

Ghenadii Korotcenkov *Editor*

Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors

Volume 2, Photodetectors

 Springer

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Volume 2, Photodetectors

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Preface

Binary and ternary semiconductors of II-VI group (ZnS, ZnSe, ZnTe, CdS, CdSe, CdTe, HgTe, HgS, HgSe, HgCdTe, CdZnTe, CdSSe, and HgZnTe) are very popular among researchers because of their remarkable physical and chemical properties, which, as a group, are unique. II-VI compounds possess a very wide spectrum of electronic and optical properties. Most materials of group II-VI are semiconductors with a direct band gap and high optical absorption and emission coefficients. In addition, binary II-VI compounds are easily miscible, providing a continuous range of properties. As results, the II-VI semiconductors possess band gap, varying over a wide range. Therefore, II-VI compounds can serve as efficient light emitters, such as light diodes and lasers, solar cells, and radiation detectors operating in the range from IR to UV and X-ray. II-VI compound-based devices can also cover terahertz range. Besides common photovoltaic applications, II-VI semiconductors are also potential candidates for a variety of electronic, electro-optical, sensing, and piezoelectric devices. In particular, nanoparticles of II-VI semiconductors, such as quantum dots, one-dimensional structures, and core-shells structures, can be used for development of gas sensors, electrochemical sensors, and biosensors. These semiconductors, when downsized to nanometer, have become the focus of attention because of their tunable band structure, high extinction coefficient, possible multiple exciton generation, and unique electronic and transport properties. It is important that II-VI semiconductors can be easily prepared in high quality epitaxial, polycrystalline, and nanocrystalline films. The concentration of charge carriers can also vary in II-VI semiconductors in wide range due to doping. Thus, the use of II-VI films represents an economical approach to the synthesis of semiconductors for various applications. It should be noted that the range of technical applications for II-VI compounds goes beyond the better-known semiconductors such as Si, Ge, and some of III-V compounds.

Formally, metal oxides such as CdO and ZnO also belong to II-VI compounds. However, we will not cover them in this book. In recent years, these compounds have been allocated to a separate group, "metal oxides," and many books have been devoted to their discussion, in contrast to other II-VI compounds. In particular,

those who are interested in exactly these compounds, we can recommend the Metal Oxides series which is published by Elsevier.

The aim of this three-volume book is to provide an updated account of the state of the art of multifunctional II-VI semiconductors, from fundamental sciences and material sciences to their applications as various sensors and radiation detectors, and, based on this knowledge, formulate new goals for further research. This book provides interdisciplinary discussion of a wide range of topics, such as synthesis of II-VI compounds, their deposition, processing, characterization, device fabrication, and testing. Topics of the recent remarkable progresses in application of nanoparticles, nanocomposites, and nanostructures consisting of II-VI semiconductors in various devices are also covered. Both experimental and theoretical approaches were used for this analysis.

Currently, there exist books on II-VI semiconductors. However, some of them were published too long ago and cannot reflect the current state of research in this area. Other published books focus on a limited number of topics, from which topics related to various sensor applications such as gas sensors, humidity sensors, and biosensors are almost completely excluded. When considering photodetectors, the focus is also only on the analysis of IR photodetectors. Although sensors operating in the visible, ultraviolet, terahertz, and X-ray ranges also hold great promise for applications. With these books, we will try to close this gap.

Our three-volume book *Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors* is the first to cover both chemical sensors and biosensors and all types of photodetectors and radiation detectors based on II-VI semiconductors. It contains a comprehensive and detailed analysis of all aspects of the application of II-VI semiconductors in these devices. This makes these books very useful and comfortable to use. Combining this information in three volumes, united by common topics, should help readers in finding the necessary information on required subject.

Chapters in *Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors. Vol. 1: Materials and Technologies* describe the physical, chemical, and electronic properties of II-VI compounds, which give rise to an increased interest in these semiconductors. Technologies that are used in the development of various devices based on II-VI connections are also discussed in detail in this volume.

Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors. Vol. 2: Photodetectors focuses on the consideration of all types of optical detectors, including IR detectors, visible detectors, and UV detectors. This consideration includes both the fundamentals of the operation of detectors and the peculiarities of their manufacture and use. An analysis of new trends in development of II-VI semiconductors-based photodetectors is also given.

Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors. Vol. 3: Sensors, Biosensors and Radiation Detector describes the use of II-VI compounds in other fields such as radiation detectors, gas sensors, humidity sensors, optical sensors, and biosensors. The chapters in this volume provide a comprehensive overview of the manufacture, parameters, and applications of these devices.

We believe that these books will enable the reader to understand the present status of II-VI semiconductors and their role in the development of new generation of photodetectors, sensors, and radiation detectors. I am very pleased that many well-known experts with extensive experience in the development and research of II-VI semiconductor sensors and radiation detectors were involved in the preparation of the chapters of these books.

The target audience for this series of books are scientists and researchers working or planning to work in the field of materials related to II-VI semiconductors, i.e., scientists and researchers whose activities are related to electronics, optoelectronics, chemical and bio sensors, electrical engineering, and biomedical applications. I believe this three-volume book may also be of interest to practicing engineers and project managers in industries and national laboratories who would like to develop II-VI semiconductor-based radiation sensors and detectors but do not know how to do it, and how to select the optimal II-VI semiconductor for specific applications. With numerous references to an extensive resource of recently published literature on the subject, these books can serve as an important and insightful source of valuable information, providing scientists and engineers with new ideas for understanding and improving existing II-VI semiconductor devices.

I believe that these books will be very useful for university students, doctoral students, and professors. The structure of these books offers the basis for courses in materials science, chemical engineering, electronics, optoelectronics, environmental control, chemical sensors, photodetectors, radiation detectors, biomedical applications, and many others. Graduate students may also find the book very useful in their research and understanding of the synthesis of II-VI semiconductors, study, and application of this multifunctional material in various devices. We are confident that all of them will find the information useful for their activities.

Finally, I thank all the authors who contributed to these books. I am grateful that they agreed to participate in this project and for their efforts to prepare these chapters. This project would not have been possible without their participation. I am also very grateful to Springer for the opportunity to publish this book with their help. I would like also to inform that my activity related to editing this book was funded by the State Program of the Republic of Moldova project 20.80009.5007.02.

I am also grateful to my family and wife, who always support me in all my endeavors.

