Recent Progress on Infrared Detectors: Materials and Applications

Xiaochuan Lyu*
Luhe International Academy, Beijing, China
*Corresponding author: 15020340325@xs.hnit.edu.cn

Abstract: It is impossible for human eyes to see infrared radiation, a type of electromagnetic wave with a wavelength that falls between visible light and microwaves. This radiation must be transformed into other physically quantifiable qualities in order to be detected and measured in order to determine whether it is present and how intense it is. Infrared detectors are tools that transform the signal from incident infrared light into an electrical signal output. With the wide application of infrared detectors in various countries, higher requirements are put forward for infrared detectors. In order to further expand the wavelength, improve the resolution and reduce the cost, infrared detectors based on class II superlattices, colloidal quantum dots, silicon-based materials and other new materials and technologies have been developed. In this paper, the development of infrared detectors at home and abroad is reviewed and the new materials and technologies of infrared detectors are reported. limitations and advantages of the current research on infrared detectors are discussed, and the future development trend of infrared detector is prospected. Furthermore, recent progress on IR detectors is outlined. The basic mechanism is introduced. Then, materials nanowire, HgCdTe, HOT and InAs/InGaAs are included. The last but not the least, further applications are displayed.

Keywords: Infrared detector, materials, applications

1.Introduction

One of the sun's numerous invisible beams is infrared (IR). In 1800, British scientist Herschel made the discovery. It also goes by the name of IR thermal radiation and has a potent thermal effect. He tried to measure the heating effect of different colors of light by splitting sunlight with a prism and placing thermometers in different ribbons. As it turns out, the thermometer outside the red light heats up the fastest. Therefore, it is concluded that in addition to the red light in the solar spectrum, there must also be invisible light, namely IR light [1]. In this case, the frequency of IR light in the solar spectrum is lower than that of visible light, ranging from 0.3 MHZ to 400 THz, corresponding to the wavelength of 1000 μm to 0.75 μm in vacuum. IR can be divided into three parts, namely near IR (high frequency IR with high energy), wavelength (3~2.5) μm~ (1~0.75 THZ) μm; Mid-IR (mid-frequency IR with medium energy) wavelength is (40-25) μm~3-2.5) μm; Far IR (low frequency IR with low energy), wavelength 1500 μm~40~25 μm. IR (especially far IR) has a strong thermal effect, it can resonate with most inorganic molecules and organic macromolecules in living bodies, causing these molecules to accelerate and friction, and then generate heat, so IR can be used for heating and molecular spectroscopy studies. Far IR ray, also known as "terahertz ray" or "terahertz light" in scientific research, is adjacent to the microwave frequency band and has the dual characteristics of IR and microwave. It has received extensive attention in scientific research and is widely used in biology, chemistry, molecular spectroscopy, organic synthesis and other disciplines [2,3].

According to the theory of blackbody radiation, ordinary materials do not easily produce far IR rays of sufficient intensity. Usually, special materials must be used for energy conversion. The interior molecules' motions will cause them to release the heat they absorb, which will cause them to emit lower-frequency far-IR light. Outside of the visible spectrum, IR light from various types of objects falls into a specific band. As a result, it is possible to detect and track the target using this particular spectrum of IR light. The following benefits of IR detection are seen from an application perspective. First, IR has more environmental adaptability than visible light, especially when it comes to working at night and in bad weather. Second, IR detection has better concealment compared with radar and laser detection. IR detectors just passively receive target signal and are not easy to be interfered with, so they are safer and more confidential. Third, because detection relies on IR radiation properties created by the temperature and emissivity differences between the target and the background, it is more able to detect camouflaged targets than visible light. Fourth, IR systems use less power, are lighter, and are smaller in size than radar systems. Based on the above-discussed unparalleled benefits, IR detection research is advancing quickly. Long waves to short waves are covered by the detector's spectral response. Detectors progress from a single to a multiple and then to a focal plane. There have also been numerous developments in detectors and systems, ranging from single band to multi-band and from room temperature to chilled detectors. At present, the mature IR detection technology in the market is mainly based on Si, Ge, InAs, InGaAs, HgCdTe and other materials planar detectors. However, since the electron energy at room temperature (0.026 eV) is comparable to the IR energy, especially for mid-far-IR light, the photocurrent is difficult to distinguish from the room temperature environment as the wavelength of the incident light increases, and the detection rate will decrease sharply. Commonly used high-precision detectors, including HgCdTe, InAs/InGaSb Class II superlattices, GaAs/AlGaAs quantum wells, etc., are refrigeration detectors. At this time, people put forward the requirements of room temperature wide spectrum, ultra-high sensitivity, ultra-fast response, ultra-small pixels, lightweight and low-cost IR detection. The development of new low-dimensional semiconductor photodetectors brings both opportunities and challenges. Compared with traditional optoelectronic systems, modern optoelectronic systems are gradually being designed in a more compact direction [4].

