Bottegoni, Alberto Ferrari,
T. L. Hoai Nguyen, Jean-Eric Wegrowe, and Guy Fishman
22.1 Introduction 552
22.2 General Definition of Current Operators 554
  22.2.1 Current associated with a quantum-mechanical operator 554
  22.2.2 Symmetry properties of current operators 558
22.3 Probability Current Related to an Effective Hamiltonian 559
  22.3.1 The general $n^{th}$-order Hamiltonian 559
  22.3.2 Velocity operator in the presence of spin–orbit interaction 560
  22.3.3 Velocity and probability-current operators in effective Hamiltonian formalism 561
22.4 Spin-Current Operator 563
22.5 BenDaniel–Duke-like Formulation and Boundary Conditions 567
22.6 Spin-Split Evanescent States in III-V Semiconductors 571
  22.6.1 Evanescent states 571
  22.6.2 The [110] direction 574
  22.6.3 Constant-$\gamma$ case: solution to the tunneling problem 576
  22.6.4 Matching conditions 579
22.7 Conclusion 583
Appendix
  22.A Complete Derivation of the Current Operator $\hat{J}$ 584
  22.C Standard Tunneling Case 587
References 589
V Applications 595

23 Current Status of Mid-infrared Semiconductor-Laser-based Sensor Technologies for Trace-Gas Sensing Applications 597
Rafal Lewicki, Mohammad Jahjah, Yufei Ma, Przemysław Stefaniski, Jan Tarka, Manijeh Razeghi, and Frank K. Tittel

23.1 Introduction 598
23.2 Tunable Diode Laser Absorption Spectroscopy (TDLAS) for Ethane Detection 602
  23.2.1 Laser characterization 602
  23.2.2 Optical sensor architecture 603
  23.2.3 Experiments and results 604
23.3 Environmental Detection of Ammonia using an EC-QCL-based C-PAS Sensor Platform 605
  23.3.1 Sensor configuration and results 606
23.4 Quartz-Enhanced Photoacoustic Spectroscopy (QEPAS) 609
  23.4.1 Methane and nitrous oxide detection 609
    23.4.1.1 7.83-μm DFB-QCL for methane and nitrous oxide detection 609
    23.4.1.2 Experiments and results 609
  23.4.2 Environmental detection of nitric oxide 611
  23.4.3 QEPAS-based ppb-level detection of carbon monoxide and nitrous oxide 614
    23.4.3.1 CW DFB-QCL-based QEPAS sensor system for CO and N₂O 615
    23.4.3.2 Experimental results and discussion 616
  23.4.4 Sulfur dioxide experiments 620
    23.4.4.1 SO₂ QEPAS sensor architecture and performance 620
23.5 Conclusions 622
Acknowledgments 624
References 624

24 Application of Quantum Cascade Lasers for Safety and Security 633
Ulrike Willer, Mario Mordmüller, and Wolfgang Schade

24.1 Introduction 633
24.2 Pulsed Laser Fragmentation 635
24.3 Experimental Setup 635
24.4 Results 637
24.5 Discussion 639
24.6 Conclusions 641
References 641
25 Broadband-Tunable External-Cavity Quantum Cascade Lasers for Spectroscopy and Standoff Detection 645
Frank Fuchs, Stefan Hugger, Quankui Yang, Jan Jarvis, Michel Kinzer, Ralf Ostendorf, Christian Schilling, Rachid Driad, Wolfgang Bronner, Andreas Bächle, Rolf Aidam, and Joachim Wagner

25.1 Introduction 646
25.1.1 Standoff detection of explosives 647
25.1.2 In-line spectroscopy of drinking water 647
25.2 Eye Safety in the Mid-infrared Spectral Region 648
25.3 External-Cavity Quantum Cascade Laser 650
25.3.1 Broadband tuning 650
25.3.2 Fast wavelength tuning 652
25.4 Standoff Detection of Explosives 653
25.4.1 Backscattering spectroscopy 653
25.4.2 Samples 656
25.5 Hyperspectral Data Analysis 656
25.5.1 Adaptive matched subspace detector 657
25.5.2 Background endmember extraction 658
25.5.3 Reference spectra 659
25.5.4 Experimental results 659
25.5.5 Larger distances 662
25.6 Spectroscopy of Hazardous Chemicals in Drinking Water 663
25.7 Conclusions 665
Acknowledgments 665
References 666

26 Emission Spectroscopy in the Mid-infrared using FTIR Spectrometry 673
Yong-gang Zhang

26.1 Introduction 673
26.2 Overall Considerations 675
26.3 System Configuration 677
26.4 Demonstrations and Discussion 680
26.5 Summary and Future Perspectives 688
Acknowledgments 689
References 689

27 Photonic Sensing of Environmental Gaseous Nitrous Acid (HONO): Opportunities and Challenges 693
Weidong Chen, Rabih Maamary, Xiaojuan Cui, Tao Wu, Eric Fertein, Dorothée Dewaele, Fabrice Cazier, Qiaozhi Zha, Zheng Xu, Tao Wang, Yingjian Wang, Weijun Zhang, Xiaoming Gao, Wenqing Liu, and Fengzhong Dong