Chisinau, Moldova

Ghenadii Korotcenkov

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About the Editor



Ghenadii Korotcenkov received his PhD in physics and technology of semiconductor materials and devices in 1976 and his Doctor of Science degree (doctor habilitate) in physics of semiconductors and dielectrics in 1990. He has more than 50-year experience as a teacher and scientific researcher. For a long time he was a leader of gas sensor group and manager of various national and international scientific and engineering projects carried out in the Laboratory of Micro- and Optoelectronics, Technical University of Moldova, Chisinau, Moldova. International foundations and programs such as the CRDF, the MRDA, the ICTP, the

INTAS, the INCO-COPERNICUS, the COST, and NATO have supported his research. From 2007 to 2008, he carried out his research as an invited scientist at Korea Institute of Energy Research (Daejeon). Then, from 2008 to 2018, Dr. G. Korotcenkov was a research professor in the School of Materials Science and Engineering at Gwangju Institute of Science and Technology (GIST) in Korea. Currently, G. Korotcenkov is a chief scientific researcher at Moldova State University, Chisinau, Moldova. Scientists from the former Soviet Union know the results of G. Korotcenkov's research in the study of Schottky barriers, MOS structures, native oxides, and photoreceivers based on III–Vs compounds such as InP, GaP, AlGaAs, and InGaAs. His current research interests since 1995 include material sciences, focusing on metal oxide film deposition and characterization (In_2O_3 , SnO_2 , ZnO , TiO_2), surface science, thermoelectric conversion, and design of physical and chemical sensors, including thin film gas sensors. G. Korotcenkov is the author or editor of 45 books and special issues, including the 11-volume Chemical Sensors series published by Momentum Press; 15-volume *Chemical Sensors* series published by Harbin Institute of Technology Press, China; 3-volume “*Porous Silicon: From Formation to Application*” issue published by CRC Press; 2-volume *Handbook of Gas Sensor Materials* published by Springer; 3-volume *Handbook of Humidity Measurements* published by CRC Press; and 6 proceedings of the

international conferences published by Trans Tech Publ., Elsevier, and EDP Sciences. In addition, currently he is a series editor of Metal Oxides book series published by Elsevier. Since 2017, more than 35 volumes have been published within this series. G. Korotcenkov is the author and coauthor of more than 650 scientific publications, including 31 review papers, 38 book chapters, and more than 200 peer-reviewed articles published in scientific journals (h-factor=42 (Web of Science), h=44 (Scopus) and h=59 (Google scholar citation), 2022). He is the holder of 17 patents. He presented more than 250 reports at national and international conferences, including 17 invited talks. G. Korotcenkov, as a cochairman or member of program, scientific, and steering committees, has participated in the organization of more than 40 international scientific conferences. Dr. G. Korotcenkov is a member of editorial boards of five scientific international journals. His name and activities have been listed by many biographical publications including Who's Who. His research activities have been honored by the National Prize of the Republic of Moldova (2022), the Honorary Diploma of the Government of the Republic of Moldova (2020), an award of the Academy of Sciences of Moldova (2019), an award of the Supreme Council of Science and Advanced Technology of the Republic of Moldova (2004), the Prize of the Presidents of the Ukrainian, Belarus, and Moldovan Academies of Sciences (2003), Senior Research Excellence Award of the Technical University of Moldova (2001, 2003, 2005), the National Youth Prize of the Republic of Moldova in the field of science and technology (1980), among others. Some of his research results and published books have won awards at international exhibitions. G. Korotcenkov also received a fellowship from the International Research Exchange Board (IREX, United States, 1998), Brain Korea 21 Program (2008–2012), and BrainPool Program (Korea, 2007–2008 and 2015–2017). <https://www.scopus.com/authid/detail.uri?authorId=6701490962> <https://publons.com/researcher/1490013/ghenadii-korotcenkov/> <https://scholar.google.com/citations?user=XR3RNhAAAAAJ&hl> https://www.researchgate.net/profile/G_Korotcenkov

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Part I
IR Detectors Based on II–VI
Semiconductors

Chapter 1

Introduction in IR Detectors



Ghenadii Korotcenkov

1.1 Introduction

Infrared (IR) range is the range of electromagnetic radiation from 0.78 to 1000 μm , which is divided into sub-ranges:

- near IR, NIR: 0.78–1 μm ;
- short wavelength IR, SWIR: 1–3 μm ;
- medium wavelength IR, MWIR: 3–6 μm ;
- long wavelength IR, LWIR: 6–12 μm ;
- very long wavelength IR, VLWIR: 12–20 μm ;
- far infrared region (FIR): 20–1000 μm

In comparison with visible and ultraviolet rays, infrared radiation has small energy, for example 1.24 eV at $\lambda = 1 \mu\text{m}$, 0.12 eV at 10 μm , and ~ 0.01 eV at 100 μm .

For the first time the presence of infrared radiation was found in 1800 in the process of experiments conducted by the English astronomer William Herschel. A clearer understanding of IR radiation was obtained in 1900 through Plank's law (Eq. 1.1). According to Plank's law, every physical object spontaneously emits radiation in a wide range of wavelengths. The peak wavelength of the radiation corresponds to the equilibrium temperature of the object. Spectral radiation emittance, calculated according to Plank's law, is shown in Fig. 1.1. As is seen, the peak radiation of objects at room temperature (~ 300 K), is $\sim 10 \mu\text{m}$. The surface of the Sun, which has a temperature of ~ 6000 K, has a maximum radiation in the visible range, although radiation in the IR region is also present.

$$M(\lambda) = C_1 \lambda^{-5} \left[\exp(C_2 / \lambda T) - 1 \right]^{-1} \quad (1.1)$$

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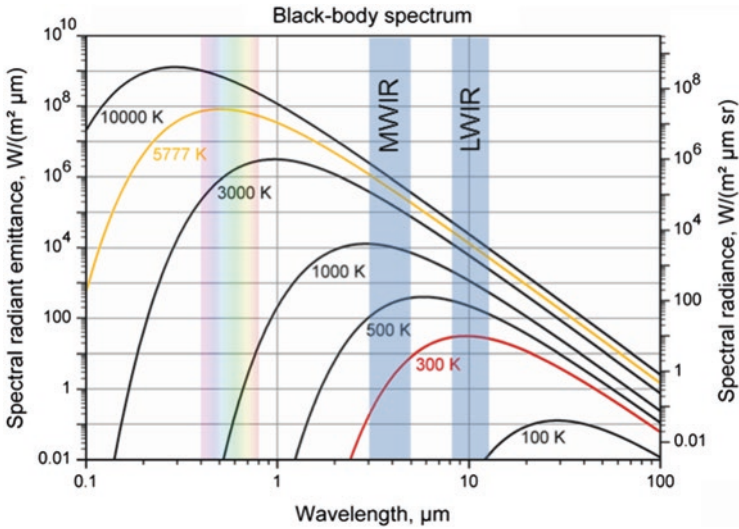


Fig. 1.1 Spectral emittance of objects at given equilibrium temperatures. (Reprinted from Karim and Andersson [10]. Published 2013 by IOP as open access)

Table 1.1 Main applications of infrared photodetectors

Community	Applications
<i>Military</i>	Reconnaissance, navigation, night vision, guided missiles.
<i>Commercial</i>	
Civil	Police, firemen, border post.
Environment	Pollution control, natural resources, energy savings, meteorology.
Industry	Maintenance, fabrication processes control, nondestructive tests, optical communications.
Medical	Thermography.
<i>Science</i>	
Astronomy	Observation of the universe in the infrared region.
Physics, chemistry	IR spectroscopy.

