Heterojunction and Superlattice Detectors for Infrared to Ultraviolet

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ABSTRACT

The interest in Infrared and Ultraviolet detectors has increased immensely due to the emergence of important applications over a wide range of activities. Detectors based on free carrier absorption known as Hetero-junction Interfacial Workfunction Internal Photoemission (HEIWIP) detectors and variations of these heterojunction structures to be used as intervalence band detectors for a wide wavelength region are presented. Although this internal photoemission concept is valid for all semiconductor materials systems, using a well studied III-V system of GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ to cover a wide wavelength range from UV to far-infrared (THz) is an important development in detector technology. Using the intervalence band (heavy hole, light hole and split off) transitions for high operating temperature detection of mid Infrared radiation is also discussed. A promising new way to extend the detection wavelength threshold beyond the standard threshold connected with the energy gap in a GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ system is also presented. Superlattice detector technology, which is another promising detector architecture, can be optimized using both Type I and Type II heterostructures. Here the focus will be on Type II Strained Layer (T2SL) Superlattice detectors. T2SL Superlattices based on InAs/(In,Ga)Sb have made significant improvements demonstrating focal plane arrays operating around 80K and with multiple band detection capability. A novel spectroscopic method to evaluate the band offsets of both heterojunction and superlattice detectors is also discussed.

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2 Introduction

A junction is formed when two types of materials are placed next to each other with the interface forming a boundary. When two semiconductor materials with the same band gaps are in contact a homojunction is formed. However these two materials can still have a difference such as a p -type material and an n -type material forming a p - n junction or an n - p - n transistor. This development was the dawn of the semiconductor age, which began with Bardeen, Schokley & Brattain's Nobel Prize winning discovery[1, 2, 3]. When two different band gap semiconductors are in contact, a semiconductor heterojunction is formed. Most of the detector structures discussed here consist of heterojunctions. The advent of the novel growth techniques such as Molecular Beam Epitaxy (MBE)[4, 5, 6, 7] or Metal Organic Chemical Vapor Deposition (MOCVD)[8] etc., and proposals for superlattice structures[9, 10] have led to the development of various heterojunction devices revolutionizing the semiconductor industry. While MBE can provide very sharp, abrupt interfaces, precision, and control, MOCVD can grow thicker layers. MOCVD can also be used to grow a wide variety of materials that are difficult to grow with other epitaxial techniques. A periodic structure consisting of a thin heterojunction or several thin layers (typical thickness of few nanometers) epitaxially grown [forms](#) a superlattice. Sai-Halasz, Tsu and Esaki in a 1977 article suggested the possibility of superlattices of InAs/GaSb for infrared detection[9]. Smith & Mailhot in a JAP article showed how promising this material will be for infrared detection[11]. Superlattice structures can be either Type I or Type II. A periodic structure consisting of layers of two lattice matched materials such as GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ can form a type I superlattice. Quantum well Infrared Photodetectors using GaAs- $\text{Al}_x\text{Ga}_{1-x}\text{As}$ (III-V) materials have been the primary focus [of](#) Type I superlattice detectors. Changing the Al fraction(x) in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ will change the band gap giving rise to various options for detection wavelength. Various writeups on superlattices can be found in the literature[12, 13, 14]. These type of structures were extensively studied as Multi Quantum Well Infrared Photodetectors (QWIPs)[15, 16, 17, 18, 19, 20, 21, 22, 23]. Although the superlattice structures could also be categorized as heterojunctions, here quantized transition based detectors are not categorized as heterojunctions.

Quantum Dot Infrared Photodetectors (QDIP) and Dot In the Well (DWELL) detector structures are also reported in detail in the literature[24, 22, 25] Although QWIP, QDIP and DWELL structures consists of heterojunctions and an interface, the transitions are between two states originating from the quantization effects inside the well material but not due to free carrier absorption. Hence the superlattice discussion here will be mostly limited to Type II superlattice detectors. InAs and InGaSb like lattice mismatched materials in a periodic pattern can form superlattices generally known as Type II Strained Layer (T2SL) superlattices. Advances in growth techniques etc., and prediction of very high performances has increased the interest in T2SL infrared detectors.

2.1 Photoemission

Photoemission, first observed and documented [26] by Hertz in 1887 using ultraviolet light, has long been recognized as an important step in the development of devices, earning Einstein the Nobel prize in 1929 for his work on external photoemission. This is also known as the photoelectric effect [27]. Einstein recognized the kinetic energy of the emitted electrons is proportional to the frequency but independent of the optical intensity. This gives rise to the existence of discrete energy “quanta” leading to quantum mechanics. In the classic Photoelectric effect, when the photons get absorbed, the energized carriers come out of the material and hence can be classified as external photoemission. In this process there is a threshold energy which is needed to eject the carriers out. When the photons are absorbed, if the carriers come out from the original state and overcome an energy barrier and enter a different region still within the material, it can be categorized as internal photoemission. For the carriers to come out there is a specific energy requirement which is historically known as the work function [<http://hyperphysics.phy-astr.gsu.edu/hbase/mod2.html>]. Here when the carriers are still within the material, the energy needed to overcome the barrier is labelled as interfacial workfunction. At a semiconductor junction there is also an interface which is the boundary between the two regions. In general an energy gap exists between the two materials. This could either be due to the band gap difference in the case of a heterojunction or band offset coming from band gap narrowing due to the doping of the material or a combination of the two effects. This energy gap at the interface of the two semiconductors can be used to detect photons with similar or higher energy. The absorbed incoming photons will provide the energy for the carriers to overcome this energy gap. The excited carrier can be collected (as a photocurrent) that completes the detection. The carriers which change the state by thermal excitation, and if collected after emission, will be the thermal current or the dark current. This dark current is not useful in the detection and usually needs to be kept low. However, the dark current also plays a role in replenishing the depleted carriers which also allows the detector to operate continuously.

In this chapter, the focus is on photon detection in heterojunction and superlattice devices, although the homojunction detectors are also reported elsewhere [28, 29, 30, 31, 32, 33, 34, 35]. This heterojunction internal photoemission interfacial workfunction (HEI-WIP) detector idea discussed here can be applied to any semiconductor material where an interface associated energy gap can be formed. Varying the interfacial work function will lead to different energy photons to be detected giving rise to different threshold wavelength detectors. This threshold wavelength (λ_t) is given by $\lambda_t = 1.24/\Delta$ where Δ is the energy gap. This idea which is valid for both n and p -type structures will be extended to show how multiband detection is achieved in a single detector. In addition controlling the operating temperature and the responsivity by adjusting the interfacial work function will also be discussed in connection with (the p -type) spin-orbit split-off detectors.

3 Free-carrier based Infrared detectors

Schottky barrier IR [detector](#) proposed by Shepherd *et al.*, [36] was the first detector type reported as using Internal photoemission (IP). Since then, several different types of internal photoemission detectors have been demonstrated. [29, 37, 38] Among the initial detector developments, the most important types were metal-semiconductor Schottky barrier IR detectors, such as PtSi/Si detectors [39] operating in 3–5 μm range; $\text{Ge}_x\text{Si}_{1-x}$ /Si detectors [40, 41] developed for 8–14 μm or even longer wavelengths. The absorber/photoemitter “electrode” is a metal or a metal silicide in the Schottky barrier and silicide detectors respectively. A similar detector concept was proposed and demonstrated by Liu *et al.*, using Si MBE multi-layer structures in the long-wave infrared (LWIR) range [42]. However, the basic operating mechanism is the same, and following the terminology of Lin and Maserjian [40], all of these detectors including the free carrier based detectors can be described as Heterojunction or Homojunction Internal Photoemission (HIP) detectors.

3.1 Heterojunction Detectors

The difficulties of controlling the barrier height and extending the threshold to high wavelengths in homojunction detectors [32, 43] has led to the development of the HEIWIP detectors [44] where the Al fraction in one or both of the layers can control the workfunction. Although the *n*-type emitters also can provide HEIWIP detectors [see Fig. 1], most of the work on HEIWIP is reported with *p*-type emitter structures. The band diagram for both *n*-type and *p*-type emitter HEIWIP detectors are shown in Fig. 1. The additional degeneracy in the *p*-type (Heavy hole, Light hole and Splitoff) has shown to be useful in obtaining an extra control in addition to the Al fraction [45] which will be discussed later.

< Figure 1 here >

3.2 Barrier height variation in HEIWIP

The HEIWIP detectors which uses free carrier absorption of the HIWIP (Homojunction Interfacial Workfunction Internal Photoemission) [30] with the material composition of QWIPs have been experimentally demonstrated [38, 45, 46, 47], covering the wavelength range from 4 to 124 μm [see Fig. 2]. The typical HEIWIP detector structure consists of an emitter (absorber) region followed by an undoped barrier region. Although the structure appears similar to a QWIP structure, the emitter/absorber in a HEIWIP is thicker than the well region of a QWIP. As a result, the carriers form a 3-dimensional distribution in HEIWIPs rather than producing quantized energy states as in a QWIP. The basic idea of HEIWIP detectors is to add the valence(Conduction) band offset for the GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ interface to the offset from the doping $N_A(N_D)$ in the emitters. The contribution from the doping (Δ_d) is the same as for HIWIPs. The Al fraction contribution is taken as $\Delta_{Al} = (x * 530)$ meV where x is the Al fraction. The total barrier at the interface is then $\Delta = \Delta_d + \Delta_{Al}$.

The threshold wavelength can be determined following the standard energy gap and wavelength formula $\lambda_t = 1.24/\Delta$ where λ_t is in μm and the workfunction Δ is in meV. One possible approach to avoid this limit is to use $\text{Al}_x\text{Ga}_{1-x}\text{As}$ as the emitter material and GaAs as the barrier material[47].

< Figure 2 here >

3.3 *p-type HEIWIP detectors*

p-type HEIWIP detectors can be categorized into two categories. The first type [Fig. 3(a)] is the standard HEIWIP detector, which uses doped GaAs emitters and undoped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers. Here the contributions from the doping and Al fraction to the workfunction are both in the same direction, i.e. decreasing the Al fraction can increase the threshold wavelength from a minimum of $\sim 2.3 \mu\text{m}$ for an AlAs emitter up to a longer limit of $\sim 110 \mu\text{m}$ for an Al fraction of 0.005. This is due to the Al fraction at which the Al starts to act as an isoelectronic dopant and does not produce a consistent change in the valence band. Also, $x = 0.005$ is a practical limit for accurate growth. While an Al fraction of zero is possible, that would correspond to the HIWIP case which had the threshold frequency limitation[43].

The second type of design uses doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ as the emitter, and undoped GaAs as the barrier as shown in Fig. 3(b). In this approach the band offset from the Al fraction is used to reduce the band offset from the doping in the emitter. In this approach, the Al fraction must be kept small ($x < 0.17$) such that the band offset does not exceed the doping offset. In theory, this approach will allow the workfunction to be reduced down to zero.

< Figure 3 here >

Most of the reported HEIWIP detectors had GaAs emitters and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers. Further increase in λ_t beyond $110 \mu\text{m}$ requires a change in the design due to the minimum $\Delta = \Delta_d$ from the bandgap narrowing. Table 1 summarizes the results on HEIWIP structures showing threshold wavelengths from $4 \mu\text{m}$ to $70 \mu\text{m}$ GaAs emitter structures and a $128 \mu\text{m}$ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ emitter detector.

< Tabel 1 near here >

3.3.1 *p-GaAs emitter and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier detectors*

Results were reported by Perera *et al.*, [38] on a device structure consisting of 20 periods of $158 \text{ \AA}$ GaAs emitters and $800 \text{ \AA}$ $\text{Al}_{0.02}\text{Ga}_{0.98}\text{As}$ barriers. The emitters were doped with Be to $3 \times 10^{18} \text{ cm}^{-3}$. The response increased as the bias was increased up to $\sim 700 \text{ mV}$ after which it started to decrease. Strong response was reported for wavelengths lower than

50 μm with a threshold wavelength of $\sim 70 \mu\text{m}$ [see Fig. 4]. At a wavelength of 20 μm for 700 mV bias, the peak responsivity(R_{peak}), specific detectivity(D^*) and Noise Equivalent Power (NEP) was $\sim 11 \text{ A/W}$, $\sim 1 \times 10^{13} \text{ cm}\sqrt{\text{Hz}}/\text{W}$ (Jones) and $\sim 3 \times 10^{-15} \text{ W}/\sqrt{\text{Hz}}$ respectively[38].

< Figure 4 near here >

The variation of λ_t with the Al fraction for $p\text{-GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ detectors is summarized in Fig. 5 (a). Device structures with three different Al fractions from 0.005 to 0.02 showing variations in the threshold from 68-92 μm as seen in Fig. 5 (b) have been reported by Matsik *et al.*, [48]. The Al fraction was varied, with $x = 0.02, 0.01$ and 0.005 for samples 2409, 2410, and 2411 respectively to adjust λ_t , with the expected barrier heights of 18, 13.5 and 11.2 meV, respectively. The responsivity results for the three samples at a bias field of 3.5 kV/cm for 4.2 K are shown in Fig. 5 (b) with a strong response for wavelengths lower than 50 μm .

< Figure 5 near here >

The threshold values (indicated by the arrows) were $\lambda_t = 65, 84$, and $92 \mu\text{m}$ for samples 2409, 2410 and 2411 respectively. The responsivity at 30 μm was $\sim 5.6 \text{ A/W}$ for samples 2409 and 2410 and 6.0 A/W for 2411. The quantum efficiency was 22% for 2409 and 2410 and 25% for 2411 at 30 μm . The D^* was 4×10^{10} Jones ($\text{cm} \sqrt{\text{Hz}}/\text{W}$) for 2409 and 2410 and 3.6×10^{10} Jones for 2411 at 4.2 K [48].

3.3.2 $p\text{-type Al}_x\text{Ga}_{1-x}\text{As}$ emitter and GaAs barrier detectors

Overcoming the long wavelength threshold limit due to the lower Al fraction limit was reported by using $\text{Al}_x\text{Ga}_{1-x}\text{As}$ emitters with a low aluminum fraction with GaAs as the barriers[47]. These structures consisted of 10 periods of $3 \times 10^{18} \text{ cm}^{-3}$ Be-doped 500 Å thick $\text{Al}_{0.005}\text{Ga}_{0.995}\text{As}$ emitters and 2000 Å thick GaAs barriers sandwiched between two contacts. In such a device the bandgap narrowing in the doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is partially offset by the increased bandgap of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ material relative to the GaAs, giving $\Delta = \Delta_d - \Delta_{Al}$. For example, a $\lambda_t = 335 \mu\text{m}$ detector would have an Al fraction of ~ 0.01 . The FIR absorption in $\text{Al}_x\text{Ga}_{1-x}\text{As}$ is very similar to GaAs[49], due to the very low Al content performing similarly to the devices with $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers. Another approach is to increase doping concentrations to reduce the bandgap narrowing contribution. This has been done in $n\text{-type GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ structures[50] leading to detectors with response out to 93 μm . The variation of the threshold wavelength with the Al fraction for $n\text{-type Al}_x\text{Ga}_{1-x}\text{As}$ HEIWIPs and $p\text{-type HEIWIPs}$ using both GaAs and $\text{Al}_x\text{Ga}_{1-x}\text{As}$ emitters is shown in Fig. 2. The experimentally observed thresholds which will be discussed later are represented by symbols ($\bullet$, $\blacktriangle$, $\blacksquare$). Absorption measurements have been performed on doped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ films giving good agreement with the model for the absorption coefficient[51] with the material parameters obtained by a linear interpolation of the values for GaAs and

AlAs.