27.1 Introduction 694
27.2 State-of-the-Art Instruments for Measurement of Atmospheric HONO 697
27.2.1 Wet chemical analytical methods 697
27.2.2 Gas phase spectroscopic analytical methods 698
  27.2.2.1 Long-path-length-absorption-based direct spectroscopic detection (DOAS, TLAS, IBBCEAS, CRDS, FTIR) 698
  27.2.2.2 Indirect spectroscopic detection (PF-LIF, CIMS, TDC) 700
27.3 HONO Sample Production and Quantification 705
  27.3.1 Production of HONO samples in the laboratory 705
  27.3.2 Quantification of HONO concentration 706
  27.3.3 HONO losses on absorption cell wall 707
27.4 Photonic Monitoring using Infrared Laser 708
  27.4.1 Environmental HONO monitoring by multipass-cell-based long-path-absorption spectroscopy using an 8-μm QCL 708
  27.4.2 HONO monitoring near 2.8 μm 711
27.5 Photonic Monitoring using LED-based IBBCEAS 712
  27.5.1 Concentration retrieval of multiple absorbers from a structured broadband absorption spectrum 713
  27.5.2 Determination of cavity mirror reflectivity 713
  27.5.3 Allan variance 714
  27.5.4 Instrumental development and application
    27.5.4.1 Open-cavity configuration 715
    27.5.4.2 Closed-cavity configuration 718
27.6 Summary and Outlook
Acknowledgments 721
References 721

28 Integrated Plasmonic Antennas with Active Optical Devices 739
  John Kohoutek, Ryan Gelfand, and Hooman Mohseni
  28.1 Introduction 739
  28.2 Near-Field Scanning Optical Microscopy (NSOM) 743
  28.3 Optical Force 746
  28.4 Deep Subdiffraction Mechanical Frequency and Amplitude Modulation 752
  28.5 Optical Switching via Near-Field Interaction 758
  28.6 Conclusions 763
  References 764

29 Quantum-Dot Biosensors using Fluorescence Resonance Energy Transfer (FRET) 773
  James W. Garland, Dinakar Ramadurai, and Siva Sivananthan
  29.1 Introduction 773
  29.2 Conjugated QDs 776
  29.3 Fluorescence Resonance Energy Transfer (FRET) 778
29.4 Biosensor using FRET and Antibody-Conjugated QDs: Concept and Bench-top Results 779
Acknowledgments 785
29.5 EpiSENSE Prototype Biosensor for Rapid Detection of Airborne Biological Pathogens 785
29.5.1 Sensor design 786
29.5.2 Testing of the EpiSENSE biosensor 788
Acknowledgments 791
29.6 Summary 791
References 791

30 Optoelectronic Applications of Monodisperse Carbon Nanomaterials 795
Heather N. Arnold and Mark C. Hersam
30.1 Introduction 795
30.2 Monodisperse Carbon Nanomaterials 797
30.3 Assembly Strategies 799
30.4 Electronics with Semiconducting SWCNT Films 801
30.5 Optoelectronics with Semiconducting SWCNT Films 804
30.6 Applications for Metallic SWCNTs 805
30.7 Applications of Solution-Processed Graphene 807
30.8 Summary and Future Outlook 810
References 811

Color Plates

31 Design of Radial p–i–n Silicon Nanowires for High-Performance Solar Cells 823
Binh-Minh Nguyen, Jinkyoung Yoo, Shadi A. Dayeh, Paul Schuele, David Evans, and S. Tom Picraux
31.1 Introduction 824
31.2 Device Fabrication 825
31.3 Estimation of Depletion Region 827
31.4 Optical Absorption Simulation 831
31.4.1 Effect of nanowire length 832
31.4.2 Effect of pitch size 834
31.5 Conclusion and Outlook 838
Acknowledgments 839
References 839

32 Nanostructured Electrode Interfaces for Energy Applications 843
Palash Gangopadhyay, Kaushik Balakrishnan, and Nasser Peyghambarian
32.1 Introduction 843
32.2 0D Nanostructured Electrodes 848
32.3 1D Nanostructured Electrodes 850
32.4 2D Nanostructures and Nanostructured Electrodes 853
Foreword

Twenty years ago, I met with Prof. Klaus von Klitzing and Prof. Manijeh Razeghi and other top researchers from around the world for the inauguration of a new Center for Quantum Devices at Northwestern University. A full two decades of research later, we have chosen the occasion of the International Conference on Infrared Optoelectronics (MIOMD-XI) to join together again at Northwestern to celebrate all of the accomplishments of the intervening years. This conference not only marks the latest progress in new materials and devices that followed from my own work in this field, it also highlighted the richest accomplishments of a full spectrum of prominent world-class scientists.

With the success of this conference, it was decided that a more permanent volume should commemorate the achievements presented there, so as cochair of MIOMD-XI, I am happy to announce the occasion in this foreword. This book collects the best and highest-impact talks from that conference, develops them into chapters, and collects them into a single condensed volume representing the current state-of-the-art in infrared materials and devices.

