Infrared detectors: Advances, challenges and new technologies

Amir Karim and Jan Y Andersson
Acreo Swedish ICT AB., Dept of Nanoelectronics, Electrum 236, 16440 Kista, Sweden
amir.karim@acreo.se

Abstract. Human knowledge of infrared (IR) radiation is about 200 years old. However it was in the late 20th century that we developed a wide range of smart technologies for detection and started to take advantage for our benefit. Today IR detector technology is in its 3rd generation and comes with challenging demands. Based on the propagation of IR radiation through free space it is divided into different transmission windows. The most interesting for thermal imaging are the mid-wave IR (MWIR) and the long-wave IR (LW IR). Infrared detectors for thermal imaging have a number of applications in industry, security, search & rescue, surveillance, medicine, research, meteorology, climatology and astronomy. Currently high-performance IR imaging technology is mainly based on epitaxially grown structures of the small-bandgap bulk alloy mercury-cadmium-telluride (MCT), indium antimonide (InSb) and GaAs based quantum-well infrared photodetectors (QWIPs), depending on the application and wavelength range. However, they operate at low temperatures requiring costly and bulky cryogenic systems. In addition there is always a need for better performance, which generates possibilities for developing new technologies. Some emerging technologies are quantum dot infrared photodetectors (QDIPs), type-II strained layer super-lattice, and QDIPs with type-II band alignment. In this report a brief review of the current and new technologies for high performance IR detectors, will be presented.

1. Introduction
This report presents a brief review of IR detectors with a focus on the challenges faced by the current IR detector technologies and demands for future. The discussion is also focused on the demands for next generation IR detectors, with a short overview about emerging technologies. However before starting the discussion about IR detectors it is worthwhile to give a brief overview of the IR radiation itself.

2. A brief overview of IR
IR radiation is the most common form of electromagnetic radiation lying between the visible and microwave part of the spectrum. In terms of wavelength it is between ~0.76µm up to 1000µm. The first discovery of IR was made by William Herschel in 1800 through a simple experiment [1]. However a more clear understanding of it was developed in 1900 through Plank’s law, which is a pioneer result of modern physics and quantum theory. Every physical object in the universe spontaneously emits radiation with a broad range of wavelengths. The peak emission wavelength corresponds to the equilibrium temperature of the object. The spectral radiant emittance follows Plank’s relation as shown in figure 1. The peak emission of objects at room temperature (~300 K) is at
10 \mu m. Whereas, the surface of the sun (~6000 K) has a peak emission in the visible range containing a great amount of IR and ultraviolet (UV) radiation.

Figure 1. Spectral emittance of objects at given equilibrium temperatures.

Upon transmission through atmosphere, IR radiation is absorbed by different chemical compounds found in the atmosphere, for example H\textsubscript{2}O and CO\textsubscript{2}. There may exist more than one definitions to subdivide the IR radiation spectrum. Under standard conditions, there are two interesting minimum absorption windows, 3-5 \mu m and 8-12 \mu m, which are referred as mid-wave IR (MWIR) and long-wave (LWIR), respectively.

3. Applications

Heat sensors were developed even before the full understanding of IR. However it was from the mid-20\textsuperscript{th} century when a wide range of IR detector technologies were developed and exploited for our benefits. IR detectors for thermal imaging have numerous applications. A few of the important applications are mentioned below.

IR radiation is less absorbed and scattered in the atmosphere compared to the visible light and provides important information about objects, for example their temperature, geometry, composition, location in space, and atmosphere. IR imaging has contributed a lot in astronomy to understand the universe [2, 3]. NASA space telescopes are equipped with high performance IR imaging systems, which have provided tremendous information of galaxies and star clusters with details that were previously unseen with visible-light imaging [4].

There are also huge applications in military [5]. Infect initially the IR technology was heavily funded and developed for military applications. Today many military aircrafts are equipped with high performance IR cameras for scanning the battlefield in poor visibility situations. Apart from that there are also ground based night vision systems used by military. There are also IR based missile tracking systems.

