

INFRARED DETECTORS

SECOND EDITION



ANTONI ROGALSKI



CRC Press
Taylor & Francis Group

INFRARED DETECTORS

SECOND EDITION

ANTONI ROGAIŃSKI



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2011 by Taylor and Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed in the United States of America on acid-free paper
10 9 8 7 6 5 4 3 2 1

International Standard Book Number: 978-1-4200-7671-4 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com ([http://www.copyright.com/](http://www.copyright.com)) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Rogalski, Antoni.
Infrared detectors / Antoni Rogalski. -- 2nd ed.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-4200-7671-4 (hardcover : alk. paper)
1. Infrared detectors. I. Title.

TA1570.R63 2011
621.36'2--dc22

2010029532

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>

and the CRC Press Web site at
<http://www.crcpress.com>

Preface

Progress in infrared (IR) detector technology has been mainly connected to semiconductor IR detectors, which are included in the class of photon detectors. They exhibit both perfect signal-to-noise performance and a very fast response. But to achieve this, the photon detectors require cryogenic cooling. Cooling requirements are the main obstacle to the more widespread use of IR systems based on semiconductor photodetectors making them bulky, heavy, expensive, and inconvenient to use.

Until the 1990s, despite numerous research initiatives and the appeal of room temperature operation and low cost potential, thermal detectors have enjoyed limited success compared with cooled photon detectors for thermal imaging applications. Only the pyroelectric vidicon received much attention with the hope that it could be made practical for some applications. Throughout the 1980s and early 1990s, many companies in the United States (especially Texas Instruments and Honeywell's Research Laboratory) developed devices based on various thermal detection principles. In the mid-1990s, this success caused DARPA (Defense Advanced Research Projects Agency) to reduce support for HgCdTe and attempt a major leap with uncooled technology. The desire was to have producible arrays with useful performance, without the burden of fast ($f/1$) long-wavelength infrared optics.

In order to access these new changes in infrared detector technology, there was need for a comprehensive introductory account of IR detector physics and operational principles, together with important references. In 2000, the first edition of *Infrared Detectors* was published with the intention of meeting this need. The last decade has seen considerable changes with numerous breakthroughs in detector concepts and performance. It became clear that the book needed substantial revision to continue to serve its purpose.

In this second edition of *Infrared Detectors*, about 70% of the contents have been revised and updated, and much of the materials have been reorganized. The book is divided into four parts: fundamentals of infrared detection, infrared thermal detectors, infrared photon detectors, and focal plane arrays. The first part provides a tutorial introduction to the technical topics that are fundamental to a thorough understanding of different types of IR detectors and systems. The second part presents theory and technology of different types of thermal detectors. The third part covers theory and technology of photon detectors. The last part concerns IR focal plane arrays (FPAs) where relations between the performance of detector arrays and infrared system quality are considered.

The short description below mainly concerns differences between the original edition and this revision. I have added a discussion of radiometry and flux-transfer issues needed for IR detector and system analysis in the first part. In the next two parts, in addition to updating traditional issues described in the previous book, I have included new achievements and trends in the development of IR detectors, most notably:

- novel uncooled detectors (e.g., cantilever detectors, antenna and optically coupled detectors);
- type II superlattice detectors; and
- quantum dot infrared detectors.

In addition, I have highlighted new approaches to terahertz (THz) arrays and a new generation of infrared detectors—so-called third-generation detectors. THz technologies are now receiving increasing attention, and devices exploiting this wavelength band are set to become increasingly important in a diverse range of human activity applications (e.g., security, biological, drugs and explosion detection, gases fingerprints, imaging, etc.). Today, researchers are developing third-generation systems that provide enhanced capabilities such as a larger number of pixels, higher frame rates, better thermal resolution, multicolor functionality, and other on-chip functions.

This book is written for those who desire a comprehensive analysis of the latest developments in infrared detector technology and basic insight into fundamental processes important to evolving detection techniques. Special attention has been given to the physical limits of detector performance and comparisons of performance in different types of detectors. The reader should gain a good understanding of the similarities and contrasts, the strengths and weaknesses of a multitude of approaches that have been developed over a century to improve our ability to sense IR radiation.