The variation of responsivity with the bias field at 4.8 K is shown in Fig. 6(a). For wavelength $< 50 \mu\text{m}$, the responsivity increases with the field with a maximum responsivity of 9 A/W at 1.5 kV/cm. Although further increase in the field decreases the lower wavelength response, the higher wavelength ($> 50 \mu\text{m}$) response increases. As expected, the band bending due to the residual doping in the barrier (Δ_b) decreases with the field, increasing the threshold to $130 \mu\text{m}$ for a bias field of 2.0 kV/cm. The semi-log scale of Fig. 6(a) clearly shows the variation of λ_t with the applied field. A dark current limited peak detectivity of 1.5×10^{13} Jones was obtained at the bias field of 1.5 kV/cm at 4.2 K. A BLIP temperature of 20 K for a 0.15 kV/cm bias field was recorded[47]. The variation of Δ obtained from Arrhenius plots with the positive bias field for three devices with different electrical areas is shown in Fig. 6(b). The Δ decreased from ~ 17 meV at zero bias to 10.5 meV at 2 kV/cm[47]. The $p\text{-Al}_{0.005}\text{Ga}_{0.995}\text{As}/\text{GaAs}$ detector reported by Rinzan *et al.*[51] has shown the longest wavelength threshold.

< Figure 6 here >

3.4 *n-type HEIWIP detectors*

As mentioned before most HEIWIP detectors reported were *p*-type, but *n*-type materials have also been utilized for HEIWIP detectors in both $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ system and $\text{GaN}/\text{Al}_x\text{Ga}_{1-x}\text{N}$ systems. Two examples of such detector reports are discussed below.

3.4.1 *n-GaAs emitter/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier HEIWIP detectors*

Results on an *n*-type $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ HEIWIP detector structure consisting of an undoped $1 \mu\text{m}$ thick $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ($x=0.04$) barrier layer sandwiched between two $1 \times 10^{18} \text{ cm}^{-3}$ Si doped GaAs contact layers were reported in 2007[50]. The 100 nm top contact and a 700 nm bottom contact layers serve as emitters in this design. The Δ was estimated to be 13-14 meV corresponding to a threshold wavelength λ_t of 88-97 μm from Arrhenius analysis[50]. The calculated Δ should be between ~ 10 -20 meV, corresponding to a 60-125 μm threshold wavelength.

< Figure 7 near here >

The peak responsivity (R_{peak}) of 6.5 A/W at 42 μm [50] was reported at a bias field of 0.7 kV/cm in the forward bias operation (top emitter positive) as shown in Fig. 7(a). The R_{peak} obtained in the reversed bias was 1.7 A/W at 0.25 kV/cm. At a bias field of 0.5 kV/cm, the R_{peak} in the forward bias was 6.1 A/W while the R_{peak} in reverse bias was 1.1 A/W. The responsivity variation in forward and reverse direction was attributed to the top and bottom contact thickness differences, with ratios in forward and reverse bias operations

agreeing with the thickness ratio of the bottom and the top contact layers[50]. Based on the spectral response, a threshold of $\sim 94 \mu\text{m}$ was observed.

3.4.2 $n\text{-GaN}/\text{Al}_x\text{Ga}_{1-x}\text{N}$ HEIWIP detectors

A $\text{GaN}/\text{Al}_x\text{Ga}_{1-x}\text{N}$ HEIWIP detector structure responding from shortwave to far-infrared range has also been reported[52], indicating the feasibility of far-infrared detector development with the rapidly developing $\text{GaN}/\text{Al}_x\text{Ga}_{1-x}\text{N}$ material system. The detector structure was grown by MOCVD on a sapphire substrate. The complete response of this detector at 5.3 K composed of three parts based on three detection mechanisms is seen in Fig. 8(c)+. The free carrier response exhibits a threshold at $11 \mu\text{m}$, while the sharp peak at $54 \mu\text{m}$ is due to the $1s\text{-}2p_{\pm}$ transition of silicon (Si) dopant atoms, which has been observed previously[53] at the same energy level of $\sim 23 \text{ meV}$. There is also a slower mechanism which provides a response out to $300 \mu\text{m}$, which was speculated to be due to either a thermal or pyroelectric effect.

< Figure 8 here >

3.5 Dualband Detectors

Both HIWIP[34, 54] and HEIWIP[55] detectors has been reported with interband transitions in the undoped barrier and intraband transitions within the emitter showing dualband response characteristics. Incident radiation with an energy greater than the band gap of the barrier is absorbed, generating an electron-hole pair. The standard detection mechanism in HIWIPs and HEIWIPs including free carrier absorption leads to the detection of far-infrared radiation. A typical band diagram shows both interband and intraband transitions leading to dual band detection as seen in Fig. 8(b). Excited carriers are then collected by the applied electric field. The interband response threshold is determined by the band gap of the barrier material. Hence, using different material systems (such as Si, $\text{GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$, $\text{GaN}/\text{Al}_x\text{Ga}_{1-x}\text{N}$, etc.), the interband response can be tailored to different wavelength regions.

Despite the interest in GaAs material for IR devices, not much work has been reported on detecting visible (VIS) or UV radiation using GaAs based systems, probably due to the availability of wide-bandgap materials for the UV region and Si and InGaAs for the VIS region. However as a detector sensitive in all of the three regions, one advantage with GaAs is that the extension to array detectors should be a relatively straightforward process.

A free carrier absorption based dual band $\text{GaN}/\text{Al}_x\text{Ga}_{1-x}\text{N}$ HEIWIP detector responding in $8\text{--}14$ and $20\text{--}70 \mu\text{m}$ ranges has also been reported[52]. A sharp peak in the $11\text{--}13.6 \mu\text{m}$ range was observed to be superimposed on the free carrier response. In addition, the response demonstrates a peak at $54 \mu\text{m}$ due to the $1s\text{-}2p$ transition of Si donors in GaN. The intraband transition shown in Fig. 8(b) gives rise to the free carrier IR response in the $8\text{-}14 \mu\text{m}$ range.

3.5.1 UV-IR dualband HEIWIP detectors

A dual band detector for both UV and IR was demonstrated[55, 56] by using n -GaN as the emitter and i -Al_xGa_{1-x}N as the barrier in a structure shown in Fig. 8(a), with the band diagram shown in Fig. 8(b). The experimental response shown in Fig. 9 was shown to agree well with the theoretically calculated response[57].

< Figure 9 here >

While the initial detector using only two contacts required separate modulations to distinguish the UV from the IR, a later design using three contacts and separate active regions for the UV and the IR was able to distinguish UV from IR without separate modulations[58] as shown in Fig. 10. The detector with a GaN/Al_xGa_{1-x}N single element structure was capable of simultaneously and separately identifying both the UV (250–360 nm) and IR (5–14 μ m) responses with near zero spectral cross talk. This approach allows tremendous variation in both thresholds. By using Al_xGa_{1-x}N in both layers with different Al fractions and adjusting the Al fraction in the barriers, the UV threshold can be tailored, while by adjusting the difference between the fractions in the emitters and barriers, the IR threshold can be tailored. However, for high performance devices, the quality of the GaN/Al_xGa_{1-x}N material system needs to be improved, which is presently the focus of many researchers.

< Figure 10 near here >

3.5.2 UV-VIS-IR multiband detector with polarization sensitivity

A multiband GaAs/Al_xGa_{1-x}As detector structure grown by molecular beam epitaxy and resembling a p - i - n structure with a p -type QWIP, i -GaAs region, and an n -type QWIP detecting UV, Visible and IR was reported by Ariyawansa *et al.*,[59]. As schematically shown in Fig. 11 (d), the three regions are sandwiched between a highly doped p -type top and an n -type bottom contact regions. The p -type QWIP region consists of 40 periods of 3.1-nm-thick GaAs wells in 25-nm-thick Al_{0.55}Ga_{0.45}As barriers, and was designed to respond around 5 μ m. The n -type QWIP region consists of 50 periods of 5.4-nm-thick GaAs wells in 40-nm-thick Al_{0.24}Ga_{0.76}As barriers, and was designed to respond around 9 μ m. To couple normal incidence light with the n -type QWIP, a 1D metal grid having a fill factor of 0.5 and a grating period of 2.8 μ m (corresponding to the first-order diffraction peak at 9 μ m) was fabricated on the top of the structure.

< Figure 11 here >

Two response peaks in the MIR region appear at 5 μ m (p -QWIP) and 8.9 μ m (n -QWIP) at 80 K for unpolarized normal incidence radiation. The responsivity of the two peaks depends on the strength of the applied bias as shown in the inset to Fig. 12 (a), the peak at

5 μm is dominant at low bias (10 V), while the peak at 8.9 μm is dominant at high bias (15 V). This bias dependency of the two response peaks agrees with the concept explained in detail elsewhere [60] for a multicolor detector consisting of three QWIP stacks.

< Figure 12 here >

When two QWIP structures, which respond to different wavelengths, are stacked to form a two color detector, the applied bias voltage is distributed between the two based on their dynamic resistance at a given voltage. If the resistance of the short wavelength QWIP is much higher at low bias, the applied bias will be mostly across the short wavelength QWIP at low bias. When the bias is increased, the dynamic resistance of the long wavelength QWIP becomes higher than that of the short wavelength QWIP, leading the applied bias to distribute across the long wavelength QWIP. Under low bias, as shown in Fig. 11(b), the applied bias applies across the p-QWIP (short wavelength), while the *n*-QWIP (long wavelength) turns on at high bias as shown in the band diagram in Fig. 11(c). Although the MIR detection is prominent for forward bias, a response for very high reverse bias voltages (near the breakdown voltage) can be observed similar to forward bias, since the high leakage current refills the well ground state. The D^* values at 8.9 μm are 8.8×10^{10} and 5.1×10^{10} Jones at 80 K under 15 and 40 V bias voltages respectively, while 5 μm peak exhibits a D^* of 1×10^{11} Jones at 80 K under 10 V bias. As shown in Fig. 12 (b), the response at 8.9 μm is sensitive to p-polarized light (perpendicular to the metal strips in the grating), as expected for an *n*-QWIP, while the peak at 5 μm is not sensitive to the polarization of the light, which is due to the fact that the hole transitions (5 μm peak) do not obey the polarization selection rules. The polarization extinction ratio for the 8.9 μm peak is 100:25, and it is reasonably consistent with standard QWIPs with similar measurement geometry. The polarization extinction ratio could be further improved by using metal grids with grid periods in the 0.5-1 μm range, where polarization properties of the metal grid as well as the quantum well would contribute to the extinction ratio. Due to the multiband response this detector was discussed even though it is a QWIP detector.

4 Inter-Valence Band detectors

The split-off (SO) band detection was initially observed in a GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ HEIWIP detector HE0204 [45] which was designed for the 10–15 μm range with a 20 μm threshold[61]. Afterwards a structure specially designed for the SO detection mechanism[46] where the Al fraction threshold matched the SO energy showed response up to 330 K. The SO detectors have a similar design to the standard HEIWIP detectors consisting of alternative highly *p*-doped absorbing layers (emitters) and undoped barrier layers sandwiched between two highly doped ($1 \times 10^{19} \text{ cm}^{-3}$) top and bottom contact layers with thickness at 0.2 and 0.7 μm , respectively. The standard interfacial work function in the HEIWIP detectors will still provide a threshold wavelength. However, this offset can be adjusted in comparison

with the SO energy for higher response (longer Al fraction threshold) or higher temperature (matching SO and Al fraction thresholds) operation. Unlike QWIP detectors, Inter-Valence Band (IVB) detectors will detect normal incidence radiation removing the need for light coupling processes and associated costs. A ring contact was used on the top surface and a window was opened through the top contact for front-side illumination.

< Figure 13 near here >

The highly doped 18.8 nm thick emitters will lead to three-dimensional energy states as opposed to quantized states. An E - k band diagram around $k = 0$ in the Brillouin Zone (BZ) for an emitter region is schematically given in Fig. 13 (a) and the band diagram for the device is shown in Fig. 13 (b). The SO band is separated from the degenerate point of the Light-Hole (LH) and Heavy-Hole (HH) bands at $k=0$ by an energy E_{E-SO} which equals to the spin splitting energy Δ_{SO} . The detector mechanism consists of three steps: (I) photo-absorption exciting the carriers from the emitters, (II) escape of the photo-excited carriers and (III) the sweep out and collection of the escaped carriers. Photo-excited carriers in the SO band can escape directly or scatter back into the LH/HH bands and then escape. The lowest barrier for the excited carriers in LH/HH bands is the threshold work function Δ , which determines the threshold wavelength for free carrier response and thermionic dark current. Hence this Δ also controls maximum operating temperature. Increasing Δ results in a reduction in the free-carrier response, making SO transitions becoming dominant, but increased Δ also decreases the escape probability and gain. The optimum value is determined by the application requirement of high operating temperature or high performance.

The spin-orbit splitting effects result from the coupling of electron spin to the orbital angular momentum via the spin-orbit interaction which is a relativistic effect and scales with the atomic number. Hence spin-effects based IR detection should be sensitive to the magnetic field allowing magnetic tunability and controllability. For semiconductors containing lighter elements the splitting energy becomes small, hence the possibility of extending the SO transition wavelength into far-infrared (FIR) spectral region increases. For example, zincblende or wurtzite crystal structures of GaN having the SO splitting energies of 20 meV ($\sim 62 \mu\text{m}$) and 8 meV ($\sim 156 \mu\text{m}$), respectively [62] would be a promising material for FIR detection.

In addition to SO-HH transitions, selection-rule allowed hole transitions between the LH and HH bands can also take place at k values other than the BZ center where the LH-HH energy separation approximately approaches 2/3 of the SO splitting energy. A broad spectral region covering mid- and long-wavelength infrared (MWIR and LWIR) can be expected as the LH-HH transition energy has no minimum limitation from the band-structure point of view since they are degenerated at Γ point. Experimental measurements on the absorption properties for p -doped semiconductor have been made over a variety of materials, e.g GaAs [63, 64];, GaP [65], GaSb [66], Ge [67], InAs [68], InP [69] and InSb [70]. All these p -type materials show broad absorption extended into the FIR region. The

Inter-Valance-Band-Absorption (IVBA) strength is generally increased with the doping. However, enhanced scattering of carriers by charged centers at higher dopings could relax the selection rule $\Delta k = 0$ leading to broad SO-HH peak and reduced intensity [71], whereas the LH-HH peak keeps a well-defined shape even at very high dopings [64]. The energy onset of LH-HH absorption band (e.g. 0.25 eV reported by Braunstein *et al.*, (1958) [63]) approximately approaches the LH-HH separation $\Delta_1(\Lambda)$ in the $\langle 111 \rangle$ direction (e.g. 0.225 eV reported by Lautenschlager *et al.* (1987) [72]), indicating most transitions could occur along $\langle 111 \rangle$ in k space. From the band structure point of view, hole transitions will see the parallel structure of the LH and HH bands along $\langle 111 \rangle$ giving rising to the narrow LH-HH peak. The use of detection mechanism involving LH-HH transitions is promising for infrared detection to co-currently cover multi-band spectral region by using a single structure e.g. p -type GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ detectors [73].

4.1 Uncooled SO detectors

Optimum response and the operating temperature are two competing requirements. Smaller Δ giving rise to a longer free-carrier threshold wavelength allows increased collection of the carrier over the SO barrier but also allows a higher dark current. In contrast, larger Δ reducing the dark current will lead to an increase in operating temperatures but accordingly will decrease the photo-carrier escape and the response.

