

Table of Contents

Preface	xi
Chapter 1. Introduction to Semiconductor Photodetectors.	1
Franck OMNES	
1.1. Brief overview of semiconductor materials	1
1.2. Photodetection with semiconductors: basic phenomena	3
1.3. Semiconductor devices.	4
1.4. p-n junctions and p-i-n structures	5
1.5. Avalanche effect in p-i-n structures	7
1.6. Schottky junction	8
1.7. Metal-semiconductor-metal (MSM) structures.	10
1.8. Operational parameters of photodetectors	11
1.8.1. Response coefficient, gain and quantum efficiency	11
1.8.2. Temporal response and bandwidth	12
1.8.3. Noise equivalent power	13
1.8.4. Detectivity	14
Chapter 2. PIN Photodiodes for the Visible and Near-Infrared. . .	15
Baudoin DE CREMOUX	
2.1. Introduction	15
2.2. Physical processes occurring in photodiodes	17
2.2.1. Electrostatics in PIN diodes: depleted region	17
2.2.2. Mechanisms of electron-hole pair generation	19
2.2.3. Transport mechanisms.	23
2.3. Static characteristics of PIN photodiodes	25
2.3.1. I/V characteristics and definition of static parameters	25
2.3.2. External quantum efficiency	27

2.3.3. Dark current	29
2.3.4. Breakdown voltage.	31
2.3.5. Saturation current.	32
2.4. Dynamic characteristics of PIN photodiodes	34
2.4.1. Intrinsic limitations to the speed of response.	34
2.4.2. Limitations due to the circuit	37
2.4.3. Power-frequency compromise, Pf^2 “law”	41
2.5. Semiconductor materials used in PIN photodiodes for the visible and near-infrared	42
2.5.1. Absorption of semiconductors in the range 400-1,800 nm	42
2.5.2. From 400 to 900 nm: silicon and the GaAlAs/GaAs family	43
2.5.3. From 900 to 1,800 nm: germanium, GaInAsP/InP.	46
2.6. New photodiode structures	49
2.6.1. Beyond the limits of conventional PIN	49
2.6.2. Photodiodes with collinear geometry	50
2.6.3. Waveguide photodiodes.	52
2.6.4. Traveling-wave photodiodes.	53
2.6.5. Beyond PIN structures	54
2.7. Bibliography	55
Chapter 3. Avalanche Photodiodes	57
G�rard RIPOCHE and Joseph HARARI	
3.1. Introduction	57
3.2. History	58
3.3. The avalanche effect	60
3.3.1. Ionization coefficients.	61
3.3.2. Multiplication factors	62
3.3.3. Breakdown voltage.	64
3.4. Properties of avalanche photodiodes	66
3.4.1. Current-voltage characteristics and photomultiplication	66
3.4.2. Noise in avalanche photodiodes.	68
3.4.3. Signal-to-noise ratio in avalanche photodiodes	71
3.4.4. Speed, response time and frequency response of avalanche photodiodes	73
3.5. Technological considerations.	76
3.5.1. Guard ring junctions	77
3.5.2. “Mesa” structures.	78
3.5.3. Crystal defects and microplasmas	79
3.6. Silicon avalanche photodiodes	80
3.6.1. Si N^+P APDs.	80
3.6.2. Si $N^+P\pi P^+$ APDs	82
3.6.3. Si $N^+\pi P\pi P^+$ APDs	84