The chapters in this book bear witness to how far we have come since the invention of manmade semiconductor superlattices in 1969. What started with the new physics of the Esaki tunnel diode has matured into nanoscale engineering of semiconductor superlattices to create whole synthetic band structures. After years of considerable effort to bring this technology to maturity, we now see the results of this formidable new science in almost every electronic and photonic device that we encounter. We see it in the electronics that flood the consumer market, the communication infrastructure that is rapidly shrinking our world, and in the specialized components such as quantum cascade lasers or type-II superlattice cameras used for defense and security—this is truly the age of nanotechnology. I look back with wonder at all of the exciting developments of the last 44 years and can only imagine where the future will take this technology and what exciting discoveries await.

Leo Esaki
University of Tokyo
Komaba, Meguro, Japan
Leo Esaki is a Japanese physicist who shared the Nobel Prize in Physics in 1973 with Ivar Giaever and Brian David Josephson for his discovery of the phenomenon of electron tunneling. He is known for his invention of the Esaki diode, which exploited that phenomenon. He studied physics at the University of Tokyo where he received his B.S. in 1947 and his Ph.D. in 1959. He was awarded the Nobel Prize for his research conducted around 1967 at Tokyo Tsushin Kogyo (now known as Sony). He moved to the United States in 1960 and joined the IBM T. J. Watson Research Center, where he became an IBM Fellow in 1967. While at IBM he pioneered the development of the semiconductor superlattice. Subsequently, he served as the President of various Japanese universities, for example, University of Tsukuba and Shibaura Institute of Technology. Since 2006, he has been serving as the President of the Yokohama College of Pharmacy. Esaki is also the recipient of The International Center in New York's Award of Excellence, the Order of Culture (1974) and the Grand Cordon of the Order of the Rising Sun (1998).
Preface

Nature is nano.

Nature starts with the atom, the building block of all matter, and works hand-in-hand with her partner the photon, the piece of light that communicates energy from one atom to another. When nature binds atoms together or creates physical structures in the micro- and nano-range, the combinations interact differently with light, providing nature with a rich palette of colors to decorate the world around us, while also giving rise to the functional complexity of nature. The wings of a butterfly, the feather of a peacock, the sheen of a pearl—all of these are examples of nature’s photonic crystals: nanostructured arrangements of atoms that capture and recast the colors of the rainbow with iridescent beauty. These diverse combinations of microstructures and atoms in molecules, crystals, proteins, and cells on the nanoscale eventually give rise to ourselves, sentient beings, who, in turn, strive to explain the natural world that we see around us.

As our tools to manipulate matter reach ever smaller length scales, we, too, are able to join in the game of discovery in the nano-world—a game that nature has long since mastered. We are able to get inside light, on the scale that atoms do, and create assemblies of atoms that intercept and launch photons according to the structure we design. We are able to shine light of any color in beams that can travel to the moon and back. We are able to create crystals of matter that allow us to see even invisible light in the infrared and ultraviolet spectrum, and we can enhance our own natural senses. We can map the universe with telescopes that see invisible colors, and we can probe the human body to find cures and treat diseases. We can communicate with each other faster, over ever larger distances, sharing ever more information.

As we marvel at our achievements thus far in the nano-world, and as we let our imaginations dive into realms that yesterday seemed too fantastic to consider, we must pause to remember who arrived here long before us and who still governs the limits of our ambitions.

Let us pay our due respects to wonder at nature as we contemplate the wonder of nanotechnology.

Klaus von Klitzing
Max Planck Institute for Solid State Research
Stuttgart, Germany

xxiii
Klaus von Klitzing is a German physicist known for discovery of the integer quantum Hall effect, for which he was awarded the 1985 Nobel Prize in Physics. In 1962, von Klitzing passed the Abitur at Artland Gymnasium in Quakenbrück, Germany, before studying physics at the Braunschweig University of Technology, where he received his diploma in 1969. He continued his studies at the University of Würzburg, completing his Ph.D. thesis “Galvanomagnetic Properties of Tellurium in Strong Magnetic Fields” in 1972, and habilitation in 1978. This work was performed at the Clarendon Laboratory in Oxford and the Grenoble High Magnetic Field Laboratory in France, where he continued to work until becoming a professor at the Technical University of Munich in 1980. Von Klitzing has been a director of the Max Planck Institute for Solid State Research in Stuttgart since 1985. Today, von Klitzing's research focuses on the properties of low-dimensional electronic systems, typically in low temperatures and in high magnetic fields.
Introduction

Nature offers us a full assortment of atoms, but nanoengineering is required to put them together in an elegant way to realize functional structures not found in nature. To design new optical properties, one must nanoengineer structures on a length scale smaller than the wavelength of light. To design new electronic properties, one must nanoengineer structures on a length scale smaller than the wavelength of the electron. In the end, our ability to control material composition and shape on nanometer length scales is what gives us the ability to achieve technological goals that transcend the properties of naturally occurring materials.

A particularly rich playground for nanotechnology is the so-called III-V semiconductors, made of atoms from columns III and V of the periodic table, and constituting compounds with many useful optical and electronic properties in their own right. Guided by highly accurate simulations of the electronic structure, modern semiconductor optoelectronic devices are literally made atom by atom using advanced growth technology such as molecular beam epitaxy and metal organic chemical vapor deposition to combine these materials in ways to give them new properties that neither material has on its own. Modern mastery of materials growth and characterization with the help of such techniques allows high-power and highly efficient functional devices to be made, such as those that convert electrical energy into coherent light or detect light of any wavelength and convert it into an electrical signal.

