Material And Techniques For Extended-Wavelength And Split-Off Band Infrared Detectors

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MATERIAL AND TECHNIQUES FOR EXTENDED-WAVELENGTH AND SPLIT-OFF BAND INFRARED DETECTORS

by

DILIP CHAUHAN

Under the Direction of Prof. A.G. Unil Perera, PhD

ABSTRACT

p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based extended-wavelength infrared photodetectors have been experimentally studied in great detail. Unlike the conventional IR photodetectors with the wavelength threshold determined by an activation energy ($\Delta$) corresponding to a minimum energy gap, a novel class of IR photodetectors show an extended-wavelength spectral photoresponse far beyond the limit set by $\Delta$ (given as $\lambda_t = \hbar c/\Delta$). p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based IR photodetectors, with non-zero barrier energy offset between the Al\textsubscript{x}Ga\textsubscript{1-x}As barriers, were used. These IR photodetectors were initially designed to have a conventional wavelength threshold of $\sim$3 $\mu$m, corresponding to $\Delta \sim$0.4 eV of p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure. However, the extended-wavelength photoresponse was observed up to $\sim$ 60 $\mu$m. The study included a set of devices with varying values of the barrier energy offset. The offset was
found to be necessary for the extended-wavelength mechanism. However, with further increase in the offset by ~0.13 eV, the extended-wavelength threshold showed a very small variation (~0.002 eV). Instead, increasing the barrier energy offset led to an increased strength of spectral photoresponse. Similarly, increasing the barrier gradient in another set of devices caused no significant change in the wavelength threshold. These observations are believed to originate from build-up of a quasi-equilibrium Fermi level, at a fixed level, irrespective of the variation of the device parameter. Split-off (S-O) band was found to be the most probable energy level to build-up a quasi-equilibrium Fermi level as consequence of hot-phonon bottleneck effect. The study of the dark current characteristics of these IR photodetectors confirmed no compromise in the dark current due to the presence of the extended-wavelength mechanism of photoresponse. In addition, from the study of a 2 – 6 µm IR photodetector, based on p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure, operating at 0 V, the specific detectivity was found to be enhanced by two orders of magnitude, to ~1.9×10$^{11}$ Jones, due to a current blocking barrier, although a small compromise in the spectral responsivity (by a factor of ~1.5) was observed. Furthermore, a 3 – 5 µm band IR photodetector based on p-InP/InAlAs heterostructure (currently under development), is discussed as an alternative for the 3 – 5 µm band detection.

INDEX WORDS: III-V semiconductor, IR photodetector, Extended-wavelength mechanism, Hot-carriers, Hot-phonon bottleneck effect, Mid infrared, Far infrared, Split-off band, Quantum dots-in-a-well, 3 – 5 µm band IR detector
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Georgia State University
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DEDICATION

To my family and friends for all love and support; and to all nice and great human beings who helped me succeed!
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Changing the $x_3$ causes the $\delta E$ variation and changing the $x_1$ causes the gradient variation,
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**Figure 2.12** A graphical depiction of the wavelength thresholds of the extended-wavelength photoresponse of the three devices SP1007, 15SP3, and GSU17I (with the increasing barrier energy offset values). The wavelength thresholds are (61.0±0.8) μm, (60.0±0.3)μm, and (55.6±0.5) μm, and the corresponding threshold energy values are (0.0203±0.0003) eV, (0.0207±0.0001) eV, and (0.0223±0.0002) eV, respectively.

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**Figure 2.19** (a) A comparison of normalized photoresponse in the of 15SP3 (-0.6 V), GSU17II (-0.8 V), and GSU17III (-0.8 V) showing similar spectral shape in the H-H/L-H regime (4 – 10 µm). (b) The spectral photoresponse becomes stronger at higher biases of – 1 V for 15SP3 and -1.2 V GSU17II and GSU17III. Similar mechanism is observed in these three
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Figure 2.20 Spectral photoresponse of the photodetector 15SP3 at 0 V, in the temperature range 50 – 100K. The extended wavelength threshold was observed to be ~11.5 µm at 50K, and ~7 µm at 77K and 90K. The photoresponse in the extended-wavelength region disappeared at 100K, and the threshold of ~3 µm then closely agrees with the designed value of Δ ~0.40 eV. Inset: TDIPS fittings of the experimental quantum yield spectra to determine the wavelength threshold. (Reprinted with permission from\textsuperscript{38}. Copyright 2017, AIP Publishing).

Figure 2.21 A schematic of a proposed design for the extended-wavelength IR photodetector based on quantum dots-in-a-well (DWELL) structure. A laser source can be used for photo-excitation from the ground state energy level in the QDs to an energy level in the QW (shown by a dashed arrow) to form a quasi-equilibrium Fermi level. Then, the background IR radiation can be detected due to transitions from the quasi-equilibrium to higher QW levels (shown by solid arrows). A QW thickness of 6 nm, similar to that reported previously,\textsuperscript{13} will have two energy levels: HH\textsubscript{1} at ~0.18 eV (~7 µm) and HH\textsubscript{2} at ~0.23 eV (~5.4 µm) from the QDs ground state. The pumping to the HH\textsubscript{1} level with (~7 µm source) can be expected to enable the detection of IR radiation of energies ~ 0.05 eV (~25 µm) due to HH\textsubscript{1} to HH\textsubscript{2} transitions. A high energy (graded) barrier is used to ensure an applied bias will not easily sweep-out carriers from the quasi-equilibrium Fermi level.

Figure 2.22 A schematic of a quantum dots-in-a-well (DWELL) structure proposed for 3 – 5 µm band IR detection. HH\textsubscript{1} and HH\textsubscript{2} represent the energy levels in the quantum well, whilst HH and SO represent the energy levels on the quantum dots. These energy levels are based
on the reported experimentally studies.\textsuperscript{76,77} Excitation from HH to HH\textsubscript{2} level can be used to build up a quasi-equilibrium Fermi level at HH\textsubscript{2} level. Then the IR detection in the 3 – 5 µm band may be achieved with an expected peak near 4.3 µm due to the energy difference of \textasciitilde0.29 eV between HH\textsubscript{2} level (0.23 eV) and SO level (0.52 eV).

**Figure 3.1** Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for LH1002 (inset shows the bias variation fitting parameter $\alpha$). The dark current curves and the fitting parameters are symmetrical due to the symmetrical design of the device. (Reprinted with permission from\textsuperscript{38}. Copyright 2017, AIP Publishing).

**Figure 3.2** Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for 15SP3 (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device. (Reprinted with permission from\textsuperscript{38}. Copyright 2017, AIP Publishing).

**Figure 3.3** Spectral photoresponse of 15SP2 and LH1002 as a function of wavelength. At 50K, a wavelength threshold of \textasciitilde5.5 µm and dark current value \textasciitilde2\times10^{-9} A (Inset) were observed in LH1002 at -1.5 V. The extended wavelength threshold of 15SP3 at -1 V is significantly longer, up to \textasciitilde13.5 µm, but the dark current at this bias is still similar to the dark current in the LH1002 (the dark current at the respective biases are marked by arrows). (Reprinted with permission from\textsuperscript{38}. Copyright 2017, AIP Publishing).

**Figure 3.4** Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for SP1001 (inset shows the bias variation of
fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device. ................................................................. 99

**Figure 3.5** (a) Arrhenius plots for device SP1001 obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device SP1001 obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier. ................................................................. 100

**Figure 3.6** Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for SP1007 (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device. ................................................................. 101

**Figure 3.7** (a) Arrhenius plots for device SP1007 obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device SP1007 obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier. ................................................................. 102

**Figure 3.8** Experimentally (with Keithley 2400 source meter) measured and fitted dark current curves in the temperature range 10 – 100K for GSU17I (inset shows the bias variation of
fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.

**Figure 3.9** (a) Arrhenius plots for device GSU17I obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device GSU17I obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/$\text{Al}_x\text{Ga}_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier.

**Figure 3.10** Experimentally measured (with Keithley 2400 source meter) and fitted dark current curves in the temperature range 10 – 100K for GSU17II (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.

**Figure 3.11** (a) Arrhenius plots for device GSU17II obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device GSU17II obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/$\text{Al}_x\text{Ga}_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier.

**Figure 3.12** Experimentally measured (with Keithley 2400 source meter) and fitted dark current curves in the temperature range 10 – 100K for GSU17III (inset shows the bias variation of
fitting parameter \( \alpha \). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.

**Figure 3.13** (a) Arrhenius plots for device GSU17III obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device GSU17III obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al\(_{x}\)Ga\(_{1-x}\)As heterostructure due to the graded barrier and energy offset of the barrier.

**Figure 4.1** (a) Schematic side view of the p-GaAs/Al\(_{x}\)Ga\(_{1-x}\)As heterostructure, including the current blocking barrier (CBB). The top (T) and bottom (B) contacts are used to measure with the CBB, and the middle (M) and bottom contacts can be used to measure the same mesa without it. (b) Top view optical image of the detector mesa showing the lateral dimensions of the top contact (400 \( \mu \)m \( \times \) 400 \( \mu \)m) and middle contact (570 \( \mu \)m \( \times \) 570 \( \mu \)m), with the optical window (260 \( \mu \)m \( \times \) 260 \( \mu \)m) at the center. (Reprinted with permission from\(^{59}\). Copyright 2016, AIP Publishing).

**Figure 4.2** (a) Schematic of the valence band alignment of the heterostructure under equilibrium showing the connections with the CBB and without the CBB. The Al\(_{x}\)Ga\(_{1-x}\)As barriers are graded by tuning the Al mole fraction, \( x \). (b) A schematic of the valence band of the GaAs near \( k = 0 \), showing some of the possible hole transitions from light hole/heavy hole to split-off bands, and also from the heavy hole to light hole band. The emitters are thick enough for bulk-like distribution of the density of states of carriers. (Reprinted with permission from\(^{59}\). Copyright 2016, AIP Publishing).
**Figure 4.3** The dark current density of the detector with CBB (T-B) is five orders of magnitude smaller at low bias, than without the CBB (M-B). The difference becomes smaller as the bias increases. The dark current across the top and middle (T-M) contacts is similar to that across T-B contacts in the low bias region. (Reprinted with permission from\textsuperscript{59}. Copyright 2016, AIP Publishing).

**Figure 4.4** Comparison of the responsivity of the detector showing that the responsivity with the CBB is \(\sim 1.5\) times smaller at zero bias, than without the CBB. For the wavelengths \(\leq 2\ \mu\text{m}\), the energy of photoexcited carriers (\(\geq 0.6\ \text{eV}\)) is much larger than the CBB height (~0.55 eV) and is a possible reason that the photoresponse is nearly the same in both cases for wavelengths \(\leq 2\ \mu\text{m}\). (Reprinted with permission from\textsuperscript{59}. Copyright 2016, AIP Publishing).

**Figure 4.5** Specific detectivity \(D^*\) showing two orders of magnitude higher detectivity with the CBB, owing to the higher \(R_0A\) despite a small reduction in the photoresponse. (Reprinted with permission from\textsuperscript{59}. Copyright 2016, AIP Publishing).

**Figure 4.6** (a) The spectral photoresponse measure with the applied bias increasing with the step size of 0.2 V, across the middle and bottom contacts, that is, without the CBB. (b) The spectral photoresponse measured across top and bottom contacts, that is, with the CBB. The photoresponse is seen increasing with the application of bias, the effect being slightly stronger in the case of without the CBB.

**Figure 4.7** (a) Peak spectral responsivity (at 2.7 \(\mu\text{m}\)) from the measurements with the CBB (top-bottom) and without the CBB (middle-bottom). The applied biases caused a slight increment in the photoresponse, the effect is more noticeable in the measurement without the CBB. (b) The specific detectivity (\(D^*\)) was observed to be maximum at zero bias and
it decreased with the application of bias, thus making the photovoltaic operation more attractive over the photoconductive operation.

**Figure 4.8** The photoresponse measured across top and middle contact, was disabled by the optical filter with $\lambda_{CO} = 2.4 \, \mu m$. (Reprinted with permission from\textsuperscript{59}. Copyright 2016, AIP Publishing).

**Figure 4.9** Optical filters of cut-on wavelengths of $\lambda_{CO} = 2.4 \, \mu m$ and $4.5 \, \mu m$ did not show any effect on the photoresponse in the spectral range longer than $\lambda_{CO}$, in the measurements – (a) with the CBB, and (b) without the CBB.

**Figure 4.10** The spectral photoresponse at temperatures 77K, 120 K, 130 K, 140 K, and 200 K. The photoresponse is seen to be reduced by an order of magnitude from 77 K to 120 K and becomes more at 130 K. At 140 K, the photoresponse beyond $\sim 2.5 \, \mu m$ is seen to be deteriorated more dramatically, showing only a very weak and noisy signal in this spectral range. The spectral photoresponse up to $\sim 2.5 \, \mu m$ was observed at 200 K.

**Figure 4.11** (a) Schematic of the valence band alignment of modified CBB device under equilibrium. In comparison to the Figure 4.2 (a), the 500 nm thick middle contact layer is replaced by a 20 nm buffer layer in the modified CBB device. The Al mole fraction of the graded barrier is slightly higher, graded from $x = 0.12$ to $0.53$. A single-period emitter/barrier is used instead of 30-periods, thus an average applied electric field corresponding to a particular bias voltage will be $\sim 30$ times higher in the modified CBB device compared to the previous CBB device. Due to the absence of middle contact, the measurements are carried out across the top-bottom contacts only, that is, with the CBB. (b) Dark current density of the modified CBB device.
Figure 4.12 (a) The spectral photoresponse of the modified CBB device at 0 V, measured at the temperatures 77 K, 90 K, 100K, and 120 K, showing no significant change in the photoresponse signal although a slight increment was observed with the temperature increasing from 77 K to 120 K. (b) Above 120 K, the photoresponse was observed to be reduced with the increasing temperature, as observed previously in Figure 4.10. An operating temperature of 150 K is observed, before the spectral photoresponse beyond ~2.5 µm disappeared. At 200 K, the spectral photoresponse is limited to ~2.5 µm, similar to previously observed result.

Figure 4.13 A comparison between the CBB device and the modified CBB device in terms of (a) spectral photoresponse, and (b) specific detectivity (D*) at 120 K, 0 V. The modified CBB device is seen to have a higher responsivity and the specific detectivity.

Figure 4.14 Schematic of the p-InP/InAlAs heterostructure for 3-5 µm IR detection. Three samples are designed: GS-LWIR-1 with p-InP doping 3.0×10^{18} cm^{-3} and emitter thickness T = 20 nm; GS-LWIR-2 with p-InP doping 3.0×10^{18} cm^{-3} and emitter thickness T = 80 nm; and GS-LWIR-3 with p-InP doping 8.0×10^{18} cm^{-3} and emitter thickness T = 80 nm.

Figure 4.15 Simulated spectral photoresponse of the p-InP/InAlAs heterostructure IR photodetector for 3-5 µm (FWHM) detection.
LIST OF ABBREVIATIONS

µm – micro-meter

0D, 1D, 2D, and 3D – Zero-, One-, Two-, Three- Dimensional

AlAs – Aluminum Arsenide

AlP – Aluminum Phosphide

Al\textsubscript{x}Ga\textsubscript{1-x}As - Aluminum Gallium Arsenide, x is Al mole fraction

B – bottom

CBB – current blocking barrier

CBIRD - complementary barrier infrared detectors

D\textsuperscript{*} - Specific Detectivity

DC or dc - Direct Current

DUT – Device Under Test

DWELL - Quantum Dots-in-Well Infrared Photodetector

e – Electronic charge

eV - Electron Volts

FPA – Focal Plane Array

FIR – Far infrared

FTIR - Fourier Transform Infrared

FWHM – Full Width Half Maximum

GaAs - Gallium Arsenide

GaInAsP – Gallium Indium Arsenide Phospide

GaP – Gallium Phospide

GaSb – Gallium Antimonide
h – Planck constant

HEIWIP - Heterojunction Interfacial Work Function Internal Photoemission

HgCdTe – Mercury Cadmium Telluride

H-H - Heavy Hole

HIWIP - Homo junction Interfacial Workfunction Internal Photoemission

InAlAs – Indium Aluminum Arsenide

InAs - Indium Arsenide

InGaAs - Indium Gallium Arsenide

InP – Indium Phosphide

IR – Infrared

IVB – intra-valence band

I-V-T - Current-Voltage-Temperature

k – Reciprocal lattice wavevector of GaAs

L-H - Light Hole

LO – Longitudinal Optic

LWIR – Long Wavelength Infrared

M – middle

MBE - Molecular Beam Epitaxy

MCT – Mercury Cadmium Telluride

MIR - Mid- Infrared

mm – millimeter

MWIR - medium-wavelength infrared

NIR - Near infrared
nm – nanometer
n-type – free electron charge carrier
PbIbN - p-type-intrinsic-n-type
p-Type – free Hole charge carrier
QDIPs - Quantum Dot Infrared Photodetectors
QDs - Quantum Dots
QWIPs - Quantum Well Infrared Photodetectors
$R_0A$ - resistance-area product
S-O - Spin-Orbit Split-off band
subMM – submillimeter
SWIR – short-wavelength infrared
T – top
T2SL - type II InAs/GaSb superlattice
TDIPS - temperature-dependent internal photoemission spectroscopy
THz – Terahertz
Ti/Pt/Au – Titanium/Platinum/Gold
TO - transverse-optical
VB - Valence Band
VLWIR - very-long wavelength infrared
$\lambda_{CO}$ - cut-on wavelength of optical filter
$\lambda_c$ - wavelength corresponding to full width at half maximum
$\lambda_\tau$ - wavelength threshold
1 P-TYPE GAAS/ALGAAS HETEROSTRUCTURE FOR INFRARED PHOTODETECTION

1.1 Introduction

Infrared (IR) radiation covers a range in the electromagnetic radiation with the wavelengths longer than the visible, but shorter than millimeter waves. More specifically, electromagnetic radiation in the wavelength range of 0.78 µm to 1000 µm (or 1 mm) constitutes IR radiation, even though this is not a strict classification. Being invisible to the human eye, IR radiation was unknown to humans until its discovery by Frederick William Herschel in 1800 while studying the spectrum of sunlight with a prism and measuring the temperature of each color. Herschel found that the highest temperature change on a thermometer was caused by an invisible spectrum of light just beyond the red, to be named as “infra-red”.

The IR radiation band is subdivided to many spectral regimes, even though a unique subdivision does not exist. The most common subdivision includes seven spectral regimes, namely near IR (NIR, 0.78 – 1 µm), short-wavelength IR (SWIR, 1 – 3 µm), medium-wavelength IR (MWIR, 3 – 6 µm), long-wavelength IR (LWIR, 6 – 15 µm), very-long wavelength IR (VLWIR, 15 – 30 µm), far IR (FIR, 30 - 100 µm), and submillimeter (subMM, 100 – 1000 µm). Furthermore, the IR radiation in the 30 – 300 µm spectral regime is also referred to as the terahertz (THz) radiation in terms of the radiation frequency (10 – 1 THz). Furthermore, the atmospheric transmission windows of 3 – 5 µm and 8 – 14 µm are also commonly referred to as MIR and LWIR bands, respectively.
Vibrating charged particles, including atoms, generate electromagnetic radiation. Naturally, all objects above absolute zero temperature emit IR radiation. The relationship between wavelength at the peak intensity of the emission spectrum ($\lambda_p$) and the temperature ($T$) of the radiating source (ideally a blackbody) is given by $\lambda_p T = 2898\ \mu\text{mK}$. Accordingly, a human body radiates with a $\lambda_p \sim 9.5\ \mu\text{m}$ (LWIR), the sun with $\lambda_p \sim 0.5\ \mu\text{m}$ (visible), and a passenger jet exhaust with $\lambda_p \sim 4\ \mu\text{m}$ ($T \sim 700$ K). Detection of IR radiation means the detection of an object, the source of the IR radiation. IR detectors and imaging systems enable one to see the objects even in the absence of visible light. IR imaging systems can easily recognize a camouflage object in the visible spectrum. Furthermore, Rayleigh-type ($\lambda^{-4}$) scattering is much smaller in the IR spectrum compared to that in the visible spectrum, rendering much better visibility with IR imaging systems through dust, smoke, and cloud.²

These fundamental characteristics of the IR radiation have found a wide range of applications³ – including military, civilian and scientific research. Historically, research and development of IR detectors was driven primarily due to military interest, and still is the case as IR imaging systems are becoming a “differentiating key-factor of military superiority”³. IR imaging systems are employed with applications in ground-based, air-based, and space based surveillance and targeting systems, such as tank-sight systems, anti-tank missiles, and air–air missiles.

Although military applications are still the major interest, the applications of the IR detectors and imaging systems are growing in recent decades in diverse areas. These areas include industrial energy loss monitoring, scientific researches such as IR astronomy and global monitoring of environmental pollution and climate change², firefighting, search and rescue²,
security surveillance, driving and navigation, and medical imaging and diagnostics. The demands for such a diverse group of applications need IR imaging systems with unique operational characteristics such as speed, resolution, power requirement, cost, size, operational temperature and so on. For example, IR astronomy requires large array size without a stringent cost restriction, whereas IR security cameras can be still useful with a small array size but a low cost is critical for large scale applications. In fact, the requirements of the new generation of IR imaging systems are not just the high-performance, large-format cooled imagers, but also medium- to high-performance uncooled imagers, and very low cost, expendable uncooled imagers. In addition, multispectral detection is crucial for increasing the target identification range, and also to overcome the problem of contrast washout between the target and background.

A functional near-IR spectroscopy (fNIRS, 700 -1000 nm) of brain tissue temperature was also studied theoretically for non-invasive brain imaging owing to the difference of the blood oxygen level dependent (BOLD) absorption of NIR (0.6 – 1.1 µm) radiation. Further studies are reported recently in fNIRS based cortical signal analysis, hemodynamic response as measured by fNIRS studies in newborns, differential path-length factor's effect on the characterization of the brain's hemodynamic response in the fNIRS method. Moreover, progress being made in wireless and wearable fNIRS systems is expected to be increasingly useful in neuroimaging in naturalistic environments and social cognitive neuroscience. Potential biomedical application of MIR and LWIR region (IR spectral fingerprint region, 5 – 10 µm or 1000 – 2000 cm⁻¹) can help us understand disease associated alteration in major biomolecules such as carbohydrates, nucleic acids proteins and lipids. Our colitis and cancer studies showed that serum changes in MIR and in the attenuated total internal reflection spectrum reflect changes in the serum due to illness. Since one type of cancer studied was also a subcutaneous tumor, a brain tumor is also likely to
demonstrate serum changes. Thus, MIR and LWIR imaging systems can be used in the diagnostics of brain tumors. Therefore, MIR and LWIR imaging systems hold promise in the diagnostics of brain tumors, and further development of MIR detectors should be undertaken with this aim in mind.

Development of fNIR spectroscopy for brain imaging primarily relies on the detection of BOLD NIR signal from the brain tissues. IR absorption properties of water is also a critical factor that can have its effect through absorption in the tissue. A careful observation of the differences on the BOLD IR absorption spectrum\(^8\) in the range of 0.6 to 1.1 µm reveals that a maximum difference in the BOLD absorption is in the wavelengths shorter than 0.7 µm, where the deoxyhemoglobin (deoxyHb) absorption is higher than the oxyhemoglobin (oxyHb) absorption. Absorption by water is also extremely small in this spectral region. However, this spectral range is in the visible region, hence ambient light can easily interfere with the BOLD signal from brain tissues. The difference in the BOLD absorption becomes smaller at further longer wavelengths and oxyHb and deoxyHb signals are same at 0.8 µm. Then the oxyHb absorption becomes stronger than deoxyHb absorption at wavelength range of 0.8 to 1.1 µm. However, absorption by water also becomes stronger at this wavelength range, the strongest peak being near 0.98 µm. Even a small absorption by water amounts to be significant given the considerable tissue thickness in the path of BOLD signal to the detector. The intensity of the signal weakens exponentially through the tissue due to water absorption according to Beer-Lambart law. This means a search for another spectral band where the IR transmission through water is very high. One of such spectral band is 3 – 5 µm with an excellent IR transmission through water\(^2\), with a peak transmission near 100% at 3.8 µm. Therefore, 3 – 5 µm spectral band is interesting for non-invasive optical imaging of brain using BOLD signal detection techniques. However, absorption properties of deoxy and
oxyHb is needed to be studied in this spectral band in order to fully assess the potential of non-invasive brain imaging in 3 – 5 \( \mu \)m IR band.

