

Infrared Detectors

A. Rogalski

Electrocomponent Science Monographs

Gordon and Breach Science Publishers

INFRARED DETECTORS

A. ROGALSKI

*Military University of Technology
Warsaw, Poland*

GORDON AND BREACH SCIENCE PUBLISHERS

Australia • Canada • France • Germany • India • Japan • Luxembourg
Malaysia • The Netherlands • Russia • Singapore • Switzerland

Contents

Introduction to the Series	xiii
Foreword	xv
Preface	xvii
Acknowledgments	xix
Part I. Introduction	
1. Infrared Detector Characterization	3
1.1. Historical background	3
1.2. General classification of IR detectors	11
1.3. Figures of merit	14
1.3.1. Responsivity	15
1.3.2. Noise equivalent power	15
1.3.3. Detectivity	16
1.3.4. Performance of IR systems	20
1.3.5. Comments on D^* and NETD values	25
References	26
2. Focal Plane Arrays	31
2.1. Overview of focal plane array architectures	34
2.2. Monolithic focal plane arrays	39
2.2.1. Charge coupled devices	39
2.2.2. Charge injection devices	41
2.2.3. Charge imaging matrixes	43
2.2.4. Silicon FPAs: IT-CCD, CSD, and MOS FPAs	44
2.2.5. Direct-charge-injection silicon FPAs	46
2.3. Hybrid focal plane arrays	46
2.3.1. Direct injection	48
2.3.2. Buffered direct injection	50
2.3.3. Gate modulation	51
2.4. Maturity, cost, applications and technology directions	51
References	57
Part II. Infrared Thermal Detectors	
3. Theory of Thermal Detectors	65
3.1. Principle of operation of thermal detectors	66
3.2. Noise mechanisms in thermal detectors	69

3.3. Detectivity and fundamental limits	71
References	75
4. Thermopiles	77
4.1. Basic principle and operation of thermopile	77
4.1.1. Thermoelectric materials	79
4.1.2. Peltier effect	81
4.2. Thermopile theory	81
4.3. Technology and properties	82
4.4. Thermopile focal plane arrays	85
References	88
5. Bolometers	91
5.1. Basic principle and operation of bolometer	91
5.2. Types of bolometers	92
5.2.1. Metal bolometers	92
5.2.2. Thermistors	93
5.2.3. Semiconductor bolometers	95
5.2.4. Composite bolometers	98
5.2.5. Micromachined room temperature silicon bolometers	99
5.2.6. Superconducting bolometers	103
5.2.7. High temperature superconducting bolometers	106
5.3. Bolometer focal plane arrays	111
References	116
6. Pyroelectric Detectors	121
6.1. Basic principle and operation of pyroelectric detector	121
6.1.1. Responsivity	122
6.1.2. Noise and detectivity	126
6.2. Pyroelectric material selection	129
6.2.1. Single crystals	130
6.2.2. Pyroelectric polymers	132
6.2.3. Pyroelectric ceramics	133
6.2.4. Dielectric bolometers	134
6.2.5. Choice of material	136
6.3. Pyroelectric vidicon	136
6.4. Pyroelectric focal plane arrays	138
6.4.1. Linear arrays	138
6.4.2. Hybrid architecture	139
6.4.3. Monolithic architecture	143
References	144

7. Other Thermal Detectors	149
7.1. Golay cell	149
7.2. p-n junction as a thermal detector	150
7.3. Comparison of thermal detectors	150
References	152
Part III. Infrared Photon Detectors	
8. Theory of Photon Detectors	155
8.1. General theory of photodetectors	155
8.2. Photoconductive detectors	160
8.2.1. Intrinsic photoconductivity theory	161
8.2.2. Extrinsic photoconductivity theory	173
8.2.3. Operating temperature of intrinsic and extrinsic infrared detectors	184
8.3. p-n junction photodiodes	189
8.3.1. Ideal diffusion-limited p-n junctions	192
8.3.2. Other current mechanisms	202
8.3.3. Response time	215
8.4. Schottky-barrier photodiodes	216
8.4.1. Schottky-Mott theory and its modifications	216
8.4.2. Current transport processes	218
8.4.3. Silicides	220
8.4.4. Comparison of different types of semiconductor photodetectors	221
8.5. MIS photodiodes	222
8.6. Photoelectromagnetic, magnetoconcentration, and Dember detectors	227
8.6.1. Photoelectromagnetic detectors	228
8.6.2. Magnetoconcentration detectors	233
8.6.3. Dember effect detectors	234
8.7. Photon-drag detectors	236
References	237
9. Heterodyne Detection	249
References	256
10. Extrinsic Silicon and Germanium Detectors	259
10.1. Technology	260
10.2. Peculiarities of the operation of extrinsic photodetectors	262
10.3. Performance of extrinsic photoconductors	264
10.3.1. Silicon doped photoconductors	264
10.3.2. Germanium doped photoconductors	267