The cover of this volume shows an example of how nanoengineering can realize an optoelectronic structure originally proposed by Esaki and Tsu—a structure that signaled the very dawn of the age of nanotechnology. This so-called superlattice is a stack of repeated nanolayers of two different semiconductors GaSb and InAs, together making up a new artificial material with properties that transcend those of either material alone. As the figure shows, this material can be grown today with atomic-layer accuracy to detect infrared light. Then nanofabrication technology can carve out individual devices from such a material and connect them in an array to make the pixels of a focal plane array, nanotechnology’s version of a retina. Finally, attaching this to readout circuitry and mounting it behind a lens in a cooled chamber.
culminates in an infrared camera that sees the heat signal given off by the same hands that crafted the device from the atom up.

In a broader scope, this volume collects the latest world-class research breakthroughs that have brought quantum engineering to an unprecedented level, creating light detectors and emitters over an extremely wide spectral range from 0.2 to 300 μm. Devices include light-emitting diodes in the deep-ultraviolet to visible wavelengths. In the infrared, compounds can be nanoengineered to create quantum cascade lasers and focal plane arrays based on quantum dots or repeated layers of one material inside another. These are fast becoming the choice of technology in crucial applications such as environmental monitoring and space exploration. Last but not least, on the far-infrared end of the electromagnetic spectrum, also known as the terahertz region, new nanotechnology allows emission of terahertz waves in a compact device at room temperature. Continued effort is being devoted to all of the abovementioned areas, with the intention to develop smart technologies that meet the current challenges in environment, health, security, and energy. This volume documents the latest contributions to the world of semiconductor nanoscale optoelectronics.

The research efforts represented here share a common genesis in the MIOMD-XI conference at Northwestern University, hosted by the Center for Quantum Devices in September 2012. The novelty and quality of the work presented at that conference inspired their collection into this special volume, representing both the state-of-the-art and the future trends of nanotechnology.

It is a privilege to be able to introduce these works here for posterity so that they might mark our remarkable progress in the past decades and usher in the wonders of what nanotechnology holds in store for our future.

Manijeh Razeghi
Center for Quantum Devices
Electrical Engineering & Computer Science Department
Evanston, Illinois, USA

Manijeh Razeghi received the Doctorat d’État es Sciences Physiques from the Université de Paris, France, in 1980. After heading the Exploratory Materials Lab at Thomson-CSF (France), she joined Northwestern University, Evanston, Illinois, as a Walter P. Murphy Professor and Director of the Center for Quantum Devices in Fall 1991, where she created the undergraduate and graduate program in solid state engineering. She is one of the leading scientists in the field of semiconductor
science and technology, pioneering the development and implementation of major modern epitaxial techniques such as MOCVD, VPE, gas MBE, and MOMBE for the growth of entire compositional ranges of III-V compound semiconductors. She has authored or coauthored more than 1000 papers, more than 30 book chapters, and 15 books, including the textbooks *Technology of Quantum Devices*, Springer Science+Business Media, Inc. (2010), *Fundamentals of Solid State Engineering*, 3rd Edition, Springer Science+ Business Media, Inc. (2009), and *The MOCVD Challenge*, 2nd Edition, CRC Press (2010), which discuss some of her pioneering work in InP-GaInAsP and GaAs-GaInAsP based systems. She holds 50 U.S. patents and has given more than 1000 invited and plenary talks. Her current research interest is in nanoscale optoelectronic quantum devices.
Advances in material science at the nanometer scale are opening new doors in the area of optics and electronics. The ability to manipulate atoms and photons, and fabricate new material structures offers opportunities to realize new emitters, detectors, optics, ever-shrinking electronics, and integration of optics and electronics. These developments are making a big impact in optoelectronics and integrated circuits, among other fields. In particular, imaging technology has the opportunity to leverage these developments to produce new products for military, industrial, medical, security, and other consumer applications.

The infusion of nanotechnology in modern times has already begun. These advances are clearly evident in the visible-wavelength band due to pixel scaling and nanometer-scale CMOS technology. CMOS cameras are available in cell phones and many other consumer products. Similarly, carbon nanotubes, graphene, and quantum dots are making inroads in the displays and visible camera market. Advances in the infrared wavelengths for imaging technology have been slow due to a lack of market volume and many technological barriers in detectors and optical materials, as well as fundamental limits imposed by the scaling laws of traditional optics. However, the advances in nanometer-scale engineering coupled with innovations in photonics, optics, focal plane arrays, and computation are paving the way for new approaches in infrared research and development. There is, of course, much room for improvement in both the visible and infrared imaging technologies. Further advancement in imaging systems requires solutions for many technical challenges related to wide field of view, resolution, pixel pitch, optics, multicolor, and form factor. Innovation is also required to lower the cost of imagers. These solutions can be realized through progress in nanometer-scale science and engineering.

Traditional research and development activities in infrared photodetectors have been largely focused on pursuing bulk or epitaxially grown semiconductor layers that are reticulated to form detector arrays. Conventional photodetectors such as $p–n$ junctions and $p–i–n$ photodiodes are some of the depletion-mode devices widely used in photoreceivers and focal plane arrays.
The optics is designed as multiple lenses made from bulk materials and aligned in a barrel. However, traditional approaches are unlikely to yield large improvements in infrared camera development. Specific limitations are large format, multiple colors, and wide-band detector design with high resolution, which require incompatible materials for different colors, scaling of pixel size, and wide-band optics, to list a few. As a consequence, infrared cameras are large and expensive, and generally limited to military applications. A paradigm shift in the way components of cameras and other optoelectronic devices are made is needed to fulfill the future requirements. This shift in approach will make smaller and lower-cost infrared cameras, lasers, and many other optoelectronic products available for both civilian and military markets.