The level of presentation is suitable for graduate students in physics and engineering who have received standard preparation in modern solid-state physics and electronic circuits. This book

is also of interest to individuals working with aerospace sensors and systems, remote sensing, thermal imaging, military imaging, optical telecommunications, infrared spectroscopy, and light detection and ranging (LIDAR). To satisfy the needs of the first group, many chapters discuss the principles underlying each topic and some historical background before bringing the reader the most recent information available. For those currently in the field, the book can be used as a collection of useful data, as a guide to the literature, and as an overview of topics covering a wide range of applications. The book could also be used as a reference for participants of relevant workshops and short courses.

This new edition of *Infrared Detectors* gives a comprehensive analysis of the latest developments in IR detector technology and basic insight into the fundamental processes important to evolving detection techniques. The book covers a broad spectrum of IR detectors, including theory, types of materials and their physical properties, and detector fabrication.

Antoni Rogalski

Acknowledgments

In the course of this writing, many people have assisted me and offered their support. I would like, first, to express my appreciation to the management of the Institute of Applied Physics, Military University of Technology, Warsaw, for providing the environment in which I worked on the book. The writing of the book has been partially done under financial support of the Polish Ministry of Sciences and Higher Education, Key Project POIG.01.03.01-14-016/08 "New Photonic Materials and Their Advanced Application."

The author has benefited from the kind cooperation of many scientists who are actively working in infrared detector technologies. The preparation of this book was aided by many informative and stimulating discussions with the author's colleagues at the Institute of Applied Physics, Military University of Technology in Warsaw. The author thanks the following individuals for providing preprints, unpublished information, and in some cases original figures, which were used in preparing the book: Drs. L. Faraone and J. Antoszewski (University of Western Australia, Perth), Dr. J. L. Tissot (Ulis, Voroize, France), Dr. S. D. Gunapala (California Institute of Technology, Pasadena), Dr. M. Kimata (Ritsumeikan University, Shiga, Japan), Dr. M. Razeghi (Northwestern University, Evanston, Illinois), Drs. M. Z. Tidrow and P. Norton (U.S. Army RDECOM CERDEC NVESD, Fort Belvoir, Virginia), Dr. S. Krishna (University of New Mexico, Albuquerque), Dr. H. C. Liu (National Research Council, Ottawa, Canada), G. U. Perera (Georgia State University, Atlanta), Professor J. Piotrowski (Vigo System Ltd., Ożarów Mazowiecki, Poland), Dr. M. Reine (Lockheed Martin IR Imaging Systems, Lexington, Massachusetts), Dr. F. F. Sizov (Institute of Semiconductor Physics, Kiev, Ukraine), and Dr. H. Zogg (AFIF at Swiss Federal Institute of Technology, Zürich). Thanks also to CRC Press, especially Luna Han, who encouraged me to undertake this new edition and for her cooperation and care in publishing this second edition.

Ultimately, it is the encouragement, understanding, and support of my family that provided me the courage to embark on this project and see it to its conclusion.

About the Author



Antoni Rogalski is a professor at the Institute of Applied Physics, Military University of Technology in Warsaw, Poland. He is a leading researcher in the field of IR optoelectronics. During the course of his scientific career, he has made pioneering contributions in the areas of theory, design, and technology of different types of IR detectors. In 1997, he received an award from the Foundation for Polish Science (the most prestigious scientific award in Poland) for achievements in the study of ternary alloy systems for infrared detectors—mainly an alternative to HgCdTe new ternary alloy detectors such as lead salts, InAsSb, HgZnTe, and HgMnTe. In 2004, he was elected as a corresponding member of the Polish Academy of Sciences.

Professor Rogalski's scientific achievements include determining the fundamental physical parameters of InAsSb, HgZnTe, HgMnTe, and lead salts; estimating the ultimate performance of ternary alloy detectors; elaborating on studies of high-quality PbSnTe, HgZnTe, and HgCdTe photodiodes operated in 3–5 μm and 8–12 μm spectral ranges; and conducting comparative studies of the performance limitation of HgCdTe photodiodes versus other types of photon detectors (especially QWIP and QDIP IR detectors).

Professor Rogalski has given about 50 invited plenary talks at international conferences. He is author and co-author of over 200 scientific papers, 11 books, and 13 book chapters. He is a fellow of the International Society for Optical Engineering (SPIE), vice president of the Polish Optoelectronic Committee, vice president of the Electronic and Telecommunication Division at the Polish Academy of Science, editor-in-chief of the journal *Opto-Electronics Review*, deputy editor-in-chief of the *Bulletin of the Polish Academy of Sciences: Technical Sciences*, and a member of the editorial boards of *Journal of Infrared and Millimeter Waves* and *International Review of Physics*.

