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ABSTRACT

Thesis Title: In$_{0.53}$Ga$_{0.47}$As-In$_{0.52}$Al$_{0.48}$As Multiple Quantum Well THz photoconductive switches and In$_{0.53}$Ga$_{0.47}$As-AlAs Asymmetric Spacer Layer Tunnel (ASPAT) diodes for THz electronics

Name: Yuekun Wang
Degree: Doctor of Philosophy
University: The University of Manchester
Date: 2017

This thesis is concerned with terahertz (THz) technology from both optical and electronic approaches. On the optical front, the investigation of optimised photoconductive switches included the characterisation, fabrication and testing of devices which can generate and detect THz radiation over the frequency range from DC to ~ 2.5 THz. These devices incorporated semiconductor photoconductors grown under low temperature (LT) Molecular Beam Epitaxy (MBE) conditions and using distributed Bragg reflectors (DBRs). The material properties were studied via numerous characterisation techniques which included Hall Effect and mid infrared reflections. Antenna structures were fabricated on the surface of the active layers and pulsed/continuous wave (CW) signal absorbed by these structures (under bias) generates photocurrent. With the help of the DBRs at certain wavelengths (800 nm and 1550 nm), the absorption coefficient at the corresponding illumination wavelength increased thus leading to significant increase of the THz output power while the materials kept the desirable photoconductive material properties such as high dark resistivity and high electron mobility. The inclusion of DBRs resulted in more than doubling of the THz peak signals across the entire operating frequency range and significant improvements in the relative THz power.

For the THz electronic approach, a new type of InP-based Asymmetric Spacer Tunnel Diode (ASPAT), which can be used for high frequency detection, was studied. The asymmetric DC characteristics for this novel tunnel diode showed direct compatibility with high frequency zero-bias detector applications. The devices also showed an extreme thermal stability (less than 7.8% current change from 77 K to 400 K) as the main carrier transport mechanism of the ASPAT was tunnelling.

Physical models for this ASPAT diode were developed for both DC (direct current) and AC (alternating current) simulations using the TCAD software tool SILVACO. The simulated DC results showed almost perfect matches with measurements across the entire temperature range from 77 K to 400 K. From RF (radio frequency) measurements, the intrinsic diode parameters were extracted and compared with measured data. The simulated zero biased detector circuits operating at 100 GHz and 240 GHz using the new InGaAs-AlAs ASPAT diode (4×4 μm$^2$) showed comparable voltage sensitivities to state of the art Schottky barrier diodes (SBDs) detectors but with the added advantage of excellent thermal stability.
DECLARATION

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A. JOURNAL PUBLICATIONS


B. CONFERENCE PAPERS AND PRESENTATIONS


5. **Yuekun Wang**, Mohd Rashid Redza Abdullah and M. Missous, “InGaAs/AlAs asymmetric space layer tunnel (ASPAT) diodes for THz electronics”, UK Semiconductors 2015, University of Sheffield, July, 2015

6. **Yuekun Wang**, Mohd Rashid Redza Abdullah, James Sexton and M. Missous, “Temperature dependence characteristics of In$_{0.53}$Ga$_{0.47}$As/AlAs asymmetric spacer-layer tunnel (ASPAT) diode detectors”, 8th UK-Europe-China Workshop on mm-waves and THz Technologies, Cardiff University, September, 2015, IEEE proceedings


8. K.N. Zainul Ariffin, S.G. Muttlak, M. Abdullah, M.R.R. Abdullah, **Y. Wang**, and M. Missous, “Asymmetric Spacer Layer Tunnel In$_{0.18}$Ga$_{0.82}$As/AlAs (ASPAT) Diode using Double Quantum Wells for Dual Functions: Detection and Oscillation”, 8th UK-Europe-China Workshop on mm-waves and THz Technologies, Cardiff University, September, 2015, IEEE proceedings


12. K.N. Zainul Ariffin, S.G. Muttlak, M. Abdullah, M.R.R. Abdullah, Y. Wang, and M. Missous, “Experimental and Physical Modelling of Temperature Dependence of a Double Quantum Well In\textsubscript{0.18}Ga\textsubscript{0.82}As-AlAs ASPAT diode,” UK Semiconductors 2016, University of Sheffield, July, 2016

13. Yuekun Wang, Khairul Nabilah Zainul Ariffin, Kawa Ian, M.J. Kelly and Mohamed Missous, “RF performance of In\textsubscript{0.53}Ga\textsubscript{0.47}As/AlAs Asymmetric spacer layer tunnel diodes,” UK Semiconductors 2017, University of Sheffield, July, 2017

1.1 THz radiation

THz radiation, also known as submillimetre radiation, encompasses frequencies from about 100 GHz to 10 THz with corresponding wavelength range from 3 mm to 0.3 mm [1]. The THz region is located between microwaves and far infrared light. The electromagnetic spectrum highlighting the THz portion is shown Figure 1.1 [2].

The many reasons that make THz such an active area of intense research are the facts that this radiation is highly absorbed by water, is transparent to many opaque materials and can penetrate deep into many organic materials. These properties make THz technology particularly suitable for use in chemistry, biology, astrophysics and many other applications. In addition, unlike X-rays, THz radiation can penetrate deep into organic materials without any damage since its energy is not high enough to break chemical bonds. This further makes THz a promising candidate for security and medical applications [3].

Before the 1980s, it was extremely difficult to generate and detect THz radiation. Thereafter, extensive reports on mode-locked picosecond and sub-picosecond pulsed lasers made it possible to create short carrier lifetime semiconductor-based switches for THz time domain spectroscopy including both generation and detection of THz radiation [4]. During the following decades, a great deal of interest was aimed at developing systems with high
output power. Currently, commercial time domain THz systems that with reasonably priced and improved reliability and performance are available [5], albeit still bulky.

1.2 THz sources

Due to the THz region lying between optics and microwave, the generation of THz radiation can be established via two different approaches: (i) frequency down conversion from the optical region and (ii) frequency up conversion from the microwave region using solid state electronic devices.

1.2.1 Optical approaches

For down conversion from the optical region, a nonlinear crystal with a large second order susceptibility can be used for THz generation and detection, an example being ZnTe which is one of the most widely used electro-optic (EO) crystals in THz applications [6]. EO crystal with large second order nonlinear optical susceptibilities can be used as both emitters and detectors. The mechanism for this THz generation is based on optical rectification and the THz radiation energy is obtained from a laser source. In practice, EO crystals acting as the THz source should be kept thin in order to minimise the velocity mismatch which is used to avoid destructive interferences [7].

In addition, for down conversion from the optical region, Gas lasers [8] and Quantum Cascade Lasers (QCL) [9] can be used. Gas lasers are optically pumped with their operation based on CO₂ lasers which excites gas molecules with the THz frequency of the molecular lasers being dependent on the spectral line of the gas used. THz QCLs are based on super-lattice semiconductor materials and the THz radiation is generated by electron propagating through coupled quantum wells. The first demonstrated THz QCLs emitting at 4.4 THz were reported in 2002 [10]. This frequency was subsequently shifted down to 0.95 THz [11]. The operating frequency of QCLs can be controlled by the quantum well designs. The main reasons which limit the wide application of THz QCLs are that the systems need cryogenic cooling and are of limited reliability [12].

Amongst all existing optically excited THz sources, one of the most extensively used sources is the photoconductive antenna which consists of electrode metals with designed geometry on the surface of a photoconductive material. The photoconductive switches are key devices which allow both the reliable generation and detection of broadband THz
radiation [13]. Using photoconductive antennas is also the most efficient way for down-converting optical signal to THz radiation and is widely used in spectroscopy and imaging applications [14, 15]. The photoconductive switches were first reported in 1970s [16]. They can not only be used as THz emitters but also as receivers.

For emission, a photoconductive antenna needs to be DC biased. Electron-hole pairs can be created in the femtosecond time scale when an ultrafast laser pulse is shone on the gap of the antenna. Due to acceleration of the carriers in the electric field originating in the surface depletion layer of the photoconductor, a THz wave can be radiated (Magnetic-field-enhanced generation of terahertz radiation in semiconductor surfaces).

The detection process can be treated as the reverse of the generation mechanism. In most cases, no bias voltage is applied across the electrodes, and the incident THz radiation induces a voltage across the antenna which accelerates the photo-carriers generated by the gating laser pulse. The induced current is proportional to the electric field when the ultrafast pulse is absorbed by the photoconductive detector then generating electron-hole pairs and increasing its conductivity. In this detection part, the detected photocurrent is proportional to the original incoming THz signal.

Figure 1.2 depicts the THz generation and detection process by using photoconductive antennas.

Figure 1.2 Photoconductive antenna acting as (a) an emitter; (b) a detector

To date, one of the most promising photoconductive materials that has attracted a lot of attentions from researchers is the low temperature grown GaAs (LT GaAs) as it fulfils all basic requirements for THz applications [17-19]. Besides LT GaAs, low temperature grown In_{0.53}Ga_{0.47}As-In_{0.52}Al_{0.48}As multi quantum wells (LT InGaAs-InAlAs MQWs)
photoconductor is also another efficient candidate [20-22]. Both materials were used in this work and their properties will be detailed in Chapter 2. Besides these, additional materials like graphene [23, 24] and other 2D materials [25], SiC and ZnSe [26], and single nanowire [27] were reported to have promising characteristics as photoconductive devices but their performances remain relatively poor to date.

1.2.2 Electronic approaches

For up conversion, three terminal devices such as High Electron Mobility Transistors (HEMTs) can accomplish THz generation [28]. The cut off frequency of a HEMT is dependent on the electron transit time across the drain and source terminals of the transistor. A THz HEMT thus needs to have both a small gate size (nanometre scale) and high electron mobility. However, the device size is limited by fabrication techniques and phonon scattering restricts mobility. These have limited the commercializing of THz HEMTs. THz emission caused by plasma instability in HEMTs were also reported [29]. The experimental investigations of THz emission from transistors can be performed with either a cyclotron resonance spectrometer system or a Fourier transform spectrometer system [29, 30].

Free electron lasers (FEL) are also available for emitting THz radiation with tuneable frequencies. Under high vacuum, the electron beam from the laser passes through a set of magnets, and then the moving electrons oscillate with the help of the magnetic field. The frequency is dependent on the electrons passing through the magnets. The pioneer system was established in the USA in the 1990s with tens of kilowatts regime output power at widely tuneable frequencies [31]. However, the high construction and operational cost limit the availability of FEL.

Besides these, various two terminal devices can also provide THz frequency operation. The most commonly used diodes are Gunn diodes for mm-wave emission, diodes based on tunnelling mechanism (such as Esaki diodes and resonant tunnelling diodes), and different types of transit-time diodes. The Gunn diode which was named after J. B. Gunn [32], normally consists of a n⁺-n-n⁺ semiconductor material system configuration, the negative resistance property makes the Gunn diodes to be used in high-frequency electronics. The Ohmic contact resistance of Gunn diodes should be kept small as it affects the working frequency. For example, a contact resistance of less than $10^{-7}$ Ω/cm² is desired to allow
device operation above 110 GHz [33]. An AlGaAs/GaAs planar Gunn diode was demonstrated to allow operation above 100 GHz [34] and an InGaAs-based Gunn diode showed oscillations at 164 GHz [35]. More recently, In$_{0.53}$Ga$_{0.47}$As submicron planar Gunn diodes were reported to have experimentally measured RF power of 20 µW at around 300 GHz [36]. Due to material limitations (such as relaxation time), the output power of Gunn diodes fall off very quickly. In addition, impact ionization transit time (IMPATT) diodes were also reported with the ability for emission at the long wavelength end of the THz region [37]. Besides these, resonant tunnelling diodes (RTD) can also provide THz oscillations. Compared with HEMTs, RTDs have the ability to operate at high switching speed (sub-millimetre wavelength region) using relatively large feature sizes. For example, HEMTs demonstrated a cut off frequency of 610 GHz with a gate length of 15 nm [38], while RTDs with a mesa size around 1 µm$^2$ can provide oscillation frequencies greater than 1THz. Recently, the highest RTD oscillation frequency up to 1.92 THz was reported by the Asada group [39]. The operating principle of RTD will be described in Chapter 2.

1.3 THz detectors

1.3.1 Direct detection

Direct detection in the millimetre and sub-millimetre regions is usually used in spectroscopic and technical vision systems. The detector used for direct signal detection cannot provide as high a spectral resolution=$\nu/\Delta\nu=10^6$ (where $\Delta\nu$ is the smallest frequency difference that can be distinguished at frequency $\nu$) as heterodyne detector systems [40]. The typical schematic of direct detection is shown in Figure 1.3, where $P_S$ represents the signal radiation power and $P_B$ is the background radiation power. Lenses, mirrors and horns can be used as focusing optics to collect the radiation signals. Furthermore, optical components which are located before the detector work as filter to remove background wavelength signals.
Operating under room temperature conditions, thermal detectors such as Golay cells [41], pyroelectric detectors [42], bolometers and micro-bolometers [43, 44] can all be used in direct THz detection systems. These systems have a relatively long response time ($\approx 10^{-2}$-$10^{-3}$ s). In case of cooled detectors [45, 46], an operating temperature at $T \leq 4$ K can provide a response time of $10^{-6}$-$10^{-8}$ s. The noise equivalent power (NEP) is one of the main quality factors for detectors. For direct detectors, the NEP is defined as:

$$NEP = \sqrt{\frac{2h\nu}{\eta} P_B}$$ (1.1)

where $h$ is Planck’s constant, $\nu$ is frequency and $\eta$ is the detector coupling efficiency. A low NEP indicates a more sensitive detector. The typical NEP value for uncooled detectors is in the range of $10^{-10}$ to $10^{-9}$ W/Hz$^{1/2}$, while for cooled detectors it is around $10^{-13}$ to $5\times10^{-17}$ W/Hz$^{1/2}$ [40].

Currently, low temperature bolometers, which are operated at temperature $\sim 100$-300 mK, provide the highest sensitivity in the mm-wave region ($NEP=7\times10^{-17}$-$1\times10^{-19}$ W/Hz$^{1/2}$) [47, 48].

One of the key advantages of direct detection systems is their relative simplicity to be designed as arrays and most imaging systems use passive direct detection [40].
1.3.2 Heterodyne detection

In the case of heterodyne detection, high frequency signals are down converted to intermediate frequencies. This type of detection can provide not only the amplitude but also the phase information of the input radiation. Furthermore, the heterodyne detection’s high resolution makes it useful for millimetre and sub-millimetre imaging applications [49]. The schematic of a typical heterodyne detection system is shown in Figure 1.4.

$$\text{Conversion Loss (dB)} = 10 \log\left(\frac{P_{IF}}{P_{RF}}\right) \quad (1.2)$$

where $P_{IF}$ is the power of the intermediate frequency (IF) and $P_{RF}$ is the RF power input from the front-part of the mixer. Basically, there are two types of heterodyne techniques. The first one includes a tunable LO and a fixed IF amplifier with filters. The second one uses a fixed LO incorporated with an IF amplifier and filters. The first technique is more
flexible compared with the second one, but cannot be used with continuous wave sources with low powers.

All electronic devices which have nonlinear properties can be used as mixers. However, the mixers used for mm and sub-mm wavelengths need to be able to achieve efficient conversion and low noise. Most commonly used mixers are Schottky barrier diodes [51], tunnel junction diodes [52] and hot electron bolometers (HEBs) [53]. All these devices have a strong electric field quadratic nonlinearity.

Compared with direct detection systems, heterodyne detection can provide both frequency and phase modulation. In addition, the dominant noise of the direct detection depends on the background radiation while it depends mainly on the LO fluctuations for heterodyne detection. However, heterodyne systems are difficult to produce in large format arrays [54].

1.3.3 Schottky barrier structures

In terms of THz waveband detection, Schottky barrier diodes (SBDs) are among the most basic components used in THz applications. They can be used for both direct and heterodyne detections [55, 56]. In 1980-1990s, cryogenically cooled SBDs were widely used but were then replaced by superconductor-insulator-superconductor structures [57]. For these replacements, the detection process is similar to SBDs, but the working processes are based on quantum-mechanical phenomena. The nonlinear I-V characteristics of diodes are responsible for the detection process. The main factor determining the quality of SBDs as detectors is their cut-off frequency which is determined by the diode series resistance and zero bias junction capacitance [58]. SBD-based devices are broadband and convenient to use at room temperature. The overall performance of the detectors considers not only the improvement of SBDs and the incorporated antenna, but also efficient matching circuits [55]. For direct detectors, one of the most often used factors to determine the quality of the device is the voltage sensitivity/voltage responsivity which indicate the ratio of the DC voltage to the absorbed RF power. In the 1980s, the sensitivity of SBD detector was approximately 350 V/W at 1 THz [59]. The reported sensitivity further increased to 2000 V/W at 1.4 THz and 60 V/W at 2.54 THz subsequently. These investigations used GaAs SBD with an anode diameter of 0.5µm, and a capacitance of 0.4-0.5 fF [60]. Epitaxial GaAs is the most widely used semiconductor for SBDs detectors/mixers as it has favorable and balanced bandgap and mobility and has a relatively easy fabrication process [56].
Other III-V semiconductor materials can also be fabricated into SBDs. InP-based SBDs have been reported to have a sensitivity of 103 V/W at 0.3 THz and 125 V/W at 1.2 THz [61]. For direct detection, the reported NEP range for SBDs is $3 \times 10^{10}$ to $10^8$ W/Hz$^{1/2}$ at 1 THz [55]. Direct detection using single-walled nanotubes with a Ti Schottky contact and Pt Ohmic contacts were reported to have potentially comparable NEP (but only from modelled data) in the order of $10^{13}$ W/Hz$^{1/2}$ at 2.5 THz at room temperature [62].

1.4 Aim and objective

This project involves the study of semiconductor THz technologies from both optical and electronic approaches. From the optical approach, the aim is to study the properties of further optimised photoconductor materials and to compare the performances of these photoconductive THz sources and receivers with baseline efficient photoconductors. A low cost, compact, portable, and all-fibre coupled 1.55 µm THz spectrometer incorporating the developed THz devices was used to measure the transparency of a series of materials. From the electronic approach, a new type of InP-based tunnelling diode was investigated. Such device can be treated as a promising zero biased detector in pure electronic THz systems.

The objectives of this project involved two main parts and all materials used in this work were grown by Molecular Beam Epitaxy (MBE), at the University of Manchester. The first part which focused on the development of optimised photoconductors can be divided into five stages. The first stage consisted of the characterisation of all grown photoconductive materials. A series of experiments were performed to study the optical and transport properties of these materials. The optical characteristics were investigated using optical reflection measurements, and the transport properties were obtained using Hall Effect measurements. The second stage comprised the fabrication of the photoconductive materials. Simple antenna geometries (such as apertures and dipoles) were fabricated on the surface of the grown materials and their I-V characteristics were studied. The fabrication used the i-line photolithography technique and with all metallisation performed using filament evaporation method. The next work stage comprised the evaluation of the fabricated antennas as THz sources and detectors in a compact time domain spectroscopy system developed at Manchester. This system was set up and tested by the collaborators in this project. The performance comparisons between
CHAPTER 1

the optimised photoconductors with the baseline devices based on original designs composed the fourth work stage. The final stage, which can be characterised as the application of the work, was using the 1.55 μm THz spectrometer system with the optimised fabricated devices as key components to measure the transparencies of a series samples.

The second part of the project was concerned with the investigations of a new type of Asymmetric Spacer Tunnel (ASPAT) Diode based on In$_{0.53}$Ga$_{0.47}$As and reported for the first time. As the devices were designed to be used for high-frequency detection, ground-signal-ground (GSG) patterns were incorporated in Co-Planar Waveguide (CPW) configurations. To achieve micrometre/sub-micrometre lateral dimension of the devices, the processing techniques also needed to be optimised. DC characterisations of the diodes were performed not only at room temperature but also over a wide range of temperatures and compared with Schottky diodes and conventional GaAs-based ASPATs. In addition, physical modelling for this type of diode was developed in the SILVACO software tool. Once the DC characteristics were obtained, the next objective was to perform and extract the RF properties of the diode. Based on AC parameters, the equivalent circuit of the ASPAT diodes were extracted.

1.5 Outline of the thesis

This thesis consists of eight main chapters. The first chapter provides an introduction to THz technology and presents an overview and aim and objectives of the project. Chapter two contains the literature review of the main concepts and background theories of relevance to the work undertaken. Chapter three introduces the experimental techniques of the project. These involve material growth, materials characterisation measurements, mask designs, fabrication processes, and device testing techniques. The results from the experiments of the optimised photoconductive materials are presented in Chapter four. The descriptions of the home made 1.55 μm THz spectrometer with its key elements (emitter and detector) fabricated using LT InGaAs-InAlAs MQWs photoconductive materials are given, and a series of measurements using this spectrometer are also described in this chapter. Chapter five discusses the DC characteristics results of the proposed novel ASPAT diodes at different temperatures. Chapter six then gives a general introduction to the SILVACO physical modelling simulation tool where the modelling of the ASPAT
diode is also discussed and developed. In Chapter seven, the RF characteristics, AC modelling, equivalent circuit of the diode and the detector circuit designs based on extracted parameters are investigated. Finally, Chapter eight comprises of the conclusion of the project, including its major achievements and proposals for further works.
CHAPTER 2: BACKGROUND THEORIES

In this chapter, the fundamental semiconductor device theories related to this work are described. The first part of this chapter gives a brief introduction of metal-semiconductor contacts which includes the theory of Schottky and Ohmic contacts. The second part focuses on THz time domain spectroscopy (TDS) theory along with photoconductive materials performance evaluations. Finally, several types of quantum mechanical tunnelling devices are introduced.

2.1 Metal-Semiconductor contacts

The metal-semiconductor contact plays a key role in semiconductor devices. ‘Schottky contact’ and ‘Ohmic contact’ are the two main types of metal-semiconductor contacts. Thermionic emission and thermionic-field emissions are the two main dominating mechanisms of electrons transport from semiconductor to metal. Thermionic emission allows electrons to be thermally excited over the top of a barrier; by contrast field & thermionic-field emission allows electrons tunnelling through a barrier.

2.1.1 Schottky Contacts

Schottky contacts are also known as rectifying contacts and show a diode-like behaviour. When the semiconductor is lightly doped \((N_D<1\times10^{17} \text{ cm}^{-3})\), the electrons can be thermionically emitted into the metal if their energy is above the potential barrier of the Schottky contact. The model for rectification of electrons passing over the potential barrier through drift and diffusion was reported by Schottky and Mott independently in 1938 [63]. The schematic band diagram of transportation across a Schottky barrier on n-type semiconductor is shown in Figure 2.1.
In Figure 2.1, $E_c$ is the bottom of the conduction band, $E_v$ is the top of the valence band, $E_F$ is the Fermi level and $E_g$ is the bandgap of the semiconductor. $q\Phi_m$ is the metal work function which represents the minimum energy required for an electron to escape from the metal into vacuum, $q\Phi_s$ and is the semiconductor work function which represents the energy difference between the Fermi level of the semiconductor and the vacuum level and $q\chi$ is the electron affinity of the semiconductor. During the formation of the contact, work function, affinity and the bandgap remain invariant. When a metal and semiconductor are joined in contact (as depicted in Figure 2.1(b)), the Fermi level in both materials align at thermal equilibrium. Hence, under ideal conditions, the barrier height $\Phi_B$ for the metal-semiconductor contact can be given as:

$$q\Phi_B = q\Phi_m - q\chi$$  \hspace{1cm} (2.1)

The built-in-voltage $V_{bi}$ can be written as

$$qV_{bi} = q\Phi_m - q\Phi_s$$  \hspace{1cm} (2.2)

The Schottky contact is defined when the barrier height is large ($q\Phi_B >> kT$) and the doping concentration is low ($N_D << 1/10^{th} N_C$, where $N_C$ is the effective density of states in the conduction band). The n-type semiconductor energy band diagram of a Schottky contact under bias is shown in Figure 2.2.
The depletion width $W$ as a function of applied voltage is given by:

$$W = \sqrt{\frac{2\varepsilon_s (V_{bi} - V)}{qN_D}}$$  \hspace{1cm} (2.3)

where $\varepsilon_s$ and $N_D$ are the dielectric permittivity and density of ionised donors of the semiconductor. Figure 2.2 (a) shows the energy band diagram under a reverse bias of $V_{Rev}$. This leads to an increasing potential from $qV_{bi}$ to $qV_{bi} + V_{Rev}$, which means an increase of the barrier for electron emission and an increase of the depletion width. However, when considering the case when the metal-semiconductor contact is under a forward bias of $V_{For}$, the total electrostatic potential across the barrier decreases from $qV_{bi}$ to $qV_{bi} - V_{For}$ and this reduces the depletion width. Thus, a higher current flow appears under forward biasing where a large number of electrons are emitted over a reduced barrier.

Under forward bias, the assumption in the thermionic emission theory is made that the transfer of electrons across the semiconductor-metal interface is the current limiting process. Thus, the I-V characteristics can be given as:

$$J = A^*T^2 \exp\left(\frac{-q\Phi_B}{kT}\right) \left\{\exp\left(\frac{qV}{kT}\right) - 1\right\}$$  \hspace{1cm} (2.4)

where $A^*$ is the Richardson constant for thermionic emission from metal into semiconductor (and which is related to the electron effective mass), $k$ is the Boltzmann’s
constant and T is the ambient temperature in Kelvin. Under reverse bias, the current density should saturate, however in practice it gradually increases via tunnelling and leads to the reverse characteristics. Thus, a Schottky contact is also rectifying owing to the much higher current flow under forward bias condition as compared to under reverse bias.

Schottky diode is one of the most commonly used devices for THz frequency detection. This two-terminal device which consists a metal-semiconductor junction features sensitive, flexible and reliable nonlinear performances throughout the THz range.