Several material systems and techniques have been explored for IR detector and imaging systems. Historically, mercury-cadmium-telluride (HgCdTe or MCT) based IR detectors are the most widely used for high-performance applications (e.g., military)\(^{22}\). However, widespread applications of these detectors have been impeded due to the fundamental material problems. The HgCdTe material system is marred by high defect density related to growth due to the weak Hg-Te bond\(^{23}\). This is a serious technological problem for the mass production of HgCdTe large sized Focal Plane Arrays (FPA), and to achieve high FPA pixel uniformity and yield. On the other hand, Quantum Well IR Photodetectors (QWIPs) based on GaAs/AlGaAs material system are considered, mostly LWIR spectral regime for high-performance applications. The industrial infrastructure in III–V materials/device growth, processing, and packaging brought about by the utility of GaAs based devices in the telecommunications industry gives QWIPs a potential advantage in producibility and cost\(^{22}\). However, QWIPs are not sensitive to normal incident light due to orthogonality between polarization vector of the incident photons and optical transition dipole moment\(^{24}\), therefore a light coupling structures are required for a 45° angle incidence of light which adds cost and complexity. In addition, a low operating temperature is typically required due to fundamental limitations associated with intersubband transitions.\(^{22}\) Studies of Quantum Dot IR Photodetectors (QDIPs) are also making progress towards the development of IR detectors.\(^{22,25}\)
1.2 Objectives of This Study

The primary objective of this work is to study the recently demonstrated extended-wavelength IR photodetectors based on p-GaAs/AlGaAs heterostructures. The extended wavelength IR photodetectors are novel class of photodetectors showing spectral photoresponse far beyond the conventional limit of $\lambda_c = \frac{hc}{\Delta}$, where $\Delta$ is the minimum energy that determines the wavelength threshold ($\lambda_c$) of the photoresponse. Since the dark current in the extended-wavelength IR photodetectors is still limited by $\Delta$ as in the conventional photodetectors, the extended-wavelength mechanism offers a new avenue for the design and development of the IR photodetectors. The device architecture used to demonstrate the extended-wavelength photoresponse utilized an offset ($\delta E$) between the energy barriers in the p-GaAs/AlGaAs heterostructure, and a reference photodetector without the offset did not show the extended-wavelength mechanism. Thus, it is important have a deeper understanding of the mechanism by studying the effect of the device parameters such as the offset and gradient of the barrier. This study is intended to carry out a detailed investigation on the extended-wavelength mechanism so that the findings from this study can set path forward to the development of IR photodetectors by utilizing the extended-wavelength mechanism in quantum nanostructures such as quantum dots-in-a-well (DWELL) IR photodetectors, and possibly achieve higher operating temperatures. The study of the dark current characteristics of the extended-wavelength photodetector along with the reference photodetector is intended to shed light on the fact that the dark current of the extended-wavelength photoresponse still offers the advantage that the dark current is limited by $\Delta$ as in the case of conventional photodetection whilst the spectral photoresponse is observed far beyond the conventional limit of $\Delta$. 
The other objective of this study is to explore possible ways to improve the performance of the p-GaAs/AlGaAs heterostructure-based split-off band MIR detectors. The effect of implementation of a current blocking barrier in order to improve the performance in MIR detection will be studied. By using the current blocking barrier on a 30-period p-GaAs/AlGaAs heterostructure with graded barrier, its effect will be investigated with and without the current blocking barrier on the same device. An operation at zero bias is achieved due to the graded AlGaAs barriers implemented in the heterostructure. The zero bias operation enabled by the graded barrier will be compared with the biased operation to find an optimum operating condition. Long pass optical filters will also be used in order to understand the fact that the current blocking barrier will not affect the spectral range of the photoresponse. In addition to split-off band IR absorber for MIR detection in p-GaAs absorber, other material options such as p-InP will also be explored in order to develop p-InP/InGaAlAs heterostructure-based 3 – 5 μm band IR photodetectors based on the split-off band detection mechanism.

1.3 An Overview of p-GaAs/AlGaAs Heterostructure-Based IR Photodetectors

The III–V material based heterostructures such as p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based IR Photodetectors would have the same advantages of the QWIPs in terms of growth, processing, and packaging and high yield and pixel uniformity, with additional advantages of sensitivity to normal incidence light, high operating temperature, and tunability to a wide spectral range. Historically, p-GaAs layers were used as IR absorber/emitter in the development Homojunction Interfacial Workfunction Internal Photoemission\textsuperscript{26,27} (HIWIP) IR photodetectors for FIR detection. A multilayered emitter/barrier structure between the top and bottom contacts is depicted in Figure 1 (a). Normal incidence of IR radiation through top contact generates photo-
Figure 1.1 (a) A 3D cartoon representation of multilayered Homojunction/Heterojunction Interfacial Workfunction Internal Photoemission (HIWIP/HEIWIP) IR photodetector. Optoelectronic characterizations require top and bottom contact electrodes. IR radiation is incident from the top, where the top contact (p⁺-GaAs) is partially etched to open an optical window. (b) A schematic of valence-band alignment of HIWIP/HEIWIP IR photodetector under an applied bias. The HIWIP structures utilized p-type doped GaAs absorber/emitter and undoped GaAs barrier whilst the HEIWIP structures utilized p-type doped GaAs absorber and undoped AlₓGa₁₋ₓAs barriers. The interfacial energy gap (Δ) is determined by the doping level in HIWIP structures. In the HEIWIP structures, Δ is determined primarily by the Al mole fraction (x) although the doping level also has a contribution. The arrows depict the photo-excitation of the carriers and internal photoemission, which will undergo sweep out and collection due to the applied bias.
excited carriers in the absorber/emitter layer. A photoresponse signal is measured across the top and bottom contact electrodes. An application of a bias voltage across the top-bottom contacts enabled the device operation. Due to the application of a (positive) bias voltage, carrier injection and collection occur at the top and bottom contacts respectively. A schematic of the valence band alignment of a HIWIP IR photodetector is depicted in Figure 1 (b). The device architecture included a multilayer stack of p-type doped (with a doping of $4 \times 10^{18}$ cm$^{-3}$) GaAs emitters and undoped GaAs barriers. The p-GaAs/i-GaAs multilayer emitter/barrier stack was sandwiched between highly p-type doped GaAs layers acting as the top and bottom contacts. Due to the doping in the emitter p-GaAs layer, the Fermi level alignment with the undoped barrier leads to an interfacial energy gap ($\Delta$) at the emitter/barrier heterojunction. As depicted in Figure 1, the incident FIR radiation is absorbed in the emitter layer by free carrier absorption mechanism. The study of the free carrier absorption in the p-type doped GaAs is weak at shorter wavelengths, but increases$^{28}$ as $\lambda^2$ with the wavelength, thus the free carrier absorption mechanism is suitable for FIR detection. The photoexcited carriers undergo an internal photoemission over the barrier provided the energy of the incident radiation is higher than $\Delta$. The applied bias voltage across the top-bottom contacts causes the sweep-out and collection of the photo-excited carriers at the bottom contact so that a measurable signal can be detected across the contacts. Thus, the in the HIWIP IR photodetectors, the mechanism of IR detection includes IR absorption to generate photo-excited carriers, internal photoemission of the photo-excited carriers, sweep-out and collection. The interfacial energy gap determines the energy threshold of the spectral photoresponse. The corresponding wavelength thresholds of 80 – 100 µm was observed,$^{26}$ which was tunable with the bias.
In addition to the HIWIP IR photodetectors, Heterojunction Interfacial Workfunction Internal Photoemission\textsuperscript{29,30} (HEIWIP) IR photodetectors were also studied. The key difference between the HIWIP and the HEIWIP IR photodetector the latter utilized undoped Al\textsubscript{x}Ga\textsubscript{1-x}As layer as barrier as opposed to an undoped GaAs layer is the former. However, the mechanism of IR detection in HEIWIP IR photodetectors is same as in the HIWIP IR photodetectors, that is, IR absorption with free carrier absorption mechanism, internal photoemission of the photo-excited carriers, and collection at the contacts. The advantage of utilizing the Al\textsubscript{x}Ga\textsubscript{1-x}As barrier in HEIWIP IR photodetectors is that the interfacial energy gap at the p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterojunction can be controlled primarily by the Al mole fraction (x). For instance, the Al mole fraction of 0.12 used in the Al\textsubscript{0.12}Ga\textsubscript{0.88}As barrier of a p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based HEIWIP IR photodetector had a 20 \(\mu\)m cut-off wavelength in the spectral photoresponse.\textsuperscript{29} A further study of the a p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based HEIWIP IR photodetector that had a peak photoresponse near 12 \(\mu\)m also showed a strong photoresponse in 1.5 – 3.5 \(\mu\)m band,\textsuperscript{31,32} which originated from the IR absorption due to intra-valence band (IVB) transitions from heavy-hole (H-H)/light-hole(L-H) to split-off (S-O) band, where the S-O band in GaAs has a 0.34 eV energy gap from L-H/H-H bands, as shown in Figure 1.2. The free carrier absorption being weak in the 1.5 – 3.5 \(\mu\)m band spectral regime, the dominant mechanism of photoresponse was found to be the S-O band absorption. With the Al mole fraction \(x = 0.12\) in the Al\textsubscript{x}Ga\textsubscript{1-x}As barrier, the spectral photoresponse in the S-O band was observed up to 130 K in the p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based HEIWIP IR photodetector.

Further study of the S-O band IR detectors based on p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructures showed higher operating temperatures as the Al\textsubscript{x}Ga\textsubscript{1-x}As barriers utilized higher Al mole fraction to increase the barrier height.\textsuperscript{33} In particular, the devices named SP1, SP2, and SP3 with \(x = 0.28\),
Figure 1.2  (a) A schematic diagram of the equilibrium valence band alignment of a typical p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based IR photodetector under equilibrium. The active region of the device is sandwiched between highly p-type doped GaAs top and bottom contact layers. Δ is the activation energy. (b) A schematic of valence band of GaAs near k = 0 showing light hole, heavy hole, and split-off bands. The split-off band lies 0.34 eV below the light hole/heavy hole bands at k = 0. The arrows show some of the possible intra-valence band (IVB) transitions due to the absorption of IR photons. (c) Operation of the IR detector under a bias voltage, showing IVB transitions to S-O band due to IR absorption in the p-GaAs layer and internal photoemission to barrier.
0.37, and 0.57, respectively, showed the operating temperatures of 140, 190 and 300 K respectively.\textsuperscript{33} Furthermore, a device modeling study\textsuperscript{34} of S-O band IR detector was carried out in order to find optimized conditions for its performance improvement. The study suggested two important device architecture modifications in order to improve the device performance. One of the suggestions was to include an offset ($\delta E$) between the energy barriers so that the low energy barrier towards the collector side would enhance the collection. The other suggestion was to include a graded barrier on the injector side so that the carrier trapping would be reduced and the injection of the carriers to the absorber/emitter would be improved.

The study of the S-O band detector devices with the barrier offset ($\delta E$) and a graded barrier showed an unprecedented result in terms of the spectral range of the photoresponse: a photoresponse that is far beyond the spectral limit\textsuperscript{35} of $\lambda_i = hc / \Delta$. In particular, the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructures-based IR detector designed with a $\Delta \sim 0.40$ eV ($\sim 3.1 \ \mu$m) for S-O (MIR) band detection also demonstrated a FIR spectral photoresponse\textsuperscript{36} up to $\sim 55 \ \mu$m, which is far beyond the spectral limit of $\Delta$ of the heterostructure. Furthermore, this mechanism of photoresponse beyond the spectral limit had interesting properties that a spectrum of high energy IR radiation with wavelengths shorter than $\sim 4.5 \ \mu$m was necessary in order to observe the FIR spectral photoresponse.$^{36}$ This observation was confirmed by using long-pass optical filters to block the incoming IR radiation in the spectra of wavelengths shorter than 4.5 $\mu$m that led to the disappearance of the FIR photoresponse. With the optical filter still in the light path, the FIR photoresponse was recovered by using an external IR source to enable the S-O band photoexcitation in the detector.$^{36}$ Furthermore, a reference p-GaAs/Al$_x$Ga$_{1-x}$As heterostructures-based IR detector without an offset did not show the extended-wavelength photoresponse.$^{36}$ Therefore, a detailed study of the extended-wavelength photoresponse mechanism, including the
effect of variations of the parameters such as the barrier offset and gradient is necessary to achieve the objectives outlined in the previous section.

This study will investigate in detail the extended-wavelength photoresponse mechanism. Here, my work is focused on the extensive experimental study of the extended-wavelength IR photodetectors, which will be presented in Chapters 2 and 3.

Although the photoresponse of a single-period p-GaAs/Al\textsubscript{1-x}Ga\textsubscript{x}As heterostructure device without the offset ($\delta E = 0$), the reference detector (LH1002), was used to compare with the extended-wavelength photoresponse,\textsuperscript{36-38} its detailed study has not been reported previously. Therefore, in the section 1.6, I will present the study of a single-period, constant barrier, p-GaAs/Al\textsubscript{1-x}Ga\textsubscript{x}As heterostructure-based IR photodetector for the MIR band detection. This device will be used as a reference detector in Chapter 2 and 3.

In Chapter 2, a detailed experimental study of p-GaAs/Al\textsubscript{1-x}Ga\textsubscript{x}As heterostructure-based IR detectors with barrier energy offset and graded barriers will be presented, to study the extended-wavelength photoresponse (up to ~60 µm), that is, beyond the limit of the $\Delta$ observed on conventional IR photodetectors (~3.1 µm). Based on the experimental results of varying the energy offset and the gradient, I will present a design concept for a promising extended-wavelength IR photodetector based on a quantum dots-in-a-well structure.

In Chapter 3, a study on the dark current characteristics of the extended-wavelength IR photodetectors will be presented to show that the dark current of these devices is limited by $\Delta$ corresponding to the MIR wavelengths related to the design parameters.
In Chapter 4, a study on the effect of a current blocking barrier on a 2 – 6 µm band p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based IR photodetector to enhance the specific detectivity will be presented. Additionally, a future outlook on ongoing study of p-InP/InAlAs heterostructure-based IR photodetector designed specifically for 3 – 5 µm atmospheric window will also be discussed.

1.4 Device Design Principles

The IR detection mechanism of the p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure-based IR detectors is based on the three fundamental processes: absorption of the IR radiation by the p-GaAs absorber (emitter), internal photoemission of the photo-excited carriers over the Al\textsubscript{x}Ga\textsubscript{1-x}As barrier, and collection at the contact layer to measure the photoresponse signal.\textsuperscript{30} Therefore, the foremost step in IR detector design is to study the absorption properties of the material used in the device as an absorber. In our study, p-type doped GaAs used as an IR radiation absorber. The IR radiation absorption properties of p-GaAs has been studied in detail in FIR spectral regime\textsuperscript{28} where the free carrier absorption is the dominant mechanism. The free carrier absorption mechanism becomes weaker at shorter wavelengths\textsuperscript{28} as \(\lambda^2\). However, the S-O and L-H/H-H intra-valence band (IVB) transitions enable strong IR absorption in the MIR and LWIR spectral regimes.\textsuperscript{39} Thus, p-type doped semiconductors such as p-GaAs is capable of IR absorption in a broad IR spectra, that is, from MIR through FIR region. The IR absorption properties of p-GaAs semiconductor has been studied\textsuperscript{39} in a detail for doping densities varying from \(10^{17}\) to \(10^{20}\) cm\(^{-3}\). IR absorption coefficient (\(\alpha\)) of p-GaAs due S-O and L-H/H-H absorption mechanisms are found to be in the range of \(10^3\) to \(10^4\) cm\(^{-1}\), for the doping levels of from \(10^{19}\) to \(10^{20}\) cm\(^{-3}\), increasing with the doping density.\textsuperscript{39} By using the Beer-Lambart law \((I/I_0 = e^{-\alpha z})\), where \(z\) is the thickness of the absorbing layer, the
fraction of the intensity of the IR radiation that can be absorbed by an absorbing layer can be estimated. Whilst the optical absorption coefficient and the thickness of the absorbing layer are important parameters to be considered in the design of an IR detector, there are other conditions such as the collection of photoexcited carriers; therefore, an optimization of all parameters should be considered.

A broad IR absorption from MIR through FIR spectral regime by p-GaAs allows development IR detectors, the spectral region of interest being easily controlled by an activation energy ($\Delta$) that is set up when the p-GaAs layer forms a heterostructure with latticed matched Al$_x$Ga$_{1-x}$As layer. The difference between the valence band energies between GaAs and Al$_x$Ga$_{1-x}$As layers is given as $\delta E_V = (0.57 - 1.39 \times 10^{-4} T) x$, where $T$ is temperature and $x$ is Al mole fraction in the Al$_x$Ga$_{1-x}$As barrier. Furthermore, p-type doping induces a Fermi level change in the p-GaAs layer. For high doping levels of $\geq 10^{19}$ cm$^{-3}$, the Fermi level in the p-GaAs layer lies in the valence band. Quantitatively, the doping density dependence of the magnitude of the energy from the valence band edge to the Fermi level is given by $E_f = k_B T \left( \ln \left( \frac{p}{N_v} \right) + 2^{-3/2} \left( \frac{p}{N_v} \right) \right)$, where $p$ is the doping density in the p-GaAs layer. Here, $N_v$ is the density of states given by $N_v = 2 \left( \frac{2 \pi m_{dh} k_B T}{\hbar^2} \right)^{3/2}$, where $m_{dh}$ is the effective mass of holes. Therefore, the activation energy ($\Delta$) and the corresponding wavelength threshold ($\lambda_t$) of the spectral photoresponse can be determined from the Al mole fraction in the Al$_x$Ga$_{1-x}$As barrier and the doping-dependent Fermi level in the p-GaAs layer.

A detailed device modelling study$^{34}$ for S-O band detectors for MIR detection has provided important insights for device design and development for optimized performance. The p-type doping is necessary for IR absorption based on S-O and L-H/H-H absorption mechanism, and
absorption coefficient is dependent on the doping density. A doping density of $1 \times 10^{19}$ cm$^{-3}$ used in the device modelling study$^{34}$ also found that a critical thickness limit should be imposed on the p-GaAs layer due to the fact that the carrier-carrier scattering becomes significant at these high levels of doping. In order to avoid the loss of photo-excited carriers due to carrier-carrier scattering, an absorber thickness of ~80 nm or less was suggested$^{34}$ for p-GaAs absorber.

Furthermore, in addition to the absorption of IR radiation, sweep-out and collection of the photo-excited carriers generates a photoresponse signal, which is measured across the top and bottom contacts. In order to optimize the photoresponse signal, it was suggested$^{34}$ to include a barrier energy offset, by implementing two Al$_x$Ga$_{1-x}$As barriers of different energy heights. A lower energy barrier on the collector side was expected to improve the collection of the photo-excited carriers. Additionally, it was also suggested$^{34}$ to include a graded Al$_x$Ga$_{1-x}$As barrier on the injector side to reduce the carrier trapping at the injector. The graded barrier would be implemented by increasing the Al mole fraction ($x$) from the injector side of the barrier towards the absorber (emitter) side.

Thus, the design and development of an IR photodetector based on p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure is primarily focuses on the IR absorption properties of p-GaAs material, suitable choice of doping density level and thickness of absorbing layer, implementation of Al$_x$Ga$_{1-x}$As barrier layer with Al mole fraction ($x$) in order to obtain an activation energy ($\Delta$) suitable for the spectral regime of interest. Additional design parameters to implement barrier energy offset and graded barrier also should be taken in to account. The processes of IR absorption at the absorber, internal photoemission of photo-excited carriers over the barrier and collection at the contact layer generate a photoresponse signal. Quantitatively, the strength of photoresponse signal is
proportional to total quantum efficiency given as \( \eta = \eta_a \eta_e \eta_c \), where \( \eta_a \) accounts for the probability of absorption of a photon, \( \eta_e \) accounts for probability of internal photoemission and \( \eta_c \) accounts for the probability of the collection of the photo-excited carrier. The probability of absorption is proportional to the IR absorption coefficient a discussed before, hence the optical absorption properties of the IR absorbing layer is important for the design of an IR photodetector. The internal photoemission probability is dependent on the energy of photo-excited carrier and the activation energy. Quantitatively, \( \eta_e \) is proportional to \( \frac{2}{3} \left\{ \left( E_F + \hbar \nu \right)^{\frac{3}{2}} - \left( E_F + \Delta \right)^{\frac{3}{2}} \right\} - (\hbar \nu - \Delta)(E_F + \Delta)^{\frac{1}{2}} / \left\{ \left( E_F + \hbar \nu \right)^{\frac{3}{2}} - (\hbar \nu)^{\frac{3}{2}} \right\} \) for \( \hbar \nu \geq E_F + \Delta \), and 0 otherwise, where \( \hbar \nu \) is the incident IR photon energy, \( E_F \) is Fermi level, \( \Delta \) the energy gap at the emitter/barrier interface. Finally, the probability of collection \( \eta_c \) of a carrier is proportional to \( e^{-z_m/L_s} \), where \( z_m \) is distance from the emitter/barrier interface to the position of maximum barrier height, and \( L_s \) is the average carrier scattering length. Here, \( \eta \) can be related to an experimentally measurable quantity, also referred to as spectral responsivity, given as \( R_i (A/W) = \eta \frac{q}{\hbar c} \lambda \), where \( q \) is electronic charge. Responsivity is a measure of output current signal due to one watt of incident IR radiation of wavelength \( \lambda \). The following section will describe the methods of experimental characterization of IR detectors.
1.5 Methods of Optoelectronic Characterizations of IR Detectors

As mentioned previously, the responsivity of an IR detector measures the output current per unit power of incident IR radiation. A Fourier-transform infrared (FTIR) spectrometer (Perkin Elmer system 2000) is used to measure the spectral photoresponse signal of the IR detectors. The Perkin Elmer system 2000 uses Spectrum 5.0 software for the spectral measurements. The FTIR spectrometer consists of a built-in source of broad IR radiation that is used as the source of IR radiation of the detector characterization. In order to measure the intensity of the incident IR radiation over a broad spectral band (NIR through FIR), a bolometer of known sensitivity over the IR spectrum is used. The bolometer is mounted inside a dewar (HD-3 or HD-5, IR Lab Inc.), where the IR radiation incident through an IR window of the dewar is focused onto the bolometer by means of a Winston cone (details in Appendix C). Then the photoresponse signal of the bolometer is measured at liquid helium temperature. The photoresponse signal from the bolometer electrode contacts is fed to a voltage pre-amplifier in order to pre-amplify the signal before sending to the computer where the Spectrum 5.0 software records the spectrum of photoresponse.

The IR detector under test is also mounted inside the dewar in the same way as the bolometer. The photoresponse signal is recorded in the similar way in the case of bolometer. The output (raw) signal is then calibrated to obtain the spectral responsivity of the detector under test as

\[
R_s(A/W) = \frac{GV_s(\lambda)}{V_c(\lambda)}R_c(\lambda)\times\left(\frac{1}{R_L} + \frac{1}{R_d}\right),
\]
where $G$ is a geometrical factor, which is used to correct for the differences between the radiation-incident-area of the device under test and the bolometer, $V_s(\lambda)$ is the raw signal measured from the device under test, $V_c(\lambda)$ is the bolometer spectra, $R_c(\lambda)$ is the sensitivity of the bolometer provided by the manufacturer. $\left( \frac{1}{R_L} + \frac{1}{R_d} \right)$ is the effective resistance, where $R_L$ resistance of the load resistor in parallel to the device under test with a dynamic resistance $R_d$. The spectra from the device under test and the bolometer are measured with the same combination of optical windows, and beamsplitter to make the optical path identical. Furthermore, if different pre-amplified gain factors are used for the bolometer and IR detector under test, a correction is applied to the responsivity by multiplying the ratio of pre-amplifier gain for bolometer and the detector under test. Usually, a pre-amplifier gains of 100 is used for both bolometer and the detector under test.

Another figure of merit is Noise Equivalent Power (NEP) defined as the minimum radiation power incident on the detector that can produce a photocurrent equivalent to the average detector noise current. Quantitatively, the NEP is given as

$$NEP = \frac{1}{R_f} i_n \sqrt{\Delta f},$$

where $i_n$ is noise current and $\Delta f$ is the noise band-width.

The NEP does not account for the area of the IR detector. Therefore, the NEP of one IR detector cannot be compared with the NEP of another IR detector unless the two detectors have
the same area. Therefore, most important figure of merit, the specific detectivity \((D^*)\) is obtained from NEP by normalizing it for the area of the detector \(A\) as follows:

\[
D^* = \frac{1}{\text{NEP}} \sqrt{A}
\]

\[
D^* = \frac{R_i}{i_n} \sqrt{A \Delta f} \quad \text{(cm Hz}^{1/2}/\text{W)}
\]

The specific detectivity can also be obtained\(^{42}\) as

\[
D^* = \frac{R_i \sqrt{A}}{\sqrt{2qI_d + \frac{4k_B T}{R_{\text{diff}}}}}
\]

Here, \(I_d\) is the current and \(R_{\text{diff}}\) is the differential resistance of the detector under test.