Professor Rogalski is an active member of the international technical community. He is a chair and co-chair, organizer and member of scientific committees of many national and international conferences on optoelectronic devices and material sciences.

Table of Contents

Prefacexvii

Acknowledgments xix

About the Author xxi

Part I: Fundaments of Infrared Detection 1

1. Radiometry 2

1.1 Radiometric and Photometric Quantities and Units 2

1.2 Definitions of Radiometric Quantities 4

1.3 Radiance..... 7

1.4 Blackbody Radiation 10

1.5 Emissivity 13

1.6 Infrared Optics 15

1.7 Some Radiometric Aspects of Infrared Systems 17

1.7.1 Night-Vision System Concepts 17

1.7.2 Atmospheric Transmission and Infrared Bands 18

1.7.3 Scene Radiation and Contrast..... 20

References 21

2. Infrared Detector Characterization..... 23

2.1 Historical Aspects of Modern Infrared Technology..... 24

2.2 Classification of Infrared Detectors..... 28

2.3 Cooling of IR Detectors 31

2.3.1 Cryogenic Dewars..... 32

2.3.2 Joule–Thompson Coolers..... 32

2.3.3 Stirling Cycle Coolers..... 32

2.3.4 Peltier Coolers 33

2.4 Detector Figures of Merit 33

2.4.1 Responsivity 34

2.4.2 Noise Equivalent Power..... 34

2.4.3 Detectivity 34

2.5 Fundamental Detectivity Limits 35

References 40

3. Fundamental Performance Limitations of Infrared Detectors 45

3.1 Thermal Detectors 45

3.1.1 Principle of Operation 45

3.1.2 Noise Mechanisms 48

3.1.3 Detectivity and Fundamental Limits..... 49

3.2 Photon Detectors 53

3.2.1 Photon Detection Process 53

3.2.2 Theoretical Model of Photon Detectors..... 56

3.2.2.1	Optical Generation Noise	58
3.2.2.2	Thermal Generation and Recombination Noise	59
3.2.3	Optimum Thickness of Photodetector	60
3.2.4	Detector Material Figure of Merit	60
3.2.5	Reducing Device Volume to Enhance Performance	62
3.3	Comparison of Fundamental Limits of Photon and Thermal Detectors.	65
3.4	Modeling of Photodetectors	69
	References	71
4.	Heterodyne Detection	75
	References	83
Part II: Infrared Thermal Detectors.		87
5.	Thermopiles.	88
5.1	Basic Principle and Operation of Thermopiles	88
5.2	Figures of Merit.	91
5.3	Thermoelectric Materials	93
5.4	Micromachined Thermopiles.	96
5.4.1	Design Optimization	97
5.4.2	Thermopile Configurations.	98
5.4.3	Micromachined Thermopile Technology	98
	References	101
6.	Bolometers	104
6.1	Basic Principle and Operation of Bolometers.	104
6.2	Types of Bolometers	107
6.2.1	Metal Bolometers	107
6.2.2	Thermistors	107
6.2.3	Semiconductor Bolometers	108
6.2.4	Micromachined Room Temperature Silicon Bolometers	111
6.2.4.1	Bolometer Sensing Materials	114
6.2.4.2	Vanadium Oxide.	114
6.2.4.3	Amorphous Silicon	115
6.2.4.4	Silicon Diodes	116
6.2.4.5	Other Materials.	116
6.2.5	Superconducting Bolometers	117
6.2.6	High-Temperature Superconducting Bolometers	121
6.3	Hot Electron Bolometers	126
	References	130
7.	Pyroelectric Detectors	138
7.1	Basic Principle and Operation of Pyroelectric Detectors.	138
7.1.1	Responsivity	139
7.1.2	Noise and Detectivity.	142
7.2	Pyroelectric Material Selection.	144