This review article is aimed at the brief introduction of the development of IR detector. Section 1 introduces mechanism. Sec.2 demonstrates the majority materials all over the world recently. Sec.3 discusses the applications of IR detector. Finally, limitations and future prospects are disposed in Sec.4.

2.Mechanism

According to different classification standards, near-IR detectors can be divided into many types. (1) According to the different physical mechanism of detection, IR detectors can be divided into two categories: photon detectors based on various photoelectric effects and thermal detectors using temperature changes to realize detection; (2) According to the different spatial resolution of the detector, it is divided into non-imaging photodetectors and imaging photodetectors; (3) According to the different detection material size, it is divided into bulk material detector, thin film material detector and nano-material detector; (4) According to the different device structure, it can be divided into vacuum photoelectric device, photo conductance detector, PN junction detector, PIN junction photodetector, avalanche diode detector, Schottky junction detector, metal-semiconductor-metal structure detector, etc [5].

Photoelectric effect can be divided into external photoelectric effect and internal photoelectric effect. According to Einstein's equation for the photoelectric effect, when a specific wavelength of light is radiated onto a metal surface, the metal will absorb photons and emit electrons, which is called the external photoelectric effect. Internal photoelectric effect refers to the physical phenomenon that when light radiation of a specific wavelength interacts with a semiconductor, bound electrons inside the semiconductor are excited, thus changing the conductive characteristics of the semiconductor. Thermoelectric effect refers to the accumulation of charge or current when electrons in a heated object move from a high temperature region to a low temperature region as the temperature gradient changes. Near-IR photodetectors based on external photoelectric effect are usually vacuum photoelectric devices, such as vacuum phototube, gas-filled phototube, photomultiplier tube, image enhancement tube, camera tube, etc. The device has the advantages of high detection sensitivity and fast response speed, which is very suitable for detecting low light signal and fast pulse low light signal. However, there are significant drawbacks, such as the need for vacuum operating environments and high-pressure systems, which make the equipment bulky and less flexible to use. In addition, the performance of vacuum optoelectronic devices is limited by the photocathode materials. The near IR photodetector based on the thermoelectric effect uses the thermal effect of near IR to realize the light-thermal-electric conversion, so the wavelength selectivity of this photodetector is poor. Furthermore, due to the influence of NIR, the temperature change of the object takes a certain time, so the response speed of such a detector is very slow. Compared with the photodetectors of the first two physical mechanisms, there are a variety of near-IR photodetectors based on the internal photoelectric effect, such as photoresist, photocell, photodiode, phototransistor, phototransistor and so on. Such devices are characterized as simple structure, small size, high detection sensitivity, good spectral selectivity and fast response speed [4,6,7].