Studies have shown that the inter-valence band absorption including the SO transitions was one critical part of optical loss for long-wavelength semiconductor lasers at elevated temperatures [69, 74], which is related to the temperature behavior of IVBA due to a higher amount of thermally populated heavy holes. In contrast, such IVBA behavior will be beneficial for infrared detectors.

< Figure 14 near here >

As discussed above, the threshold work function Δ (shown in Fig. 13) determines the thermionic dark current allowing it to control the maximum operating temperature. By designing structures with optimized Δ values, high-operating-temperature SO detectors is possible. Such designs were reported [46, 75] on three detector structures SP1, SP2, and SP3 which have different Δ values of 155, 207, and 310 meV (corresponding Al fractions are $x = 0.28, 0.37, 0.57$). All these detectors were composed of $3 \times 10^{18} \text{ cm}^{-3}$ p -doped 18.8 nm GaAs emitters and 60 nm undoped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers. The current voltage (I-V) characteristics measured from 70 to 300 K as seen in Fig. 14(a) indicate the dark current density at 1 V bias reached the same order at 140, 190 and 300 K for samples SP1, SP2, and SP3, respectively. The measured dark current densities of SP1, SP2, and SP3 at 150 K temperatures (solid lines) are consistent with a thermionic model (dots) as shown in Fig. 14(b).

< Figure 15 near here >

The measured spectral response of SP1, SP2, and SP3 at temperatures of 140, 190,

and 330 K, respectively, are shown in Fig. 15. The threshold wavelengths for the response mechanisms 1 and 2 shown in Fig. 13 can be identified in Fig. 15 at 2.9 and 3.4 μm respectively. The higher responsivity was seen for longer wavelength threshold samples (SP1 and SP2), possibly due to impact ionization (gain), compared to the shorter threshold samples, as shown in the inset of Fig. 15. The D^* values calculated based on the noise measurements for each sample are listed in Table 3.

< Table 3 near here >

An experimental and model response[76] comparison as shown in Fig. 15, shows an agreement with the predicted peak response within 20 % of the measured value for all the biases. The theoretical analysis gives an understanding to the observed SO response by which related optimization on detector structures can be carried out. The model details are discussed elsewhere [76].

As the SO detectors work at high temperatures, increased thermal emission currents could bring about the issue of electrical uniformity due to the device configuration under discussion (square mesa with ring metal contacts) [73]. The temperature-dependent zero-bias differential resistance (R_0A) extracted from the current-voltage-temperature (I-V-T) measurements are plotted in Fig. 16 for detectors SP1~3[77]. The deviation in R_0A indicates the reduced current-conduction smaller than the cross-sectional geometry area A occurs at high temperatures. The temperature effects can be related to a conductivity ratio of the vertical component to the lateral: $\alpha = \bar{\sigma}_z/\bar{\sigma}_x$ where $\bar{\sigma}_z$ and $\bar{\sigma}_x$ are the averaged vertical and lateral component of conductivity respectively. The $\bar{\sigma}_x$ shows temperature dependence via hole mobility, while the $\bar{\sigma}_z$ is determined by the thermal current across the potential barrier with an exponential behavior over the temperatures. Therefore α also shows an exponential increase with temperatures as shown in Fig. 17(a), which is consistent with the R_0A deviation. A clear understanding of this electrical characteristic is to numerically calculate the 2-D current distribution based on the α -T relationship in Fig. 17(a). The vertical current at the interface between the active region and the bottom contact layer for the sample SP2 is calculated as a function of lateral position x , and shown in Fig. 17 (b) which denotes the current at the interface between the active region and bottom contact layer. Obviously, current localization is induced at temperatures above 190 K. Analysis indicates the barrier height is of importance for improving the electrical uniformity.

< Figure 16 near here >

< Figure 17 near here >

4.2 LH-HH transitions for long-wavelength infrared detection

While the SO transitions give rise to absorption in the spectral region with photon energy larger than the SO splitting energy, the LH-HH transitions (another IVB transition) al-

lowed by the selection rule produce absorption in the MWIR and LWIR region [73]. A schematic of IVBA processes and room-temperature absorption spectra for p -GaAs are shown in Fig. 18 (a) and (b). The IVBA appears as on top of FCA lines, where the broad peak around 4–16 μm is due to the LH-HH transitions. The broad LH-HH feature is related to two factors contributing to the IVBA strength: the difference in hole distribution functions between the initial and final states relating the Fermi level, and the joint density of states (JDOS) $|\vec{k} \cdot \nabla_k(E_{ki} - E_{kj})|^{-1}$ (i and j represent band indexes). Due to the parallel structure of LH and HH bands, JDOS shows singularities at large k hence yielding considerable absorption in the short-wavelength part of the LH-HH absorption band.

< Figure 18 near here >

Since the SO and LH-HH transitions are all IVBA processes occurring in p -type materials, the LH-HH transition-based response can be observed in SO detectors. Figure 19 shows the spectral responsivity for detectors with different zero-response threshold (λ_t) and emitter dopings. Sample HE0206 consists of 16 periods of 18.8 nm p -GaAs emitters doped to $1 \times 10^{17} \text{ cm}^{-3}$ and 125 nm undoped $\text{Al}_{0.12}\text{Ga}_{0.88}\text{As}$ barriers. Sample 1332 has 12 periodic units with the same thick emitters and barriers as HE0206 but the emitter doping level is at $3 \times 10^{18} \text{ cm}^{-3}$ and the Al fraction of barriers is 0.15.

< Figure 19 near here >

The detector with long-wavelength threshold in Fig. 19 shows a broad response between 4–16.5 μm involving the FCA and IVBA contributions together. The FCA response alone can be calculated by the escape cone model[78] in which the escape rate of holes out of the emitter region is determined by the photoemission process. However, thermally assisted tunneling contribution at high biases will mix in this process deteriorating the model accuracy. Therefore, the model FCA response for low biases was compared to detector 1332 shown Fig. 19(a). The comparison indicates LH-HH transitions can produce spectral response up to 10 μm . The LH-HH IVBA process is rather prominent in terms of similar responsivity features observed in detector HE0206 although its emitters are relatively low doped at $1 \times 10^{17} \text{ cm}^{-3}$. High-operating-temperature capability was measured on detectors SP1, SP2 and SP3 shown in Fig. 19 (b), indicating promising uncooled operation. The range above λ_t could be due to the thermal detection mechanisms. Thermal-related processes such as phonon scattering increase the response time at high temperatures at which enhanced responsivity was observed by using a lower optical-path-difference (OPD) velocity of the FTIR. The peak at $\sim 13 \mu\text{m}$ is due to the cavity enhancement of the p -GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ structure.

In the LH-HH response region, two peaks determined by their center positions at 5.50 and 6.46 μm were observed. Their corresponding energy values (0.225 and 0.192 eV, respectively) are matched with reported LH-HH separations along the Λ and Δ directions, respectively, e.g. $\Delta_1(\Lambda) = 0.224 \text{ eV}$ in Ref. Lautenschlager *et al.*[72] and $\Delta'_0(\Delta) = 0.193 \text{ eV}$

in Ref. Zollner, [79]. Therefore, hole transitions at points in $\vec{k}$ space along the Λ and Δ directions are the reason for this result.

The LH-HH transition-based concept builds up the factors including the SO and the FCA mechanisms for GaAs allowing multi-spectral infrared detection in an internal photoemission detector. In comparison with MCT detectors which have been realized for uncooled operation within the 2–16 μm spectral range and are commercially available, the discussed GaAs-based device will be a viable alternative with the robustness of the III–V material system. Uncooled operation is also possible for this type of device which can be promising for some special applications such as high-intensity detection.

4.3 SO-HH transitions for spectral extension

As the SO splitting energy scales with the atomic number of the atom, extended spectral response range can be achieved by using different materials. Arsenide and Phosphide material have SO energies which will correspond to 3–5 and 8–14 μm atmospheric windows. A bandgap vs. lattice constant plot of selected arsenide and phosphide materials is shown in Fig. 20. The use of $\text{GaAs}_{0.4}\text{P}_{0.6}$ is possible for a full coverage of 3–5 μm range as its SO threshold is near 5 μm , however lattice mismatching with the GaAs substrate is an issue for high-quality epitaxy. The GaP and AlP have the lattice constant at 5.4505 and 5.4510 Å [80], respectively, and thus the $\text{Al}_x\text{Ga}_{1-x}\text{P}$ ternary alloy is naturally lattice matched with the GaP substrate. A SO detector with GaP emitter and $\text{Al}_x\text{Ga}_{1-x}\text{P}$ barrier will give rise to 80 meV (16 μm) of SO threshold energy (wavelength). Growth of $\text{Al}_x\text{Ga}_{1-x}\text{P}$ -based structures should not be difficult since characteristics of GaP/AlGaP heterojunctions [81], superlattice [82], and heterostructure based detectors, [83]) have already been reported.

< Figure 20 near here >

$\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ is lattice matched to InP when $x = 0.47y$. The SO splitting energy can be tuned from 0.11 to 0.379 eV (3.3–11 μm) by changing the As alloy fraction y from 0 to 1 ($\Delta_{\text{SO}} = 0.11 + 0.24y$) (Yamazoe *et al.*, (1981) [84]). Since the valence band discontinuity of the $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}/\text{InP}$ heterostructure can be expressed as $\Delta E_v = 0.502y - 0.152y^2$ (Levinshtein *et al.*, (1996) [80]), the free-carrier threshold wavelength will also be tunable. By setting y within 0.5–0.7 range, the ΔE_v will be close to Δ_{SO} for optimum escape of photo-excited carriers, corresponding to a threshold wavelength in the 4–5 μm range. A calculated ΔE_v and Δ_{SO} for different Arsenic fractions y is shown in the inset of Fig. 20.

Another potential application of the SO detection mechanism is to develop detectors for THz range. High-temperature capability would be expected since the uncooled GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ detectors have already been demonstrated by operating in SO detection mode. The extension of SO response toward far-infrared range can be expected by zincblende or wurtzite crystal structures of GaN which have the SO splitting energies of 20 meV (62 μm) and 8 meV (156 μm) respectively [62]. Matsik, *et al.* (2009) [76] reported a design for a zincblende $p\text{-GaN}/\text{Al}_x\text{Ga}_{1-x}\text{N}$ SO band detector which is expected to respond

up to 71 μm .

5 Threshold Extension beyond the band gap spectral limit

A new concept for photodetection based on a hot-cold hole energy transfer mechanism has been recently demonstrated [85]. This enables a dramatic spectral extension, surpassing the standard limit set by the spectral rule $\lambda_t = 1.24/\Delta$ [86], where λ_t is the maximum wavelength limit and where Δ is the activation energy of the optical transition during operation. This spectral extension is interpreted as a result of energy transfer from injected hot holes to the cold holes in the absorber. The cold holes are therefore excited into higher energy states, and capable of responding to longer-wavelength infrared radiation than would be possible without the hot-hole injection. This idea also enables λ_t and Δ to be individually optimized in order to achieve targeted wavelengths for detection whilst simultaneously minimizing the detector noise and dark current. Moreover, as the hot carriers divert their energy to cold carriers rather than heating up the lattice, improvement in the energy efficiency of devices is expected. Semiconductor heterostructures based on p -type GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ were used to demonstrate this effect. As shown in Fig. 21 (a), they consist of three p -type GaAs regions ($p = 1 \times 10^{19} \text{ cm}^{-3}$), i.e., an injector, absorber and collector, for which the valence-band (VB) alignment is schematically plotted in Figs. 21 (b). The injector provides a hot-hole reservoir upon photoexcitation. Holes surmounting the barrier are “hot” because of their excess energies relative to the band edge of the absorber [87].

< Fig. 21 near here >

5.1 Extension up to Far infrared range

The photoresponse showing a very long wavelength infrared response up to 55 μm was reported [85] at 5.3 K, as seen in Fig. 21 (c). However, the conventional limit expected for this design is only 3.9 μm according to the internal work function (i.e., Δ) [88] of the absorber/constant barrier junction ($\Delta = 0.32 \text{ eV}$). The agreement between λ_t and Δ in terms of $\lambda_t = hc/\Delta$ is typically found to be good in a variety of detectors, [47, 89] and has been used as a guideline to tune spectral response through varying Δ , [48] and to determine band offsets. [88] However, the observed VLWIR response is much longer than the expected threshold in this case.

In general the observed VLWIR response could be due to a bolometric effect, [90] or an impurity-band/free-hole carrier [47, 48] based response. Possible optical transitions contributing to photon absorption by the p -type GaAs absorber in the infrared range include the impurity band-to-valence band transition, [91] and intra-/inter-valence band transitions, [92] both of which are free-carrier type effects. Increasing the doping concentration shifts the absorption peak and broadens the absorption width, as a result of enhanced carrier

scatterings, and the shifting/increasing of the Fermi level/free-carrier plasma frequency, respectively[92, 71]. The absorber, though, has a major effect on the bolometric response and impurity-band absorption. A control sample which contains the same GaAs absorber was used to exclude these two mechanisms as a cause of the VLWIR response. Additionally, the bolometric response, proportional to the temperature variation of the absorber upon photon absorption and the corresponding resistance change, monotonically increases with increasing bias. This effect contrasts with the strongly non-monotonically bias-dependent VLWIR response. The observed VLWIR response agrees with a fitting value $\Delta = 0.012$ eV (escape-cone model[78]), [85] although the design and Arrhenius plot gives $\Delta = 0.32$ eV.

The hot-cold carrier energy transfer mechanism is in part supported by the differential photocurrent. The short-wavelength portion of light from either a Fourier transform infrared (FTIR) spectrometer, or from an external optical excitation source (denoted as the “pump”), is essential to generate photoexcited hot holes and establish the VLWIR response. The pump-excited holes with energies higher than all of the barriers can be described by a three-dimensional drift model,[93]

$$I_{ph}^{\text{pump}} = e \cdot v(F) \int_{\Delta}^{+\infty} N(\epsilon) d\epsilon \quad (1)$$

where I_{ph}^{pump} is the pump current. $N(\epsilon)$ is the concentration of holes with energy ϵ . [94] The electric field F is evaluated across the barrier regions. The drift velocity $v(F)$ is associated with an empirical fitting parameter – the mobility,[93] which is dependent upon both the doped GaAs absorber and undoped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier. Despite its simplicity, Eq. 1 accounts for the current-voltage characteristics reasonably well in most devices.[93] Taking the derivative of I_{ph}^{pump} with respect to F gives

$$\frac{dI_{ph}^{\text{pump}}}{dF} = e \cdot \frac{dv(F)}{dF} \int_{\Delta}^{+\infty} N(\epsilon) d\epsilon - e \cdot v(F) \frac{d\Delta}{dF} \cdot N(\Delta) \quad (2)$$

in which $d\Delta/dF$ is mainly determined by the image-force barrier lowering[88] and tilting of the graded barrier by applied bias. In the high-field region, the first term of Eq. 2 vanishes since $v(F)$ approaches a constant saturation velocity. The energy distribution of holes is thus proportional to the differential I_{ph}^{pump} , which consists of photocarriers with different energies. I_{ph}^{pump} can be evaluated as being proportional to the spectral weight (SW) of the response, defined as

$$SW \propto \int_{\lambda_{\min}}^{\lambda_{\max}} \mathcal{R}(\lambda) d\lambda \quad (3)$$

where $\mathcal{R}(\lambda)$ is the spectral responsivity. The differential SW displays three distribution peaks at -0.12 , -0.40 and 0.10 V, which were confirmed by photocurrent-voltage characteristics measured using different optical excitation source. As a comparison, another sample, which does not display the VLWIR response peaks, only displays one differential SW peak at 0 V. In terms of hot-carrier spectroscopy,[94, 95] the occurrence of distribution peaks is a sign of a hot-cold carrier interaction which leads to the excitation of cold carriers

into higher energy states. With increasing negative bias, the slope of the graded barrier is reduced (towards a horizontal shape). An increase in the injection of hot holes and enhanced hot-cold interactions is then expected, which consequently leads to an increase in cold holes occupying higher energy states. This explains the distribution peak at -0.12 V. When the bias is further increased, the electric field is distributed uniformly throughout the structure.[96] The lowering of the constant barrier by the image-force effect[88] will facilitate the escape of higher-energy cold holes over the barrier, which leads to another distribution peak at higher negative bias (-0.40 V). At high biases, the hot-hole related current is also high, which overwhelms the VLWIR radiation caused photocurrent. Observing the positive-bias hole distribution peak (0.10 V) is uncommon. A possible reason is the non-linear increase of photocurrent with bias due to the asymmetric band alignment. However, applying a negative bias leads to the optimum VLWIR response, which is much stronger than that under positive bias. The three distribution peaks rely on the structural details such as the graded barrier and the barrier offset. Ability to control these peaks should lead to tunability of the hot-hole photodetection.