Nanotechnology is paving the way for a new dimension involving more versatile material designs that enable large format, multicolor, and wide-band infrared focal plane arrays. One example is the type-II superlattice approach that uses a set of different compound semiconductor materials to design multiple band detectors on a single substrate. The type-II superlattice technique takes advantage of nanometer-scale stacking of different exotic materials to tailor the bandgap. The nanometer-scale manipulation of different exotic materials, therefore, allows for a new material design whose optical properties can be modified from the individual bulk material. Thus, an artificially created new “lattice structure” can be formed in mixed semiconductor crystals, allowing for bandgap engineering. Another example is the nanometer-scale structuring of a thin compound semiconductor material to fabricate a photonic crystal. Subwavelength-sized semiconductor pillar arrays within a single detector can be designed and structured as an ensemble of photon trapping units to significantly increase absorption and quantum efficiency for a wide band of wavelengths. Each sub-element in each pixel can be a 3D photonic structure fabricated using either a top-down or bottom-up process. The sub-element architecture can be of different shapes such as pyramidal, sinusoidal, or rectangular. Additionally, the sub-elements themselves can have p–n junctions. The motivation for this design is to significantly increase photon trapping of a wide range of wavelengths, and their subsequent absorption and generation of electron–hole pairs in the absorber material. Such a design also leads to a reduction in the material volume and, thus, a decrease in the dark current. The subwavelength photonic trap allows for high absorption and increases the signal-to-noise ratio.

Metamaterials to manipulate light is yet another technique leveraged by nanotechnology and can be used to develop monolithic filters directly on wide-band detectors. Such an arrangement offers a real shift in the way infrared focal plane arrays are designed. Nanometer-scale structuring also has merit in solar cells, lasers, and light-emitting diodes. Bandgap engineering and nanometer-scale structuring both modify the fundamental building block of the materials.
Nanotechnology is making a significant impact in the optics field. The advances in nanophotonics and the associated physics of surface plasmon-polaritons and subwavelength-aperture extraordinary optical transmission will allow detector size to shrink smaller than the wavelength it detects. SPPs are electromagnetic excitations on the surface of a metal whose electromagnetic field is confined to the vicinity of the dielectric–metal interface, leading to a significant enhancement of the electromagnetic field. This field enhancement facilitates incident light to be funneled through subwavelength apertures exhibiting extraordinary optical transmission. Nanophotonic designs can be used to couple photons to very thin and tiny detectors. These nanometer-scale optical designs would make it possible to make very high-density, large-format focal plane arrays. Advances in the aforementioned nanotechnology, if realized with high efficiency, will open doors for infrared cameras with unprecedented form factors and functionality. These cameras could be as small as CMOS cell-phone cameras and yet provide multicolor coverage of a broad range of wavelengths in a single unit.

Efforts are underway to integrate optically efficient compound materials into an electronically mature common platform such as silicon to produce very efficient hybrid optoelectronics products. Incompatibility in different material systems has been the primary barrier in identifying a unitary host material for large-scale integration of electronics and photonics to produce efficient optoelectronic systems. Over the last ten or more years, developments and advances in the bottom-up synthesis of 1D nanowires and colloidal quantum dots with precise control on the chemical compositions, morphologies, and sizes have enabled researchers to fabricate novel nanometer-scale devices such as photodetectors, displays, nanowire field effect transistors, light-emitting diodes, complementary inverters, complex logic gates, lasers, and chemical sensors. Simultaneously, the current state-of-the-art silicon CMOS technology has already been scaled down to nanometer feature sizes and is approaching the physical lower limit of beneficial scaling. These trends motivate a search for new technologies that may allow widespread and cost-effective integration of nanometer-scale components in devices and circuits for electronic as well as optoelectronic applications. For instance, quantum dots of different sizes respond to different wavelengths. Direct integration of these quantum dots on silicon integrated circuits opens the door for a new approach to focal plane arrays and infrared cameras.

Nanometer-scale architectures play an important role in nature. Many biological systems exhibit interesting structures that manipulate light. For example, the Morpho butterflies are known for their brilliant colors arising from the nanometer nature of the scales on their wings. The Melanophila acuminata beetle, pythons, and other species use their thermal pits to sense infrared light. These thermal pits are made up of nanometer-sized pigments. Using quantum dots, bio-inspired nanometer engineering can lead to...
fabricating artificial thermal pits similar to beetles’ or pythons’ thermal pits. Biology, therefore, offers rich insight into the science and wonders of light interaction at the nanometer scale.

