

Systematic analysis of New Technologies and trends of infrared photodetectors

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Abstract. Infrared detection has always been regarded as an important technology with significant applications in military, industrial, and daily life. Infrared photodetectors (IRPDs) have experienced the development process from thermal IRPDs to photonic IRPDs, until now, the latter can be widely used in focal plane array (FPA). For a long time, IRPD technology based on HgCdTe and InSb materials has dominated the market, but there are still limitations in operating temperature and detectable wavelength region. Since the 21st century, people have been committed to researching new types of IRPDs. Type-II superlattice system technology is considered an alternative solution to the long wave region, and its performance can be improved by adding unipolar potential barriers, which only allow one type of carriers to pass normally. Quantum well and quantum dot are new IRPD technologies based on quantum theory. The former is based on developed GaAs growth technology and can reduce production costs; The latter utilizes the binding mechanism of quantum dots to increase the operating temperature, but whether it can be applied to large-scale devices remains to be researched. All these technologies will contribute to the development and application of the third generation of IRPD.

Keywords: IRPD; type-II superlattice; potential barrier; quantum well; quantum dot.

1. Introduction

Since the presence of infrared (IR) radiation was discovered in 1800, People have been devoted to finding technologies to detect this invisible light. At first, people used the characteristic of resistance changing with temperature to create thermal infrared detectors. In 1940s, with the development of semiconductor technology, semiconductor materials were widely used in the manufacturing of infrared photodetectors (IRPDs). In 1960s, photodiodes were gradually occupying the market due to their high sensitivity, short response time and long range of detectable wavelength. At the end of the last century, photodiodes based on HgCdTe and InSb were the most popular IRPDs [1].

The application of IRPD technology is very extensive, covering multiple aspects from military, industrial to civilian fields. The military applications include guidance, fire control tracking, surveillance, target reconnaissance, weapon thermal sights, ship navigation, etc. The application of these technologies has improved the efficiency and safety of military operations. IRPDs play an important role in industrial equipment monitoring, safety monitoring, disaster relief, remote sensing, traffic management, and other fields. Especially in harsh environments such as high temperature, high pressure, and high humidity, IRPDs can improve the safety and efficiency of industrial production. In addition, IRPDs are also applied in meteorological forecasting, airport security checks, medical inspections, environmental monitoring, etc.

This paper first briefly presents a review of the basic theory and development history of IRPDs, and then introduces several new technologies that can improve the performance of IRPDs to some extent. Plank's Law indicates that most objects emit IR radiation at room temperature, which is why the IRPD is such a crucial technology for humans. IRPDs can be classified into two main types—thermal and photonic, and the latter can be classified as photoconductors, photodiodes and phototransistors. Relatively advanced IRPDs are based on semiconductor materials, mainly HgCdTe and InSb. In the past two decades, although both of these systems have seen enhancements, their progress has not been as significant as that of the detectors based on quantum phenomena. The main content of this paper is about the new technologies and trends of IRPDs, including high operating

temperature (HOT) detectors, quantum well infrared photodetectors (QWIPs), type-II strained-layer superlattice(T2SLS), barrier infrared detectors, and quantum dot infrared photodetectors (QDIPs). This article provides a basic introduction to the principles of these detectors, analyzing and comparing the advantages and disadvantages of them. Finally, conclusions and outlooks are made.

2. The Basic Theory of Infrared Photodetectors

2.1. The Infrared radiation

Infrared photodetectors are devices that convert incident infrared radiation signals into electrical signals for output. In 1800, the English astronomer William Herschel first found the exist of infrared radiation. Plank's Law, proposed in 1900, states that every physical object emits radiation spontaneously. The blackbody radiation equation (1) can roughly represent the spectrum of this radiation, where λ is the radiation wavelength and T is the blackbody's temperature [2]. C_1 and C_2 are constant.

$$M(\lambda) = \frac{C_1 \lambda^{-5}}{\exp\left(\frac{C_2}{\lambda \cdot T}\right) - 1} \quad (1)$$

At the room temperature, an object emits IR radiation around 9.5 μ m according to the equation above. Although objects in the real world are not blackbody, most of them still emit long-wave IR radiation. This illustrates why IRPDs attract so much researchers since 20th century.

The wavelength of IR radiation is a wide range, which cannot be completely covered by any single photodetector, so it is difficult to compare two detectors at totally different absorption wavelengths. To better compare the performance of IRPDs, The IR spectrum has been partitioned into several constituent sub-regions shown in Table 1.