3.Materials

3.1 HgCdTe IR photodetector

Among the existing low-temperature IR detection materials, HgCdTe materials use the principle of electron absorption infrared spectrum to excite the transition, the frequency band is adjustable, and it can cover the whole wavelength detection wave-number range, so it is suitable for various wavelength detectors, such as short-wave detector (SWIR), medium-wave detector (MWIR) and long-wave detector (LWIR). CdTe is a pseudo-binary system consisting of a mixture of HgCdTe and PbTe. The lattice constants of HgTe and CdTe are very close, which are 6.46Å and 6.48Å, respectively. They all have sphalerite structure, which enables them to form continuous solid solution (HgTe)1-X(CdTe)X pseudo-binary system in any proportion, namely HgCdTe mixed crystalline materials. By adjusting the composition, the band gap width of the direct band gap semiconductor HgCdTe can be continuously varied from -0.3 eV to 1.6 eV, resulting in a continuous wavelength response of 1-30 μm covering the entire IR band. HgCdTe also has the advantages of high quantum efficiency, long carrier lifetime, easy access to different range of carrier concentrations, high electron mobility and low dielectric constant. However, there are some problems with the HgCdTe IR detector. CdTe is mainly composed of ionic bonds with little interaction between them. Elemental mercury is prone to escape from CdTe materials, resulting in material defects, material heterogeneity and device performance heterogeneity. Another issue is the high cost of epitaxial substrates grown on HgCdTe thin film materials. To obtain a larger size HgCdTe material, alternative substrates must be considered, but the resulting lattice mismatch will greatly reduce the material quality [8].

3.2 Semiconductor nanowires

The main characteristics of nano materials are small size, high surface energy, large specific surface area2. Therefore, nano materials have very different physical properties from macroscopic materials, including surface effects, small size effects, quantum size effects and macroscopic quantum tunneling effects2. Compared with near-IR photodetectors based on bulk materials and thin films, nano material photodetectors have the following advantages :(1) the size of nano material is small, which is in line with the development trend of miniaturization and integration of optoelectronic devices; (2) When the size of the nano materials is comparable to the wavelength of the NIR light they interact with, some very strange photoelectric phenomena can be observed; (3) The huge specific surface area of nano materials can help absorb more near-IR radiation, which is the basis of converting near-IR light into electrical signal; (4) Due to the small size of nano materials, the charge transfer time in the detector is greatly shortened, which will improve the response speed of the detector to a large extent; (5) The resistance of nano materials is very large, and the dark current of their optoelectronic components can usually be controlled at the nano ampere level or even smaller. Nanowires are defined as one-dimensional structures with a diameter of less than 100 nm. Compared with conventional materials, the electrons of nanowires can only move in the one-dimensional direction, which is considered as an ideal electron transport material. In addition, nanowires also have unique advantages in photoelectric detection applications. For example, reduced size and dimensions help to reduce dark current, device size, and device energy consumption. High surface area and Debye length can effectively improve the optical absorption efficiency, prolong the life of photo carriers, and shorten the carrier transport time. The abundant surface states can be used to modulate optoelectronic properties, such as facilitating the separation and collection of photoelectrons. The enhanced stress release on the side wall of the nanowires and the small contact area with the substrate can greatly reduce the retarding effect of lattice mismatch on epitaxial growth. The compatibility of nanowire manufacturing process with traditional silicon based process can promote its wide application in integrated circuits. For semiconductor nanowire, fewer defects are more conducive to the axial transport of charge carriers along the nanowire, thus increasing the photocurrent. On the other hand, the surface state of the nanowires can affect carrier transport and photo conductance by binding to environmental molecules and in other ways. Therefore, it is necessary to find a controlled growth method of nanowires with high crystal quality, high mobility, low defects, low surface states or heterojunction to achieve high performance IR detection [3,9].

3.3 Antimonide

In the semiconductor superlattice material system, III-V group semiconductor is the research hotspot. The band gap is between 0.1 and 1.7 eV. It can be used as a material for IR band photoelectronic devices, but also for industrial exploration, monitoring, temperature measurement, medicine, photoelectric search, detection, weather satellites and climate monitoring. As ideal materials for high temperature IR detectors, antimonide will face many key challenges in different applications. In recent years, significant progress has been made in refrigerated class ⅱ superlattice technology by studying the epitaxial growth theory and techniques of family III-V materials [10]. In addition, InAs/InAsB superlattices are also proposed9. In order to avoid the introduction of composite center in Ga band gap and effectively improve the lifetime of minority carriers, with the continuous improvement of ⅱ superlattice technology and theory, antimonized superlattice infrared focal plane wave technology has been widely used in the aspects of operability, uniformity, scalability, scalability and so on. Avalanche Photo Diode batteries and superlattice InAs/InAsSb based on antimonides are still on the exploration stage, but have certain development potential. This study is of great research significance and practical value for the development of the third to fourth generation antimony IR detectors. Based on the structural stability caused by the great ionic bond strength of III-V group materials, the mature preparation technology of InSb IR detectors, and the extension of the photoresponse band to the long-wave IR range after alloying InSb based materials, the new InSb based IR detection materials will be more widely used for the preparation of high-performance IR detectors [11–13].