The I-V and C-V performances of a Schottky diode can be accurately analyzed using quasi-static approximations. Figure 2.3 shows the quasi-static equivalent circuit of the diode.

![Figure 2.3 The equivalent circuit of a diode [63]](image)

R\(_j\) represents the junction resistance which is caused by the thermionic emission of the carrier over the metal-semiconductor barrier. C\(_j\) is the junction capacitance related to the parallel plate spacing (depletion width) of the device. The series resistance R\(_s\) is the parasitic element of the diode which accounts for Ohmic losses. This basic model can be also used for other high-frequency diodes [64]. The RF performance of the Schottky diode is determined by its nonlinear diode I-V and C-V characteristics [58].

The SBD can be used as both direct detector and mixer within the operating temperature range from 4 K to 450 K. As a detector/mixer, the SBD relies on its nonlinear I-V characteristics to mix the signal with a local oscillator, but it is not as sensitive as a superconductor-insulator-superconductor or hot electron bolometer mixers when operating at ambient or cryogenic temperatures [65]. The ability of rectifying THz signals to DC makes Schottky diode a commonly used antenna-coupled square-law THz direct detector [66]. The first lithographically defined GaAs Schottky diode was developed by Young and Irvin in the 1960s [67]. Figure 2.4 gives an example of a waveguide based zero bias
Schottky detector from Virginia Diodes Inc.

![Image of Schottky detector and RF filter]

**Figure 2.4** Schematic and photo of a waveguide based zero bias detector and (b) RF performance of a VDI Schottky detector [68]

### 2.1.2 Ohmic contact

For Ohmic contacts, the current-voltage characteristics show a linear relationship in both directions of current flow. This is essential for most of the semiconductor devices as only a small voltage drops across the contact without disturbing the device characteristics.

The current-voltage characteristic of the field and thermionic-field emission can be given approximately by

\[
J = J_s \exp \left( \frac{V}{E_o} \right) \tag{2.5}
\]

where \(E_o\) is the tunnelling parameter which is proportional to doping concentration. Hence higher doping leads to a large current flowing resulting in a small voltage drop (due to the smaller depletion region width in Figure 2.1 (b)).

The specific contact resistivity \( \rho_c \) is a fundamental figure of merit for Ohmic contacts. It is defined as:

\[
\rho_c = \left( \frac{\partial I}{\partial V} \right)^{-1} \text{ at } V = 0 \tag{2.6}
\]

where \(I\) and \(V\) are current and voltage that form the I-V relationship of the contact. For tunnelling, the specific contact resistance can be expressed as:
\[ \rho_c \propto \exp \left( \frac{\vartheta_b}{E_o} \right) \] (2.7)

It is clear that either reducing the barrier height or increasing the semiconductor doping can provide a smaller contact resistance. Practically, reducing the barrier height is a notoriously difficult task. Thus, in order to produce a contact resistance as small as possible, higher doping concentrations are the preferred method for making smaller Ohmic contacts. In this work, doping concentrations for n-type GaAs and In\textsubscript{0.53}Ga\textsubscript{0.47}As are \(4 \times 10^{18}\) cm\(^{-3}\) and \(1.5 \times 10^{19}\) cm\(^{-3}\) respectively. These can provide small enough Ohmic contact resistances since they give rise to thin depletion widths.

2.2 THz time domain spectroscopy

The development of reliable generation and detection of THz system was extremely hard until Auston and his colleagues reported the first well established THz spectroscopy method in the early 1980’s [4, 69]. The time domain spectroscopy (TDS) technique results in a generation and detection of a single-cycle transient of radiation with frequencies across the THz band [70]. Unlike detecting the frequency-dependent intensity in traditional spectroscopy, this type of spectroscopy detects the time-dependent signal of the electric field. The starting point of a THz TDS system is a laser source, which should have enough photon energy for excitation of the photoconductors. In this THz TDS, a sample is placed in the beam and the time domain electric fields are measured both with and without the sample. A typical THz TDS system is shown in Figure 2.5.

![Figure 2.5 Typical THz TDS system setup][71]

Depending on the type of laser sources used, there are two groups of THz TDS systems:
pulsed mode and continuous wave (CW) mode. The time-dependent transient’s electric field can be achieved by scanning the relative delay between the pump beam and probe beam. Both systems are widely used in THz TDS and THz time domain imaging nowadays. For most of the industrial imaging applications, signal reflections are used and additional apparatus such as more parabolic mirrors are required [72].

2.2.1 THz Pulsed systems

The pulsed THz radiation system is normally driven by an ultrashort mode-locked laser which can produce pulses typically with durations of 10 to 200 fs focused on the photoconductive antennas [73-75]. From each pulse, the delivered energy is equal to the average optical power divided by the laser repetition rate. This repetition rate is normally smaller than 100 MHz. In THz TDS systems, the output beam from the laser is split into a pump beam and a probe beam (or gating pulse) using a beam splitter. The pump beam is focused onto the surface of the emitter while the probe beam is delayed and focused onto the detector. High resistivity hyper-hemispherical Si lenses are attached at the substrate side of the emitter and detector in order to collimate and focus the THz radiation, respectively. Parabolic mirrors are used to collect the transmitted THz signal and focus it onto the detector. Emitting and receiving antennas can be made on the same semiconductor material with the difference being that the emitter is biased whereas the receiver is connected to a current meter. The probe beam is usually a variable optical path. This relative delay between pump beam and probe beam can change the arrival time of the THz signal and gate pulse to the detector. By scanning the delay, the time-domain form of electric field can be mapped out. The THz pulse waveform is obtained by measuring the average photocurrent versus the time delay between the THz pulses and the gating optical pulses. Amplitude and phase spectrum are calculated by further Fourier analysis of the temporal profile of the detected THz pulse [75].

2.2.2 THz Continuous Wave (CW) systems

For the pulsed systems, the requirements are specific. Due to the bulky size, high cost and complicated operation of the femtosecond laser, most applications could only be conducted in scientific labs. However, for long term industrial operations, THz pulsed systems are not stable and reliable enough [76]. As an alternative solution, systems based on CW lasers seem to be promising for replacing pulsed lasers [77]. Two lasers with a frequency
difference which can be tuned to the THz region are used [77]. A CW system is based on mixing two single mode lasers onto a photomixer (a photoconductor is called a photomixer in CW mode) to produce narrowband THz radiation [78]. The THz antenna based CW system was first pioneered by using two CW Ti: Sapphire lasers in the 1990’s [79]. Siebert et al. reported the first CW THz imaging system in 2002 [80]. In order to make photomixing efficient, it is necessary to collimate and align the two laser beams precisely to achieve a good spatial mode matching of the laser beam. In a CW system, the beam splitter can be replaced by a coupler or combiner. By mixing these two lasers, the produced beating can modulate the conductance of the photoconductor. Two laser beams are collinear in space and the total electric field is the sum of the individual fields. The angular frequencies of two lasers ($\omega_1$ and $\omega_2$), have a slight difference in their wavelength which result in a beating waveform at the surface of the antenna with angular frequencies of $\omega_2-\omega_1$ and $\omega_2+\omega_1$. The photoconductive antennas are able to respond to the frequency of $\omega_2-\omega_1$ which is located in the THz region. CW mode results in a narrow band system. By comparison with a pulsed mode system, a CW mode system can provide lighter and more compact system and the cost is 1/6 of a typical pulsed system [81].

### 2.3 Photoconductive materials

For most THz photoconductive antennas, such as dipoles, bow-ties, spiral antennas, etc., the delivered THz powers can be found by using its equivalent circuit. The equivalent circuit of a photoconductive antenna is given in Figure 2.6.

![Figure 2.6 Equivalent circuit model for a THz photoconductive antenna [82]](image)

According to the equivalent circuit, the dynamic current equation for the device can be written as:
CHAPTER 2

\[ C \frac{dV}{dt} = \frac{V_b - V}{R_L} - G(t)V \]  

(2.8)

where \( C \) is the capacitance across the antenna gap, \( R_L \) is the antenna-radiation resistance, \( V_b \) is the applied DC bias voltage of the emitter and \( G(t) \) is the time dependent conductance modulated at angular frequency \( \omega \) which is given by:

\[ G(t) = G_0(1 + \beta \sin(\omega t + \phi)) \]  

(2.9)

where \( G_0 \) \((G_0 \propto \mu \tau)\) is the DC conductance for an average incident power \( P_0 \), which is related to the carrier mobility \( \mu \) and carrier lifetime \( \tau \) of the photoconductive material and \( \phi = \tan^{-1}(1/\omega t) \).

When \( G_0R_L \ll 1 \), the output THz power can be simplified as [82]:

\[ P_{THz} = \frac{1}{2} V_b^2 G_0^2 \frac{R_L}{1+(\omega R_L C)^2} \frac{1}{1+(\omega \tau)^2} = \frac{1}{2} I_{ph}^2 \frac{R_L}{1+(\omega R_L C)^2} \frac{1}{1+(\omega \tau)^2} \]  

(2.10)

where \( I_{ph} = G_0 V_b \) is the DC photocurrent. From the equation above, it is clear that the THz radiation power is proportional to the square of the bias voltage and the total incident power along with the carrier mobility, carrier lifetime and the radiation resistance. Thus, in order to enhance the output THz power, efficient emitters and detectors need to have short carrier lifetime, high electron mobility, high resistivity and high electric breakdown fields [83]. The shorter carrier lifetime (sub picosecond time scales) and higher mobility mean that the material is able to have very fast responses. To be more specific, the optimal emitters tend to have high carrier mobility even if the carrier lifetime is not as short [84], and the short carrier lifetime is more important for direct mode detection. For both cases, high resistivity and high breakdown field play key roles [85] as these characteristics allow the fabricated emitter to have large external bias across them and higher resistivity can further minimise the dark current in the detection process.

**2.3.1 Low temperature grown GaAs (LT GaAs)**

The photoconductor is one of the core components in a TDS system. In another word, a photoconductive material which follows the requirements described above can highly improve the TDS system performance. The very short carrier lifetime can be achieved by incorporating additional energy levels in the bandgap of the semiconductor through various
native point defect types [86]. But at the same time, these defects will result in new scattering centres leading to a decrease of the carrier free path, thus reducing the carrier mobility and the thermal conductivity of the material [87]. The THz photoconductive detector was pioneered in the 1980’s by Auston with an antenna fabricated on an epitaxial Si layer grown on sapphire [88]. By using Ar$^+$ ions irradiation in Si, defects in the crystal can be produced, however this comes at the cost of lowering the mobility of the material. Shortly thereafter, low temperature grown GaAs was found to be a better replacement for Si. LT GaAs became the most promising photoconductive material for both pulsed and CW mode operations [75, 89]. Its unique properties fulfil all the demands for efficient THz photoconductors. The growth at low temperatures, normally $T \leq 250$ °C, using the Molecular Beam Epitaxy (MBE) process makes all the requirements possible as the low temperature growth technique results in the formation of deep energy levels in the middle of the energy band gap of the semiconductor material. This allows the material to have short recombination carrier lifetime and high resistivity due to compensation processes [90]. In the case of LT GaAs, the growth at low temperature leads to the incorporation of excess arsenic (As) atoms and the point defect densities can be as high as $10^{17}$-$10^{20}$ cm$^{-3}$. The arsenic (As) and gallium (Ga) vacancies have been found to be deep donor-like and acceptor-like defects and the density of these point defects in LT GaAs is dependent on both the exact low temperature used and the overpressure of arsenic during MBE growth. The deep energy levels cannot be ionised at room temperature, thus they will not affect the conduction mechanism [91]. Alternatively, they contribute to the shorter recombination time of the carriers. In LT GaAs, and with help of the incorporated excess As, mid gap states are formed and located at 0.75 eV below the conduction band. This thermally stable and donor-like deep energy becomes vital as it works as an electron trap [92]. However, the mid gap state leads to low resistivity of the material and the dark resistivity of the as grown LT GaAs is only around 0.2-2 $\Omega$cm.

Post growth annealing is one of the breakthroughs in the use of LT GaAs as it leads to great improvements in the material characteristics. Gregory et al reported the effects of post growth annealing for LT GaAs in 2003 [90]. This paper demonstrated that the fine controlled post annealing process is critical in defining the properties of LT GaAs. The study showed that material characteristics were vastly improved by annealing for 10-15 minutes in the temperature range of 450 °C-600 °C.
Figure 2.7 shows the resistance and the carrier lifetime measurements as a function of annealing temperature for a THz LT GaAs photoconductor. It can be seen that the annealing process can increase the resistance of the photoconductor; however the drawback of annealing is that the carrier lifetime increases significantly as the annealing temperature increases above 550 °C. The annealing process allows the formation of precipitates from excess As which turn into the primary carrier traps acting as buried Schottky barriers and leading to a substantial increase in the resistivity. The material properties become similar to those of a semi-insulating GaAs substrate when the annealing temperature is above 550 °C. This is due to the fact that the point defects are eliminated and the lattice constant relaxes to that of bulk GaAs. The lattice mismatch between the substrate and the epitaxial layers can be found by using X-ray rocking curves measurements. The X-ray diffraction of annealed and as grown LT GaAs has been studied by W.C. Lee et.al [93]. From X-ray rocking curves, the splitting of the main peaks is a measure of the lattice mismatch, thus the single peak observed for 600 °C post growth annealed LT GaAs means that the lattice constant of the LT GaAs become the same as the GaAs substrate.

Besides X-ray diffraction, the electrical and optical characteristics of LT GaAs have also been studied using Hall Effect and infrared absorption measurements. These techniques are used to provide the carrier mobility and absorption wavelengths. Hozhabri and other researches have studied the absorption behaviour of LT GaAs [94]. They reported that the
concentration of defects drops when increasing the annealing temperature. In addition, the absorption spectra indicated that the increase of the annealing temperature leads to a shifting of the absorption defect band towards the conduction band. Beside these, the transmission coefficient stayed the same when the annealing temperature is below 400 ºC, increased exponentially in the range of 400 ºC to 500 ºC and this value became saturated when the temperature was above 500 ºC. As another key parameter for optoelectronic devices, the carrier mobility determines the efficiency and the sensitivity of the photoconductor. Unlike the mobility of GaAs grown at high temperature which depends mainly on the interaction of electrons with the lattice (and shallow ionised impurities), the mobility of LT GaAs is primarily defined by the ionised defects and elastic carrier scattering with neutral defects. This is because in LT GaAs the non-stoichiometric properties lead to high densities of lattice imperfections. In 1990’s, D. C. Look and others first studied the mobility of LT GaAs by using the Hall Effect technique [95]. Figure 2.8 shows the sheet resistivity versus inverse temperature and Hall mobility versus temperature of the as grown LT GaAs, annealed LT GaAs and SI GaAs substrate with the LT GaAs layer etched away [96].

![Figure 2.8](image.png)

**Figure 2.8 (a) Sheet resistivity versus inverse measurement temperature for as grown and annealed LT GaAs; (b) Hall mobility versus temperature for as grown and annealed LT GaAs [96]**

The negative sign in Figure 2.8 (b) indicates electron mobility for all tested samples. By increasing the annealing temperature, the resistivity and the Hall mobility were both increased and these characteristics of LT GaAs tend to be like those of SI GaAs substrate. Besides the annealing temperature, the growth temperature of LT GaAs versus the mobility were also been investigated [97], and the results listed in Table 2-1.
### Table 2-1 Mobility of GaAs grown at different temperatures [97]

<table>
<thead>
<tr>
<th>Experiment temperature (°C)</th>
<th>( \text{T(growth)}=225,^\circ\text{C} )</th>
<th>( \text{T(growth)}=300,^\circ\text{C} )</th>
<th>( \text{T(growth)}=350,^\circ\text{C} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>2000</td>
<td>3200</td>
<td>4000</td>
</tr>
<tr>
<td>60</td>
<td>2250</td>
<td>3300</td>
<td>3850</td>
</tr>
<tr>
<td>90</td>
<td>3000</td>
<td>3250</td>
<td>3500</td>
</tr>
<tr>
<td>120</td>
<td>3200</td>
<td>3200</td>
<td>3250</td>
</tr>
</tbody>
</table>

The growth temperature of LT GaAs must be well controlled, thus various approaches have also been investigated to find easier growth procedures. Methods such as embedded thin layers of ErAs in GaAs during growth [98] to reduce the carrier lifetime without affecting the material mobility, or the use of ion-implanted GaAs: C [99] and GaAs: As [100] instead of LT GaAs can be treated as alternative and complementary approaches for THz photoconductors.

#### 2.3.2 Low temperature grown \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As-In}_{0.52}\text{Al}_{0.48}\text{As Multiple Quantum Wells (LT InGaAs-InAlAs MQWs)} \)

Although LT GaAs meets all the requirements for photoconductive material, the large band gap energy 1.42 eV makes the ideal excitation wavelength of this type of photoconductor around 800 nm which is well matched to Ti: Sapphire femtosecond lasers. This cumbersome and costly requirement limits the use of LT GaAs. In recent years, Yb: fiber and Er: fiber lasers with wavelengths of 1050 nm and 1550 nm have shown significant advantages as femtosecond sources due to their lower costs, robustness, portability, and low maintenance requirements. Unfortunately, the LT GaAs based photoconductors are incompatible with these fast lasers [101]. Thus, the challenge becomes one of synthesising materials with similar properties to those of LT GaAs but with narrower band gaps to match femtosecond Er: fiber lasers.

1550 nm is the most widely used wavelength in telecommunication systems. The material which can be excited at this most desired wavelength is the lattice matched \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As} \) grown on InP substrate with the use of LT InGaAs photoconductive antennas already reported for TDS applications [102]. Similar to the native defects in the LT GaAs, the
excessing arsenic incorporation in low temperature grown In\textsubscript{0.53}Ga\textsubscript{0.47}As (LT In\textsubscript{0.53}Ga\textsubscript{0.47}As) also leads to ultrafast recombination properties. However, compared with LT GaAs, the InP-lattice-matched In\textsubscript{0.53}Ga\textsubscript{0.47}As shows a much lower resistivity as the induced defects level (n-type) is close to the conduction band edge of In\textsubscript{0.53}Ga\textsubscript{0.47}As [103]. This, unfortunately, is detrimental to THz applications. To avoid this drawback, doping the material with an acceptor element can be used to compensate the free electron concentration in LT In\textsubscript{0.53}Ga\textsubscript{0.47}As. Adding Beryllium (Be) dopants helps the In\textsubscript{0.53}Ga\textsubscript{0.47}As Fermi level shifts towards the middle of the band gap and increases the available traps numbers. The In\textsubscript{0.52}Al\textsubscript{0.48}As layer grown under the same conditions as LT InGaAs is used to “simulate” LT GaAs since it has a similar band gap. The purpose of this layer is to further increase the resistivity and reduce the response time to the femtosecond range. The free electrons from In\textsubscript{0.53}Ga\textsubscript{0.47}As can be trapped by the high amount of deep electron trap levels in the In\textsubscript{0.52}Al\textsubscript{0.48}As at the interface [104]. To make the trapping effect efficient, the distance between the electrons and trapping centers need to be short. Thus the thicknesses of In\textsubscript{0.53}Ga\textsubscript{0.47}As layers need to be limited within the range from 100 Å to 150 Å. Also, the band gap of In\textsubscript{0.52}Al\textsubscript{0.48}As is 1.44 eV which is higher than that of In\textsubscript{0.53}Ga\textsubscript{0.47}As, thus making the material transparent at 1550 nm. The photoconductive layer and trapping layer are repeated many times in order to enhance the absorbance. This design therefore consists mainly of LT In\textsubscript{0.53}Ga\textsubscript{0.47}As-In\textsubscript{0.52}Al\textsubscript{0.48}As multiple quantum wells (LT InGaAs-InAlAs MQWs). Chen’s group reported three LT InGaAs-InAlAs MQWs designs with different Be doping profiles [105]. This report concluded that the reduction of the residual conductivity was primarily due to the increase of the Be concentration.

Be doped LT InGaAs-InAlAs MQWs grown in the range of 100 °C-200 °C has been investigated by Kuenzel’s group [106]. Their results show that the annealed material has a higher response time, even though the response time for both as grown and the annealed material are still in the range of femtoseconds, 230 fs for as grown and 1500 fs after annealing (see Figure 2.9).
Under the same conditions, the material showed a high sheet resistance of \( \sim 10^6 \, \Omega/\text{sq} \) and motilities in the range of 500-1500 cm\(^2/\text{Vs}\).

Unlike the incorporation of ErAs into GaAs which helps LT GaAs to have even higher resistivity and short carrier lifetime, the same method results in a lower resistivity of InGaAs material [107]. Researcher found out that a thin layer of ErAs island embedded in the In\(_{0.53}\)Ga\(_{0.47}\)As-In\(_{0.52}\)Al\(_{0.48}\)As can be used to make efficient photoconductor operating at 1500 nm [108]. Up to an overgrowth ErAs thickness of 2.4 ML, the structure revealed a smooth crystalline structure, after which the crystalline coherency was lost. The mobility of the material at room temperature ranged from 1500 to 5700 cm\(^2/\text{Vs}\).

Another approach for developing 1550 nm excited photoconductive materials is to implant heavy ions in standard In\(_{0.53}\)Ga\(_{0.47}\)As. The bombardment of Fe ions in In\(_{0.53}\)Ga\(_{0.47}\)As leads to a material resistivity of \( \sim 100 \, \Omega \text{cm} \), carrier lifetime of 300 fs and THz pulses width in the range of 100 fs to 700 fs [109, 110]. The bombardment of Br (Bromine) ions in In\(_{0.53}\)Ga\(_{0.47}\)As leads to a material with a resistivity of \( \sim 5 \, \Omega \text{cm} \), recombination time of 200-300 fs and carrier mobility of 490 cm\(^2/\text{Vs}\) [111].

### 2.4 Electronic devices based on Quantum Mechanical tunnelling

For up conversion, electronic devices can be used as alternatives for THz sources and detectors. This method can avoid the bulky and costly lasers and largely reduce the price.
and simplify THz system. The following section will focus on electronic devices based on quantum mechanical tunnelling mechanism.

2.4.1 Quantum tunnelling phenomena

Tunnelling is a quantum-mechanical phenomenon which was first discovered at the beginning of the twentieth century as a result of extensive studies of radioactivity. In classical physics, carriers are completely confined by potential walls or barriers. Only those carriers with excess energy higher than the barriers can escape, via the thermal emission transport mechanism described previously for Schottky diodes. By contrast, from the viewpoint of quantum mechanics, a small particle (electron) can have both wave and particle properties [63], and thus an electron can be represented by its wave function which permits the probability for the electron to be on the other side of a barrier even if its energy is much less than that of the barrier. In semiconductor technology, homojunction semiconductor structures with abrupt doping concentration or heterojunction structures with multi-layer can be used to create potential barriers. The thinner the barrier is, the higher is the probability that an electron can be found on the other side of the barrier.

The probability of electron tunnelling through a barrier can be found by solving Schrödinger’s equation. The electrons travelling in a semiconductor crystal can be described using wave functions (ψ) that are solutions of the Schrödinger equation:

\[
\frac{d^2 \psi}{dx^2} + \frac{2m^*}{\hbar^2} [E - V(x)] \psi = 0 \tag{2.11}
\]

Where \(x\) is the position vector, \(m^*\) is the effective mass of electron, \(V(x)\) is the potential energy at position \(x\), \(E\) is the total energy of the electron and \(\hbar\) is the reduced Planck constant. Figure 2.10 depicts the potential structure, which is divided into two regions, and how an electron tunnels through the barrier due to its wave property.
In the case of a single potential barrier of height $U_0$ and width $W$, $\psi$ has a general form $\exp(\pm ikw)$, and $k = \frac{\sqrt{2m^* (E - U_0)}}{\hbar}$. As the carrier which can tunnel through barrier has the energy $E$ lower than $U_0$, the value under the square root is negative and $k$ is then imaginary. For the simple rectangular barrier, the solution of the wave functions and the tunneling probability can be calculated by using:

$$T_t = \frac{|\Psi_B|^2}{|\Psi_A|^2} \approx \frac{16E(U_0 - E)}{U_0^2} \exp \left( -2 \frac{2m^*(U_0 - E)}{\hbar^2} W \right)$$ (2.12)

For a certain energy $E$, a finite transmission coefficient can be obtained through having a small effective mass, and a thin barrier with low barrier height. The probability is exponential with width and root height. Unlike the conventional concept of transit time, the time for carriers to tunnel through the potential barrier is dominated by the quantum transition probability per unit time which is very short. Thus, the devices based on tunneling mechanism are very useful in the millimetre and sub-millimetre wave regions [63].

### 2.4.2 Esaki diodes

The Esaki diode is a p-n junction device that operates in certain regions of its I-V characteristic by the quantum mechanical tunneling of electrons through the potential barrier of the junction. The invention of this tunnel diode was disclosed by Leo Esaki, whose name is used to describe this special type of diode [112]. L. Esaki received the
Nobel Prize in recognition for his discovery of this first device which takes advantage of quantum tunnelling phenomena. The tunnelling mechanism and its related devices are considered very attractive for THz applications in oscillation and detection. This is largely due to the short transit time for the device which further contributes to extremely high speed of operation.

The Esaki diode is a p-n junction where both p- and n-type regions are heavily doped semiconductor materials. Because of the heavy doping concentrations, the Fermi level in the n-type material is above the minimum of the conduction band and the Fermi level in the p-type material is below the maximum of the valence band. The depletion region which can be treated as the barrier is very thin due to the same reasons. Thus, this extremely thin barrier (compared to conventional p-n junction) leads the carriers to tunnel through the barrier. Under the equilibrium condition of a p-n junction between two degenerate semiconductors, the Fermi level is constant throughout the junction (the energy bands are illustrated in Figure 2.11).