Table 1. The region of IR radiation

IR regions	Wavelength
Near infrared (NIR)	0.78–1 μ m
Short wavelength infrared (SWIR)	1–3 μ m
Medium wavelength infrared (MWIR)	3–6 μ m
Long wavelength infrared (LWIR)	6–12 μ m
Very long wavelength infrared (VLWIR)	12–20 μ m
Far infrared (FIR)	20–1000 μ m

2.2. IR Detectors

According to the forms of energy conversion, IRPDs are classified into two types –thermal and photonic. Thermal IRPDs usually occupy the market of IR detectors because of a number of advantages. Firstly, these devices are designed with minimum complexity and do not require cryogenic temperatures for operation, resulting in reduced power consumption. Furthermore, there is hardly any requirement for maintenance. Due to these advantages, thermal IRPDs are inexpensive and can be utilized in lots of fields [3]. Nevertheless, there are conspicuous drawbacks when thermal IRPDs are used in industries that need high parameters, such as military equipment. Thermal IRPDs are insensitive to temperature fluctuations and vibrations. Also, it is difficult to reduce the pixel size to below 40 μ m [4]. Because of these disadvantages, it is challenging to use thermal IRPDs to acquire sharp images at far distances.

Compare to thermal IRPDs, photonic IRPDs are more sensitive but expensive. They are classified into devices with an exterior photoelectric effect and devices with an interior photoelectric effect, and in modern IR systems, the latter are most widely used. These devices are further divided into three

categories: photoconductors, photodiodes and phototransistors. InSb and HgCdTe are the main components used to create IR photoresistors [5].

The alteration in electrical conductivity brought on by photo radiation is the basis for the functioning of photoconductors. The first IRPDs were photoconductors due to the simplicity of this technology. Besides, photoconductors have other advantages, such as small size and weight, low supply voltage, and a wide spectral range. On the other hand, it was found that the most sensitive photoconductors are also the most inertial, which means that it is unable to obtain photoconductors with both high sensitivity and low response time. Because of this flaw, people usually use photodiodes instead of photoconductors in devices of high sensitivity and response speed.

A photodiode operates on the photovoltaic effect of a p–n junction. Illumination on both sides of the junction generates electron-hole pairs, causing a significant change in the concentration of minority carriers. The minority carriers on both sides move in opposite directions because of the internal electric field, producing photocurrent. Currently, Ge, Si, and InSb are the most common materials used to make IR photodiodes. Ternary compounds like InGaAs and HgCdTe are also used. The sensitivity of photodiodes is determined by the temperature of the semiconductor used in their manufacturing. With temperature decreasing, the dark current and the noise level decrease. Therefore, cryogenic temperatures—or even lower—are required for photodiode operation. The response time of photodiodes is short, and usually the time constant τ can reach 10^{-5} s. In certain thin-film photodiodes, τ can achieve 10^{-10} s [5].

A phototransistor is a device with two p–n junctions. It has a high quantum efficiency and the capacity of amplifying photocurrent. Nevertheless, during the process of operation, the noise significantly increases in the second p–n junction. Moreover, phototransistors have other disadvantages such as the instability of parameters and characteristics with temperature changing, and the lower detection ability than photodiodes.

2.3. Parameters and Materials of IRPDs

In the modern times, the main applications of IRPDs are photodetector (PD) arrays used in military and astronomical fields. Combining multiple photosensitive elements on a single chip results in a focal plane array (FPA) of PDs. A single detector in an array is typically referred to as a pixel, which is usually considered as the smallest individual component in digital images. In an FPA, besides metrics used to describe the performance of a single pixel detector such as dark current and noise level mentioned before, additional metrics used to evaluate the overall image quality are necessary. The number of pixels is important. A larger number of pixels can achieve more precise imaging. Another crucial factor is pixel size, wherein smaller pixels enable more accurate imaging. The noise equivalent temperature difference (NETD), which is defined in equation (2) and can be used to approximate the least resolvable temperature difference of the FPA, is a more usable statistic for FPAs.

$$NETD = \frac{i_n h \nu P}{k_B T_B^2} \quad (2)$$

Where T_B is the blackbody radiation temperature, k_B is the Boltzmann constant, and P is the incident power of light on the detector. Because it indicates the ability for finer, more accurate imaging, a smaller NETD is preferable [2].

