State-of-the-Art
Infrared Detector Technology
State-of-the-Art

Infrared

Detector Technology

Michael A. Kinch

SPIE PRESS
Bellingham, Washington  USA
To
Patrick Michael Kinch
—the future
# Table of Contents

**Introduction** xiii

**List of Acronyms** xvii

## 1 Cooled Infrared Detector Architectures 1

1.1 Extrinsic Photoconductors 2

1.2 Intrinsic Photoconductors 4

1.3 Si Schottky Barrier Photodiodes 7

1.4 Metal-Insulator Semiconductor (MIS) Photodiodes 8

1.5 Photodiodes 11

1.6 Barrier Layer Photoconductors 13

1.7 Bandgap-Engineered Devices 15

1.8 Electron Avalanche Photodiodes 16

1.9 PIN Photodiodes 18

1.10 Summary 19

**References** 20

## 2 Infrared Focal Plane Array Considerations 23

2.1 Modulation Transfer Function (MTF) 23

2.2 Noise Equivalent Flux (NEΔΦ) or Noise Equivalent Temperature Difference (NETD) 24

2.2.1 Detector dark current 30

2.2.2 Excess noise 32

2.3 Collection Efficiency 34

2.4 Summary 35

2.4.1 Photodiodes 35

2.4.2 Barrier layer photoconductors 36

**References** 36

## 3 Dark Current Considerations 37

3.1 Minority Carrier Lifetime 37

3.1.1 Radiative recombination 38

3.1.2 Auger recombination 38

3.1.3 Shockley–Read recombination 40

3.1.4 Minority carrier generation rate 42
## 5.1.15 Type III superlattices
- **5.1.15.1 Superlattice bandstructure**
- **5.1.15.2 Absorption coefficient**
- **5.1.15.3 Effective mass**
- **5.1.15.4 Minority carrier lifetime**
- **5.1.15.5 Interdiffusion in HgTe/CdTe superlattices**

## 5.2 III-V Alloys
- **5.2.1 Material growth**
- **5.2.2 Band structure**
- **5.2.3 Optical properties**
- **5.2.4 Transport properties**
- **5.2.5 Minority carrier lifetime**
  - **5.2.5.1 Radiative**
  - **5.2.5.2 Auger**
  - **5.2.5.3 Shockley–Read**
- **5.2.6 Dark current generation rates**
  - **5.2.6.1 Diffusion**
  - **5.2.6.2 Depletion**
- **5.2.7 Systemic 1/f noise**
- **5.2.8 Minority carrier diffusion lengths**
- **5.2.9 Surface passivation**
- **5.2.10 Electrical contacts**
- **5.2.11 Physical properties**
- **5.2.12 III-V type II superlattices (T2SLs)**

## 5.3 IV-VI Alloys
- **5.3.1 Minority carrier lifetime**
- **5.3.2 Doping concentrations**
- **5.3.3 Dark currents**
- **5.3.4 Systemic 1/f noise**

## 5.4 Summary
- **5.4.1 II-VI alloys**
- **5.4.2 III-V alloys**
- **5.4.3 IV-VI alloys**

## References
- 146

### 6 HgCdTe FPA Technologies

#### 6.1 Photodiodes
- **6.1.1 Bump bond hybridization**
  - **6.1.1.1 Monocolor MBE mesa P⁺/N heterojunction**
  - **6.1.1.2 Monocolor planar MBE P⁺/N arsenic implant heterojunction**
  - **6.1.1.3 Monocolor MOCVD mesa N⁺/P heterojunction**
  - **6.1.1.4 Monocolor LPE planar N⁺/N⁻/P ion-implanted homojunction**
6.1.2 Metal via hybridization 161
   6.1.2.1 Monocolor HDVIP® 161
6.1.3 Two-color FPAs 165
   6.1.3.1 Bump bond hybridization 165
   6.1.3.2 Metal via hybridization 168
6.2 Barrier Layer Photoconductor: nBn 168
   6.2.1 Monocolor nBn 169
   6.2.2 $P^+$/N/N double-layer heterojunction photodiode 172
   6.2.3 Two-color nBn 173
6.3 Avalanche Gain HgCdTe FPAs 174
6.4 Type III Superlattice FPA Fabrication 175
6.5 Summary 175
References 176