There is an unlimited potential in nanotechnology. Scientists have only scratched the surface. Progress in nanometer-scale fabrication will drive low-cost manufacturing and continue to open new doors in optoelectronics technology. This volume, The Wonder of Nanotechnology: Quantum Optoelectronic Devices and Applications, edited by Manijeh Razeghi, Leo Esaki, and Klaus von Klitzing presents the latest developments in the application of nanotechnology to modern semiconductor optoelectronic devices. The coeditor Prof. Razeghi is a Walter P. Murphy Professor and Director of the Center for Quantum Devices at Northwestern University. She has pioneered nanometer-scale architectures in semiconductor technology. Her research in quantum materials has culminated in various technologies such as type-II strained-layer superlattice infrared detectors, lasers, and terahertz technology, to name a few. This volume is also blessed with the participation of Nobel Prize winners, Leo Esaki and Klaus von Klitzing. Their contributions in quantum physics have revolutionized nanometer-scale science and have paved the way for nanotechnology to advance. The collection of research efforts represented here provides a glimpse of a wide range of activities in the optoelectronics science motivated by nanotechnology. The collection is compiled from a recent MIOMD-XI conference held at Northwestern University, Center for Quantum Devices in September 2012.

Nibir K. Dhar
Program Manager
Defense Advanced Research Project Agency
Arlington, Virginia, USA

Nibir K. Dhar received the Ph.D. in electrical engineering from the University of Maryland in 1997. After heading the Electro-Optics and Photonics branch at the Army Research Laboratory, he joined the Microsystems Technology Office at Defense Advanced Research Project Agency as a program manager in 2008. He is one of the leading scientists in the field of infrared imaging science and technology. He has pioneered the development of infrared focal plane arrays on silicon substrates for large-format-camera technology. He has developed and managed numerous research projects in epitaxial and bandgap-engineered materials including type-II superlattice, quantum dots, quantum wires, detectors, lasers, and systems design. His current efforts at DARPA have led to novel
architectures in focal plane array designs for wide-band and multi-color, pixel sizes at subwavelengths, wafer scale optics, wafer scale IR cameras, novel system architectures for gigapixel-class cameras, and bio-inspired nanometer-scale sensor technologies. These efforts have culminated into a new set of infrared camera technologies and tools that are revolutionizing the way focal plane arrays, optics, and cameras are produced. Dr. Dhar has authored numerous papers and chapters on infrared technology, served as chairperson on numerous conferences and committees, and served as coeditor of several conference proceedings. He mentored and served on eight doctoral thesis advisory committees on various subjects. He is also Fellow of SPIE.
List of Contributors

Masayuki Abe
3D-bio Co., Ltd., Hadano, Kanagawa, Japan

Rolf Aidam
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Kian Siong Ang
Nanyang Technological University, Singapore

Mehdi Anwar
University of Connecticut, Storrs, Connecticut, USA

Heather N. Arnold
Northwestern University, Evanston, Illinois, USA

Andreas Bächle
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Kaushik Balakrishnan
The University of Arizona, Tucson, Arizona, USA

Can Bayram
T. J. Watson Research Center, Yorktown Heights, New York, USA

J. Reinhardt Botha
Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

Federico Bottegoni
Politecnico di Milano, Milano, Italy and École Polytechnique, Palaiseau, France

Wolfgang Bronner
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Gail J. Brown
Air Force Research Laboratory, Wright-Paterson Air Force Base, Ohio, USA

Peter J. Carrington
Lancaster University, Lancaster, United Kingdom

Fabrice Cazier
University of the Littoral Opal Coast, Dunkerque, France

Oray Orkun Cellek
Arizona State University, Tempe, Arizona, USA
Weidong Chen  
University of the Littoral Opal Coast, Dunkerque, France

Hung Chi Chou  
University of Connecticut, Storrs, Connecticut, USA

Xiaojuan Cui  
University of the Littoral Opal Coast, Dunkerque, France and Nanchang Hangkong University, Nanchang, China

Leonid V. Danilov,  
Ioffe Physical Technical Institute, St. Petersburg, Russia

Shadi A. Dayeh  
Los Alamos National Laboratory, Los Alamos, New Mexico, USA and University of California, San Diego, La Jolla, California, USA

Dorothée Dewaele  
University of the Littoral Opal Coast, Dunkerque, France

Gianni Di Domenico  
Université de Neuchâtel, Neuchâtel, Switzerland

Fengzhong Dong  
Anhui Institute of Optics & Fine Mechanics, Hefei, China

Rachid Driad  
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Henri-Jean Drouhin  
École Polytechnique, Palaiseau, France

Said Elhamri  
University of Dayton, Dayton, Ohio, USA

David Evans  
Sharp Laboratories of America, Camas, Washington, USA

Jenyu Fan  
AdTech Optics, Inc., City of Industry, California, USA

Ferdinand Felder  
ETH Zurich, Zurich, Switzerland and Phocone AG, Zurich, Switzerland

Alberto Ferrari  
Politecnico di Milano, Milano, Italy

Eric Fertein  
University of the Littoral Opal Coast, Dunkerque, France

Matthias Fill  
ETH Zurich, Zurich, Switzerland and Phocone AG, Zurich, Switzerland

Guy Fishman  
Université Paris-Sud, Orsay, France

Frank Fuchs  
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany
Palash Gangopadhyay
The University of Arizona, Tucson, Arizona, USA

Xiaoming Gao
Anhui Institute of Optics & Fine Mechanics, Hefei, China

James W. Garland
Episensors, Inc., Bolingbrook, Illinois, USA and Sivananthan Laboratories, Inc., Bolingbrook, Illinois, USA