The occurrence of the VLWIR response due to the hot-cold carrier interaction means that one can tune the degree of hot-hole injection to control this response. The experimental setup shown in Fig. 22 was used to demonstrate the tuning of the VLWIR response.

< Fig. 22 near here >

A cut-on wavelength (λ_{CO}) is selected, and a long-pass filter is used to block high-energy photons from the FTIR spectrometer from being incident onto the sample. Fig. 21 (c) plots results measured using filters with different λ_{CO} (the GaAs beamsplitter and optical excitation source are not used in this case). Increasing λ_{CO} reduces the energies of the injected hot holes, thus reducing the VLWIR response. The use of $\lambda_{CO} = 4.5 \mu\text{m}$ fully suppresses the VLWIR response because of the absence of hot holes in the absorber. However, the VLWIR response can be recovered by utilizing an optical excitation source which induces hot hole injection. These results are in good agreement with the hot-cold hole energy transfer mechanism.

To show the tunability of the VLWIR response, we carried out a further detailed set of measurements using the optical excitation source. A $\lambda_{CO} = 4.5 \mu\text{m}$ (corresponding to 0.28 eV) long-pass filter is used throughout to block the high-energy (> 0.28 eV) photons (from spectrometer) from being incident onto the sample. The generation of hot holes is enabled by sending an external high-energy light. Figure 23 (a) plots the excitation power spectra, and the corresponding spectral response is shown in Fig. 23 (b). The results indicate that the VLWIR response is enabled by increasing the excitation intensity, demonstrating the response tunability varying the degree of hot-hole injection.

< Fig. 23 near here >

The VLWIR response spectra at different temperatures are shown in Fig. 24. It can be seen that responsivities at short- and long-wavelength (i.e., < 4 and $> 4 \mu\text{m}$, respectively) display the opposite temperature dependences. The VLWIR ($> 4 \mu\text{m}$) response decreases with temperature and can be observed only up to 30 K. In contrast, an increase in the concentration of cold holes at higher temperatures contributes to the increased response for wavelengths $< 4 \mu\text{m}$. This explains the increase in the short-wavelength response with increased temperature. It should be noted, though, that the sample response was seen only up to $4 \mu\text{m}$ for temperatures above 30 K.

< Fig. 24 near here >

5.2 Mid IR detectors with wavelength extension at high temperatures ($> 80\text{K}$)

The response threshold for a GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ photodetector with a designed threshold wavelength of $3.1 \mu\text{m}$ (at 0 V) is also extended up to the mid/long-wave infrared range with the operating temperature as high as 90 K, as shown in the inset of Fig. 25 (a). The results demonstrate the possibility of extending the wavelength operating range of photodetectors to high temperatures. The extension behavior is studied by concentrating on the 60 K spectral response, as shown in Fig. 25 (a) for a number of bias voltages. A particular feature of the spectral response curves is a zero-response notch (between $2.9 - 4.2 \mu\text{m}$) when the bias is between $-0.4 \sim 0.7$ V. This is a consequence of photocurrent cancellation because of the co-existence of positive and negative photocurrents; here, the positive current corresponds to holes moving from the top contact to the bottom contact.

< Fig. 25 near here >

The wavelength extension under positive bias originates from a negative photocurrent co-existing with the positive photocurrent, as can be seen from the occurrence of the zero-response notch shown in the inset of Fig. 25 (b). At voltages > 0.8 V, the negative photocurrent is negligible, leaving only the positive photocurrent being measured. In further support of this result is the agreement of the zero-response position with the activation energies from Arrhenius plots, as shown in Fig. 25 (b). The zero-response position can be considered as the onset of the positive response, and thus should be in accordance with the threshold energy measured under positive biases and in dark conditions.

To understand better the spectral response, temperature-dependent internal photoemission spectroscopy (TDIPS) [88] was used to obtain the behavior of the photoemission threshold at different biases; details are discussed in Sec. 7.4. The threshold energies (i.e., the values of Δ) at different biases are shown in Fig. 25 (b) ($\blacksquare$, $\blacktriangledown$), along with a comparison to the activation energy as a function of bias obtained from Arrhenius plots ($\square$), derived from the current-bias-temperature (I-V-T) characteristic under dark conditions. It is notable that for voltages < 0.6 V, good agreement with experiment [Fig. 25 (b)] can

be achieved by modeling the system using two photoemission processes. The thresholds with low-energy values agree with those obtained by the one-threshold TDIPS fittings. The high-energy thresholds are associated with the “normal” response where the threshold is determined by Δ .

The threshold energies obtained by TDIPS fittings display three distinct features: 1) low (negative and positive) bias operation, where the spectral threshold energies (i.e., 0.14 eV in energy or 8.9 μm in wavelength) are independent of bias; 2) large negative bias (with magnitude > 2 V), where the fitted threshold energy is less than the Arrhenius value; [88] and 3) high positive bias, where at > 0.7 V the threshold energy jumps to a high value beyond which the threshold energies extracted from the response spectra agree with those obtained from I-V-T data. We thus ascribe the wavelength extension in spectral response as occurring between $-2.0 \sim 0.7$ V.

The extended response displays a non-monotonically bias-dependent behavior as shown in the calculated spectral weight (SW) in Fig. 26. The response extension contributes additional spectral weight at -0.6 V–0.8 V, while sample LH1002 with symmetrical and flat barriers showing the normal response has an increasing spectral weight with increasing bias.

< Fig. 26 near here >

It has been shown that the use of long-pass filters to vary the energies of incident photons can tune the spectral response. A long-pass filter can thus be used to disable high-energy photons from the FTIR spectrometer from being incident onto the sample, disabling the wavelength extension. This characteristic was measured as shown in Fig. 27 (a)–(d) where the use of a filter with cut-on wavelength of 4.5 μm [Fig. 27 (b)] disables the 3.1–8.9 μm photovoltaic response (at zero-bias operation). The increase of the response threshold wavelength at higher bias is due to image-force barrier lowering. [88] Fig. 27 (c) shows that the responsivity in the long-wavelength region decreases as the cut-on wavelength of the long-pass filter is increased. However, the wavelength threshold as confirmed by the TDIPS fittings remains the same. Figure 27 (d) demonstrates that using an external optical excitation source enables the wavelength extended response being recovered.

< Fig. 27 near here >

5.3 Extended Mid IR photovoltaic detectors at 80K

A photovoltaic detector architecture using the standard structure of internal-photoemission detectors, [73] in which a highly p -type doped GaAs acts as the photon absorber and emitter is used to study the wavelength thresholds using TDIPS. Figure 28 (a) shows the valence band, which has a non-symmetrical band configuration. In addition to an offset (δE_v) between the barriers below and above the emitter, one of the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barriers is graded to further increase the non-symmetry, and facilitate the transport of photoexcited holes

at zero bias. The room-temperature photovoltaic operation has been reported elsewhere. [97] For comparison, different gradients of Al fractions [i.e., x varies from 0.45 to 0.75, or remains a constant] were investigated. Figure 28 (b) schematically shows the inter-valence band (IVB) transitions mainly responsible for photon absorption and hole escape over the barrier (through internal photoemission).

< Fig. 28 near here >

To determine E_A , the characteristics of dark current-voltage-temperature (I-V-T) were measured, as shown in Fig. 29 (a). Fig. 29 (b) plots R_0A values extracted from I-V-T data, where a previous symmetrical GaAs/Al_{0.57}Ga_{0.43}As detector (sample SP3) [46] is also shown for comparison. The Arrhenius plots are used to fit R_0A and determine E_A to be 0.37, 0.40 and 0.49 eV for samples SP1005, SP1007, and SP1001, respectively. Except for SP1001, the obtained E_A values are comparable to the designed internal work function (Δ) of ~ 0.40 eV, in accordance with the p -type GaAs/Al_{0.75}Ga_{0.25}As junction by taking into account p -type-doping effects into account. [88] The R_0A - T characteristic giving $E_A \sim 0.4$ eV demonstrated that both SP1005 and SP1007 behave like a 3- μ m threshold detector.

< Fig. 29 near here >

The photovoltaic responsivity and detectivity (D^*) at 80 K are shown in Figs. 30 (a) and (b), respectively. D^* was obtained [98] by using $D^* = \mathcal{R}/(2qJ + 4kT/R_{diff}A)^{1/2}$, where $\mathcal{R}$ is the responsivity, J is the dark current density, and R_{diff} is the differential resistance. At zero bias where the shot noise vanishes, this expression is reduced to the normal form in terms of the Johnson noise. [99] With decreasing temperature, R_{diff} rapidly increases for the bias around 0 V. To calculate photovoltaic D^* at 80 K, extrapolation of R_0 in terms of the Arrhenius plots (Fig. 29 (b)) has been carried out.

< Fig. 30 near here >

An interesting feature in the spectral response of the graded-barrier samples is the large redshift in the threshold wavelength under photovoltaic operation (doubling the operating wavelength range). From the photoresponse characteristic point of view, the device with $E_A \sim 0.40$ eV acts as an 8- μ m threshold detector. Notice that the flat-barrier sample SP1001 does not respond beyond 3.9 μ m, which is similar to the symmetrical GaAs/Al_{0.57}Ga_{0.43}As detector as observed before (sample SP3)[46]. Another feature being observed is the zero-responsivity point lying between 3.4–3.5 μ m, which is an indication of bidirectional photocurrents simultaneously existing in the sample [see Fig. 28 (a)]. This can be understood since photoexcited holes in the emitter can emit over both sides of the barriers, which normally have the threshold wavelengths of 3 and 4 μ ms, corresponding to the heterointerfaces of GaAs/Al_{0.75}Ga_{0.25}As and GaAs/Al_{0.57}Ga_{0.43}As respectively. The photocurrent cancel-

lation leads to the occurrence of zero response between 3 and 4 μms . Several zero-response points taking place in sample SP1001 are related to its band alignment.

In general, threshold redshifting mostly results from bias-related effects, such as image-force barrier lowering and quantum tunneling. However, these effects are absent in the photovoltaic operating mode. A testimony of our observations was justified as being due to the high-energy photon excitation. Since the bottom contact (BC), emitter and top contact (TC) are highly doped, photoexcited holes can be created in all of these layers. Because of the graded barrier, high-energy photons can give rise to a net flow of photoexcited holes from BC to emitter. Some of the photoexcited holes are captured by the emitter. These high-energy captured holes tend to increase the energies of holes [76] originally in the emitter, and excite them to high-energy states. As a consequence, the energies of photons needed in order to excite holes to escape over the barrier can be correspondingly reduced, giving rise to a long-wavelength response. This process takes place in the hole transport from BC to TC, in agreement with observed wavelength-extended response corresponding to the reverse photocurrents (Fig. 30).

< Fig. 31 near here >

To justify the above mechanism, spectral response has been measured with the use of different long-pass filters (with the cut-on wavelength of λ_{CO}) and different intensities of incoming light, as shown in Fig. 31. This varies the energy or the concentration of photoexcited holes injected into the emitter. By using a filter with $\lambda_{\text{CO}} = 3.60 \mu\text{m}$, the short-wavelength response [labeled region 1 of Fig. 30] should disappear, as the escape of holes from the emitter to the BC cannot be accomplished because of the missing of the $h\nu > 0.34 \text{ eV}$ ($\lambda < 3.60 \mu\text{m}$) photons. For the same reason, photoexcited holes in the BC will be unable to overcome the graded barrier (highest barrier $\sim 0.4 \text{ eV}$) to enter into emitter. This suppresses the long-wavelength response as well [labeled region 2 of Fig. 30], according to the aforementioned energy-transfer mechanism. As expected [Fig. 31 (a)], photovoltaic response was unseen throughout the entire spectral range. In contrast, the use of a filter with $\lambda_{\text{CO}} = 2.40 \mu\text{m}$ gives rise to both short- and long-wavelength response owing to allowed emitter-to-BC and BC-to-emitter hole transport. The efficiency of energy transfer between photoexcited holes and holes in the emitter could be a critical factor determining the long-wavelength response. Such energy transfer results from carrier scatterings, and could be subject to degradation from hole-impurity scattering as the emitter is highly doped. With increasing the concentration of photoexcited holes, enhanced hole-hole scatterings can be expected, leading to distinct response in long-wavelength range, as shown in Fig. 31 (b). By calibrating the variation of the incoming light intensity, the short-wavelength portion of the response is expected to remain the same. However, the long-wavelength portion is almost negligible when the light intensity is reduced to 2.9 %, and quickly rises up when the incoming light increases to 7.3 %, where 100 % of light corresponds to the default optical aperture in the experiment. This may also explain the response characteristic of sample SP1001 not beyond $3.9 \mu\text{m}$, where because of the flat-barrier configuration the net injection

of photoexcited holes from the BC to emitter is negligible.

Higher activation energy of the dark current-voltage characteristics than the photore-sponse threshold energy can provide a significant improvement of the detector perfor-mance. According to $R_0A \sim \exp(-E_A/kT)$, the R_0A value (at 80 K) of our detector with $E_A = 0.40$ eV (responding up to $8 \mu\text{m}$) is nearly 10^{15} times higher than a conventional detector with E_A of 0.155 eV (without wavelength extension, also responding up to $8 \mu\text{m}$), which gives nearly 10^7 improvement in D^* . To experimentally evaluate the D^* improvement factor, the same type of internal-photoemission detectors [73] were compared, as in shown Fig. 30 (b) (this detector contains 30 periods of emitters and barriers), which is nearly 10^5 times less than the present detector.