7.2.1	Single Crystals	145
7.2.2	Pyroelectric Polymers	147
7.2.3	Pyroelectric Ceramics	147
7.2.4	Dielectric Bolometers	148
7.2.5	Choice of Material	152
7.3	Pyroelectric Vidicon	152
	References	153
8.	Novel Thermal Detectors	157
8.1	Golay Cell	157
8.2	Novel Uncooled Detectors	157
8.2.1	Electrically Coupled Cantilevers	160
8.2.2	Optically Coupled Cantilevers	163
8.2.3	Pyro-Optical Transducers	166
8.2.4	Antenna-Coupled Microbolometers	168
8.3	Comparison of Thermal Detectors	169
	References	171
	Part III: Infrared Photon Detectors	175
9.	Theory of Photon Detectors	176
9.1	Photoconductive Detectors	176
9.1.1	Intrinsic Photoconductivity Theory	176
9.1.1.1	Sweep-Out Effects	178
9.1.1.2	Noise Mechanisms in Photoconductors	180
9.1.1.3	Quantum Efficiency	182
9.1.1.4	Ultimate Performance of Photoconductors	183
9.1.1.5	Influence of Background	184
9.1.1.6	Influence of Surface Recombination	184
9.1.2	Extrinsic Photoconductivity Theory	185
9.1.3	Operating Temperature of Intrinsic and Extrinsic Infrared Detectors	194
9.2	p-n Junction Photodiodes	197
9.2.1	Ideal Diffusion-Limited p-n Junctions	198
9.2.1.1	Diffusion Current	198
9.2.1.2	Quantum Efficiency	201
9.2.1.3	Noise	202
9.2.1.4	Detectivity	203
9.2.2	Real p-n Junctions	205
9.2.2.1	Generation-Recombination Current	206
9.2.2.2	Tunneling Current	208
9.2.2.3	Surface Leakage Current	210
9.2.2.3	Space-Charge Limited Current	211
9.2.3	Response Time	213

9.3	p-i-n Photodiodes	214
9.4	Avalanche Photodiodes	216
9.5	Schottky-Barrier Photodiodes	222
9.5.1	Schottky-Mott Theory and Its Modifications	222
9.5.2	Current Transport Processes	223
9.5.3	Silicides	225
9.6	Metal-Semiconductor-Metal Photodiodes	226
9.7	MIS Photodiodes	227
9.8	Nonequilibrium Photodiodes	232
9.9	nBn Detector	233
9.10	Photoelectromagnetic, Magnetoconcentration, and Dember Detectors	234
9.10.1	Photoelectromagnetic Detectors	235
9.10.1.1	PEM Effect	235
9.10.1.2	Lile Solution	236
9.10.1.3	Fabrication and Performance	238
9.10.2	Magnetoconcentration Detectors	239
9.10.3	Dember Detectors	240
9.11	Photon-Drag Detectors	242
	References	245
10.	Intrinsic Silicon and Germanium Detectors	256
10.1	Silicon Photodiodes	256
10.2	Germanium Photodiodes	264
10.3	SiGe Photodiodes	266
	References	269
11.	Extrinsic Silicon and Germanium Detectors	272
11.1	Technology	273
11.2	Peculiarities of the Operation of Extrinsic Photodetectors	274
11.3	Performance of Extrinsic Photoconductors	276
11.3.1	Silicon-Doped Photoconductors	276
11.3.2	Germanium-Doped Photoconductors	278
11.4	Blocked Impurity Band Devices	280
11.5	Solid-State Photomultipliers	284
	References	285
12.	Photoemissive Detectors	290
12.1	Internal Photoemission Process	290
12.1.1	Scattering Effects	294
12.1.2	Dark Current	296
12.1.3	Metal Electrodes	297
12.2	Control of Schottky-Barrier Detector Cutoff Wavelength	298
12.3	Optimized Structure and Fabrication of Schottky-Barrier Detectors	299
12.4	Novel Internal Photoemissive Detectors	300

12.4.1	Heterojunction Internal Photoemissive Detectors	300
12.4.2	Homojunction Internal Photoemissive Detectors	301
	References	303
13.	III-V Detectors	309
13.1	Some Physical Properties of III-V Narrow Gap Semiconductors	309
13.2	InGaAs Photodiodes	315
13.2.1	p-i-n InGaAs Photodiodes	316
13.2.2	InGaAs Avalanche Photodiodes	318
13.3	Binary III-V Detectors	321
13.3.1	InSb Photoconductive Detectors	321
13.3.2	InSb Photoelectromagnetic Detectors	322
13.3.3	InSb Photodiodes	324
13.3.4	InAs Photodiodes	331
13.3.5	InSb Nonequilibrium Photodiodes	335
13.4	Ternary and Quaternary III-V Detectors	337
13.4.1	InAsSb Detectors	339
13.4.1.1	InAsSb Photoconductors	339
13.4.1.2	InAsSb Photodiodes	341
13.4.2	Photodiodes Based on GaSb-Related Ternary and Quaternary Alloys	348
13.5	Novel Sb-Based III-V Narrow Gap Photodetectors	350
13.5.1	InTlSb and InTlP	350
13.5.2	InSbBi	351
13.5.3	InSbN	352
	References	352
14.	HgCdTe Detectors	366
14.1	HgCdTe Historical Perspective	366
14.2	HgCdTe: Technology and Properties	369
14.2.1	Phase Diagrams	369
14.2.2	Outlook on Crystal Growth	370
14.2.3	Defects and Impurities	376
14.2.3.1	Native Defects	376
14.2.3.2	Dopants	378
14.3	Fundamental HgCdTe Properties	379
14.3.1	Energy Bandgap	379
14.3.2	Mobilities	380
14.3.3	Optical Properties	383
14.3.4	Thermal Generation-Recombination Processes	387
14.3.4.1	Shockley-Read Processes	387
14.3.4.2	Radiative Processes	389
14.3.4.3	Auger Processes	389
14.4	Auger-Dominated Photodetector Performance	391