History of the development of IRPDs is shown as Fig.1 [6]. After 1970s, with FPAs emerging, the development of IRPDs has intensified significantly. HgCdTe (MCT) and InSb are two of the most popular materials since 1960s, and by 2000 the technology of IRPDs manufactured by MCT and InSb was mature.

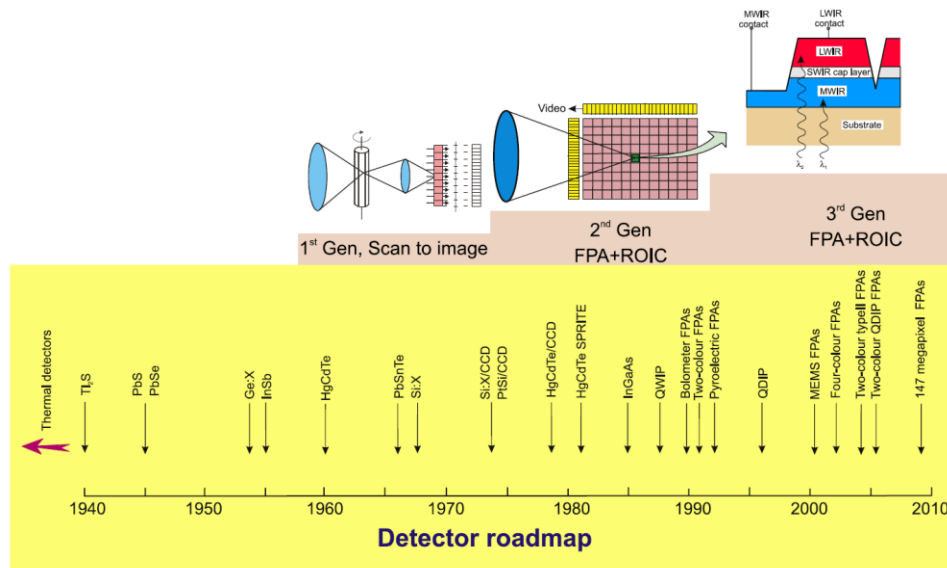


Fig.1 The evolution of infrared systems and detectors throughout history [6]

As Fig.2 shows, by changing the composition of Hg and Cd in MCT, the energy gap can cover entire 1-30 μ m [6]. Therefore, the IRPDs based on MCT materials can be used to detect SWIR region to VLWIR region. In addition, InSb can also be alloyed with Ga and As. Compared to HgTe and CdTe, the band gap difference between InSb and InAs is significantly smaller, so these III-V compounds materials are hard to use outside the MWIR region. However, the tolerance of material composition is eased when creating an IRPD with a certain wavelength due to this small difference in band gaps, providing devices with high stability.

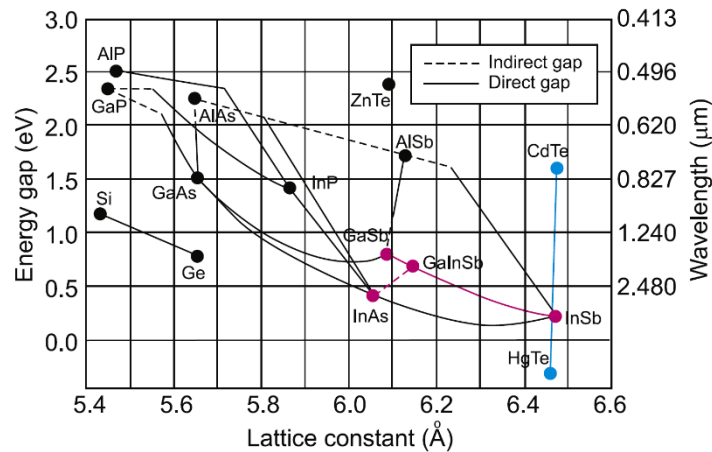


Fig2. The semiconductors' energy band gap at low temperatures and their lattice constants [6]

3. Comparative analysis of different types of IRPDs

As is mentioned in the 2th chapter, MCT and InSb materials have some limitations. New technologies that enable the formation of structures with distinct optoelectronic properties based on III-V and II-VI compounds are being developed in order to lower prices, raise working temperatures, and improve device efficiency. This chapter will introduce some of them and make a simple comparison and summary.