7 III-V Detectors 179
7.1 Photodiodes 179
   7.1.1 Monocolor alloy photodiodes 180
   7.1.2 Monocolor T2SL photodiodes 182
   7.1.3 Two-color T2SL photodiodes 184
7.2 III-V Barrier Layer Photoconductors 184
   7.2.1 Monocolor barrier layer photoconductor with alloy absorber 185
   7.2.2 Monocolor barrier layer photoconductor with T2SL absorber 186
   7.2.3 Two-color barrier layer photoconductor with T2SL absorber 193
7.3 III-V $P^+$/N/N Double-Layer Heterojunction Photodiode 193
7.4 Summary 194
References 196

8 A Technology Comparison 199
8.1 HOT MWIR FPAs 199
   8.1.1 MTF 199
   8.1.2 NETD 200
   8.1.3 Operability 204
   8.1.4 HOT MWIR summary 208
8.2 HOT LWIR FPAs 209
   8.2.1 MTF 209
   8.2.2 NETD 209
   8.2.3 Operability 212
   8.2.4 HOT LWIR summary 215
8.3 SWIR FPAs 216
   8.3.1 MTF 216
   8.3.2 Noise equivalent irradiance 216
   8.3.3 Operability 220
   8.3.4 SWIR summary 221
8.4 A Technology Comparison: Conclusions 222
References 223
9 The Future of Infrared FPA Technology 225

9.1 MTF 225

9.2 NETD 226

9.2.1 MWIR FPAs 227
9.2.1.1 \( J_d = 0 \) 227
9.2.1.2 \( J_d > 0 \) 229

9.2.2 LWIR FPAs 231
9.2.2.1 \( J_d = 0 \) 231
9.2.2.2 \( J_d > 0 \) 232

9.2.3 SWIR FPAs 235
9.2.3.1 \( J_d = 0 \) 235
9.2.3.2 \( J_d > 0 \) 236

9.3 Operability 238

9.3.1 Systemic 1/f noise: surface passivation 239
9.3.2 Isolated defect 1/f noise: dislocations 239

9.4 Summary 240

9.4.1 Conclusions 241
9.4.1.1 Diffusion-current-limited architectures 241
9.4.1.2 Depletion-current-limited architecture: PIN 241
9.4.1.3 S-R lifetime 241
9.4.1.4 Doping 242
9.4.1.5 Surface passivation 242
9.4.1.6 Dislocations 243

9.4.2 Issues 243
9.4.2.1 Pixel delineation 243
9.4.2.2 Hybridization 243
9.4.2.3 ROICs 244
9.4.2.4 Multicolor FPAs 244
9.4.2.5 Electron avalanche gain 244

9.5 Room Temperature Detection: Photon versus Thermal 245

9.6 A Final Thought 246

References 247

Appendix A: Reverse-Biased Heterojunctions 249
Appendix B: Shockley–Read Bandgap States 253
Index 257
Introduction

The future of infrared focal plane array (IRFPA) technology is seemingly in a state of flux. The current third generation of IR systems utilizes large staring focal plane arrays of photodiodes fabricated with the ternary II-VI alloy HgCdTe, and the binary III-V alloy InSb as their workhorses, in formats of increasing size, complexity, and functionality. InSb has been limited to MWIR applications operating at temperatures not much in excess of 80 K. The various $x$ compositions of the ternary alloy $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ cover the entire IR spectrum with a capability of operating at temperatures greatly in excess of 80 K. These cooled technologies are currently expensive and for many future potential applications are unattractive due to their prohibitive size, weight, and power signature. For this reason, significant paradigm shifts are required in IR technology in order to achieve the desired end goals of cost and performance, beginning with the IR focal plane array itself.