Dark current-voltage measurements are carried out by mounting the detector under test on a sample holder of a cryostat cold finger. Then the cold finger is enclosed by double shielding metallic shrouds to completely shield the detector under test from the any ambient radiation. The sample chamber inside the shield is pumped to \(~10^{-6}\) Torr and cooled to cryogenic temperatures by an APD HC2 closed-cycle refrigerator, which can achieve a temperature as low as 10 K. A computer-controlled Keithley 2635B (or 2400) source-meter was used to measure the I-V characteristics, with the temperature steps being controlled by Lakeshore 330 temperature controller (details in Appendix B). A DC bias voltage is applied to the detector by the source meter. A positive bias refers to the voltage connected to the top contact electrode of the device under test with the bottom contact grounded and a negative bias refers to the voltage connected to the bottom contact with the top contact being grounded.
Analysis of the IR detector characteristics involves various studies such as minimum energy of internal photoemission to produce a spectral photoresponse. This analysis of vital importance, particularly when a spectral photoresponse is observed beyond the limit of interfacial activation energy as discussed before. In such cases, a technique called Temperature Dependent Internal Photoemission Spectroscopy (TDIPS) method is used. The details of this method will be discussed in the next section to demonstrate its applications with the experimental data of a single-period, constant barrier, p-GaAs/AlGaAs heterostructure-based IR photodetector. Furthermore, temperature variation of dark current can also be used to obtain Arrhenius plots, which can be used to obtain the activation energy under dark conditions. This technique will also be discussed in the next section.
1.6 A Single-Period, Constant Barrier, p-GaAs/AlGaAs Heterostructure-Based IR Photodetector

1.6.1 Device Parameters and Measurements

A p-GaAs/Al$_{x}$Ga$_{1-x}$As heterostructure device (LH1002) was grown on semi-insulating GaAs substrate by molecular beam epitaxy. The equilibrium condition valence band alignment of this heterostructure is shown schematically in Figure 1.2(a) and a side view of the processed mesa of the device is shown schematically in Figure 1.3(a). The active region of the photodetector consists of an Al$_{0.57}$Ga$_{0.43}$As barrier (60 nm), followed by a p-GaAs emitter (20 nm), and then another Al$_{0.57}$Ga$_{0.43}$As barrier (60 nm). These emitter/barrier layers are sandwiched between the bottom and top contact layers of p-type doped GaAs, with thicknesses of 0.5 µm and 0.2 µm, respectively. The emitters, and the top and bottom contact layers, are degenerately doped at $1 \times 10^{19}$ cm$^{-3}$. The thickness of the emitter is sufficiently large to have a bulk-like distribution of the energy states.

Mesas with an electrically active area of 400×400 µm$^2$ were fabricated by conventional photolithography and wet etching, and the contact electrodes were formed by a Ti/Pt/Au metal evaporation and lift-off. By partially etching the top contact layer (p-GaAs), an optical window of ~260×260 µm$^2$ was opened for normal incidence optical illumination of the detector. A top view optical image of a processed mesa is shown in Figure 1.3(b). The packaging (mounting and wire-bonding on a chip carrier) is explained in Appendix A.

Current-voltage-temperature (I-V-T) characteristics of the device were measured using a Keithley 2635B source meter, with the temperature being controlled by a Lakeshore 330.
Figure 1.3 (a) A schematic of valence band alignment of p-GaAs/Al_{x}Ga_{1-x}As heterostructure corresponding to the layers in the schematic diagram (b) Side view of a processed mesa of a p-GaAs/Al_{x}Ga_{1-x}As heterostructure-based IR photodetector (LH1002). All p-GaAs layers—bottom contact (0.5 µm), top contact (0.2 µm) and the emitter (20 nm) are doped at 1×10^{19} cm^{-3}. (c) Top view optical image of a processed mesa (before wire bonding). Electrically active area of the mesa is 400 µm × 400 µm, and the optically active area of the mesa is 260 µm × 260 µm.
temperature controller. A positive voltage connected to the top contact with the bottom contact grounded contact grounded is referred to as a positive bias. Similarly, a positive voltage connected to the bottom contact with the top contact grounded is referred to as a negative bias. A Fourier transform infrared (FTIR) spectrometer (Perkin-Elmer system 2000) was used to measure spectral photoresponse, and a commercial Si composite bolometer with known sensitivity was used to measure the background intensity of a blackbody source to calibrate the photoresponse. The spectral photoresponse measurement set-up is also shown schematically in Appendix C. In addition, the spectral photoresponse calibration process is also explained in the Appendix C.

1.6.2 Results and Discussion

The experimentally measured dark current of the LH1002 device is shown in Figure 1.4, from 80 K to 200 K, in the applied bias range from -3.0 V to 3.0 V. The theoretical model fitting of the dark current will be presented in Chapter 3. By design, the device has two identical Al$_{0.57}$Ga$_{0.43}$As barriers (60 nm) with a flat/constant barrier shape. This makes the device a symmetrical one from the operational point of view in the positive and negative applies biases. The measured current-voltage characteristics also confirm the symmetrical operation of the device.

The dark current characteristics are important to determine an optimum operating condition. Whilst the lowest possible dark current is desired for the operation of an IR photodetector, a certain amount of bias voltage must be applied to operate photo-conductive photodetectors. With suitable barrier engineering, an optimized operation is possible without an applied bias in a p-GaAs/ Al$_x$Ga$_{1-x}$As heterostructure-based IR photodetector (to be presented in Chapter 4). However, study of dark current characteristics offers important insights into the device parameters such as activation energy ($\Delta$). Dark current in the semiconductor devices such as
Figure 1.4 Dark current characteristics (measured with Keithley 2635B source meter) of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure (LH1002) in the applied bias range from -3.0 V to 3.0 V. The current-voltage characteristics show the near-symmetrical in dark current in the positive and negative applied biases.
p-GaAs/ Al\(_{1-x}\)Ga\(_x\)As heterostructures is temperature dependent, which can be expressed as\(^{38,44}\)

\[
I_{\text{dark}} = Ae - \frac{\mu F}{1 + \left( \frac{\mu F}{v_{sat}} \right)^2} \frac{2}{\pi \hbar^2} \left( \frac{m^* k_B T}{2 \pi \hbar^2} \right)^{3/2} \exp \left( - \frac{\Delta}{k_B T} \right). \tag{1.1}
\]

Here, \(A\) is the electrically active area of the detector, \(e\) is the electronic charge, \(\mu(F)\) is the hole drift velocity as function of applied field, \(v_{sat}\) is the saturation velocity, \(m^*\) is the effective mass, \(k_B\) is Boltzmann’s constant, \(T\) is temperature, \(\hbar\) is the reduced Planck constant. The explicit time-dependence of the dark current can be expressed as

\[
I_{\text{dark}} \propto T^{3/2} \exp \left( - \frac{\Delta}{k_B T} \right).
\]

The experimentally measured dark current can be used to extract the value of \(\Delta\) from the slope of Arrhenius plots of \(\ln \left( \frac{I_{\text{dark}}}{T^{3/2}} \right)\) versus \(1/T\) for each of the applied biases (details in Appendix E).

The Arrhenius plots obtained from the dark current of the device LH1002 are shown in Figure 1.5. The dashed lines depict the best fit line implemented to obtain the slope of the Arrhenius plots for each bias voltage. The X-axis is used in the form of 100/T, instead of 1/T for convenience. Thus, a correction by a factor of 100 is needed to obtain the value of \(\Delta\), which is given as \(\Delta = -slope \times 100 \times k_B\) Joules (or \(\Delta = -slope \times 100 \times k_B \times 6.242 \times 10^{18}\) eV). The activation energy of the device LH1002 obtained from the Arrhenius plots will be presented in Figure 1.8 together with the activation energy obtained from the spectral photoresponse by using Temperature-Dependent Internal Photoemission Spectroscopy (TDIPS) method.\(^{40}\)
Figure 1.5 The Arrhenius plots of for the device LH1002 obtained from the temperature dependent dark current, in the temperature range of 100 – 200 K. The dashed lines represent the linear fit to the each of the plots implemented to obtain the slope of the plots.
The spectral photoresponse of the device LH1002 is shown in Figure 1.6 for positive biases and in Figure 1.7 for negative biases. The photoresponse spectra in the positive and negative biases are closely comparable at the biases of the same magnitude. The photoresponse due to L-H/H-H to S-O transitions is limited to ~3.5 µm due to the S-O band energy of 0.34 eV. The strong peak near the 2.7 µm may be attributed to the direct transitions from the H-H/L-H bands to the S-O band, whilst indirect transitions contribute for the broad photoresponse spectrum. Beyond ~3.5 µm, the photoresponse is due to the L-H/H-H intra-valence band absorption, which does not have a clear minimum energy threshold. However, the activation energy imposes the minimum energy limit on the internal photoemission and escape over the barrier, and hence the wavelength threshold of the spectral photoresponse. Unlike the natural band-gap between the conduction and valence bands, interfacial energy gap at the heterojunction is determined by the material type and composition of the layers forming the heterojunction, therefore, the activation energy can be tuned by changing the composition, for instance, Al mole fraction \( x \) in this study.

A small photoresponse was observed at 0 V, even though this result may not be expected in the perfectly symmetrical heterostructure. Assuming an isotropic momentum distribution of the photoexcited carriers, the probabilities of emission from emitter to either of the barriers are equal in the absence of an external applied bias. Thus, a net photocurrent cannot be detected between the top and the bottom contacts. However, the photoresponse observed at 0 V indicates a small but finite asymmetry in the heterostructure. Some of the possible reasons for this miniature asymmetry may be the small but unintentional gradient of the barrier, originating from the epitaxial growth. With the application of small negative biases, (for example, -0.01 V and -0.015 V as shown in the inset of Figure 1.7), the effect of this slight asymmetry is observed to get canceled resulting in a reduced photoresponse signal compared to that at 0 V. Based on the nearly vanishing
Figure 1.6 Spectral photoresponse of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure-based IR photodetector (LH1002) at 78K under positive biases. Intra-valence band transitions to S-O band (0.34 eV, up to ~ 3.6 µm) contribute to the photoresponse, an in the L-H/H-H bands (beyond 3.6 µm) contribute to the photoresponse. A small photoresponse is also observed at 0 V, indicating a slight asymmetry in the heterostructure, possibly originating from the wafer growth. Inset shows the equilibrium valence band diagram of the device.
Figure 1.7 Spectral photoresponse of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure-based IR photodetector (LH1002) at 78K under negative biases. The spectral photoresponse is similar to that in the positive biases. Inset shows the reduced strength of the photoresponse at lower applied biases of -0.01 V and -0.015 V in comparison to that at 0 V. This effect also indicates the presence of a slight asymmetry of the barriers, the effect being canceled at those small negative biases.
photoresponse at -0.01 V (-0.83 keV/cm), the gradient at 0 V appears to be ~0.83 keV/cm or less, which is much smaller compared to the intentionally designed gradient of ~20 keV/cm or higher, which will be seen in Chapter 2. At further higher biases, the photoexcited carriers (holes) gain momentum towards direction of the electric field, enhancing their sweep out and collection to produce stronger photoresponse. The wavelength threshold of the photoresponse becomes red-shifted with the increasing applied bias in both the positive and negative voltage regime. The wavelength threshold of the spectral photoresponse corresponds to the minimum energy required for the internal photoemission to contribute to the photoresponse. The bias-dependent red-shifting of the wavelength threshold indicates a lowering of the activation energy due to the applied bias. This is due to the image force lowering\(^{35}\) of the barrier energy height, by a magnitude of \(\Delta \varphi = 2|F|z_m\), where \(F\) is the applied field and \(z_m\) is the distance of the maximum barrier energy position from the heterointerface. At 0 V, image force lowering does not exist. Therefore, we expect the wavelength threshold to agree with the activation energy under equilibrium, which is determined\(^{40}\) by the Al mole fraction \(x\) as

\[
\Delta E_c = (0.570 - 1.39 \times 10^{-4} T)x \quad (1.2)
\]

for the p-GaAs/Al\(_x\)Ga\(_{1-x}\)As heterostructures. Accordingly, the activation energy for the device LH1002 is expected to be ~ 0.30 eV (~ 4.1 \(\mu\)m) at 0 V.

In addition to the Arrhenius plots method, the TDIPS method was also used to determine the activation energy, as shown in Figure 1.8. In the TDIPS method, the line shape of the spectral quantum yield of the experimentally measured photoresponse is considered.\(^{46}\) Quantum yield is given as
Figure 1.8 Activation energy of the IR photodetector device (LH1002) obtained from the Arrhenius plots (details of the fittings and the uncertainties are presented in Appendix E) of the dark current in the temperature range 100 – 200 K (solid circles) and the activation energy obtained by employing the temperature-dependent internal photoemission spectroscopy (TDIPS) fitting of the photoresponse at 78K (hollow triangles). Small deviations are observed in values obtained from the two methods, at a few high bias points in both positive and negative biases. The deviation is more noticeable in the negative bias than in the positive bias, possibly due to the small asymmetry, which causes more image force lowering in the negative biases.
\[ Y(h\nu) = Y_0 + C_0 \int_{\Delta}^{\infty} f(\varepsilon, h\nu) \rho(\varepsilon, h\nu - E_f) P(\varepsilon, \Delta) d\varepsilon , \]  

where \( \rho(\varepsilon, h\nu - E_f) \) is an energy distribution function and \( P(\varepsilon, \Delta) \) is a probability function and is calculated by an escape cone model of internal photoemission,\(^{30,47,48} \) \( C_0 \) is a constant, \( \varepsilon \) is the energy of the photoexcited carrier, and \( \Delta \) is the activation energy to be extracted as a fitting parameter. The function \( f(\varepsilon, h\nu) = 1/(1 + e^{(\varepsilon - h\nu)/kT}) \) describes the distribution of the carriers. The term \( Y_0 \) accounts for the background signal, for example, the thermionic emersion. It can be determined by giving the value of experimental quantum yield in the energy range less than the value of \( \Delta \). \( P(\varepsilon, \Delta) \) is proportional to \( (\varepsilon - \Delta) \) for \( \varepsilon \geq \Delta \), and 0 for \( \varepsilon < \Delta \). The energy distribution function \( \rho(\varepsilon, \varepsilon_0) \) of the photo-excited carriers is the key factor to influence on the quantum yield, and takes form \( \rho(\varepsilon, \varepsilon_0) \sim (\varepsilon - \varepsilon_0)^{1/2} \) under a parabolic-band approximation\(^{46} \) near \( k = 0 \).

A small region of the spectral quantum yield near the onset of \( Y(h\nu) \) is selected for the TDIPS fitting and the value of \( \Delta \) is obtained as the fitting parameter. In the examples shown in the Figure 1.9, the experimental spectrum of quantum yield is taken in the energy range of 0.15 eV to 0.39 eV. As can be seen in the Figure, the quantum yield near 0.15 eV appears to be flat at the background noise level. Therefore, the constant \( Y_0 \) is provided with the experimental value of quantum yield near 0.15 eV. The values of \( Y_0 \) used in the fittings were \( \sim 10^{-6} \) for 0 V and \( 10^{-5} \) for both 1 V and -1 V. Similarly, the values of \( Y_0 \) were used from the experimental quantum yield in the background noise level for the fitting of the spectral quantum yield at different biases. Similarly, the energy \( \varepsilon \) has a lower limit of \( \Delta \), which is a fitting parameter to be determined and can be different for spectral at different biases. The upper limit of \( \varepsilon \) is chosen to be 0.35 eV for
0 V spectrum, and 0.28 eV for 1 V and -1 V spectra. Here, primary focus is to obtain a fitting for near threshold region, therefore the line shape of the quantum yield in this region is considered, and the line shape of spectra at further higher energies is not important. Thus, the upper limit of $\varepsilon$ is chosen from energy axis corresponding to a near-parabolic line shape near the threshold of quantum yield. The constant $C_o$ is an arbitrary number that scales the intensity of the fitted curve. Therefore, the value of $C_o$ chosen such that the intensity of the fitted curve matches the experimental curve. The TDIPS fitting applied to the experimental quantum yield is shown in the Figure 1.9 for the device LH1002 at 0 V, 1.0 V and -1.0 V on the top, middle, and bottom panels, respectively. The dashed lines and the solid lines represent the experimental and the fittings curves respectively.

The activation energy obtained from both the Arrhenius plots and the TDIPS method agree closely overall as seen in the Figure 1.8. At 0 V, the values of the $\Delta$ appear to be in sufficiently close to the value expected from the design of the heterostructure. Even though a small deviation of the activation energy obtained from the Arrhenius plots at a few bias points towards both the negative and positive high bias ends is observed, the Arrhenius plots in general are useful to obtain activation energy of a heterostructure. The deviation is more noticeable in the negative bias than in the positive bias, possibly due to the small asymmetry, which causes stronger image force lowering in the negative biases. However, it should be noted that the TDIPS method takes into account the actual physical processes occurring in presence of IR radiation onto the photodetector to produce quantum yield spectra, and this is a more precise method for determining the activation energy required for internal photoemission. Therefore, applications of these two methods may find their importance under different conditions. For example, activation energy for the internal
Figure 1.9 TDIPS fitting of quantum yield for the device LH1002 at 78K to determine the activation energy (Δ). The top, middle and bottom panel show the fittings curves (solid lines) to experimental quantum yield (dashed lines) at 0 V, 1.0 V, and -1.0 V, respectively.
photoemission determined from the TDIPS may not correspond to the actual interfacial workfunction under dark conditions at the heterojunction if an extended wavelength photoresponse mechanism (to be presented in Chapter 2) is observed. In this condition, the Arrhenius plots are still useful to determine the values of Δ. Nevertheless, the TDIPS offers a standardized procedure to determine the wavelength threshold as long as experimental quantum yield is available from the spectral photoresponse, including the extended-wavelength mechanism. The techniques used to study the p-GaAs/AlₓGa₁₋ₓAs heterostructure-based IR photodetector here can be applied further to various III-V semiconductor-based IR photodetectors.

1.7 Summary

Recent research and development on p-type p-GaAs/AlₓGa₁₋ₓAs heterostructures-based IR photodetector are summarized. In addition, a study of a single-period, p-GaAs/AlₓGa₁₋ₓAs heterostructure-based IR photodetector with constant barriers and no barrier energy offset, showing a spectral photoresponse in SWIR and MIR spectral regime, due to the S-O band and H-H/L-H band IVB transitions, has been presented in this Chapter. The simplistic design of this device will be used as a reference IR photodetector in Chapters 2 and 3, to study the extended-wavelength IR photodetectors.
2 EXTENDED-WAVELENGTH INFRARED PHOTODETECTORS

2.1 Introduction

Conventionally, the fundamental rule that determines the wavelength threshold of the spectral photoresponse in an IR photodetector is given by the equation

\[ \lambda_i = \frac{hc}{\Delta}, \]  

where \( \lambda_i \) is the wavelength threshold of the photoresponse, and \( \Delta \) is the minimum energy for the photo-excitation, also known as the activation energy. However, \( \Delta \) is no longer a critical parameter to determine the wavelength threshold of the spectral photoresponse in a novel class of photodetectors referred to as extended-wavelength IR photodetectors. In conventional IR photodetectors, \( \Delta \) determines not only the wavelength threshold of the spectral photoresponse, but also the dark current levels.

In this chapter, I will present the study on the photoresponse characteristics of the extended-wavelength IR photodetectors. In this class of IR photodetectors, the Al\(_x\)Ga\(_{1-x}\)As barriers are designed to have different barrier heights, thereby setting up an energy offset (\( \delta E \)) between the two barriers. It has been experimentally found that the energy offset is a necessary condition for the extended wavelength photoresponse. In terms of physical mechanism, the hot-carrier effect is deemed to play an important role for the photoresponse in the spectral region beyond the limit set by \( \Delta \) as seen in equation (2.1).

Photoexcited carriers are considered as hot-carriers since their energies are larger than those of thermal excitations at ambient temperatures. The discovery of the photoelectric effect
by Heinrich Hertz in 1887 not only played a critical role in the development of the quantum mechanics, but also in the study of the photodetectors and solar energy harvesting. The research interests in this area are still growing. Optoelectronic devices based on hot-carrier driven effects have received broad attention owing to their breadth of potential applications in areas ranging from photodetectors to solar energy harvesting.\textsuperscript{50-52} For example, a hot-carrier based IR photodetector with wavelength tunability, but independent of the semiconductor bandgap, was explored as one candidate for IR photodetectors.\textsuperscript{53} Recently, a photo-detection extended up to FIR spectral regime (\textasciitilde 55 µm) was demonstrated\textsuperscript{36} with a photodetector of conventional \( \Delta \) value corresponding to \textasciitilde 3.1 µm. In this case, p-GaAs/ Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructures with a \( \delta E \sim \text{0.10 eV} \) were used, where the p-GaAs layer, sandwiched by Al\textsubscript{x}Ga\textsubscript{1-x}As barrier layers, works as an absorber and emitter. The underlying mechanism leading to this FIR photoresponse is deemed to be the hot-carrier phenomena in the p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure device that is barrier-engineered to have a non-zero \( \delta E \).

This study is focused on the further study of the “extended-wavelength IR photodetectors” in order to obtain a deeper understanding of the extended-wavelength mechanism. The results from these studies have been published\textsuperscript{37,38} or is in press.\textsuperscript{54} Photo-excited carriers have an energy larger than those in thermal equilibrium,\textsuperscript{50} and undergo relaxation processes dominated by optical phonon emission.\textsuperscript{55} However, a phonon-bottleneck,\textsuperscript{51,56,57} slows down the hot-carrier relaxation process. Therefore, the photo-excited carriers will have a transient energy distribution at higher energies compared to that in the thermal equilibrium, leading to a transient elevation of the Fermi level, often referred to as the quasi-equilibrium Fermi level. The energy difference between the quasi-equilibrium Fermi level in the emitter and the height of the emitter-collector barrier thus becomes smaller, reducing the activation energy for holes to pass to the collector. As a result, a
photoresponse can be observed in the extended-wavelength regime, that is, beyond the limit set by the \( \Delta \). The experimental demonstration of the fact that, the \( \Delta \) related to the band gap of a material or an interfacial energy gap of a heterostructure can no longer limit the wavelength threshold of the photoresponse, has offered a novel avenue towards the development of IR photodetectors. A better understanding of the mechanism of the extended-wavelength IR photoresponse, and the effect of the device parameters such as the energy offset and the shape of the potential barriers on the performance of the IR photodetector is crucial towards the advancement of this field.

2.2 Device Parameters for Barrier Offset and Gradient Variation

The p-GaAs/Al\(_{x}\)Ga\(_{1-x}\)As heterostructure devices (LH1002, SP1001, SP1007, 15SP3, GSU17I, GSU17II, GSU17III) were grown on semi-insulating GaAs substrate by molecular beam epitaxy.\(^{43}\) The details of the device LH1002 have been presented in Chapter 1. For all other heterostructure devices, a schematic of the sideview of the heterostructure layers is depicted in Figure 2.1. Each heterostructure device consists of an Al\(_{x}\)Ga\(_{1-x}\)As barrier at the bottom, followed by a p-GaAs emitter, and then another Al\(_{x}\)Ga\(_{1-x}\)As barrier at the top. The bottom Al\(_{x}\)Ga\(_{1-x}\)As barrier is graded by increasing Al mole fraction from a lower value \( x_1 \) at the bottom of this layer to higher value \( x_2 \) at the top, except for SP1001 with \( x_1 = x_2 \) to form a constant barrier. These emitter/barrier layers are sandwiched between the bottom and top contact layers of p-type doped GaAs, with thicknesses of 0.5 \( \mu \)m and 0.2 \( \mu \)m, respectively. The emitter, and the top and bottom contact layers, are degenerately p-type doped at \( 1 \times 10^{19} \) cm\(^{-3} \), whilst the Al\(_{x}\)Ga\(_{1-x}\)As barriers are undoped. The thickness of the p-GaAs emitter in all devices is sufficiently large to have a bulk-like distribution of energy states.\(^{58}\) The emitter thicknesses of 80 nm were chosen to be comparable to the carrier-carrier scattering length \(^{34} \) (~80 nm), which also changes with the doping level, to
Figure 2.1 A schematic diagram of the side view of a processed mesa of p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure-based IR photodetectors. The bottom and top p-GaAs contact layers were doped to $1 \times 10^{19}$ cm$^{-3}$ and have the thicknesses of 0.5 and 0.2 µm, respectively. The bottom and top Al$_x$Ga$_{1-x}$As barrier layers are undoped and have the thicknesses of 80 and 400 nm, respectively. The p-GaAs emitter is 80 nm thick with a $1 \times 10^{19}$ cm$^{-3}$ doping. Mesas were processed by conventional photolithography, wet etching, Ti/Pt/Au metal evaporation, and lift-off. The top p-GaAs contact layer is partially etched to open an optical window for normal incidence illumination. The bottom Al$_x$Ga$_{1-x}$As barrier is constant in SP1001 but it is graded by increasing the Al mol fraction $x$ from the bottom towards the top of this layer in the devices SP1007, 15SP3, GSU17I, GSU17II, GSU17III. The details for all device parameters are presented in Table 2.1.
minimize carrier loss due to the scattering. The IR absorption properties of p-GaAs have been studied in a wide range of doping levels (≈10^{17} to 10^{20} \text{ cm}^{-3}). The doping level also causes a shift in the Fermi level, thus a 1×10^{19} \text{ cm}^{-3} level was chosen to get the Fermi level near valence band edge based on the recommendation from the theoretical study. A schematic of the valence band of the heterostructures is depicted in Figure 2.2 to illustrate the differences in the devices in terms of barrier engineering. The details of each device parameters are summarized in Table 2.1. The device LH1002 serves as a reference IR photodetector due to the absence of an energy offset ($\delta E = 0$) and constant Al_{0.57}Ga_{0.43}As barriers. The device SP1001 consists of an energy offset ($\delta E \sim 0.10 \text{ eV}$) but both the bottom Al_{0.57}Ga_{0.43}As barrier and the top Al_{0.75}Ga_{0.25}As have constant potential profile. Thus, a comparison between the experimental results from LH1002 and SP1001 will highlight the effect of a non-zero barrier offset. The device SP1007 is similar to SP1001 in all aspects, except for the graded bottom barrier, which is achieved by increasing the Al mole fraction from $x_1 = 0.45$ at the bottom of this layer to $x_2 = 0.75$ at the top. This difference between SP1001 and SP1007 allows us to compare the extended-wavelength photoresponse with the shape of Al$_x$Ga$_{1-x}$As barrier as will be seen in section 2.4.2. The study of the intensity and wavelength threshold of extended-wavelength photoresponse on the set of devices with $\delta E$ variation will be presented in the section 2.4.3, and the study on the set of devices with the gradient variation in the section 2.4.5.