3.6.4. SiPt-Si N Schottky APDs.	87
3.7. Avalanche photodiodes based on gallium arsenide	88
3.8. Germanium avalanche photodiodes	90
3.8.1. Ge APDs with N ⁺ P, N ⁺ NP and P ⁺ N structures for 1.3 μm communication	91
3.8.2. Ge APDs with P ⁺ NN ⁻ structures for 1.55 μm communication	93
3.9. Avalanche photodiodes based on indium phosphate (InP).	95
3.9.1. InGaAs/InP APDs for optical communications at 2.5 Gbit/s	97
3.9.2. Fast InGaAs/InP APDs	99
3.10. III-V low-noise avalanche photodiodes.	100
3.10.1. III-V super-lattice or MQW APDs	101
3.10.2. Spin-orbit resonance APDs.	102
3.11. Prospects.	104
3.11.1. Si/InGaAs APDs	104
3.11.2. “Waveguide” MQW APDs.	104
3.11.3. Low-noise APDs with a very thin multiplication region.	105
3.12. Conclusion.	106
3.13. Bibliography	107
Chapter 4. Phototransistors	111
Carmen GONZALEZ and Antoine MARTY	
4.1. Introduction	111
4.2. Phototransistors	112
4.2.1. Phototransistors according to their fabrication materials	112
4.2.2 Phototransistors classified by structure.	114
4.3. The bipolar phototransistor: description and principles of operation.	118
4.3.1. The phototransistor effect.	119
4.3.2. The response coefficient of a phototransistor	124
4.3.3. Static electrical and optical gains of the phototransistor.	125
4.3.4. Dynamic characteristics of phototransistors	126
4.3.5. Noise in phototransistors	138
4.4. Photodetector circuits based on phototransistors.	140
4.4.1. Amplification circuits	140
4.4.2. Nonlinear circuits.	141
4.5. Applications	142
4.5.1. Galvanic isolation	142
4.5.2. Phototransistors for optical telecommunications	145
4.6. Conclusion	150
4.7. Bibliography	151

Chapter 5. Metal-Semiconductor-Metal Photodiodes	155
Joseph HARARI and Vincent MAGNIN	
5.1. Introduction	155
5.2. Operation and structure	156
5.2.1. Fundamentals	156
5.2.2. Materials used	161
5.3. Static and dynamic characteristics	165
5.3.1. Response coefficient	165
5.3.2. Dynamic behavior	172
5.3.3. Noise	175
5.4. Integration possibilities and conclusion	177
5.5. Bibliography	178
Chapter 6. Ultraviolet Photodetectors	181
Franck OMNES and Eva MONROY	
6.1. Introduction	181
6.2. The UV-visible contrast	189
6.3. Si and SiC photodetectors for UV photodetection	190
6.3.1. UV photodiodes based on silicon	191
6.3.2. SiC-based UV photodetectors	194
6.4. UV detectors based on III-V nitrides	195
6.4.1. Photoconductors	196
6.4.2. Schottky barrier photodiodes based on AlGaN	202
6.4.3. MSM photodiodes	209
6.4.4. p-n and p-i-n photodiodes	210
6.4.5. Phototransistors	214
6.5. Conclusion	216
6.6. Bibliography	218
Chapter 7. Noise in Photodiodes and Photoreceiver Systems	223
Robert ALABEDRA and Dominique RIGAUD	
7.1. Mathematical tools for noise	224
7.1.1. Known signals with finite energy or power	224
7.1.2. Random signals and background noise	226
7.2. Fundamental noise sources	227
7.2.1. Thermal noise	227
7.2.2. Shot noise	228
7.2.3. Multiplication noise	229
7.3. Excess noise	232
7.3.1. Generation-recombination noise	232
7.3.2. 1/f noise	233

7.4. Analysis of noise electrical circuits	235
7.4.1. Representation of noise in bipoles	235
7.4.2. Representation of noise in quadripoles	237
7.5. Noise in photodetectors	239
7.5.1. Characteristic parameters	240
7.5.2. PIN photodiodes	242
7.5.3. Avalanche photodiodes	244
7.6. Noise optimization of photodetectors	245
7.6.1. Formulation of the problem	246
7.6.2. Concepts for photodetector-transistor matching	251
7.7. Calculation of the noise of a photoreceiver	253
7.7.1. Basic equations	253
7.7.2. Models of transistor noise	255
7.7.3. Example calculation: a PIN-FET photoreceiver	259
7.8. Comments and conclusions	266
7.9. Bibliography	268
List of Authors	269
Index	271