3.4 High working temperature (HOT) detector based on barrier structure

3.4.1 nBn barrier structure characteristics

By eliminating the depleted electric field in the material of the narrow-gap photonic absorption layer, the nBn detector completely inhibits the generation of a large amount of synthetic current and completely inhibits the contribution of G-R current to the dark current of the photonic absorption layer, thus presenting a low dark current. Therefore, nBn detectors are also called depletion free devices [14].

3.4.2 XBn barrier structure characteristics

The maximum operating temperature of an IR detector is usually determined by the dark current, which increases exponentially with temperature. The XBn detector based on heterogeneous materials is similar to the standard homogeneous P-N junction detector, but the difference is that the XBn detector does not have any narrow bandgap regional depletion region, which is confined to the wideband gap barrier material. Therefore, the contribution of G-R current to the dark current is almost completely suppressed, and the dark current enters the diffusion restricted region4. Compared with the traditional P-N junction detector of the same materials, the dark current mainly in the diffusion limit of XBn detector can increase the operating temperature with almost no performance degradation. In addition, because the wideband gap depletion barrier layer provides isolation for adjacent mesa, and no part of the narrowband gap absorption layer is exposed to air, the XBn detector is easier to prepare and more likely to achieve good focal plane uniformity [14].

4.Applications

The most frequent usage of pyroelectric IR detectors is motion detection. Usually, this can be accomplished with inexpensive thermoelectric ceramic sensors. Other uses include non-dispersive infrared gas analysis as well as infrared flame detection and monitoring. High-quality single crystal lithium is the thermoelectric substance of choice in these fields. This makes it possible for performance to remain consistent over time at high SNR. Spectral or radiometric measurements can also be made with pyroelectric IR detectors.

4.1 Thermography in Aerospace Industry

As mentioned in Figure 1, long waves to short waves are covered by the detector's spectral response. Detectors progress from a single to a multiple and then to a focal plane. There have also been numerous developments in detectors and systems, ranging from single band to multi-band and from room temperature to chilled detectors.

Figure 1. Thermography in aerospace industry [15]

4.2 High-Speed Thermography

As demonstrated in Figure 2, new thermal imaging opportunities are made possible by high-speed image capturing, which enables the monitoring of fast thermal processes. This enables a thorough examination of components and systems. In conjunction with potent measuring and reporting tools, it will help you comprehend chemical processes that react fast and provide a wealth of information. Snapshot detectors are specialised detectors and acquisition systems used by these cameras. Their capacity for concurrent data acquisition and presentation enables millisecond-level accuracy in thermal image measurements.