The devices SP1007, 15SP3, and GSU17I constitute a set with an increasing energy offset ($\delta E$) between the two Al$_x$Ga$_{1-x}$As barriers. The offset in the three devices SP1007, 15SP3, and GSU17I have the offset values of $\delta E \sim 0.10, 0.19, \text{ and } 0.23 \text{ eV}$, respectively, corresponding to the Al mole fraction of $x_3 (= x_4) = 0.57, 39, \text{ and } 30$, respectively on the Al$_x$Ga$_{1-x}$As barrier. All other parameters have the same values in these three devices.
Figure 2.2 Schematic diagrams of the valence band alignment of the devices under equilibrium: (a) SP1001 consists of a p-GaAs emitter (80 nm), an 80 nm Al$_{0.75}$Ga$_{0.25}$As barrier at the bottom, and a 400 nm Al$_{0.57}$Ga$_{0.43}$As barrier at the top. These layers are sandwiched between highly doped p-GaAs top and bottom contact layers. SP1001 has an energy offset ($\delta E$) of $\sim$0.10 eV between the barriers. (b) In SP1007, 15SP3, GSU17I, GSU17II, and GSU17III, the bottom Al$_x$Ga$_{1-x}$As barrier (80 nm) has a graded potential profile obtained by increasing the Al mole fraction from $x_1$ at the bottom of this layer to $x_2$ at the top. The top Al$_x$Ga$_{1-x}$As barrier (400 nm) has constant barrier potential profile with $x_3 = x_4$. The emitters (80 nm) are thick enough to have a bulk-like distribution of energy states. Changing the $x_3$ causes the $\delta E$ variation and changing the $x_1$ causes the gradient variation, as summarized in Table 2.1. (Reprinted with permission from\textsuperscript{37}. Copyright 2016, SPIE Digital Library).
Table 2.1 Summary of the device parameters. The emitters, and the top and bottom contacts (p-GaAs), are p-type doped at $1 \times 10^{19}$ cm$^{-3}$. The devices with highlighted values of the energy offset and the gradients constitute two sets with a variation of the respective parameters.

<table>
<thead>
<tr>
<th>Device</th>
<th>$\Delta$ (eV)</th>
<th>Energy offset $(\delta E)$ (eV)</th>
<th>Al mole fraction</th>
<th>we (nm)</th>
<th>w1 (nm)</th>
<th>w2 (nm)</th>
<th>Gradient $(kV/cm)$: $(\Delta E_v(x_2) - \Delta E_v(x_1)) / w_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH1002</td>
<td>0.30</td>
<td>0</td>
<td></td>
<td>0.57</td>
<td>0.57</td>
<td>0.57</td>
<td>20</td>
</tr>
<tr>
<td>SP1001</td>
<td>0.40</td>
<td>0.10</td>
<td></td>
<td>0.75</td>
<td>0.75</td>
<td>0.57</td>
<td>80</td>
</tr>
<tr>
<td>SP1007</td>
<td>0.40</td>
<td>0.10</td>
<td></td>
<td>0.45</td>
<td>0.75</td>
<td>0.57</td>
<td>80</td>
</tr>
<tr>
<td>15SP3</td>
<td>0.40</td>
<td>0.19</td>
<td></td>
<td>0.45</td>
<td>0.75</td>
<td>0.39</td>
<td>80</td>
</tr>
<tr>
<td>GSU17I</td>
<td>0.40</td>
<td>0.23</td>
<td></td>
<td>0.45</td>
<td>0.75</td>
<td>0.30</td>
<td>80</td>
</tr>
<tr>
<td>GSU17II</td>
<td>0.40</td>
<td>0.19</td>
<td></td>
<td>0.33</td>
<td>0.75</td>
<td>0.39</td>
<td>80</td>
</tr>
<tr>
<td>GSU17III</td>
<td>0.40</td>
<td>0.19</td>
<td></td>
<td>0.21</td>
<td>0.75</td>
<td>0.39</td>
<td>80</td>
</tr>
</tbody>
</table>
Similarly, 15SP3, GSU17I, and GSU17II constitute another set with varying values of the gradient \( \sim 20.6, 28.9, \) and \( 37.1 \) kV/cm, given by \( \frac{\Delta E_v(x_2) - \Delta E_v(x_1)}{w_1} \) for \( x_1 = 0.45, 0.33, \) and 0.21, respectively. The gradients are the only differences in these three devices. It should be noted that the device 15SP3 is common in both sets with an \( \delta E \sim 0.19 \) eV and gradient 20.6 kV/cm.

The MBE growth and the mesa processing of the devices is similar to the processes explained in Chapter 1.6.1. The packaging (mounting and wire-bonding on a chip carrier) is explained in Appendix A.

2.3 Experimental Measurements

The experimental characterizations of the p-GaAs/Al\(_x\)Ga\(_{1-x}\)As heterostructure devices listed on Table 2.1 (LH1002, SP1001, SP1007, 15SP3, GSU17I, GSU17II, GSU17III) were carried out by following the procedure described in Chapter 1.5. Perkin Elmer system 2000 FTIR spectrometer with Spectrum 5.0 software was used for photoresponse measurements. A bolometer with known sensitivity was to measure the intensity of the spectrum of IR radiation from the built-in IR source in FTIR spectrometer. Vacuum dewar for IR measurements (HD-3 or HD-5, IR Lab Inc.) was used for mounting the detector under test and bolometer. Incoming IR radiation from the IR source in FTIR spectrometer was focused onto the detector under test and bolometer by a Winston cone. The photoresponse spectrum of the bolometer measured under similar optical set up with the detectors under test was used to calibrate the photoresponse of the detectors by following the methods outlined in Chapter 1.5. Current-voltage characteristics under dark conditions were measured by using Keithley 2635B (or Keithley 2400) by mounting the detector onto the sample holder of cold finger of a cryostat. The cold finger was covered with shrouds and pumped to \( \sim 10^{-6} \) Torr and cooled to cryogenic temperatures by an APD HC2 closed-cycle
refrigerator. A DC bias voltage is applied to the detector by the source meter where a positive bias refers to the voltage connected to the top contact electrode of the device under test with the bottom contact grounded and a negative bias refers to the voltage connected to the bottom contact with the top contact being grounded. Dark current-voltage characteristics were measured from 10 K to room temperature with the temperature steps being controlled by a Lakeshore 330 temperature controller.

2.4 Results and Discussion

2.4.1 Dark Current and Photoresponse Characteristics of Device 15SP3

A detailed study of the experimental results of the will be presented to study the extended-wavelength photoresponse mechanism by comparing the experimental results of the devices LH1002, SP1001, SP1007, 15SP3, GSU17I, GSU17II, GSU17III in the next section and onwards. In this section, the device 15SP3 is selected to present its detail device characterizations and results.

Dark current-voltage characteristics of the device 15SP3 is presented in Figure 2.3. An asymmetrical bias dependence of dark current is observed. This asymmetry in can be related to the fact that the p-GaAs/Al_{x}Ga_{1-x}As heterostructure is asymmetrical in nature owing to the graded barrier and an energy offset between the barriers as depicted in its valence band alignment in Figure 2.2 (b). Further detail study of the dark current characteristics with a theoretical model will be presented in Chapter 3. Here, Arrhenius plots obtained from the dark current of the device 15SP3 are presented in Figure 2.4 (a). The method of obtaining the plots are explained in Chapter 1.6.2.
Figure 2.3 Dark current-voltage characteristics (measured with Keithley 2635B source meter) of 15SP3 device. An asymmetrical bias dependence of the dark current is observed owing to the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to graded barrier and barrier energy offset.
Figure 2.4 (a) Arrhenius plots for device 15SP3 obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device 15SP3 obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence is the result of the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier.
**Figure 2.5** A comparison of the dark current density of different mesas. Three mesas showing the dark current curves in solid lines have electrical area of $400 \times 400 \mu\text{m}^2$. The dashed line shows the dark current density of a mesa with an electrical area of $600 \times 600 \mu\text{m}^2$. 
From the plots of \( \ln\left(\frac{I_{\text{dark}}}{T^{3/2}}\right) \) versus \( 100/T \) as shown in Figure 2.4 (a), a linear fit of the plot was used to obtain the slope of the plot shown by the dashed line. Then slope was used to obtain the activation energy \( (\Delta = -\text{slope} \times 100 \times k_B \times 6.242 \times 10^{18} \text{eV}) \) of the device 15SP3 as shown in Figure 2.4 (b). The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence is the result of the asymmetry of the p-GaAs/Al\(_x\)Ga\(_{1-x}\)As heterostructure due to the graded barrier and energy offset of the barrier.

Furthermore, dark current density (current per unit area) of different mesas were compared in order to assess the uniformity between different mesas. A comparison of the dark current density of different mesas is shown in Figure 2.5. Solid lines represent the dark current density of the three mesas with electrical area of \( 400 \times 400 \mu\text{m}^2 \). The dashed line represents the dark current density of a mesa with an electrical area of \( 600 \times 600 \mu\text{m}^2 \). These results show a considerable uniformity of the mesas.

The device operation of spectral photoresponse measurements of a of p-GaAs/Al\(_x\)Ga\(_{1-x}\)As heterostructure IR detector with graded barrier and barrier energy offset under an applied bias voltage is depicted in Figure 2.6 (a). The applied bias causes the barrier bending, whereas the emitter energy band is not affected significantly owing to its high doping level that leads to insignificant voltage drop across it. Arrows show possible optical transitions to S-O band due to the absorption of IR photons that leads to the emission of the photo-excited carriers to the barrier. The partially etched top contact p-GaAs layer also contributes to the photoresponse. The spectral photoresponse of the device 15SP3 measured at 5.3 K with -1 V bias voltage is shown in Figure 2.6 (b). Ten of such photoresponse spectra are plotted on the top of each other. The background
Figure 2.6 (a) A schematic representation of operation of an IR detector with barrier gradient and offset under a negative bias, which causes a barrier bending. Arrows show the possible transitions to S-O band. (b) Spectral responsivity and specific detectivity of 15SP3 measured at 5.3 K with -1 V bias showing extended-wavelength photoresponse to 60.0 ± 0.4 µm. Ten spectra are plotted on the top of each other. Also, ten spectra of the background noise level measured by blocking the IR source are also shown, where the dark solid curve is the average of ten noise spectra. Inset shows the expended view of near threshold spectra to compare with the average noise level.
noise level was also measured by blocking the IR radiation and ten of such background noise spectra are plotted in the Figure 2.6 (b) together with the photoresponse spectra. The dark solid curve represents the average of ten background noise spectra. Inset in Figure 2.6 (b) shows the expanded view of near threshold region of photoresponse showing the comparison of the photoresponse spectra to with the average background noise level. The wavelength at which the photoresponse signal becomes the same as the background noise level is noted to find out the wavelength threshold. The wavelength threshold of the spectral photoresponse by this comparison is found to be 60.0 ± 0.4 µm. In the remaining part of this study, the TDIPS fitting will be used to determine the wavelength threshold of the photoresponse. The specific detectivity was estimated by using \( D^* = \frac{R \sqrt{A}}{2qI_d + \frac{4k_b T}{R_{diff}}} \), and a peak value of \( D^* \) was found to be \( 2.7 \times 10^9 \) Jone near 35 µm.

As discussed before, the primary focus of this study is to understand the extended-wavelength mechanism, a comparative study of the the spectral photoresponse of the different devices will be carried out based on the parameters of the each heterostructure.

2.4.2 *Spectral photoresponse: Non-zero barrier energy offset vs zero barrier energy offset; and the graded barrier vs the constant barrier*

The photoresponse from LH1002 at 5.3K was observed in a spectral regime nearly up to 4.5 µm at -0.2 V, without an indication of extended-wavelength mechanism, as shown in Figure 2.7. This device serves as the reference IR photodetector in terms of barrier energy offset due to the absence of the offset (i.e., \( \delta E = 0 \) eV) and standard (flat band) barriers. A small deviation from the zero-bias wavelength threshold (~4.1 µm), is the effect of the image force barrier lowering due
Figure 2.7 The spectral photoresponse of the device LH1002 (with $\delta E = 0$ eV) was observed only in the MIR region, without an extended-wavelength mechanism. However, the device SP1001 (with $\delta E = 0.10$ eV) showed a photoresponse in VLWIR and FIR region with the wavelength threshold of $50\pm0.3$ $\mu$m (determined from TDIPS method, details in Appendix D), clearly indicating the extended-wavelength mechanism. The device SP1007 ($\delta E = 0.10$ eV) with the graded barrier showed a stronger photoresponse in VLWIR and FIR regime, with the wavelength threshold of $56\pm0.3$ $\mu$m. The features associated with the AlAs-like and GaAs-like phonons are marked by the arrows. Inset shows the photoresponse of LH1002, enlarged to show details, clearly showing no extended wavelength mechanism.
Figure 2.8 TDIPS fitting for the spectral quantum yield of the devices: (a) LH1002, (b) SP1001 and (c) SP1007. The solid line represents the fitted quantum yield near the wavelength threshold region, and the dashed line represents the experimental quantum yield. The wavelength threshold determined by this method for the devices LH1002, SP1001, and SP1007 are 4.50±0.01 µm, 50.0±0.3 µm, and 56.0±0.5 µm respectively (details in Appendix D). The results are summarized in Table 2.2.
to applied bias (similar to the photoresponse at 78 K, Chapter 1.6.2). In contrast, SP1001 with $\delta E \sim 0.10$ eV showed the photoresponse in the VLWIR and FIR regime, up to $\sim 50 \mu$m, at 5.3 K and -0.4 V, clearly indicating the extended-wavelength mechanism. Without an extended-wavelength mechanism, the spectral photoresponse would be limited to MIR regime, corresponding to $\Delta = 0.40$ eV ($\sim 3.1 \mu$m). The striking difference in the spectral range of the photoresponse in the device SP001 as opposed to LH1002 due to the presence of the energy offset in SP1001. Next, the photoresponse of the device SP1007 with the same the same value of the offset ($\delta E \sim 0.10$ eV) but with a graded bottom Al$_x$Ga$_{1-x}$As barrier showed a stronger photoresponse with the extended-wavelength mechanism up to $\sim 56 \mu$m, at 5.3 K with a bias of -0.1 V. Overall, the shape of the photoresponse spectra appear for both SP1001 and SP1007 to be similar, with the differences in only in the intensity, mainly in the FIR spectral regime. Furthermore, the same features associated with AlAs-like and GaAs-like phonons are observed, which are marked by the arrows in the Figure 2.7. The TDIPS fitting applied to determine the wavelength threshold of the spectral quantum yield of the devices LH1002, SP1001, and SP1007 is shown in Figure 2.8.

The results, in general, confirm that the barrier energy offset is a necessary condition for the extended-wavelength mechanism, whilst a graded barrier (SP1007) is found to be related to a higher photoresponse as opposed to a constant barrier (SP1001). The negative bias operation drives the carrier injection from the bottom contact over the bottom barrier to the emitter, and the collection at the top contact. The graded barrier was suggested to be included in the device to improve the performance by reducing the carrier trapping, and hence may be related to what has been observed in the photoresponse of SP1007 compared to SP1001. However, the existence of
similar nature of extended-wavelength mechanism for both SP1001 and SP1007 can be inferred based on the similar spectral shape and extended-wavelength thresholds (compared to the conventional limits ~3.1µm), even though the exact physical processes underlying the mechanism are yet to be fully understood. The detailed bias-dependence spectral photoresponse of SP1007 has been published\textsuperscript{36}, showing that the photoresponse up to FIR regime (~55 µm) due to extended-wavelength mechanism was observed only in a narrow range of applied biases smaller than -0.2 V. For the higher values of the negative applied biases, the spectral photoresponse was observed only in the MIR regime (< 7 µm).

2.4.3 Spectral photoresponse with barrier energy offset variation

It is desirable to find an operating condition for optimized performance of the IR photodetector. One of the improvements needed for optimization is to overcome the limitation of the extended-wavelength mechanism in a narrow region of low applied biases, since the intensity of the photoresponse is usually weak at low biases. Furthermore, a deeper understanding of the extended-wavelength mechanism requires further study of the heterostructure devices to determine the effects of the variation in the device parameters. Since the barrier energy offset is found to be a critical parameter, further study with a change in the value of this parameter is important. Therefore, the next study was carried out in the device 15SP3, which is similar to the SP1007 in all aspects, except with a higher barrier energy offset (δE ~ 0.19 eV) with the Al mole fraction \(x_3\) (\(= x_4\)) = 0.39 in the top Al\(_x\)Ga\(_{1-x}\)As barrier. The spectral photoresponse of the device 15SP3 was observed up to FIR regime, as shown in Figure 2.9, owing to extended-wavelength mechanism. Without the extended-wavelength mechanism, the photoresponse of this device would be limited
Figure 2.9 The spectral photoresponse of the device 15SP3 ($\delta E \sim 0.19$ eV) was observed in the VLWIR and FIR region, up to ~60 µm, due to the extended-wavelength mechanism. Without the extended-wavelength mechanism, the photoresponse would be limited to the MIR region, with $\Delta = 0.40$ eV (~3.1 µm). The wavelength threshold appears to have no significant effect of applied bias, even though the intensity of the photoresponse showed a variation with the applied bias. (Reprinted with permission from\textsuperscript{38}. Copyright 2017, AIP Publishing).
to the MIR regime. In contrast to the device SP1007, the photoresponse due to extended-wavelength mechanism is not limited to a small range of applied biases. Moreover, the wavelength threshold of the spectral photoresponse appears to have no significant variation with the applied biases even though the intensity of the photoresponse showed a variation with the applied biases. In general, shape of the photoresponse spectra in the device 15SP3 is similar to that in the device SP1007, indicating that the nature of the extended-wavelength mechanism has not altered. However, the intensity of the photoresponse is significantly higher in 15SP3 compared to that in SP1007. The improvements can be attributed to the higher barrier energy offset ($\delta E \sim 0.19$ eV) in the device 15SP3, since the offset is the only difference in this device compared to SP1007 ($\delta E \sim 0.10$ eV).

The encouraging results from the device 15SP3 motivated us to take this study a step further by increasing the barrier energy offset. The offset was increased to a further higher value, $\delta E \sim 0.23$ eV, in the design of the next device GSU17I, with the Al mole fraction $x_3 (= x_4) = 0.30$ in the top $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier. It should be noted that the increased barrier energy offset is achieved by lowering the top $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier energy, without any change in the bottom graded $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier. Therefore, the other operating conditions such as carrier injection from the bottom contact over the graded barrier will not be altered. The spectral photoresponse of the device GSU17I is shown in Figure 2.10. The photoresponse was observed in the VLWIR and FIR spectral regime, up to $\sim 61$ µm due to extended-wavelength mechanism. The intensity of the photoresponse was found to increase with the applied bias, but a significant effect was not observed in terms of wavelength threshold. In comparison to the device 15SP3, a higher photoresponse was observed in GSU17I.
Now, the devices SP1007, 15SP3, and GSU17I together constitute a set of detector structures only with increasing barrier energy offset, whilst the rest of the parameters remain unchanged. This means the absorption of the IR radiation in the emitter and carrier injection from the bottom contact would remain essentially the same in all three devices. However, lowering the barrier between the emitter and the top contact will have a higher probability of internal photoemission over the barrier, which will cause the collection at the top contact to be different. Thus, increasing the barrier energy offset also causes the collection efficiency to be higher. A comparison of spectral photoresponse of the devices SP1007, 15SP3, and GSU17I is shown in Figure 2.1. The photoresponse is observed to be increasing as the offset increases, which is equivalent to the lowering of the top Al$_x$Ga$_{1-x}$As barrier. Specifically, nearly an order of magnitude enhancement in the photoresponse can be seen in the device GSU17I (the highest offset) compared to SP1007 (the lowest offset), with the photoresponse of 15SP3 being somewhat smaller than that of GSU17I.

On the other hand, the wavelength threshold is found to be only slightly affected by the change in the barrier energy offset. The TDIPS fitting applied to the spectral quantum yield of the devices SP1007, 15SP3, and GSU17I is shown in inset of Figure 2.11. In addition, the TDIPS fitting for each device was carried out by choosing slightly different ranges of spectrum in the near threshold region (details in Appendix D) in order to evaluate the possible uncertainty in the wavelength threshold. The energy values ($\Delta_{TDIPS}$) corresponding to the wavelength threshold determined by this method for the devices GSU17I, 15SP3, and SP1007 are (0.0203±0.0003) eV, (0.0207±0.0001) eV, and (0.0223±0.0002) eV, respectively, and the corresponding wavelength thresholds are (61.0±0.8) µm, (60.0±0.3) µm, and (56.0±0.5) µm, respectively. The results are also depicted in Figure 2.12 showing the wavelength threshold values against the offset variation. The difference between the $\Delta_{TDIPS}$ values of SP1007 and GSU17I is (0.0020±0.0004) eV.
Figure 2.10 The spectral photoresponse of the device GSU17I ($\delta E \sim 0.19$ eV) was observed in the VLWIR and FIR regime, up to ~61 $\mu$m, due to the extended-wavelength mechanism. Without the extended-wavelength mechanism, the photoresponse would be limited to the MIR region, with $\Delta = 0.40$ eV (~ 3.1 $\mu$m). Similar to 15SP3, the intensity of the photoresponse was found to increase with the applied bias, but a significant effect was not observed in terms of the wavelength threshold.
Figure 2.11 A comparison of the spectral photoresponse of the devices SP1007 ($\delta E \sim 0.10$ eV), 15SP3 ($\delta E \sim 0.19$ eV), and GSU17I ($\delta E \sim 0.23$ eV). The photoresponse is observed to be increasing as the barrier energy offset increases. The photoresponse of the device SP1007 is scaled-up by a factor of two for a better visualization. Inset: TDIPS fitting for the spectral quantum yield of the devices GSU17I, 15SP3, and SP1007. The solid line represents the fitted quantum yield near the wavelength threshold region, and the dashed line represents the experimental quantum yield. The energy values ($\Delta_{TDIPS}$) corresponding to the wavelength threshold determined by this method for the devices GSU17I, 15SP3, and SP1007 are $(0.0203 \pm 0.0003)$ eV, $(0.0207 \pm 0.0001)$ eV, and $(0.0223 \pm 0.0002)$ eV, respectively, and the corresponding wavelength thresholds are $(61.0 \pm 0.8)$ µm, $(60.0 \pm 0.3)$ µm, and $(55.6 \pm 0.5)$ µm, respectively (details in Appendix D). The wavelength threshold is found to be only slightly affected by the changes in the barrier energy offset. The results are summarized in Table 2.2. (Reprinted with permission from^54. Copyright 2018, IEEE).
Figure 2.12 A graphical depiction of the wavelength thresholds of the extended-wavelength photoresponse of the three devices SP1007, 15SP3, and GSU17I (with the increasing barrier energy offset values). The wavelength thresholds are (61.0±0.8) µm, (60.0±0.3) µm, and (55.6±0.5) µm, and the corresponding threshold energy values are (0.0203±0.0003) eV, (0.0207±0.0001) eV, and (0.0223±0.0002) eV, respectively.
By comparison, the barrier energy offset from SP1007 to GSU17I changes by a magnitude of ~0.13 eV >> 0.0020 eV, the corresponding change in the value of ΔTDIPS. Therefore, the effect of the change in the barrier energy offset on the wavelength threshold is found to be insignificant.

These findings have two implications regarding the extended-wavelength mechanism. The first is that the quasi-equilibrium Fermi level, which causes the extended-wavelength photoresponse, is practically unchanged from device to device, irrespective of the barrier energy offset. The second is that the increasing spectral photoresponse with the increasing barrier offset is due to the lowering of the top Al_{x}Ga_{1-x}As barrier and hence higher probability of internal photoemission and escape over the barrier.