Other applications of thermal imaging are in, medical [6], surveillance, search and rescue, meteorology, and climatology.
4. Types of IR detectors

There are two main types of IR detectors, thermal and photonic. Thermal detectors operate based on detecting the thermal effects of the incident IR radiation. The thermal sensing mechanism occurs through many temperature dependent phenomena. Examples of thermal detectors are thermocouples, thermopiles and bolometers. Bolometers are the most common type of thermal detectors, which are based on changes in resistance of the heat sensing material due to the incident IR radiation. Thermocouples and thermopiles use the thermoelectric effect. On the other hand in photonic detectors the incident IR radiation causes intrinsic or extrinsic electronic excitations. Photonic IR detectors can be photoconductive or photovoltaic. In photoconductors the resistivity of the detector element is monitored. Whereas photovoltaic detectors are basically pn diodes and a photoelectric current is generated upon the IR illumination.

From the IR market point of view one can talk about mainly three parameters, volume, performance and cost. The thermal detectors are basically high volume but low performance and low cost technology. However the photonic detectors are low volume but high performance and high cost market. One of the big factors that contribute in their cost is the cooling system. Photonic detectors need to operate at low temperatures. Most of them operate at liquid nitrogen temperature (77K), or ~100K, depending on the wavelength and the detector material. Whereas thermal detectors operate at room temperature. There is another range of photonic detectors with intermediate volume, performance and cost. This is the region where a lot of new competing technologies are emerging.

5. IR detector technologies

5.1. Early detector technologies

The early detector technologies were developed in 1940’s mainly based on compound semiconductors. The first practical IR detector was based on lead sulfide (PbS) for detection up to 3µm wavelength range [7]. In late 40’s this detection wavelength was extended up to 5µm using lead selenide (PbSe), lead telluride (PbTe), and indium antimonide (InSb). Activities on group III/V, IV/IV and II/VI semiconductor alloys started in 1950’s which lead to the development of new semiconductor alloy materials. Mercury-cadmium-telluride (MCT) was one of them, which covers a broad range of IR wavelengths.

5.2. Current technologies and challenges

The current IR technology is mainly based on MCT, which is a narrow and direct bandgap zincblende II-VI ternary alloy of CdTe and HgTe [8, 9]. It has a tunable bandgap spanning the shortwave IR to the very long wave IR regions. The amount of cadmium (Cd) in the alloy can be chosen to tune the optical absorption cutoff wavelength of the material to the desired infrared wavelength. CdTe is a semiconductor with a bandgap of approximately 1.5 eV at room temperature and HgTe is a semimetal with zero bandgap energy. Hence by mixing these two materials one can obtain any bandgap energy between 0 and 1.5 eV. The IR detection mechanism is based on interband transitions between conduction band and valance band, as shown in figure 2.

MCT is a high cost technology mainly due to the fact that it is grown on ZnCdTe. Apart from that there are also uniformity issues for long wave region, where the detection wavelength is more sensitive to compositional variations. Other than compositional inaccuracies, high Auger recombination rates lead to large dark currents. Nevertheless it is currently the dominating IR detector technology for applications with multiple wavelength ranges, where cost is not an issue.

Another existing IR technology is quantum-well infrared photodetectors (QWIPs) [10, 11]. The detector material is based on AlGaAs/GaAs QWs grown on GaAs substrates. The detection mechanism is dependent on intersubband transitions as shown in figure 2, where the excitation of electrons from QW ground state to excited state is shown. It can also cover a wide range of wavelengths. It is a lower cost technology compared to MCT, with high uniformity and best for large
format arrays. But it suffers from low quantum efficiency and operating temperature is also lower than MCT. There is also polarization dependence of the incident IR radiation, which requires fabrication of special grating structures on top of each pixel. Acreo Swedish ICT has contributed to a large extent in developing QWIPs for several years and QWIP based high-performance detector arrays [12, 13, 14].

6. New IR technologies

The motivation for the current and new IR detector technology developments is to look for higher operating temperatures, higher efficiency and lower cost. The continuous quest for larger detectivities, lower operating power and higher operating temperatures necessitates new exotic materials. Two of these new technologies are quantum dot based infrared photodetectors (QDIPs) [15-17] and type-II strained layer superlattice [18-20]. Apart from that there is another technology with a new type of QDIP scheme based on QDs with type-II band alignment [21-24]. These are the technologies we at Acreo Swedish ICT, Sweden, have been involved for some years [17, 20, 22-25]. In this report QDIPs and type-II superlattice are briefly introduced and a more detailed description about QDIPs with type-II band alignment is given.