10.4.	Blocked impurity band devices	269
10.5.	Solid state photomultipliers	274
10.6.	Focal plane arrays	275
10.6.1.	Monolithic photodetector arrays	275
10.6.2.	Accumulation-mode charge-injection device (CID) arrays	277
10.6.3.	Bulk-accumulation-mode arrays	278
10.6.4.	Extrinsic charge-extraction device (XCED) arrays	279
10.6.5.	Direct readout extrinsic photodetector arrays	281
10.6.6.	Blocked impurity band hybrid FPAs	283
	References	285
11.	Schottky-Barrier Photoemissive Detectors	291
11.1.	Internal photoemission process	291
11.1.1.	Scattering effects	295
11.1.2.	Dark current	297
11.1.3.	Metal electrodes	299
11.2.	Control of Schottky-barrier detector cutoff wavelength	300
11.3.	Optimised structure and fabrication of Schottky-barrier detectors	301
11.4.	Focal plane arrays	303
11.5.	Novel internal photoemissive detectors	313
11.5.1.	Heterojunction internal photoemissive detectors	313
11.5.2.	Homojunction internal photoemissive detectors	315
	References	317
12.	III-V Detectors	325
12.1.	Some physical properties of III-V narrow gap semiconductors	325
12.2.	Technology and properties of InSb photoconductive detectors	331
12.3.	Technology and properties of InSb photoelectromagnetic detectors	335
12.4.	Technology and properties of III-V photodiodes	335
12.4.1.	InSb and InAs photodiodes	335
12.4.2.	InSb non-equilibrium photodiodes	345
12.5.	Technology and properties of InAs _{1-x} Sb _x detectors	350
12.5.1.	InAs _{1-x} Sb _x photodiodes	350
12.5.2.	InAs _{1-x} Sb _x photoconductors	358
12.6.	Technology and properties of In _x Ga _{1-x} As detectors	362
12.7.	Focal plane arrays	367
12.7.1.	Hybrid InSb/Si focal plane arrays	367
12.7.2.	InSb charge injection devices	370

12.7.3.	InSb charge-coupled devices	375
12.7.4.	Hybrid InGaAs/Si focal plane arrays	375
References		378
13.	HgCdTe Detectors	391
13.1.	HgCdTe: properties and technology	392
13.1.1.	Semiconductor properties	392
13.1.2.	Growth of bulk crystals and epilayers	399
13.1.3.	Defects and impurities	404
13.2.	Photoconductive detectors	406
13.2.1.	Technology	407
13.2.2.	Performance of photoconductive detectors	411
13.2.3.	Excluded photoconductors	418
13.2.4.	SPRITE detectors	423
13.3.	Photovoltaic detectors	429
13.3.1.	Fundamental limitation to photodiode performance and ideal design	430
13.3.2.	Non-fundamental sources of dark current	436
13.3.3.	Technology	439
13.3.4.	Properties of HgCdTe photodiodes	444
13.3.5.	Dual-band detectors	452
13.3.6.	Non-equilibrium photodiodes	456
13.3.7.	MIS photodiodes	457
13.3.8.	Schottky-barrier photodiodes	461
13.4.	Focal plane arrays	461
13.4.1.	Hybrid FPAs	462
13.4.2.	Monolithic FPAs	474
References		479
14.	HgZnTe and HgMnTe Detectors	507
14.1.	HgCdTe versus alternative materials	507
14.2.	HgZnTe detectors	511
14.2.1.	Photoconductive detectors	511
14.2.2.	Photovoltaic detectors	512
14.3.	HgMnTe detectors	515
References		518
15.	IV-VI Detectors	521
15.1.	Some physical properties of lead salts	521
15.2.	Binary lead salt photoconductive detectors	526
15.2.1.	Deposition of lead salts	527
15.2.2.	Fabrication	528
15.2.3.	Performance of lead salt photoconductive detectors	529

15.3. Photovoltaic detectors	533
15.3.1. R_0A product	534
15.3.2. Technology and properties of p-n junction photodiodes	543
15.3.3. Schottky-barrier photodiodes	552
15.3.4. Unconventional thin film photodiodes	559
15.4. Lead salt FPAs	562
References	564
16. Semiconductor Superlattice and Quantum Well Detectors	577
16.1. Semiconductor superlattices and quantum wells	578
16.1.1. Confined electrons in relation to the quantum well	579
16.1.2. Classification of multiple quantum wells and superlattices	582
16.1.3. Optical transitions in superlattices and multiple quantum wells	588
16.1.4. Intersubband relaxation time	594
16.2. Intersubband quantum well III-V photoconductive detectors	595
16.2.1. Technology of intersubband detectors	595
16.2.2. Dark current	597
16.2.3. Performance of GaAs/AlGaAs QWIPs	602
16.2.4. p-doped GaAs/AlGaAs QWIPs	608
16.2.5. QWIPs with other material systems	609
16.3. Superlattice miniband QWIPs	611
16.4. Hot-electron transistor detectors	615
16.5. Multicolor QWIPs	617
16.6. Focal plane arrays	621
16.6.1. Uniformity	622
16.6.2. Light coupling	623
16.6.3. Array performance	625
16.7. SiGe/Si QWIPs	630
16.8. Strained layer superlattice detectors	633
16.8.1. InAsSb/InSb strained layer superlattice detectors	635
16.8.2. InAs/GaSb strained layer superlattice detectors	637
16.9. HgTe/CdTe superlattice detectors	644
16.10. Doping superlattice detectors	647
References	650
Final remarks	667
References	672
Index	675