3.1. High Operating Temperature (HOT) Detectors

When using photodiodes as IRPDs, one of the main problems is the low operating temperatures. Usually, photodiodes need to operate at 8-80 K in order to reduce the dark current [7]. This greatly

increases the difficulty of utilization and the cost of manufacturing such devices. Numerous techniques have been put forth to raise operating temperatures, and they are all focused on lowering the dark current, which can be divided into two categories: intrinsic processes and defect-related mechanisms. The dark current is mostly impacted by intrinsic processes at low temperatures; while with the temperature rising, the defect-related mechanisms gradually dominate the change of dark current. Accordingly, People need to eliminate or minimize the dark current caused by defects in order to raise the operating temperatures. It has been demonstrated that new methods for achieving special band gap structures by using different semiconductor materials can partially resolve this issue, which enable people to develop new types of detectors with lower sensitivity to defects. The type-II strained-layer superlattice(T2SLS) is one of the new emerging strategies of band-gap engineering.

3.2. T2SLS

As mentioned in chapter 2, there are two main types of compounds used as material of IRPD designing: the II-VI semiconductors such as MCT, and the III-V semiconductors such as InSb. In general, III-V semiconductors have stronger chemical bonding than II-VI semiconductors, so their structure is relatively more difficult to break. Therefore, compared to MCT devices, FPAs based on III-V semiconductors have higher device yield, lower fragility, and higher device stability. Chapter 2 mentions that the radiation wavelengths detected by IRPDs based on III-V compounds are limited inside the MWIR region. However, a great degree of cutoff wavelength flexibility is possible with T2SLS. There are two main combinations to form T2SLS: InAs/GaSb and InAs/InAsSb. The former is well-established, and the latter, which has a longer minority lifetime, higher defect tolerance, and simpler growth, has surfaced as an alternative more recently [8].

Taking InAs/GaSb as an example, the structure is composed of InAs and GaSb monolayers. An IR absorption area is created by the interleaving of these layers more than 300 times. As Fig.3 shows, these quantum structures have a broken band gap and type-II band arrangement, which cause electron states to be localized in InAs layers and hole states to be localized in GaSb layers [9]. The capacity of these structures to change the band gap, as in MCT, is a significant benefit. However, contrary to MCT, this is accomplished by altering the thickness and composition of the layers that make the components of the superlattice rather than the composition of compounds.

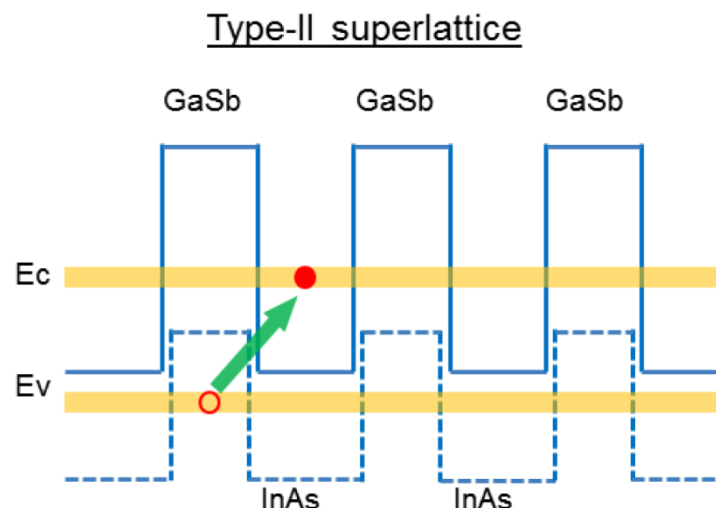


Fig.3 Energy band diagram of type-II superlattice [9]

In recent years, InAs/InAsSb T2SLS IRPDs have developed rapidly and are considered as replacement for InAs/GaSb. Technologies of growth of InAs/InAsSb T2SLS have developed rapidly these years, so MWIR InAs/InAsSb T2SLS FPAs are comparable to InSb in terms of manufacturability and economy. However, the operating temperature of the former is 40K higher than that of the latter.

3.3. QWIPs

Compared to other detectors that came before it, quantum well infrared photodetectors (QWIPs) function on a completely different concept. QWIPs depend on quantum scale physical processes, rather than operating on larger scale effects. As Fig.4 shows, QWIPs are typically created by periodically overlaying two materials with dissimilar band gaps. A well layer is defined as having a low band gap and a barrier layer as having a high band gap. Because the well layers are doped, there are still a large number of charge carriers in the ground state without illumination. After that, photons excite these carriers to an energy state close to the barrier material's conduction band edge, where carriers leave the well under the function of an electric field. By utilizing this principle, people can change quantum well depth and width to change the QWIPs' electron binding energy in order to achieve the appropriate infrared wavelength.