Ryan Gelfand
Northwestern University, Evanston, Illinois, USA

Matthew A. Grayson
Northwestern University, Evanston, Illinois, USA

Sarth D. Gunapala
California Institute of Technology, Pasadena, California, USA

Heather J. Haugan
Air Force Research Laboratory, Wright-Paterson Air Force Base, Ohio, USA

Manus Hayne
Lancaster University, Lancaster, United Kingdom

Mark C. Hersam
Northwestern University, Evanston, Illinois, USA

Cory J. Hill
California Institute of Technology, Pasadena, California, USA

Daniel Hofstetter
Université de Neuchâtel, Neuchâtel, Switzerland

Linda Höglund
California Institute of Technology, Pasadena, California, USA

Alice Hospodková
Institute of Physics, Prague, Czech Republic

Stefan Hugger
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Eduard Hulicius
Institute of Physics, Prague, Czech Republic

Edward V. Ivanov
Ioffe Physical Technical Institute, St. Petersburg, Russia

Mohammad Jahjah
Rice University, Houston, Texas, USA

Juanita James
Lancaster University, Lancaster, United Kingdom

Jan Jarvis
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Karina V. Kalinina
Ioffe Physical Technical Institute, St. Petersburg, Russia
<table>
<thead>
<tr>
<th>Name</th>
<th>Affiliation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ehsan Kamrani</td>
<td>École Polytechnique de Montréal, Québec, Canada</td>
</tr>
<tr>
<td>Sam A. Keo</td>
<td>California Institute of Technology, Pasadena, California, USA</td>
</tr>
<tr>
<td>Arezou Khoshakhlagh</td>
<td>California Institute of Technology, Pasadena, California, USA</td>
</tr>
<tr>
<td>Mu J. Kim</td>
<td>Air Force Research Laboratory, Wright-Paterson Air Force Base, Ohio, USA</td>
</tr>
<tr>
<td>Michel Kinzer</td>
<td>Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany</td>
</tr>
<tr>
<td>Paul Koenraad</td>
<td>Technical University of Eindhoven, Eindhoven, The Netherlands</td>
</tr>
<tr>
<td>John Kohoutek</td>
<td>Northwestern University, Evanston, Illinois, USA</td>
</tr>
<tr>
<td>Anthony Krier</td>
<td>Lancaster University, Lancaster, United Kingdom</td>
</tr>
<tr>
<td>Sanjay Krishna</td>
<td>University of New Mexico, Albuquerque, New Mexico, USA</td>
</tr>
<tr>
<td>Tim LaFave, Jr.</td>
<td>University of Texas at Dallas, Richardson, Texas, USA</td>
</tr>
<tr>
<td>Frédéric Lesage</td>
<td>École Polytechnique de Montréal, Québec, Canada</td>
</tr>
<tr>
<td>Rafal Lewicki</td>
<td>Rice University, Houston, Texas, USA</td>
</tr>
<tr>
<td>Hua Li</td>
<td>Arizona State University, Tempe, Arizona, USA</td>
</tr>
<tr>
<td>John K. Liu</td>
<td>California Institute of Technology, Pasadena, California, USA</td>
</tr>
<tr>
<td>Shi Liu</td>
<td>Arizona State University, Tempe, Arizona, USA</td>
</tr>
<tr>
<td>Wenqing Liu</td>
<td>Anhui Institute of Optics &amp; Fine Mechanics, Hefei, China</td>
</tr>
<tr>
<td>Arkadiy Lyakh</td>
<td>Pranalytica, Inc., Santa Monica, California, USA</td>
</tr>
<tr>
<td>Yufei Ma</td>
<td>Rice University, Houston, Texas, USA and Harbin Institute of Technology, Harbin, China</td>
</tr>
<tr>
<td>Rabih Maamary</td>
<td>University of the Littoral Opal Coast, Dunkerque, France</td>
</tr>
<tr>
<td>Krishnamurthy Mahalingam</td>
<td>Air Force Research Laboratory, Wright-Paterson Air Force Base, Ohio, USA</td>
</tr>
</tbody>
</table>
Richard Maulini  
Pranalytica, Inc., Santa Monica, California, USA

Anas Mazady  
University of Connecticut, Storrs, Connecticut, USA

Maya P. Mikhailova,  
Ioffe Physical Technical Institute, St. Petersburg, Russia

William C. Mitchel,  
Air Force Research Laboratory, Wright-Paterson Air Force Base, Ohio, USA

Hooman Mohseni  
Northwestern University, Evanston, Illinois, USA

Mario Mordmüller  
Clausthal University of Technology, Clausthal-Zellerfeld, Germany

Jason M. Mumolo  
California Institute of Technology, Pasadena, California, USA

Geok Ing Ng  
Nanyang Technological University, Singapore

Binh-Minh Nguyen  
Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Jean Nguyen  
California Institute of Technology, Pasadena, California, USA

T. L. Hoai Nguyen  
Institute of Physics, Hanoi, Vietnam

Ralf Ostendorf  
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Jiří Pangráč  
Institute of Physics, Prague, Czech Republic