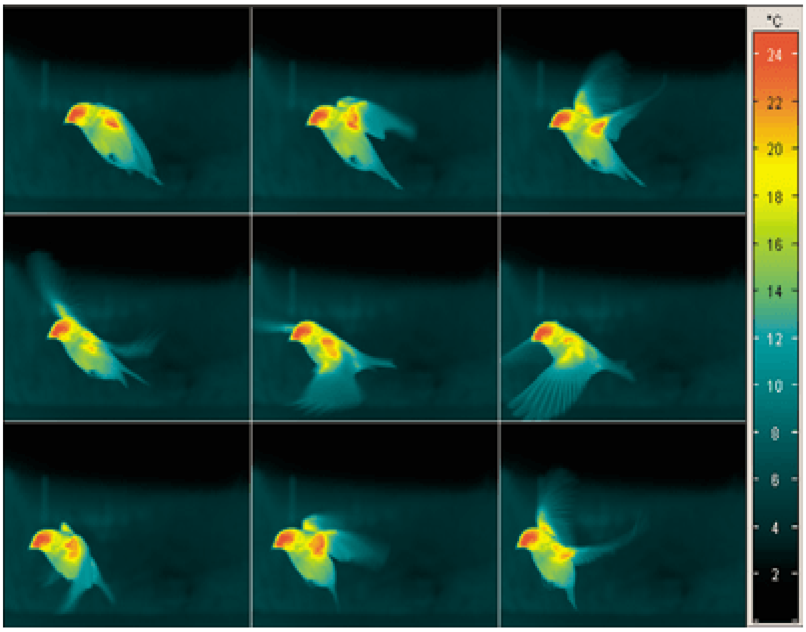

Figure 2. High-speed thermography [15]

4.3 Thermography in Chemical Industry

As shown in Figure 3, infrared cameras can be useful in detecting the heat flow produced by chemical processes in industries working with both hazardous and non-hazardous chemical compounds. The temperature distribution can be more easily captured and measured using thermal imaging technology, and chemical reactions along the entire process chain can be more precisely analyzed. Most importantly, since thermal imaging is non-intrusive and non-contact, individuals should maintain a safe distance once the thermographic camera has finished gathering all the necessary information.

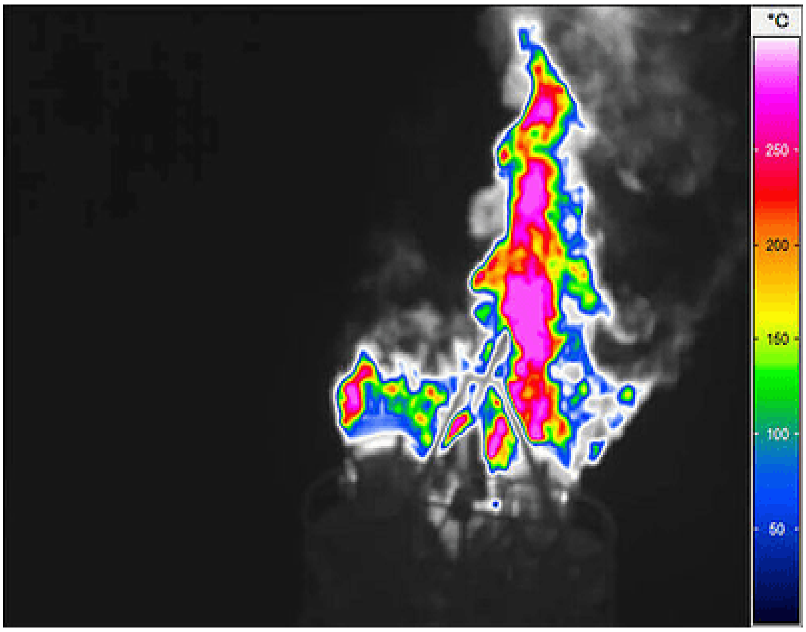

Figure 3. Thermography in chemical industry [15]

4.4 Thermography for Material Testing

As shown in Figure 4, a potent substitute for nondestructively inspecting materials or analysing structural problems is the use of infrared thermal imaging cameras. As long as the temperature is higher than absolute zero, everything in the world emits infrared, making it feasible to employ infrared for nondestructive materials testing since it can be used to detect and interpret heating or cooling from any surface. In these settings, infrared cameras may do non-destructive and non-invasive thermal imaging.

For instance, IR testing can be used for building inspections. The usage of infrared cameras may significantly assist enhance building structures to handle energy loss and resource waste in the drive to increase energy efficiency and lead the world in combating climate change.