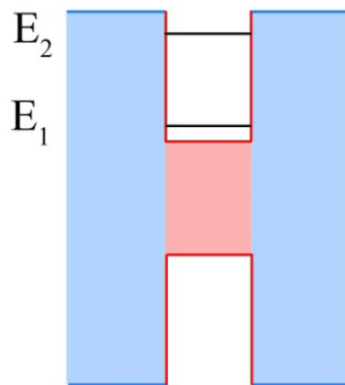


Fig.4 A quantum well's band diagram in a QWIP

GaAs/AlGaAs quantum well devices have numerous potential advantages over MCT detectors, one of which is the utilization of standard production procedures based on established GaAs growth and processing technologies. Furthermore, this structure can grow on GaAs wafers over 6 inches with high yield, resulting in low cost and higher thermal stability. However, QWIPs cannot absorb particularly large photon energy because there is an energy difference at the edge of the material's conduction band, and the photon energy cannot exceed this difference. Therefore, QWIPs are rarely used in the SWIR spectral range. The relatively high amount of thermal excitation at $T > 70$ K, which prevents QWIP IRPDs from competing with MCT IRPDs in this temperature range, is another significant problem with these devices. However, due to the limitations of MCT material, its advantages are not as significant under 50 K. T2SLS and these two technologies were compared in greater detail by Rogalski and Tidrow et al. The essential characteristics of three different kinds of devices at 77 K are contrasted in Table 2 [6].

Table 2. Basic characteristics of LWIR HgCdTe and Type-II SL photodiodes, and QWIPs at 77K [6]

Parameter	HgCdTe	QWIP(n-type)	InAs/GaInSb SL
IR absorption	Normal incidence	Vertical incidence of well required Normal incidence: no absorption	Normal incidence
Quantum efficiency	$\geq 70\%$	$\leq 10\%$	$\approx 30\text{-}40\%$
Spectral sensitivity	Wide-band	Narrow-band (FWHM $\approx 1\mu\text{m}$)	Wide-band
Optical gain	1	0.2-0.4 (30-50wells)	1
Thermal generation lifetime	$\approx 1\mu\text{s}$	$\approx 10\text{ps}$	$\approx 0.1\mu\text{s}$
R_0A product ($\lambda_c=10\mu\text{m}$)	$300\Omega\text{cm}^2$	$10^4\Omega\text{cm}^2$	$100\Omega\text{cm}^2$
Detectivity ($\lambda_c=10\mu\text{m}$, FOV=0)	$2 \times 10^{12}\text{cm Hz}^{1/2}\text{W}^{-1}$	$2 \times 10^{10}\text{cm Hz}^{1/2}\text{W}^{-1}$	$5 \times 10^{11}\text{cm Hz}^{1/2}\text{W}^{-1}$

Despite being photoconductors, QWIPs' high resistance, quick response time, and low consumption of power all meet the specifications required to fabricate large FPAs. Furthermore, QWIPs have the potential to be more cost-effective and easily produced due to the advancements in GaAs production and processing technology.

3.4. Barrier Infrared Detectors

The structure of IRPDs can be significantly changed by adding unipolar potential barriers to T2SLS-based designs. Unipolar potential barrier is a potential barrier which can block one type of carrier but allow another type of carrier to flow unobstructed, as Fig.5 shows [6]. In photoconductors, the majority carriers are bound by potential barriers and cannot pass smoothly, so the dark current will be reduced. Minority carriers are not affected, so the photocurrent will not change. Therefore, the n-B-n detector formed on this basis can effectively reduce dark current and noise. The band diagram of n-B-n is shown in Fig.5. Its structure is very similar to a p-n junction, except that a potential barrier region is used instead of the junction, and an n-type semiconductor is used instead of one side of the p-type semiconductor. It can be said that n-B-n design is a mix of photoconductors and photodiodes. Research have demonstrated that the performance of infrared p-n photodiodes can be greatly enhanced by unipolar potential barriers, particularly at low temperatures [10]. The n-B-n detector has two significant benefits: it has a higher signal-to-noise ratio than traditional diodes at the same temperature, and compared to traditional diodes with the same dark current, this detector will operate at higher temperatures.