6 Type II Strained Layer Superlattice Infrared detectors

The initial proposal from the Nobel laureates, Esaki and Tsu [100, 101] of synthatic artifi-cial superlattices took some time to get accepted, probably due to the formidable task of engineering a crystal consisting of ultra-thin layers. Efforts of others in improving thin film materials growth techniques such as MBE and MOCVD has allowed one to obtain high quality heterostructures with designed potential profiles and impurity distributions with a precise dimensional control of the order of the interatomic spacing.[102, 103]. The proposal for infrared detection using superlattices by Smith and Mailhot in 1987 [11] has initiated a strong interest in deveoping various type-II Strained layer (T2SL) superlattices for Infrared detection. [24, 104]

The type-II InAs/GaSb superlattices have a few properties that make them advanta-geous for developing infrared photodetectors: 1) their band gaps can be tuned by varying the thicknesses of individual layers; 2) compared with bulk materials, band-to-band tunnel-ing can be avoided, and 3) type-II InAs/Ga(In)Sb superlattices have been shown to reduce the Auger recombination. The use of strain in type-II InAs/GaInSb [105] strained layer superlattice can enhance its absorption compared with that of the InAs/GaSb superlattice. However, the lattice mismatch between the two alternating superlattice layers gives rise to an elastic strain, limiting the layer thickness in order to avoid the generation of mismatch defects. [106] Most of the T2SL detector works reported are based on the InAs/GaSb sys-tems with the wavelength coverage from 3 to 32 microns through varying the thickness of one or both T2SL layers. [107, 108, 109, 110]. However, AlSb can act as a blocking layer for electrons (holes) in the conduction (valence) band since it has a larger energy bandgap with the conduction band offset higher than that of GaSb and the valence band offset higher than that of InAs.

As an alternate or complement to HgCdTe (MCT) materials, InAs/Ga(In)Sb SL has im-portant applications for developing third-generation infrared photodetectors. [24] Although quantum efficiency greater than $> 90 \%$ can be obtained by MCT detectors, non-uniformity is one of the issues existing in the growth of the MCT materials. InAs/Ga(In)Sb T2SL pho-todetectors are predicted to have a number of advantages over MCTs and have a higher performance than that of MCT devices, [111] including lower tunneling current, which is

owing to the fact that the carrier effective masses in T2SL are not directly dependent on the band gap energy and are larger than MCT (for the same band gap). The T2SL photodetectors are predicted to have greater lifetime than MCTs but was observed to be low due to processes such as Shockley-Read-Hall (SRH) recombination, as discussed below. In addition, T2SL detectors allow for normal incidence response, as opposed to QWIPs.

< Figure 32 here >

As shown in Fig. 32 (a), InAs/Ga(In)Sb exhibits the staggered type-II band alignment with the InAs conduction band (CB) edge (the dash-dotted line) lying below the GaSb valence band (VB) edge (the solid line). However, quantum confinement in a SL structure, as shown in Fig. 32 (b), pushes electron states up moving them above the hole states. This leads to a positive bandgap ΔE_g^{SL} determined by the minimum separation between electron and hole energy levels. Figure 33 shows the wave functions of the lowest conduction subband and the highest valence subband have maxima in InAs and GaSb layers, respectively. [112, 113] The infrared detection is based on the optical transition between the highest hole (heavy-hole) and the lowest conduction minibands. By increasing the InAs layer thickness, the electron miniband approaches the hole level, leading to a smaller ΔE_g^{SL} . This makes InAs/Ga(In)Sb Type- II SL behave similar to a semimetal with thicker SL layers (wells and barriers), or a narrow-gap semiconductor with thinner SL layers. The broken gap SL also results in the spatial separation of electrons and holes confined in InAs and Ga(In)Sb respectively, largely suppressing the Auger recombination rate and increasing carrier lifetime.

< Figure 33 here >

The electronic structure of SLs (electron and hole energies) and the device properties are largely affected by the band offset and the SL layer thickness. If the band offset is known, SL layer thickness will solely determine the transition energy. Unfortunately, the InAs/Ga(In)Sb band offset suffers a large uncertainty in the reports. For example, a review paper by Vurgaftman *et al.* [114] indicates the ΔE_v range spanning more than 0.2 eV in different reported references. The typical range used in device modeling is about 0.51–0.56 eV based on measurements such as tunneling measurements, resonant Raman scattering, X-ray photoemission spectroscopy, absorption/excitation spectroscopy and so on. The uncertainty in the InAs/Ga(In)Sb band offset is partially due to its dependence on the specific growth process, which means that the same structure grown by different research groups could lead to different values of the band offset. The possible causes include [114]: i) the influence of the growth conditions on the interface, ii) non-ideal growth of the structure, and iii) uncertainty in layer-thickness calibrations.

In addition to the clarification of the band offset for InAs/GaSb heterojunctions, measuring band offsets at the interface between two T2SLs is also of importance to developing T2SL unipolar-barrier detectors. Internal photoemission (IPE) spectroscopy has been developed [88] and used to characterize a pBp T2SL detector. [115] IPE refers to such a case where carriers are photoexcited and transmit from one material to another by passing

through an interface. A pBp T2SL detector is studied, where two *p*-type InAs/GaSb T2SL absorbers responsible for mid/long-wave infrared (MWIR/LWIR) absorption are separated by a B-region consisting of an InAs/AlSb T2SL. Different optical transitions can be resolved by switching the bias polarity. Possible transitions include those occurring across the band gaps of the absorbers (I) and the B-region (II), and across the VB offset at the absorber/B-region interface (III). The details of this method will be discussed in Sec. 7. This determines the band gaps (average) of the LWIR and MWIR absorbers to be 0.117 ± 0.002 eV and 0.157 ± 0.001 eV, respectively, agreeing with the nominal values of 0.103 eV and 0.159 eV, respectively. [116] Based on the obtained VB offset [$0.661 (\pm 0.002)$ eV], the CB offset at the LWIR absorber/B-region interface is determined as 0.004 ± 0.004 eV, close to the designed value (0.009 eV). [116] Such a small value should barely affect the transport of minority electrons.

The key to achieving high-performance infrared detection is to achieve high quantum efficiency and low dark current. By growing high-quality superlattices that leads to high absorption coefficient and large diffusion length, high quantum efficiency can be achieved. The dark current of T2SL detectors is approaching the empirical benchmark of MCT's performance level, Rule 07; [117] however, the dark-current density demonstrated by the T2SL detectors is still significantly higher than that of bulk MCT detectors, especially in the MWIR range, as illustrated in Fig. 34.

< Figure 34 here >

To achieve a high collection efficiency of excited carriers the minority carrier lifetime should be long. The minority carrier lifetime is dependent on the radiative lifetime, as well as the nonradiative lifetime. The nonradiative lifetime is influenced by several different recombination processes of which the most important ones are the Shockley-Read-Hall (SRH) recombination, Auger processes, and surface recombination. Several methods have been employed to measure lifetime of photogenerated carriers of T2SL, including optical modulation response, [118] time-resolved PL, [119] and photoconductive response variation measurements. [120] Time-resolved photoluminescence measurements reveal a minority carrier lifetime of > 412 ns at 77 K under low excitation for a long-wavelength infrared InAs/InAs_{0.72}Sb_{0.28} type-II superlattice. [119] Radiation damage was found in T2SL detector with a decrease in the carrier lifetime and QE. [121] In addition, SRH lifetime in "Ga free" SL has been measured to be much longer compared to InAs/GaSb T2SL. [119, 122]

To reduce the dark current, [123, 124] relevant current mechanisms in T2SL detectors should be understood, which include [113, 125] Auger processes, SRH generation-recombination processes, the band-to-band tunneling leakage, trap-assisted tunneling and surface leakage. materials. Experimentally measured values of carrier lifetimes yielded ~ 325 ns for bulk InAs and ~ 100 ns for bulk GaSb, thereby confirming the initial observation [98]. It may then be hypothesized that native defects associated with GaSb are responsible for the SRH-limited minority-carrier lifetimes observed in InAs/GaSb T2SL. The surface leakage is a major challenge in the fabrication of InAs/GaSb T2SL detectors and arrays. High surface leakage current prevents full operation of the detector due to

the high $1/f$ noise or can lead to excess charging of the ROIC and cause saturation. This requires the ROIC to have a larger electron capacity or high diode impedances in order to maximize full potential of the camera system. Reducing the surface leakage can be achieved in part by surface passivation which is typically done by using a thick layer of dielectric, [126] organic material, or sulfidization. Passivation with organic materials employs polyimide or various photoresists (PRs). Chalcogenide passivation is due to the formation of III-S bonds, responsible for the reduction of surface states within band gap.

The T2SL detectors employ unipolar barrier in order to block one carrier type (electron or hole), while without blocking photocurrent. The barrier suppresses thermally generated diffusion currents significantly. The T2SL detectors using the unipolar barrier include nBn, [127, 128] pBiBn, [108, 129] M-structure, [123] W-structure, [24, 130], CBIRD, [131] and N-structure. [132] The nBn or XBn detector structure uses the unipolar barrier to suppress dark current associated with Shockley-Read-Hall processes. Figure 35 shows a type-II InAs/(In)GaSb nBn design, reported by Khoshakhlagh *et al.*. [127] Structures A and B consist of MWIR and LWIR absorber layers, shown as the insets of Fig. 35, respectively. Two color responses ($\lambda_{c1} \sim 3.5 \mu\text{m}$ and $\lambda_{c1} \sim 4.5 \mu\text{m}$) and ($\lambda_{c1} \sim 3.5 \mu\text{m}$ and $\lambda_{c1} \sim 8 \mu\text{m}$) were seen at different polarities of applied bias. Figure 36 shows the conduction band profile of structures A and B under forward and reverse biases. Under forward bias, the photocarriers from the absorber are collected. When the device is under reverse bias, the photocarriers from the heavily n -doped top contact layer are collected and the photocarriers from the absorber are blocked by the barrier.

< Figure 35 here >

< Figure 36 here >

The typical nBn detector is composed by two narrow band-gap absorbers (n) the different IR regions separated by a wide-band-gap material layer with a large barrier for electrons and no barrier for holes (B). As a result, the majority carrier current between the two electrodes is blocked by the large energy offset, while there is no barrier for photogenerated minority carriers. However, photocarriers in this case are the low mobility holes. It would be desirable to have the inverted structure, (i.e., pBp detector) in which the photocarriers are the higher mobility electrons, as shown in the inset of Fig. 37. The normalized spectral response under different polarities of applied bias was measured at 77 K, as shown in Fig. 37. Under forward bias, which is defined as positive voltage applied to the top contact, the photogenerated **carriers are collected from the MWIR absorber**. At 77 K, the dark current density was equal to $6 \times 10^{-5} \text{ A/cm}^2$ at 0.1 V (MWIR absorber) and $5 \times 10^{-4} \text{ A/cm}^2$ at -0.1 V (LWIR absorber). The specific detectivity **has** reached 5×10^{11} Jones ($V_b = 0.1 \text{ V}$, $\lambda = 5 \mu\text{m}$) and 2.6×10^{10} Jones ($V_b = -0.4 \text{ V}$, $\lambda = 9 \mu\text{m}$). The corresponding values of responsivity and quantum efficiency were 1.6 A/W and 39 % (MWIR) and 1.3 A/W and 17 % (LWIR). It should be noted that the detector is operated under small values of applied bias compared with nBn dual-band SLS detector, thus illustrating the advantages of the pBp design.

< Figure 37 here >

A very important feature of InAs/GaInSb detectors used for developing focal plane arrays (FPAs) [24] is the high uniformity of the materials. The 256×256 FPAs based on SL MWIR detectors [133, 134, 135] were initially reported. In 2007, 288×384 [136] and 320×256 [137] FPAs were demonstrated by Fraunhofer IAF and NWU, respectively. In the same year, JPL and Raytheon Vision Systems (RVS) reported 256×256 *p-i-n* detector based FPA with a cutoff wavelength of $10.5 \mu\text{m}$. [138] UNM demonstrated a 256×256 MWIR FPA in 2008 based on nBn T2SL detectors. [139] A 640×512 LWIR FPA based on heterostructure designs was also reported by JPL. [140] RVS and JPL have demonstrated CBIRD-based 256×256 LWIR FPA. [141] The $1k \times 1k$ FPA was demonstrated by Manurkar *et al.* in 2010. [142].

7 Temperature Dependant Internal Photoemission Spectroscopy

This section discusses the application of TDIPS (Temperature Dependant Photoemission Spectroscopy) as a probe to characterize band structure and the band offset at the semiconductor heterointerfaces. Internal photoemission (IP) spectroscopy is an attractive method [88, 143, 144, 145] for studying the properties of materials and optical processes that take place at the interface of two materials. Although initial reports dated back four decades ago, [143] internal photoemission spectroscopy remains attractive, in particular with recent demonstration of its advantages in characterizing new material systems such as graphene and oxide-based structures. [144, 145] Previous applications of IP mainly focused on bulk heterojunctions, for example, to obtain their barrier heights. [143] The internal photoemission can be characterized by the quantum yield, [88] which can be obtained by taking the multiplication of spectral responsivity and photon energy. The details of the IP principle and formalism used to fit yield spectra are described in Refs. [88, 115]. Quantum yield is dominantly determined by the photoexcitation of electrons in the absorber, described by an energy distribution function (ρ), and their escape over the barrier, described by a probability function [88]. The energy distribution is proportional to the joint density of states (JDOS) which can be deduced from the absorption coefficient [$\alpha(h\nu)$] using the relationship: $\text{JDOS} \sim \alpha \times h\nu$. This also means that one can study the absorption property through IP analysis of the quantum yield spectra.

Photoresponse in the near-threshold regime comes with two features determined by the optical transitions in the active region which create photo-carriers, and the escape of photo-carriers which leads to photocurrents. The escape capability can be mitigated by the loss in the energy or redirection of the carrier as a result of scattering with phonon. The onset of the carrier-phonon scattering depends on the excess kinetic energy of photocarriers [143]. It is expected that this occurs at the above-threshold regime, and after excitation, the excess kinetic energy of carriers should be greater than the phonon energy. Upon scatterings, a portion of photocarriers could be remained in the absorber, unable to escape, which leads to degradation in the photoresponse. A detailed study on this phenomenon should benefit

future improvement of the device performance. The IP approach studying the scattering effects has been recently demonstrated [115] through fitting of the near-threshold quantum yield spectra.

7.1 The theory of the IP spectroscopy

The theoretical basis of IP can be traced back to Fowler's work[146] on external photoemission of electrons from metal to vacuum deriving a photoemission yield function containing T -dependent terms, expressed by

$$Y \sim (kT)^2 f(\mu) \quad (4)$$

where Y denotes the quantum yield, defined as the number of emitted carriers per one absorbed photon. $f(\mu)$ is defined as, [146]

$$f(\mu) = \begin{cases} e^\mu - e^{2\mu}/4 + e^{3\mu}/9 - \dots & (\mu \leq 0) \\ \pi^2/6 + \mu^2/2 - (e^{-\mu} - e^{-2\mu}/4 + e^{-3\mu}/9 - \dots) & (\mu \geq 0) \end{cases} \quad (5)$$

in which $\mu \equiv (h\nu - \Delta)/kT$ and $h\nu$ is the photon energy. Other symbols have their usual meanings. Fowler's yield function can be actually reduced [86] to a T -independent form for $h\nu > \Delta + 3kT$, i.e.,

$$Y(h\nu) \sim (h\nu - \Delta)^2 \quad (6)$$

In spite of its original derivation for external photoemission the Fowler's yield function was applied [147] to many IP cases; including the T -independent yield expression (Eq. 6). To account for the difference in the electronic structures between semiconductors and metal, replacing the exponent "2" in Eq. 6 with a constant p was proposed. [148, 149, 150, 151] Typically, p varies from 1 to 3. [151] In spite of acceptable fittings by using best-fit values of p , the meaning of such a yield function is obscure, and importantly its independence on temperature leads to underestimated Δ values. Such underestimation is more significant in semiconductor junctions where Δ is much less than 1 eV.