Where T – absolute temperature (K), C_1 – first radiation constant = $3.74 \cdot 10^4$ $W\mu m^2/cm^2$, C_2 – second radiation constant = $1.44 \cdot 10^4$ μmK , λ – wavelength (μm).

It should be noted that the development of the IR technologies has intensified significantly only in the last 40–50 years. The main applications of the IR devices are shown in Table 1.1. During this period, significant advances have been made in the development of various IR photoreceivers (see Fig. 1.2) and as a result, it is currently impossible to imagine many extremely important applications without the use of IR detectors. IR detectors have become the basis of space surveillance systems, ballistic missile launch detection systems, non-contact temperature measurement, motion sensors, IR spectroscopy, night vision devices, warhead homing

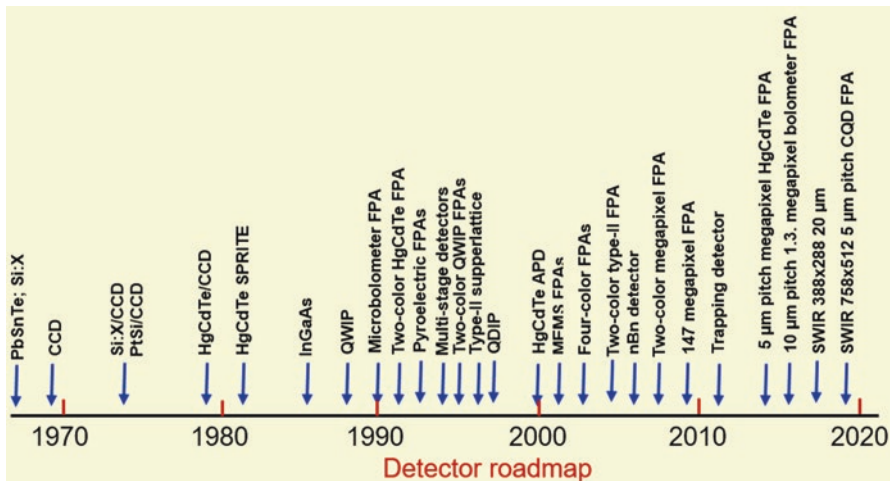


Fig. 1.2 History of the development of infrared detectors and systems. (Adapted from Rogalski et al. [21]. Published 2020 by PAS as open access)

systems, and holographic information recording and processing systems. IR sensors are widely used in astronomy, medicine, ultra-long range optical communication systems, rangefinders, meteorological exploration, climatology, laser search and visualization, etc. [4, 8, 12, 30]. It is the photodetectors, which in the overwhelming majority of cases determines such basic parameters of IR systems as range, sensitivity, spectral scope, noise immunity, resolution, dynamic range and other characteristics of the equipment.

1.2 IR Photodetectors

Two types of detectors are currently used to detect infrared radiation – photonic (cooled and uncooled) and thermal.

1.2.1 Thermal (Non-selective) IR Detectors

Thermal radiation detectors are non-selective devices, i.e. they have the same spectral characteristic over a wide range of the electromagnetic spectrum (up to hundreds of micrometers) [4, 23, 34]. The operation of thermal radiation detectors is based on the conversion of radiation energy into heat, and then into electrical energy. In bolometers and thermistors, an increase in the temperature of the receiver changes its electrical conductivity, in thermopiles, a thermo-EMF appears, in a pyroelectric receiver, the value of the surface charge changes, and in dielectric bolometers using

ferroelectric capacitors (barium strontium titan) as sensing elements, its dielectric changes with a change in temperature constant and, therefore, the capacitance of the capacitor. Thermal detector manufacturing technologies have reached a certain degree of perfection and predetermined a number of advantages, due to which sensors of this type occupy a quantitatively dominant position in the market of the IR detectors. Their advantages are well known. In its most general form, this is the simplicity of the design and the absence of the need for cryogenic temperatures, which leads to significantly lower power consumption for power supply. In addition, there is practically no need for service. For pyroelectrics and thermopiles, this is the absence of both a power supply and the need for temperature compensation. As a result, the noise ($1/f$) of such devices is sharply reduced. Competitive price also plays a significant role when choosing a thermal sensor [23].

In the development of thermal radiation detectors, the maximum effect was achieved in recent years, when silicon micro-electromechanical systems (MEMS) technology began to be used in their manufacture [2, 3, 13, 34]. This made it possible to manufacture micro-sized elements of thermal sensors and provide them with good thermal isolation. In particular, the state-of-the-art technology has made it possible to fabricate monolithic silicon-based focal plane arrays (FPAs) with more than 10^5 pixels and a pixel size of $50\ \mu\text{m}$. When using vanadium oxide (VOx) as a sensitive material for MEMS microbolometers, fabricated using Si-based MEMS technology, a temperature noise equivalent (NETD) of $40\text{--}50\ \text{mK}$ for an aperture number of 1 has been achieved, which is an undeniable progress [16, 29]. The achievement of such results has led to the fact that of all types of IR thermal detectors, uncooled MEMS-based detectors are of the greatest interest. Their appearance and structure are shown in Fig. 1.3. The interest in such devices is due to the fact that MEMS-based detector arrays combine the ability to form images of very good quality with the low cost and ease of use inherent in uncooled detectors. While their sensitivity does not come close to that of the best HgCdTe detector arrays, uncooled MEMS-based detector arrays provide a level of performance that most users are satisfied with. Currently MEMS-based detector arrays, including microbolometer