It was suggested that the formation of the quasi-equilibrium Fermi level is the result of interaction between hot-carriers, injected from the bottom contact to the emitter, and the cold-carriers in the emitter. To test this idea, incident IR radiation from the FTIR source in the MIR regime was blocked using long-pass cut-on filters with the cut-on wavelengths of \( \lambda_{CO} = 2.4, 3.6, \) and 4.5 \( \mu \)m. The results showed that the VLWIR and FIR photoresponse became weaker with increasing cut-on wavelengths and vanished with \( \lambda_{CO} = 4.5 \) \( \mu \)m. With the \( \lambda_{CO} = 4.5 \) \( \mu \)m filter still in place, the VLWIR and FIR photoresponse was recovered with the exposure of an external MIR source. These results led to the deduction that the hot-carrier injection, with the excitation source with IR radiation of wavelengths shorter that 4.5 \( \mu \)m is needed for a quasi-equilibrium Fermi level to build up in the emitter to enable the VLWIR and FIR photoresponse. However, the origin of the VLWIR and FIR photoresponse without an applied bias (i.e., 0 V) cannot be understood based on this explanation, which will be discussed next.
2.4.4 Extended-wavelength photoresponse at zero bias

In order to understand the extended wavelength mechanism at zero bias, the spectral photoresponse of GSU17I, at 0 V, showing the V LWIR and F IR photoresponse, as shown in Figure 2.13, will be discussed. Note that the hot-carrier injection from the bottom contact to the emitter will not occur at 0 V. As a matter of fact, at 0 V, there will be a net carrier flow from the emitter to the bottom contact, exactly the opposite of the hot-carrier injection. This can be explained based on the barrier collection efficiency, defined as the probability that a carrier travels from the hetero-interface to the barrier maximum \( z_m \) without scattering, given by

\[
\eta_c = \exp(-z_m / L_s),
\]

where \( L_s \) is the carrier scattering length. It should be noted that the IR absorption occurs in the top contact, emitter, and bottom contact simultaneously since all three layers are doped, with the same concentration. Therefore, hot-carrier generation occurs in all three layers. However, the external measurement is carried out between the top and bottom contacts to detect a change in the potential difference, which is the result of a net flow of carriers from the emitter towards either of the contacts. In the absence an external applied bias to drive the carriers, a net carrier flow occurs depending on the difference in the barrier collection efficiency in different directions. In the case of the bottom graded barrier, the \( \eta_c \sim 1 \) for a photo-excited carrier in the emitter since the barrier maximum is near emitter-barrier interface, i.e., \( z_m \sim 0 \) nm (inset in Figure 2.13). However, \( z_m \sim 80 \) nm for a photo-excited carrier in the bottom contact, therefore \( \eta_c \ll 1 \) in this case. This is the basis for the net carrier transport over a graded barrier in the direction of decreasing barrier energy,
Figure 2.13 The photoresponse of device GSU17I without an external applied bias showing the VLWIR and FIR photoresponse due to extended-wavelength mechanism. This photoresponse is due to the net carrier flow from the emitter to the bottom contact. At zero bias, the graded barrier causes net carrier flow as the collection efficiency is higher for carrier flow from the emitter to the bottom contact, compared to that for carrier flow from bottom contact to the emitter. The inset depicts a schematic band-diagram of the device showing the barrier maximum position of the graded barrier \( z_m \) near the emitter/graded barrier interface at 0 V.
Figure 2.14 A comparison of the spectral photoresponse of the device GSU17I at 0 V, -0.2 V, and -0.4 V. The spectral photoresponse at 0 V is from a net carrier flow towards the bottom contact. A small negative bias (-0.2 V) tends to drive the carriers in the opposite direction, thus reducing the photoresponse. At -0.4 V, note that there is a notch in the spectral photoresponse near 2.7 µm, indicating a photocurrent cancellation at this point due to the equal and opposite direction of the photocurrents. For wavelengths < 2.7 µm, the net photocurrent is still directed towards the bottom contact. However, for wavelengths > 2.7 µm, the net photocurrent is directed towards the top contact, which is also evident from the shape change in the spectra beyond ~6 µm compared to that in the case of 0 V and -0.2 V. Further increase in the negative bias overcomes the cancelation and leads to stronger photoresponse towards the top contact, as shown in Figure 2.10.
enabling the 0 V operation of the IR photodetector.\textsuperscript{59,60} Thus, at 0 V, there will be a net hot-carrier flow from the emitter to the bottom contact, which is opposite of the hot-carrier injection.

This fact is further supported by the observed results under low negative biases. For instance, at -0.2 V, the applied bias tends to drive the carrier flow towards the top contact (opposite of the net carrier flow at 0 V), thus reducing the photoresponse as shown in Figure 2.14. At a slightly higher negative bias (-0.4 V) the photoresponse is further reduced. Also, a notch is noticeable near 2.7 µm, which is an indication that photocurrents due to the IR radiation near 2.7 µm are equal in magnitude but opposite in direction, thus causing the cancellation. For wavelengths < 2.7 µm, the net photocurrent is still directed towards the bottom contact. However, for wavelengths > 2.7 µm, the net photocurrent is directed towards the top contact, which is also evident from the spectral shape change beyond ~6 µm at -0.4 V compared to that in the case of 0V and -0.2 V. Further increase in the negative bias overcomes the cancellation and leads to stronger photoresponse towards the top contact, as shown in Figure 2.10.

It is clear at this point that VLWIR and FIR photoresponse is observed even without the hot-carrier injection from the bottom contact to the emitter. In order to understand the precise mechanism, it is important to consider two facts for the experimental results. The first is the disappearance of VLWIR and FIR spectral photoresponse with the use of the long-pass cut-on filters to block the incident IR radiation in the SWIR and MIR regime, mostly in the < 4 µm range, indicating that this regime of IR radiation is a critical requirement. The second is that the variation in the barrier offset energy did not cause any significant alteration in the wavelength threshold, indicating that the quasi-equilibrium Fermi level is built-up at a certain energy level, which remains unchanged from device to device.
Figure 2.15 The spectral photoresponse of the device SP1001 at 0 V, -0.15 V, and -2V. The VLWIR photoresponse was not observed at 0 V due to the absence of directional preference of carrier flow in contrast to the graded barrier devices. But VLWIR photoresponse was observed with the application of external bias to drive the carriers.
These facts lead to a situation where the quasi-equilibrium Fermi level is built up in the S-O band, owing the photo-excitation from L-H/H-H bands to the S-O band. With the $\lambda_{CO} = 4.5 \mu m$ long-pass cut-on filter, the S-O band transition is not possible. Therefore, the quasi-equilibrium Fermi level will not be built-up, hence the VLWIR and FIR spectral photoresponse disappears. However, with the $\lambda_{CO} = 2.4 \mu m$ long-pass cut-on filter, a portion of the incident IR radiation will have enough energy for the S-O band transition, which explains the observation of VLWIR and FIR spectral photoresponse observed with the use of this filter. The S-O band ($= 0.34$ eV) is a fixed energy level, thus the quasi-equilibrium remains unchanged from device to device. Furthermore, the quasi-equilibrium will be built-up not only in the emitter, but also in the bottom and top contact layers as long as there is photo-excitation to the S-O band. The net flow of the photo-excited carriers will determine the spectral photoresponse.

The net flow of the photoexcited carriers at 0 V is seen to be directed from the emitter towards the bottom contact due to the graded barrier. However, the barrier between the emitter and the top contact has a constant potential profile. This means the collection efficiency over the constant barrier will remain the same for carrier flow from the emitter to the top contact and vice-versa. The carrier flow from the emitter to the bottom contact (over the graded barrier) will be compensated by the carrier flow from the top contact towards the emitter (over the constant barrier), thus maintaining the photoresponse signal at 0 V. However, in the case of the device SP1001, absence of the graded barrier will make the net carrier flow unlikely at 0 V. This may be the reason that a VLWIR photoresponse was not observed at 0 V as shown in Figure 2.15. However, the VLWIR photoresponse was observed with the application of external bias to drive the carriers, where the bias also causes the barrier shape change.
It is also important to analyze the physical processes in the presence of a non-zero barrier energy offset ($\delta E > 0$), since the reference device LH1002 with $\delta E = 0$ did not show the V LWIR and FIR spectral photoresponse. As explained before, the barrier energy offset is the energy difference between the bottom and the top barriers. Each of the barrier layers can be considered as an individual resistor connected in series, with the resistance being a function of applied bias (i.e., dynamic resistance) at a given temperature. The differences in the barrier energy will lead to a non-uniform drop of the applied bias among the two barriers, the higher magnitude of voltage dropped being across the higher energy barrier. Thus, the non-uniformity in the applied bias distribution is validated by experimental results.$^{59,61}$ In addition, the dynamic resistance of the high energy barrier decreases with increasing applied field. As the dynamic resistance becomes comparable to that of the low energy barrier, the applied electric field is more uniformly distributed to the low energy barrier, too. This means, when the applied bias is small, it will drop mostly across the higher energy barrier, and will be able drive the carrier flow over it. But the effect of the small applied bias will be much smaller across the low energy barrier. Specifically, in a small bias regime, the applied bias efficiently drives the carrier flow over the high energy barrier to the emitter, but the carrier flow will not occur with the same efficiency from the emitter to the top contact. Therefore, a fraction of a population of photoexcited carriers will be maintained in the emitter, leading to the quasi-equilibrium Fermi level being built-up. As the applied bias is further increased to a magnitude high enough to achieve a more uniform field distribution, the photoexcited carriers in the emitter are easily swept-out, over the top barrier, to be collected at the top contact. Hence, the quasi-equilibrium Fermi level will not be sustained. The disappearance of the V LWIR and FIR spectral photoresponse in SP1007 at the applied biases beyond -0.2 V as reported previously$^{36}$ can be understood in terms of non-uniform field distribution in the low bias regime.
However, with a significant increase in the barrier energy offset (in case of 15SP3 and GSU17I), the difference between the resistances of the two barriers also increases (exponentially, since \( R_0 \sim \exp(\Delta/kT) \), where \( R_0 \) is the resistance at 0 V) significantly. Then, the applied bias of a higher magnitude, compared to that in SP1007, will be needed to approach a uniform field distribution. This explains the VLWIR and FIR spectral photoresponse of the devices 15SP3 and GSU17I at considerably higher biases compared to SP1007.

Finally, in case of the device LH1002, the absence of the barrier energy offset (i.e., \( \delta E = 0 \)), causes a uniform field distribution across the both barriers. Therefore, the photo-excited carriers in the emitter are swept-out over the barrier, to the top contact with negative bias and vice-versa. This will produce the spectral photoresponse in the SWIR and MIR regime. The VLWIR and FIR spectral photoresponse was not observed owing to the absence of the quasi-equilibrium Fermi level.

The implications of these findings will be important towards the future developments of IR photodetectors, especially with the extended-wavelength mechanism. The study can be extended to different types of IR photodetectors such as quantum wells infrared photodetectors (QWIPs) and quantum dots infrared photodetectors (QDIPs). The key to the design of such IR photodetectors is to find a condition that leads to a quasi-equilibrium Fermi level at a certain energy level of photo-excitation.

### 2.4.5 Spectral photoresponse with barrier gradient variation

The set of devices 15SP3, GSU17II, and GSU17III include the gradients of bottom Al\(_x\)Ga\(_{1-x}\)As barrier of \(~20.6\), 28.9, and 37.1 kV/cm respectively. These devices have the same values for the
rest of the parameters, including the barrier energy offset ($\delta E = 0.19$ eV). The spectral photoresponse for the device 15SP3 was already presented in Figure 2.9. Here, the spectral photoresponse of the device GSU17II is presented in Figure 2.16. The extended-wavelength photoresponse is observed in VLWIR and FIR regime with a wavelength threshold of $57\pm0.3$ µm at -1 V, determined from the TDIPS method (details in Appendix D). Similarly, the spectral photoresponse of the device GSU17III is shown in Figure 2.17. The VLWIR and FIR photoresponse is observed with a wavelength threshold of $58\pm0.3$ µm at -1 V. In both GSU17II and GSU17III, the photoresponse increases significantly for -0.8 V to -1 V, but further increased bias of -1.2 V does not show the same effect. The transition from -0.8 V to -1 V (~21 keV/cm for total barrier thickness of 480 nm) may be an indication of approaching a uniform distribution of applied field. In general, due to the increasing barrier gradient, the spectral photoresponse appears to become slightly weaker. A comparison of the spectral photoresponse at -1 V from all three devices is shown in Figure 2.18. It can be seen that the photoresponse in the FIR regime to be slightly reduced with the increasing barrier gradient, whilst the effect is more noticeable in the MIR and LWIR regime. The TDIPS fitting applied to the experimental quantum yield is shown in the inset of Figure 2.18. The energy values ($\Delta_{TDIPS}$) corresponding to the wavelength threshold determined by this method for the devices 15SP3, GSU17II and GSU17III are $(0.0207\pm0.0001)$ eV, $(0.0217\pm0.0001)$ eV, and $(0.0214\pm0.0001)$ eV, respectively, and the corresponding wavelength thresholds are $(60.0\pm0.3)$ µm, $(57.0\pm0.3)$ µm, and $(58.0\pm0.3)$ µm, respectively (details in Appendix D). These results are summarized in Table 2.2. Thus, nearly doubling the barrier gradient from 20.6 to 37.1 kV/cm did not show a significant change in the wavelength threshold. This is further confirmation of the extended-wavelength mechanism originating from the quasi-equilibrium Fermi level at a fixed energy level.
Figure 2.16 The spectral photoresponse of the device GSU17II at 5.3K showing the VLWIR and FIR photoresponse. The wavelength threshold determined by the TDIPS method (details in Appendix D) is 57±0.3 µm at -1 V. The photoresponse is seen to increase significantly from -0.8 V to -1 V. At -1.2 V, the photoresponse in the MIR and LWIR regime increases, but remains fairly the same in the rest of the spectrum.
Figure 2.17 The spectral photoresponse of the device GSU17III showing the VLWIR and FIR photoresponse. The wavelength threshold determined by the TDIPS method (details in Appendix D) is $58 \pm 0.3 \, \mu m$ at -1 V. The photoresponse is seen to increase significantly from -0.8 V to -1 V. At -1.2 V, the photoresponse is only slightly higher compared to -1 V bias voltage.
Figure 2.18 A spectral photoresponse comparison among the devices 15SP3, GSU17II, and GSU17III, with the barrier gradients 20.6, 28.9, and 37.1 kV/cm respectively. The spectral photoresponse in the FIR regime can be seen to be slightly being reduced with the with the increasing barrier gradient, whilst the effect is more noticeable in the MIR and LWIR regime. Inset: The solid line represents the fitted quantum yield near the wavelength threshold region, and the dashed line represents the experimental quantum yield. The energy values (ΔTDIPS) corresponding to the wavelength threshold determined by TDIPS method (details in Appendix D) are found to be (0.0207±0.0001) eV, (0.0217±0.0001) eV, and (0.0214±0.0001) eV respectively, and the corresponding wavelength thresholds are (60.0±0.3) µm, (57.0±0.3) µm, and (58.0±0.3) µm, respectively, for 15SP3, GSU17II, and GSU17III. The results are summarized in Table 2.2. (Reprinted with permission from\textsuperscript{54}. Copyright 2018, IEEE).
Table 2.2 Summary of the results from the TDIPS fitting method with corresponding device parameters.

<table>
<thead>
<tr>
<th>Device</th>
<th>$\Delta$ (eV)</th>
<th>Energy offset ($\delta E$) (eV)</th>
<th>Al mole fraction</th>
<th>Gradient (kV/cm)</th>
<th>$\Delta_{TDIPS}$ (eV)</th>
<th>Wavelength threshold ($\lambda_t$) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LH1002</td>
<td>0.30</td>
<td>0</td>
<td>0.57 0.57 0.57 0</td>
<td>0.2781</td>
<td>±0.0006</td>
<td>4.50±0.01</td>
</tr>
<tr>
<td>SP1001</td>
<td>0.40</td>
<td>0.10</td>
<td>0.75 0.75 0.57 0</td>
<td>0.0248</td>
<td>±0.0001</td>
<td>50.0±0.3</td>
</tr>
<tr>
<td>SP1007</td>
<td>0.40</td>
<td>0.10</td>
<td>0.45 0.75 0.57 20.6</td>
<td>0.0223 ±0.0002</td>
<td>56.0±0.5</td>
<td></td>
</tr>
<tr>
<td>15SP3</td>
<td>0.40</td>
<td>0.19</td>
<td>0.45 0.75 0.39 20.6</td>
<td>0.0207 ±0.0001</td>
<td>60.0±0.3</td>
<td></td>
</tr>
<tr>
<td>GSU17I</td>
<td>0.40</td>
<td>0.23</td>
<td>0.45 0.75 0.30 20.6</td>
<td>0.0203 ±0.0003</td>
<td>61.0±0.8</td>
<td></td>
</tr>
<tr>
<td>GSU17II</td>
<td>0.40</td>
<td>0.19</td>
<td>0.33 0.75 0.39 28.9</td>
<td>0.0217 ±0.0001</td>
<td>57.0±0.3</td>
<td></td>
</tr>
<tr>
<td>GSU17III</td>
<td>0.40</td>
<td>0.19</td>
<td>0.21 0.75 0.39 37.1</td>
<td>0.0214 ±0.0001</td>
<td>58.0±0.3</td>
<td></td>
</tr>
</tbody>
</table>
Although a graded barrier was found to be more favorable than a constant barrier, a sharply steep barrier is seen to be not favorable either, evident from the fact that increasing the barrier gradient from 20.6 to 37.1 kV/cm showed an indication of a deterioration of the spectral photoresponse. If we consider a range of 0 to 40 kV/cm of barrier gradient, a 20 kV/cm or moderately lower barrier gradient may be recommended based on the experimental results.

Additionally, the spectral photoresponse in the LWIR spectral regime, particularly the 4 – 10 µm photoresponse due to H-H/L-H absorption mechanism is observed to become stronger with increasing bias. This is different from the extended-wavelength photoresponse in the FIR regime as the FIR response does not increase in the same proportion as the LWIR response at high biases. Normalized photoresponse of 15SP3 (-0.6 V), GSU17II (-0.8 V), and GSU17III (-0.8 V) compared in Figure 2.19 (a) show similar spectral shape in the H-H/L-H regime (4 – 10 µm). The spectral photoresponse in this spectral regime becomes stronger at higher biases of –1 V for 15SP3 and –1.2 V for GSU17II and GSU17III as shown in Figure 2.19 (b). These three devices have same parameters in the p-GaAs emitter, which can be related to similar mechanism is observed in these three devices. A slightly smaller bias needed for 15SP3 compared to GSU17II and GSU17III may be related to the fact that a lower barrier gradient in 15SP3 requires less amount of applied field to compensate for barrier bending in comparison to higher gradients in GSU17II and GSU17III. Although GSU17II and GSU17III require a slightly higher bias voltage than 15SP3 to observe the similar shape of photoresponse spectrum in 4 – 10 µm regime, all three devices show similar pattern of increasing photoresponse with bias in this spectral range indicating the similarity of the photoresponse mechanism in the 4 – 10 µm spectrum.
Figure 2.19 (a) A comparison of normalized photoresponse in the of 15SP3 (-0.6 V), GSU17II (-0.8 V), and GSU17III (-0.8 V) showing similar spectral shape in the H-H/L-H regime (4 – 10 µm).
(b) The spectral photoresponse becomes stronger at higher biases of −1 V for 15SP3 and -1.2 V GSU17II and GSU17III. Similar mechanism is observed in these three devices, with slightly smaller bias needed for 15SP3 compared to GSU17II and GSU17III.
2.4.6 Effect of temperature on the extended wavelength IR photoresponse

So far, the reported results of the extended-wavelength photoresponse was based on the experimental results at operating temperature of 5.3 K. However, the increased operating temperature was found to affect the extended-wavelength mechanism, as the VLWIR photoresponse became weaker above 5.3 K and disappeared above 30 K.\textsuperscript{36,62} At further higher temperatures in the range of 50 – 100 K, the behavior of the extended-wavelength photoresponse of the device 15SP3 at 0 V is shown in Figure 2.20. The wavelength threshold determined from the TDIPS method (inset in Figure 2.20) were found to be $\sim$11.5 µm at 50 K, and $\sim$7 µm at 77 and 90 K. The photoresponse in the extended-wavelength regime completely disappeared at 100 K, showing the photoresponse only up to $\sim$3 µm, closely agreeing with the designed value of $\Delta \sim$0.40 eV. It should be noted that there will be no image force lowering at 0 V, therefore the photoresponse beyond $\sim$3 µm is considered to be due to the extended-wavelength mechanism.

A deeper understanding of why the increasing temperature causes the extended-wavelength mechanism to become gradually weaker and disappear at a high enough temperature is vital towards further optimization of these IR photodetectors. Additionally, the prospect of utilizing the artificial band-engineering in quantum nano-structures such as QDIPs and QWIPs for achieving extended-wavelength photoresponse, it is imperative to layout the minimum physical conditions that can be found to favor the origin of the mechanism. Thus, it is important to investigate, at least qualitatively, the temperature-dependent dynamics of photo-excited carriers, such as carrier-phonon interaction and its consequences in the extended-wavelength mechanism.
Figure 2.20 Spectral photoresponse of the photodetector 15SP3 at 0 V, in the temperature range 50 – 100K. The extended wavelength threshold was observed to be ~11.5 µm at 50K, and ~7 µm at 77K and 90K. The photoresponse in the extended-wavelength region disappeared at 100K, and the threshold of ~3 µm then closely agrees with the designed value of Δ ~0.40 eV. Inset: TDIPS fittings of the experimental quantum yield spectra to determine the wavelength threshold. (Reprinted with permission from38. Copyright 2017, AIP Publishing).
The carrier-phonon dynamics will be discussed here, in order to set a path forward to design a most promising IR photodetector with extended-wavelength mechanism.

Photo-excitation or application of a strong electric field causes the carriers (electrons, holes, or both) to become ‘hot’ relative to their surroundings. The dominant mechanism of energy-relaxation process (or thermalization) is through longitudinal-optical (LO) phonon emission, even though transverse-optical (TO) phonon emission may follow at a delayed time scale. A high phonon emission rate in the presence of a high hot-carrier population sends the phonon population into a non-equilibrium condition, consequentially slowing down the energy-relaxation of hot-carriers, the effect being referred to as the hot-phonon bottleneck effect. The hot-carrier energy-relaxation rate is very fast in the bulk (3D) material, hence a very short carrier lifetime, for instance, ~1 picosecond in GaAs. Furthermore, the phonon bottleneck effect has been studied in the low dimensional structures, such as in quantum wells (2D), quantum nanowires (1D), and quantum dots (0D).

The reduced dimensionality leads to energy level quantization. This causes an energy mismatch between the LO phonons and the hot-carriers, hence slows down the phonon emission rate. Experimental results demonstrated the hot-carrier cooling slowed down by hundreds of picoseconds in the high carrier density (>10^{18} cm^{-3}) regime in quantum wells. Furthermore, remarkably long carrier lifetimes in quantum dots, in nanosecond-scale, have been recently reported. Besides III-V semiconductors, the phonon-bottleneck effect was found to slow down the hot carrier cooling by three orders of magnitude in the high carrier density regime of ≥6×10^{18} cm^{-3} in lead-iodide perovskites. An obvious advantage of the slower hot-carrier cooling in
optoelectronic devices, such as solar cells, would be an improved carrier extraction increasing the efficiency.\textsuperscript{73}

LO phonon energy ($\hbar \omega_{LO}$) is \(^\sim\)0.036 eV for GaAs.\textsuperscript{74} Their occupation number under equilibrium at a temperature $T$ is given by

$$\langle n_\omega \rangle = \frac{1}{\exp \frac{\hbar \omega_{LO}}{kT} - 1}$$

(2.2)

A temperature-dependence of the occupation number (see Appendix F) shows a dramatic variation from \(^\sim\)0.042 at 100 K to be practically non-existent at 5.3 K. This is a fundamental material property and provides a qualitative indication of how easily the phonon population can become non-equilibrium at very low temperatures such as 5.3 K and hence lead to the phonon bottleneck effect.

Evidently, the phonon bottleneck effect is the underlying reason that the energy-relaxation rate of the photoexcited carriers is slow enough to maintain a quasi-equilibrium Fermi level near the S-O band and enable the extended-wavelength mechanism at very low temperatures. However, the dramatic temperature-dependence of the phonon occupation number may be related to the weakening and subsequent disappearance of the VLWIR photoresponse when temperature is increased above 5.3 K.
2.5 Future Work

Based on the results and discussion in the previous section, two fundamental requirements can be outlined, in order to observe an extended-wavelength photoresponse in an IR photodetector:

1. Carriers should be photo-excited from a low energy level (ground state) to a higher energy state. In future studies, a laser source of suitable wavelength may be the most appropriate option. The process may be referred to as ‘pumping’.

2. A hot-phonon bottleneck effect must be present in order to maintain a quasi-equilibrium Fermi level at the higher energy state.

The first requirement can be met fairly easily, for example, by using an intrinsic III-V semiconductor with a suitable band-gap ($E_g$), such as InAs ($E_g = 0.354$ eV; 3.5 µm). p-type III-V semiconductors may also be used with a suitable S-O band energy. In fact, the p-GaAs has been used exclusively and extensively in this work.

However, the second requirement is more challenging to satisfy, especially when the bulk material is used. The stringent requirement of a very low temperature to achieve a phonon bottleneck effect may not be in the best interest of different applications that use IR photodetector and imaging systems. In general, the operating temperature of the IR photodetectors (photon-detector type) depends on their spectral regime; for example, a LWIR or longer wavelength range requires cooling, typically 77 K or lower. On the other hand, the MIR photodetectors operate at some elevated temperatures of 100 – 200 K, depending on the properties of the absorbing material, and device architecture. Therefore, in order to exploit fully the advantage of wavelength-extension mechanism, a careful choice of device design (bulk versus low dimensional) is necessary. Further
caution is needed to determine the most suitable operating condition for applied bias, in order to avoid sweep-out of the photo-excited carriers in the absorber/emitter before a quasi-equilibrium Fermi level is built-up, but at the same time to be able to observe the spectral photoresponse.

