High-Operating-Temperature Infrared Photodetectors

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Acronyms and Abbreviations

A1	Auger 1
A7	Auger 7
AR	antireflection
APD	avalanche photodiode
CBD	chemical bath deposition
DAG	direct alloy growth
D^*	detectivity
DARPA	Defense Advanced Research Projects Agency (U.S.)
DLHJ	double-layer heterojunction
EMI	electromagnetic interference
FOV	field of view
FPA	focal plane array
G-R	generation-recombination
HWE	hot wall epitaxy
HOT	high operating temperature
IMP	interdiffused multilayer process
IR	infrared
ISOVPE	isothermal vapor phase epitaxy
JESS	junction-enhanced semiconductor structure
LN	liquid nitrogen
LPE	liquid phase epitaxy
LWIR	long-wavelength infrared
MBE	molecular beam epitaxy
ML	monolayer
MOCVD	metalorganic chemical vapor deposition
MTBF	mean time before failure
MWIR	middle-wavelength infrared
NEP	noise equivalent power
NETD	noise equivalent temperature difference
PACE	Producible Alternative to CdTe for Epitaxy
PEM	photoelectromagnetic
PC	photoconductive
PV	photovoltaic
QWIP	quantum well infrared photodetector
RA	normalized resistivity

$R_\nu A$	normalized responsivity
RIE	reactive ion etching
ROIC	readout integrated circuit
rms	root mean square
SL	superlattice
SLS	strained layer superlattice
SNR	signal-to-noise ratio
SR	Shockley-Read
TE	thermoelectric
THM	traveling heater method
UV	ultraviolet
VPE	vapor phase epitaxy

Preface

Cryogenic cooling of detectors has always been the burden of sensitive infrared (IR) systems, particularly those operating in the middle-wavelength (MWIR) and long-wavelength (LWIR) range of the IR spectrum. Many efforts have been made to develop imaging IR systems that would not require cryogenic cooling. Until the 1990s—despite numerous research initiatives and the attractions of ambient-temperature operation and low-cost potential—room-temperature IR detector technology enjoyed only limited success in competition with cooled photon detectors for thermal imaging applications. Only the pyroelectric vidicon received much attention, because it was hoped that it could be made practical for some applications. However, the advent of the staring focal plane array (FPA) at the beginning of the 1980s marked the arrival of devices that would someday make uncooled systems practical for many commercial applications.

Throughout the 1980s and early 1990s, many companies in the USA, especially Texas Instruments and Honeywell's research laboratories, developed devices based on various thermal detection principles. By the early 1990s, good imagery was being demonstrated with 320×240 arrays. This success resulted in a decision in the mid-1990s by the U.S. Defense Advanced Research Projects Agency (DARPA) to redirect its support of HgCdTe to uncooled technologies. The goal was to create producible arrays that gave useful performance without the burden of fast ($f/1$) LWIR optics.

Infrared detectors with limited cooling have obvious advantages, including the elimination of power-consuming cryogenics; a reduction in size, weight, and cost; and greater reliability (an increase in the useful life and mean time to failure). The number of applications potentially affected by near room temperature IR detector technology is widespread, including military applications such as battlefield sensors; submunition seekers; surveillance, marine vision, and firefighting devices; hand-held imagers; and general "walking around" helmet-mounted sights. This technology also has widespread civilian applications in areas such as thermography, process control, sensitive heterodyne detection, fast pyrometry, Fourier and laser spectrophotometry, imaging interferometry, laser technology and metrology, long-wavelength optical communication, new types of gas analyzers, imaging spectrophotometers, thermal wave nondestructive material testing, and many others.

The room-temperature operation of thermal detectors makes them lightweight, rugged, reliable, and convenient to use. However, their performance is modest, and they suffer from slow response. Because they are nonselective detectors, their imaging systems contain very broadband optics, which provide impressive sensitivity at a short range in good atmospheres.

During the last decade we have observed a revolutionary emergence of FPAs based on thermal detectors. Their slow speed of response is no limitation for a staring system that covers the whole field of view without mechanical scanning, and their moderate performance can be compensated by a large number of elements in the array.

At present, full TV-compatible arrays are used, but they cannot be expected to replace the high-performance cryogenically cooled arrays without a scientific breakthrough. A response much shorter than that achievable with thermal detectors is required for many applications. Thermal detectors seem to be unsuitable for the next generation of IR thermal imaging systems, which are moving toward faster frame rates and multispectral operation. A response time much shorter than that achievable with thermal detectors is required for many nonimaging applications.

Photon detectors (photodetectors) make it possible to achieve both high sensitivity and fast response. The common belief that IR photodetectors must be cooled to achieve a high sensitivity is substantiated by the huge and noisy thermal generation in their small threshold energy optical transitions. The need for cooling is a major limitation of photodetectors and inhibits their more widespread application in IR techniques. Affordable high-performance IR imaging cameras require cost-effective IR detectors that operate without cooling, or at least at temperatures compatible with long-life, low-power, and low-cost coolers. Since cooling requirements add considerably to the cost, weight, power consumption, and inconvenience of an IR system, it is highly desirable to eliminate or reduce the cooling requirements. Recent considerations of the fundamental detector mechanisms suggest that, in principle, near-perfect detection can be achieved in the MWIR and LWIR ranges without the need for cryogenic cooling.*

This book is devoted to high-operating-temperature (HOT) IR photodetectors. It presents approaches, materials, and devices that eliminate the cooling requirements of IR photodetectors operating in the middle- and long-wavelength ranges of the IR spectrum. This text is based mainly on the authors' experiences in developing and fabricating near room temperature HgCdTe detectors at Vigo Systems Ltd. and at the Institute of Applied Physics Military University of Technology (both in Warsaw, Poland).