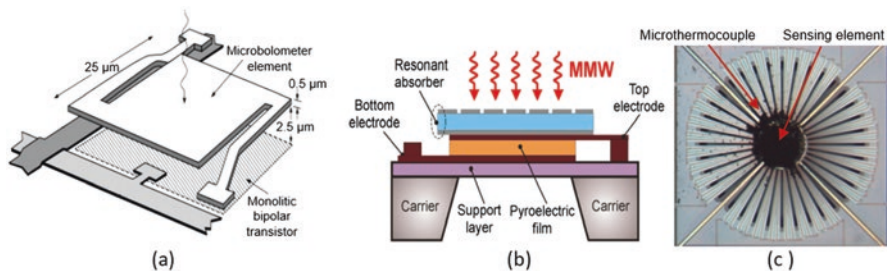


Fig. 1.3 (a) Modern $25\ \mu\text{m}$ Microbolometer pixel (<https://movitherm.com/>), (b) Pyroelectric sensor. Sketch of the pyroelectric sensor with an integrated resonant absorber. (c) The CMOS-MEMS thermopile after drop-coating of graphene. ((b) Reprinted from Kuznetsov et al. [13]. Published 2018 by Nature as open access; (c) Reprinted from Chen and Chen [3]. Published 2020 by MDPI as open access)

Table 1.2 Thermal detectors

Mechanism	Comment	Advantages	Disadvantages
<i>nn</i>			
Mercury in glass	Thermometer	Simple	Low R Very slow
Gas in chamber	Golay cell	Available Simple	Very slow
<i>Thermal coefficient of resistance</i>			
Carbon resistor	First bolometer	Easy to model Easy to make	Need T_{LHe} (4 K)
Vanadium oxide (VO_x)	Microbolometer FPAs	Available Silicon processing Good stability	Low R
Amorphous Si	Microbolometer FPAs	Available Silicon processing	Less sensitive than VO_x
<i>Thermal EMF (Seebeck effect)</i>			
Thermocouple	One junction pair		Slow, low R
Thermopile	Many junction pairs MEMS thermopile	Available Simple Inexpensive	Slow, low R
<i>Ferroelectric and pyroelectric</i>			
Barium strontium titanate	First high volume AC coupled	Available High R Inexpensive	Needs chopper

Source: Reprinted with permission from Vincent et al. [33]. Copyright 2016: Wiley

arrays and MEMS-based thermoelectric (thermopile) arrays with acceptable parameters, are commercially available worldwide [6, 34]. Comparative characteristics of thermal detectors are given in Table 1.2.

However, thermal detectors also have disadvantages that turn out to be quite significant when choosing an IR sensor for work in applications, requiring high parameters, such as military equipment [29]. Such disadvantages are the structural and technological complexity of thermal insulation of many detector pixels from each other and from the substrate, their sensitivity to temperature fluctuations and vibrations with relatively small relative changes in the electrical characteristics of the material per one degree of change in the object temperature, the inertia of the spectral response and low uniformity of the image. For thermal detectors, there is also the problem of decreasing pixel size. For example, the pixel sensitivity of a microbolometer is highly dependent on the pixel area; therefore, there is a need to maximize both the optical absorption area and thermal insulation. Unfortunately, when the pixel size is reduced, this condition cannot be fulfilled, and therefore, when using conventional single-level micromachining processes, performance degradation is observed as the unit cell size is reduced below 40 μm . That is why, in most MEMS bolometers, the pixel size does not decrease below 50 μm . Due to the problems mentioned earlier, when using thermal detectors, there are often problems with obtaining a clear image at long distances [29].

1.2.2 Photonic Radiation Detectors

The main group of IR detectors in terms of various applications is the so-called photon or quantum radiation detectors [23]. Photonic radiation detectors ensure the conversion of the incident photon flux into an electrical signal due to the direct interaction of photons with the electronic subsystem of the receiver material (see Fig. 1.4). The sensitivity of the photon detector is proportional to the number of absorbed photons. Such a receiver is selective, i.e. it only reacts to photon of radiation with a certain frequency (wavelength). In other words, photonic detectors respond to photons whose energy exceeds certain threshold values, for example, the semiconductor band gap (“intrinsic” detectors).

In turn, photonic radiation detectors are divided into receivers with an external photoelectric effect (photomultipliers) and receivers with an internal photoelectric effect (photoresistors, photodiodes, phototransistors, etc.). In modern infrared systems, receivers with an internal photoelectric effect are most widely used. In receivers of this type, three main physical phenomena are used, caused by the effect of radiation on a semiconductor: the phenomenon of photoconductivity, photovoltaic and photoelectric effects. Since IR radiation has small energy (energy is inversely proportional to wavelength), these detectors are cooled down to cryogenic temperatures in order to increase infrared detection efficiency/sensitivity. Quantum detectors react very quickly to IR radiation (response time is order of μs), but they have response curves with a detectivity that varies greatly with wavelength.

Photoconductors The operation of a photoresistor (PR) or photoconductor (PC) is based on the change in the electrical conductivity of the sensitive layer during irradiation (read Chap. 2, Vol. 2). It is important to note that the first IR photonic receivers were photoconductive because of the simplicity of the technology, and the relative ease of achieving near-ideal infrared performance and excellent reliability. At the same time, it was found that the most sensitive PRs are also the most inertial. For a number of them, a direct relationship has been established between the PR

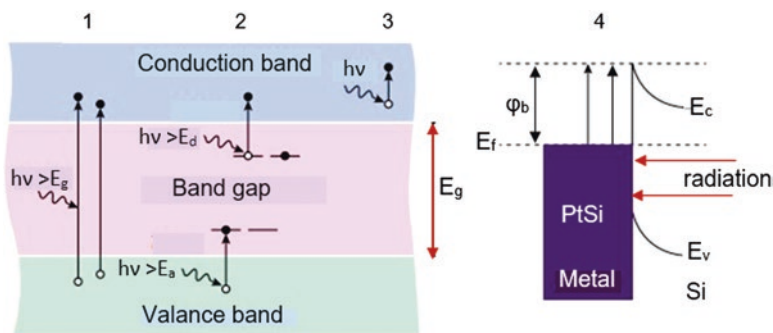


Fig. 1.4 Photonic mechanisms of excitation of the electron subsystem in photonic detectors: (1) intrinsic excitation, (2) impurity excitation, (3) absorption by free carriers, (4) excitation in Schottky diodes. (Idea from Kulchitsky et al. [12])

sensitivity threshold and the time constant τ . Often, the mobility of electrons and holes in a semiconductor is very different, as a result of which faster carriers can pass through the detector several times before the carriers recombine. This provides a gain mechanism. Operating temperature is another important factor. Decreasing the temperature of the sensitive layer expands the spectral range of its operation in the IR spectral region and increases its integral sensitivity. With cooling, the noise decreases, and, consequently, the detecting ability of the PR increases. In addition, upon cooling, the time constant and its dark resistance increase.