Temperature-dependent IP spectroscopy (TDIPS) probe provides an accurate option to determine the temperature variation of the threshold. The operating principle of TDIPS is depicted in Fig. 28 (a) (p -type structures) in which two doping cases with E_f lying (i) above and (ii) below the valence band (VB) edge are schematically shown. Here, photoemission occurs by following one-photon excitation. High energetic holes, originating from states around E_f by absorbing photons, are injected into the VB of the barrier. Typical photoemission processes [labeled as (1) and (2)] include optical transitions and the escaping of holes. Shown in the inset of Fig. 28 (a) are the schematic transfers of carriers from the VB of the emitter to the VB of the barrier. This may include photon absorption and scattering events which direct the excited holes passing over the interface and injecting into the barrier. The holes in the emitter can be optically excited through both direct and indirect transitions. However, the transitions which provide the majority contribution to the quantum yield would rely on the incident photon energy. For the near-threshold regime, holes must end up at states near the edge of the potential barrier in order to escape over

the heterointerface; hence, indirect transitions have a higher probability to occur. When the photon energy is greater than the threshold, photoexcited holes from direct transitions which end up at higher energy states of the VBs, are capable of escaping over the barrier. This leads to a majority contribution to yield by direct transitions, because direct transitions have much higher transition rates than indirect transitions.

To determine band offsets, the most important factor is to account for the spectral line shape of the quantum yield. Therefore, the consideration of dominant processes affecting the energy distribution of carriers and their escape probabilities across the interface will be sufficient. By taking into account the photoexcitation of holes in the emitter through inter-valence-band (IVB) transitions [73], described by an energy distribution function $\rho(\epsilon, h\nu - E_f)$, and the transmission of holes over the barrier described by a probability function of $P(\epsilon, \Delta)$, [152] the quantum yield reads

$$Y(h\nu) = Y_0(kT) + C_0 \int_{\Delta}^{\infty} \rho(\epsilon, h\nu - E_f) f(\epsilon, h\nu) \cdot P(\epsilon, \Delta) d\epsilon \quad (7)$$

where C_0 is a constant independent of ϵ and $h\nu$. ϵ is the energy of photoexcited holes. Δ is defined as the energy difference between the Fermi level and the VB edge of the barrier. The energy is scaled downward with the zero reference at the Fermi level. Eq. 7 describes the case of degenerate (highly) doped emitters (E_f lying within the VB), and can adapt to the non-degenerate doping case by changing the sign of E_f . At finite temperatures, carriers occupy energy states above the Fermi level in terms of the Fermi-Dirac (FD) statistics. An FD-like function $f(\epsilon, h\nu) = [1 + e^{(\epsilon - h\nu)/kT}]^{-1}$ was used as the distribution function. This is based on an assumption that photoexcited holes remain in the same distribution as before photoexcitation, with the only difference in energy by $h\nu$.

As a result of the FD distribution, holes with energies greater than Δ can escape without the need of absorbing incident photons, leading to a thermionic emission term Y_0 included in Eq. 7. The photocurrent measurements [152] typically need to separate the thermionic emission component from the photoemission yield, and hence require accurate knowledge of the sample temperature which could vary due to light absorption. As suggested by R. Williams [152], the true origin of the observed currents, either due to photoemission or thermionic emission, can be resolved by taking spectral measurements, since the thermionic emission current is independent of the photon energy and only gives a constant background signal. By setting Y_0 to the experimental yield value at the spectral range far below Δ , the thermionic emission background can be distinguished from the yield spectra, allowing for a fitting to the photoemission yield component alone. In addition, a calibration of the sample temperature may be required if absorption of infrared light causes appreciable temperature variations in the sample. However, such a variation is negligible in our experiment, as our temperature controller typically has the stabilization accuracy of $< \pm 0.1\text{K}$.

The transmission of photocarriers passing through the heterointerface is described by a probability function of $P(\epsilon, \Delta)$, taken as $\sim (\epsilon - \Delta)$ for $\epsilon \geq \Delta$ and 0 for $\epsilon < \Delta$. This results from the escape cone model where carriers are capable of escaping over a barrier by having the normal (to the interface) momentum greater than that of the potential barrier. These carriers occupy energy states on a spherical Fermi cap in the $\mathbf{k}$ space. [152, 153]

The spectral line shape of the quantum yield is primarily determined by the energy distribution $[\rho(\epsilon, \epsilon_0)]$ of photocarriers in the emitter. As direct transitions associate with the joint density of states (JDOS) and indirect transitions in a limited photon-energy range (e.g., the near-threshold regime with final states near the Γ point of the barrier) are mainly determined by the occupation of initial states [154], $\rho(\epsilon, \epsilon_0)$ approximates to taking the density of states (DOS) line shape of the VB. Therefore, the direct and indirect transitions actually lead to the same energy dependency. For optical transitions occurring around the Γ point, the parabolic-band approximation (PBA) is taken, giving $\rho(\epsilon, \epsilon_0) \sim (\epsilon - \epsilon_0)^{1/2}$.

As a result of doping into emitters, the IP model should also handle dopants caused effects such as the band tail. Dopants introduce potential fluctuations and a band tail atop the VB. The PBA DOS is thus modified in terms of the Kane model [155], as shown in Fig. 28 (b). Dopants perturbed DOS mainly changes the near-threshold line shape of the quantum yield, by increasing the yield for $h\nu > E_f + \Delta$ due to optical transitions from the extended states in the forbidden gap, and slightly reducing the yield for $h\nu < E_f + \Delta$. This results in smaller Δ extracted from fittings to yield spectra, compared to those using the unperturbed DOS. Influence of the band tailing on E_f is believed to be negligible. [156]

The determination of the IP threshold is primarily affected by the IP probability $P(\epsilon, \Delta)$. In addition to this, $\rho(\epsilon, \epsilon_0)$ is associated with the optical transitions. As f and P are slowly-varying functions (in the energy regime around Δ_0), we take the dominant contribution of ρ for calculating derivatives, i.e., $dY/d(h\nu) \sim \rho(\Delta - h\nu, E_f)$, and hence

$$d^2Y/d(h\nu)^2 \sim d(\text{JDOS})/d(h\nu) \quad (8)$$

where ρ takes the line shape of JDOS if only direct IVB transitions are considered. This indicates the relationship between the band structure and the IP yield.

7.2 TDIPS analysis of *n*-type GaAs/Al_xGa_{1-x}As heterojunctions

Here a reappraisal of Coluzza *et al.*'s [147] IPE data (*n*-type GaAs/Al_xGa_{1-x}As) is provided with a comparison of the results based on both the TDIPS method and the Fowler fitting method [146]. Coluzza *et al.*, [147] reported the conduction band offset (ΔE_c) of *n*-type ($n = 3 \times 10^{16} \text{ cm}^{-3}$) GaAs/Al_xGa_{1-x}As heterojunctions by IPE measurements with the Vanderbilt free-electron laser as the optical source. They used the Fowler's yield function [146] of Eq. 6 to fit the near-threshold regime, as shown in Fig. 38 (b), which gives ΔE_c of 0.218 eV. In terms of the relationship between ΔE_c and x reported by O'Shea *et al.* [157]: $\Delta E_c = 0.84x$ (eV) where ΔE_c varies between 0.21–0.23 eV by taking into account experimental uncertainties [147], the equivalent Al fraction is $x = 0.25$ – 0.27 , which is, however, less than their photoluminescence (PL) determined value of $x = 0.30$. They ascribed this difference to the changes in the stoichiometry of MBE grown Al_xGa_{1-x}As on going from the bulk ($x = 0.3$) to the region immediately close to the interface ($x = 0.2$). This would result in a potential grading in the barrier around the GaAs/Al_xGa_{1-x}As interface. Thus, electrons should see a varied barrier height due to the barrier tilting under applied bias. However, such observations were not identified in their experiments.

As discussed in Sec. 7.1, Δ is typically underestimated by the Fowler method. With increasing the temperature, the Fermi level shifts deep into the bandgap, whereas the higher energy states of the CB will be more populated by electrons. This results in the shift of the near-threshold yield edge toward the lower photon energy end. Such temperature related effects have to be taken into account in the quantum yield expression, in order to properly extract Δ . To apply our TDIPS model (Eq. 7) to the non-degenerate case, [147] we set E_f to -9 meV. Here, the negative sign of E_f means the Fermi level lying below CB. The fitting shown in Fig. 38 (b) gives the $\Delta E_c \sim 0.258$ eV or $x \sim 0.307$, which is consistent with Coluzza *et al.*'s [147] PL result, and also indicates the accuracy of the TDIPS analysis.

< Fig. 38 near here >

7.3 TDIPS analysis of *p*-type GaAs/Al_xGa_{1-x}As heterojunctions

The VB offsets of GaAs/Al_xGa_{1-x}As heterojunctions (Table 4) and their T -dependence were obtained through analyzing quantum yield spectra at different temperatures, as shown in Figs. 39 (a)–(d). Originating from IVB transitions, the IPE spectra can show characteristics related to the VB structure [73] such as the spin-orbit SO band and heavy-hole band (SO-HH) splitting. By comparing with direct transitions, indirect transitions could have the majority contribution to the IPE yield in the near-threshold regime. This is in contrast to absorption measurement dominated with the direct transitions, and may provide experimental evidence for phonon-assisted IVB absorption [158].

< Table. 4 near here >

< Fig. 39 near here >

To reduce the uncertainty related to the calculation of MIF barrier lowering $\Delta\phi_i$, Δ is extrapolated at zero bias voltage, as shown in Fig. 40 (a) where typical plots of Δ against (Electric Field)^{1/2} are shown. The linear variations of Δ with (Electric Field)^{1/2} confirm the MIF effects. The VB offsets were then obtained by $\Delta E_v = \Delta - \Delta_{\text{BGR}} + E_f + \Delta\phi_i$. In order to compare with previous reported T -independent values (Table 5), [159, 157, 160, 114] the ΔE_v data were averaged over various temperatures and fitted by a linear dependence of ΔE_v on the Al mole fraction, as shown in Fig. 40 (b). Our result agrees well with Batey *et al.*'s data [159] obtained from the Arrhenius plots over the temperature range from ~ 80 K to RT, and is in the middle of Yi *et al.*'s 4.2 K data [160] and Vurgaftman *et al.*'s RT data for GaAs/AlAs [114]. To reconcile the slight difference between different temperatures, ΔE_v has to vary with temperature.

< Table. 5 near here >

< Fig. 40 near here >

This can be seen from the plots of TDIPS data at different temperatures as shown in Fig. 41 (a). The temperature coefficients of ΔE_v^T are thus fitted, where recent reported data at 4.2 K by *et al.* Yi [160] were taken into account. This also results in T -dependent ΔE_v as a function of Al mole fraction: $\Delta E_v = (0.570 - 1.39 \times 10^{-4} \cdot T) x$ (eV). The band offset can also be described by the offset ratio of $r = \Delta E_c : \Delta E_v$. Taking into account the T -variations, r varies from 59:41 at 4.2 K [160] to 61:39 at 300 K for $x = 0.4$. The latter value is close to 62:38 suggested by Kroemer [161]. It is also clear that $\Delta E_v = 0.59$ eV of GaAs/AlAs predicted by the first-principle calculations and model-solid theory [162, 114] is closer to the offset value at the $T \rightarrow 0$ K limit.

< Fig. 41 near here >

7.4 TDIPS analysis of photodetectors with wavelength extension

TDIPS [88] has been applied to analyze photodetectors with wavelength extension as discussed in Sec. 5.2. Figure 42 plots the TDIPS fitting results compared to experimental yield spectra in the near-threshold regime. It is notable that for voltages < 0.6 V, good agreement with experiment [Fig. 42] can be achieved by modelling the system using two photoemission processes, leading to two threshold energies [as illustrated in the inset of Fig. 42]. The thresholds with low-energy values agree with those obtained by the one-threshold TDIPS fittings. They originate from the wavelength extended response. In contrast, the high-energy thresholds are associated with the “normal” response where the threshold is determined by Δ .

< Fig. 42 near here >

7.5 TDIPS analysis of Type II Strained Layer Superlattice Detectors

As for a pBp T2SL detector shown in Fig. 43 (a) where two p -type InAs/GaSb T2SL absorbers responsible for mid/long-wave infrared (MWIR/LWIR) absorption are separated by a B-region consisting of an InAs/AlSb T2SL, different optical transitions can be resolved by switching the bias polarity, as shown in Fig. 43 (b). Possible transitions include those occurring across the band gaps of the absorbers (I) and the B-region (II), and across the v-b offset at the absorber/B-region interface (III), the latter two of which can be observed in the higher photon energy regime. This is shown in the quantum yield (Y) spectra plotted in Fig. 43 (c). Y , defined as the number of collected photocarriers per incident photon, is proportional to the multiplication of spectral responsivity and photon energy. [88] Spectral response was measured by a Perkin-Elmer system 2000 Fourier transform infrared (FTIR)

spectrometer. A commercial bolometer with known and flat sensitivity is used for background measurements and calibrating the responsivity, in order to eliminate the influence of light source and optical components on the spectral line shape.

< Fig. 43 near here >

8 Conclusion

A schematic diagram indicating the spectral response ranges and the peak responsivity values of the internal photoemission detector structures (HEIWIP, SO and Type II) discussed in this chapter is shown in Fig. 44. In this figure, the solid lines represent the full response wavelength ranges for each detector, while the peak response wavelengths are indicated by the symbols. An $\text{Al}_x\text{Ga}_{1-x}\text{As}$ emitter based terahertz HEIWIP detector, which has a threshold of $128\ \mu\text{m}$ (2.3 THz), was reported by Rinzan *et al.*[47] Other HEIWIPs are based on the work reported by Jayaweera *et al.*,[35] Esaev *et al.*,[50], Matsik *et al.*,[48] and Ariyawansa *et al.*[52]. The detectors using IVBA mechanisms are based on the work reported by Jayaweera *et al.*. (2008) [46] and Lao *et al.*. (2010) [73].

$\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ HEIWIP detectors have shown a broad response with a threshold at $130\ \mu\text{m}$, while the IVB detectors discussed in this chapter are actually type of HEIWIP with detection mechanism based on IVBA processes. The use of this mechanism provides a novel approach realizing uncooled or near room-temperature operation by which greatly reduced weight and/or power requirements are of importance for practical applications

< Figure 44 near here >

Another figure showing the spectral response ranges and the peak responsivity values of some of the T2SL structures found in publication are shown in Fig. 45. These include InAs/GaSb T2SL detectors ranging from MWIR to LWIR wavelength range.