C. Kumar N. Patel  
Pranalytica, Inc., Santa Monica, California, USA and University of California, Los Angeles, USA

Nasser Peyghambarian  
The University of Arizona, Tucson, Arizona, USA

S. Tom Picraux  
Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Elena A. Plis  
University of New Mexico, Albuquerque, New Mexico, USA

Lu Qi  
Lancaster University, Lancaster, United Kingdom

Sir B. Rafol  
California Institute of Technology, Pasadena, California, USA

Dinakar Ramadurai  
Episensors, Inc., Bolingbrook, Illinois, USA and Sivananthan Laboratories, Inc., Bolingbrook, Illinois, USA

Ari Handono Ramelan  
Sebelas Maret University, Surakarta, Indonesia
List of Contributors

Manijeh Razeghi
Northwestern University, Evanston, Illinois, USA

Antoni Rogalski
Military University of Technology, Warsaw, Poland

Devendra K. Sadana
T. J. Watson Research Center, Yorktown Heights, New York, USA

Mohamad Sawan
École Polytechnique de Montréal, Québec, Canada

Wolfgang Schade
Clausthal University of Technology, Clausthal-Zellerfeld, Germany and Fraunhofer Heinrich Hertz Institute, Goslar, Germany

Christian Schilling
Fraunhofer Institute for Applied Solid State Physics, Freiburg, Germany

Stéphane Schilt
Université de Neuchâtel, Neuchâtel, Switzerland

Paul Schuele
Sharp Laboratories of America, Camas, Washington, USA

Xiaomeng Shen
Arizona State University, Tempe, Arizona, USA

Siva Sivananthan
Sivananthan Laboratories, Inc., Bolingbrook, Illinois, USA and University of Illinois at Chicago, Chicago, Illinois, USA

Erwin Smakman
Technical University of Eindhoven, Eindhoven, The Netherlands

David J. Smith
Arizona State University, Tempe, Arizona, USA

Alexander Soibel
California Institute of Technology, Pasadena, California, USA

Elizabeth H. Steenbergen
Air Force Research Laboratory, Wright Patterson Air Force Base, Ohio, USA

Przemysław Stefanński
Rice University, Houston, Texas, USA and Wroclaw University of Technology, Wroclaw, Poland

Nikolay D. Stoyanov,
Ioffe Physical Technical Institute, St. Petersburg, Russia

Frank Szmulowicz
Air Force Research Laboratory, Wright-Paterson Air Force Base, Ohio, USA

Boris Tadjikov
Pranalytica, Inc., Santa Monica, California, USA

Jan Tarka
Rice University, Houston, Texas, USA and Wroclaw University of Technology, Wroclaw, Poland
List of Contributors

William E. Tennant
Teledyne Imaging Sensors,
Camarillo, California,
USA

David Z. Ting
California Institute of Technology,
Pasadena, California, USA

Frank K. Tittel
Rice University, Houston, Texas,
USA

Lionel Tombez
Université de Neuchâtel, Neuchâtel,
Switzerland

Mariano Troccoli
AdTech Optics, Inc., City of
Industry, California, USA

Stanley Tsao
Northwestern University, Evanston,
Illinois, USA

Alexei Tsekoun
Pranalytica, Inc., Santa Monica,
California, USA

Raphael Tsu
University of North Carolina at
Charlotte, Charlotte, North
Carolina, USA

Gene Tsvid
AdTech Optics, Inc., City of
Industry, California, USA

Magnus C. Wagener
Nelson Mandela Metropolitan
University, Port Elizabeth,
South Africa

Joachim Wagner
Fraunhofer Institute for Applied
Solid State Physics, Freiburg,
Germany

Hong Wang
Nanyang Technnological
University, Singapore

Tao Wang
The Hong Kong Polytechnic
University, Hong Kong, China

Xiaojun Wang
AdTech Optics, Inc., City of
Industry, California, USA

Yingjian Wang
Anhui Institute of Optics & Fine
Mechanics, Hefei, China

Jean-Eric Wegrowe
École Polytechnique, Palaiseau,
France

Ulrike Willer
Clausthal University of Technology,
Clausthal-Zellerfeld, Germany

Zheng Xu
The Hong Kong Polytechnic
University, Hong Kong,
China

Yury P. Yakovlev
Ioffe Physical Technical Institute,
St. Petersburg, Russia

Quankui Yang
Fraunhofer Institute for Applied
Solid State Physics, Freiburg,
Germany
Jinkyoung Yoo
Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Robert J. Young,
Lancaster University, Lancaster, United Kingdom

Georgy G. Zegrya
Ioffe Physical Technical Institute, St. Petersburg, Russia

John Zeller
Magnolia Optical Technologies, Inc., Woburn, Massachusetts, USA

Qiaozhi Zha
The Hong Kong Polytechnic University, Hong Kong, China

Weijun Zhang
Anhui Institute of Optics & Fine Mechanics, Hefei, China

Yong-gang Zhang
Shanghai Institute of Microsystem and Information Technology, Shanghai, China

Yong-Hang Zhang
Arizona State University, Tempe, Arizona, USA

Chuanle Zhou
Northwestern University, Evanston, Illinois, USA

Qiandong Zhuang,
Lancaster University, Lancaster, United Kingdom

Markéta Zíková
Institute of Physics, Prague, Czech Republic

Hans Zogg
ETH Zurich, Zurich Switzerland