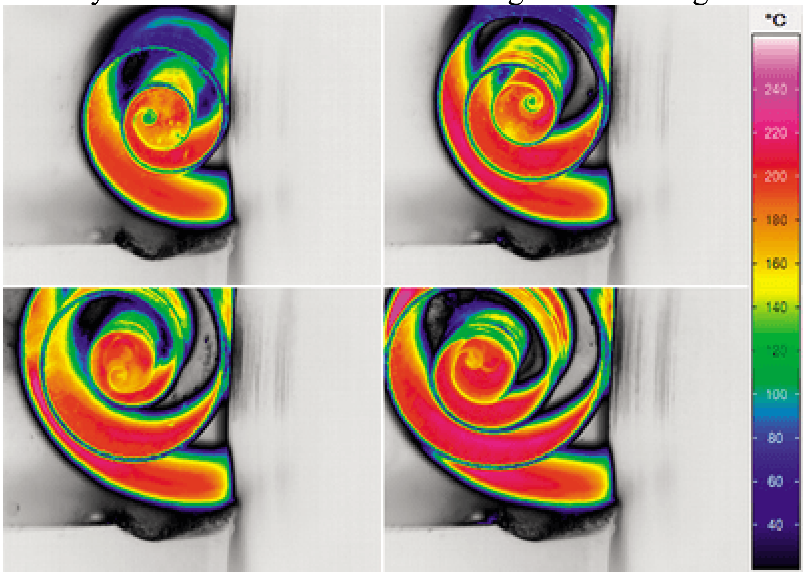

Figure 4. Thermography for material testing [15]

4.5 Thermography in Medicine

As given in Figure 5, applications for thermal imaging are frequently employed in healthcare for both people and animals. The use of infrared thermography can assist identify the origins of arthritis, determine the early stages of cancer, and even identify circulation issues. Infrared cameras may be used by medical professionals like doctors and veterinarians to spot early muscle and bone issues. The growing use of infrared cameras to give horses safer saddles is an illustration of thermal imaging in action.

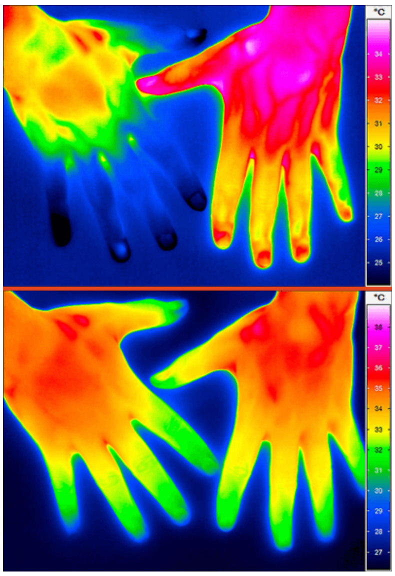

Figure 5. Thermography in medicine [15]

4.6 Thermography in Metallurgy

As Figure 6 has been the case, in order to achieve the desired outcomes, the area of metallurgy revolves around heating the appropriate materials to the appropriate temperature. In this situation, thermal imaging and infrared cameras have several advantages. First and foremost, by identifying insulation flaws in heating chambers, POTS fractures, or other issues with the equipment, infrared thermal imaging in metallurgy may assist in reducing energy usage. The metallurgical industry may easily use infrared cameras to their advantage because of their speed and precision in thermal imaging.

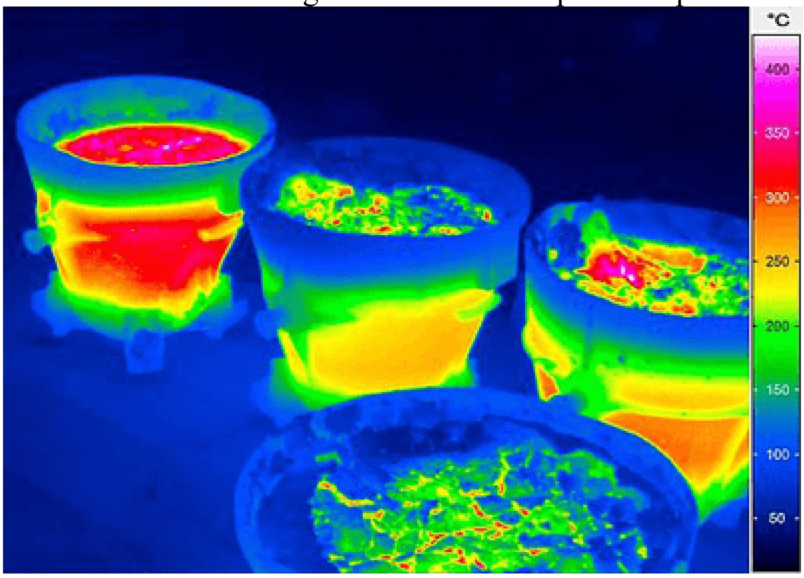

Figure 6. Thermography in metallurgy [15]