The advantages of PR are small size and weight, lower supply voltage compared to photoemission detectors and the ability to work in a wide spectral range. The PRs usually have a very high integral sensitivity and low power consumption not exceeding several watts. The disadvantages of photodetectors of this class include increased inertia, a significant dependence of characteristics and parameters on temperature, a small linear zone of the energy characteristic, and the dependence of the output signal on the illumination area of the sensitive layer. Currently, the main materials used for the manufacture of IR photoresistors are CdS, PbS, PbSe, InSb, Ge: Au and HgCdTe. Photo detectors on CdS, PbS, PbSe, InSb, and HgCdTe are intrinsic, and Ge: Au-based devices are extrinsic IR photoconductive detectors.

Photodiodes A photodiode (PD) is usually called a semiconductor radiation detector based on the use of one-way conductivity of a p-n junction, upon illumination of which an electromotive force (EMF) is formed (photovoltaic mode), or in the presence of a voltage source in the photodiode circuit, its reverse current changes (photodiode mode). Currently, materials for the manufacture of IR photodiodes are mainly Ge, Si, InSb, as well as ternary compounds such as InGaAs and HgCdTe. The features of the operation of HgCdTe-based photodiodes are described in [1] and the Chaps. 2, 3, 4, 5, 6, 7, and 8. There are many methods for manufacturing IR PDs, each of which has its own strengths and weaknesses, depending on the specific design of the photodetector and its purpose. For HgCdTe, this information can be found in [17, 19] and Chap. 15, Vol. 1.

The spectral sensitivity of PDs changes when switching from photovoltaic mode to photodiode mode. This sensitivity also depends on the temperature of the semiconductor material used for PDs fabrication. With decreasing temperature, the spectral characteristic and its maximum shift to the short-wavelength region, and the dark current as well as the noise level also decreases. Therefore, IR detectors, especially those designed to work in the LWIR spectral range, are forced to operate at low temperatures, down to cryogenic temperatures. In many cases, the temperature of operation is a critical parameter, because the cooling system often dominates the size, weight and reliability of the detector system.

The time constant of the photodiode τ_{PD} largely depends on the method of its manufacture and the size of the photosensitive area. For PDs, the τ_{PD} value is usually close to 10^{-5} s; for diffusion p-n junction with small areas, τ_{PD} can reach 10^{-6} s. In special PDs with a small thickness, $\tau_{PD} \sim 10^{-10}$ s can be achieved. Comparatively large dark currents when conventional photodiodes are switched on in the

photodiode mode make it impossible to use them for measuring low light flows. In this case, it is necessary to work in the photovoltaic mode, in which the detecting ability of the system is determined not by the low noise of the receiver, but by noises of its electronic circuit or subsequent electronic links.

To improve the sensitivity for detecting infrared radiation, avalanche photodiodes (APDs) are often used [16]. Avalanche photodiodes include areas of high electrical field. Carrier multiplication is carried out by transferring sufficient kinetic energy to the carrier to create an additional electron-hole pair by impact ionization. There is always some excess noise associated with multiplication, but this can be minimized with designs that allow one carrier to be multiplied. The ideal APD is an inexpensive device with low dark noise, wide spectral and frequency response, and a gain from 1 to 10^6 or more. The characteristics of avalanche diodes based on HgCdTe are discussed in the Chap. 3, Vol. 2.

In addition to the above devices, it is possible to note the Schottky barrier photodiodes belonging to the group of photoemissive detectors (see Fig. 1.4). They are characterized by a relatively simple manufacturing technology and their parameters are close to those of p-i-n PDs. The most popular Schottky-barrier IR detector is the PtSi-p-Si detector, which can be used for IR detection in the 3–5 μm spectral range [11]. Radiation is transmitted through the p-type silicon and is absorbed in the metal PtSi (Platinum silicide) layer, producing hot holes which are then emitted over the potential barrier into the silicon, leaving the silicide negatively charged. This fundamental difference in the detection mechanism underlies the unique properties of Schottky IR detectors, including their exceptional spatial uniformity and their modified Fowler spectral response. The Schottky barrier height of the PtSi detector is ~ 0.22 eV, corresponding to a cutoff wavelength of ~ 5.6 μm . Due to the Fowler dependence, the quantum efficiency (QE) of the PtSi detector in the 3–5 μm MWIR regime is relatively low [14]. The main advantage of the Schottky-barrier detectors is that they can be fabricated as monolithic arrays in a standard silicon process [23].

Photodiodes formed on the basis of heterostructures are also present in a large number on the market of IR detectors [5]. Some options for using heterostructures in the development of IR detectors are described in Chaps. 5 and 6, Vol. 2.

Phototransistors A phototransistor (PT) is a semiconductor device with photocurrent amplification properties with two p-n junctions, in which there is a directional movement of current carriers. Phototransistors have a high quantum efficiency (about 100). However, the presence of the second p-n junction leads to a significant increase in noise. Therefore, it is often preferable to use photodiodes with an additional stage of the signal amplifier, the noise of which affects the detection ability of the device less than the noise arising in the phototransistor. The disadvantages of phototransistors also include: significant instability of parameters and characteristics over time when the ambient temperature changes; and lower detection ability than photodetectors. It should be noted that some PTs have a “blind spot” in the center of the sensitive layer due to the shading of a part of the base by the emitter. Therefore, when using them, it is necessary to distribute the flow over the entire photosensitive surface of the PT.