The $E_{Fp}$ (Fermi level of p-type semiconductor) lies below the valence band edge on the p side, and the $E_{Fn}$ (Fermi level of n-type semiconductor) lies above the conduction band edge on the n side. In order for the Fermi level to be constant, the bands must overlap on the energy scale. The overlapping means that with a small bias (forward or reverse bias), the filled and empty states are separated by essentially the width of the depletion region, and appear opposite to each other. If the doping concentrations are very high, the depletion region will be very narrow, and the electron field at the junction will be quite large, thus meeting the electron tunnelling conditions.

When applying a small forward bias, $E_{Fn}$ moves up in energy. Electron tunnelling occurs from n to p thus resulting in a conventional current from p to n, and the current increases continually with increased bias as more filled states are placed opposite the empty states. In Figure 2.11 (b), the current keeps on increasing with the biased voltage until it reaches a maximum value when the number of available unoccupied states in the opposite side (p-types) is maximum. The voltage bias at which the maximum current is obtained is called the peak voltage ($V_p$).

By increasing the bias voltage (bias voltage is higher than $V_p$) the bands begin to pass by each other, the number of states for electrons to occupy becomes less thus resulting in a
decrease of the current. The bias voltage at which the minimum value of current is obtained is called the valley voltage \( (V_v) \). This region of the I-V characteristic is very important since the dynamic resistance \( (dV/dI) \) is negative, and the negative differential resistance (NDR) is a key property for high frequency oscillator circuits.

From \( V_v \) and onward, the diffusion and drift currents start to govern current flow as in conventional p-n junctions. The full I-V characteristics are depicted in Figure 2.11 (d).

Under reverse bias, electrons tunnel from the filled valence band states below \( E_{F_p} \) to the empty conduction band states above \( E_{F_n} \). As the bias increases, \( E_{F_n} \) continually moves down and the numbers of electrons from p to n increase. The conventional current direction is opposite to the electron flow. Thus, at equilibrium, there is equal tunnelling from n to p and from p to n.

![Figure 2.11 Band diagrams of tunnel diode at (a) thermal equilibrium (zero bias); (b) forward bias \( V \) such that peak current is obtained; (c) forward bias approaching valley current; (d) forward bias with diffusion current and no tunnelling current; and (e) reverse bias with increasing tunnelling current [63]

2.4.3 Resonant tunnelling Diode (RTD)

The first double-barrier heterostructure using GaAs/Al\(_{0.7}\)Ga\(_{0.3}\)As was demonstrated by Chang, Esaki and Tsu in 1974 [113]. The resonant tunnelling diode (RTD) is a two-terminal device that consists of a narrow band gap semiconductor material (quantum well) sandwiched by two wide band gap layers (barriers). In such a device, the resonant tunnelling of electrons was empirically observed, and its IV characteristic exhibited a
CHAPTER 2

Negative Differential Region (NDR). Among all types of RTDs, the Double Barrier Quantum Well (DBQW) RTD is the most commonly used.

Table 2-2 depicts an example of the generic DBQW RTD based on the In$_x$Ga$_{1-x}$As-AlAs material system used in our lab in Manchester [114]. It is made by a single highly compressive indium rich quantum well structure (In$_{0.8}$Ga$_{0.2}$As) sandwiched between two thin AlAs tensile barrier layers. Other In$_{0.53}$Ga$_{0.47}$As layers are used as emitters or collectors and lattice matched to an InP substrate.

### Table 2-2 In$_{0.8}$Ga$_{0.2}$As-AlAs RTD with Indium-rich quantum well grown by MBE

<table>
<thead>
<tr>
<th>Layer</th>
<th>Material</th>
<th>Doping (cm$^{-3}$)</th>
<th>Thickness (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collector 1</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As (n++)</td>
<td>$2 \times 10^{19}$</td>
<td>450</td>
</tr>
<tr>
<td>Collector 2</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As (n+)</td>
<td>$3 \times 10^{18}$</td>
<td>250</td>
</tr>
<tr>
<td>Spacer</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>undoped</td>
<td>200</td>
</tr>
<tr>
<td>Barrier</td>
<td>AlAs</td>
<td>undoped</td>
<td>13</td>
</tr>
<tr>
<td>Quantum Well</td>
<td>In$<em>{0.3}$Ga$</em>{0.7}$As</td>
<td>undoped</td>
<td>45</td>
</tr>
<tr>
<td>Barrier</td>
<td>AlAs</td>
<td>undoped</td>
<td>13</td>
</tr>
<tr>
<td>Spacer</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>undoped</td>
<td>45</td>
</tr>
<tr>
<td>Emitter 2</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As (n+)</td>
<td>$3 \times 10^{18}$</td>
<td>250</td>
</tr>
<tr>
<td>Emitter 1</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As (n+)</td>
<td>$1 \times 10^{19}$</td>
<td>4000</td>
</tr>
<tr>
<td>Substrate</td>
<td>InP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The lattice constant and band gap of common III-V binary and ternary compound semiconductors at 300K are listed in Table 2-3.

### Table 2-3 Lattice constant and band gap of common III-V binary and ternary semiconductors [115]

<table>
<thead>
<tr>
<th>Material</th>
<th>GaAs</th>
<th>AlAs</th>
<th>InP</th>
<th>In$<em>{0.53}$Ga$</em>{0.47}$As</th>
<th>Al$<em>{0.7}$Ga$</em>{0.3}$As</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice constant (Å)</td>
<td>5.653</td>
<td>5.661</td>
<td>5.869</td>
<td>5.868</td>
<td>5.66</td>
</tr>
<tr>
<td>Band gap (eV)</td>
<td>1.42</td>
<td>2.14/2.83</td>
<td>1.344</td>
<td>0.753</td>
<td>2.058</td>
</tr>
</tbody>
</table>

For a ternary material which is made up of two semiconductor material A and B, the lattice constant obeys Vegard’s Law:

$$a_{(\text{alloy})} = xa_{(A)} + (1 - x)a_{(B)} \quad (2.13)$$

And the band gap of the alloy usually follows the virtual crystal approximation:
\[ E_{g(\text{alloy})} = xE_{g(A)} + (1 - x)E_{g(B)} \]  (2.14)

Figure 2.12 depicts the energy band diagram of the RTD under different bias conditions and the RTD I-V characteristics. \( E_f \) and \( E_c \) are the Fermi level and conduction band edge of the material. The superscript L and R presents the left side (emitter) and right side (collector) respectively. \( E_r \) shows the resonant energy state inside the quantum well.

The operational principle of the DBQW RTDs can be explained by the conduction band diagrams in Figure 2.12. Under equilibrium condition, no current flows as the resonant quantised stated is above the Fermi level. The resonant levels in the quantum well are dependent on the quantum well thickness and the electron effective mass of the semiconductor material. A reduced quantum well thickness and electron effective mass can
result in a higher resonant level. When forward bias is applied, electrons can obtain kinetic energy in the electric field and the tunnelling probability also increases in accordance with the bias. When the bias voltage further increases, the resonant state is pulled down and leads to the resonant tunnelling through the double barrier to occur. The resonant tunnelling takes place when electrons coming from the left side (emitter) have the same energy of the quantised state in the quantum well and results in a peak current flow. The voltage, at which current flow is maximum (point c in Figure 2.12), is called the peak voltage \( (V_p) \) and the peak DC current is \( I_p \). After reaching the peak point, the resonant energy will further move down with increasing bias voltage. Thus, the current drops due to this off resonance condition. The transmission coefficient reduces with increase in the voltage bias until thermal emission mechanism takes place, as shown in Figure 2.12 (after point d). The voltage, at which current flow is minimum, is called the valley voltage \( (V_v) \) and the valley DC current is \( I_v \). The region between the peak and valley voltages is referred to as negative differential resistance (NDR) as the current drops when increasing the applied voltage. One of the important parameters from the DC characteristics is the peak-to-valley-current ratio (PVCR) which can be expressed as: 
\[
PVCR = \frac{I_p}{I_v}.
\]
The PVCR should be as large as possible. The other key parameter for RTDs is the negative differential conductance \( G_n \) which can be expressed as:
\[
G_n = \frac{1}{R_n} = \frac{(I_p - I_v)}{(V_p - V_v)}.
\]
and decreases with increasing operating frequency. When the negative differential conductance is equal to zero, the operational frequency at which this happens is called the cut-off frequency for the RTD.

To achieve a high PVCR together with low peak voltage (for low power dissipation) and high current density, III-V compound semiconductors are natural choices for RTDs because of their ability to engineer the materials properties. An ideal material system for RTD should have a large conduction band offset with a matching lattice constant and small electron effective masses [117]. Silicon is always a preferred semiconductor material as it is compatible with IC technology. However the Si/SiGe material system has not been successful to date in achieving high PVCR and the effective quantum confinement is also not sufficient as the conduction band discontinuity between Si and SiGe is very small [118]. For RTD designs based on GaAs substrates, the GaAs/Al\(_x\)Ga\(_{1-x}\)As material system is used extensively. However, this material system suffers from a relatively low current density and high leakage problem due to the materials relatively high electron effective
mass and low conduction band offset. In order to increase the potential barrier height and achieve higher current density, the GaAs-AlAs was used as a replacement. The GaAs-AlAs material system was first introduced in 1985 by Tsuchiya [119]. Another promising material system is the In$_{0.53}$Ga$_{0.47}$As-In$_{0.52}$Al$_{0.48}$As RTD latticed matched with InP [120]. A higher current density can be achieved using this RTD because In$_{0.52}$Al$_{0.48}$As has a lower electron effective mass than Al$_x$Ga$_{1-x}$As. In$_{0.53}$Ga$_{0.47}$As-AlAs can also be used as the RTD material system, and the In$_{0.55}$Ga$_{0.47}$As quantum well can be replaced by an indium-rich In$_{0.8}$Ga$_{0.2}$As well. This idea makes the system able to produce large peak currents at low peak voltages [121]. Up to date, the highest peak current density of 23 mA/μm$^2$ using an indium-rich material system was achieved by the Asada et.al [122]. The highest RTD oscillation frequency of 1.92 THz was also reported by Asada [39].

### 2.4.4 Asymmetric spacer layer tunnelling (ASPAT) diode

The Asymmetric SPAcer layer Tunnelling (ASPAT) diode, invented by Syme and Kelly [123, 124], has a very thin single barrier sandwiched by two intrinsic spacer layers with asymmetrical thicknesses which results in an asymmetric I-V characteristics. The characteristics make the ASPAT diode a competitive candidate for use as a zero-bias high frequency detector [123-125]. The conduction band profile of the ASPAT diode is shown in Figure 2.13.

![Figure 2.13 The conduction band profile of ASPAT under different bias](attachment:figure2.13.png)

The epi-layer structure of a GaAs based ASPAT is shown in Figure 2.14. It consists of a 300 nm thick heavily doped GaAs buffer with a doping concentration of $4 \times 10^{18}$ cm$^{-3}$ grown on a SI GaAs substrate. This is followed by a lightly doped 40 nm thick GaAs with a doping concentration of $1 \times 10^{17}$ cm$^{-3}$. The main active layers of the ASPAT diode
contains a 2.83 nm AlAs (10 monolayers) barrier and two intrinsic GaAs spacer layers at both sides of the AlAs barrier with thicknesses of 200 nm and 40 nm respectively. On top of the main active layers, there is another GaAs layer with a doping concentration of $1 \times 10^{17}$ cm$^{-3}$. The top layer is a heavily doped GaAs with a doping concentration of $4 \times 10^{18}$ cm$^{-3}$. The heavily doped layers are included to facilitate the formation of low resistance Ohmic contacts. The lightly doped layers play the roles of emitter or collector when the device is biased under different conditions (forward or reverse). Both sides of the AlAs barrier are undoped spacers of unequal thicknesses, and this asymmetry in the doping profile is responsible for the asymmetry in the I-V characteristics. At the interface, a layer is formed due to electrons diffusing from the n$^+$ region into the intrinsic region. The electric field opposes further diffusion resulting in the band bending shown in Figure 2.13 (under bias).

Theoretically, the DC properties of the ASPAT can be obtained by solving the Schrödinger equation and Poisson equation. Thus, the transmission coefficient of the ASPAT is a function of energy. It depends on barrier’s properties such as electron effective mass, thickness and height. By considering carrier statistics and the perpendicular energy, the current density through the barrier $T(E)$ is determined by using the expression [125]:

$$ J = \frac{q m^* kT}{2 \pi^2 \hbar^3} \int_0^\infty T(E) \ln \left( \frac{1 + e^{\left(\frac{E_F - E}{kT}\right)}}{1 + e^{\left(\frac{E - E_F}{kT}\right)}} \right) dE \quad (2.15) $$

Where $m^*$ is the material effective mass, $k$ is Boltzmann’s constant and $\hbar$ is the Planck constant. $E_{F_R}$ and $E_{F_L}$ represent the quasi fermi levels of the spacers located at the right and left side of the barrier.
The E-k diagrams of GaAs and AlAs are shown in Figure 2.15. As can be seen in the figure, AlAs is a multi-valley semiconductor material which has a lower conduction band minima close to the X point and a higher conduction band minima close to the Γ point. For a thick AlAs layer, the electrons travel mostly via the X-valley. In case of the ASPAT, the thickness of the AlAs barrier is only 10 ML. This causes a Γ-Γ direct tunnelling with the AlAs bandgap of 2.83 eV (direct band gap) and the Γ-X current makes a minor contribution to transport and thus can be neglected.

2.4.5 ASPAT detector properties

The vital parameters used to evaluate the performance of high frequency detectors are transfer function, tangential sensitivity and NEP. When the power of the incoming signal is low, the output voltage of the detector follows a square law while it is linear when the incoming signal voltage is at high power. The detector will be saturated when the power is further increased (this is known as the saturation regime). The minimum signal which can be detected by a detector is given in terms of tangential sensitivity $T_{ss}$. The dynamic range of the detector is the ratio of the minimum detectable signal to the saturation signal. As a candidate for a high frequency zero bias detectors, the ASPAT diode shows a suitable dynamic range, low noise performance, and a comparable transfer function with other zero bias detector [125]. In addition, compared with the commonly used Schottky diode, the ASPAT is much more insensitive to temperature [127, 128] which makes the ASPAT more adapted to different operational environment without the need for temperature compensation. The minimum detectable signal, $T_{ss}$ of -50 dBm at 40 GHz was achieved by using SBD. For an RTD the corresponding values are -35 dBm at 33 GHz [129], while it is -55 dBm at 10 GHz for GaAs-AlAs ASPAT diodes [130].
CHAPTER 3: EXPERIMENTAL TECHNIQUES

3.1 Introduction

In order to investigate the performance of the samples, the growth, fabrication and sample characterisation techniques need to be discussed. All the samples used in this work were grown using the solid source Molecular Beam Epitaxy technique and therefore this technique is described first. Next in the chapter, the main characterisation techniques used are introduced. The characterisation processes of the materials comprised of Hall Effect measurements in order to obtain the carrier concentration, electrical mobility and the sheet resistance and mid-infrared reflectivity measurements in order to obtain the optical characteristics. Then the design of a photo mask using a ground-signal-ground (GSG) configuration for the ASPAT diodes is described, followed by the detailed descriptions of the fabrication process of the devices, which was based on i-line photolithography technique. Finally, DC and RF measurement techniques are explained.

3.2 Molecular Beam Epitaxy (MBE) growth technique

Both low temperature photoconductive materials and materials for tunnelling diodes in this work were grown using the solid source Molecular Beam Epitaxy (MBE) technique. The use of the MBE and the low temperature (~200 °C) growth technique results in semiconductor materials which have carrier recombination times in the femtoseconds regime due to the formation of native defects and nano-clusters of arsenic precipitates. Furthermore, the epitaxial layers thicknesses can be controlled within a monolayer precision. This is essential for the ASPAT diode as the performance of this tunnelling device is highly dependent on the barrier thickness. The desired control and precision of layer thickness in ASPAT diode have been previously reported by our group [131].

By heating up solid sources (elements such as In, Ga, Be and As sources in ultra-pure forms) under ultra-high vacuum condition [132] (≈10^{-10} - 10^{-11} Torr), a beam is produced, which is directed on the surface of the substrate (i.e GaAs or InP), for example, the growth of In_{0.53}Ga_{0.47}As material is on an InP substrate (lattice matched). The uniformity of the deposited materials is achieved by rotating the heated substrate. The schematic diagram of a typical MBE system for the growth of In_{0.53}Ga_{0.47}As on InP substrate is illustrated in
Figure 3.1 (a) and a photo of the actual MBE growth system (V100HU) is shown in Figure 3.1(b), HU stands for High Uniformity.

During the growth process, the epitaxial layers are monitored by the reflection high energy electron diffraction (RHEED) technique, while mechanical shutters are used to precisely control the thickness of each layer [134].

3.3 Hall Effect measurements

The Hall Effect is described in Figure 3.2 where an applied current in a semiconductor sample is in the y direction and a magnetic field is applied in the z direction. Then a voltage in the x direction can develop across the sample. The type of majority carrier is indicated by the sign of the measured voltage while the concentration and the mobility can be obtained based on the magnitude of the measured Hall voltage.
The Hall Effect measurements are used to obtain the electronic transport properties of the photoconductive materials based on the Van der Pauw method. The standard four contact technique is used to perform the measurement. A known current is passed through two contacts $I_{AB}$ and the voltage is measured across the other two contacts $V_{CD}$. According to the Van der Pauw method, the conductivity of the sample is given as:

$$\sigma = \frac{\ln 2 \cdot I_{AB}}{\pi d \cdot V_{CD}} \quad (3.1)$$

where $d$ is the active layer thickness.

In the Hall Effect measurements, the majority and minority carrier types, concentration and mobility can be obtained. When both mobility and concentration are known, the resistivity $\rho$ can be deduced using the following expression:

$$\rho = \frac{1}{q \mu n} \quad (3.2)$$

where $q$ is the electron charge, $\mu$ is the mobility and $n$ is the free carrier concentration of the material. All these factors are vital for analysing THz photoconductive materials.

The other reason for choosing the Van der Pauw method is that the samples are easier to prepare for the measurements. The test material needs to be patterned using a cloverleaf geometry and a standard photolithography technique. Four indium (In) dots at each corner of the mesa etched area are used as Ohmic contacts. The Van der Pauw geometry Hall Effect sample is shown in Figure 3.3.
In order to form good Ohmic contacts the test sample should be annealed at the proper temperature (420 °C for LT GaAs and 310 °C for LT InGaAs-InAlAs MQWs) in a Nitrogen (N₂) atmosphere. The preparation of Hall Effect samples is described in detail in Appendix A1.

In this work two customised set-ups were used for the Hall Effect measurements. The first system, which is shown in Figure 3.4 (a), includes a Hall Probe Test Unit and a Fluke 45 Dual Display Multimeter. This multimeter is able to supply a minimum of 10 μA. This set up is suitable for low resistivity samples. For very high resistivity samples, an alternative set-up (shown in Figure 3.4 (b)), which contains a Keithley 196 system DMM, Keithley 705 scanner, Keithley 220 Programmable current source and a Keithley 485 Auto ranging picoameter, can be used. This set-up can supply a minimum current as low a 1 nA. The second set-up is also able to do the Hall Effect measurements under different temperatures. Samples were held in an Oxford Instruments liquid nitrogen cryostat model DN1711 and a LakeShore 330 Autotuning Temperature Controller were used to vary the temperature.

Figure 3.3 Van der Pauw geometry Hall Effect sample

Figure 3.4 Hall Effect measurements set ups used in this work
3.4 Mid-infrared reflectivity measurements

One of the main objectives of this project is to evaluate the optimised photoconductive materials incorporated with a distributed Bragg reflector (DBR). A DBR is formed by multiple layers structure of different material with varying refractive index which can causes a high reflection at a specified wavelength. The periodic layers in DBRs thus act as a high-quality reflector. The reflectivity measurement is a non-destructive optical procedure to test the quality of the DBRs at the desired wavelength.

![Figure 3.5 Reflectivity measurement system](image)

The setup of the mid infrared measurement is shown in Figure 3.6. The source of this mid-infrared reflectivity measurement is a tungsten halogen broadband source Oceanoptics LS1™. Two different detectors are used in this work. In the wavelength range of 400 nm
to 1100 nm, a Si CCD array was used. In the wavelength range of 900 nm to 2500 nm an extended InGaAs detector was used. Depending on the material being tested, each appropriate detector was used. In order to obtain reliable measurements, a calibration should be performed before testing the samples. Under dark conditions (source turned off), the background noise needs to be stored first. The next step is to measure the reflectivity of a reference sample with the light source on. As the reflectivity of the sample is highly dependent on the reference sample, a reflectivity of the chosen sample must be set and stored as the reference before the measurement can be performed.

3.5 Device fabrication

After material characterisations, devices need to be fabricated and tested. The performance of the device is critically dependent on the geometrical design of the device and their epitaxial structure.

3.5.1 Mask design

The antenna geometry of the photoconductive materials in this work will be described in Chapter four and Chapter five. The following sections concentrate only on the mask design of the ASPAT diodes. The mask was designed using the commercial Advanced Design Software (ADS) package and patterned as a mask by the CompGraphics Ltd.

In order to work at high frequencies, the mesa area of the diode needs to be small to decrease the junction capacitance. Such junction capacitance increases the operating frequency of the device [135]. One of the tasks in this project was to design a mask including diodes with different dimensions suitable for operation over different frequencies. In addition, the design should also be compatible with RF measurement, requiring a ‘Ground-Signal-Ground’ (GSG) contact structure.

There were two kinds of mask designs attempted. The first (design 1) was used for fabricating the GaAs-AlAs ASPAT diodes and relied on a dielectric passivation layer. This design contains 7 layers in total. The fabrication process steps for design 1 can be seen in Figure 3.7 (a). The second design (design 2), which includes 5 layers, used the air-bridge technique. This mask was used for fabricating InGaAs-AlAs ASPAT diodes. The fabrication process is shown in Figure 3.7 (b). For design 2, step 4 can be neglected as the pad structure (mask 5) covers the area of the bottom contacts in step 4.
Both design 1 and design 2 are suitable for dry and wet etching methods. In this work, wafer tiles of dimensions 15×15 mm² dimensions were diced using standard dicing procedure of 2”, 3” or 4” wafers. In both designs, the total number of die chips was four hundred and fifty (450) having eight kinds of mesa areas (100×100 µm², 50×50 µm², 30×30 µm², 20×20 µm², 15×15 µm², 10×10 µm², 6×6 µm² and 2×2 µm²). For each chip, the die size is 600 µm×600 µm. The strip width (2a) was designed to be 40 µm while the spacing between the micro-strip and the ground pad was designed to be 60 µm. The strip width to ground plane spacing ratio is kept to 0.25, considering the losses in coplanar waveguides [136]. The ratio equals to 2a/2b as shown in Figure 3.8.

![Figure 3.7 Fabrication process flow for (a) design 1; (b) design 2](image)

![Figure 3.8 Geometry of coplanar waveguide](image)
To minimise the interaction between diodes as well as to decrease potential current leakage, the isolation area was designed 5 μm wider from the edge of the contacts. The distance between top and bottom contacts affect the series resistance of the diode so the tolerance between contacts was kept at 2 μm. The complete layouts of both designs are shown in Figure 3.9. The close-up view of a single ASPAT diode with 6 μm×6 μm mesa area is shown in Figure 3.10. The dielectric layer is not shown in Figure 3.10 (a) since this layer is designed as a negative layer for passivation via opening. The working principle of the air-bridge is described along with the DC properties of the devices in Chapter five.

Figure 3.9 The complete 15×15 mm² mask designed using Agilent ADS software (a) dielectric design (b) air-bridge design

Figure 3.10 Close-up view of a single ASPAT diode with 6 μm×6 μm mesa area (dielectric layer and air-bridge)
3.5.2 Fabrication process

The fabrication method used in this work is contact photolithography. Compared with electron-beam lithography (EBL), photolithography cannot produce features below 500 nm [137]. However, photolithography is a relatively easier and low-cost way to fabricate devices. In general, the photolithography method includes tile preparation, spin coating, exposure and developing [138].

Appendix A2 describes the recipe for the fabrication steps for photoconductive antennas while Appendix A3 and Appendix A4 show the final recipes for GaAs-AlAs and InGaAs-AlAs ASPAT diode respectively.

3.5.2.1 Sample Cleaning

For every type of fabrication process, the first step is to clean the sample. Samples were carefully cleaned using N-Methyl-Pyrrolidone 1165 (NMP) solution, H₂O, Acetone, and Isopropanol (IPA). This is important although the fabrication is conducted in the cleanroom as any contaminants can still affect the performance of the devices. Here, the contaminants generated by various sources, such as operation crew, facilities in the clean room and chemical residues. NMP and Acetone are used to remove organic materials while IPA removes Acetone residues.

The cleaning process in the clean room at room temperature is:

1. Sample is put in NMP solution to eliminate organic residue for 5 mins (in an ultrasonic bath under power 1)
2. NMP is removed by using de-ionised (DI) water and blown with a nitrogen (N₂) gun to dry the sample
3. Acetone is then applied for another 5 mins in an ultrasonic bath
4. IPA is used after Acetone to remove Acetone. This step also takes 5 mins.
5. Due to the rapid evaporation of IPA, the sample needs to be dried using N₂ gun as fast as possible.

After the sample cleaning steps are completed, the sample is visually inspected under a microscope to ensure there are no particles on the surface. If an acceptable cleanliness is
not achieved, the cleaning steps need to be repeated. During the entire fabrication process, visual inspections are taken frequently to ensure adequate cleanliness of the sample surface.