In lieu of these specific requirements to achieve an extended wavelength photoresponse, a particular type of IR photodetector, the quantum dots-in-well\textsuperscript{75,76} (DWELL), appears to be the most attractive detector structure owing to the long carrier lifetime in the QDs and energy level tunability of QWs by changing the thickness. A typical energy diagram of a DWELL is depicted in Figure 2.21. It should be noted that the diagram is a conceptual representation, and the dimensions and the energy levels are schematic depiction. The example presented here is intended to demonstrate the extended-wavelength mechanism in a quantum nanostructure with discrete energy levels that are capable of being changed with the structure parameters. The valence band is depicted, assuming a p-type dopant will be used, even though the conduction band energy levels also exist. The p-type is chosen due to their lower dark current being advantageous for higher operating temperatures.\textsuperscript{76-79} InAs QDs and InGaAs QWs are used to illustrate this proposal. The 6 nm QW width used in the p-type DWELL studied\textsuperscript{13} had two energy levels: HH\textsubscript{1} at \(\sim 0.18\) eV (\(\sim 7\) µm) and HH\textsubscript{2} at \(\sim 0.23\) eV (\(\sim 5.4\) µm) from the QDs ground state. The bound-to quasi-bound transition to HH\textsubscript{2} level showed a strong photoresponse (\(\sim 5.4\) µm) due to higher escape efficiency\textsuperscript{61}. However, due to a lower escape efficiency from the bound HH\textsubscript{1} level, the photoresponse was not observed at 7 µm. Thus, the proposed structure may include a QWs thickness of 6 nm. The laser sources in the mid-infrared, such as a quantum cascade laser\textsuperscript{80} (QCL), or optical parametric sources\textsuperscript{81} can be used for pumping (shown by a dashed arrow in Figure 2.21). The pumping to the HH\textsubscript{1} level with (\(\sim 7\) µm source) can be expected to enable the detection of IR radiation of energies \(\sim 0.05\) eV (\(\sim 25\) µm) due to the HH\textsubscript{1} to HH\textsubscript{2} level transitions.
Figure 2.21 A schematic of a proposed design for the extended-wavelength IR photodetector based on quantum dots-in-a-well (DWell) structure. A laser source can be used for photo-excitation from the ground state energy level in the QDs to an energy level in the QW (shown by a dashed arrow) to form a quasi-equilibrium Fermi level. Then, the background IR radiation can be detected due to transitions from the quasi-equilibrium to higher QW levels (shown by solid arrows). A QW thickness of 6 nm, similar to that reported previously, will have two energy levels: HH$_1$ at $\sim$0.18 eV ($\sim7$ µm) and HH$_2$ at $\sim$0.23 eV ($\sim5.4$ µm) from the QDs ground state. The pumping to the HH$_1$ level with ($\sim7$ µm source) can be expected to enable the detection of IR radiation of energies $\sim$ 0.05 eV ($\sim25$ µm) due to HH$_1$ to HH$_2$ transitions. A high energy (graded) barrier is used to ensure an applied bias will not easily sweep-out carriers from the quasi-equilibrium Fermi level.
These energy levels can also be changed by using different well thicknesses; for instance, reducing the QW thickness will increase the separation between the energy levels. A GaAs barrier is used on the collector side, whilst a graded Al,Ga_{1-x}As high energy barrier is used on the injector side. The commonly used thicknesses for the barriers\textsuperscript{76,77} are in the range of 60 – 80 nm, which can be adopted in this proposed structure as well. A high energy (graded) barrier is used to ensure an applied bias will not easily sweep-out carriers from the quasi-equilibrium Fermi level.

A specific spectral band detection, particularly the 3 – 5 μm detection, may be more challenging due to the fact that the difference between HH\textsubscript{1} and HH\textsubscript{2} energy levels in the InAs/InGaAs/GaAs DWELL structure are not large enough. However, recently reported\textsuperscript{77} results on p-type InAs/GaAs QDIPs showed a weak photoresponse near 2.3 μm due to the ground state to SO band (\sim 0.52 eV) transition. The photoresponse was weak due to the fact that the S-O band lies in the continuum. In order to make the SO level a bound state, the GaAs barrier can be replaced with an AlGaAs (or AlAs) barrier. Then, the energy difference of 0.29 eV (\sim 4.3 μm) between the HH\textsubscript{2} and SO levels can be highly suitable for the 3 – 5 μm band detection. A schematic of a possible DWELL structure for 3 – 5 μm band detection is depicted in Figure 2.2. Pumping to the HH\textsubscript{2} level will require a 5.4 μm laser source. Unlike the IR detection due to SO band transitions by using the bulk (3D) materials, the DWELL structures will have the advantage of long carrier lifetime. Therefore, the phonon bottleneck effect can be expected to be maintained at higher temperatures due to the significantly larger HH\textsubscript{2} energy level (\sim 0.23eV) compared to the InAs LO phonon energy (0.029 eV).
Figure 2.22 A schematic of a quantum dots-in-a-well (DWELL) structure proposed for 3 – 5 µm band IR detection. HH₁ and HH₂ represent the energy levels in the quantum well, whilst HH and SO represent the energy levels on the quantum dots. These energy levels are based on the reported experimentally studies.⁷⁶,⁷⁷ Excitation from HH to HH₂ level can be used to build up a quasi-equilibrium Fermi level at HH₂ level. Then the IR detection in the 3 – 5 µm band may be achieved with an expected peak near 4.3 µm due to the energy difference of ~0.29 eV between HH₂ level (0.23 eV) and SO level (0.52 eV).
There are several advantages of using the DWELL architecture over other possibilities. The energy levels in QWs can be tuned to achieve the most suitable combination of the levels for extended-wavelength mechanism. The highest energy level in the QW can be set to bound or continuum, without altering the ground state QDs levels. Furthermore, the intensity of the external laser used for pumping may also be separately tailored to a high intensity, if necessary, to maintain a high photo-excited carrier population to sustain the phonon bottleneck effect. As a matter of fact, the review of the published reports presented in the previous section strongly indicates that the phonon bottleneck effect is stronger at higher densities of photo-excited carriers. Thus, the ability to tune the pumping separately is also an important feature.

This structure will also benefit from the long carrier lifetime in QDs. The energy gap between the ground state in QDs and an excited state in the QW should be much higher than the LO phonon energy of InAs (~0.029 eV), which can be achieved by choosing a suitable well width. Due to the energy quantization, the energy-relaxation to the ground state will be possible only with multi-phonon emission\textsuperscript{66,76} to match the energy difference, essentially slowing down the relaxation process. Since the pumping can be controlled separately, a high density of photo-excited carriers can be maintained to sustain the phonon bottleneck effect. It should be noted, however, that the photo-excited carriers due to the laser can cause a higher dc current through the device. This can be overcome by using a pulsed laser, and the pulsing frequency being suitably synchronized (possibly in the multiples in terms of numbers) with the read-out frequency of the focal plane arrays.
The DWELL is preferred due to its sensitivity to normal incidence of the IR radiation unlike the n-type QWIPs. Furthermore, in the p-type DWELL, the higher effective mass of the holes compared to the electrons enables densely packed energy levels near continuum, thus a broader spectral response can be observed. The higher effective mass also makes the holes less sensitive to thermionic emission compared to electrons, therefore p-type structure is preferable since a higher operating temperature is also the goal.

Besides the experimental aspects of the design, there will be more questions that need answers, for example, the optimized pumping, optimized barrier height and applied bias to enable measurement of the photoresponse without severe sweep-out, and so on. Furthermore, it may be possible that a high pumping intensity can compensate for the effect of temperature on the phonon bottleneck effect to some extent. Therefore, along with the experimental study, a theoretical study of hot-carrier and phonon dynamics, and carrier transport under applied field non-uniformity across the structure, will be necessary.

2.6 Summary

In this Chapter, a detailed experimental study of extended-wavelength IR photodetectors has been presented. p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure-based IR photodetectors, with non-zero barrier energy offset, were used. The detectors had conventional wavelength thresholds of ~3 µm, corresponding to Δ ~0.4 eV of p-GaAs/Al$_x$Ga$_{1-x}$As heterostructures. However, with a barrier energy offset, an extended-wavelength photoresponse was observed up to ~50 µm (in SP1001, constant barrier device). With the graded barriers and the offset, the extended-wavelength photoresponse was observed with a slightly longer wavelength threshold, 56, 60 and 61 µm (in SP1007, 15SP3, GSU17I, respectively). The wavelength threshold of the extended-wavelength
photoresponse showed a very small variation (~0.002 eV, from 56 µm to 61 µm) whilst the barrier energy offset was changed by ~0.13 eV. Instead, increasing the barrier energy led to increased spectral photoresponse strength. Similarly, increasing the barrier gradient caused no significant change in the wavelength threshold. However, the spectral photoresponse was observed to become weaker. These strongly indicated that the quasi-equilibrium Fermi level is at a fixed level, irrespective of the device parameter: S-O band being the most probable energy level. Analysis of the observed results suggested that the hot-phonon bottleneck is the underlying cause of the extended-wavelength mechanism. An extended-wavelength IR photodetector is proposed, based on DWELL structure, which appears to be the most attractive option due to its flexibility in energy level tuning, and it is relatively easy to achieve and maintain the hot-phonon bottleneck effect. A laser source may be used to photo-excite the carriers and tuning the carrier density with the laser intensity is expected to enhance significantly the extended-wavelength mechanism.
3 DARK CURRENT CHARACTERISTICS OF EXTENDED WAVELENGTH PHOTODETECTORS

3.1 Introduction

The extended-wavelength mechanism enables to overcome the $\Delta$-dependence of the wavelength threshold set by equation 2.1. However, it is also necessary to study the $\Delta$-dependence of the dark current in order to understand fully the advantages of the mechanism. It is clear from the experimental results in the Chapter 2 that the extended-wavelength mechanism is exclusively an IR radiation-induced phenomenon, in particular the IR radiation with enough energy to cause a S-O band transition. Therefore, under the dark conditions, the physical properties of the devices are expected to be unaffected, hence the $\Delta$-dependence of the dark current is expected to agree with the designed value of $\Delta$ for each of the devices. In general, the dark current and the related noise level of a photoconductive IR detector is dependent on the $\Delta$ of the device, in addition to the other physical properties such as mobility, at a given temperature. A relatively smaller $\Delta$ and corresponding longer spectral wavelengths of a photodetectors would inevitably have a higher dark current. Therefore, it is important that the dark current of the device is not significantly compromised due to the extended-wavelength mechanism discussed before.

Two p-GaAs/ Al$_x$Ga$_{1-x}$As heterostructure devices, LH1002 and 15SP3 (details in Table 2.1 in Chapter 2.2), were used for the study. In addition to the spectral photoresponse characteristics, LH1002 also serves as a reference device to study the dark current characteristics, due to its symmetric design in terms of the shape of the Al$_x$Ga$_{1-x}$As barriers and absence of a barrier energy offset. The experimentally measured dark current in the temperature range 10 – 100 K was
compared with the calculated fitting curves at the respective temperatures. The results were published in Journal of Applied Physics\textsuperscript{38}.

### 3.1.1 3D Carrier Drift Model of Dark Current

A 3D carrier drift model,\textsuperscript{44} given by the relation:

\[
I_{\text{dark}} = Aep_{3D}v(F)
\]  \hspace{1cm} (3.1)

Here, \(A\) is the electrically active area of the detector, \(e\) is the electronic charge, \(p_{3D}\) is the thermally-excited carrier (hole) density on the top of the barrier, and \(v(F)\) is the hole drift velocity as function of applied field \(F\). Using \(p_{3D}\) and \(v(F)\) given by\textsuperscript{44}

\[
p_{3D} = 2 \left( \frac{m^*k_B T}{2\pi\hbar^2} \right)^{3/2} \exp \left( - \frac{E_{\text{act}}}{k_B T} \right),
\]  \hspace{1cm} (3.2)

and

\[
v(F) = \frac{\mu F}{1 + \left( \frac{\mu F}{v_{\text{sat}}} \right)^2} \hspace{1cm} (3.3)
\]

eq. (3.1) reduces to the familiar form:\textsuperscript{30,44}

\[
I_{\text{dark}} = Ae \frac{\mu F}{1 + \left( \frac{\mu F}{v_{\text{sat}}} \right)^2} 2 \left( \frac{m^*k_BT}{2\pi\hbar^2} \right)^{3/2} \times \exp \left( - \frac{\Delta - \alpha F - E_f}{k_B T} \right). \hspace{1cm} (3.4)
\]
Here, $E_{act} = \Delta - \alpha F - E_f$ is the activation energy, $\mu$ is the mobility of the holes, $v_{sat}$ is the saturation velocity, $m^*$ is the effective mass, $k_B$ is Boltzmann’s constant, $T$ is temperature, $\hbar$ is the reduced Planck constant, $\alpha$ is a fitting parameter that determines effective barrier lowering due to the applied field, and $E_f$ is the Fermi level. In the p-GaAs layers the mobility of the holes ($\mu_{p-GaAs}$) will be much smaller$^{74}$ due to high carrier-impurity scattering, compared to that in undoped Al$_x$Ga$_{1-x}$As layers ($\mu_{AlGaAs}$). Thus, the effective mobility is equivalent to $\mu_{p-GaAs}$ within an approximation of Matthiessen rule$^{35}$: $\mu \approx \left(1/\mu_{p-GaAs} + 1/\mu_{AlGaAs}\right)^{-1}$. For degenerately doped p-GaAs, $E_f$ is given by$^{35}$

$$E_V - E_f = k_B T \left[ \ln \left( \frac{p}{N_V} \right) + 2^{-3/2} \left( \frac{p}{N_V} \right) \right],$$

(3.5)

where $E_V$ is the energy at the valence band-edge, $p$ is the doping density, and $N_V$ is the density of states in the valence band given by$^{35}$

$$N_V = 2 \left( \frac{2\pi m_{dh} k_B T}{\hbar^2} \right)^{3/2}.$$

(3.6)

By substituting $k_B$, $m_{dh}$ (the density-of-state effective mass for holes), and $\hbar$ (Planck constant), equation (3.6) reduces (for Al$_x$Ga$_{1-x}$As, $x<0.4$) to$^{82}$

$$N_V = 4.82 \times 10^{15} T^{3/2} (0.51 + 0.25 x)^{3/2} \left( \text{cm}^{-3} \right).$$

(3.7)
Since both structures (LH1002 and 15SP3) consist of p-GaAs doped to the same level, the same values of $\mu$ and $v_{sat}$ were used at a given temperature. At a doping density of $1\times10^{19}$ cm$^{-3}$, $\mu \sim 50$ cm$^2$/Vs at room temperature, and an empirical temperature dependence is given\textsuperscript{74} as:

$$\mu(T) = \left[2.5\times10^{-5} \left(\frac{T}{300}\right)^{2.3} + 4\times10^{-21} p \left(\frac{300}{T}\right)^{1.5}\right]^{-1} \text{ (cm}^2\text{/Vs).} \quad (3.8)$$

Similarly, $v_{sat} \sim 10^7$ cm/s at room temperature, and an empirical temperature dependence is given\textsuperscript{83} as:

$$v_{sat}(T) = \frac{v_{sat,300K}}{(1 - A) + A \frac{T}{300}} \text{ (cm/s),} \quad (3.9)$$

with $A = 0.59$ for p-GaAs.\textsuperscript{83} Finally, $\alpha$ is the parameter used to obtain the fitting of the dark current curves at each temperature.

### 3.2 Results and Discussion

The measured dark current of the photodetector LH1002 is shown in Figure 3.1, represented by the dashed lines, and the fittings obtained for the model are represented by the solid lines in the temperature range of 10 – 100K. The inset in Figure 3.1 shows the fitting parameter $\alpha$. A constant value of the parameter $\alpha$ ($\sim 18$ nm) was used to fit the dark current for a HEWIP device\textsuperscript{30} that operated in a very small range of applied electric field ($<1$ kV/cm). However, the devices used in this study operate at 10-100 times higher applied electric fields. Therefore a variation in the value of $\alpha$ was needed to fit the dark currents, particularly at low temperatures and biases. Noticeably, the parameter $\alpha$ had a constant value ($\sim 8$ nm) with the bias at 100 K.
Figure 3.1 Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for LH1002 (inset shows the bias variation fitting parameter $\alpha$). The dark current curves and the fitting parameters are symmetrical due to the symmetrical design of the device. (Reprinted with permission from\textsuperscript{38}. Copyright 2017, AIP Publishing).
The value of the $\Delta = 0.30$ eV was used for the fitting. The fitted dark current curves are found to agree closely with the experimental curves, but a deviation is observed in the small applied biases and more importantly, at lower temperatures. The dc resistance of a semiconductor is dynamic in nature: it changes with the applied bias, and also with the temperature. Thus, the dynamic resistance keeps increasing as the temperature is decreased. But at a constant temperature, it decreases with increasing applied bias, the maximum value being observed as the applied bias approaches 0 V. However, the maximum value of the dynamic resistance cannot keep increasing to become an infinitely high value: there will be a limit on the maximum value of the dynamic resistance of a semiconductor device. At low enough temperature and applied bias, the dynamic resistance approaches its maximum value, hence by further lowering the temperature and/or applied bias will have less effect on the dynamic resistance. This causes the deviation of experimental dark current from the fitted one, since the fittings are based on the assumption that the physical property (for example, the dynamic resistance) of the device uniformly varies at all temperatures and applied biases. In general, the deviation in the shape of dark current curves at the low temperatures and specifically at low biases are commonly observed in the published experimental results.\textsuperscript{84-87}

The experimentally measured dark current curves agreed closely with the fitted curves, for the device 15SP3 as well, as seen in Figure 3.2. The inset in the Figure 3.2 shows the fitting parameter $\alpha$. However, the deviation at low applied biases and low temperatures are observed, similar to the device LH1002. Therefore, this behavior is not related to specific design conditions, such as barrier energy offset or graded barrier. However, the effect of the graded barrier is
manifested in the asymmetrical bias-dependent shape of the dark current curves. The activation energy $\Delta = 0.40$ eV was used for the fittings. The results strongly suggest that the dark current

Figure 3.2 Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for 15SP3 (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device. (Reprinted with permission from$^{38}$. Copyright 2017, AIP Publishing).
**Figure 3.3** Spectral photoresponse of 15SP2 and LH1002 as a function of wavelength. At 50K, a wavelength threshold of ~5.5 µm and dark current value ~2×10⁻⁹ A (Inset) were observed in LH1002 at -1.5 V. The extended wavelength threshold of 15SP3 at -1 V is significantly longer, up to ~13.5 µm, but the dark current at this bias is still similar to the dark current in the LH1002 (the dark current at the respective biases are marked by arrows). (Reprinted with permission from 38. Copyright 2017, AIP Publishing).
levels are always determined by the $\Delta$ corresponding to the heterojunction parameters, even though the photoresponse characteristics at particular temperatures defy the limit set by $\Delta$ due to extended-wavelength mechanism. Thus, the dark current was not found to be compromised in the IR photodetector with the extended-wavelength mechanism.

In order to further illustrate the dark current advantage of the IR photodetector with the extended-wavelength mechanism, the photoresponse of LH1002 (without the offset) and 15SP3 (with offset) at 50K are shown at biases of -1.5 V and -1V, respectively in Figure 3.3. At these biases, the dark currents of the two detectors are close to each other ($\sim 2 \times 10^{-9}$ A, as indicated by the arrows in the Inset). However, the photoresponse of 15SP3, with the wavelength threshold extension, is observed up to $\sim 13.5$ $\mu$m, which is significantly longer compared to the wavelength threshold of $\sim 5.5$ $\mu$m for LH1002. It should be noted that there is a small increase in the wavelength threshold of LH1002, compared to its designed value, due to image force effects. The importance of the wavelength threshold extension mechanism is thus clearly illustrated, with its application for future IR photodetector design and development.

Furthermore, the experimentally measured dark current of other devices (SP1001, SP1007, GSU17I, GSU17II, and GSU17III) were also fitted following the same process. It should be noted that the designed value of the $\Delta$ had the same value ($\sim 0.4$ eV) as in the case of 15SP3. Therefore, $\Delta \sim 0.4$ eV was used in the fitting of the dark current of these devices. In addition, Arrhenius plots were used to obtain activation energy of these devices. The dark current fittings of the devices SP1001, SP1007, GSU17I, GSU17II, and GSU17III are shown in Figure 3.4, 3.6, 3.8, 3.10, and 3.12 respectively. Similarly, the Arrhenius plots and the activation energy of the devices SP1001, SP1007, GSU17I, GSU17II, and GSU17III are shown in Figure 3.5, 3.7, 3.9, 3.11, and 3.13 respectively.
Figure 3.4 Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for SP1001 (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.
Figure 3.5 (a) Arrhenius plots for device SP1001 obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device SP1001 obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier.
Figure 3.6 Experimentally measured (with Keithley 2635B source meter) and fitted dark current curves in the temperature range 10 – 100K for SP1007 (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.
Figure 3.7 (a) Arrhenius plots for device SP1007 obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device SP1007 obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier.
Figure 3.8 Experimentally (with Keithley 2400 source meter) measured and fitted dark current curves in the temperature range 10 – 100K for GSU17I (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.
Figure 3.9 (a) Arrhenius plots for device GSU17I obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device GSU17I obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier.
Figure 3.10 Experimentally measured (with Keithley 2400 source meter) and fitted dark current curves in the temperature range 10 – 100K for GSU17II (inset shows the bias variation of fitting parameter $\alpha$). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.
Figure 3.11 (a) Arrhenius plots for device GSU17II obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device GSU17II obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure due to the graded barrier and energy offset of the barrier.
Figure 3.12 Experimentally measured (with Keithley 2400 source meter) and fitted dark current curves in the temperature range 10 – 100K for GSU17III (inset shows the bias variation of fitting parameter α). The dark current curves and the fitting parameters are asymmetrical due to the asymmetrical design of the device.
Figure 3.13 (a) Arrhenius plots for device GSU17III obtained from the dark current measurements. The dashed line represents the linear fit applied to the Arrhenius plot in order to obtain the slope of the plot. (b) The activation energy of the device GSU17III obtained from the slope of Arrhenius plots. The activation energy decreases with the increasing bias voltage due to image force lowering of the barrier height. The asymmetrical bias dependence of activation energy is the result of the asymmetry of the p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As heterostructure due to the graded barrier and energy offset of the barrier.
3.3 Summary

The study of the dark current characteristics of the p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure-based IR photodetectors confirmed that the dark current is not compromised due to the presence of the extended-wavelength mechanism of photoresponse. Both in a reference device (LH1002) and an extended-wavelength IR photodetector, the experimentally measured dark current closely agreed with the dark current fittings obtained by using a 3D carrier drift model. These results supported the fact that the extended-wavelength mechanism of IR photoresponse is an exclusively IR radiation induced phenomenon, and hence the physical properties under dark are not affected by this phenomenon. These findings are important for further development of IR detectors based on the extended-wavelength mechanism. These results could be beneficial in developing different types of optoelectronic devices in the future.
4 P-TYPE GAAS/ALGAAS MID-INFRARED PHOTODETECTOR WITH A CURRENT BLOCKING BARRIER

4.1 Introduction

In a number of recent publications, a significant interest has seen in the area of IR photodetectors incorporating current blocking structures into detector architectures into detector designs.\textsuperscript{86-100} For example, AlGaAs current blocking layers have been utilized in QDIPs in order to enhance performance,\textsuperscript{88-93} and also achieve elevated operating temperatures.\textsuperscript{94-96} Similarly, in type II InAs/GaSb superlattice (T2SL) IR photodetectors, majority carrier (hole) blocking layers were implemented.\textsuperscript{97} In complementary barrier infrared detectors (CBIRD)\textsuperscript{98} and p-type-intrinsic-n-type (PbIbN) photodiodes,\textsuperscript{99} electron blocking\textsuperscript{96} and hole blocking\textsuperscript{97} unipolar barriers were incorporated. Furthermore, dark current suppressing structures were demonstrated, such as conduction band barriers in nBn photodetectors\textsuperscript{100,101} and XBn barrier photodetectors.\textsuperscript{102} In general, the important goal in these device architectures is to lower the dark current, but with a relatively small compromise to the photoresponse, enabling a significant improvement in the specific detectivity ($D^*$).