Table 1.3 Infrared detectors used in single detector assemblies

Detector	(μm)	Common applications, and comments
Si (PV)	0.1–1.1	Optical communication, fire sensing, light and laser power measurement, photon counting
InGaAs (PV)	0.7–1.8	Optical communications, FTIR, gas detection, light and laser power measurement, tunable diode laser spectroscopy (TDLS), moisture analyzers. Replaces Ge (faster)
InAs (PV)	0.9–3.5	FTIR, non-contact temperature measurement, laser monitoring, gas analyzers, spectrophotometry.
InSb (PC, PV)	1.0–5.5	FTIR, spectrophotometry, thermometry, remote sensing, gas analysis
InAsSb (PV)	3.3–11	Gas measurement (CH_4 , CO_2 , CO , NH_3 , O_3 , etc.), flame monitoring (CO_2 resonance radiation), radiation thermometry
PbS (PC)	1–3.6	Non-contact temperature measurement, spark detecting, flame control, moisture measurement, spectrophotometry. These detectors are used especially when large-area detectors are required because they are significantly less expensive than comparable III-V (InGaAs) detectors.
PbSe (PC)	1–5.8	Gas analysis, laser power measurement, medical CO_2 detection, non-contact temperature measurement, flame detection, fire detection, moisture monitoring.
HgCdTe (PC, PV)	1.0–16	FTIR, industrial process control, heat-seeking guidance, laser warning receiver, laser monitoring, temperature monitoring, gas detection, remote sensing. Используется вместо PbSe and PbS where high detectivity is needed, low bias voltage, selective peak wavelength response, and fast response times.
Thermopile	0.1–100	Fire sensing, intrusion, laser power, temperature measurement, gas detection.
Pyroelectric (piezoelectric)	0.1–100	Fire sensing, motion detection, laser power, temperature measurement. Most sensitive of thermal detectors, sensitive to vibration
Bolometer and microbolometer	0.1–100	FTIR, astronomy
Golay cell and microgolay cell	0.1–100	FTIR

FTIR Fourier-transform infrared spectroscopy, *NDIR* nondispersive infrared spectroscopy, *PC* photoconductive, *PV* photovoltaic

As for the most common commercial and science applications of IR detectors, they are listed in Table 1.3. A description of some of these applications can be found in [33].

1.2.3 IR Photodetectors Array

A certain share in the market of modern IR photodetectors is occupied by photodetector (PD) arrays developed for thermal imaging equipment [12] and for astronomical application [8]. The main distinctions of photodetector arrays from single photodetectors are listed in the Table 1.4.

Table 1.4 Comparison of two general IR detector configurations

eature	Single detector assembly	PDs array
Detectors (pixels)	A few: 1, 2, 4, perhaps 16	Thousands, millions
Equipment and software	Can be simple	Specialized
Output and responsivity measurement	AC (usually)	DC (usually)
Record data for every element	Yes	Yes
Report data for every element	Yes – tabular	No, or graphical only
Report array statistics	Optional	Essential
Figures of merit	Basic	Basic + some unique
Relative cost	Low	Expensive
Quantity per year	Many	Few
Electronics	Discrete or small ASICs	ROIC
Primary applications	Various nonimaging	Imaging

Source: Data extracted from Vincent et al. [33]

ASICs application-specific ICs, ROIC a readout- integrated circuit

A focal plane array (FPA) of photodetectors is created by combining separate, usually identical, photosensitive elements on a single chip. The individual detectors in an array are often referred to as pixels, short for picture elements; pixel is generally thought of as the smallest single component of a digital image. However, the process of developing an integrated detector array is much more complicated than manufacturing a separate detector element (read the Chap. 4, Vol. 2). A fundamental limitation in the design of detector arrays is that light easily hits adjacent pixels in the array, resulting in false counts or crosstalk. There are approaches that can be taken to mitigate this limitation, but they add additional complexity to production. In addition, the manufacturing process of the array becomes even more complex due to the requirement to maintain low leakage currents in individual pixels, which makes the manufacturing process even more cumbersome.

It is important to note that the first HgCdTe-based photodetector arrays were made on the basis of photoconductive detectors. HgCdTe photoconductive detectors have been in routine production since the early 1980s and are often called first-generation detectors. They have been designed for spectral ranges of 8–12 μm and 3–5 μm . Detectors operated at 80 K for LWIR and at 80–200 K for MWIR spectral range. The reliable performance, low levels of defects and easily understood physics has led to a long product life for photoconductive arrays. However, the size of the matrix in such detectors was limited, and the first-generation thermal imaging systems had to use sophisticated optics to scan the infrared image over the matrix to construct the scene. Therefore, photoconductive HgCdTe detectors have been very successful in producing arrays of up to a few hundred elements for use in first-generation thermal imaging systems. The limitations of photoconductive detectors emerged when the need arose for very large focal plane arrays. In addition, the low impedance of the photoconductor made it unsuitable for injecting into silicon charge transfer devices or field effect transistors; hence, each element required a lead-out

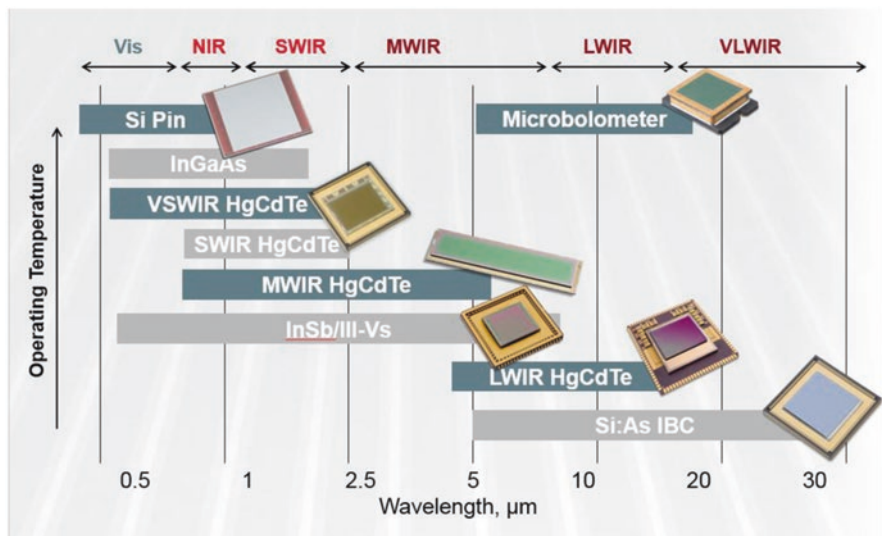


Fig. 1.5 Materials used for development of large format FPAs. (<https://www.raytheon.com>)

through the vacuum encapsulation to an off-focal plane amplifier. All this significantly limited the capabilities of matrices based on photoconductive detectors. In this regard, the use of photoconductive detectors in the development of photodetectors arrays has now been limited. Currently, photodiodes and heterostructures of various types are the basis of such photodetectors arrays. For a more detailed discussion of photodetectors arrays, see Chap. 4, Vol. 2.