### 3.5.2.2 Photolithography

In the photolithography technique, the device patterns are transferred onto the surface of the sample according to the designed mask. This method uses ultra-violet (UV) light with wavelengths between 200 nm to 450 nm to expose the sample and print the patterns. In this work, a Karl Suss MA4 mask aligner was used. The source produced a UV light at 365 nm (i-line) wavelength with intensity at 0.9 mW.

![Figure 3.11 Picture of MA4 mask aligner system](image)

The process begins with a spin-coating step. In this step, a thin layer of light-sensitive material is coated on the surface of the cleaned sample. There are three different types of light sensitive materials, known as positive, negative and reversible photoresist. The chemical bonds of the positive photoresist break during exposure to UV light, thus the remaining positive photoresist keeps the same pattern as the designed structure shown on the mask. The opening area for this type of photoresist will be slightly larger than the pattern on the mask due to scattering phenomenon. The negative photoresist when it is exposed to UV light strengthens its chemical bonds (crosslinking) so that the unexposed areas are dissolved in a developer while the exposed ones remain. This means that the remaining negative photoresist shows an opposite pattern to the mask. The opening for the negative photoresist will be smaller than the designed pattern. In the case of reversible resist, it can be used as both positive and negative photoresist and the UV light produces a reversal image.
The positive photoresists used throughout in this work are commercially available from Microposit S1800 series. To be more specific, S1805 and S1813 have thickness of 0.5 µm and 1.3 µm respectively. Furthermore, negative photoresists with 2.0 µm, 1.0 µm and 0.5 µm thickness supplied by MicroChemicals were also used. In general, positive photoresist is used for etching steps and negative photoresists are used in single layer lift-off processes due to their side wall profile.

The existence of an edge bead (shown in Figure 3.13) will affect the contact between sample and mask, thus leading to an undesired scattering during exposure. The latter makes the printed pattern different from the designed one. To avoid the effect of edge beads, an edge bead remover (EBR) has to be used after spinning off the negative photoresist for the contact masks.
In order to stabilize the photoresist, the samples need to be put on a hot plate or in an oven after exposure. Different concentrations of developers are used for positive and negative photoresists. The developer solution for positive photoresist is MF 319 while, MF 326 acts as a negative photoresist developer solution.

The recipes for use of the photoresists with their corresponding spinner setting and development times are shown in Table 3-1.

Table 3-1 Photoresists with their corresponding spinner setting and developing times

<table>
<thead>
<tr>
<th>Photoresist</th>
<th>Thickness (µm)</th>
<th>Spin Speed (r.p.m)</th>
<th>Spin time (s)</th>
<th>Exposure time (s)</th>
<th>Developer</th>
<th>Development time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1805</td>
<td>0.5</td>
<td>4000</td>
<td>30</td>
<td>22-25</td>
<td>MF319</td>
<td>1</td>
</tr>
<tr>
<td>S1813</td>
<td>1.3</td>
<td>4000</td>
<td>30</td>
<td>120</td>
<td>MF319</td>
<td>2</td>
</tr>
<tr>
<td>Az 2.0</td>
<td>2</td>
<td>3000</td>
<td>40</td>
<td>5.5</td>
<td>MF326</td>
<td>1</td>
</tr>
<tr>
<td>Az 1.0</td>
<td>1</td>
<td>3000</td>
<td>40</td>
<td>8</td>
<td>MF326</td>
<td>1</td>
</tr>
<tr>
<td>Az 0.5</td>
<td>0.5</td>
<td>3000</td>
<td>40</td>
<td>12</td>
<td>MF326</td>
<td>1</td>
</tr>
</tbody>
</table>

3.5.2.3 Sample Etching

Etching is one of the main steps in microelectronics manufacturing and it creates well-defined active area or mesa. Normally, there are two different etching methods: wet and dry [140]. Wet etching is more common to use as it is usually fast and cost effective. The etching rate depends on the etchant solution and the operational environment (temperature and humidity). One disadvantage of wet etching is that it not only etches vertically, but also laterally (isotropic etching). Basically, the lateral etching is undesirable as it changes the active area size. However, the opening of air-bridge for InGaAs-AlAs ASPAT diode relies on this lateral etching. In the case of dry etching, the etching rate is less sensitive to temperature and more repeatable (anisotropic etching) but relatively expensive. Both methods are used in this study.
(1) Wet etching

The etchant for GaAs-system starts from oxidising the surface and then dissolving the oxide and hence both Ga and As atoms can be removed. Two groups of etchants were studied. As the etching rates for the etchants are sensitive to the operating environment [141], clean room temperature was controlled within 18 °C - 20 °C with the humidity from 47%-61% throughout these studies. Orthophosphoric-based etchants are mixtures of Orthophosphoric acid, Hydrogen Peroxide and DI Water (H₃PO₄: H₂O₂: H₂O). For each solution, there were at least forty runs (including calibration samples and real samples) for GaAs and InGaAs. The average etching rates for GaAs and InGaAs using Orthophosphoric-based etchants with ratios of H₃PO₄: H₂O₂: H₂O=2:1:2, H₃PO₄: H₂O₂: H₂O=1:1:38 and H₃PO₄: H₂O₂: H₂O=3:1:50 are shown in Figure 3.14.

By using H₃PO₄: H₂O₂: H₂O=2:1:2, the average etching rates for GaAs and InGaAs are 48nm/sec and 39nm/sec respectively. Throughout the fabrications in this work, the highest etching rates using H₃PO₄: H₂O₂: H₂O=2:1:2 for GaAs and InGaAs are 52 nm/sec and 45nm/sec while the lowest rates were 43 nm/sec and 35 nm/sec respectively. As the etching rates using H₃PO₄: H₂O₂: H₂O=2:1:2 are faster, during the process, the etching time should be well controlled, down to seconds. In the case of GaAs, using H₃PO₄: H₂O₂: H₂O=1:1:38 and H₃PO₄: H₂O₂: H₂O=3:1:50, the highest etching rates variation were 0.05 nm/sec for both etchants. For InGaAs, only H₃PO₄: H₂O₂: H₂O=3:1:50 were used, and the variation was about 0.1 nm/sec. Since the etch rate is small in comparison to other concentrations, there is no need to control the etching time to the one second precision. Thus, the etching time for H₂O₂: H₂O=1:1:38 and H₃PO₄: H₂O₂: H₂O=3:1:50 were normally controlled to within one minute or half a minute.
Figure 3.14 Average etching rates for (a) GaAs and (b) InGaAs using Orthophosphoric-based etchant at different ratios

By using the Orthophosphoric-based etchants, the absolute vertical cross-sectional structure cannot be achieved. In the case of the InGaAs material system, the cross-sectional views of the device are depicted in Figure 3.15.
The Ammonium Hydroxide: Hydrogen Peroxide: DI Water (NH$_4$OH: H$_2$O$_2$: H$_2$O) was reported as a highly anisotropic wet chemical etching for 2° mis-oriented GaAs substrate [142]. This etchant can be useful to vertically etch GaAs samples. The etching rates for GaAs with Ammonium Hydroxide- based etchants with different ratios are shown in Figure 3.16.

![Figure 3.15 Cross sectional view of InGaAs device (a) ideal etch (b) practical wet etch](image)

**Figure 3.15 Cross sectional view of InGaAs device (a) ideal etch (b) practical wet etch**

The etching rates for Ammonium Hydroxide-based etchant were tested with three different ratios: NH$_4$OH: H$_2$O$_2$: H$_2$O=1:1:8, NH$_4$OH: H$_2$O$_2$: H$_2$O=1:1:18 and NH$_4$OH: H$_2$O$_2$: H$_2$O=1:1:40. The deviation between each run can be up to 3 nm/sec, 0.7 nm/sec and 0.5 nm/sec.
nm/sec respectively. Amongst all three etchants, NH₄OH: H₂O₂: H₂O=1:1:40 showed the best stability, thus this etchant was used for wet etching the GaAs samples.

As can be seen in Figure 3.14 and Figure 3.16, the etching rates did fluctuate. This is due to the variation of temperature and humidity of the clean room during processing. Thus, calibration before each is extremely important, especially if the samples need careful control of etching depths.

(2) Dry etching

Compared to wet etching, dry etching can provide higher resolution anisotropic etching [143]. There are several dry etching techniques commonly used. The first type is ion milling [144]. The energetic noble gas ions, such as Argon (Ar +), bombard the sample surface and erosion occurs by physically knocking atoms off the surface. This method provides highly anisotropic etching, but significant displacement damage which can extend to hundreds of nanometres into the material. The second method uses plasma which contains ions, free radicals and by-products. The material erosion occurs when free radicals and by-products decrease the activation energy (in chemical reaction) [145]. The method used in this work was the reactive ion etching (RIE), and the schematic of a RIE system is shown in Figure 3.17. In the reactive gas, an applied radio frequency (13.56 MHz) between two parallel electrodes generates the plasma. The electric field across the area between the plasma and electrodes (plasma sheath) leads to the accelerations of ions at the edge of the plasma across the plasma sheath. The sample which is placed on the cathode is targeted by the ion bombardment, neutral gas atoms and molecules from the plasma[146]. The class of gas mixture used in this work is based on methane (CH₄) and hydrogen (H₂). This mixture can etch both gallium- and indium- based semiconductor smoothly and is highly anisotropic. The etch products for this mixture can be AsH₃ (or PH₃) and (CH₃)nGa (most probably methyl adduct) for group V and III species respectively [147].

In this work, samples used the deposited metal (top contact) as the mask while S1805 was used to protect the TLM pattern (See Section 3.6). Material such as CₙHₙX can remain on the surface of the sample which obstructs the etching reaction [148]. Thus, in the dry etching process, the system settings need to be well controlled to reduce the polymer residues. The sample was etched at a forward biased power of 150 W with a gas flow for CH₄ of 10 sccm and H₂ of 80 sccm providing a pressure of 42 mTorr. Under these
conditions, the etching rate of GaAs and InGaAs were 15±5 nm/min and 21±3 nm/min respectively. After each run of the semiconductor etching, a polymer removal step needs to be followed. This is done by using a forward power of 100 W oxygen (O₂) flow of 30 sccm under 100 mTorr.

![Schematic of RIE system](image)

**Figure 3.17 Schematic of RIE system**

### 3.5.2.4 Post growth annealing

The post growth annealing is an essential step specifically for low temperature grown photoconductive materials. It was proved to improve the crystallinity and the structural integrity of the epilayers [149]. In addition, the strain in the lattice caused by the excess arsenic relaxes. Gregory et al have reported the effects of post growth annealing on LT GaAs material [90]. Sometimes, due to the characteristics and properties of the material, annealing cannot be done during the growth process and samples need to be annealed ex-situ. A Rapid thermal annealer (RTA) allows the formation of precipitates from the arsenic excess incorporated as point defects [21]. Post growth annealing in this work was performed in all the samples using a Process Products Corporation Rapid Thermal Module. A picture of the RTA is shown in Figure 3.18.
Figure 3.18 Rapid Thermal Annealer used in this work

The annealing process can change the properties of the material. The characterization of samples under different annealing temperature and time were described by our group before [150]. The consequence of annealing the samples was a significant decrease in the residual carrier density. The group showed previously that the characteristics are improved significantly by annealing the material in the range of 500-600 °C for 10-15 minutes. For LT GaAs and LT InGaAs-InAlAs MQW samples, the optimum RTA temperatures used in the fabrication process were set to 580 °C and 600 °C respectively. During the annealing process, samples were covered by high purity SI GaAs substrates to prevent arsenic loss from the sample surface and annealed in an N₂ environment for 10 min.

3.5.2.5 Metallisation

In order to make working devices, the fabricated semiconductor device should be able to be connected to components in the outside world. This means that the deposition of a conductive material (metal) on the surface of the device is necessary. There are several methods used for metal deposition such as Filament Evaporation, Electron-Beam Evaporation and Sputtering [151]. The technique used in this work was based on the filament evaporation technique. The filament current of a boat is increased until the metal starts to melt and evaporate. Two evaporators were used in this work. For the photoconductive antennas, a BioRad evaporator was used. The picture of this equipment is shown in Figure 3.19 (a). Before metal deposition, the patterned sample was de-oxidized in a HCL: H₂O=1:1 solution. For the photoconductive antennas, a 1.5 cm Titanium (Ti) and a 5 cm Gold (Au) were loaded in separate boats in the evaporator. This resulted in final
metal contacts with thickness of 50 nm for Ti and 100 nm for Au. The process conditions require a low-pressure environment (10^{-6} mbar) to minimise contaminations and reduce scattering. In the case of the ASPAT diodes, this process is performed using an Edwards Auto 306 (shown in Figure 3.19 (b)) which has a lower base pressure of 10^{-7} mbar. For ASPAT diodes, the same metals are evaporated with contact thickness of 55 nm for Ti and 250 nm (minimum) for Au.

![Evaporator set-ups](image)

**Figure 3.19 Evaporator set-ups (a) Bio Rad and (b) Edwards Auto 306**

### 3.5.2.6 Lift-off

After mettallisation, a uniform metallic film is evaporated on the material surface. The purpose of lift-off is to remove any undesired metal. This is based on the elimination of the deposited photoresist in the previous spin-coating step. Figure 3.20 shows the lift-off process with a negative photoresist undercut profile.

![Lift-off process](image)

**Figure 3.20 Lift-off process with the negative photoresist undercut profile**
3.5.2.7 Annealing

Annealing is a critical step for all devices fabricated in this work. For contacts, annealing forms an Ohmic contact with a smaller contact resistance compared with the un-annealed sample. The annealing temperature for the photoconductive antennas was 250 °C for 1 min using an alloying jig. For the ASPAT diodes, the samples were kept into a furnace for 2 mins at 420 °C (GaAs sample) or 280 °C (InGaAs sample). Pictures of the annealing equipment are shown in Figure 3.21.

![Annealing equipment](image)

(a) (b)

Figure 3.21 Annealing equipment (a) alloying jig and (b) furnace

3.6 Current-Voltage testing

The current-voltage testing is the step following the fabrication process. The electronic characteristics of devices can be obtained in this step. Moreover, the I-V testing is a useful tool to check the quality of the fabrication process. An Agilent Technologies B1500A semiconductor devices analyser was used for the I-V measurement at room temperature in this work. In addition, it is also common to perform the measurements at different temperatures. The temperature variation measurements were performed using a Lakeshore Cryogenic probe station. As liquid Nitrogen was used to cool down the system, the lowest temperature possible was 77 K. In order to protect the sample holder, the highest temperature was limited to 400 K. In that set-up the temperature could be maintained within ±0.1 K around the nominal value during data acquisition. To avoid the influence from light, all measurements were performed under dark conditions. The IC-CAP software program with predefined voltage and current compliances were used to acquire and analyse the data.
The metal-semiconductor contacts play a vital role for the semiconductor device characteristics hence the contact should be evaluated. In this project, in order to assess the metal-semiconductor contact, the transmission line model (TLM) technique was used [152].

The side-view for a typical Four-point probes TLM structure is shown in Figure 3.23. It consists of a series of metal contacts with different separations $d_n$ ($n=1,2,3,4,5$) in between. The separations of TLM testing pattern used in this work were from 5 $\mu$m up to 45 $\mu$m with a 5 $\mu$m increase step. These contacts are placed on a thin conducting layer (heavily doped material). This structure allows current to flow in the direction defined by the pattern.

The top view of this structure is illustrated in Figure 3.24. All the metal pads are defined with the same size with a length of $l$ and width $w$. $L_T$ is the transfer length (effective length) where most of the current flows into the semiconductor.
From the TLM measurements, a linear plot of the resistance versus distance can be obtained (as shown in Figure 3.25).

Two key values can be extracted from this plot. The first one is the contact resistance $R_c$ which can be evaluated from the slope of the plot. Assuming the contact resistances $R_c$ are the same, thus the total resistance $R_{\text{total}}$ between the first and second contact is given by:

$$R_{\text{total}} = 2R_c + R_{\text{sh}} \frac{d}{W} \quad (3.3)$$

where $R_{\text{sh}}$ is the sheet resistance (in $\Omega$/sq).

The second key value is the transfer length $L_T$. When $R_{\text{total}} = 0$, the interception of the measured line with the separation-axis gives a value of $2|L_T|$. 

---

**Figure 3.24** Schematic drawing for top-view of TLM structure

**Figure 3.25** Plot of resistance versus spreading distance in TLM structure
Once the values of contact resistance $R_c$ and transfer length $L_T$ are extracted, the series resistance $R_s$ of the fabricated diodes can be calculated. In the case of the RTD diode, $R_s$ includes the contact resistance, resistance due to the epi-layers $R_{epi}$ and the spreading resistance from the bottom contact layer [153]. The series resistance for the ASPAT diode can be calculated by the same method.

![Figure 3.26 Cross section of an ASPAT showing the epi-layers and contacts](image)

**Figure 3.26 Cross section of an ASPAT showing the epi-layers and contacts**

Based on $R_c$ and $L_T$ obtained from TLM measurement, the specific contact resistance can be expressed as [154]:

$$\rho_c = R_c L_T \frac{\sinh \left( \frac{l_c}{L_T} \right)}{\cosh \left( \frac{l_c}{L_T} \right)}$$  \hspace{1cm} (3.4)

where $l_c$ is the length of the contact pad.

The resistance of the epi-layers $R_{epi}$ can be given by the following equation:

$$R_{epi} = \rho \frac{l_{epi}}{A}$$  \hspace{1cm} (3.5)

where $\rho$ and $l_{epi}$ represent materials resistivity and the thickness of specific epilayers while $A$ refers to the active mesa area of the diode.

The spreading resistance $R_{spr}$ can be approximated as [39]:

$$R_{spr} = \frac{1}{\pi \sigma d_{ohmic2}} \ln \left( \frac{a}{a_{mesa}} \right)$$  \hspace{1cm} (3.6)
where $\sigma$ is the conductivity of the bottom ohmic layer (Ohmic 2) and $d_{\text{ohmic2}}$ is the thickness of Ohmic 2. In addition, $a_{\text{mesa}}$ is half of the length of the device length, $a$ refers to the length indicated in Figure 3.26.

Hence, the series resistance of the ASPAT diode is calculated by dividing the specific contact resistance to the diode active mesa size and adding the epi-layer resistance $R_{\text{epi}}$, and spreading resistance $R_{\text{spr}}$:

$$R_S = \frac{\rho_c}{A} + R_{\text{epi}} + R_{\text{spr}} \quad (3.7)$$

The series resistance decreases with increasing device mesa area. Lowering the ASPAT series resistance is a must for operation at THz frequencies.

### 3.7 Radio frequency (RF) measurements

RF measurement is an on-wafer measurements technique used to perform microwave characterisation of devices. In this work, an Anritsu 37369A vector network analyser (VNA) was used to acquire the scattering parameters (S-parameters) from 40 MHz to 40 GHz. The VNA is the key instrument to accurately measure the scattering parameters of devices in the microwave and millimetre wave ranges [155]. The fabricated GSG-designed ASPAT diodes were tested for each emitter dimension at room temperature using the equipment shown in Figure 3.27. The results from this experiment would provide an optimum design in terms of yield versus performance, providing a suitable reference for future work.

![Photo of VNA system set up](image)

**Figure 3.27 Photo of VNA system set up**
CHAPTER 4: LOW TEMPERATURE GROWN PHOTOCONDUCTIVE MATERIALS INCORPORATING DISTRIBUTED BRAGG REFLECTORS

4.1 Introduction

Even though the LT GaAs and LT InGaAs-InAlAs MQWs already showed good performances in TDS applications, the demand for high output THz power still remains for real time, fast acquisition data. Since the number of photo-carriers generated by illumination is the key factor in determining the efficiency of THz photoconductive devices, finding a way to generate more photo-carriers is essential to improve the performance of this type of THz devices. The photo-carrier generation is related to the strength of the electric field and the absorption coefficient of the photoconductive material. In the first case, the decay of the electric field strength can be prevented by vertically biasing the device [22]. In the second case, distributed Bragg reflector (DBR) layers can be incorporated during the growth process [156]. This work concentrates on the second case. Taylor and Brown have reported a significant improvement of the photoconductive switches performances by using a resonant-optical-cavity at 300 GHz [157]. The main idea for this chapter is to investigate photoconductive antenna performances incorporating with DBR layers.

This chapter includes a description of the epitaxial layers and doping profiles of the low temperature grown photoconductive materials incorporating DBRs. An extensive material characterisation and photoconductor antennas fabrication processes are presented. The summarised results from the measurements are then compared with conventional photoconductors. In addition, the fabricated transmitters and detectors are evaluated in a TDS system under pulsed operation. The characteristics of this optimised THz devices with DBR under the active layers revealed enhanced THz output power leading to further improvements in the performance of these already efficient devices.

The next part of this chapter introduces details of a home built 1.55 µm THz spectrometer with its key elements (emitter and detector) fabricated using the LT InGaAs-InAlAs
MQWs photoconductive material. A series of measurements using the full 1.55 µm THz spectrometer are also presented in this chapter.

4.2 LT GaAs DBRs structure

The THz photoconductive devices are based on laser-driven excitation. The relationship between the energy of a photon and the laser wavelength of the light (λ) is given by:

\[ E = \frac{hc}{\lambda} \]  

(4.1)

where \( h \) is Planck’s constant and \( c \) is the speed of light. The Equation 4.1 can be rewritten as:

\[ E(eV) = \frac{1.24}{\lambda(\mu m)} \]  

(4.2)

Currently, LT GaAs is the most promising photoconductive material as it presents a high resistivity, high electron mobility and ultrafast carrier lifetimes [90]. To date, this type of photoconductor is widely used in various optoelectronic THz applications. However, as the bandgap of this material is 1.42 eV at room temperature, the driving laser of the THz system should be operated at wavelengths around 800 nm. Such lasers can be femtosecond pulse Ti: Sapphire lasers and generate broadband pulsed THz radiation [73, 74].

However, even using LT GaAs as the transmitter and receiver in the THz system, the output power still hasn’t reached desirable levels. Thus, an optimised LT GaAs incorporating DBRs was developed.

In this section, two samples were evaluated. The first sample is a LT GaAs labelled as XMBE305, which was grown on a SI-GaAs substrate, and consists of a 240 nm GaAs buffer layer followed by a 50 nm AlAs layer and a 1 µm thickness low temperature grown GaAs layer. The optimised LT GaAs labelled as XMBE316 wafer has the same thickness of low temperature grown GaAs layer, but it has in addition 8 pairs of GaAs-AlAs DBR layers (centered around 800nm) between the low temperature grown GaAs and the 100 nm GaAs buffer layer. The total thickness of the DBR is 1.02 µm. Figure 4.1 illustrates the physical structures along with the layer thicknesses XMBE 305 and XMBE 316.
Figure 4.1 Physical structures along with the layer thicknesses of (a) XMBE 305 and (b) XMBE 316 (Both structures were designed to operate at 800 nm wavelength)

Both the GaAs and AlAs layers are $\lambda/4$ thick at 800 nm (with GaAs thickness= $800/4 \times 3.2=62.6$ nm, refractive index is 3.2 and AlAs thickness= $800/4 \times 3.02=66$ nm, refractive index is 3.02).

Note that the simulation module used in this work is the Reflection Calculator provided by FILMетRICS based on the complex-matrix of Fresnel Equation. Up to 20 films can be simulated in this system. Figure 4.2 shows the reflectance as a function of wavelength for the GaAs-AlAs DBRs. From this figure, the reflectance bandwidth of the GaAs-AlAs DBRs can be obtained.

Figure 4.2 Reflectance as a function of wavelength (GaAs-AlAs DBRs)

From Figure 4.2, it can be seen that when applying more GaAs-AlAs pairs, the bandwidths of the DBR layers decreases while the reflectance increases. The peak reflectance is
achieved at 880 nm. The full width at half maximum (FWHM)/reflectance bandwidths for this type of DBRs decreased from 210 nm to 128 nm when using 4 pairs or 10 pairs of GaAs-AlAs. The reflectance at 800 nm (designed wavelength) and 880 nm (peak reflectance wavelength) are listed in Table 4-1. The FWHM of the DBRs are also listed in this table.

<table>
<thead>
<tr>
<th>Pairs of GaAs-AlAs</th>
<th>Reflectance at 800 nm</th>
<th>Peak Reflectance (obtained at 880 nm)</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.54</td>
<td>0.58</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.64</td>
<td>0.68</td>
<td>180</td>
</tr>
<tr>
<td>6</td>
<td>0.68</td>
<td>0.86</td>
<td>150</td>
</tr>
<tr>
<td>8</td>
<td>0.70</td>
<td>0.92</td>
<td>134</td>
</tr>
<tr>
<td>10</td>
<td>0.70</td>
<td>0.95</td>
<td>124</td>
</tr>
</tbody>
</table>

As can be seen in Table 4-1, with an increase in the number of GaAs-AlAs DBR pairs, the reflectance gets higher. The reflectance at 800 nm increased significantly when the GaAs-AlAs increased from 2 to 4 pairs. Even though, the reflectance of the GaAs-AlAs DBRs haven’t reach the high reflectance range (higher than 97%), eight pairs of GaAs-AlAs still results in a reflectance of 0.7 at 800 nm and 0.92 at peak reflectance wavelength. This changes only slightly with further increase of DBR pairs up to 10. Therefore larger number of GaAs-AlAs pairs can result in a higher reflectance. The design of the DBRs in XMBE316 only repeats the GaAs and AlAs layers (with thicknesses of 62.6 nm and 66 nm respectively) 8 times but was able to achieve a high enough reflectance at 800 nm. As the main purpose of this optimisation is not the design of a very high reflectivity DBR, the resulting reflectance is high enough. The advantage of reducing the periodicity to 8 also reduces the growth time for the fully optimised LT GaAs materials with DBRs.