In addition to the mature growth and established processing technology for p-GaAs/Al\textsubscript{x}Ga\textsubscript{1-x}As materials systems, S-O band and L-H/H-H IVB transitions in the p-GaAs spanning the MIR spectral regime makes this material system attractive for the MIR photo-detection. Moreover, by including a graded Al\textsubscript{x}Ga\textsubscript{1-x}As barrier, the IR photodetector is capable of operation in photovoltaic mode (i.e., at 0 V) as discussed in Chapter 2.4.2. The photovoltaic operation is significantly advantageous over photoconductive operation due to its thermal noise limited performance and reduced power consumption. Additionally, a current blocking barrier (CBB)
further reduces the dark current under photoconductive operation and increases the resistance-area product \( (R_0A, R_0 \text{ is the resistance at } 0 \text{ V and } A \text{ is the electrical area}) \) under photovoltaic operation. In this chapter, a 30-period p-GaAs/ Al\(_{x}\)Ga\(_{1-x}\)As heterojunction IR photodetector with graded barriers and a CBB, will be presented. This detector shows a full-width half-maximum (FWHM) spectral photoresponse in the range of \(~2–6 \mu\text{m}\) under photovoltaic operation. The CBB was found to increase the \( R_0A \) by approximately five orders of magnitude, resulting in a two orders of magnitude enhancement in \( D^* \). The responsivity with the CBB was compromised, but only by a factor of \(~1.5\) compared to that without the CBB.

### 4.2 Device Parameters and Measurements

#### 4.2.1 A 30 period, three terminal, p-GaAs/ Al\(_{x}\)Ga\(_{1-x}\)As heterostructure with a current blocking barrier

A p-GaAs/Al\(_{x}\)Ga\(_{1-x}\)As heterostructure IR detector was grown on a semi-insulating GaAs substrate by molecular beam epitaxy. A schematic of the side view of the heterostructure is depicted in Figure 4.1 (a), and a top view optical image is shown in Figure 4.1 (b). The active region of the photodetector consists of 30 periods of a 20 nm p-GaAs emitter and 60 nm graded Al\(_{x}\)Ga\(_{1-x}\)As barrier layer, sandwiched between highly doped p-GaAs contact layers. The p-GaAs emitters are doped at \( 1\times10^{19} \text{ cm}^{-3} \) throughout, whereas all Al\(_{x}\)Ga\(_{1-x}\)As barriers are undoped. A 60 nm graded Al\(_{x}\)Ga\(_{1-x}\)As CBB layer, followed by another p-GaAs contact layer, were then grown on top of the active region. As a result, there are three p-GaAs contact layers - the top (T), middle (M) and bottom (B) contacts, with thicknesses of 0.2 \( \mu\text{m} \), 0.5 \( \mu\text{m} \), and 0.7 \( \mu\text{m} \) respectively. Measurements across the top and bottom (T-B) contacts include the CBB, whilst the middle and bottom (M-B) contacts measure the same mesa without the CBB, as shown in the schematic.
Figure 4.1 (a) Schematic side view of the of the p-GaAs/Al_{x}Ga_{1-x}As heterostructure, including the current blocking barrier (CBB). The top (T) and bottom (B) contacts are used to measure with the CBB, and the middle (M) and bottom contacts can be used to measure the same mesa without it. (b) Top view optical image of the detector mesa showing the lateral dimensions of the top contact (400 µm × 400 µm) and middle contact (570 µm × 570 µm), with the optical window (260 µm × 260 µm) at the center. (Reprinted with permission from^{59}. Copyright 2016, AIP Publishing).
Figure 4.2 (a) Schematic of the valence band alignment of the heterostructure under equilibrium showing the connections with the CBB and without the CBB. The Al$_x$Ga$_{1-x}$As barriers are graded by tuning the Al mole fraction, $x$. (b) A schematic of the valence band of the GaAs near $k = 0$, showing some of the possible hole transitions from light hole/heavy hole to split-off bands, and also from the heavy hole to light hole band. The emitters are thick enough for bulk-like distribution of the density of states of carriers. (Reprinted with permission from$^{59}$. Copyright 2016, AIP Publishing).
The Al$_x$Ga$_{1-x}$As barriers are intentionally graded to create an asymmetry, by tuning $x$, from $x_1 = 0.03$ at the bottom to $x_2 = 0.50$ at the top of each barrier. As a result, a potential gradient is built-up across the barrier. The valence band offsets at the p-GaAs/Al$_x$Ga$_{1-x}$As interface are ~ 0.017 eV, and ~ 0.28 eV for $x = 0.03$ and $x = 0.50$, respectively. This leads to an average potential gradient of ~ 44 kV/cm across each Al$_x$Ga$_{1-x}$As barrier. Similarly, the Al$_x$Ga$_{1-x}$As CBB was graded by tuning $x$, from $x_1 = 0.53$ at the bottom to $x_2 = 1$ at the top, with valence band offsets of ~ 0.29 eV and ~ 0.55 eV, respectively, so that the potential gradient across it is also ~ 44 kV/cm.
4.3 Results and Discussion

4.3.1 Dark current and the Resistance-area product

The dark current-voltage characteristics measured at 77 K across top-bottom, middle-bottom and top-middle contacts are presented in Figure 4.3. Positive bias across top-bottom contacts is defined as the voltage connected to the top contact, with the bottom contact grounded. Similarly, in the middle-bottom contacts measurements, voltage is connected to middle contact and the bottom contact is grounded, leaving the top contact open. In the measurements across the top-middle contacts, the voltage is connected to the top contact and middle contact is grounded, leaving the bottom contact open. The asymmetrical bias dependence of the dark current densities is a result of the asymmetrical barrier structure.

We found that the CBB lowers the dark current density by as much as five orders of magnitude at low biases, with the difference becoming smaller as the bias increases. The differential resistance-area product \((R_0A)\) at zero bias with the CBB had a value of \(\sim 7.2 \times 10^8 \ \Omega \text{cm}^2\), compared to a value of \(1.6 \times 10^9 \ \Omega \text{cm}^2\) obtained without the CBB. The dark current measured across top-middle contacts is similar to that measured across top-bottom contacts in the bias region \(< 1.4 \text{ V}\). At low biases, the dc voltage is dropped across the different elements of the device in proportion to their dc resistances.\(^6\) Therefore, most of the applied voltage will be dropped across the CBB, which has a high resistance compared to the rest of the device. For biases > 1.4 \text{ V}, the dark current measured across the top-bottom contacts deviates from that across the top-middle contacts, indicating redistribution of the applied voltage across the whole structure (i.e. across top-bottom), hence the dark current does not increase monotonically across top-bottom contacts, in contrast to that across top-middle contacts. Similar behavior is observed in negative bias higher than 0.3 \text{ V}.
Figure 4.3 The dark current density of the detector with CBB (T-B) is five orders of magnitude smaller at low bias, than without the CBB (M-B). The difference becomes smaller as the bias increases. The dark current across the top and middle (T-M) contacts is similar to that across T-B contacts in the low bias region. (Reprinted with permission from 59. Copyright 2016, AIP Publishing).
4.3.2 Spectral photoresponse and specific detectivity

The spectral responsivity measured from the same mesa both with and without the CBB, is shown in Figure 4.4. The 0.34 eV separation of the S-O band from the L-H/H-H band limits the spectral photoresponse due to the L-H/H-H to S-O bands IVB transitions to ~ 3.6 µm. The spectral photoresponse beyond 3.6 µm is due to the H-H and L-H band IVB transitions. As a result, two distinct photoresponse peaks are observed at 2.7 µm and 5.0 µm with responsivities of 0.67 mA/W and 0.38 mA/W, respectively, in the measurements without the CBB. The FWHM (i.e., 50% cut-off levels from these peaks) encompasses a ~ 2 – 6 µm spectral range. With inclusion of the CBB, the measured responsivity of 0.47 mA/W at 2.7 µm is reduced by only a factor of ~ 1.5 from that obtained without the CBB.

Specific detectivity ($D^*$) under dark condition was obtained using:

$$D^* = R_i \sqrt{\frac{R_i A}{kT}}$$  \hspace{1cm} (4.1)

where $R_i$ (A/W) is the spectral responsivity, $k$ is the Boltzmann constant, $T$ is the temperature, and $A$ (cm$^2$) is the electrically active area of the detector (400 µm × 400 µm with the CBB, and 570 µm × 570 µm without the CBB). $D^*$ was found to be ~ 1.9×10$^{11}$ Jones at 2.7 µm for the detector with the CBB, and ~ 4.1×10$^8$ Jones without the CBB. A two orders of magnitude higher $D^*$ is therefore obtained with the CBB at zero bias as shown in Figure 4.5. Clearly, the significant enhancement in the $D^*$ is achieved with the high valued of $R_0A$ due to the CBB in spite of a small compromise in the spectral responsivity.
Figure 4.4 Comparison of the responsivity of the detector showing that the responsivity with the CBB is ~ 1.5 times smaller at zero bias, than without the CBB. For the wavelengths \( \leq 2 \, \mu m \), the energy of photoexcited carriers (\( \geq 0.6 \, eV \)) is much larger than the CBB height (~0.55 eV) and is a possible reason that the photoresponse is nearly the same in both cases for wavelengths \( \leq 2 \, \mu m \).

(Reprinted with permission from\textsuperscript{59}. Copyright 2016, AIP Publishing).
Figure 4.5 Specific detectivity $D^*$ showing two orders of magnitude higher detectivity with the CBB, owing to the higher $R \rho A$ despite a small reduction in the photoresponse. (Reprinted with permission from\textsuperscript{59}. Copyright 2016, AIP Publishing).
In addition to the measurements at 0 V bias, the photoresponse was measured in the photoconductive mode as well, with the CBB and without it. The photoresponse increased slightly with the bias increasing in small steps of 0.2 V as shown in the Figure 4.6 (a) and (b). The bias-dependence of the peak spectral photoresponse (at 2.7 µm) is shown in Figure 4.7 (a), which depicts increasing photoresponse with the bias. The effect of applied bias is seen to be more noticeable at the higher bias region in both cases, that is, with the CBB and without it. The specific detectivity ($D^*$) under photoconductive operation was obtained by using

$$D^* = \frac{R_i}{\sqrt{2qJ + \frac{4kT}{R_{diff}A}}},$$

where $R_{diff}$ is the differential resistance, $q$ is electronic charge, $J$ is dark current density, and the other symbols have the same meaning as before. The specific detectivity with and without the CBB are shown in Figure 4.7 (b). The results show that the specific detectivity (at 2.7 µm) has a maximum value at 0 V and decreases with the increasing applied bias. This effect is observed to be stronger at lower biases for the measurements with the CBB. At higher biases, the difference in the specific detectivity with and without the CBB appears to be small (less than one order of magnitude). The reason for the decreasing specific detectivity is that the dark current keeps increasing significantly with increasing bias, whilst the photoresponse increases by a much smaller magnitude. Therefore, the photovoltaic operation is advantageous over the photoconductive operation. Since the photovoltaic operation is enabled by the utilization of the graded barriers, they are also the crucial elements of the heterostructure device architecture.
Figure 4.6 (a) The spectral photoresponse measure with the applied bias increasing with the step size of 0.2 V, across the middle and bottom contacts, that is, without the CBB. (b) The spectral photoresponse measured across top and bottom contacts, that is, with the CBB. The photoresponse is seen increasing with the application of bias, the effect being slightly stronger in the case of without the CBB.
Figure 4.7 (a) Peak spectral responsivity (at 2.7 μm) from the measurements with the CBB (top-bottom) and without the CBB (middle-bottom). The applied biases caused a slight increment in the photoresponse, the effect is more noticeable in the measurement without the CBB. (b) The specific detectivity ($D^*$) was observed to be maximum at zero bias and it decreased with the application of bias, thus making the photovoltaic operation more attractive over the photoconductive operation.
One obvious curiosity is whether the presence of CBB impairs the carrier injection under photovoltaic operation. In order to test its effect, we carried out photoresponse measurements in selective spectral ranges, using long-pass optical filters with characteristic cut-on wavelengths ($\lambda_{CO}$) to block the portion of the incident IR light with wavelengths shorter than the $\lambda_{CO}$. In absence of any optical filters, a spectral photoresponse up to $\sim 2.4 \ \mu m$ was observed across the top-middle contacts (i.e., across the CBB), closely agreeing with $\Delta = 0.55$ eV for the CBB. This photoresponse disappeared (Figure 4.8) when an optical filter with $\lambda_{CO} = 2.4 \ \mu m$ was introduced on the IR light path (Appendix C). These results strongly suggest that an IR radiation of wavelengths shorter than 2.4 μm is needed if the injection of carriers over the CBB through photoexcitation has to occur.

The process occurring due to IR absorption may be referred to as active injection. Next, the spectral photoresponse (after the correction for the transmission of the cut-on filters) with the CBB, and also without it, is shown in Figure 4.9 (a) and (b), respectively. Clearly, the photoresponse was unaltered in the spectral range longer than $\lambda_{CO}$, with or without the optical filters ($\lambda_{CO} = 2.4 \ \mu m$ and 4.5 μm).

The observation, that disabling the active injection of photo-excited carriers from the top contact to the middle contact (using the optical filters) did not affect the photoresponse of the detector with the CBB in the longer than $\lambda_{CO}$ range suggests that there must be an alternative carrier injection mechanism. In Ref 93, carriers were injected from a quantum well reservoir to an active region comprising quantum dots by tunneling through a blocking barrier. However, the bulk-like distribution of energy states, and rather a thick CBB in our device rule out the possibility of hole injection through tunneling. Since an external electric field is not applied, thermal-assisted or photon-assisted tunneling processes are also unlikely to contribute to hole injection through the CBB to the middle contact. Instead, thermionic emission of holes over the CBB is most likely to
Figure 4.8 The photoresponse measured across top and middle contact, was disabled by the optical filter with $\lambda_{\text{CO}} = 2.4 \ \mu\text{m}$. (Reprinted with permission from\textsuperscript{59}. Copyright 2016, AIP Publishing).
Figure 4.9 Optical filters of cut-on wavelengths of $\lambda_{CO} = 2.4 \, \mu\text{m}$ and $4.5 \, \mu\text{m}$ did not show any effect on the photoresponse in the spectral range longer than $\lambda_{CO}$, in the measurements – (a) with the CBB, and (b) without the CBB.
refill the middle contact. Under IR illumination, the middle contact is depleted of holes due to a net flow of the photo-excited holes towards the bottom contact, leading to eventual collection at the bottom contact. As a result, an electric field builds up across the CBB, acting like an internal field. Then, a net carrier transport towards the middle contact through a thermionic process is possible, thereby refilling the middle contact. The process may be referred to as a passive injection.

4.3.3 Effect of temperature on the spectral photoresponse

The photoresponse characteristics presented so far were measured at 77 K. However, it is always preferable to find a higher operating temperature. To find the temperature dependent photoresponse, the measurements were carried out at increased temperatures up to 200 K. The spectral photoresponse is shown in Figure 4.10 at temperatures 120 K, 130 K, 140 K, and 200 K in addition to the photoresponse at 77 K. The photoresponse is seen to be reduced by more than an order of magnitude from 77 K to 120 K, and it becomes weaker at 140 K. At 140 K, the photoresponse beyond ~2.5 µm is seen to be deteriorated more dramatically, showing only a very weak and noisy signal in this spectral range. However, the photoresponse up to ~2.5 µm was observed up at 200 K. This wavelength threshold is close to the barrier energy ~0.55 eV of the CBB, and hence similar to the photoresponse measured only across the CBB.

These results indicate that the increasing temperature affects the photoresponse in one spectral regime more than in the other. One possible reason is that the carriers that are photo-excited due to longer wavelength IR radiation have relatively low energy, thus the carrier transport becomes less efficient due to increased carrier-phonon scattering with temperature. A rather thick middle contact (p-GaAs, 500 nm) was suspected to compound the effect at the increasing
The spectral photoresponse at temperatures 77 K, 120 K, 130 K, 140 K, and 200 K. The photoresponse is seen to be reduced by an order of magnitude from 77 K to 120 K and becomes more at 130 K. At 140 K, the photoresponse beyond ~2.5 µm is seen to be deteriorated more dramatically, showing only a very weak and noisy signal in this spectral range. The spectral photoresponse up to ~2.5 µm was observed at 200 K.
temperatures. In order to test the effect of this thick middle contact, another device with a reduced thickness was designed and tested, which will be described in the following section.

4.3.4 A single-period, two-terminal p-GaAs/Al₅Ga₁₋₅As heterostructure with a current blocking barrier (Modified CBB device)

In the previous study, the three-terminal device was used to test the effect of the CBB on the performance on the same mesa, with and without the CBB. Since the effect has been demonstrated as seen from the results presented in the previous sections, the new device was designed to carry out the measurements only across the top and bottom contacts. Therefore, the middle contact was replaced by a 20 nm p-GaAs as a buffer layer. A schematic of valence band diagram of the modified CBB device is shown in in Figure 4.11 (a), and Figure 4.11 (b) shows the dark current density of the device. As shown in Figure 4.11 (a), a single-period emitter-barrier active region was used instead of the 30-periods used in the previous CBB device. The CBB parameters were unchanged, whilst the average Al mole fraction in the lower AlₓGa₁₋ₓAs graded barrier was slightly higher, from \( x₁ = 0.12 \) at the bottom to \( x₂ = 0.53 \) to achieve a slightly shorter wavelength threshold. Due to this modification, together with the removal of the 500 nm thick middle contact, the modified CBB device was expected to show an improved spectral photoresponse at higher operating temperatures.

The spectral photoresponse measured at the temperatures increasing from 77 K to 200 K, are shown in Figure 4.12 (a) and (b). Unlike the significant reduction in the photoresponse from 77 K to 120 K observed in the previous CBB device (Figure 4.10), the modified CBB device did not show a reduction in the photoresponse signal from 77 K to 120 K. Instead, the photoresponse
Figure 4.11 (a) Schematic of the valence band alignment of modified CBB device under equilibrium. In comparison to the Figure 4.2 (a), the 500 nm thick middle contact layer is replaced by a 20 nm buffer layer in the modified CBB device. The Al mole fraction of the graded barrier is slightly higher, graded from $x = 0.12$ to 0.53. A single-period emitter/barrier is used instead of 30-periods, thus an average applied electric field corresponding to a particular bias voltage will be ~30 times higher in the modified CBB device compared to the previous CBB device. Due to the absence of middle contact, the measurements are carried out across the top-bottom contacts only, that is, with the CBB. (b) Dark current density of the modified CBB device.
Figure 4.12 (a) The spectral photoresponse of the modified CBB device at 0 V, measured at the temperatures 77 K, 90 K, 100K, and 120 K, showing no significant change in the photoresponse signal although a slight increment was observed with the temperature increasing from 77 K to 120 K. (b) Above 120 K, the photoresponse was observed to be reduced with the increasing temperature, as observed previously in Figure 4.10. An operating temperature of 150 K is observed, before the spectral photoresponse beyond ~2.5 µm disappeared. At 200 K, the spectral photoresponse is limited to ~2.5 µm, similar to previously observed result.
became slightly higher at 120 K compared to 77 K. The cause of the differences in the results between the two devices in this temperature range is not clearly understood. However, above 120 K the photoresponse became weaker with increasing temperature and this observation is similar in both devices. At 77 K, the peak responsivity of the modified CBB device is ~78 µA/W is smaller than ~0.47 mA/W observed previously, hence the $D^* \sim 1.6 \times 10^{10}$ Jones is also smaller. However, at 120 K, a significant reduction in the photoresponse of the previous CBB device causes it to have a lower peak responsivity (~28 µA/W) than the modified CBB device (~89 µA/W), as shown in Figure 4.13 (a). Hence, the modified CBB device has a higher $D^*$ (~9.3 $\times 10^9$ Jones) compared to the previous CBB device (~3.8 $\times 10^9$ Jones) at 120 K, as shown in Figure 4.13 (b). The operating temperature of 150 K before the spectral photoresponse beyond ~2.5 µm disappeared, is slightly higher in the modified CBB device than 140 K seen in the previous case. At 200 K, the spectral photoresponse is limited to ~2.5 µm, similar to the previously observed result.

Even though the results indicated that the modified CBB device shows a small improvement at increased temperatures, the removal of the middle contact appears to have no significant improvement in the operating temperature. The slightly increased Al$_x$Ga$_{1-x}$As barrier could also have caused a marginal improvement in the operating temperature. A further increment in the Al$_x$Ga$_{1-x}$As barrier height may be necessary to understand its role. However, with a shorter wavelength threshold, the peak photoresponse near 5 µm will become weaker, possibly making the 3 – 5 µm band photoresponse go below the full-width at half-maximum (FWHM) level. Therefore, a conclusive remark cannot be made on the possible ways to achieve further higher operating temperature.
Figure 4.13 A comparison between the CBB device and the modified CBB device in terms of (a) spectral photoresponse, and (b) specific detectivity ($D^*$) at 120 K, 0 V. The modified CBB device is seen to have a higher responsivity and the specific detectivity.
4.4 Future work on MIR (3 – 5 µm) photodetectors based on p-type InP and GaInPAs based III-V semiconductor materials

The S-O band energy ($\Delta_{S-O} = 0.34$ eV) of the GaAs limits the spectral photoresponse to ~3.6 µm, with the peak response being near 2.7 µm. The H-H/L-H transitions give rise to the photoresponse with a peak near 5 µm or beyond. In between the two peaks, the photoresponse is weak, in the 3 – 5 µm regime, which is the most important band being an atmospheric window.

Other materials with the S-O band energy in the IR regime are InAs ($\Delta_{S-O} = 0.41$ eV), AlAs ($\Delta_{S-O} = 0.30$ eV), InP ($\Delta_{S-O} = 0.11$ eV), GaP ($\Delta_{S-O} = 0.08$ eV), and AlP ($\Delta_{S-O} = 0.07$ eV). InAs and AlAs are not much different from GaAs for the 3 – 5 µm band. However, InP with the S-O energy of 0.11 eV can cover the spectral absorption up to ~11 µm. In fact, the experimentally measured absorption\(^{104}\) of p-type InP show a uniform absorption in a broad spectral range, including the 3 – 5 µm. Therefore, p-type InP based heterostructures are proposed for the 3 – 5 µm band IR detection.

A design of the p-InP/InAlAs heterostructure based IR photodetector is depicted in Figure 4.14. Three heterostructures (GS-LWIR-1, GS-LWIR-2, and GS-LWIR-3) are under production at the time of this writing. These structures are grown by MBE on InP substrate. The active region of the device consists of p-type doped (with Be dopant) InP emitter between undoped $\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ (60 nm) barriers. This region is sandwiched between the top and bottom contacts. The top contact consists of p-type, highly doped ($>1.0\times10^{19}$ cm\(^{-3}\)) p-$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ (50 nm) and p-type InP (20 nm). The bottom contact consists of highly doped ($>1.0\times10^{19}$ cm\(^{-3}\)) p-$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ (400 nm). The p-InP emitter in the device GS-LWIR-1 is 20 nm, with $3.0\times10^{18}$ cm\(^{-3}\) doping. But in the device GS-LWIR-2, the p-InP emitter is 80 nm, with $3.0\times10^{18}$ cm\(^{-3}\) doping. In the GS-LWIR-3, the p-InP
**Figure 4.14** Schematic of the p-InP/InAlAs heterostructure for 3-5 μm IR detection. Three samples are designed: GS-LWIR-1 with p-InP doping $3.0 \times 10^{18}$ cm$^{-3}$ and emitter thickness $T = 20$ nm; GS-LWIR-2 with p-InP doping $3.0 \times 10^{18}$ cm$^{-3}$ and emitter thickness $T = 80$ nm; and GS-LWIR-3 with p-InP doping $8.0 \times 10^{18}$ cm$^{-3}$ and emitter thickness $T = 80$ nm.

**Table 4.1** Summary of parameters differences between the devices GS-LWIR-1, GS-LWIR-2, and GS-LWIR-3

<table>
<thead>
<tr>
<th></th>
<th>p-InP doping (cm$^{-3}$)</th>
<th>p-InP Emitter Thickness T (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GS-LWIR-1</td>
<td>$3.0 \times 10^{18}$</td>
<td>20</td>
</tr>
<tr>
<td>GS-LWIR-2</td>
<td>$3.0 \times 10^{18}$</td>
<td>80</td>
</tr>
<tr>
<td>GS-LWIR-3</td>
<td>$8.0 \times 10^{18}$</td>
<td>80</td>
</tr>
</tbody>
</table>
Figure 4.15 Simulated spectral photoresponse of the p-InP/InAlAs heterostructure IR photodetector for 3-5 μm (FWHM) detection.
emitter is 80 nm, with a higher doping at $8.0 \times 10^{18}$ cm$^{-3}$. The differences in the parameters in the three devices are summarized in Table 4.1.

The spectral photoresponse is simulated by using the absorption coefficient data$^{104}$ for $3.0 \times 10^{18}$ cm$^{-3}$ doping of p-InP is shown in Figure 4.15. The FWHM of photoresponse is observed in the $3 – 5 \mu$m band. The simulation is based on escape cone model$^{41}$ of internal photoemission. It is encouraging to see the photoresponse peak is in the $3 – 5 \mu$m band, and the devices are expected show their spectral photoresponse similar to the simulated result.

Once the experimental results of these devices are studied, further modifications in the designs are possible to include graded barrier by gradually increasing the Al mole fraction in the In$_{0.52}$Al$_{0.48}$As barrier. The graded barrier will enable photovoltaic operation and enhance the $D^*$ due to thermal noise limited operation. A current-blocking barrier may also be used to further enhance the $D^*$.