First and foremost, the drive is on to minimize the pixel pitch of the array. A reduction in the pixel pitch within the limits of diffraction for the cutoff wavelength in question will result in a direct saving in the size of the FPA, the optics, and the cooler. This enables a corresponding saving in the size, weight, and power of the IR system. An approximate rule of thumb suggests that the system size will vary approximately as the cube of the pixel pitch. Pixel pitches of 12 $\mu$m have already been reported for various hybridization technologies such as metalized vias and indium bumps. Efforts are now underway to reduce the pixel pitch down to 4 $\mu$m. To achieve the full benefit in image resolution of such a reduction in pitch will be extremely demanding on the chosen device architecture, both from a fabrication point of view and with regard to limiting potential cross-talk or modulation transfer function (MTF) issues. If the appropriate device architecture and hybridization technology can be developed to accommodate such a pitch, this development would enable a 2000 × 2000-pixel IRFPA to be fabricated on a 400-mil × 400-mil chip of IR material.

Secondly, IRFPAs are being driven to operate at significantly higher temperatures for all of the relevant spectral bands, from the LWIR band (8- to 14-$\mu$m cutoff) through the MWIR midwavelength band (3- to 5-$\mu$m cutoff) to the SWIR band (1.5- to 2.5-$\mu$m cutoff). The ultimate temperature goal is determined by the cold shield efficiency associated with the system optics and
cutoff wavelength, assuming that the necessary well capacity is available in the
detector unit cell to accommodate the integrated charge. The basic individual
detector requirement is then simply twofold: first, that the detector dark current
be less than the system background flux current, and second, that the detector 1/f
noise be insignificant relative to the shot noise on the background flux.

There are currently two significant schools of thought with regard to
achieving these future system requirements. The schools can be divided into two
broad IR materials technology categories, namely, III-V and II-VI IR
semiconductors. With this in mind, it is of interest to consider the history of
the evolution of these two technologies. III-V binary alloys were first
compounded in the early 1950s, and InSb was among the earliest materials to
be utilized for IR detection, even though it was limited specifically to the MWIR
band. The perceived requirement for detection in the other main IR atmospheric
window, the LWIR band, led to the development of alternative narrow-bandgap
ternary alloy systems composed of II-VI and IV-VI semiconducting materials.
This ternary alloy market eventually came to be dominated by the II-VI
compound $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, with a variable bandgap across the composition range
from the semi-metal $\text{HgTe}$ ($x = 0$) with a $-0.3$-eV bandgap to the semiconductor
$\text{CdTe}$ ($x = 1$) with a 1.5-eV bandgap. In this manner, the composition of the
ternary alloy was varied to cover the complete range of the IR spectrum, from a
0.9-μm cutoff wavelength to values in excess of 20 μm.

In the period up to 1980, the IR world in the U.S. was dominated by these two
materials technologies, InSb and $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, which were developed almost
exclusively within the confines of the defense industry. The first-generation Common
Module, developed in 1972, was the brainchild solely of Texas Instruments, utilizing
LWIR $\text{Hg}_{0.8}\text{Cd}_{0.2}\text{Te}$ photoconductors configured in a 180-element linear scanning
array format, on a 50-μm pitch. This technology came to dominate the IR systems
business for the next 20 years and is still in production today.