As can be seen in Figure 4.2, the 800 nm is located at the rising edge of the DBRs. In order to further optimise the DBR design, the thickness of GaAs can be reduced. This can not only help to increase the reflection at 800 nm, but also help to further decrease the growth time. The simulated reflections of the DBRs with 8 pairs GaAs-AlAs material system (58nm of GaAs and 66nm of AlAs for each pair) are shown in Figure 4.3.
In the case of this optimised design, the peak reflectance is only 0.86 at 815 nm, which is not as high as the original design. However, the reflection at 800 nm shows a much higher reflection of 0.85 compare with the original design and is now located much closer to the peak reflection wavelength (815 nm). In this case, the optimised GaAs-AlAs material system showed a FWHM of 137 nm. This center wavelength shifting is due to the fact that the simulation module takes into account the material refractive index changes at different wavelengths.

![Graph comparing reflectance for original and optimised designs](image)

**Figure 4.3** Comparison of the reflection for 8 pairs of GaAs-AlAs DBRs with theoretical thicknesses and the optimised thicknesses

### 4.2.1 Mid-Infrared reflectivity measurements

The reason for using DBR is to enhance the absorption coefficient of the photoconductive devices. The DBR layers incorporated with photoconductors had been proved to improve the antenna performance for both emitters and detectors [156, 158]. In the case of XMBE305 material system, only a part of the incident power is absorbed by the active layers (low temperature grown layers). However, with the help of the DBR layers, most of the not-absorbed radiation is reflected back towards the active layers. To show evidence of this reflectance, the reflectivity at the working frequency of 800 nm for XMBE316 was tested using Mid-Infrared reflectivity measurements. In this measurement, an Ocean Optics LS1 tungsten halogen light source and an Ocean Optics S200 CCD detector were used. As mentioned in Chapter three, the reference used in the reflectivity measurements is vital. The reference used here was the as grown XMBE305 and its reflectivity was set to as 100% by the software. Under this condition and by etching the test sample (XMBE316) at
different depths, the effect of the DBR layers can be evaluated. For this reason, two XMBE316 samples were prepared using a wet etching method. The first one etched marginally above the DBR layers (960 nm) while the second one etched into the DBR layers (1020 nm). Figure 4.4 shows the normalized reflectivity of these two samples.

![Normalized reflectivity of XMBE316 with different etching depths](image)

**Figure 4.4 Normalised reflectivity of XMBE316 with different etching depths**

The dotted red line in Figure 4.4 shows the contribution of both active and DBR layers. Compared with the reference sample (blue dashed line), this sample had a majority of the active layer removed. Thus, the normalized reflectivity for this sample shows a much higher value than the reference at specific wavelengths due to the thicker active layer absorbing more incident light in the reference. The dotted line gives further evidence of this explanation and also shows that the design of the DBR layers can reflect radiation at a specific wavelength as the low temperature grown material had been removed and all DBR layers were remained. From the reflection trend shown in Figure 4.4, the 800 nm point is located at the rising edge which is in good agreements with the data obtained from the reflection calculator.

### 4.2.2 Hall Effect

Hall Effect measurements were performed to check whether the DBR layers affect the mobility or not. Samples XMBE305 and XMBE316 were prepared and tested under the same conditions. Both Hall Effect samples were annealed at 600 °C for 10 mins and etched till the substrate using a standard ‘cloverleaf’ pattern. For each sample, four pieces
of Indium alloys were used as Ohmic contacts at the corners of the sample. Figure 4.5 shows an example of the cloverleaf patterned Hall Effect sample.

![Cloverleaf Van der Pauw geometry Hall Effect sample](image)

**Figure 4.5 Photo of Cloverleaf Van der Pauw geometry Hall Effect sample**

The results from Hall Effect are shown in Table 4-2 for both XMBE305 and XMBE316 samples.

<table>
<thead>
<tr>
<th>GaAs samples</th>
<th>Annealing Temperature: 600°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample ID</td>
<td>Mobility (cm²/Vs)</td>
</tr>
<tr>
<td>XMBE305</td>
<td>2401</td>
</tr>
<tr>
<td>XMBE316</td>
<td>2190</td>
</tr>
</tbody>
</table>

At room temperature under dark condition, the conventional LT GaAs sample (XMBE305) exhibited a mobility of 2401 cm²/Vs, carrier concentration of 2.79×10¹⁰ cm⁻³, and a calculated sheet resistance of 9.33×10⁸ Ω/sq. In the case of the LT GaAs incorporating the DBR (XMBE316) sample, the mobility was measured to be 2190 cm²/Vs, with a carrier concentration of 2.95×10¹⁰ cm⁻², thus the sheet resistance was then calculated to be 9.67×10⁸ Ω/sq. Both samples exhibited a similar mobility and carrier concentration and thus similar sheet resistance. The latter indicates that DBR layers do not affect the electronic properties of the LT GaAs samples. Note that the exceptionally high values of sheet resistances imply that it is mainly the substrates that are being measured.

4.2.3 Antenna Characterisations

After the optical and electronic characterisations, antennas with different geometries were fabricated on the samples (shows in Figure 4.6). The aperture antennas were designed to be
3.5 mm height, 500 µm width with 400 µm gap. While the dipole antennas have the same height and width as the aperture antennas but with a 5 µm gap between the arms with a length of 20 µm.

![Antenna geometries](image)

**Figure 4.6 Antenna geometries (a) Aperture and (b) Dipole**

The aperture structures were used as emitters while the dipole antennas were used as detectors in the THz TDS system. The evaluation was performed at room temperature under pulsed excitation. The detailed TDS system description under pulsed operations was explained in Chapter two. In the 800nm setup system, a Mai Tai pulse laser from Spectra Physics was used. The pump beam was focused onto the emitter surface and the probe beam was focused onto the detector after delay. At the back side of emitter and detector, a high resistivity hyper-hemispherical Si lenses were attached to collimate and focus the THz radiation. The system used in this section was operated at 800 nm, with an optical pulse duration of 100 fs and pulse repetition rate of 80 MHz. The power of the pump beam and probe beam were 25 mW and 10 mW respectively.

To investigate the improvement by using the LT GaAs photoconductive antenna with DBRs, both XMBE305 and XMBE316 were tested and evaluated under the same conditions. There were two measurements performed. In the first one, the aperture used as emitter and the dipole as detector were both fabricated on sample XMBE305. In the second measurement, the detector was kept the same but as emitter an aperture antenna fabricated on sample XMBE316 was used. Both emitters were biased at 50 V. Figure 4.7 illustrates the emitted THz pulses and their normalized Fourier power spectrum for both setups.
Figure 4.7 (a) THz pulses and (b) normalized Fourier transform power spectrum emitted from large aperture antenna fabricated on the XMBE316 (LT GaAs with DBR) and detected by a dipole antenna fabricated on the XMBE305 (LT GaAs)

Figure 4.7 depicts the THz pulse emitted from the optimised LT GaAs photoconductive antenna and the calculated Fourier power spectrum. The FWHM in the THz pulse figure gives an indication of the material carrier lifetime and the field amplitude indicates the strength of the THz signal.

The THz peak signal for XMBE316 was 11.5 nA with FWHM of 0.533 ps. The 20 dB bandwidth for this measurement indicates a spectral extent around 1.45 THz. In addition, the power to noise ratio is more than 60 dB with frequency extending up to 3.5 THz. In comparison to the conventional LT GaAs system (using XMBE305 as emitter), the optimized system shows a 0.02 ps smaller FWHM. This means the XMBE316 antenna has a slightly faster photoconductive switch speed than that of sample XMBE305.
Furthermore, under 50 V bias, the photocurrent measured at the XMBE316 large aperture antenna side was 1.8 µA which was more than double of the photocurrent generated by XMBE305 with the same antenna geometry design under the same bias voltage. The relative THz power can be in arbitrary units by taking into account the measured current and the incident THz electric field. Therefore, the relative magnitudes of the THz power of XMBE305 and XMBE316 are 2050 and 6900 respectively. Considering the photocurrent and the probe beam power, the responsivities of XMBE305 and XMBE316 are 0.57 nA/mW and 1.15 nA/mW. In addition, the system using sample XMBE316 also shows a 0.12 THz wider 20 dB bandwidth.

Thus, the conclusion after comparing the two systems is that DBRs under LT GaAs active layers slightly shorten the switching speed and enhance the THz peak signal by more than twice as well as increasing the transmitter photocurrent.

4.3 LT In\textsubscript{0.53}Ga\textsubscript{0.47}As-In\textsubscript{0.52}Al\textsubscript{0.48}As MQWs DBRs structure

LT GaAs and its optimised material show properties that fulfil all the requirements for an efficient THz TDS. However, femtosecond laser used in 800 nm system is bulky and costly thus limiting its widespread usage. In order to build a cheaper and portable TDS system, alternative materials which are compatible with lasers operating at longer wavelengths are required. These materials should also have similar properties as LT GaAs but a smaller bandgap. The most desired lasers operate at the telecommunication wavelength of 1.55 µm. Therefore, a cost effective material system candidate can be the LT InGaAs-InAlAs MQWs. In this work, the materials used to be excited at the 1.55 µm wavelength were grown on a semi-insulating iron-doped InP substrate (SI InP) with a Be doped LT InGaAs-InAlAs MQWs epitaxial layers. This design was inspired from an initial material system reported by Chen et al [105]. Two LT InGaAs-InAlAs MQWs samples were evaluated. Both samples were grown in the V100HU MBE system in the University of Manchester. The first one, XMBE290, was grown on a SI-InP substrate following a normal temperature grown 100 nm InAlAs buffer layer. The active layers were all grown at low temperature and consisted of a 50 periods of 12 nm In\textsubscript{0.53}Ga\textsubscript{0.47}As and 9 nm In\textsubscript{0.52}Al\textsubscript{0.48}As super lattice structure and an In\textsubscript{0.53}Ga\textsubscript{0.47}As cap layer. Be atoms were uniformly doped throughout all active layers with a doping concentration of 2×10\textsuperscript{18} cm\textsuperscript{-3}. The second one, XMBE329, was similar to XMBE290, having a slightly thicker barrier (from 9 to 12 nm) which however
does have any effect on the designed wavelength of 1550 nm. Additionally, 8 pairs of In$_{0.53}$Ga$_{0.47}$As-In$_{0.52}$Al$_{0.48}$As DBRs were grown in between the InP and active layers at normal temperature for XMBE329. Each pair contained a 103.3 nm InGaAs and 103.3 nm InAlAs. Both structures of XMBE290 and XMBE329 are shown in Figure 4.8.

![Figure 4.8 Physical structures along with the layer thicknesses of (a) XMBE 290 and (b) XMBE 329 (Both structures were designed to operate at 1550 nm)](image)

The design for the InGaAs-InAlAs DBRs was similar to that of the GaAs-AlAs DBRs. Both the InGaAs and InAlAs layers are λ/4 thick at 1550 nm (with InGaAs thickness=1550/4×3.8=102 nm, refractive index is 3.8 and AlAs thickness=1550/4×3.6=107.6 nm, refractive index is 3.6). In order to simplify the growth process and taking into account the refractive index at the main wavelength, both InGaAs and InAlAs were designed to have a thickness of 103.3 nm.

Figure 4.9 shows the reflectance as a function of wavelength for InGaAs-InAlAs DBRs. From this figure, the reflectance bandwidth of the InGaAs-InAlAs DBRs can be obtained.

![Figure 4.9 Reflectance as a function of wavelength (GaAs-AlAs DBRs)](image)
From Figure 4.9, it can be seen that when using more InGaAs-InAlAs pairs, the bandwidths of the DBR layers decreases while the reflectance increases. The peak reflectance is achieved at 1520 nm. Due to the light absorption property of InGaAs material near 1550 nm, the peak reflectance did not reach a high reflectance range (reflectance higher than 0.9) even for 10 pairs of InGaAs-InAlAs DBR layers. However, the InGaAs-InAlAs still show a good enough DBR quality to fulfill the demand of this project. The bandwidths for this type of DBRs decrease from 473 nm to 159 nm when using 4 pairs or 10 pairs of InGaAs-InAlAs. The reflectance at 1550 nm and 1520 nm are listed in Table 4-3. The FWHM of the DBRs are also listed in the table.

<table>
<thead>
<tr>
<th>Pairs of GaAs-AlAs</th>
<th>Reflectance at 1550 nm</th>
<th>Peak Reflectance (obtained at 1520 nm)</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>0.44</td>
<td>0.44</td>
<td>473</td>
</tr>
<tr>
<td>6</td>
<td>0.51</td>
<td>0.52</td>
<td>274</td>
</tr>
<tr>
<td>8</td>
<td>0.57</td>
<td>0.59</td>
<td>197</td>
</tr>
<tr>
<td>10</td>
<td>0.62</td>
<td>0.65</td>
<td>159</td>
</tr>
</tbody>
</table>

As can be seen in Table 4-3, more InGaAs-InAlAs DBR pairs lead to higher reflectance. The reflectance at 1550 nm increased significantly when using 4 to 6 pairs InGaAs-InAlAs layers. In the case of the InGaAs-InAlAs material system, 1550 nm is close enough to the center wavelength obtained (1520 nm) and does not show much differences in terms of the reflectance. In order to shorten the growth time, the design of the DBRs in sample XMBe329 uses 8 pairs of InGaAs and InAlAs with a common thickness of 103.3 nm. The reflection value also indicates that this design is able to result in a high enough reflectance at 1550 nm.

4.3.1 Mid-Infrared reflectivity measurement

To study the optical effect of the DBRs, the reflectivity measurements of XMBe290 and XMBe329 were carried out using the same broadband light source as XMBe305 and XMBe316 but an Ocean Optics NIR256-2 was used as detector. The reference sample used here was the asgrown XMBe290, and its reflectivity was set to 100% for the
following two measurements. Two XMBE329 samples with 1070 nm and 1270 nm etching depths were prepared. The responses of both samples are shown in Figure 4.10.

![Diagram showing normalised reflectivity of XMBE329 with different etching depths.](image)

**Figure 4.10 Normalised reflectivity of XMBE329 with different etching depths**

The dotted red line in Figure 4.10 shows the contribution of both LT InGaAs-InAlAs MQWs and InGaAs-InAlAs DBR layers. Compared with the reference sample (blue dashed line), this sample had a majority of the active layer removed. Thus, the normalized reflectivity for this sample shows a much higher value than the reference at specific wavelengths due to the thicker active layer absorbing more incidents light in the reference. The black solid line gives further evidence of this explanation and also shows that the design of the DBR layers can reflect radiation in the regime of 1550 nm as the low temperature grown material had been removed and all DBR layers were remained. The highest normalised reflectivity of XMBE329 is approximately twice that of the reference sample at 1550 nm. From Figure 4.10, it can be seen that the peak reflection happens at the wavelength of 1520 and 1550 nm located at the right side of the peak reflection value. These all give good agreements with the simulations.

### 4.3.2 Hall Effect

Both XMBE290 and XMBE329 samples were prepared and tested under the same conditions. These samples were annealed at 580 °C for 10 mins and etched to the substrate using the standard ‘cloverleaf’ pattern, four pieces of In alloys were used as Ohmic contacts at the corners of the sample. Four point measurements were then taken under dark
condition at room temperature. The results from Hall Effect measurements are shown in Table 4-4 for both XMBE290 and XMBE329 samples.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Mobility (cm²/Vs)</th>
<th>Concentration (cm⁻³)</th>
<th>Sheet resistance (Ω/sq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XMBE290</td>
<td>423</td>
<td>2.04×10¹³</td>
<td>7.24×10⁶</td>
</tr>
<tr>
<td>XMBE329</td>
<td>412</td>
<td>1.91×10¹³</td>
<td>7.94×10⁶</td>
</tr>
</tbody>
</table>

XMBE290 exhibited a mobility of 420 cm²/Vs, carrier concentration of 2.0×10¹³ cm⁻², and a calculated sheet resistance of 7.2×10⁶ Ω/sq, while XMBE326 exhibited a mobility of 410 cm²/Vs, carrier concentration of 1.9×10¹³ cm⁻², and a calculated resistance of 7.9×10⁶ Ω/sq. Both samples exhibited a similar mobility and carrier concentration and thus similar sheet resistance. The latter implies that the DBR layers do not affect the electronic properties of the LT InGaAs-InAlAs MQW samples. These LT In₀.₅₃Ga₀.₄₇As-In₀.₅₂Al₀.₄₈As samples exhibit one order of magnitude higher sheet resistance than the best LT In₀.₅₃Ga₀.₄₇As-In₀.₅₂Al₀.₄₈As reported in the literature [159].

4.3.3 Antenna Characterisations

After the optical and electronic characterizations, dipole antennas were fabricated on the XMBE329 sample (shown in Figure 4.6 (b)). These dipole antennas act as emitters and detectors for the evaluation of the LT InGaAs-InAlAs MQWs with DBRs. In the TDS system, a FemtoFiber FFS short pulse laser from Toptica Photonics AG was used. This laser was operated at 1550 nm which makes the pump beam and probe beam easily coupled to the antenna by using optical fibers. The TDS system operated at 1550 nm is not only cheaper than the one operated at 800 nm but also more compact and portable. The optical pulse duration was 100 fs with a repetition rate of 86 MHz. The average power of pump and probe beam were 14.5 mW and 14 mW respectively.
The THz pulse emitted from the optimized LT InGaAs-InAlAs photoconductive dipole antenna and the calculated normalized Fourier transform power spectrum are shown in Figure 4.11 (a) and (b) respectively.

![Figure 4.11](image)

**Figure 4.11** (a) THz pulses and (b) normalized Fourier transform power spectrum emitted and detected by dipole antennas made on XMBE329

The THz peak signal for XMBE329 was 1.2 nA with FWHM of 2.104 ps. The 20 dB bandwidth for this measurement indicates a spectral extent around 0.89 THz. In addition, the power to noise ratio is more than 50 dB with frequency extending up to 2 THz. Compared with the previous reported work [21], the LT InGaAs-InAlAs MQWs incorporating DBRs demonstrated a slower switching speed and a narrower bandwidth. The poor bandwidth compared to previous systems reported by our group or compared to other commercial available systems can be explained by the fact that XMBE329 were
doped throughout active layers and also due to the tested antenna geometry. Nevertheless, the relative magnitude of the THz power of XMBE329 was 57 while a similar material systems [20] showed only 0.83. Furthermore, with the inclusion of DBRs, the responsivity of XMBE329 was 0.086 nA/mW. This is more than 10 times higher than the similar material systems with the responsivity of 0.008 nA/mW.

In brief, the optimised LT GaAs and LT InGaAs-InAlAs photoconductive switches coupled with DBR layers were introduced. The results indicated that the combinations of DBRs with photoconductive materials excited at both 800 nm and 1550 nm resulted in remarkable enhancements of the THz peak signals which in turn increase the transmitter photocurrents. Hence, the coupling of DBRs and the active layers result in a better THz response and can further improve the performance of THz devices and allow high quality THz measurements.

4.4 1.55 µm THz spectrometer system

THz TDS system can be widely used for spectroscopic in the THz range. These spectrums are able to fingerprint many materials (such as: TNT explosives and methamphetamine drugs). As mentioned before in this chapter, it is desirable to develop a low cost and compact THz TDS system based on 1.55 µm fibre lasers. The next section of this chapter introduces details of a home built 1.55 µm THz spectrometer with its key elements (emitter and detector) fabricated using the LT InGaAs-InAlAs MQWs described previously. Along with the 1.55 µm THz spectrometer, six series of measurements using this spectrometer will be presented. These measurements reveal the THz spectrum of semiconductors such as InP and GaAs, materials which are of interest for security applications including papers and cotton clothes, and biological sample like leaves and human hands.

4.4.1 Low temperature grown InGaAs-InAlAs MQWs material

The transmitter and receiver used in this spectrometer were fabricated on LT InGaAs-InAlAs MQWs materials. There were two sets of doping concentration for the LT InGaAs-InAlAs MQWs designs. The sample with Be doping of 1.5×10^{18} cm^{-3} is denoted as ‘VMBE2021’, and the sample with Be doping of 2.0×10^{18} cm^{-3} is denoted as ‘XMBE290’. Both materials were grown using the MBE technique. The key reason that makes these THz photoconductive materials suitable for generating and detecting strong THz pulses in
a time domain spectrometer is the material physical property. The dark resistances of both materials are higher than $10^6 \, \Omega$, while the mobility is greater than $1000 \, \text{cm}^2/\text{Vs}$ and the carrier lifetimes are shorter than $500 \, \text{fs}$. The optical and electrical properties of these materials have already been characterised, evaluated and reported [150].

VMBE2021 and XMBE290 were fabricated by following the process flow described in Chapter three. In order to optimise the material characteristics, an annealing temperature of 580 °C for 10 mins in the RTA system was used. The wet etching method was used and performed using $\text{H}_3\text{PO}_4$: $\text{H}_2\text{O}_2$: $\text{H}_2\text{O}$ in the ratio of 2:1:2. The large aperture and dipole structures were then patterned onto the surface of these materials. The geometries of the aperture and dipole antennas for THz emitters and detectors respectively are shown in Figure 4.6. In the case of the emitter antenna, a ‘Large aperture’ was used. The height of the large aperture was 3.5 mm and the width was 1.3 mm. This aperture antenna had a 500 µm gap between the two bias pads. The dipole antenna, which worked as detector, had a 100 µm gap and a 40 µm arm length.

The VMBE2021 samples were fabricated to be used as emitters based on the large aperture antennas design and the XMBE290 samples were fabricated to be used as detectors based on the dipole antennas design. The combination of large aperture and dipole chips were evaluated in the THz spectrometer system. The reason for the selection of these materials and this combination of geometries is due to their operational properties and radiation efficiencies, which had been described by I. Kostakis and et al [22]. The dipole on the XMBE290 chip provided higher dark resistance than the one on the VMBE2021. The latter implies that the dark current is less on this material and therefore the noise is expected to be much less. Thus, a dipole device on the XMBE290 material is a better option for a detector antenna.

4.4.2 1.55 µm THz spectrometer

In this work, the fabricated LT InGaAs-InAlAs MQWs devices were diced into 4 mm × 4 mm chip. Pairs of the combination of aperture and dipole described above were then packaged by the industrial partner (TeTechS Inc.). In the packaging process, hyper-hemispherical silicon lens were attached at the back side of the photoconductive antenna and then mounted on a package having an SMA (SubMiniature version A) connector. The silicon lenses improve the THz coupling by collimating the THz emission at the emitter.
side and collecting the radiation at the detector side [5]. A picture of the THz device modules is shown in Figure 4.12.

![THz device modules](image)

**Figure 4.12 Compact THz photoconductive antenna modules**

By using the THz photoconductive antenna modules, a newly built 1.55 µm THz spectrometer denominated as Rigel 1550 Spectrometer was built by the industrial partner in Canada and is located at the University of Manchester in the B22 cleanroom. This is a versatile instrument and is now commercially available. The Rigel 1550 spectrometer is a portable, modular, compact, and reconfigurable terahertz time-domain spectrometer system (under pulsed excitation). By using the optical fiber, the laser source is directly coupled to the photoconductive antennas. The fiber coupled transmitter and receiver heads can be mounted around the sample under test, thus leading to the transmitter and receiver heads being stable and portable. The terahertz transmitter and receives are driven by a Femtosecond fiber laser at 1550 nm. The laser source is divided into the pump beam and probe beam with power of 100 mW and 70 mW respectively. The transmitter works under a bias voltage of 50 V. Furthermore, both slow and fast scans are included in the system. These allow users to adjust the distance between the sensor heads, up to 1 m. The instruction of the Rigel 1550 THz spectrometer can be found in Appendix B.

### 4.4.3 Substrate transparency

As described in Chapter two, the generation of THz signal is from the back side of the photoconductor (substrate). Considering the limitation to the output power of the generated signal, any THz absorption from the substrate needs to be evaluated. The substrate for the substrate for LT InGaAs-InAlAs antennas is SI InP: Fe, and SI GaAs for LT GaAs antennas. To investigate the transparency of these substrates, the following measurements were taken using the Rigel 1550 nm THz spectrometer.
(1) To investigate the transparency of the substrates in the structure operating at 1.55 μm excitation wavelength, a two-inch SI InP: Fe wafer was tested. The generated THz signal was focused on the wafer and passed through the wafer. Then the signal was collected by the detector. A measurement without any sample on the sample holder was taken as a reference. The response of the SI InP: Fe wafer versus the reference air measurement can be seen in Figure 4.13.

![Figure 4.13 Rigel 1550 THz spectrometer measurements](image)

**Figure 4.13 Rigel 1550 THz spectrometer measurements**

(a) THz pulses with air reference and SI InP: Fe wafer in the sample holder (b) comparison of the power spectrums from both measurements

The delay and the slightly reduction of the signal peak in the time domain measurements are due to Fresnel reflection and optical stage design [160]. Based on this property, this gives an alternative method of measuring sample thickness. From the power spectrums, it can be seen that the power to noise ratios for both air reference and SI InP: Fe are more than 60 dB with the frequency extending up to 1.2 THz. The differences in the power
spectrums above 0.8 THz is mainly due to environmental vibrations in the cleanroom as the sample was hanging in free space.

By comparing the two measurements, it is obvious that the SI InP: Fe material is transparent to the THz radiation. Thus, using SI InP: Fe as the substrate does not affect the output power.

(2) To investigate the transparency of the substrates in a structure operating at 800 nm excitation wavelength, a two-inch SI GaAs wafer was used. The response of SI GaAs wafer versus reference air measurement can be seen in Figure 4.14.