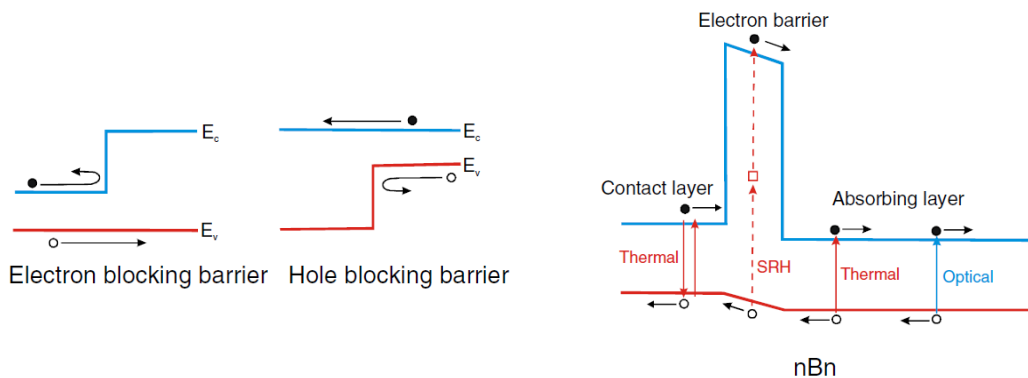


Fig.5 Diagrammatic representations of unipolar barriers that block electrons and holes, as well as the band gap diagram of an n-B-n barrier detector [6]

In order to achieve optimal effect, the barrier needs to be meticulously designed. Firstly, the material requirements for the potential barrier are constricted. One of its conduction and valence bands needs to have a significant offset, while the other cannot, and must have a strong lattice match with the surrounding materials. The barrier should be high enough to inhibit thermally excited electrons, and thick enough to avoid tunneling. In addition, away from the area of light absorption, the potential barrier should be situated close to the minority carrier aggregation region. Although barrier detectors can be implemented in various semiconductor materials, including InAsSb, InAs/GaSb, InAs and HgCdTe, the most suitable materials for n-B-n structures are InAs/GaSb due to the valence band offset that is almost negligible as compared to AlAsSb barriers [11].

3.5. Quantum Dot Infrared Photodetectors

Because of quantum confinement, zero-dimensional semiconductor structures known as quantum dots (QDs) with special optical and electrical capabilities first appeared in the 1970s. In fact, the developments in QWIP have fueled the creation of quantum dots-based infrared photodetectors (QDIPs). QDIPs and QWIPs are comparable, however because of the 3D limitation in QDs, they offer more advantages. One of the biggest expected advantages of QDIP is the ability to perform normal incident detection, thus eliminating the need for manufacturing grating couplers on imaging arrays. Additional advantages of QDIP technology include extended carrier lifetime, leading to reduced dark current, elevated operating temperature, multi-color image detection, and decreased cost. Although QDIPs have previously shown imaging in the mid-and long-wavelength infrared range, they still have a lower absorbing quantum efficiency than inter band photodetectors.

Fig.6 displays one of the single pixel QDIP production choices [9]. A p-i-n device structure can be formed by adding an intrinsic InAs layer with QDs in the middle of the p-n junction. Quantum dots can generate electron hole pairs and absorb infrared radiation. Electrons can move freely in the conduction band to generate photocurrent, but holes are confined in the quantum state of dots and must have sufficient energy to overcome potential barriers. This phenomenon leads to an increase in the photo response of the device with the rise of temperature.

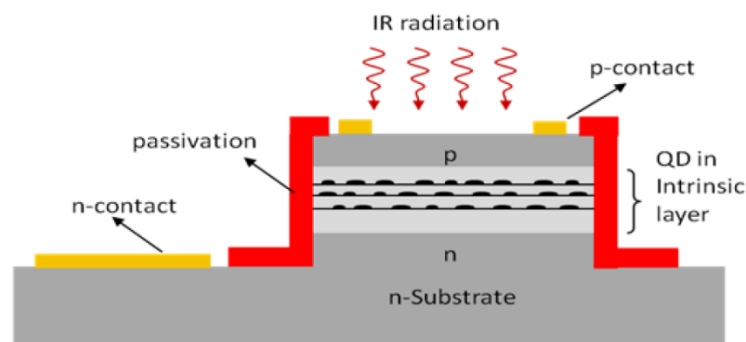


Fig.6 Diagram of a p-i-n diode device with a QD basis [9]

3.6. Systematic Analysis

The strengths and drawbacks of the three IRPDs that were previously discussed are compiled in Table 3.