6.1. QDIPs

Quantum dots emerged in 1970’s as nanometre size features of one semiconductor material in another. These are zero dimensional semiconductor structures with unique optical and electronic properties as a result of quantum confinement. The development of QDIP structures was actually stimulated after the success of QWIPs. They are similar as QWIPs but with extra advantages due to the three dimensional confinement in the QDs. The detection mechanism in QDIPs is also based on intersubband transitions between the quantized energy levels of the dots and continues states [15-17]. QDIP has emerged as a promising technology for third-generation imaging system and there has been a fast development of this technology over the last decade. The material system of QDIPs is mainly based on InAs QDs grown on GaAs substrate. However, several other heterostructure designs have also been investigated for use as IR photodetectors [26-28].

One of the biggest anticipated advantage of QDIPs is the possibility of normal incident detection, unlike in QWIPs, therefore removing the fabrication of grating coupler on imaging arrays. Other expected benefits of QDIP technology are longer carrier life time compared to QWIPs leading to lower dark currents, higher operating temperatures, multicolour detection, and lower cost compared to MCT.

QDIPs have already demonstrated imaging in MWIR and LWIR range, however currently it suffers from lower absorption quantum efficiency in comparison with the interband type of photodetectors. Nevertheless, there might be applications where incident photon flux is high. For example, in the photon-rich terrestrial regime QDIPs can achieve similar performance as the interband type of photodetectors due to very low dark current levels.

6.2. Type-II superlattice

The type-II superlattice strained layer structures have recently emerged as a promising material for high-performance IR photodetectors in MWIR as well as LWIR range [18-20]. This material system consists of a few monolayers (MLs) of InAs and a few MLs of GaSb, which are repeated in a number of periods. These layers are basically grown on GaSb (100) substrates. Although the lattice mismatch
between InAs and GaSb is less than one percent, InAs is tensile strained. These quantum structures are characterized by a broken bandgap with type-II band alignment leading to spatially indirect transitions between hole states localized in the GaSb layers and delocalized electronic states in the InAs layers, as shown in the schematic energy band diagram of figure 3. The effective band gap of these structures can be tailored from 0.3 eV to values below 0.1 eV by varying the thickness and composition of the superlattice layers. The detector devices based on this material system are photovoltaic. There has been a lot of work on device development leading to exotic type of device structures in order to optimize detector performance.

Dark current is an important issue in these devices. The dark current has two components, bulk leakage and surface leakage. The bulk component depends on the material quality whereas the surface component is a result of device fabrication. Over the years the material quality has been greatly improved due to advancements in growth techniques, particularly using the growth technique of MBE. Minimization of surface leakage is essential in device fabrication. A proper etching and sidewall passivation can improve the situation greatly. A good understanding of mesa sidewall and passivation interface is essential to control surface leakage [20]. For cost reduction it would also be beneficial to realize InAs/GaSb SL growth on GaAs substrates.

6.3. QDIPs with type-II band

This is another new technology for IR detector applications. Although there has not been much work done on this area, it offers some very interesting advantages for realizing IR detectors [21-24]. It is also based on QDs but with type-II band alignment. In this case the conduction band of the matrix material is lower in energy than the valance band of the dot material. The energy band alignment in this material system is such that the holes are confined in the quantized energy states of dots and electrons are free to move in the conduction band of the matrix material. The detection mechanism in this system is based on the spatially indirect band-to-band transitions between QDs and the bulk material, as shown in figure 3. Hence it combines all the predicted advantages of QDIPs, as mentioned in section 6.1, with the expectation of stronger interband absorptions as compared to intersubband absorptions.

![Type-II superlattice and QDIP with type-II band alignment](image)

Figure 3. Energy band diagram of type-II superlattice and QDIPs with type-II band alignment, showing electronic transition.

6.3.1. Material system

There are more than one possible QD material systems with type-II band alignment, for example GaAs QDs on InAs [22] and InSb QDs in InAs [29]. Both of these material systems have similar lattice mismatches of about 7%, which leads to the formation of self-assembled QD after the critical thickness of GaAs or InSb deposition. At room temperature GaAs has a bandgap of ~1.4eV and InAs has bandgap of ~0.35eV. The lattice constant of GaAs is smaller than InAs, hence GaAs dots on InAs are tensely strained. On the other hand InSb with a room temperature bandgap of ~0.17eV has a larger lattice constant than InAs and InSb QDs on InAs are compressively strained.