![Figure 4.14 Rigel 1550 THz spectrometer measurements (a)THz pulses with air reference and SI GaAs wafer in the sample holder and (b) comparison of the power spectrums from both measurements](image-url)
CHAPTER 4

For the same reason discussed in the previous comparison of air versus SI InP: Fe, there is a delay and reduction in the THz pulses. From Figure 4.14 (b), it can be seen that the power to noise ratios for both air reference and SI GaAs are more than 60 dB with the frequency extending up to 1.4 THz. The differences in the power spectrums above 1.2 THz is mainly due to environmental vibrations in the cleanroom as the sample was hanging in the free space. By comparing the results of the reference air and SI GaAs wafer, it is obvious that the SI GaAs material is also transparent to the THz radiation. Thus, a similar conclusion can be made: using SI GaAs as the substrate does not affect the output power. The delay of the signal peak in the time domain measurement is due to the Fresnel reflection and optical stage design.

In conclusion, both SI InP: Fe and SI GaAs are transparent to THz radiation and suitable to be used as substrates for LT InGaAs-InAlAs and LT GaAs photoconductive antennas respectively. Thus, the output will only depend on the absorption coefficient of the photoconductive material, applied electric field strength and the antenna geometry. Therefore, there is no need to remove the substrate. The latter is important as the substrate helps to fabricate robust and high yielding photoconductive antennas.

4.4.4 THz measurements on other sample objects

(1) The first sample was a simple piece of paper (80g/m²) which is used for printing. To investigate the transparency of the paper, the same spectrometer was used. The response of the paper versus the reference air measurement can be seen in Figure 4.15.
Figure 4.15 Rigel 1550 THz spectrometer measurements: comparison of (a) Field amplitude spectrums and (b) the power spectrums from paper and air measurements

The thickness of the paper is approximately 0.13 mm and this was responsible for the delay of the peak in the field amplitude figure. The result of the power spectrum with the signal to noise ratio of 45 dB up to 0.9 THz shows paper is also transparent to THz radiation.

(2) In order to further study the THz transparency of paper, ten pieces of paper were treated as one sample for the next measurement. The response of the ten pieces of paper versus the reference air and one piece of paper measurement can be seen in Figure 4.16.
In this measurement, the sample was much thicker (approximately 1.5 mm in total). The results illustrate that a much thicker bunch of paper is also transparent to the THz radiation, even though there is a clear shift in frequency and therefore the system can be used to measure accurately the thickness of the samples. It is clear that a thickness of 130 µm is readily observable from Figure 4.16.

The absorption of the sample can be determined by dividing the spectra without and with sample in the THz path. Figure 4.17 shows the result of the absorption spectrum of the bunch of paper. The spikes are in very good agreement with the absorption lines of water vapor [161]. This indicates that the paper is not absolutely dry and the measured power
spectrums of the paper contained water. Therefore, the system can also be used to measure moisture in samples.

![Absorption spectrum for ten pieces of paper](image)

**Figure 4.17 Absorption spectrum for ten pieces of paper**

(3) The next tested sample is chosen to be a normal cloth piece made of cotton. The cloth had a thickness around 0.25 mm. A double-layers sample was also measured under the same conditions. These measurements give the transparency of the cotton fibre. The response of the cotton fibre with different thickness versus the reference air can be seen in Figure 4.18.
Figure 4.18 Rigel 1550 THz spectrometer measurements: comparison of (a) Field amplitude spectrums and (b) the power spectrums from cotton fibre and air measurements

The result shows the cotton fibre is also transparent to the THz radiation. The reduction of the THz peak signal indicated that the cotton is not completely dry and contains moisture.

4.4.5 THz characterisation of biological samples

(1) Haploid and doubled haploid plants

Testing the plants to be haploid or double haploid plants is important since double haploid plants are generally considered to be more beneficial to plant breeding. However, traditional testing methods are usually complicated and detrimental to plants. In order to investigate the possibility to find signal differential between haploid and double haploid
plants using the THz TDS, plants samples from other research group in Manchester University were tested. In this section, two leaves denoted as sample ID #215-07 and #215-13 from haploid and doubled haploid plants were measured using the in-house 1.55 μm THz spectrometer. Both leaves were roughly 3 mm×20 mm of size. During the measurements, the plant sample was suspended in air in the path of the THz beam and scans performed in the y-direction (vertical) at 1 mm intervals to give enough statistical data. Twenty points were taken for each sample and the average spectrum of these measured points are shown in Figure 4.19.

![Power Spectrum](image)

**Figure 4.19** power spectrums from haploid and doubled haploid plants measurements

It is clear to see that there is evidence of absorption in both plants in the 0.42 to 0.45 THz band. Some evidences given by the spectrums show that absorption in #215-13 is less than that in #215-07 by around 5dB, but unfortunately not absolutely clear cut is visible. These measurements show a promising possibility to distinguish the haploid and doubled haploid plants (at least for these tested samples). However, two samples are not sufficient enough, thus to achieve a more general conclusion, more haploid and doubled haploid plant samples need to be measured in order to give enough statistical evidences.

(4) In order to test more biological objectives, as a simple example, a human hand (the student own hand!) was used as a sample in this measurement. The responses of the human hand versus reference air measurement are shown in Figure 4.20.
Figure 4.20 Rigel 1550 THz spectrometer measurements: comparison of (a) Field amplitude spectrums (b) the power spectrums from human hand and air

Figure 4.20 (b) describes the absorbance of THz signals quite well. This is due to the water in human body cells. This simple measurement can be used to illustrate that THz signals are strongly absorbed by water.

4.5 Summary

This first part of this chapter described the optimised LT GaAs and LT InGaAs-InAlAs photoconductive switches. The results indicated that the combinations of DBRs with photoconductive materials excited at both 800 nm and 1550 nm resulted in a remarkable enhancement of the THz peak signal and the relative magnitude of the THz power which in
turn increases the transmitter photocurrent. Hence, the coupling of DBRs and the active layers result in a better THz response and can further improve the performance of THz devices and allow high quality of THz measurements.

The second part of this chapter focused on a new compact 1.55 µm THz spectrometer with the fabricated InGaAs-InAlAs MQWs THz photoconductive switches as key components. By using this newly built 1.55 µm THz Spectrometer, the transparencies of a series of samples were investigated. Through these measurements, the semiconductor SI InP: Fe and SI GaAs (substrates for the photoconductor materials LT InGaAs-InAlAs MQWs and LT GaAs respectively) showed they were indeed transparent to THz signals. These results proved that these materials were not affecting the output THz power thus there was no need to remove the substrate and consequently the fabrication of the THz photoconductive antennas can be robust and high yielding. The THz spectrometers measurements for the cotton cloths and paper show both materials were transparent to THz radiation and these gave further evidences that this type of spectrometer had the ability to be used for security related applications. Furthermore, the test for haploid and doubled haploid plants and human hand gave the probability that some biological samples may have fingerprints at THz range thus the 1.55 µm THz Spectrometer THz has promising capability for specific biological researches.
CHAPTER 5: In\(_{0.53}\)Ga\(_{0.47}\)As-AlAs ASYMMETRIC SPACER LAYER TUNNEL DIODES

5.1 Introduction

This chapter presents a novel kind of asymmetric spacer layer tunnel (ASPAT) diode. The first section depicts the epitaxial layer structure of the diode along with the idea of developing this novel diode. The second part presents the room temperature current-voltage characterisation of this InGaAs-AlAs ASPAT diode using different fabrication techniques. In order to compare the device performances with that of Schottky diodes and conventional GaAs-AlAs ASPAT diodes, the next section describes the epitaxial layer structure of these diodes and their fabrication details. Then, the DC characterisations in the range of 77 K to 400 K for the InGaAs-AlAs devices are investigated and compared with fabricated Schottky diodes and conventional GaAs-AlAs ASPAT diodes.

5.2 In\(_{0.53}\)Ga\(_{0.47}\)As-AlAs asymmetric spacer layer tunnel diodes

The In\(_{0.53}\)Ga\(_{0.47}\)As-AlAs asymmetric spacer layer tunnel diode (InGaAs-AlAs ASPAT) is a novel type of ASPAT diode developed at the University of Manchester. This new type of material grown by MBE technique was based on In\(_{0.53}\)Ga\(_{0.47}\)As-AlAs materials with the AlAs thickness finely defined to within the 0.1 monolayer thickness accuracy. The MBE growth technique has been reported to produce the desired precision of ASPAT materials [131].

The sample studied here was labelled as XMBE326. Following the growth steps, a 420nm thickness In\(_{0.53}\)Ga\(_{0.47}\)As (lattice matched to InP) with a Si doping concentration of 1.5\(\times\)10\(^{19}\) cm\(^{-3}\) was grown on a SI InP substrate. This layer was used as Ohmic contact layer. Following this Ohmic layer, a 35 nm thick In\(_{0.53}\)Ga\(_{0.47}\)As layer with a doping concentration of 1.0\(\times\)10\(^{17}\) cm\(^{-3}\) was grown. An AlAs barrier with 10 ML (2.83 nm) thickness was sandwiched by two In\(_{0.53}\)Ga\(_{0.47}\)As intrinsic layers. These two spacer layers were designed with asymmetric thickness of 200 nm and 5 nm respectively. Above the thinner spacer, another In\(_{0.53}\)Ga\(_{0.47}\)As layer with a donor concentration of 1.0\(\times\)10\(^{17}\) cm\(^{-3}\) was grown. The top layer of XMBE326 was a 300 nm thick In\(_{0.53}\)Ga\(_{0.47}\)As Ohmic layer with a doping
concentration of $1.5 \times 10^{19}$ cm$^{-3}$. The physical structure along with the layer thicknesses of XMBE 326 is shown in Figure 5.1 (not in scale).

![Physical structure and band profile along with layers thicknesses of XMBE 326](image)

Theoretically, there are two kinds of electron transport mechanisms in the ASPAT diode. When a high-enough bias is applied, electrons can thermionically ‘go over’ the AlAs barrier. In the other case, electrons can tunnel through the thin AlAs from the In$_{0.53}$Ga$_{0.47}$As spacer layer before the barrier. Since the thickness of the AlAs barrier is only 10 ML, the electron transport in the ASPAT is largely based on tunneling mechanism. In$_{0.53}$Ga$_{0.47}$As has a narrower band gap than GaAs (used in the conventional ASPAT design), this leads to a much higher conduction band discontinuity and hence to a larger barrier height. Thus, with the same barrier thickness, the higher barrier further limits the thermionic emission transport and makes tunneling the dominant mechanism in In$_{0.53}$Ga$_{0.47}$As-AlAs ASPAT diodes. Figure 5.2 shows the schematic conduction band profiles of both GaAs-AlAs and InGaAs-AlAs ASPAT (under bias). From this property, it can be predicted that InGaAs-AlAs material system should provide a much more temperature insensitive diode compared to the conventional GaAs-AlAs ASPAT structure.
Figure 5.2 Schematic conduction band profile of an ASPAT diode under bias (In$_{0.53}$Ga$_{0.47}$As-AlAs ASPAT in red and GaAs-AlAs in black)

5.3 Current-Voltage characterisation

5.3.1 Room temperature DC characterisation

In order to monitor the fabrication process, the same transmission line model (TLM) model is used for different diode mask designs. By performing the TLM measurements, the contact resistance ($R_c$) and the effective length ($L_T$) can be extracted. Figure 5.3 shows the TLM measurements for the top contact after annealing at 280 °C for 2 mins. Three groups of TLM measurements, shown in Figure 5.3, were chosen from the top, center and bottom of the 15×15 mm$^2$ wafer tile.

Figure 5.3 XMBE326 TLM measurements for the top contact after annealing at 280 °C for 2 mins.
At room temperature, the DC characteristics of the InGaAs-AlAs ASPAT are measured under dark condition using an HP 4145B DC analyser. This measurement set-up is shown in Figure 5.4 (The photo of the device at the top side of this figure is an InGaAs-AlAs ASPAT diode with a mesa area of 30×30 µm²).

Figure 5.4 The DC measurement set-up (device size is 30×30 µm²)

As described in Chapter three, the devices designed for high frequency applications should have small mesa sizes. However, for a smaller mesa size device (smaller than 6×6 µm²), it is difficult to direct probe to the device and obtain the DC characterisation as the probe manipulators mechanical tolerances are ±5 µm. Thus, it is necessary to design a large bond pad to interconnect to the device. There are two methods to approach this task. The first one is using dielectric layer, such as polyimide [162], silicon dioxide or silicon nitride [163, 164]. The dielectric layer used in this work was a hard-baked S1805 at 250°C for 30mins due to its simplicity. The second method, which is used for most devices in this work, was the air-bridge technology, shown in Figure 5.5. The air-bridge technique is widely used for high frequency applications [165]. This method relies on the undercut that occurs during the wet etching process, the semiconductor beneath the thin metal (bridge part) is dissolved opening up the air bridge.
For the air-bridge to totally open (as shown in Figure 5.5: etched until substrate), wet
etching must be performed. Dry etching was also used to make the anisotropy structure.
Thus, a method combining dry etching and wet etching was used for the air-bridge
designed devices with the smallest mesa size being less than 6×6 µm² for InGaAs-AlAs
ASPAT diodes fabrication process. Different patterns with various widths and lengths were
designed on the edge of the ASPAT mask. By using these test patterns, the opening for the
air-bridge can be easily checked and the undercut area sizes can also be approximately
calculated.

To further investigate the difference between using dielectric and air-bridge technology,
two runs of fabrications were processed. In the first run, devices with sizes larger than 6×6
µm² were fabricated. The dielectric layers were created by patterning the entire wafer tile
(besides the device mesa area) with S1805 which was then baked at 250 °C for 30 mins.
Throughout this run, H₃PO₄: H₂O₂: H₂O=3:1:50 etchant was used. For the final lift-off of
this run, the NMP temperature and the lift-off time were carefully controlled to avoid
attacking the dielectric layer. There were three different diode sizes included in this run.
The designed active areas for these devices were 8×8 µm², 10×10 µm² and 13×13 µm².
During the exposure, light scattering always causes slight differences from the designed
patterns. Considering this difference and the undercut, the optimized sizes of the devices
were 63.5 µm², 98.5 µm² and 167.5 µm² respectively determined from the measurements.
In this case, the current densities of devices showed excellent scalability. The current densities under forward bias of these devices are shown in Figure 5.6.

![Figure 5.6 Current densities of XMBE326 ASPAT diodes using baked dielectric bridge](image)

**Figure 5.6 Current densities of XMBE326 ASPAT diodes using baked dielectric bridge**

In terms of the air-bridge devices, there were five types of diodes with designed mesa areas of 6×6 µm², 5×5 µm², 4×4 µm², 3×3 µm² and 2×2 µm². The samples were dry etched for 30 mins (in three 10 minutes cycles), followed by dipping into H₃PO₄: H₂O₂: H₂O=3:1:50 etchant for more than 7 mins to entirely open the air-bridge. The wet etching time can be achieved using the test structures, and may vary for different runs.

![Figure 5.7 Current densities of XMBE326 ASPAT diodes using as-designed air-bridge](image)

**Figure 5.7 Current densities of XMBE326 ASPAT diodes using as-designed air-bridge**
In Figure 5.7, the current density of each device was directly calculated by dividing the current with their designed area. As it clearly evident, the devices do not scale well.

The schematic of the device undercut can be approximately extracted from test structure (shows in Figure 5.8). The undercut area for all devices besides 2×2 µm² were 1.5 µm², while in case of 2×2 µm², the undercut area was 1.0 µm². With the help of the test structures, the more accurate device sizes can be deduced.

Correcting for the undercut area, the areas of these devices then change to 34.5 µm², 23.5 µm², 14.5 µm², 7.5 µm², and 3 µm². Once the current densities of devices were further calculated using these new areas, a better scaling was obtained as shown in Figure 5.9.
Due to the slight differences between undercut of devices with different mesa sizes on the fabricated tile, the device areas were then tuned to further improve the scalabilities. The tuned sizes of devices were 34 µm², 23.5 µm², 14.7 µm² and 2.5 µm².

Figure 5.10 shows the current densities of the air-bridge devices achieved using their tuned active area sizes and also gives the comparison with the devices using dielectric technique.

![Image showing current densities of XMBE326 ASPAT Factoring in optimised undercut]

Figure 5.10 Current densities of XMBE326 ASPAT Factoring in optimised undercut

Figure 5.10 also indicates that the current densities produced via air-bridge and dielectric technique are comparable. This further demonstrates that these different runs of fabrications were both successful and that the dry etching technique does not lead to any side wall damage either.

5.3.2 Temperature dependency characteristics

The Schottky diode is the workhorse THz detector and has been successfully commercialised for decades. The main reason of this is due to the asymmetric I-V characteristic of the metal-semiconductor Schottky barrier which is essential for millimetre/THz applications (as described in the first chapter). However, the electron transport in Schottky diodes is due to thermionic emission with the charge carriers going over the potential barrier and thus leading to a strong temperature dependence of the I-V characteristics.
By comparison, the dominant transport mechanism in the ASPAT diode is tunnelling instead of thermionic emission since the AlAs barrier in between the asymmetric spacers limits the thermionic transport of elections [123, 125, 131]. In the case of the InGaAs-AlAs ASPAT, the smaller bandgap of InGaAs leads to a relatively higher conduction band discontinuity as opposed to GaAs. This property further limits the thermionic emission and hence should further improve the temperature insensitivity of ASPAT diodes.

In order to prove this hypothesis, the InGaAs-AlAs ASPAT, a conventional GaAs-AlAs ASPAT and a Schottky diode were fabricated with the same mesa size (100×100 µm²) and variable temperature measurements were performed using a Lakeshore Cryogenic probe station. The system setup was described in Chapter three (Figure 3.22 (b)).

The conventional GaAs-AlAs ASPAT diode (sample XMBE304) is comprised of a top 300 nm 4×10^{18} cm⁻³ doped contact layer and a more lightly doped emitter layer (1×10^{17} cm⁻³). The main structure thicknesses (spacers and barrier) for GaAs-AlAs and InGaAs-AlAs ASPAT were kept the same to make the comparison between both diodes meaningful. Below the thicker spacer, two other doped layers with the same doping concentrations of 1×10^{17} cm⁻³ and 4×10^{18} cm⁻³ were located on top of the SI-GaAs. The epitaxial layer profile for XMBE304 is shown in Figure 5.11 (not in scale).

![Epitaxial layer profile for XMBE304 (GaAs-AlAs ASPAT)](image)

Figure 5.11 Epitaxial layer profile for XMBE304 (GaAs-AlAs ASPAT)

The Schottky Barrier Diodes (SBDs) used in this study were fabricated on an n-type GaAs wafer (sample XMBE104). XMBE104 was used as the reference comparison sample in this study and its layer details and thicknesses are given in Figure 5.12 (not in scale). The
n-region comprises of 750 nm thick lightly doped epitaxial layer ($N_D=5\times10^{15}$ cm$^{-3}$) on the top of other various doping on a conducting GaAs substrate.

<table>
<thead>
<tr>
<th>Depth (nm)</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>750</td>
<td>GaAs (5×10^{15} cm$^{-3}$)</td>
</tr>
<tr>
<td>750</td>
<td>GaAs (3×10^{16} cm$^{-3}$)</td>
</tr>
<tr>
<td>750</td>
<td>GaAs (1×10^{17} cm$^{-3}$)</td>
</tr>
<tr>
<td>750</td>
<td>GaAs (5×10^{17} cm$^{-3}$)</td>
</tr>
<tr>
<td>750</td>
<td>GaAs (3×10^{18} cm$^{-3}$)</td>
</tr>
<tr>
<td>750</td>
<td>GaAs (2×10^{18} cm$^{-3}$)</td>
</tr>
</tbody>
</table>

Figure 5.12 Epitaxial layers for XMBE104 (SBD)

5.3.3 In$_{0.53}$Ga$_{0.47}$As-AlAs ASPAT diode and Ti/Au SBD

The main reason that a SBD shows I-V characteristics that are very sensitive to temperature is due to the thermionic emission transport mechanism. The current density of a SBD is exponentially sensitive to temperature as shown in equation (2.1).

In the case of the SBD fabricated in this work, only the bottom contact using a AuGe/Ni/Au contact scheme was annealed at 420 ºC for 2mins. A Ti/Au metal stack was used to form the Schottky contact.

The temperature range of the Lakeshore Cryogenic probe station used in this work ranges from 100 K to 400 K. From 100 K, the DC measurements were performed in 25 K steps. In order to protect the measured devices, the current compliance was set to 0.05A (50mA). The temperature dependency measurements of XMBE104 and XMBE326 are shown in Figure 5.13.
It is clearly apparent that the current changes in the SBD devices were far larger than those in InGaAs-AlAs ASPAT diodes. The AlAs barrier in the ASPAT diode limits the thermionic emission and the dominant transport mechanism is tunneling. As a consequence, the current flow in the ASPAT should be less sensitive to temperature. The experimental DC results for both a SBD and an InGaAs-AlAs ASPAT over the temperature range of 77 K to 400 K at specific bias voltages (0.3 V, 0.5 V and 0.8 V) are shown in Figure 5.14.
Figure 5.14 Temperature dependence of the current for both SBD and ASPAT for 100×100 µm² size devices

Figure 5.14 plots the relationship of current under different bias voltages versus temperatures. The currents at three set voltages were used to illustrate the temperature dependence of the SBD and the InGaAs-AlAs ASPAT diode. At low temperatures, and when applying biases of 0.3 V and 0.5 V, the SBD does not turn on, thus showing a very small current at these two points. By contrast with the Ti/Au SBD, the current of the ASPAT diode under the same bias voltages, shows very little change in the temperature range from 77 K to 400 K. Thus, the electric characteristic of the ASPAT diode is significantly less sensitive to temperature. This property allows the ASPAT diode based circuits to be used under severe working environment without the need for temperature compensation circuitry.

5.3.4 In₀.₅₃Ga₀.₄₇As-AlAs and GaAs-AlAs ASPAT diodes

The key reason for using In₀.₅₃Ga₀.₄₇As in the new ASPAT structure (as opposed to using GaAs) is due to the fact that In₀.₅₃Ga₀.₄₇As has a smaller band gap. This property leads to a much higher conduction band discontinuity with the AlAs barrier. The higher relative barrier height in the In₀.₅₃Ga₀.₄₇As-AlAs ASPAT diode further limits the thermionic transport of electrons. Hence, this property should lead to improved temperature insensitivity compared to the conventional GaAs-AlAs ASPAT.

The GaAs-AlAs sample under investigation here was the one using a dielectric-bridge technique with the detailed fabrication process described in Appendix A3. S1805 baked at
250 °C for 30 min was used as a dielectric layer and an annealing temperature of 420 °C was used to produce the Ohmic contacts using an alloyed AuGe/Ni/Au contact scheme for the GaAs-AlAs ASPAT sample.

The current densities of this run can be seen in Figure 5.15. By using the similar mesa size optimisation method described before in this chapter, the current densities of all XMBE304 devices almost overlapped. This illustrates a controlled and scalable fabrication process for XMBE304.

![Graph](image.png)

**Figure 5.15 Current densities of XMBE304 ASPAT diodes using dielectric bridge**

The idea of designing the InGaAs-AlAs ASPAT is based on the hypothesis that the higher band discontinuity can lead to a less temperature sensitive property. The temperature dependence of the IV characteristics of GaAs-AlAs and InGaAs-AlAs ASPAT diodes can give direct evidence of this hypothesis.

In order to perform this comparison, the GaAs-AlAs ASPAT with the same mesa size (100×100 µm²) as the InGaAs-AlAs ASPAT diode was measured. The temperature variation measurements from 77 K to 100 K of the GaAs-AlAs ASPAT diode were then performed, and shown in Figure 5.16.
From the raw data of the GaAs-AlAs ASPAT and InGaAs-AlAs ASPAT diodes, it is obvious that the current changes due to the temperature variations in the GaAs-AlAs scheme is much larger than in the InGaAs-AlAs scheme. To be more specific, the comparisons of currents for both ASPAT diodes at 0.1 V, 0.3 V and 0.8 V operating at different temperatures were made as shown in Figure 5.17.

The data shown in Figure 5.17 were selected from both Figure 5.13 (b) and Figure 5.16. In this figure, it is clear that even though the GaAs-AlAs ASPAT shows slightly higher...
currents compared with the InGaAs-AlAs ASPAT diode at high temperature (as expected because of the lower effective barrier height), the currents for both ASPAT diodes show only a very minor increase with the temperature and both are fairly insensitive to temperature. However closer examination reveals that, as a function of temperature, the currents for both ASPAT diodes are similar and both increase only marginally from 77 K up to 200 K. But when the operating temperature increased above 225 K, the current separations between InGaAs-AlAs ASPAT and GaAs-AlAs ASPAT become distinguishable. As the operating temperature kept increasing, there was clear distinction between the two types of ASPAT diodes. It is evident that the InGaAs-AlAs ASPAT diode has a much weaker temperature dependence than the conventional GaAs-AlAs ASPAT diode. Compared with GaAs, InGaAs has a narrower bandgap and consequently higher conduction band discontinuity which limits thermionic transport. This leads to a much weaker temperature dependence of the I-V characteristics.

To be more specific, assuming the current variation, \( \Delta I \), over the entire temperature range (100 K to 400 K), is defined as:

\[
\Delta I = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}}} \tag{5.1}
\]

The smaller this current variation illustrates that the device has a weaker temperature dependence property.

Figure 5.18 showed the calculated current variations for both GaAs-AlAs and InGaAs-AlAs ASPAT diodes over the entire temperature range.
From 100K to 400K, the GaAs-AlAs ASPAT diode shows an increasing trend of current variation along with increasing bias voltages, and the InGaAs-AlAs ASPAT diode shows a similar trend. These indicate that even through the main transfer mechanism for both ASPATs are highly likely to be tunnelling, the high bias voltage can still lead to thermionic emission. Under the same bias voltage, when comparing both ASPAT schemes, the higher potential barrier height in InGaAs-AlAs ASPAT diode results in a much smaller current variation over the entire temperature range. To be more specific, as the promising application for ASPAT diodes is high frequency zero bias detection, the performance of the device at low bias voltage in the nonlinear range of the DC characteristics is attractive. The GaAs-AlAs ASPAT diode has a current at 100 K (with a 0.1 V bias voltage) which is 0.32 times its value at 400 K (with a 300 K temperature difference) whereas under the same condition, the variation for the InGaAs-AlAs ASPAT was only around 0.078. This is less than a quarter of the GaAs-AlAs ASPAT. Thus, the conclusion can be made that the InGaAs-AlAs ASPAT diodes show much more stable performances over the entire temperature range at all bias voltages than GaAs-AlAs ASPAT diodes.