Table 3. Summary of the strengths and drawbacks of three types of IRPDs

Parameter	T2TLS	QWIP	QDIP
Operating temperature	High	Low	High
Wavelength region	SWIR to VLWIR	MWIR to VLWIR	MWIR to VLWIR
Cost	High	Low	High
Material production process	Developed (InAs/GaSb)	Developed (GaAs)	Not developed
Absorption efficiency	High	High (but it can only absorb vertical incidence)	High
Quantum efficiency	High	Low	Low
Possibility for FPA fabrication	Developed	Developed	Not developed

In general, the next generation of IRPDs needs these attributes: higher operating temperature, higher pixel sensitivity and density, lower cost and larger detectable wavelength range. At present, the main competitor of these new technologies is MCT based IRPDs. Because of its superior qualities, MCT technology is expected to hold a dominant position in the IRPD industry going forward. However, MCT may not be the optimal solution for applications operating in the MWIR/LWIR/VLWIR bands. The technologies mentioned in this article can effectively replace MCT IRPDs, and the main reason is that these technologies are mostly based on materials such as Ga, In, Al and Sb, which have more developed manufacturing technology leading to lower cost.

4. Conclusion

This paper briefly discusses some important emerging IRPD technologies. However, these new technologies have not yet fully matured and commercialized, although some have developed well while others are relatively rare. T2TLS is the most mature development among new IRPD technologies. Depending on the thickness and composition of superlattice, it has a flexible bandgap that is comparable to MCT. The successful demonstration of a MWIR imaging array operating at 120K has been reported, with an efficiency close to 40%. QWIP has the greatest ease of material growth, which makes it easy to manufacture. It also has lower dark current, higher detection rate, and higher NETD. However, it has low quantum efficiency and cannot absorb vertically incident light. QDIP based IRPDs have advantages such as high operating temperature, low dark current and capacity of absorbing vertically incident light. A considerable amount of research has been conducted on QDIP, and many of its advantages have been validated, but the technology still faces the problem of low quantum efficiency.

The third generation IRPDs will continue to develop in the future. Despite slower progress than expected, MCT technology will not face serious challenges in many applications due to its excellent performance. However, in the case of LWIR and VLWIR, the performance of MCT was not as good. T2TLS and QWIP are two relatively new alternative IR technologies with great potential in the LWIR/VLWIR spectral range. QDIP requires more research to make it applicable, especially the possibility for FPA fabrication.

References

- [1] Rogalski A. History of infrared detectors. Opto-electronics review, 2012, 20: 279-308.
- [2] Downs C, Vandervelde T E. Progress in infrared photodetectors since 2000. Sensors, 2013, 13(4): 5054-5098.
- [3] Corsi C. History highlights and future trends of infrared sensors. Journal of modern optics, 2010, 57(18): 1663-1686.

- [4] Rogalski A. Infrared detectors: status and trends. *Progress in quantum electronics*, 2003, 27(2-3): 59-210.
- [5] Korotcenkov G. *Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors*. 2021.
- [6] Rogalski A. Recent progress in infrared detector technologies. *Infrared Physics & Technology*, 2011, 54(3): 136-154.
- [7] Ting D Z, Soibel A, Khoshakhlagh A, et al. Mid-wavelength high operating temperature barrier infrared detector and focal plane array. *Applied Physics Letters*, 2018, 113(2).
- [8] Klipstein P C, Benny Y, Cohen Y, et al. Type II superlattice detectors at SCD. *Infrared Technology and Applications XLVII*. SPIE, 2021, 11741: 102-112.
- [9] Karim A, Andersson J Y. *Infrared detectors: Advances, challenges and new technologies*. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2013, 51(1): 012001.
- [10] Chen Y, Wang Y, Wang Z, et al. Unipolar barrier photodetectors based on van der Waals heterostructures. *Nature Electronics*, 2021, 4(5): 357-363.
- [11] Khoshakhlagh A, Myers S, Plis E, et al. Mid-wavelength InAsSb detectors based on nBn design. *Infrared Technology and Applications XXXVI*. SPIE, 2010, 7660: 948-954.