In 1981, DARPA’s concern at the secretive and inefficient nature of the IR
R&D effort within the U.S. resulted in the introduction of the U.S. Workshop
on the Physics and Chemistry of II-VI Materials series, the first of which was
held in Minneapolis. The next nine years saw the science of II-VI IR materials
proceed at a breakneck pace because of strongly coordinated efforts between the
laboratories of academia and industry. The II-VI vapor phase growth
technologies of molecular beam epitaxy (MBE) and metal-organic chemical
vapor deposition (MOCVD) were developed as a direct result of this effort.
Significant advances were made in the understanding of the surface science of
$\text{HgCdTe}$. The role of native defects in II-VI semiconductors was characterized
and modeled. Models were also developed to describe the electronic band
structure of the ternary alloy $\text{HgCdTe}$. The $\text{HgTe/CdTe}$ type III superlattice
was also conceived as an alternative IR materials technology to the ternary
alloy. As a consequence of all of this, in the late 1980s, the second generation of
IR systems was born, based on $\text{HgCdTe}$ with scanning and staring array
formats, and InSb with a staring array format.
After a brief unsuccessful foray into surface-mode charge-coupled devices (CCDs) and charge-injection devices (CIDs), the architecture of choice for second-generation systems became the bipolar photodiode. At this point, DARPA funding of the science of HgCdTe essentially ceased, and the remainder of the U.S. Defense agencies seemingly reached the conclusion that it had invested enough in this technology. HgCdTe had proven to be a somewhat difficult material, whose successful growth and development was confined primarily to research laboratories that were vertically integrated into the confines of the larger defense contractors. This did not apparently lend itself easily to the government’s desired end-goal, namely, the fabrication of inexpensive large-area staring IRFPAs with foundry-like processing. R&D funding was still available for HgCdTe FPAs, but essentially for development work, and was again provided mainly through the major prime U.S. defense contractors. IR system development reverted back to its somewhat secretive and inefficient pre-1980 mode and still operates in this manner, even to this day.

In 1990, the U.S. Government switched its research emphasis to III-V materials, as an alternative technology option to HgCdTe, to attain its stated goal of inexpensive large-area IRFPAs amenable to fabrication by the horizontal integration of material foundries and processing centers of excellence. The various III-V materials technologies that have since received government funding have all involved bandgap engineering of one form or another. This concept typically involves the fabrication of superlattices to tailor the bandgap of the material to detect the desired IR radiation. There are essentially two types of III-V superlattice, namely, type I and type II. Type I superlattices quantize electron motion in one dimension and utilize the bandgaps generated in the majority carrier band to absorb IR radiation, albeit somewhat inefficiently. Such type I superlattices are majority carrier photoconductors, with all of the trappings that entails. Quantum well infrared photoconductors (QWIPs) and quantum dots (QDOTs) are two particular manifestations of this technology. Type II superlattices (T2SLs), on the other hand, quantize carrier motion in both the conduction and valence bands of adjacent semiconductor layers, and the necessary IR bandgap is generated between the interacting levels of the conduction band of one layer and the valence band of the adjacent layer. As such, type II superlattices are minority carrier devices. Yet another topical application of bandgap engineering is the barrier layer photoconductor concept, in which a barrier is introduced to prevent current flow in the majority carrier band of an IR absorber but allows unimpeded flow in the minority carrier band. This concept has recently been applied to resurrect the performance of III-V FPAs, allowing them to operate at considerably higher temperatures than their photodiode counterparts simply by the elimination of depletion regions in the absorber volume. The absorber layers of these devices can be either a MWIR ternary alloy such as InAsSb or a LWIR T2SL.

The science of bandgap engineering has proceeded at a rapid rate. Type I superlattices, designed in-house, are fabricated in the III-V vapor phase
foundries set up to support flourishing electro-optics businesses, based primarily on arsenic-based semiconductors. Type II superlattices (T2SLs), on the other hand, are based primarily on antimony-based materials, and such foundries are not as readily available, initially leading to the development of growth chambers within the confines, mainly, of government and academic laboratories. The sophisticated physics associated with the bandgap engineering concept has resulted in a great deal of interest in these technologies within academic and national laboratories. The mandatory open nature of this research in academia has allowed the science associated with bandgap engineering to flourish in much the same manner as the DARPA-led era of HgCdTe in the 1980s.