Another alternative of IR absorber with S-O band transition is the quaternary III-V material Ga$_x$In$_{1-x}$As$_y$P$_{1-y}$ with the $\Delta_{S-O}(y)$ varying from 0.38 eV to 0.11 eV as $(0.11+0.421y-0.152y^2)$ with the As composition.$^{82}$ The As composition with $y = 0.36$ will give a $\Delta_{S-O} (0.36) \sim 0.24$ eV, which yields a wavelength close to $5 \mu$m. This composition may be useful to achieve a S-O band absorption peak in the $3 – 5 \mu$m band. Furthermore, undoped Al$_x$Ga$_{1-x}$As layers can be used as barriers, with a flexibility in terms of Al mole fraction variation for graded barriers, except for some lattice-matching restriction at the beginning of the layer growth.
4.5 Summary

A 2 – 6 µm IR photodetector, based on p-GaAs/Al$_x$Ga$_{1-x}$As heterostructure, operating at 0 V, was found to benefit from a current blocking barrier. S-O band and H-H/L-H band IVB transitions due to IR absorption enabled the photodetection. The specific detectivity was increased by two orders of magnitude, to $\sim 1.9 \times 10^{11}$ Jones, due to the current blocking barrier although a small compromise in the spectral responsivity (by a factor of $\sim 1.5$) was observed. Selective spectral measurements, by using long-pass optical filters, confirmed that the spectral photoresponse carrier injection is not affected by the current blocking barrier. Furthermore, a 3 – 5 µm band IR photodetector, currently under development, is discussed as an alternative to p-GaAs absorber, since the S-O band peak ($\sim 2.7$ µm) and H-H/L-H peak ($\sim 5$ µm) cause a slightly weaker photoresponse in this atmospheric window. A S-O band tuning is possible in another material system, GaInAsP from $\sim 3.2$ µm to $\sim 11$ µm. The possibility of using this material system is also discussed to develop a S-O band IR photodetector for 3 – 5 µm band use.
REFERENCES

1. William Herschel, Philosophical Transactions of the Royal Society of London 90, 284 (1800).


Mark L. Brongersma, Naomi J. Halas, and Peter Nordlander, Nat Nano 10 (1), 25 (2015).


APPENDICES

Appendix A

Packaging and wire-bonding

A top view optical image of a piece of the wafer after mesa-processing is shown in the Figure below. The smallest mesa-size is 400 µm x 400 µm with the optical window of 260 µm x 260 µm, which were used for the experimental characterizations.

Top view optical image of a piece of wafer after mesa-processing, showing different mesa sizes (400 µm x 400 µm, 600 µm x 600 µm, 800 µm x 800 µm, 1000 µm x 1000 µm, and 1500 µm x 1500 µm).

The wafer was diced with a diamond dicer tip and mounted on a Mini-Systems chip-carrier 3J24M (~0.135” x 0.29” in dimension, 24 pins) by using silver-epoxy. Then the mesas were wire-bonded onto the chip carrier with MEI wedge-bonder using 1 mil (25 µm) gold wire, with the sample-stage temperature at 150 degree Celsius. The figure below shows the wedge-bonder (left) and a wire-bonded device on the chip-carrier.
The parameters setting of the wire bonder are as follows. The tool height is adjusted at 0.450”. The first bond (to be made on the chip carrier contact pad) had a setting of Power1: 5.0, and Time1: 5.0. The second bond (to be made on the detector contact pad) had a setting of Power2: 4.0, and Time2: 4.0. The other parameters, common to both bonds, had a setting of Loop: 2.0, and Bond Force: 3.0. The work stage temperature was set at 150 degree Celsius.

MEI wedge-bonder (left) and a wire bonded detector on the chip-carrier (right), with separate mesa connections and a common ground connection.
Appendix B

*Electrical Characterization*

The device was mounted on a sample holder of a cryostat cold finger with double shielding shrouds. After pumping to ~$10^{-6}$ Torr, the cold finger was cooled by an APD HC2 closed-cycle refrigerator, which can achieve a temperature as low as 10 K. A computer-controlled Keithley 2635B with a current sensitivity of $\sim 1.3 \times 10^{-13} \text{A}$ (or 2400 with a current sensitivity of $\sim 10^{-10} \text{A}$) source-meter was used to measure the I-V characteristics, with the temperature steps being controlled by Lakeshore 330 temperature controller.

Block diagram of the electrical characterization set up. The device is mounted on the sample holder of a cryostat cold finger with double shielding shrouds.
Appendix C

Spectral Characterization

A Fourier-transform infrared (FTIR) spectrometer (Perkin Elmer system 2000) is used to measure the spectral photoresponse signal of the IR detectors. The Perkin Elmer system 2000 uses Spectrum 5.0 software for the spectral measurements. The FTIR spectrometer consists of a built-in source of broad IR radiation that is used as the source of IR radiation of the detector characterization. In order to measure the intensity of the incident IR radiation over a broad spectral band (NIR through FIR), a bolometer of known sensitivity over the IR spectrum is used. The bolometer is mounted inside a dewar (HD-3 or HD-5, IR Lab Inc.), where the IR radiation incident through an IR window of the dewar is focused onto the bolometer by means of a Winston cone (details in Appendix C). Then the photoresponse signal of the bolometer is measured at liquid helium temperature. The photoresponse signal from the bolometer electrode contacts is fed to a voltage pre-amplifier in order to pre-amplify the signal before sending to the computer where the Spectrum 5.0 software records the spectrum of photoresponse.

The IR detector under test is also mounted inside the dewar in the same way as the bolometer. The photoresponse signal is recorded in the similar way in the case of bolometer. The output (raw) signal is then calibrated to obtain the spectral responsivity of the detector under test as

\[
R_s(A/W) = \frac{GV_s(\lambda)}{V_C(\lambda)} \times \frac{1}{R_L + \frac{1}{R_d}},
\]

(C.1)
where $G$ is a geometrical factor, which is used to correct for the differences between the radiation-incident-area of the device under test and the bolometer, $V_S(\lambda)$ is the raw signal measured from the device under test, $V_C(\lambda)$ is the Si bolometer spectra, $R_C(\lambda)$ is the sensitivity of the bolometer provided by the manufacturer. $\left(\frac{1}{R_L} + \frac{1}{R_d}\right)$ is the effective resistance, where $R_L$ resistance of the load resistor in parallel to the device under test with a dynamic resistance $R_d$. The spectra from the device under test and the bolometer are measured with the same combination of optical windows, and beamsplitter to make the optical path identical.
A block diagram of the spectral photoresponse measurement set up. A long pass optical filter can be introduced on the path of light to measure selective spectral measurements.

An image of an HDL-5 dewar (IR Lab Inc.) showing IR window for sample illumination.
Appendix D

**TDIPS fitting by choosing different spectral ranges in the near-threshold region of extended-wavelength photoresponse**

The TDIPS fitting process of a spectral photoresponse curve in the near-threshold region requires selection of a range of spectrum to be fitted. The experimental quantum yield is used for the fitting by selecting the spectrum in an energy range $\Delta_1 < \varepsilon < \Delta_2$ such that the energy threshold lies within this range, where $\Delta_1$ is an energy at which the experimental quantum yield spectrum is flat at background noise level and $\Delta_2$ is an energy at which the experimental quantum yield spectrum is clearly above the background noise level. This background noise level ($Y_0$) is taken from the experimental quantum yield for each spectrum and its value is usually a small number ($\sim 10^{-4}$ to $\sim 10^{-6}$). Upper energy limit of the spectrum ($\Delta_2$) is an energy at which the experimental quantum yield spectrum is clearly above the background noise level. For example, in the figure below shown for the device GSU17I, $\Delta_1 = 0.017$ eV is chosen. On the other hand, $\Delta_2$ can be chosen near 0.025 eV or higher as the quantum yield spectrum is seen to be higher than the background level at these energy values. Since there is no hard and fast rule to choose the value of $\Delta_2$, a range of values are chosen, and the TDIPS fittings are obtained for each case to find the activation energy $\Delta$. Thus, this process gives a number of fittings on one experimental spectral curve. In order to evaluate any possible uncertainty in the $\Delta_{TDIPS}$ due to error in judgement in the selection of $\Delta_2$, different $\Delta_2$ points were selected. For 15SP3 and GSU17I, 11 different $\Delta_2$ points were chosen, in the range of 0.024 to 0.029 eV with 0.0005 eV increments. Similarly, 8 different $\Delta_2$ points were chosen for SP1007 in the range of 0.0245 to 0.028 eV. The TDIPS fittings were also carried out with two additional $\Delta_2$ points at ± 0.00025 eV from the $\Delta_2$ corresponding to the minimum $\chi^2$ value.
(shown below, following the TDIPS fitting graphs). The TDIPS fittings so obtained for GSU17I, 15SP3, and SP1007 are shown below.

A chi-square ($\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i^2}$) statistic was calculated to compare the goodness of fit among the different fittings. The $\chi^2$ values were calculated in the range of 0.0186 to 0.029 eV was used for GSU17I fittings so that the degree of freedom is same for each case. Similarly, a range of 0.0186 to 0.029 eV was used for 15SP3 as well. For SP1007, the $\chi^2$ values were calculated in the range of 0.0222 to 0.028 eV. The $\Delta_{TDIPS}$ values, picked up from the fitting corresponding to the smallest value of $\chi^2$ for GSU17I, 15SP3, and SP1007 are (0.0203±0.0003) eV, (0.0207±0.0001) eV, and (0.0223±0.0002) eV, respectively, and the corresponding wavelength thresholds are (61.0 ± 0.8) µm, (60.0 ± 0.3) µm, and (56.0 ± 0.5 µm) respectively. Here, 3×standard error is adopted as a measure of uncertainty as it is often found to be in practice in sensor community. The difference between the $\Delta_{TDIPS}$ values of SP1007 and GSU17I is (0.0020±0.0004) eV.
TDIPS fittings for spectral photoresponse of the device GSU17I for different upper energy limits ($\Delta_2$) range of 0.024 to 0.029 eV with 0.0005 eV increments, and with two additional $\Delta_2$ points at ± 0.00025 eV from the $\Delta_2$ corresponding to the minimum $\chi^2$ value (with $\Delta_2 = 0.027$ eV).
TDIPS fittings for spectral photoresponse of the device 15SP3 for different upper energy limits ($\Delta_2$) range of 0.024 to 0.029 eV with 0.0005 eV increments, and with two additional $\Delta_2$ points at $\pm 0.00025$ eV from the $\Delta_2$ corresponding to the minimum $\chi^2$ value (with $\Delta_2 = 0.027$ eV).
TDIPS fittings for spectral photoresponse of the device SP1007 for different upper energy limits ($\Delta_2$) range of 0.0245 to 0.028 eV with 0.0005 eV increments and with two additional $\Delta_2$ points at $\pm 0.00025$ eV from the $\Delta_2$ corresponding to the minimum $\chi^2$ value (with $\Delta_2 = 0.028$ eV).
Table showing the $\Delta_{\text{TDIPS}}$ values for GSU17I at different $\Delta_2$ values chosen for the TDIPS fitting.

<table>
<thead>
<tr>
<th>$\Delta_2$ (eV)</th>
<th>$\Delta_{\text{TDIPS}}$ (eV)</th>
<th>$\chi^2$</th>
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<td>0.0201727</td>
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<tr>
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<td>0.0198054</td>
<td>18.5</td>
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</table>

*standard deviation 0.0002944
*Standard error 0.0000817
*3*standard error 0.0002450

The values of $\Delta_{\text{TDIPS}}$ and $\chi^2$ depicted for corresponding $\Delta_2$ value chosen for TDIPS fittings are shown in the figure above. It should be noted that the purpose of choosing a different ranges of quantum yield spectrum between $\Delta_1 < \varepsilon < \Delta_2$ is to find a fitting such that a minimum $\chi^2$ value can be obtained for one of the fittings from the set of $\Delta_2$ values chosen. In other words, there is no specific relationship between $\Delta_2$ and $\Delta_{\text{TDIPS}}$. The $\Delta_{\text{TDIPS}}$ value corresponding to minimum $\chi^2$ value is reported for each detector, that is, by looking up the table as shown above. Therefore, a table of the values including $\Delta_2$ and corresponding $\Delta_{\text{TDIPS}}$ and $\chi^2$ values will be presented for each of the other devices.
Table showing the $\Delta_{\text{TDIPS}}$ values for 15SP3 at different $\Delta_2$ values chosen for the TDIPS fitting.

<table>
<thead>
<tr>
<th>$\Delta_2$ (eV)</th>
<th>$\Delta_{\text{TDIPS}}$ (eV)</th>
<th>$\chi^2$</th>
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</thead>
<tbody>
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<td>0.024</td>
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<td>0.0245</td>
<td>0.0206804</td>
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<tr>
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*standard deviation: 0.0001133
*standard error: 0.0000314
*3*standard error: 0.0000943

Table showing the $\Delta_{\text{TDIPS}}$ values for SP1007 at different $\Delta_2$ values chosen for the TDIPS fitting.

<table>
<thead>
<tr>
<th>$\Delta_2$ (eV)</th>
<th>$\Delta_{\text{TDIPS}}$ (eV)</th>
<th>$\chi^2$</th>
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<td>12.6</td>
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</table>

*standard deviation: 0.0002012
*standard error: 0.0000636
*3*standard error: 0.0001909
Similarly, the $\Delta_{TDIPS}$ values of the devices GSU17II and GSU17III are $(0.0217 \pm 0.0001)$ eV and $(0.0214 \pm 0.0001)$ eV respectively. The TDIPS fittings of the spectral photoresponse of the devices GSU17II and GSU17III are presented below.

TDIPS fittings for spectral photoresponse of the device GSU17II for different upper energy limits ($\Delta_2$) range of 0.024 to 0.029 eV with 0.0005 eV increments, and with two additional $\Delta_2$ points at $\pm 0.00025$ eV from the $\Delta_2$ corresponding to the minimum $\chi^2$ value (with $\Delta_2 = 0.0275$ eV).
TDIPS fittings for spectral photoresponse of the device GSU17III for different upper energy limits ($\Delta_2$) range of 0.024 to 0.029 eV with 0.0005 eV increments, and with two additional $\Delta_2$ points at $\pm 0.00025$ eV from the $\Delta_2$ corresponding to the minimum $\chi^2$ value (with $\Delta_2 = 0.0265$ eV).
Table showing the $\Delta_{TDIPS}$ values for GSU17II at different $\Delta_2$ values chosen for the TDIPS fitting.

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<th>$\Delta_2$ (eV)</th>
<th>$\Delta_{TDIPS}$ (eV)</th>
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*standard deviation 0.0001284
standard error 0.0000356
3*standard error 0.0001069

Table showing the $\Delta_{TDIPS}$ values for GSU17III at different $\Delta_2$ values chosen for the TDIPS fitting.

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<td>0.0285</td>
<td>0.0211951</td>
<td>8.4</td>
</tr>
<tr>
<td>0.029</td>
<td>0.0212832</td>
<td>9.5</td>
</tr>
</tbody>
</table>

*standard deviation 0.0001380
standard error 0.0000383
3*standard error 0.0001149
Furthermore, the TDIPS fittings of the spectral photoresponse of the device SP1001 is shown below.

TDIPS fittings for spectral photoresponse of the device SP1001 for different upper energy limits ($\Delta_2$) range of 0.0255 to 0.028 eV with 0.0005 eV increments, and with two additional $\Delta_2$ points at $\pm 0.00025$ eV from the $\Delta_2$ corresponding to the minimum $\chi^2$ value (with $\Delta_2 = 0.027$ eV).
The $\Delta_{\text{TDIPS}}$ values for the device SP1001 are shown below.

Table showing the $\Delta_{\text{TDIPS}}$ values for SP1001 at different $\Delta_2$ values chosen for the TDIPS fitting.

<table>
<thead>
<tr>
<th>$\Delta_2$ (eV)</th>
<th>$\Delta_{\text{TDIPS}}$ (eV)</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0255</td>
<td>0.0250064</td>
<td>8.4</td>
</tr>
<tr>
<td>0.026</td>
<td>0.0248681</td>
<td>5.4</td>
</tr>
<tr>
<td>0.0265</td>
<td>0.0251267</td>
<td>6.8</td>
</tr>
<tr>
<td>0.02675</td>
<td>0.0251563</td>
<td>5.5</td>
</tr>
<tr>
<td>0.027</td>
<td>0.0249434</td>
<td>3.3</td>
</tr>
<tr>
<td>0.02725</td>
<td>0.0249358</td>
<td>4.6</td>
</tr>
<tr>
<td>0.0275</td>
<td>0.0247742</td>
<td>5.7</td>
</tr>
<tr>
<td>0.028</td>
<td>0.0248364</td>
<td>4.7</td>
</tr>
</tbody>
</table>

*standard deviation* 0.0001349
*standard error* 0.0000427
*3* standard error 0.0001280

The $\Delta_{\text{TDIPS}}$ values of the SP1P1001 device is corresponding to the smallest $\chi^2$ value is 0.0249±0.0001 eV and the corresponding wavelength threshold is 50.0±0.3 µm.
Appendix E

Arrhenius Plots and Activation Energy of LH1002

The dark current of a device based on thermionic emission at temperature T can be expressed as

\[ I_{dark} = Ae \left[ 1 + \left( \frac{\mu F}{v_{sat}} \right)^2 \right]^{1/2} 2 \left( \frac{m^* k_B T}{2 \pi \hbar^2} \right)^{3/2} \times \exp \left( - \frac{\Delta}{k_B T} \right) \]

where \( A \) is the electrically active area of the detector, \( e \) is the electronic charge, \( \mu(F) \) is the hole drift velocity as function of applied field, \( v_{sat} \) is the saturation velocity, \( m^* \) is the effective mass, \( k_B \) is Boltzmann’s constant, \( T \) is temperature, \( \hbar \) is the reduced Planck constant. In order to extract the value of activation energy (\( \Delta \)) from the temperature dependent dark current, explicit temperature-dependence of the dark current can be expressed as

\[ I_{dark} \propto T^{3/2} \times \exp \left( - \frac{\Delta}{k_B T} \right) \]

Taking log on both sides and rearranging, we get

\[ \Delta = - \frac{\ln \left( \frac{I_{dark}}{T^{3/2}} \right)}{\frac{1}{k_B T}} = - \frac{\ln \left( \frac{I_{dark}}{T^{3/2}} \right)}{\frac{1}{T}} k_B . \]
For convenience, $100/T$ is used in x-axis to obtain the Arrhenius plot of $\ln \left( \frac{I_{dark}}{T^{3/2}} \right)$ versus $100/T$.

Then the slope of the Arrhenius plot is obtained by a linear fit of the plot. The value of the slope so obtained is used to obtain the activation energy ($\Delta$) as $\Delta = -slope \times 100 \times k_B \times 6.242 \times 10^{18} \text{ eV}$. For LH1002, the Arrhenius plots are depicted in figure below where the dashed lines are the linear fit of the plots.

![Arrhenius plot for LH1002](image)

The Arrhenius plots of for the device LH1002. The dashed lines represent the linear fit to the each of the plots.
The activation energy obtained based on the Arrhenius plots are shown below with the standard error.

Table showing the activation energy obtained from Arrhenius plots for device LH1002

<table>
<thead>
<tr>
<th>Bias (V)</th>
<th>Δ (eV)</th>
<th>standard error (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1.8</td>
<td>0.1690</td>
<td>0.0062</td>
</tr>
<tr>
<td>-1.6</td>
<td>0.1847</td>
<td>0.0049</td>
</tr>
<tr>
<td>-1.4</td>
<td>0.1964</td>
<td>0.0030</td>
</tr>
<tr>
<td>-1.2</td>
<td>0.2110</td>
<td>0.0025</td>
</tr>
<tr>
<td>-1</td>
<td>0.2224</td>
<td>0.0018</td>
</tr>
<tr>
<td>-0.8</td>
<td>0.2313</td>
<td>0.0015</td>
</tr>
<tr>
<td>-0.6</td>
<td>0.2499</td>
<td>0.0018</td>
</tr>
<tr>
<td>-0.4</td>
<td>0.2668</td>
<td>0.0016</td>
</tr>
<tr>
<td>-0.2</td>
<td>0.2810</td>
<td>0.0014</td>
</tr>
<tr>
<td>0.2</td>
<td>0.2868</td>
<td>0.0017</td>
</tr>
<tr>
<td>0.4</td>
<td>0.2784</td>
<td>0.0007</td>
</tr>
<tr>
<td>0.6</td>
<td>0.2656</td>
<td>0.0010</td>
</tr>
<tr>
<td>0.8</td>
<td>0.2538</td>
<td>0.0010</td>
</tr>
<tr>
<td>1</td>
<td>0.2416</td>
<td>0.0017</td>
</tr>
<tr>
<td>1.2</td>
<td>0.2269</td>
<td>0.0022</td>
</tr>
<tr>
<td>1.4</td>
<td>0.2163</td>
<td>0.0028</td>
</tr>
<tr>
<td>1.6</td>
<td>0.2071</td>
<td>0.0031</td>
</tr>
<tr>
<td>1.8</td>
<td>0.1978</td>
<td>0.0036</td>
</tr>
</tbody>
</table>
**TDIPS Fitting of spectral photoresponse LH1002**

The TDIPS fittings of the spectral photoresponse of the device LH1002 are shown below.

The TDIPS fitting of the spectral photoresponse of the device LH1002 at positive biases. The solid and dashed lines represent the fittings and experimental curves, respectively.
The TDIPS fitting of the spectral photoresponse of the device LH1002 at negative biases.
In order to obtain the uncertainties in the $\Delta_{TDIPS}$, the spectral photoresponse measurement was repeated to get multiple curves at 0.2 V and 1 V, as shown below.
Multiple spectral photoresponse curves (10 each) at 0.2 V (top panel) and 1 V (bottom panel). The insets show the zoomed in section to show the multiple curves.

The $\Delta_{TDIPS}$ values from 10 curves each at 0.2 V and 1 V for the device LH1002 are shown below.

<table>
<thead>
<tr>
<th>$\Delta_{TDIPS}$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 V</td>
</tr>
<tr>
<td>0.2827032</td>
</tr>
<tr>
<td>0.2824678</td>
</tr>
<tr>
<td>0.2831114</td>
</tr>
<tr>
<td>0.2843925</td>
</tr>
<tr>
<td>0.2841176</td>
</tr>
<tr>
<td>0.2836154</td>
</tr>
<tr>
<td>0.2842717</td>
</tr>
<tr>
<td>0.2834729</td>
</tr>
<tr>
<td>0.2839264</td>
</tr>
<tr>
<td>0.2837816</td>
</tr>
<tr>
<td>1 V</td>
</tr>
<tr>
<td>0.2417796</td>
</tr>
<tr>
<td>0.2418151</td>
</tr>
<tr>
<td>0.2416721</td>
</tr>
<tr>
<td>0.2415248</td>
</tr>
<tr>
<td>0.2420442</td>
</tr>
<tr>
<td>0.2417660</td>
</tr>
<tr>
<td>0.2412862</td>
</tr>
<tr>
<td>0.2419682</td>
</tr>
<tr>
<td>0.2424358</td>
</tr>
<tr>
<td>0.2419122</td>
</tr>
</tbody>
</table>

| **standard deviation** | 0.000652002 | 0.0003088 |
| **standard error** | 0.000206181 | 0.0000977 |
| **3*standard error** | 0.000618544 | 0.0002930 |

Based on these results, the wavelength thresholds are (4.37 ±0.01) µm, and (5.13 ±0.01) µm at 0.2 V and 1 V respectively. Since the uncertainty in the wavelength threshold is consistently small, ±0.01 µm may be adopted for the device LH1002 at all biases.
Appendix F

**Phonon occupation number**

The phonon occupation number $\langle n_\omega \rangle$ with a LO phonon energy $\hbar \omega_{LO}$ at a temperature $T$ is given as

$$\langle n_\omega \rangle = \frac{1}{\exp \left( \frac{\hbar \omega_{LO}}{kT} \right) - 1}$$

For GaAs, $\hbar \omega_{LO} \sim 0.036$ eV. The temperature-dependence of the LO phonon occupation number is depicted in figure below.

The temperature-dependence of the LO phonon occupation number for GaAs with the LO phonon energy $\hbar \omega_{LO} \sim 0.036$ eV.
A table showing the dramatic variation of GaAs LO phonon occupation numbers with temperature.

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Occupation number</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.4x10^{-36}</td>
</tr>
<tr>
<td>10</td>
<td>2.0x10^{-18}</td>
</tr>
<tr>
<td>20</td>
<td>2.3x10^{-09}</td>
</tr>
<tr>
<td>50</td>
<td>6.4x10^{-04}</td>
</tr>
<tr>
<td>80</td>
<td>1.5x10^{-02}</td>
</tr>
<tr>
<td>100</td>
<td>4.2x10^{-02}</td>
</tr>
</tbody>
</table>

The dramatic variation of the phonon occupation numbers can also be seen in the table below. From 5 K to 10K this number increases by a multiple of ~10^{18}, and from 5 K to 100 K it increases by a multiple of ~10^{34}. However, at higher temperatures, this number increases from 80K to 100K only by a factor of 3. Thus, requirement of very low temperatures to observe extended-wavelength mechanism can be related to the role of phonon population for the build-up of quasi-equilibrium Fermi level.