14.4.1	Equilibrium Devices	391
14.4.2	Nonequilibrium Devices	392
14.5	Photoconductive Detectors	394
14.5.1	Technology	394
14.5.2	Performance of Photoconductive Detectors	396
14.5.2.1	Devices for Operation at 77 K	396
14.5.2.2	Devices for Operation above 77 K	400
14.5.3	Trapping-Mode Photoconductors	402
14.5.4	Excluded Photoconductors	402
14.5.5	SPRITE Detectors	406
14.6	Photovoltaic Detectors	410
14.6.1	Junction Formation	411
14.6.1.1	Hg In-Diffusion	411
14.6.1.2	Ion Milling	412
14.6.1.3	Ion Implantation	412
14.6.1.4	Reactive Ion Etching	415
14.6.1.5	Doping during Growth	416
14.6.1.6	Passivation	417
14.6.1.7	Contact Metallization	419
14.6.2	Fundamental Limitation to HgCdTe Photodiode Performance	420
14.6.3	Nonfundamental Limitation to HgCdTe Photodiode Performance	432
14.6.4	Avalanche Photodiodes	437
14.6.5	Auger-Suppressed Photodiodes	442
14.6.6	MIS Photodiodes	446
14.6.7	Schottky-Barrier Photodiodes	448
14.7	Hg-Based Alternative Detectors	449
14.7.1	Crystal Growth	450
14.7.2	Physical Properties	451
14.7.3	HgZnTe Photodetectors	453
14.7.4	HgMnTe Photodetectors	454
	References	456
15.	IV-VI Detectors	485
15.1	Material Preparation and Properties	485
15.1.1	Crystal Growth	485
15.1.2	Defects and Impurities	488
15.1.3	Some Physical Properties	489
15.1.4	Generation-Recombination Processes	494
15.2	Polycrystalline Photoconductive Detectors	498
15.2.1	Deposition of Polycrystalline Lead Salts	498
15.2.2	Fabrication	499
15.2.3	Performance	501

15.3	p-n Junction Photodiodes	501
15.3.1	Performance Limit	502
15.3.2	Technology and Properties	507
15.3.2.1	Diffused Photodiodes	510
15.3.2.2	Ion Implantation	512
15.3.2.3	Heterojunctions	512
15.4	Schottky-Barrier Photodiodes	514
15.4.1	Schottky-Barrier Controversial Issue	514
15.4.2	Technology and Properties	517
15.5	Unconventional Thin Film Photodiodes	522
15.5	Tunable Resonant Cavity Enhanced Detectors	525
15.6	Lead Salts Versus HgCdTe	527
	References	529
16.	Quantum Well Infrared Photodetectors	542
16.1	Low Dimensional Solids: Background	542
16.2	Multiple Quantum Wells and Superlattices	548
16.2.1	Compositional Superlattices	548
16.2.2	Doping Superlattices	549
16.2.3	Intersubband Optical Transitions	551
16.2.4	Intersubband Relaxation Time	555
16.3	Photoconductive QWIP	556
16.3.1	Fabrication	557
16.3.2	Dark Current	558
16.3.3	Photocurrent	564
16.3.4	Detector Performance	566
16.3.5	QWIP versus HgCdTe	570
16.4	Photovoltaic QWIP	573
16.5	Superlattice Miniband QWIPs	575
16.6	Light Coupling	577
16.7	Related Devices	580
16.7.1	p-Doped GaAs/AlGaAs QWIPs	580
16.7.2	Hot-Electron Transistor Detectors	581
16.7.3	SiGe/Si QWIPs	582
16.7.4	QWIPs with Other Material Systems	584
16.7.5	Multicolor Detectors	585
16.7.6	Integrated QWIP-LED	588
	References	589
17.	Superlattice Detectors	601
17.1	HgTe/HgCdTe Superlattice	601
17.1.1	Material Properties	601
17.1.2	Superlattice Photodiodes	604