The main approaches to minimizing thermal generation in the active element of a detector without sacrificing quantum efficiency include:

- Optimization of the material bandgap and doping;
- Reduction of the detector volume using optical concentrators, backside reflectors, and optical resonant cavities;

*See, e.g., J. Piotrowski in *Infrared Photon Detectors*, A. Rogalski (Ed.), 391–494, SPIE Press, Bellingham, WA (1995); C. T. Elliott, N. T. Gordon, and A. M. White, *Appl. Phys. Lett.* **74**, 2881–2883 (1999); and M. A. Kinch, *J. Electr. Mater.* **29**, 809–817 (2000).

- Suppression of Auger thermal generation with nonequilibrium depletion of the semiconductor; and
- Use of new natural and engineered semiconductors with reduced thermal generation.

This text also discusses solutions to other specific problems of high-temperature detection, such as poor collection efficiency due to a short diffusion length, the Johnson-Nyquist noise of parasitic impedances, and interfacing of very low-resistance devices to electronics.

We also consider different types of IR photodetectors, especially photoconductors, photoelectromagnetic (PEM) detectors, Dember effect detectors, and photodiodes, with major emphasis on devices based on HgCdTe alloys. Special attention is given to optimization of the devices for room-temperature operation and the new detector designs that are necessary to solve specific problems of high-temperature operation. Additional topics include an approach proposed by British workers to reduce photodetector cooling requirements based on a nonequilibrium mode of operation, and alternative material systems to the current market-dominant HgCdTe, such as a number of II-VI and III-V semiconductor systems (HgZnTe, HgMnTe, InAsSb) and some artificial narrow-gap semiconductors based on type-II superlattices (InAs-GaInSb).

This book was written for those who desire a comprehensive analysis of the latest developments in HOT IR photodetector technology and a basic insight into the fundamental processes that are important in room-temperature detector operation. Special efforts are focused on the physical limits of detector performance and a performance comparison of different types of detectors. The book is suitable for graduate students in physics and engineering who have received a basic preparation in modern solid state physics and electronic circuits. This book will also be of interest to individuals who work with aerospace sensors and systems, remote sensing, thermal imaging, military imaging, optical telecommunications, IR spectroscopy, and lidar. To satisfy all these needs, each chapter first discusses the principles needed to understand the chapter topic as well as some historical background before presenting the reader with the most recent information available. For those currently in the field, this book can be used as a collection of useful data, as a guide to literature in the field, and as an overview of topics in the field. The book also could be used as a reference for participants of educational short courses, such as those organized by SPIE.

The book starts with two overview chapters. Chapter 1 describes figures of merit, which characterize IR thermal imagers and their cooling requirements. Chapter 2 is an overview of the fundamental limitations to IR photodetector performance imposed by the statistical nature of the generation and recombination process in semiconductor material. Radiometric considerations are also included. In this chapter we try to establish the ultimate theoretical sensitivity limit that can be expected for a detector operating at a given temperature. The model presented in Chapter 2 is applicable to any class of photodetector.

Chapter 3 describes the properties of material systems used to fabricate HOT IR photodetectors. Although the HgCdTe ternary alloy currently holds the dominant market position, a number of II-VI and III-V semiconductor systems are described as alternatives. Chapter 4 presents the general theory of intrinsic detectors with an emphasis on electrical and optical properties, together with the generation-recombination mechanisms that directly influence the performance of IR detectors at near room temperature. The next two chapters describe specific approaches to the most popular HgCdTe detectors: photoconductors and photodiodes. In contrast to photoconductors, photodiodes, with their very low-power dissipation, can be assembled in 2D arrays containing a very large ($>10^6$) number of elements, limited only by existing technologies. At present, photodiodes are the most promising devices for uncooled operation, and significant efforts are directed toward improving the fabrication of multiple heterojunction and Auger-suppressed devices.

Other than photoconductors and photodiodes, three other junctionless devices are used for uncooled IR photodetectors: photoelectromagnetic (PEM) detectors, magnetoconcentration detectors, and Dember effect detectors. The technologies and performances of these three devices are described in Chapter 7. Chapter 8 is devoted to lead salt photodetectors, which were brought to the manufacturing stage of development during World War II. More than 60 years later, low-cost PbS and PbSe polycrystalline photoconductors remain the choice for many applications in the 1–3 μm and 3–5 μm spectral regions. The objective of Chapter 9 is to present the status of alternatives to the current market-dominant HgCdTe detectors. Detectors fabricated from a number of II-VI and III-V semiconductor systems such as HgZnTe, HgMnTe, InAsSb, and type-II InAs/GaInSb superlattices are presented. Chapter 10 presents our final remarks.

The authors have benefited from the kind cooperation of many scientists who are actively working in narrow-gap semiconductor detectors. The preparation of this book was aided by many informative and stimulating discussions between the authors and their colleagues at Vigo System S.A. and the Institute of Applied Physics, Military University of Technology in Warsaw, Poland. These colleagues provided many illustrations and practical results. Special thanks are also extended to L. Faraone, C. Musca, J. Dell, and J. Antoszewski of the Microelectronics Research Group, University of Western Australia, for numerous discussions and their help with manuscript preparation. Thanks also go to SPIE Press, especially Margaret Thayer for her cooperation and care in publishing this text.

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