**5.4 Summary**

This chapter focuses on the introduction of a new designed InGaAs-AlAs ASPAT diode. The DC properties of the InGaAs-AlAs ASPAT diode were investigated via fabricated devices using dielectric technique and air-bridge methods. The diodes fabricated using
both methods showed the same current densities which indicated that the two fabrication process flows were both successful. In addition, SBDs and GaAs-AlAs ASPAT diodes with the same mesa size were also fabricated and measured under the same condition with InGaAs-AlAs ASPAT diodes. As opposed to SBDs, the temperature variation measurements showed that tunnelling mechanism leads the ASPAT diode to have a much more temperature insensitive behaviour. Furthermore, the narrower band gap InGaAs leads in this new design leads to a much higher conduction band discontinuity than GaAs-AlAs ASPAT enhancing tunnelling mechanism more and making the InGaAs-AlAs scheme even more insensitive to temperature. In brief, the InGaAs-AlAs ASPAT DC characteristics showed that this new type of diode has much stable properties over a wide applicable temperature range.
CHAPTER 6: PHYSICAL MODELLING OF InGaAs-AlAs ASPAT

6.1 Introduction

Since the fabrication of semiconductor technology is time consuming and costly, physical modelling is advantageous. In this approach, an accurate and precisely simulated model of a successful fabrication run is essential. The device modelling should also be able to predict further device performances. The semiconductor device modelling is exploited to construct the device behaviour based on fundamental physics like doping profiles, epitaxial layer thickness and materials compositions.

The first section of this chapter gives a general introduction of the simulation tool used for physical modelling of the device. The following section describes in detail the physical modelling for the InGaAs-AlAs ASPAT including the material and model specifications. The third part discusses comparisons between simulations and measurements of the device DC characteristics. With the help of the physical model, physical insights into the working mechanism of the ASPAT diodes can be obtained. Furthermore, the temperature variation modelling of the InGaAs-AlAs ASPAT diode are also described and compared with GaAs-AlAs ASPAT diode. Finally, the last section of this chapter gives suggestions for material optimisations of this novel InGaAs-AlAs ASPAT.

6.2 SILVACO: introduction and specification

The commercial semiconductor device simulation software “SILVACO” is used throughout this work. SILVACO was developed by Dr. Ian Pesic in 1984, and became part of an alliance with Electronic Design Automation (EDA) and Technology Computer Aided Design (TCAD) communities in 2012. SILVACO is now one of the major tools for physically simulating electronic devices and integrated circuits which allows users to model devices under different conditions such as electrical, thermal, optical, and under desired bias. The following section reports the fundamentals of this software which comprises the simulator package, basic modes, device structure, and simulator analysis. All information stated here are from the SILVACO ATLAS Manual and device simulation guide.
There are several major tools included in this software, such as Athena, Deckbuild, ATLAS, and Tonyplot. Athena is the device designer which provides general capabilities for semiconductor industry processes such as oxidation, physical etching, lithography etc. Deckbuild is an interactive runtime tool used to load the device structures designed by Athena and other TCAD and EDA products. ATLAS is the main core of the SILVACO which is used extensively in academia. It is a versatile and modular simulator which is a replication of the actual processed semiconductor configuration. ATLAS is the product for both two-dimensional and three-dimensional device simulation. The physically-based models used in ATLAS simulation package are quantified descriptions of various phenomena such as carrier generation, recombination and transport. As the finite difference method is used in SILVACO, the simulated device is divided into small pieces on a two or three-dimensional grid (mesh). Then the simulator attempts to use mathematical equations to solve one initial value and the next value will take into account the initial one. These results can not only be used to approach the DC and AC characterizations of the device but also to provide physical insights of the device operation. In order to use ATLAS simulator, the user needs to initialize it via the command: ‘Go ATLAS’. The SILVACO simulation instructions can be found in Appendix C.

### 6.3 Material and model definitions of InGaAs-AlAs ASPAT diode

The layer structure used for physical modelling of the InGaAs-AlAs ASPAT diode multilayer structure is shown in Figure 6.1. The model procedure starts by setting the layer thickness in the structure specification statement.

---

**Figure 6.1 XMBE326 structure and layer profile used in the simulation**
The SILVACO composition configuration for InGaAs is defined as In(1-x)Ga(x)As. In the XMBE326 structure, the compound In_{0.53}Ga_{0.47}As-AlAs is used, thus a gallium composition of 0.47 must be stated in the region statement.

region num=1 name=contact1 material=Gold y.min=0 y.max=0.1
region num=2 name=ohmic1 material=InGaAs x.comp=0.47 y.min=0.1 y.max=0.4
region num=3 name=emit material=InGaAs x.comp=0.47 y.min=0.4 y.max=0.435
region num=4 name=spacer1 material=InGaAs x.comp=0.47 y.min=0.435 y.max=0.44
region num=5 name=barrier material=AlAs y.min=0.44 y.max=0.44283 x.min=0 x.max=8
region num=6 name=spacer2 material=InGaAs x.comp=0.47 y.min=0.44283 y.max=0.64283
region num=7 name=coll material=InGaAs x.comp=0.47 y.min=0.64283 y.max=0.67783
region num=8 name=ohmic2 material=InGaAs x.comp=0.47 y.min=0.67783 y.max=1.09783
region num=9 name=etch material=Air y.min=0 y.max=0.85283 x.min=8 x.max=20

In SILVACO, one of the most crucial procedures is the definition of each material’s physical parameters. Since the default value for InGaAs is for the material with the composition of 0.5, the material’s physical parameters for In_{0.53}Ga_{0.47}As must be user defined. These definitions normally include the material bandgap, affinity/align statement, permittivity, effective density of states for electrons and holes, effective masses (using parabolic assumption), etc. These parameters are calculated based on definition given in ‘Handbook series on semiconductor parameters’[167]. The simulated results using these parameters will be presented once the appropriate models are found and after defining the numerical methods.

The ‘eg300’ represents the material bandgap at 300 K. In the case of In(1-x)Ga(x)As, the energy bandgap can be calculated by using:

\[ e_{g300} = 0.36 + 0.63x + 0.43x^2 \] (6.1)

Based on this calculation, the bandgap of In_{0.53}Ga_{0.47}As is 0.75 eV. But in the simulation code, this number was set to 0.74 eV, which is also closer to measured values for this material. For heterojunctions, there are two types of tunnelling probabilities that can occur: direct tunnelling and indirect tunnelling. In the case of In_{0.53}Ga_{0.47}As-AlAs ASPAT structures, the AlAs barrier is only 28.3 Å which results in most of the electrons tunnelling at the Γ point. Thus, the tunnelling happening at the Γ point contributes dominantly to the
tunnelling current. This means that the AlAs bandgap used here is 2.83 eV instead of 2.16 eV [124].

The conduction band discontinuity can be determined by using the electron affinity of materials. However in SILVACO users can define this using the Align statement. “Align” is used to define the heterojunction band alignment using the following equation:

$$Align = \frac{\Delta E_c}{\Delta E_g} \quad (6.2)$$

where $\Delta E_c$ refers to the conduction band offset for the heterojunction, and $\Delta E_g$ is the bandgap difference between the two materials. Defining either affinity of the material or ‘Align’ results in the same outcome in the SILVACO simulation. In this work, the affinity definition of AlAs and InGaAs were used with the values of 3.01 eV and 4.51 eV respectively.

The key physical parameters used in the simulation are listed in Table 6-1. These are the parameters used after the optimisation procedure. This procedure will be discussed in the next section.

<table>
<thead>
<tr>
<th>Material</th>
<th>AlAs</th>
<th>In$<em>{0.53}$Ga$</em>{0.47}$As</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (300), eV</td>
<td>2.83</td>
<td>0.74</td>
</tr>
<tr>
<td>$m_e^*$</td>
<td>0.268</td>
<td>0.04</td>
</tr>
<tr>
<td>Affinity, eV</td>
<td>3.01</td>
<td>4.51</td>
</tr>
</tbody>
</table>

Based on the parameters listed in Table 6-1, the band diagram of InGaAs-AlAs ASPAT is shown in Figure 6.2. The band discontinuity of the InGaAs-AlAs ASPAT interface can be calculated as 1.5 eV. The 10 ML (28.3 Å) thick AlAs with the barrier height of 1.5 eV ensures that the main transport mechanism of the ASPAT is tunnelling. Furthermore, the conduction band profile for the ASPAT under bias can also be derived at this stage of the simulation (shown in Figure 6.3).
The conduction band profile for ASPAT under bias from SILVACO Simulation

The numerical calculation for ASPAT diodes was developed by Syme and Kelly [123, 124]. However, their method was not sufficient enough as the mismatch between simulations and measurements were very large. For the physical modelling of ASPAT diodes using SILVACO, the configuration used for quantum mechanical tunnelling is the semiconductor-insulator-semiconductor (SIS) model in the ATLAS simulator as this model deals with quantum barrier tunnelling.
The emitter and collector are under quasi equilibrium and the main active region is under non-equilibrium condition. The SIS model enables calculations of the tunnelling current through the potential barrier sandwiched by two semiconductor regions. In addition, the SIS model can also be used for semiconductor-semiconductor-semiconductor tunnelling if the material is specified. SIS.EL is used for electrons (EL) tunnelling, SIS.HO is for holes (HO) tunnelling, and SIS.NLDERIVS is for poor convergence conditions. In order to inform ATLAS of the location of the barrier, the simplest technique is to specify the QTREGION parameter at the tunnelling regions.

After defining both material and correct model specifications, the numerical method, solution and result analysis instructions can be easily coded.

6.4 ASPAT diode DC Modelling

Up to now, the simulation using ATLAS for the tunnelling device can only be made for two dimensional (2D) structures. The device is first designed to be on the x-y plane and extended to the z-axis by defining the ‘width’ in the structure statement. The three dimensional (3D) ASPAT is shown in Figure 6.4. Note that this 3D figure is not drawn to scale.

![Figure 6.4 3D Structure of ASPAT including contacts and semi-insulating substrates](image)

As described in the previous section, the first step of this simulation is the structure specification. In previously reported works [125, 131], all the simulations were based on back-contacted structure. The contact locations of this type of device structure are shown in Figure 6.5.
In section 3.6, the influence of the gap between top and bottom contacts was discussed. In order to see this clearer, the first attempt of the physical modelling for the InGaAs-AlAs ASPAT diode was focused on the effect on this gap influence. As a way of comparison with the back-contacted structure, the device structure shown in Figure 6.5 is a full planar structure. Simulations with different contacts structures were made and comparisons are shown in Figure 6.6. In this comparison, all simulated device sizes were set to be the same (64 µm²).

Figure 6.5 Back-contacted structure (3D Structure)

The Back-contacted structure was relatively easy to define in the code as no added regions needed to be involved. However, in practice fabricated devices rarely used this contact
structure. In the mask design used, the gap between contacts was designed to be 1.5 µm. Thus, in one of the planar structure simulations, a 1.5 µm gap was added in the simulation code. Then the other planar structure simulation kept the same region design but reduced the gap to 0 µm. As shown in Figure 6.6, simulations using a back-contacted structure and a planar structure with 1.5 µm gap had obvious differences in the device DC characteristics. There is thus clear evidence that the total resistance of the ASPAT diode is the sum of all contact resistances, the spreading resistance and the resistance of the various epi-layers as described in Chapter three. With the help of high doping of the Ohmic layers, the contact resistance only contributes a small portion of the total resistance. Similarly, the resistance of the epi-layers is only counted for the main active layers. Thus, it can be seen that the spreading resistance accounts for most of the total resistance and should not be neglected in the simulation. When reducing the gap to 0, the simulated results overlapped with the data of the back-contacted structure. Thus, this comparison gives further indication that the simulated result differences between back-contacted and planar structure with a 1.5 µm gap were due solely to the influence of the gap. To make the simulations more accurate, all subsequent simulations used the planar structure with the same gap as that of the fabricated device contacts gap (1.5 µm).

The next step of the simulation was focusing on finding the applicable material parameters. Due to the fact that the DC characteristics only show the influence of all parameters as a combination, a few simulations runs were performed where changes only occurred in one parameter. Take the bandgap as an example, the bandgap of InGaAs were simulated in the range of 0.74 eV to 0.76 eV. The simulated data extracted from SILVACO were then plotted in Figure 6.7.
Figure 6.7 Simulated DC characteristics for InGaAs-AlAs ASPAT with different bandgaps

It can be seen that when using a bandgap for InGaAs with a lower value, the simulated current was lower. This is consistent with the hypothesis that a lower bandgap lead to a larger band discontinuity and limit the thermionic emission. When the device was under low bias, the current differences were not distinguishable. These differences became more obvious when a higher voltage was applied. These further indicated that the possibility of thermionic emission for the device with relatively lower barrier height was higher thus leading to a larger current flow.

Similar simulations using other material parameters were also made. A brief conclusion can be made that a larger ‘Align’ value lead to a higher barrier height and produces a smaller current thus further making tunnelling the dominant transport mechanism. When applying a larger electron effective mass value for InGaAs, the simulated current dropped due to the reduction of the electron mobility. As a combination, the key parameters (with optimisation values within ±2% variation of the theoretical values) used for the simulations of the material definitions in this work are listed in Table 6-1 previously.

The current-voltage measurements at room temperature for the fabricated devices along with their respective simulated results are depicted in Figure 6.8. The simulation code was first designed for a device with a mesa area of 64 µm² with the length and width being both 8 µm as this was the mesa area of the mask layout. Then, to better fit with the measurements, the simulated device size was tuned to 63.2 µm² with the length of the device set to 8 µm and width set to 7.9 µm. From the inner figure of Figure 6.8, and though
differences of the simulated results using either 64 $\mu$m$^2$ or 63.2 $\mu$m$^2$ were small, still using 63.2 $\mu$m$^2$ showed a better fit especially under higher bias voltage. As mentioned in Chapter five, the real mesa size of the diode designed for 64 $\mu$m$^2$ was 63.5 $\mu$m, this further showed that the use of 63.2 $\mu$m$^2$ was closer to the practical device. The entire program code for XMBE326 ASPAT diode with a mesa area of 63.2 $\mu$m$^2$ can be found in Appendix D.

![Diagram](image)

**Figure 6.8** Room Temperature measured vs simulated data of I-V characterisations for XMBE326 ASPAT diodes with mesa area of 63.2 $\mu$m$^2$

At zero bias, the simulated results show much smaller values than the measured ones, due to the effect of the measurement equipment (analyser, cables and connections). Once the simulated data matched with the measurements, the epitaxial layer thickness, doping concentration, physical parameters, and the model specification of the device can be fixed.

![Diagram](image)

**Figure 6.9** Room Temperature measured vs simulated data of I-V characterisations for XMBE326 ASPAT diodes with various mesa sizes
Once all parameters were set for the fit shown in Figure 6.9 and the physical model validated, the next step was to examine whether the model was scalable. To that effect, simulations of various sizes devices were conducted as shown in Figure 6.9 where only the device sizes were changed in the simulated code keeping all other parameters fixed. Figure 6.9 shows that the simulations of various device sizes fit very well with measurements. In order to achieve these fitting, the simulated device sizes needed fine tuning of their areas compared with those of the fabricated devices, but the device area differences between simulations and fabrications were smaller than 0.5 µm². These comparisons further validate the successfully developed scalable physical model for the InGaAs-AlAs ASPAT diodes.

6.4.1 Temperature dependence

6.4.2 Temperature dependence simulations of InGaAs-AlAs ASPAT diodes

As discussed previously in section 6.3, a room temperature scalable physical modelling of the InGaAs-AlAs ASPAT was successfully developed. By using this model, excellent agreements between simulation and measured data were achieved at room temperature, and it was only natural that the next step was to investigate the temperature performance of the device from the physical aspect.

For both ASPAT designs, material parameters change as a function of temperature. Amongst all parameters, the effective mass is one of the key factors which can affect the characteristics of the diode most profoundly. The effective mass changes due to temperature variations for In$_{0.53}$Ga$_{0.47}$As can be obtained from [168]. In the case of binary materials, the relationship between effective mass and temperature can be written as

$$m = m_{0(n)} + m_{1(n)} \left( \frac{T}{300K} \right)$$  \hspace{1cm} (6.3)

where $m_{(n)}$ is the electron mass.

For ternary material, the equation can be rewritten as

$$m_{AB} = m_A(1 - x) + m_Bx + Cx(1 - x)$$  \hspace{1cm} (6.4)

where $m_A$ and $m_B$ are the effective masses of InAs and GaAs respectively while $C$ is a bowing parameter with the range from 0.038 to 0.044 (0.04 was used in this work).
The calculated effective masses of GaAs and In$_{0.53}$Ga$_{0.47}$As are listed in Table 6-2.

<table>
<thead>
<tr>
<th>Temperature(K)</th>
<th>GaAs($m_0$)</th>
<th>In$<em>{0.53}$Ga$</em>{0.47}$As($m_0$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>0.06608</td>
<td>0.04325</td>
</tr>
<tr>
<td>100</td>
<td>0.0658</td>
<td>0.04301</td>
</tr>
<tr>
<td>125</td>
<td>0.0655</td>
<td>0.04275</td>
</tr>
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<td>150</td>
<td>0.0652</td>
<td>0.04249</td>
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<td>0.04223</td>
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<td>200</td>
<td>0.0646</td>
<td>0.04197</td>
</tr>
<tr>
<td>225</td>
<td>0.0643</td>
<td>0.04171</td>
</tr>
<tr>
<td>250</td>
<td>0.064</td>
<td>0.04145</td>
</tr>
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<td>275</td>
<td>0.0637</td>
<td>0.04119</td>
</tr>
<tr>
<td>300</td>
<td>0.0634</td>
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</tr>
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</tr>
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<td>375</td>
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<td>0.04015</td>
</tr>
<tr>
<td>400</td>
<td>0.0622</td>
<td>0.03989</td>
</tr>
</tbody>
</table>

Besides the effective masses, the energy band gap of the material also plays a vital role for the ASPAT diodes. For GaAs, the band gaps as a function of temperature can be expressed as [169]:

$$E_g = E_{g,0} - \frac{\alpha T^2}{\beta + T}$$  \hspace{1cm} (6.5)$$

where $E_{g,0}$ is the band gap energy at 0K, $T$ is the operating temperature in Kelvin, $\alpha$ is a fitting parameter and $\beta$ is a constant. Previous work [170] indicated that the value of $\alpha$ and $\beta$ are $5.405\times10^{-4}$ and 204 respectively.
The variation of the band-gap energy $E_g$ with composition of the ternary alloy $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ as a function of temperature can be expressed as:

$$E_{\text{InGaAs}}(x) = E_{\text{InAs}}(T) + \left( E_{\text{GaAs}}(T) - E_{\text{InAs}}(T) \right)x + A(x - 1) \quad (6.6)$$

where $x=0.47$ and $A$ is a bowing parameter equal to 0.475 for $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ [171]. The calculated band gaps for AlAs, GaAs and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ are shown in Table 6-3 (Note that for AlAs, it is the direct band gap which is of importance)

<table>
<thead>
<tr>
<th>Temperature(K)</th>
<th>AlAs(eV)</th>
<th>GaAs(eV)</th>
<th>$\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$(eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>77</td>
<td>2.903665</td>
<td>1.507596</td>
<td>0.810607</td>
</tr>
<tr>
<td>100</td>
<td>2.899189</td>
<td>1.50122</td>
<td>0.805877</td>
</tr>
<tr>
<td>125</td>
<td>2.893411</td>
<td>1.49333</td>
<td>0.799893</td>
</tr>
<tr>
<td>150</td>
<td>2.886806</td>
<td>1.484646</td>
<td>0.793179</td>
</tr>
<tr>
<td>175</td>
<td>2.879482</td>
<td>1.475325</td>
<td>0.785853</td>
</tr>
<tr>
<td>200</td>
<td>2.871526</td>
<td>1.465485</td>
<td>0.77801</td>
</tr>
<tr>
<td>225</td>
<td>2.863014</td>
<td>1.455217</td>
<td>0.769725</td>
</tr>
<tr>
<td>250</td>
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<td>1.444592</td>
<td>0.76106</td>
</tr>
<tr>
<td>275</td>
<td>2.844565</td>
<td>1.433665</td>
<td>0.752066</td>
</tr>
<tr>
<td>300</td>
<td>2.834729</td>
<td>1.422482</td>
<td>0.742785</td>
</tr>
<tr>
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<td>0.733252</td>
</tr>
<tr>
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</tr>
<tr>
<td>375</td>
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<td>0.713544</td>
</tr>
<tr>
<td>400</td>
<td>2.793081</td>
<td>1.376778</td>
<td>0.704233</td>
</tr>
</tbody>
</table>
By using the calculated effective masses and band gaps, the simulated I-V characteristics can be obtained. The simulated results are compared with the measurements at 125 K, 225 K and 350 K. The comparisons are shown in Figure 6.10. These results give very close agreement with the measured data from low temperature (125 K) to high temperature (350 K) validating the physical models used.

![Figure 6.10 Measurements and simulations comparisons at 125 K, 225 K and 350 K](image)

From Table 6-3, the energy band gap difference between AlAs and InGaAs is 0.004 eV from 77 K to 400 K. In the case of AlAs and GaAs, the energy band gap difference is 0.020 eV from 77 K to 400 K. The good agreements between simulations and measurements at different temperatures indicate the correct physical parameters have been used in the code. Hence, by exporting the data from the model, the conduction band discontinuity can be deduced. Both ASPAT systems showed similar conduction band discontinuities at all temperatures compared to room temperature, as expected.
Figure 6.11 Potential barrier height: simulated results comparison between GaAs-AlAs and In$_{0.53}$Ga$_{0.47}$As-AlAs ASPAT diodes

The conduction band diagrams of both ASPAT designs (Figure 6.11) clearly show that the simulated potential barrier height of InGaAs-AlAs ASPAT is ~30% larger than it is for the GaAs-AlAs system. Based on the calculated results from Table 6-2, the changes of effective masses of GaAs and In$_{0.53}$Ga$_{0.47}$As, in the temperature range from 77 K to 400 K, are 0.038 m$_0$ and 0.036 m$_0$ respectively. Based on Table 6-3, the band gap differences between GaAs and InGaAs over the range 77 K to 400 K are from 0.697 eV to 0.673 eV. According to the extracted results from SILVACO, the conduction band difference between InGaAs and GaAs maintains an almost constant value (of approximately 0.5 eV) at all measured temperatures.

6.5 Material optimisation suggestion

From the I-V characteristics of the ASPAT diode, the second derivative of the IV characteristics of the diode can be extracted as shown in Figure 6.12.
Figure 6.12 Second derivative of the InGaAs-AlAs ASPAT diode IV characteristics

This figure indicated that the ASPAT diode can be used as an efficient zero-bias diode as the curvature coefficient of the diode is maximum near zero bias.

Following the successful and validated DC physical modelling of the InGaAs-AlAs ASPAT diode, it was therefore possible to use this model to predict future device behaviour. This will not only save on material resources, but also reduces process time and further help to optimise designs.

In case of the InGaAs-AlAs ASPAT material design, there are two key parameters that control the IV characteristics: thickness of the barrier and spacers ratio.

(1) Barrier

The dominant transport mechanism in InGaAs-AlAs ASPAT is tunneling and thus the barrier thickness acts as the main factor in the performance of the diode. In order to investigate the barrier thickness influence, two monolayer barrier thickness variations over the nominal 10 ML were made in the SILVACO simulation.
Figure 6.13 Barrier thickness variations of InGaAs-AlAs ASPAT (4×4 μm²)

As can be seen in this figure, the barrier thickness contributes substantially to the ASPAT I-V characteristics. Under a bias voltage of 1.5 V, the current increases 6.7 times for 8 ML and decreases 0.27 times for 12 ML compared with the nominal 10 ML control sample. This exponential change must be controlled in practice and uniformities of better than 0.1ML are required for manufacturable ASPAT devices as discussed previously.

(2) Spacers thickness ratio

Spacer thickness also plays a key role to the asymmetry of the I-V characteristics of ASPAT. In the original design, the spacer thickness ratio was designed to be 1:40. At this stage, the thickness of the thinner spacer was kept the same as the original design (5nm). The thickness of the thicker spacer (200 nm in original design) was then changed to make the spacers ratio of 1:30 and 1:50.
Figure 6.14 Thicker spacer thickness variation for InGaAs-AlAs ASPAT (4×4 μm²)

The current changes caused by the thicker spacer thickness change under forward bias can be neglected as these values are smaller than 0.2 μA (at 1.5 V). By contrast, in reverse bias, the higher spacer ratio leads to a lower current. For a zero-bias direct detector, the leakage current does not affect the detection performance a great deal. However for mixers applications, leakage current of the diode needs to be as small as possible as the I-V is achieved by using two diodes in an anti-parallel diode pair configuration [172].

6.6 Summary

The DC physical modelling for InGaAs-AlAs APAT diodes was developed and described in detail in this chapter. The planar structure was found to be the most precise structure as it included the spreading resistance influences as in practical fabricated devices. The key material parameters used in the simulation were also discussed. In addition this model showed it ability to predict device performance for various sizes and wide operating temperature ranges.

Furthermore, the optimisations of the InGaAs-AlAs ASPAT material structure designs via physical modelling also show the possibility to shape the IV characteristics to suit particular purposes or applications.