17.2	Strained Layer Superlattices.	608
17.3	InAsSb/InSb Strained Layer Superlattice Photodiodes.	609
17.4	InAs/GaInSb Type II Strained Layer Superlattices	611
17.4.1	Material Properties.	611
17.4.2	Superlattice Photodiodes.	615
17.4.3	nBn Superlattice Detectors	620
	References	622
18.	Quantum Dot Infrared Photodetectors	629
18.1	QDIP Preparation and Principle of Operation	629
18.2	Anticipated Advantages of QDIPs	631
18.3	QDIP Model	632
18.4	Performance of QDIPs.	638
18.4.1	R_cA Product.	638
18.4.2	Detectivity at 78 K	638
18.4.3	Performance at Higher Temperature.	639
	References	641
	Part IV: Focal Plane Arrays	645
19.	Overview of Focal Plane Array Architectures.	646
19.1	Overview.	646
19.2	Monolithic FPA Architectures.	650
19.2.1	CCD Devices	653
19.2.2	CMOS Devices	657
19.3	Hybrid Focal Plane Arrays.	660
19.3.1	Interconnect Techniques	660
19.3.2	Readout Integrated Circuits	662
19.4	Performance of Focal Plane Arrays.	665
19.4.1	Noise Equivalent Difference Temperature.	667
19.4.2	NEDT Limited by Readout Circuit	670
19.4.2.1	Readout Limited NEDT for HgCdTe Photodiode and QWIP	671
19.5	Minimum Resolvable Difference Temperature.	673
19.6	Adaptive Focal Plane Arrays	673
	References	676
20.	Thermal Detector Focal Plane Arrays.	680
20.1	Thermopile Focal Plane Arrays.	681
20.2	Bolometer Focal Plane Arrays	686
20.2.1	Manufacturing Techniques.	689
20.2.2	FPA Performance	692
20.2.3	Packaging.	696
20.3	Pyroelectric Focal Plane Arrays	697
20.3.1	Linear Arrays	697
20.3.2	Hybrid Architecture.	698
20.3.3	Monolithic Architecture	701

20.3.4 Outlook on Commercial Market of Uncooled Focal Plane Arrays 703

20.4 Novel Uncooled Focal Plane Arrays 705

References 707

21. Photon Detector Focal Plane Arrays 715

21.1 Intrinsic Silicon and Germanium Arrays 715

21.2 Extrinsic Silicon and Germanium Arrays 719

21.3 Photoemissive Arrays 725

21.4 III-V Focal Plane Arrays 731

21.4.1 InGaAs Arrays 731

21.4.2 InSb Arrays 735

21.4.2.1 Hybrid InSb Focal Plane Arrays 735

21.4.2.2 Monolithic InSb Arrays 738

21.5 HgCdTe Focal Plane Arrays 742

21.5.1 Monolithic FPAs 744

21.5.2 Hybrid FPAs 745

21.6 Lead Salt Arrays 751

21.7 QWIP Arrays 755

21.8 InAs/GaInSb SLS Arrays 759

References 762

22. Terahertz Detectors and Focal Plane Arrays 776

22.1 Direct and Heterodyne Terahertz Detection: General Considerations 778

22.2 Schottky-Barrier Structures 780

22.3 Pair-Braking Photon Detectors 784

22.4 Thermal Detectors 786

22.4.1 Semiconductor Bolometers 787

22.4.2 Superconducting Hot-Electron Bolometers 790

22.4.3 Transition Edge Sensor Bolometers 792

22.5 Field Effect Transistor Detectors 795

22.6 Conclusions 798

References 799

23. Third-Generation Infrared Detectors 808

23.1 Benefits of Multicolor Detection 808

23.2 Requirements of Third-Generation Detectors 810

23.3 HgCdTe Multicolor Detectors 812

23.3.1 Dual-Band HgCdTe Detectors 813

23.3.2 Three-Color HgCdTe Detectors 821

23.4 Multiband QWIPs 822

23.5 Type-II InAs/GaInSb Dual-Band Detectors 832

23.6 Multiband QDIPs 836

References 839

Final Remarks 846

Index 849

PART I

FUNDAMENTS OF

INFRARED DETECTION