< Figure 45 near here >

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Reference	Material System	λ_t (μm)	R_P (mA/W) @ λ_P (μm)	D^* (Jones) @T (K)
Rinzan et al. [47]	p^+ -Al _{0.005} Ga _{0.995} As/GaAs	128	7300 @31	5.3×10^{11} @4.8
Perera et al. [38]	p^+ -GaAs/Al _{0.02} Ga _{0.98} As	70	500 @40	1×10^{13} @4.2
Matsik et al. [61]	p^+ -GaAs/Al _{0.12} Ga _{0.88} As	20	95 @12.5	5×10^9 @40
Perera et al. [45]	p^+ -GaAs/Al _{0.12} Ga _{0.88} As	20	200 @1.8	2.2×10^7 @90
Jayaweera et al. [46]	p^+ -GaAs/Al _{0.28} Ga _{0.72} As	8	2.7 @2.7	2.1×10^6 @140
Jayaweera et al. [46]	p^+ -GaAs/Al _{0.37} Ga _{0.63} As	6	2.3 @2.7	1.8×10^6 @190
Jayaweera et al. [46]	p^+ -GaAs/Al _{0.57} Ga _{0.43} As	4	0.3 @2.7	6.8×10^5 @300

Table 1: Several HEIWIP detectors along with their performances. Here, λ_t is the threshold wavelength, R_P is the peak responsivity, λ_p is peak wavelength, D^* is specific detectivity and T is operating temperature

Reference	Number of bands	1st band (μm)	2nd band (μm)	3rd band (μm)	4th band (μm)	5th band (μm)	6th band
Ariyawansa et al. [52]	Two	8 – 14	20 – 70	–	–	–	–
Jayasinghe et al. [58]	Two	0.25 – 0.36	5 – 14	–	–	–	–
Ariyawansa et al. [163]	Three	1.35 – 6.25	6.5 – 10.5	23.1 – 23.3	–	–	–
Ariyawansa et al. [164]	Three	5.1-6	7-9	20-28	–	–	–
Ariyawansa et al. [165]	Three	4.5-6.2	7.6-12.5	15.8-17.5	–	–	–
Ariyawansa et al. [59]	Four	0.2 – 0.87	0.59 – 0.87	3 – 7	7 – 11	–	–
Ariyawansa et al. [23]	Five	0.6 – 0.8	0.8 – 0.9	0.9 – 1.0	3 – 4	4 – 8	–
Ariyawansa et al. [22]	Six	2.7-3	3-3.4	4.2-5.0	4.4-5.3	7.2-7.6	10-13

Table 2: A comparison of different multiple-band detectors.

Sample	$\Delta_{(L/H)}$ (meV)	λ_t (μm)	1 V bias	4 V bias at 2.6 μm	D*
			Dark current (A/cm^{-2})	Responsivity (mA/W)	
SP1	155	8	2.34×10^0	2.3 ± 0.1	$2.1 \pm 0.1 \times 10^6$
SP2	207	6	3.01×10^{-2}	0.96 ± 0.01	$2.0 \pm 0.1 \times 10^7$
SP3	310	4	1.72×10^{-6}	$(2.1 \pm 0.1) \times 10^{-3}$	$2.2 \pm 0.1 \times 10^{10}$

Table 3: Sample parameters and figures of merit at 150K temperatures.

Sample No.	Al mole fraction x	Barrier thickness (nm)	Emitter doping (cm^{-3})	Periodicity	Δ_{BGR} [Cal.] (meV)
S12a	0.12	125	1×10^{17}	16	6
S12b	0.12	125	1×10^{18}	16	13
S15	0.15	125	3×10^{18}	12	20
S28	0.28	60	3×10^{18}	30	20
S37	0.37	60	3×10^{18}	30	20
S57	0.57	60	3×10^{18}	30	20

Table 4: GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterojunction parameters. All samples have the same emitter thickness of 18.8 nm. Δ_{BGR} is the bandgap renormalization (BGR) caused VB shifting and calculated according to Ref. [166].

Reports	Methods	Temperature Range	ΔE_v (eV)
Yi <i>et al.</i> , [160]	BEES/BHES	4.2 K	$(0.578 \pm 0.015) x$
Batey <i>et al.</i> , [159]	JVT	80–300 K	$0.55 x$
O’Shea <i>et al.</i> , [157]	BEES	77 and 300 K	$0.53 x$
Vurgaftman <i>et al.</i> , [114]	–	300 K	$0.53 x$ ($x = 1$)
This work	TDIPS	20–200 K	$(0.570 - 1.39 \times 10^{-4} \cdot T) x$

Table 5: Comparison of ΔE_v from different reports for GaAs/Al_xGa_{1-x}As heterojunctions. Previously reported offset data [160, 159, 157, 114] are T -independent. [BEES/BHES: ballistic electron/hole emission spectroscopy; JVT: current-voltage-temperature]

Figure Captions:

Figure 1: Schematic band diagrams for GaAs/AlGaAs (a)*n*-type/(b)*p*-type HEIWIP structures.

Figure 2: The experimentally observed (symbols) and the calculated (lines) thresholds for *p*-GaAs/Al_xGa_{1-x}As, *p*-Al_xGa_{1-x}As/GaAs, and *n*-GaAs/Al_xGa_{1-x}As HEIWIP detectors with different Al fractions are shown. In all of the detectors considered here, the actual Al fraction after the growth of the structure in Al_xGa_{1-x}As layers has not been reported, instead the designed Al fraction has been considered for the plot, which could be the possible reason for the slight deviation in the threshold.

Figure 3: The band diagram for a HEIWIP detector using doped GaAs emitters, and undoped Al_xGa_{1-x}As barriers. The contributions from both the doping and the Al fraction will increase the workfunction. (b) The band diagram for a HEIWIP detector using doped Al_xGa_{1-x}As emitters, and undoped GaAs barriers. Here the contribution from doping increases the work function while the contribution from the Al fraction decreases it. Reprinted with permission from [78]. Copyright 2004, American Institute of Physics.

Figure 4: Responsivity spectra for HEIWIP detector at 0.7V bias obtained at 4.2K. The cutoff wavelength indicated by the vertical arrow where the responsivity reaches the noise level was $70 \pm 2 \mu\text{m}$. The sharp decrease between 35 and 40 μm is due to reflection from the front face of the detector. The responsivity remained the same at 20 μm and then decreased at higher temperatures. Inset (i) shows the responsivity at 20 μm . Inset (ii) shows the raw spectrum at shorter wavelengths with a zero response at 25 μm due to a beam splitter minimum. Reprinted with permission from [38]. Copyright 2001, American Institute of Physics.

Figure 5: The variation of the threshold wavelength (λ_t) in *p*-GaAs/Al_xGa_{1-x}As heterojunction detectors. The solid square represents the experimentally observed thresholds in which the data from detectors using inter-valence band transitions as discussed in section 4 is also included. (b) Experimental responsivity spectra for 2409, 2410 and 2411 at 3.5 kV/cm obtained at 4.2 K. The only difference in the samples was the Al fraction which was $x = 0.02, 0.01$ and 0.005 for 2409, 2410 and 2411 respectively. The data shows an increase in λ_t with decreasing x . The sharp decrease near 38 μm is due to the reststrahlen effect. The threshold (indicated by the arrows) variation, with $\lambda_t = 65, 84$, and $92 \mu\text{m}$ for samples 2409, 2410 and 2411 respectively can be clearly seen. Reprinted with permission from [48]. Copyright 2003, American Institute of Physics.

Figure 6: (a) The variation of responsivity with applied field for *p*-Al_xGa_{1-x}As/GaAs HEIWIP (sample V0207) at 4.8 K. The peak responsivity, 9 A/W at 9.6 THz, was obtained at 1.5 kV/cm. The increase in response with the field around λ_t is due to threshold shift with the bias. The sharp dip at $\sim 38 \mu\text{m}$ is due to the interaction of radiation with GaAs-like TO phonons. The bias field decreases the effective work function pushing λ_t towards 150

μm with the increasing field. (b) Variation of workfunction, Δ with the positive bias field for three mesas with different electrical areas. The workfunction at different bias fields were obtained using Arrhenius plots. The zero bias workfunction is ~ 17 meV for all the mesas. Reprinted with permission from [47]. Copyright 2005, American Institute of Physics.

Figure 7: Responsivity variation of the $n\text{-GaAs}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ HEIWIP for 0.7 and 1.5 kV/cm is shown. The highest R_{peak} is 6.5 A/W at 0.7 kV/cm at 6 K. The λ_t is 94 μm . The λ_t which is 94 μm was determined by the instrument noise level. Reprinted with permission from [50]. Copyright 2007, Optical Society of America.

Figure 8: (a) The schematic diagram of a dual band HEIWIP structure. The emitter (top contact) and the bottom contact are doped, while the barrier is not intentionally doped. (b) The band diagram showing the conduction/valence band (CB/VB) profile of the structure and the transitions leading to UV and IR responses. (c) The response of the GaN/AlGaN HEIWIP detector at 5.3 K and -1 V bias. There are three response mechanisms, which can contribute to the photocurrent: free carrier response, impurity-related response, and a flat far-infrared response.

Figure 9: (a) Shows both interband and intraband response at different temperatures under -50 mV bias. The left and right axes are corresponding to NIR and FIR responsivity respectively and a break on the wavelength axis at 2 μm has been made in order to expand the view in both regions. Reprinted with permission from [54]. Copyright 2005, American Institute of Physics.

(b) Shows Calculated UV/IR responses (dashed line) of the detector, fitted with experimental results (solid line). UV response at 300 K and a -0.5 V bias, and response at -1.0 V and 5.3 K. Note that although the response is only shown in the two ranges of interest, the model calculates the response over the entire range from the UV to the IR. Reprinted with permission from [57]. Copyright 2008, American Institute of Physics.

Figure 10: Simultaneously measured photo currents (solid lines) from (a) UV-active region and (b) IR-active region at 77 K, when both IR and UV radiation were incident onto the detector. The UV wavelength was varied between 250–400 nm, while IR was fixed at 9.3 μm (using a CO_2 laser). The dashed line in (a) represents the photocurrent when only UV radiation was incident and the dashed line in (b) indicates the response level (which is constant with time), as a reference level for the "UV+IR" response from the IR-active region, when only IR radiation was incident which only corresponds to the bottom axis. The lower and upper x-axes of (a) are also the upper axis of (b). (c) The IR response from IR- and UV-active regions at 77 K. The UV-active region showed almost zero response for IR radiation under reverse bias configuration as expected. Reprinted with permission from [58]. Copyright 2008, Optical Society of America.

Figure 11: Conduction and valence band profiles of the detector at (a) zero bias, (b) low forward bias (top-contact positive), and (c) high forward bias. Note that the band bending affects at the interfaces are not shown to reduce the complexity. Interband transitions across

the bandgap leads to UV/VIS detection, while electron intersubband transitions in the two QWIP regions lead to two-color IR detection. (d) Schematic structure of the GaAs-based detector. This structure consists of a *p*-type QWIP (5 nm) at the top, an intrinsic GaAs region (middle), and an *n*-type QWIP (9 nm) at the bottom. Reprinted with permission from [59]. Copyright 2009, Optical Society of America.

Figure 12: (a) Two color IR response at 80 K. (b) Response for s- and p-polarized light, showing a 100:23 polarization extinction ratio. Variation of the responsivity for the two peaks with bias is shown in the inset. Reprinted with permission from [59]. Copyright 2009, Optical Society of America.

Figure 13: E-k diagram for an emitter region of the detector and (B) band diagram of the detector structure illustrating the different IR detection threshold mechanisms. The horizontal dashed lines EBL/H and EBSO indicate the LH/HH and SO band maximum ($k = 0$) positions in the barrier. The horizontal dotted lines EF and EBSO indicate the Fermi energy and the SO energy in the emitter at $k = 0$. The arrows indicate the possible threshold transition mechanisms: (1) a direct transition from LH band to SO band followed by scattering back to LH band (2) an indirect transition followed by scattering back to LH band. Reprinted with permission from [75]. Copyright 2009, Elsevier Inc.

Figure 14: (a) The dark current density vs. temperature for samples SP1, SP2, and SP3 under 1 V applied bias. The dark current densities reached 1 A/cm² for each sample at 140, 190, and 300 K. (b) The dark current density for the three samples measured at 150 K showing thermionic emission. Reprinted with permission from [75]. Copyright 2009, Elsevier Inc.

Figure 15: The measured responsivity of the sample SP3 under four different biases at 330 K. The inset shows the responsivity of the samples SP1 and SP2 at 140 and 190 K, respectively. Also shown is the comparison of experimental spectra with the calculated response showing good agreement except at the longer wavelengths. The disagreement at long wavelengths is due to the thermal mechanism which is not included in the model. Reprinted with permission from [76]. Copyright 2009, American Institute of Physics.

Figure 16: Temperature dependent R_0A for detectors SP1~3. The solid square and hollow circle data are for square-mesa devices with sizes of 400 and 800 μm , respectively. A fit to the low-temperature region (solid line) based on thermionic currents is extended to compare R_0A deviation at high temperatures. Reprinted with permission from [77]. Copyright 2010, Institute of Electrical and Electronics Engineers.

Figure 17: (a) The calculated conductivity ratio α as a function of operating temperature. (b) and (c) are calculated lateral current distribution for detector SP2 with the mesa 400 $\mu\text{m} \times 400 \mu\text{m}$ at the interface between the active region and bottom contact layer. $x = 0$ represents the device center. The non-uniformity becomes remarkable when the temperature is increased. Reprinted with permission from [77]. Copyright 2010, Institute

of Electrical and Electronics Engineers.

Figure 18: (a) Schematic of the valence-band structure along the direction of $\langle 111 \rangle$ (Λ) and $\langle 100 \rangle$ (Δ). Various IVBA transitions are indicated. The (1), (2) and (3) represent LH-HH transitions at different wavevectors. The Fermi level is calculated for $3 \times 10^{18} \text{ cm}^{-3}$ p -doped GaAs at 80 K. (b) Measured room-temperature absorption spectra of p -GaAs compared with the calculated FCA curves plotted by dashed lines. Also shown is data from Refs. [Songprakob, W. et al. (2002)] (curves 1) and [Braunstein, R. et al. (1962)] (curve 4); the doping levels for curves 1–4 are 2.7×10^{19} , 8.0×10^{18} , 3.0×10^{18} and $2.7 \times 10^{17} \text{ cm}^{-3}$, respectively. Reprinted with permission from [73]. Copyright 2010, American Institute of Physics.

Figure 19: (a) Spectral response of detectors with varied threshold wavelengths (λ_t). The curves from top to bottom are measured at the bias of 8, 2, 1 and 2 V, respectively. In comparison with the FCA response (dashed line) calculated for the detector 1332, LH-HH transitions produce response between 4–10 μm . (b) High-operating-temperature capability was measured on samples SP1, SP2 and SP3 under 0.2, 0.3 and 3 V respectively, showing broad range from 4–16.5 μm . The wavelength region above designed threshold is due to a thermal detection mechanism. Cavity interference modes are all marked with the arrows in (a) and (b). Reprinted with permission from [73]. Copyright 2010, American Institute of Physics.

Figure 20: Band gap and lattice constant of selected III-V semiconductors (data were taken from Levinshtein, M. E. et al. (1996)[80]. Solid lines represent direct band region and dashed lines represent indirect band region. GaP/AlGaP would be a high-quality, lattice matched system similar to GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$. $\text{Al}_x\text{Ga}_{1-x}\text{As}$ acts as an indirect bandgap material in the region where $0.45 < x < 1$. Similarly $\text{Ga}_x\text{In}_{1-x}\text{P}$ and $\text{GaAs}_{1-x}\text{P}_x$ are indirect bandgap materials for $0.7 < x < 1$ and $x > 0.45$ respectively. Also, InGaAs and InGaP can be lattice matched to InP and GaAs, respectively. The inset shows the variation of the valence band offset energy (ΔE_v) and SO energy (E_{SO}) of the $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}/\text{InP}$ heterostructure with Arsenic fraction y where $x = 0.47y$ where $\text{In}_{1-x}\text{Ga}_x\text{As}_y\text{P}_{1-y}$ will be lattice matched to InP. To achieve ΔE_v similar to E_{SO} , the Arsenic fraction should be in the 0.5-0.7 range.