The market for high performance thermal imaging cameras based on FPAs is currently split between two material systems: InSb and HgCdTe [12, 31]. FPAs present on the market are shown on Fig. 1.5. InSb has a large share of the market of cooled thermal imaging cameras because the first FPAs were originally obtained from this material. At the same time, HgCdTe has several key advantages that could make it the material of choice for the development of third generation thermal imaging cameras. HgCdTe can operate at much higher temperatures ($T_{oper}^{max} < 200\text{K}$), than InSb ($T_{oper}^{max} < 100\text{--}120\text{K}$), and therefore MCT-based cameras can be smaller and consume less power. For FPAs designed to operate in the SWIR range, other materials can also be used, mainly InGaAs (<https://www.flir.com>). However, InGaAs / InP-based FPAs can have high noise in the spectral range above $1.7\ \mu\text{m}$ due to defects caused by the lattice mismatch between InGaAs and InP, which is used as substrate for growing InGaAs epitaxial layers.

As for astronomical applications, in addition to InSb and HgCdTe, they also use Si:As-based FPAs [8, 31]. The fabrication of FPAs on the base of Si:As does not present any particular difficulties, as standard technologies are used and large, high quality silicon wafers are available. In addition, there are no problems with thermal expansion mismatch between the FPA and the multiplexer. As a result, the best

samples of matrices based on Si:As with a sensitivity up to 28–40 μm have more than $2\text{ k} \times 2\text{ k}$ pixels with a pixel size of 18 μm [32]. For Si:As devices, the more challenging task is to develop a multiplexer capable of operating at temperatures around 10 K required to achieve low detector dark currents. However, this temperature is outside the range in which standard commercial silicon CMOS devices operate. The development of special multiplexers requires additional costs, which sometimes compensate for the advantages of Si:As. This is due to the fact that the market for astronomical Si:As-based devices is very small [8].

1.2.4 Photosensitive Materials for IR Technology

If we turn to the history of the development of IR technology [4, 22, 23], then in the early stages it was based on the use of complex semiconductors. The first practical IR detector was manufactured in 1933 on the basis of lead sulfide (PbS) with an operating sensitivity range of up to 3 μm . In the late 1940s, this detection wavelength was increased to 5 μm through the use of lead selenide (PbSe) and lead telluride (PbTe). In the 1950s, research began on semiconductor compounds from III-V, IV-IV and II-VI groups, which led to the emergence of new photosensitive materials suitable for the development of various IR photodetectors. InSb, $\text{InAs}_{1-x}\text{Sb}_x$, $\text{Pb}_{1-x}\text{Sn}_x\text{Te}$ (LTT), InGaAs and HgCdTe (MCT) were one of them. A large number of other combinations of compounds were also tested, but in most cases, there were problems with crystal growth or there were limitations on doping, which made them unsuitable for the manufacture of IR devices.

It should be noted that in the late 1960s – early 1970s, PbSnTe was actively developed in parallel with HgCdTe [7]. Unlike HgCdTe, PbSnTe of the required quality was easy to grow, and therefore high-quality IR photodiodes on their basis for the LWIR spectral range were demonstrated relatively quickly. However, in the late 1970s, work on PbSnTe-based detectors was discontinued [1]. There were two reasons for this: a high dielectric constant and a large mismatch in the temperature coefficient of expansion (TCE) of PbSnTe with TCE of the Si. The scanning-based IR imaging systems required relatively fast response times so that the scanned image was not blurred. The high dielectric constant did not allow the development of devices with the low capacitance required for fast operation. Large TCE, led to the destruction of indium bonds in the hybrid structure between the silicon-based reader and the PbSnTe-based detector array during repeated thermal cycling from room temperature to cryogenic operating temperature.

Concerning current IR technology (www.hamamatsu.com; www.teledynejudson.com; www.photonicsolutions.co.uk; <https://vigo.com.pl>), it is mainly based on InSb, InGaAs and HgCdTe [17]. One should note that the use of HgCdTe allowed to cover a wider range of wavelengths of infrared radiation compared to other materials. Depending on the composition of $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$, photodetectors based on this material can cover the entire spectral IR range from SWIR to VLWIR (see Fig. 1.6). In addition, HgCdTe has nearly ideal properties for the development of electronic

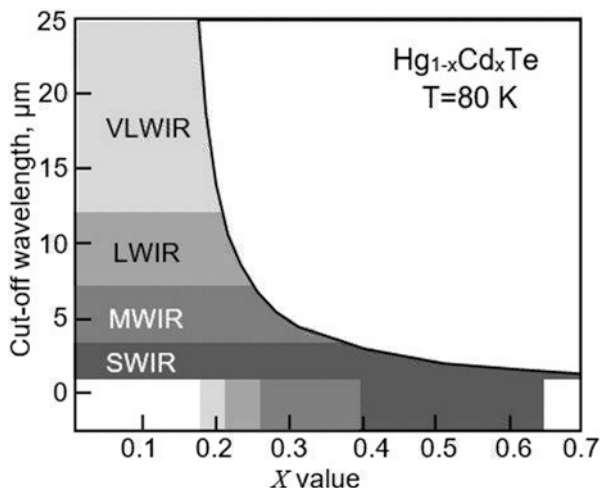


Fig. 1.6 The cut-off wavelength for $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ as a function of composition, x

avalanche photodiodes (e-APDs) for the infrared region (read the Chap. 3, Vol. 2). The high mobility ratio of HgCdTe contributes to the creation of conditions under which single-carrier multiplication with low noise figures take place. Such IR detectors are effective when used in photon-starved applications, such as long-range imaging and astronomy [1]. Other advantages of HgCdTe can be found in the Chap. 4, Vol. 1.

Currently, HgCdTe-based detectors are mainly used for spectral ranges of 1–2.5 μm , 3–5 μm and 8–14 μm . InSb is more suitable for the spectral range of 3–5 μm , while InGaAs is more suitable for the spectral range of 0.4–2.3 μm [9, 17]. The spectral areas of their application are shown in Figs. 1.5 and 1.7. However, even until now, inexpensive polycrystalline thin-film photoconductive detectors based on PbS and PbSe remain the preferred choice for many applications in the spectral range of 1–3 μm and 3–5 μm . It should be noted that in recent decades there has also been interest in such compounds as $\text{Hg}_{1-x}\text{Mn}_x\text{Te}$, $\text{Hg}_{1-x}\text{Zn}_x\text{Te}$ and $\text{Hg}_{1-x}\text{Cd}_x\text{Se}$ as potential alternatives to HgCdTe for infrared detectors. Photoconductive and photovoltaic detectors have been reported using these materials, but the devices have not yet reached technology perfection like $\text{Hg}_{1-x}\text{Cd}_x\text{Te}$ [26, 27].