The trade-offs between these two competing III-V and II-VI IR materials technologies, with regard to the roles that they might play in the development of the ultimate in photon detection, namely, operation at room temperature, form the basis of this book. It should be pointed out that, although the majority of the physics employed herein is considered accepted practice in today’s IR world, a number of the proposed models that are utilized are somewhat original and possibly controversial. It is the author’s hope that these models will be held up to earnest examination in subsequent investigations and, if found wanting, will perhaps inspire the development of alternative, more exact concepts to replace them. After all, this is how real progress is made.

Michael A. Kinch
September 2014
## List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>APD</td>
<td>avalanche photodiode</td>
</tr>
<tr>
<td>BIB</td>
<td>blocked impurity band</td>
</tr>
<tr>
<td>BLIP</td>
<td>background-limited performance</td>
</tr>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CID</td>
<td>charge-injection device</td>
</tr>
<tr>
<td>CTE</td>
<td>coefficient of thermal expansion</td>
</tr>
<tr>
<td>DLHJ</td>
<td>double-layer heterojunction</td>
</tr>
<tr>
<td>DSID</td>
<td>double-sided interdiffusion</td>
</tr>
<tr>
<td>EAPD</td>
<td>electron avalanche photodiode</td>
</tr>
<tr>
<td>EFA</td>
<td>envelope function approximation</td>
</tr>
<tr>
<td>FPA</td>
<td>focal plane array</td>
</tr>
<tr>
<td>HDVIP®</td>
<td>high-density vertically integrated photodiode</td>
</tr>
<tr>
<td>HOT</td>
<td>high operating temperature</td>
</tr>
<tr>
<td>IR</td>
<td>infrared</td>
</tr>
<tr>
<td>IRFPA</td>
<td>infrared focal plane array</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>LPE</td>
<td>liquid phase epitaxy</td>
</tr>
<tr>
<td>LWIR</td>
<td>long-wavelength infrared</td>
</tr>
<tr>
<td>MBE</td>
<td>molecular beam epitaxy</td>
</tr>
<tr>
<td>MIS</td>
<td>metal-insulator semiconductor</td>
</tr>
<tr>
<td>MISFET</td>
<td>MIS field-effect transistor</td>
</tr>
<tr>
<td>MOCVD</td>
<td>metal-organic chemical vapor deposition</td>
</tr>
<tr>
<td>MTF</td>
<td>modulation transfer function</td>
</tr>
<tr>
<td>MWIR</td>
<td>mid-wavelength infrared</td>
</tr>
<tr>
<td>NEI</td>
<td>noise equivalent irradiance</td>
</tr>
<tr>
<td>NETD</td>
<td>noise equivalent temperature difference</td>
</tr>
<tr>
<td>NEΔΦ</td>
<td>noise equivalent flux</td>
</tr>
<tr>
<td>QDOT</td>
<td>quantum dot</td>
</tr>
<tr>
<td>QMSA</td>
<td>quantitative mobility spectrum analysis</td>
</tr>
<tr>
<td>QWIP</td>
<td>quantum well infrared photoconductor</td>
</tr>
<tr>
<td>rms</td>
<td>root mean square</td>
</tr>
<tr>
<td>ROIC</td>
<td>readout integrated circuit</td>
</tr>
<tr>
<td>RSRE</td>
<td>Royal Signals and Radar Establishment (UK)</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>S-R</td>
<td>Shockley–Read</td>
</tr>
<tr>
<td>SWIR</td>
<td>short-wavelength infrared</td>
</tr>
<tr>
<td>T2SL</td>
<td>type II superlattice</td>
</tr>
<tr>
<td>VIP</td>
<td>vertically integrated photodiode</td>
</tr>
<tr>
<td>VPE</td>
<td>vapor phase epitaxy</td>
</tr>
</tbody>
</table>