Since the confinement in the dots is dependent on QD size and compositions, therefore the corresponding interband electronic transition can be tuned by controlling the dot size and composition.
It is evident that for larger dot sizes the quantized energy states of dots would shift closer to the matrix (InAs) conduction band leading to a red shift of the absorption wavelength, and vice versa. A possibility of composition variation for wavelength tuning in case of GaAs dots is discussed in reference 22 by incorporating Al and Sb in the dots. Whereas, in InSb dots the incorporation of Ga influences the dot to matrix transition in order to achieve LWIR absorption, as reported in reference 24. Apart from that there are a number of growth parameters that influence dot formation and as a result the transition wavelength. For example in case of material grown using the technique of metal organic vapour phase epitaxy (MOVPE) growth development is performed by optimizing growth temperature, group V and group III molar ratios, growth rate, and amount of material deposited.

6.3.2. Detector device structure

The detector devices are fabricated by well-known III-V device fabrication technology using wet and dry etching followed by side wall chemical polishing and metallization. Surface leakage is an important issue in these devices as well. Therefore a proper sidewall passivation is required to reduce dark currents generated by surface leakage. Apart from that there is also need for device design optimization to develop barrier structures.

Nevertheless, the device structure is pin diode type with multiple QD layers embedded in the intrinsic InAs layer between the p and n doped layer. Schematic view of a fabricated single pixel device is shown in figure 4. The IR radiation is incident from the top which is absorbed by the dots generating electron hole pairs. The photo generated electrons are free to move in the conduction band of matrix material to contribute in photocurrent, however holes are bound in the quantized states of dots. This is the reason for thermally activated photoresponse reported in In(Ga)Sb/InAs QD based IR photodetectors [24].

![Figure 4. Schematic of a QD based pin diode device.](image)

Among all the new emerging technologies, QDIPs with type-II band is the least evolved. There has not been much work done for photodetectors application, although there has been more work performed using this approach for IR light emitters. Currently the most severe issue in the material technology is the low quantum efficiency.

7. Conclusions and future outlook

High-performance IR detector technology is entering into its 3rd generation with high demands on detection efficiency, operating temperatures and particularly ability to perform multicolour detection. A few of the important emerging IR detector technologies were briefly discussed in this report. However none of these new technologies are fully mature and commercialised yet, although some are more and some are less developed.

QDIP based IR photodetectors are anticipated to have advantages of low dark current, high operating temperature, normal incidence and multicolour detection. There has been quite some work performed on QDIPs and many of these advantages have been demonstrated but this technology is suffering from low quantum efficiencies. Nevertheless there might be applications where incoming photon flux is high.
QDIPs with type-II band alignment are expected to have all the advantages offered by QDs as well as higher detections efficiencies because of the band-to-band transitions, unlike in conventional QDIPs. However the quantum efficiency values experimentally demonstrated so far are still very low. The dark current values reported are also not yet close to theoretically anticipated. Among all the three emerging technologies discussed in this report QDIPs with type-II band is the least developed one. The most challenging parameters are full control of the self-assembled QDs, in terms of their size, compositions and material quality. Apart from that device processing and device design also need to be improved to reduce dark currents. Efforts are also required to address the thermal activation of photoresponse, which is a result of holes trapped in the dots after photo excitation.

Type-II strain layer superlattice is the most developed among the new IR detector technologies. It has a flexible bandgap like MCT, depending on the SL thickness and composition. Successful demonstrations of MWIR imaging arrays operating at 120K are reported with efficiencies close to 40%. Reports of single pixel LWIR detectors have also been made based on type-II superlattice. The challenges in this technology are SL interfaces and device passivation. Large developments have been made in terms of material growth particularly applying the technique if MBE. Since this technology is based on number of very thin QWs on top of each other, a good understanding and control of SL interfaces is essential. Apart from that growth of these SL on GaAs would also be beneficial for reducing cost.

A vision for future of IR detector technology is photodetectors integrated with powerful hardware performing smart algorithms. We also may see arrays with each pixel sensing the whole IR spectrum. This may lead to bio-inspired sensing and perhaps fabrication of a complete IR retina.

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