We must also not forget about extrinsic (photon energies smaller than the band-gap) photoconductive detectors, which were developed in the early 1950s. Research has shown that using extrinsic photoconductive response from germanium, doped by copper, mercury, zinc, and gold allows developing IR receivers capable to work in the 8–14 μm (LWIR) and 14–30 μm (VLWIR) spectral range. However, they must operate at very low temperatures (30–50 K) to achieve similar performance to intrinsic detectors, and they sacrifice quantum efficiency to avoid the need for thick detectors.

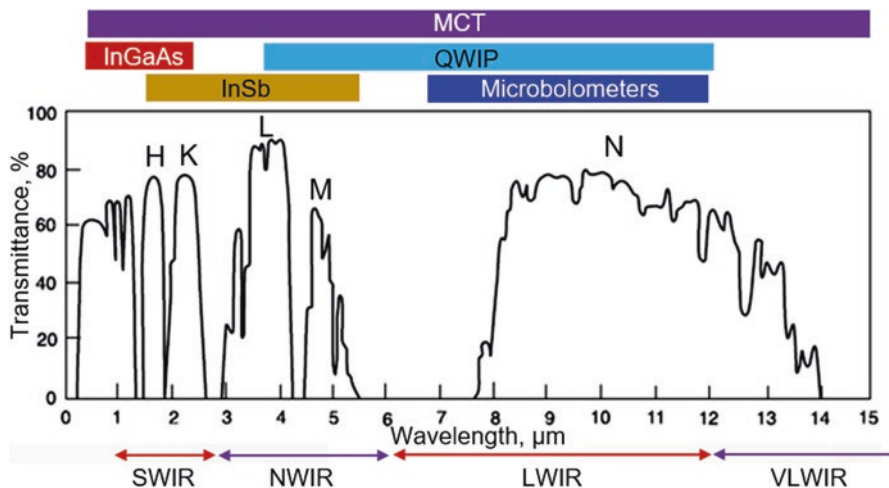


Fig. 1.7 Basic semiconductor materials for cooled thermal imaging arrays and operating spectral ranges. This Figure also shows the specific absorption bands of the atmosphere. (Data extracted from Rogalski [22, 23] and Piotrowski and Rogalski [17])

There are also Si-based intrinsic and extrinsic IR photoconductive detectors. Silicon intrinsic IR detectors are usually designed and fabricated as Schottky-barrier detectors (PtSi detector). Such detectors can be used for detection in the range of 3–5 μm . As for longer wavelengths, in this area can be used extrinsic silicon IR photodetectors, such as Si:As or Si:Sb [20]. The developed devices are designed to operate in the range of 5–40 μm . However, the sensitivity range can be extended up to approximately 300 μm . As well as Ge-based IR PDs, operating temperatures of Si-based extrinsic detectors lies in the cryogenic temperature range (8–30 K). A detailed review of a bulk Si and Ge IR detectors can be found in [28].

It is important to note that in recent years there has been a significant increase in interest in extrinsic IR photoconductive detectors based on germanium and especially silicon [20]. This interest is due to the creation of multi-element FPAs for use in space and land infrared astronomy, as well as on spacecraft for various purposes. Advances in Si-based FPAs technology, the creation of low-noise semiconductor preamplifiers and deep-cooled multiplexers, as well as unique designs of extrinsic silicon IR PDs and deep-cooling equipment have achieved record-breaking detectivity, close to the emission limit even under exceedingly low backgrounds in space [15].

1.2.5 Comparison of Thermal and Photonic Infrared Detectors

Comparing the relative response of photon and thermal detectors as a function of wavelength with either a vertical scale of W^{-1} or photon^{-1} , then as seen in Fig. 1.8, photon detectors show a linear increase in response on the dependences, recalculated

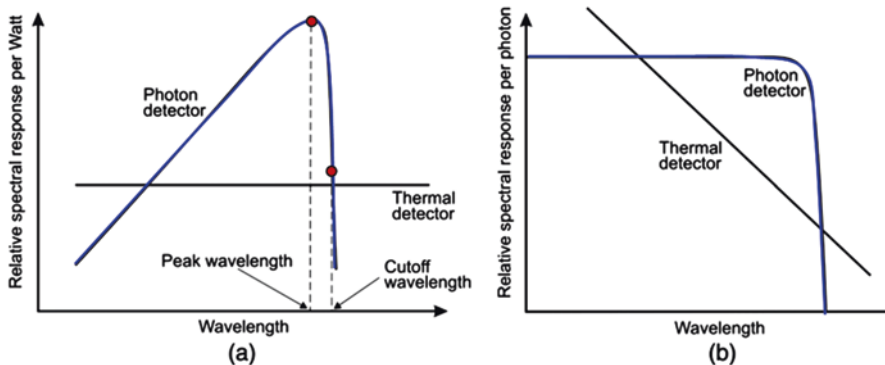


Fig. 1.8 Relative spectral response for a photon and thermal detector for (a) constant incident radiant power and (b) photon flux, respectively. (Reprinted with permission from Rogalski et al. [24]. Copyright 2000: SPIE)

per unit power of the incident radiation, until the cutoff wavelength is reached. An increase in response is associated with an increase in the number of photons to achieve the same power with increasing wavelength. The cutoff wavelength is determined by the detector material used. At the same time, thermal detectors tend to be spectrally flat in this case. This is due to the fact that their response is proportional to the energy absorbed, which, when recalculated per unit of incident radiation power, does not depend on the wavelength. If the sensor response is recalculated per photon, then the photon detectors in this case are usually flat, and the thermal sensors have a linearly decreasing response.

Compared to thermal detectors, cooled photonic sensors have a NETD of 10–20 mK, and this indicator practically does not change over a wide range of integration times (5–7 ms and more). The detectivity of photonic detectors is about two orders of magnitude higher than that of thermal detectors. This allows large aperture ratios to be used when designing thermal imaging cameras [29]. In addition, photon-type detectors have better signal-to-noise ratio and faster response time. For many applications, thermal detectors may not provide the required response time. Consequently, heat detectors are not suitable for infrared thermal imaging cameras that use higher frame rates and multispectral performance. At the same time, photon detectors require deep cryogenic cooling, and this leads to a complication of the device, an increase in its geometric dimensions, weight and high power consumption. Only in the last decade, due to progress in the development of photodetectors, it was possible to increase the operating temperatures from 77 to 150 K. In addition, if the service life of the photodetector array of the photon detector itself can be determined for decades, then the service life of the cooler does not exceed 30 thousand operating hours (the best models), after which the cooler must be replaced. All this leads to an increase in the cost of sensors of this type in comparison with thermal detectors, as well as to an increase in the cost of their operation. Nevertheless, the price criterion, as a rule, is not decisive in applications such as military and