4.7 IR Cameras for Plant Inspections

As illustrated in Figure 7, the utmost level of surveillance is necessary during plant inspections to look for any flaws that can cause an accident or endanger worker safety. Thermal imaging is frequently used in manufacturing and electronics firms to discover flaws during predictive maintenance. The use of IR systems allows for efficient inspection without affecting regular operations, putting maintenance workers in risk, or even touching them. The technique is safer and more productive when using infrared cameras, which give an overview and early data.

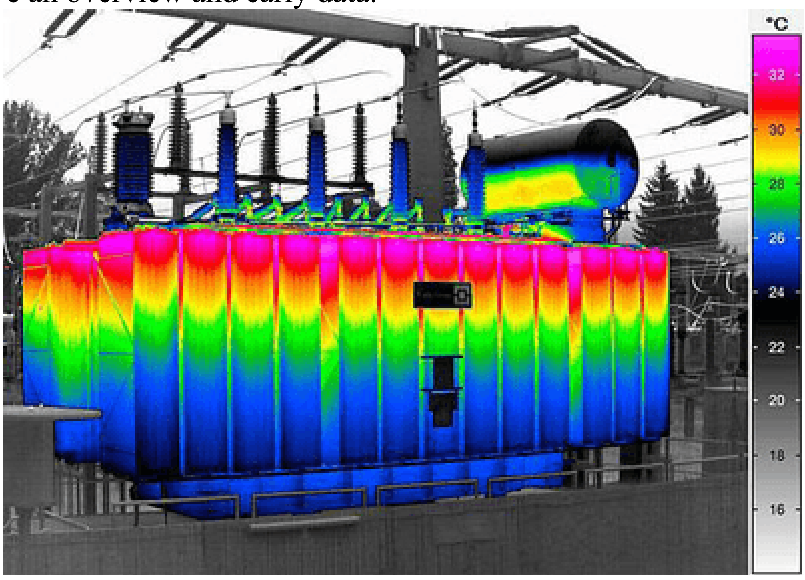

Figure 7. IR Cameras for plant inspections [15]

4.8 IR Cameras for Security

As displayed in Figure 8, IR cameras are more effective for security than basic danger detection and battlefield adversary movement. Applications of thermal imaging for security may be used to find weapons and chemicals brought into county or prisons illegally, identify smoke-filled rooms, offer efficient home security, and even give effective home security.

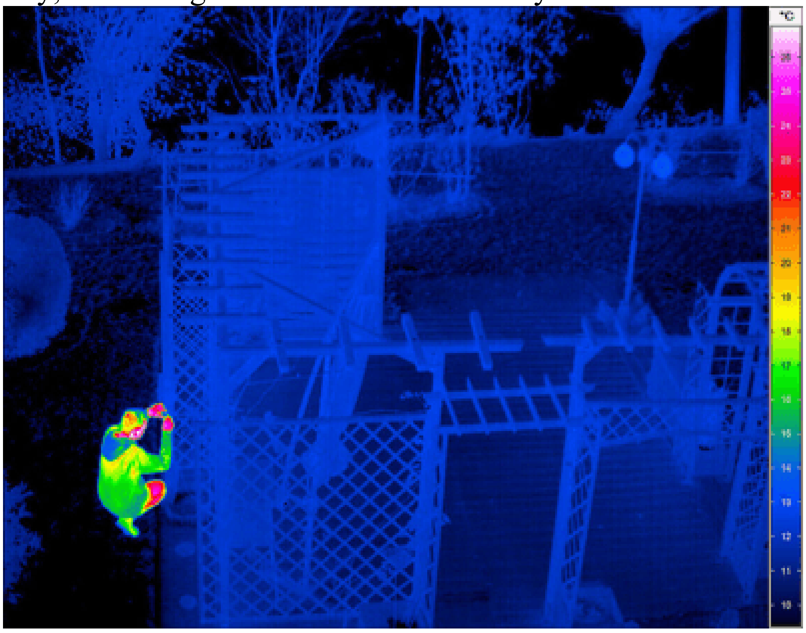

Figure 8. IR cameras for security [15]