Figure 21: Sample structure and the VLWIR response at 5.3 K. (a) Schematic diagram of the p -type GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ structures. (b) Schematic valence band diagrams (including band bending) under negative bias (positive polarity applied on the injector), with a comparison of hole photoexcitation and emission without (top) and with (bottom) the hot-cold hole energy transfer. (c) Photoresponse at 5.3 K. Spectral response was also measured using long-pass filters with different cut-on wavelengths (λ_{CO}). The VLWIR response is gradually diminished by increasing λ_{CO} , and is barely seen when a $\lambda_{\text{CO}} = 4.5 \mu\text{m}$ filter is used. The VLWIR response is recovered by providing hot holes through an external optical excitation source, measured with a $4.5 \mu\text{m}$ long-pass filter. The marked features are associated with GaAs and AlAs-like phonons.

Figure 22: Experimental apparatus, where the double-side polished semi-insulating GaAs wafer acts as a beamsplitter.

Figure 23: Tuning the VLWIR response. The experiment was carried out on sample SP1006, which has a very similar VLWIR response to SP1007. (a) Power spectra of the optical source (incident on the sample with an active area of $260 \times 260 \mu\text{m}^2$). A quartz glass filter is used to block the long-wavelength portion (up to $4.8 \mu\text{m}$). (b) The dependence of the VLWIR response (at -0.1 V) on the excitation power.

Figure 24: Photoresponse of SP1007 at different temperatures (at -0.1 V). Inset: the values of responsivity as a function of temperature at 2.75 and $20 \mu\text{m}$.

Figure 25: (a) Spectral response measured at 60 K without using an external optical source. The inset plots the photovoltaic operation (0 V) in which a response is observed up to a maximum temperature of 90 K . The behavior of the response varies with bias (e.g., $-0.4 \sim 0.7 \text{ V}$), and is affected by the zero-response notch (between $2.9 - 4.2 \mu\text{m}$) where the negative and positive photocurrents cancel. (b) The activation energy obtained from Arrhenius plots derived from the I-V-T characteristics under dark conditions, plotted as a function of bias. The activation energy at 0 V (0.40 eV) is consistent with the structure design (see Fig. 28). Also shown are the extracted threshold energies from the one-threshold and two-threshold TDIPS fittings. Inset: the zero-response notch disappears when the bias increases beyond 0.8 V .

Figure 26: Variation of the spectral weight (SW, defined as $SW \propto \int_{\lambda_{\min}}^{\lambda_{\max}} \mathcal{R}(\lambda) d\lambda$) for samples (a) SP1007 (graded barrier structure) and (b) LH1002 (symmetrical and flat-barrier structure) with bias and $\lambda_{\min}$, where $\lambda_{\max}$ is $10 \mu\text{m}$.

Figure 27: The response spectra (60 K) measured by using long-pass filters with cut-on wavelengths (λ_{CO}) of (a) $2.4 \mu\text{m}$, and (b) $4.5 \mu\text{m}$. A response (at 0 V) is observed with the $2.4 \mu\text{m}$ cut-on filter, while it is disabled by using a $4.5 \mu\text{m}$ cut-on filter. (c) Response variation with different cut-on wavelengths of the filters. The extended wavelength responsivity reduces as the cut-on wavelength of the filter is increased. The TDIPS fitting verifies that the response threshold stays the same. (d) Comparison of the response measured using a $4.5 \mu\text{m}$ cut-on filter, with and without an external lamp. The lamp excites holes up to high energy states and allows a response extension to be recovered.

Figure 28: (a) The VB diagram of a p -emitter/ i -barrier IP system. $\rho(\epsilon, -E_f)f(\epsilon)$ is the multiplication of the hole energy distribution (ρ) and the FD function (f). Shown are the (i) non-degenerate and (ii) degenerate doped emitter. Typical IP processes are labeled as (1) and (2), consisting of optical transitions in the emitter and the escaping of holes from the VB of the emitter to the VB of the barrier. (b) Schematic DOS as a function of energy. By including a band tail, hole states are extended into the forbidden gap (atop the VB). The DOS tail contributes a higher photoemission yield at $h\nu > E_f + \Delta$ compared to that without the DOS tail. Reprinted with permission from [88]. Copyright 2012, American

Physical Society.

Fig. 29: (a) Dark I-V characteristics at different temperatures. (b) The Arrhenius plots of R_0A against $1000/T$, to determine the activation energies (E_A). All of data result from measurements of $400 \times 400 \mu\text{m}^2$ mesas, except for SP1005, for which an additional device with the dimension of $800 \times 800 \mu\text{m}^2$ (open circles) is plotted to confirm the consistency. Also shown is a previously reported [46] symmetrical flat-barrier detector (SP3), which has the zero barrier offset, i.e., $\delta E_v = 0$ eV. Its E_A corresponds to the activation energy of the p -type GaAs ($3 \times 10^{18} \text{ cm}^{-3}$)/Al_{0.57}Ga_{0.43}As junction. Reprinted with permission from [167]. Copyright 2014, American Institute of Physics.

Fig. 30: The spectral (a) responsivity and (b) detectivity at 80 K. The vertical arrows indicate the occurrence of zero response due to bidirectional photocurrents simultaneously existing in the device, owing to the photovoltaic operating mode. Labeled response (1) and (2) correspond to the forward [$I_f(+)$] and reverse [$I_r(-)$] photocurrents. Long-wavelength response beyond $3.9 \mu\text{m}$ was not observed in flat-barrier sample SP1001. Table 4 summarizes the threshold wavelengths of photovoltaic response for three samples. The D^* value of SP1007 is 10^5 times higher than 30-period photoconductive detectors previously reported[73]. Reprinted with permission from [167]. Copyright 2014, American Institute of Physics.

Fig. 31: (a) Photovoltaic response measured by using different long-pass filters (λ_{CO} is the cut-on wavelength). A filter with $\lambda_{\text{CO}} = 3.60 \mu\text{m}$ blocks the transport of photoexcited holes overcoming the graded-barrier region, thus suppressing both the short and long-wavelength response. (b) Variation of photovoltaic response with the intensities of incident light (through adjusting the optical aperture size of the spectrometer), where 100 % of light corresponds to the default aperture size. The calibration of responsivity takes into account the variation of light, which leads to nearly unchanged responsivity values for the $< 3 \mu\text{m}$ wavelength range. The $> 3.5 \mu\text{m}$ response becomes almost negligible when the intensity of incoming light is reduced to 2.9 %. Reprinted with permission from [167]. Copyright 2014, American Institute of Physics.

Figure 32: (a) Band alignment of GaSb and InAs, exhibiting a staggered type-II configuration. The valence and conduction band offsets (ΔE_v and ΔE_c) are indicated corresponding to difference between VBs and between CBs, respectively. (b) Typical band structure of InAs/GaSb SL photodetectors. Heavy holes are mainly localized in GaSb layers, while the electron miniband (shaded region) is formed due to electron wave functions overlap from one InAs layer to another. Absorption mainly occurs in the near-interface regime arising from the overlap between electron and hole wave functions. The SL bandgap ΔE_g^{SL} is the minimum separation between electron and hole energy levels. A heterojunction for internal-photoemission measurements will have the band diagram close to (a) without giving rise to quantum effects.

Figure 33: Type-II band alignment of InAs/GaSb T2SL system and the wave functions. Reproduced from [113]. Copyright 2014(Open Access), Hindawi Publishing Corporation.

Figure 34: Dark-current density of T2SL detectors compared with Rule 07. [117] Abbreviations for the different institution working on T2SL detectors: Fraunhofer-Institut (IAF), Jet Propulsion Laboratory (JPL), Naval Research Laboratory (NRL), Northwestern University (NWU), Raytheon Vision Systems (RVS), University of California, Santa Barbara (UCSB), Columbia University (Columbia), University of Illinois, Urbana-Champaign (UIUC), and University of New Mexico (UNM). Reproduced from [113]. Copyright 2014(Open Access), Hindawi Publishing Corporation.

Figure 35: (a) Spectral response of structure A ($\lambda_{c1} \sim 3.5 \mu\text{m}$ and $\lambda_{c1} \sim 4.5 \mu\text{m}$) at different temperatures under forward and reverse bias; V_b is the applied voltage. The inset shows the schematic of structure A for midwave infrared. (b) Spectral response of structure B ($\lambda_{c1} \sim 3.5 \mu\text{m}$ and $\lambda_{c1} \sim 8 \mu\text{m}$) at different temperatures under forward and reverse bias; V_b is the applied voltage. The inset shows the schematic for structure B for midwave-long wave infrared. Reprinted with permission from [127]. Copyright 2007, American Institute of Physics.

Figure 36: Conduction band diagram for two color nBn device under (a) forward bias (negative on top) and (b) reverse bias (positive on top). Reprinted with permission from [127]. Copyright 2007, American Institute of Physics.

Figure 37: Normalized spectral response of dual-band pBp detector measured at 77 K. MWIR and LWIR responses are observed under forward and reverse bias polarity, respectively. Inset: Cross section of fabricated pBp dual-band detector. Reprinted with permission from [116]. Copyright 2011, Institute of Electrical and Electronics Engineers.

Fig. 38: (a) TDIPS fittings to the quantum yield spectra of samples S12a and S12b the emitters of which are non-degenerate and degenerate doped, respectively. The higher yield of S12b at the low-energy end than S12a results from the thermionic emission. Their Fermi level difference was obtained to be $E_{f_b} - E_{f_a} = 24.5 \text{ meV}$. The corresponding band pictures with E_f lying in the bandgap (S12a) and in the VB (S12b) are shown in the insets. The different sharpnesses of barriers close to the heterointerface are due to the MIF barrier lowerings. (b) TDIPS fitting (solid line) to the IPE data (scattered data points) of the n -type GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterojunction adopted from *et al.* Coluzza [147], along with the comparison with their Fowler fitting [146] (dashed line). Reprinted with permission from [88]. Copyright 2012, American Physical Society.

Fig. 39: (a)–(d) are typical experimental quantum yield spectra (scattered data) of

GaAs/Al_xGa_{1-x}As heterojunctions (see Table 4 for sample structures) at different bias voltages and temperatures. Solid lines are the TDIPS fitting curves based on Eq. 7 with Y_0 , C_0 and Δ as the fitting parameters. The thermionic emission yield (Y_0) increases with increasing biases and temperatures. Insets plot the yield spectra in a larger energy range to show the IVB transitions where arrows indicate the SO-HH onsets. The rectangle frames indicate the regions where fittings were made. Reprinted with permission from [88]. Copyright 2012, American Physical Society.

Fig. 40: (a) Typical plots of Δ against (Electric Field)^{1/2}. Solid lines are the least-square fits according to the relationship between the MIF barrier lowering and the electric field. Extrapolated Δ values at zero field were used to obtain band offsets. (b) The average VB offsets [$\Delta E_{v\{av\}}$] over various temperatures, in order to compare with previously reported T -independent data [159, 157, 114]. The composition dependent $\Delta E_{v\{av\}}$ was obtained by a linear fit. Also shown are ΔE_v data adopted from Refs. [157, 159, 114]. Reprinted with permission from [88]. Copyright 2012, American Physical Society.

Fig. 41: (a) Temperature dependent VB offsets (scattered data) for different GaAs/Al_xGa_{1-x}As samples. Shown are the temperature coefficients of ΔE_v obtained by linear fittings (dashed lines) and taking into account *et al.* Yi's data [160] at 4.2 K. The T -dependent ΔE_v as a function of x was also obtained to be $\Delta E_v = (0.570 - 1.39 \times 10^{-4} \cdot T) x$ (eV). (b) Calculated [$\Delta E_g^T / \Delta E_g^{0K} - 1$] as a function of temperature by using reported bandgap parameters [114, 168, 169, 170, 171]: i) GaAs/Si, ii) InP/GaAs, iii) InAs/GaSb, iv) GaAs/Al_xGa_{1-x}As, and v) HgTe/Hg_{1-x}Cd_xTe. The scattered data points are calculations using TDIPS determined ΔE_v^T and *et al.* O'Shea's ΔE_c data [157]. The shaded areas correspond to heterojunctions with varied alloy fractions. The larger T -dependence of bandgaps implies more prominent T -dependence in band offsets. Reprinted with permission from [88]. Copyright 2012, American Physical Society.

Fig. 42: Quantum yield spectra along with the near-threshold fittings by TDIPS. [88] The quantum yield, defined by the number of collected photocarriers per incident photon, was obtained as the multiplication of spectral responsivity and photon energy. For (negative) biases (greater than 0.6 V), the TDIPS fittings consist of two thresholds, as shown in the inset.

Fig. 43: (a) Schematic of a two-color type-II InAs/GaSb superlattice photodetector, based on a pBp architecture. The contact layers are the same as the absorbers except for the doping concentrations. (b) Band alignment under forward and reverse biases. The forward bias means a positive polarity applied on the top electrode of the detector. Shown are effective optical transitions contributing to photocurrents (depending on the bias polarity), including those across the band gaps (I and II), and band offset (III). The band offset transition under reverse (the vertical arrow with a dashed line) can theoretically occur, but is not observed in experiment. (c) The quantum yield spectra, along with IP fittings (solid line) based on Eq. 7. The thresholds of optical transitions I–III can be obtained by fitting different energy regimes. Inset: comparison of fittings using different transmission

probabilities. Reprinted with permission from [115]. Copyright 2013, American Institute of Physics.

Figure 44: A summary of the response for different internal photoemission detectors. The vertical axis gives the peak responsivity for each detector. The horizontal solid lines represent the response range (ends corresponding to zero response threshold), while the symbols represent the peak response wavelength. The detectors used in this figure are listed below with their operating temperature (the temperature at which the data was reported at T), reported maximum operating temperature (T_{max}), and BLIP temperature (T_{BLIP}). [47]: $p\text{-Al}_x\text{Ga}_{1-x}\text{As}$ HEIWIP ($T = 4.8\text{ K}$, $T_{BLIP} = 20\text{ K}$); [50]: $n\text{-GaAs}$ HEIWIP ($T = 6\text{ K}$, $T_{max} = 25\text{ K}$); [48]: $p\text{-GaAs}$ HEIWIP ($T = 4.2\text{ K}$); [48]: $p\text{-GaAs}$ HEIWIP ($T = 4.2\text{ K}$); [172]: $p\text{-GaAs}$ HEIWIP ($T = 4.2\text{ K}$); [173]: SO detector ($T = 330\text{ K}$); [73]: LH-HH detectors (SP1, SP2, SP3), ($T = 8\text{ K}$); [85]: Hot Carrier (HC) detectors (SP1005, SP1006, SP1007), ($T = 5.3\text{ K}$).

Figure 45: A summary of the response for different T2SL detectors. The vertical axis gives the peak responsivity for each detector. The horizontal solid lines represent the response range (ends corresponding to zero response threshold), while the symbols represent the peak response wavelength. The detectors used in this figure are listed below with their operating temperature (the temperature at which the data was reported at T and bias voltage V). [108]: InAs/GaSb pBiBN SL ($T = 77\text{ K}$, $V = -0.5\text{ V}$); [174]: InAs/GaSb pBiBN SL ($T = 77\text{ K}$, $V = -0.25\text{ V}$); [131]: SL Complimentary Barrier Infrared Detector (CBIRD) ($T = 77\text{ K}$, $V = 0.2\text{ V}$); [175](A): InAs/GaSb p-i-n SL ($T = \text{Room Temperature}$); [175]: InAs/GaSb p-i-n SL ($T = 77\text{ K}$); [176]: InAs/GaSb nBn SL ($T = 300\text{ K}$); [122]: Gallium free InAs/InAs $_x$ Sb $_{1-x}$ SL ($T = 77\text{ K}$, $V = -10\text{ mV}$); [128]: InAs/GaSb nBn SL ($T = 77\text{ K}$, $V = -0.5\text{ V}$);.

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