5.Conclusion

This paper offers a succinct explanation of the design procedure, detection theory, and basic uses of infrared photons photodetectors. A variety of semiconductor technologies, such as nanotechnology can be used to detect the near-red outer band. Over bulk materials and thin film materials, photodetectors based on nanoparticles offer unsurpassed performance advantages. Over the past few years, research on near-infrared photodetectors has made tremendous strides. This has turn out to list the application of IR detector. Motion detection is the pyroelectric IR detector's most popular application. Usually, inexpensive thermoelectric ceramic sensors are able to achieve this. Infrared flame surveillance and detection are two additional applications. Semi infrared gas assessment is another. The development of IR detectors is also outlined in this work, which can assist readers in swiftly becoming familiar with related research, facilitating the retrieval of previous research findings, and enabling readers to quickly get a broad understanding of the context of a topic.

References

[1] Ma Runze, Zhang Xiaoming, Feng Shuai, Zheng Jun, Xu Yingqiang, Li Chuanbo. Research status and prospect of infrared photoelectric detection technology [J]. Act Photonica Sinica, 2021, 50(10): 1004006

[2] Ma Xu, Li Yunxue, Huang Runyu, Ye Haifeng, Hou Zepeng, Shi Yanli. Development and application of short wavelength infrared detectors [J]. Infrared and Laser Engineering, 2022, 51(1): 20210897

[3] Guo Yanan, Liu Dong, Miao Chengcheng, Sun Jiamin, Yang Zai-xing. Recent advances in semiconductor nanowires infrared photodetectors [J]. Infrared and Laser Engineering, 2021, 50(1): 20211010

[4] Wu Guoan, Luo Linbao. Development and application of near-infrared photoelectric detector [J]. Physics, 2018, 47(3): 137-142

[5] Zhao Zhigang, Wang Xin, Peng Tinghai, et al. Development and application of medium and long wave dual-band infrared imaging technology abroad [J]. Infrared Technology, 2020, 42(4): 312-319

[6] Sui Xiu-bao, Chen Qian, Gu Guo-hua. Influence of ambient temperature on infrared image inhomogeneity [J]. Acta Photonica Sinica, 2008, 37(12): 2572-2575

[7] Hu Weida, Li Qing, Chen Xiaoshuang, et al. Infrared photoelectric detector with transformative characteristics [J]. Acta Physica Sinica, 2019, 68(12): 120701

[8] Luo Bingwei, Liu Dabo, Luo Fei, et al. Study on two kinds of typical infrared detection materials for low temperature applications [J]. Materials Review, 2018, 32(3): 398-404

[9] Yang Qi, Shen Jun, Wei Xingzhan, Shi Haofei. Recent progress on the mechanism and device structure of graphene-based infrared detectors [J]. Infrared and Laser Engineering, 2020, 49(1): 0103003

[10] Junjie Si. Novel InSb-based infrared detector materials [J]. Infrared and Laser Engineering, 2022, 51(1): 20210811

[11] Du Pengfei, Ye Wei, Xiao Sheng, Li Mengfei. research progress of antimony-based type-ii superlattice InAs/InAsSb infrared detector [J]. Laser & Optoelectronics Progress, 2022, 59(17): 1700004

[12] Zhang Jiangfeng, Tian Xiaohan, Zhang Xiaoling, et al. Study on local layered failure mechanism of InSb infrared focal plane array detector [J]. Infrared and Laser Engineering, 2022, 51(3): 20210133-1-20210133-7

[13] Yu Lijing, Tang Libin, Yang Wenyun Hao Qun. Research progress of uncooled infrared detectors [J]. Infrared and Laser Engineering, 2021, 50(1): 20211013

[14] Zhang Kunjie. Research progress and trends of high operating temperature infrared detectors [J]. Infrared Technology, 2021, 43(8): 766

[15] Infra Tec. https://www.infratec.eu/cn/thermography/. Last accessed 2022/9/6.