In brief, the InGaAs-AlAs ASPAT DC modelling were well developed and showed that this modelling was able to predict the diode performance over a wide range of temperature.
CHAPTER 7: DETECTOR CIRCUIT DESIGN USING

InGaAs-AlAs ASPAT DIODES

7.1 Introduction
AC modelling is a useful tool to predict the high frequency performance of electronic devices. From AC simulations, the capacitance-voltage, conductance-voltage performances and S-parameters of the ASPAT diodes can be extracted. These characteristics are then compared with measurements. The second part of this chapter is focused on detector circuit designs using InGaAs-AlAs ASPAT diodes. The equivalent circuits of the ASPAT diodes were extracted and integrated detector circuits working at 100 GHz and 240 GHz are designed and discussed.

7.2 AC modelling of ASPAT Diode
As a promising candidate for high frequency zero bias detectors, the physical modelling of ASPAT diode should be made not only to provide insights into the device phenomena observed from the diodes but also to assist in the prediction of the diode performance in complex circuit designs.

Following the development of the SILVACO DC model, an AC code can then be devised. As a post-processing operation to DC simulation, the AC simulation can be performed as an extension from the DC syntax. The AC analysis in SILVACO uses small signal analysis method where linear and non-linear elements are connected in an organised and established topology [166]. From the AC simulation, the capacitance and conductance of the device can be obtained. For the AC simulation, ‘ac.analysis’ command is used in the solve statement while specifying the input signal frequency in the same statement. The start and step frequencies are used for defining the signal frequency in the AC simulation. In addition, the S-parameters which are used to describe the high frequency behaviour can also be obtained from the AC modeling. The specific statements of the AC simulations are listed in Appendix E (for 4×4 μm² InGaAs-AlAs ASPAT).
7.3 De-embedding techniques

For RF measurements, de-embedding techniques are widely used to extract the extrinsic parameters which are associated with the additional transmission lines that are part of the GSG layout. The pad capacitance and inductance can be accurately extracted from the S-parameters of the CPW ‘open’ and ‘short’ structures respectively.

![Photographs of the CPW Structures (a) Open and (b) Short](image)

**Figure 7.1 Photographs of the CPW Structures (a) Open and (b) Short**

The RF characterises of the ASPAT diodes were measured at room temperature using an Anritsu VNA, and the S-parameters were measured on-wafer under different bias conditions from 40 MHz to 40 GHz.

The main simulator package used for circuit simulations in this project is Advanced Design System (ADS). By using ADS, the empirical model simulations can be compared with the imported measured data. The equivalent circuit of the ‘open’ mode is represented by a capacitor, where it is below real axis meaning its behaviour is capacitive with an infinite resistance. The behaviour is shown in Figure 7.2 (a). According to the method reported by Ren [173], the open CPW capacitance can be extracted from

\[
C_p = \frac{Im\left(Y_{11_{open}}\right)}{\omega} \quad (7.1)
\]

The equivalent circuit of the ‘short’ mode is represented by an inductor with its behaviour depicted in Figure 7.2 (b) on the Smith chart where it is above the real axis meaning it is inductive with a low resistance. The inductance of the short is determined from
The extracted pad capacitance and the parasitic inductance are approximately 10 fF and 50 pH respectively. Over different runs of measurements, the fluctuations of parasitic capacitance and inductance are 1 fF and 2 pH respectively which are negligible.

As the contacts of fabricated devices were interconnected with the GSG patterns, the measured RF characterises of the device include the performance of the intrinsic diode and the parasitic components. The measured capacitance of the fabricated devices is the sum of the diode junction capacitance and the pad capacitance. Thus, the junction capacitance can be extracted from the measurement data by using \( C_{\text{junction}} = C_{\text{total}} - C_{\text{pad}} \). Total capacitance \( C_{\text{total}} \) can be measured directly from the VNA, and the \( C_{\text{junction}} \) is the difference between the total capacitance \( C_{\text{total}} \) and parasitic capacitance \( C_{\text{pad}} \), which indicates the value of the diode capacitance.

### 7.4 Comparisons of AC simulation and RF measurement

The junction capacitance of the diode can be extracted directly from the SILVACO AC simulation. The total capacitance was measured directly from the VNA, and the measured junction capacitance used the difference of total capacitance and pad capacitance.
Theoretically, the fully depleted junction capacitance of the ASPAT diode can be calculated using

\[ C_{\text{junction}} = \frac{\varepsilon_0 \varepsilon_r A}{d} \]  \hspace{1cm} (7.3)

Where \( \varepsilon_0 \), \( \varepsilon_r \), \( A \), and \( d \), are the permittivity of free space, material permittivity, device area and depletion width respectively. The minimum junction capacitance of the ASPAT diode can be obtained when the diode is fully depleted. When the diode is fully depleted, the width of the depletion region is equal to the sum of two spacers and the barrier thickness.

As mentioned in Chapter six, the developed model can be used for various device sizes, the RF characterisation comparison will focus only on the fabricated device with size of 4×4 \( \mu \text{m}^2 \) which is appropriate for high frequency applications.

![Figure 7.3 Simulated and Measured Capacitance for GaAs-AlAs and In\(_{0.53}\)Ga\(_{0.47}\)As /AlAs ASPAT Diodes (4×4 \( \mu \text{m}^2 \))](image)

The C-V characteristics of both GaAs-AlAs and In\(_{0.53}\)Ga\(_{0.47}\)As-AlAs ASPAT diode are shown in Figure 7.3. Measured capacitances were extracted from RF measurements (already de-embedded), and the simulated capacitances were simulated directly by using SILVACO AC analysis. The simulated and measured RF frequencies were both 40 GHz. The theoretical fully depleted capacitance is 9.5 fF for In\(_{0.53}\)Ga\(_{0.47}\)As-AlAs ASPAT diode and 8.8 fF for GaAs-AlAs. From Figure 7.3, it can be seen that both ASPAT diodes were fully depleted at a reverse bias of -0.25 V. Through this comparison, the measured and
simulated junction capacitances show excellent agreements including the fully depleted capacitances.

Conductance is also a vital parameter for the diode as it is an indication of leakage current under reverse bias. For high frequency applications, such as anti-parallel diode pair detectors and mixers, the negative cycle of the input power applied to the detector will be removed by I-V characteristic under reverse bias. Thus, the conductance of the diode needs to be as small as possible.

![Conductance vs Voltage Graph](image)

**Figure 7.4 Simulated Conductance for GaAs-AlAs and In$_{0.53}$Ga$_{0.47}$As-AlAs ASPAT Diodes (4×4 μm$^2$)**

Figure 7.4 shows the simulated conductance values of both GaAs-AlAs and In$_{0.53}$Ga$_{0.47}$As-AlAs ASPAT diodes. When ASPAT diodes are biased at high reverse voltages, the probabilities of thermionic emission increase. However, the higher barrier of the InGaAs-AlAs ASPAT forces tunnelling to be the dominant transport mechanism. Thus, this higher barrier results in a much smaller conductance than in the case of the GaAs-AlAs ASPAT diode. The smaller conductance of In$_{0.53}$Ga$_{0.47}$As-AlAs ASPAT diode also indicates its smaller leakage current, and thus it can potentially show better performance in RF applications compared with the GaAs-AlAs ASPAT diode.

Besides junction capacitance and conductance, S-parameters can also be extracted from SILVACO AC simulation. The simulated S-parameters were then imported into the ADS software and compared with the measured ones. It should be noted that the measured data for the diode includes the GSG patterns, while the simulated S-parameter is for an intrinsic
diode. The ADS simulation was then designed to give result of the simulated S-parameter block incorporating the parasitic components (parasitic capacitance $C_{pad}$ and parasitic inductance $L_{pad}$). This equivalent circuit is shown in Figure 7.5 (a), where the simulation data were compared with RF measurements for both GaAs-AlAs and InGaAs-AlAs ASPAT diodes.

![SILVACO S-Parameter Block](image)

**Figure 7.5 (a) ADS Equivalent Circuit for ASPAT diode (4x4 µm²): SILVACO S-parameter Block incorporating parasitic and (b) Physical Modelling vs. Measurement Results of the ASPAT diodes**

Both GaAs-AlAs and InGaAs-AlAs ASPAT diodes show excellent fittings of the S-parameters at zero bias.

To the best of the author’s knowledge this is the first time that physically simulated s-parameters are compared with measured S-parameters for tunnel diodes. These highlights and emphasis the accuracy and predictive power of SILVACO AC simulations once proper material parameters are properly inputted. This therefore sets the scene for predicting RF performance for ASPAT diodes.

Device parameters listed, (i.e. $R_j$, $C_j$ and $R_s$: series resistance of the diode) in Table 7-1 are important for designing the matching circuits.
Table 7-1 Extracted values for the intrinsic components for 4 × 4 µm² devices at zero bias

<table>
<thead>
<tr>
<th>Device ID</th>
<th>Method</th>
<th>$R_j$ (kΩ)</th>
<th>$S_C$</th>
<th>$R_s$ (Ω)</th>
<th>$C_j$ (fF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GaAs ASPAT</td>
<td>Measured</td>
<td>95</td>
<td>14</td>
<td>11</td>
<td>22.8</td>
</tr>
<tr>
<td></td>
<td>SILVACO Model</td>
<td>92</td>
<td>-</td>
<td>-</td>
<td>23.6</td>
</tr>
<tr>
<td>InGaAs ASPAT</td>
<td>Measured</td>
<td>190</td>
<td>75</td>
<td>4.6</td>
<td>18.1</td>
</tr>
<tr>
<td></td>
<td>SILVACO Model</td>
<td>215</td>
<td>-</td>
<td>-</td>
<td>18</td>
</tr>
</tbody>
</table>

The junction resistance, $R_j$, for the measured data is calculated using the first derivative of the I-V characteristics, while for the SILVACO modelling, it is was obtained from the reciprocal of the conductance. $R_j$ is proportional to the device sensitivity and thus can help in evaluating detector circuit performance. $S_C$ is the current sensitivity of the diode which is equal to half of the curvature coefficient extracted from the I-V characteristics of the diode. Based on our knowledge, the current responsivity of 75 provided by InGaAs ASPAT is the highest reported to date.

In spite of the fact that this diode offers a very good current responsivity, it demonstrates a low current density meaning that it has a very high $R_j$, making matching circuit sizes larger. However, the structure can be carefully optimised to compromise between $R_j$ and current responsivity.

### 7.5 Equivalent Circuit for ASPAT

The ASPAT diode equivalent circuit is used to extract the intrinsic components, such as series resistance $R_s$, diode junction capacitance $C_j$, and junction resistance $R_j$. In this simulation process, the lumped components are used to represent the DC performance of the diode and are then compared with measurements. By using the de-embedding technique described earlier, $C_{pad}$ and $L_{pad}$ can be easily extracted.
The series resistance $R_s$ of the ASPAT diode can be extracted from the TLM measurement and calculated using the method described in Chapter three. For the $4\times4 \ \mu m^2$ InGaAs-AlAs ASPAT diode, $R_s$ was 4.7 $\Omega$. At zero bias, the junction capacitance $C_{j0}$ is 18.5 fF (the same as the one extracted from the SILVACO C-V simulation). In order to get a better fit with the measured data, the series resistance and junction capacitance were tuned to be 5 $\Omega$ and 19 fF.

7.6 Detector circuit design

7.6.1 ASPAT diode model

The detector circuit design is mainly focused on the $4\times4 \ \mu m^2$ InGaAs-AlAs ASPAT diode. The DC block of the device used for the ADS simulation is based on using a polynomial model which fit with the diode I-V and also includes discrete components [174]. In the case of the ASPAT diode, there is a junction capacitance in parallel with the polynomial component. The regular residuals (errors) between the measurements and polynomial fitting can be limited $\sim 10^{-7}$. 
After finding the most accurate fit, the coefficients of the polynomial are imported into ADS, and an SDD (Symbolically Defined Device) model which represents this particular ASPAT diode can be created. In practice, additional components (a parallel capacitor for ASPAT diode) need to be added. Theoretically, the ASPAT diode can be used as a zero-bias detector. However, an applied RF signal would immediately drive the diode in its non-linear region. Thus, the SDD-block empirical model can provide sufficient accuracy for the ADS simulation.

In the circuit design process, the diode selection is usually the starting point. The theoretical cut-off frequency \( f_{\text{cut-off}} = \frac{1}{2\pi R_s C} \) is determined by the diode series resistance and junction capacitance. From the measurement, the series resistance and junction capacitance of the 4x4 \( \mu \text{m}^2 \) InGaAs-AlAs ASPAT diode at zero bias were 4.6 \( \Omega \) and
and 18.5 fF respectively. Thus the estimated cut-off frequency of the diode is 1.87 THz. To make the detector efficient, the operation frequency should be no more than 1/3 of the cut-off frequency. Thus, for the work presented in this thesis, the detector circuits using 4×4 \( \mu m^2 \) InGaAs-AlAs ASPAT diode operating at 100 GHz and 240 GHz were investigated.

### 7.6.2 Input power and matching circuit design

As a non-linear component, the performance of the diode detector is dependent on the amount of power supplied and the port impedances of the detector are also related to the input power. In the case of ASPAT diodes, a large range of achievable RF powers was run in the simulations to find the optimal RF power level.

Once a certain power level is found, the matching circuit can be designed. In reality, having good matching at all frequencies is an extremely difficult work. Normally, the matching circuits can be treated as filters for the supplied signals as the networks are generally narrowband structures. The matching circuit increases the amount of RF power delivered to the diode by reducing the reflection between the RF signal and the diode impedance at specific frequencies, as a result of that, the detector circuit performance can be further improved. Designing the matching stubs to be short or open is highly dependent on the planar technology. Short circuits are much easier to implement in CPWs, while open circuits are widely used in micro strip technology.

### 7.6.3 Detector circuits

The detector circuit using the nonlinear component is shown in Figure 7.9. The power supply provides the optimal RF power. The stubs help to match the diode block with a 50Ω impedance. In the diode block, the DC block uses the SDD model derived previously. For zero-bias detection, the junction capacitance uses the diode capacitance at zero bias. The output signal appears at the load as shown in Figure 7.9.
As an Anritsu 37369A VNA was used to obtain the S-parameters of the devices, the highest frequency of RF data for the ASPAT diodes is 40 GHz, nevertheless the fit should be valid to several hundred GHz. Throughout the circuit simulations, the main aim was to extract the voltage sensitivity of the detector circuit. The zero-bias junction resistance of the InGaAs-AlAs ASPAT diode was more than 200 kΩ and thus the load resistance $R_{\text{load}}$ can be neglected in the load circuit. In addition, the other advantage of providing a large junction resistance at low voltage is that there is no need to apply a high input power to drive the diode into its nonlinear region. Thus, the diode can be operated with very low RF input power.

### 7.6.3.1 100GHz InGaAs-AlAs ASPAT detector simulation

When diodes are working at high frequencies (GHz or THz), the junction capacitance of diodes often increases with frequency as the permittivity of the material changes. The SILVACO AC simulated junction capacitance of the 4×4 μm² InGaAs-AlAs ASPAT diode was 22 fF at 100 GHz.

Figure 7.10 shows the transfer functions of the InGaAs-AlAs ASPAT diode at 100 GHz. The output voltage saturation started when the input power was higher than -10 dBm. The saturation indicates that the diode is now working beyond its nonlinear region and no longer acts as a detector.
The voltage sensitivity of the detector to incident power is expressed as

$$\beta_V = 2Z_o\kappa$$  \hspace{1cm} (7.4)

where $Z_o$ is the line impedance and $\kappa$ is the curvature coefficient which is proportional to the diode junction resistance [125]. Thus, as the voltage sensitivity depends on the junction resistance of the diode, a larger value of $R_{\text{junction}}$ provides a higher sensitivity.

At 100 GHz, the highest simulated voltage sensitivity is 8300 V/W when the input power is -29 dBm. When the input power is higher than 10 dBm, the diode loses its ability for detection. Therefore the 4×4 μm² InGaAs-AlAs ASPAT diode can work with an input power range from -30 dBm to -10 dBm.
The next step for the simulation was to set the input power to -29 dBm, and sweep the input frequency. As can be seen in Figure 7.12, the peak sensitivity is 8300 V/W at 98 GHz (slightly lower than target of 100 GHz), this is due to the matching circuit not being exactly matched at 100 GHz. However, this mismatch only had a very minor effect on the sensitivity which changed from 8300 to 8260 V/W.

![Figure 7.12 Voltage sensitivity of 4×4 μm² InGaAs-AlAs ASPAT diode with respect of input RF frequency (100 GHz)](image)

**7.6.3.2 240 GHz InGaAs-AlAs ASPAT detector simulation**

The other detector circuit using a 4×4 μm² InGaAs-AlAs ASPAT diode was designed to work at 240 GHz. By using the same design method, and redefined the matching circuits, the transfer functions and voltage sensitivity of the 4×4 μm² InGaAs-AlAs ASPAT diode at 240 GHz were obtained as depicted in Figure 7.13 The output voltage starts to saturate when the applied input power was higher than -4 dBm.
Sweeping the input power, the highest simulated voltage sensitivity achieved at 240 GHz was 1340 V/W when the input power was -21 dBm.

The input power was then fixed to -21 dBm and the signal frequency swept from 210 GHz to 270 GHz. The highest sensitivity was 1410 V/W which was achieved at 235 GHz. The shift of the peak value is due to the mismatch of the matching circuit. At the design frequency 240 GHz, the voltage sensitivity was 1390 V/W, which is almost the same as the peak value.
Figure 7.15 Voltage sensitivity of $4 \times 4 \ \mu m^2$ InGaAs-AlAs ASPAT diode with respect of input RF frequency (240 GHz)

7.6.3.3 Detector performance comparisons between SBDs and InGaAs-AlAs ASPAT diode

Comparing with the commonly used SBDs, the simulated results show that the InGaAs-AlAs ASPAT diode has promising potential in high frequency detection. The detailed voltage sensitivity/responsivity comparisons of various devices reported in the literature and operating in the 100 GHz and 250 GHz regions are listed in Table 7-2.

When the operating frequency is around 100 GHz, the simulated peak sensitivity of the InGaAs-AlAs ASPAT diode is 8300 V/W (at 98 GHz), which is much higher than some commoditised SBDs and reported results listed in Table 7-2.

In the range around 240 GHz, the peak voltage sensitivity of the InGaAs-AlAs ASPAT diode is around 1410V/W, this was also comparable with the best reported responsivity of the SBDs.
### Table 7-2 Comparisons of SBDs and InGaAs-AlAs ASPAT detectors

<table>
<thead>
<tr>
<th>Detector Type</th>
<th>Operation frequency (GHz)</th>
<th>Responsivity (V/W)</th>
<th>Peak Responsivity (V/W)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Schottky</strong></td>
<td>89</td>
<td>896</td>
<td>-</td>
<td>[175]</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>~400</td>
<td>-</td>
<td>[176]</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>4000</td>
<td>-</td>
<td>[177]</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>3800</td>
<td>-</td>
<td>[175]</td>
</tr>
<tr>
<td></td>
<td>110-170</td>
<td>2000</td>
<td>-</td>
<td>[178]</td>
</tr>
<tr>
<td><strong>ASPAT (this work)</strong></td>
<td>93-106</td>
<td>&gt;6000</td>
<td>8300 @98GHz</td>
<td></td>
</tr>
<tr>
<td><strong>Schottky</strong></td>
<td>200</td>
<td>900</td>
<td>-</td>
<td>[176]</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>1900</td>
<td>-</td>
<td>[175]</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>430</td>
<td>-</td>
<td>[179]</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>1080</td>
<td>-</td>
<td>[176]</td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>336</td>
<td>-</td>
<td>[180]</td>
</tr>
<tr>
<td><strong>ASPAT (this work)</strong></td>
<td>217-254</td>
<td>&gt;1300</td>
<td>1410@235GHz</td>
<td></td>
</tr>
</tbody>
</table>

In addition, the voltage sensitivity drift with temperature of the SBDs has been reported [175]. The results showed that for the same SBDs, the responsivity dropped from 3800 to 3000 V/W when the operation temperature decreased from 40 °C to room temperature at 100 GHz, and fell from 2000 to 1800 V/W at 200 GHz. In the case of InGaAs-AlAs ASPAT diodes, as the temperature dependence measurements showed in Chapter five, the I-V characteristics changed only very little over large temperature ranges. Take the detector circuit operating at 100 GHz as an example. The simulated voltage sensitivity of
the InGaAs-AlAs ASPAT at 350 K is shown in Figure 7.16. In this simulation, the matching circuits were kept the same as they were at room temperature.

When comparing with the sensitivity achieved at room temperature, the peak value which was 8180 V/W only changed by 120 V/W (1.5%). This drop was due to mismatching with the matching circuits and the junction resistance decreased as the current slightly increased. With a larger temperature range (50 K), this change was much smaller than it is for the SBDs which dropped by 27%. Thus two conclusions can be made. The first is that the responsivity of the InGaAs-AlAs ASPAT detector was almost the same as its room temperature value. The second is the circuit temperature performance, with the InGaAs-AlAs ASPAT diode more stable than SBDs. Thus, this temperature stability property can lead the InGaAs-AlAs ASPAT detector to be used in a much wider applicable temperature range without the need for temperature compensation circuitry.

Figure 7.16 Voltage sensitivity of 4×4 μm² InGaAs-AlAs ASPAT diode with respect of input RF frequency (350 K)

However, note that all the responsivities of the InGaAs-AlAs ASPAT detectors were simulated values and not experimental ones (even though the design of the detector circuits was based on real, fabricated ASPAT devices). In the simulation, all the designs, such as matching designs and the other lumped components, were set under perfect conditions. For future work, a mask layout based on these simulations will be designed and fabricated detector circuits measured to calibrate the simulated models.
7.7 Summary

This chapter focuses on the AC performances of ASPAT diode. The junction capacitances, diode conductance and the S-parameters of both GaAs-AlAs and InGaAs-AlAs ASPAT diodes were obtained, for the first time, from SILVACO AC simulations. The junction capacitance and S-parameters showed excellent fits with measurements. The equivalent circuit of the InGaAs-AlAs ASPAT diode were then extracted taking into account proper de-embedding methods. By using the parameters extracted from the equivalent circuit, 100 GHz and 240 GHz zero bias InGaAs-AlAs ASPAT detector circuits were designed. The simulated voltage sensitivity of InGaAs-AlAs ASPAT detector was 1.5 times higher than that of the SBDs at 100 GHz, and 1.2 times higher at 250 GHz. The simulated results showed that the InGaAs-AlAs ASPAT detectors had higher voltage sensitivities for operations at both frequencies. In addition, the comparison of the voltage sensitivity at room temperature and 350 K proved that the diode performance was much more stable than a SBD. When compared with SBDs, the temperature insensitive property of the InGaAs-AlAs ASPAT diode makes it a more stable and efficient RF device under a wide range of operating temperatures.
CHAPTER 8: CONCLUSIONS AND FUTURE WORK

The final Chapter of this thesis provides a brief summary of the work presented in Chapters 4 through 7, together with the main conclusions. The ideas and directions of future work are also given in this chapter.

8.1 Conclusions

The work in this thesis detailed an extensive and in-depth study of semiconductor tunnel diodes and photoconductive switches to investigate both optical and electronic approaches to THz generation and detection.

For the optical approach, optimised THz photoconductive devices based on III-V semiconductor grown at low temperature conditions using Molecular Beam Epitaxy were investigated. The optical and transport properties as well as the TDS characteristics of these photoconductive samples operating at excitation wavelengths of 800 nm and 1.55 µm were studied. The effect of coupling the DBR layers with the active layers of photoconductors were compared with the base line efficient photoconductors. The results showed that the DBR layers did not affect the mobility and the resistivity of the photoconductive materials and the reflectivity of DBRs at the desired wavelengths (800nm and 1.55 µm) were matched with the designed structures. In the TDS testing, LT GaAs optimised photoconductive switches based system had responses with THz pulses having power up to 4 THz and dynamic range of 60 dB or more, while the LT InGaAs-InAlAs optimised photoconductive switches based system had responses with power up to 2.5 THz and with 50 dB noise floor. For both optimised LT GaAs and LT InGaAs-InAlAs switches, coupling DBRs layers also results in an increase of the transmitter photocurrent, a marked enhancement of the THz peak signal (more than twice), and a doubling of the optical to electrical efficiency. Thus, the performances of these optimised photoconductive switches excited at 800 nm and 1.55 µm show better performances and allow for higher quality THz applications to be investigated.

Our main industrial partner (TeTechs) commercialises switches (incorporating our devices) and operating at 800 nm and 1.55 µm by mounting the photoconductive antennas into THz modules with a hyper-hemispherical silicon lens and an SMA connector. In addition, the collaboration also resulted in the Rigel 1550 Spectrometer which is an innovative low cost,
portable, room temperature operated and reconfigurable fiber coupled THz spectrometer. The beam delivery part is independent of the laser and can be easily connected to any femtosecond laser at telecom wavelength. By using the Rigel 1550 Spectrometer, the transparencies of a series of materials were obtained. From these measurements, SI InP and SI GaAs substrate of the structures operating at excitation wavelengths of 800 nm and 1.55 µm were found to be transparent to the signal in the THz frequency range. Thus, there is no need to remove the substrates as they do not affect the generation of THz radiation. This further allows the photoconductive antennas to be low cost and high yielding devices. Objects such as cotton clothes and paper were also transparent to THz signals suggesting potential THz application in security checking. In addition, the associated absorption spectrum of a bunch of paper also showed good agreement with the absorption lines of water vapor. THz measurements on biological sample objects such as leaves and a human hand were also made and showed the potential for interdisciplinary between biological research and THz technology. In the future, this spectrometer will benefit the University of Manchester for medical, biological and other fields for as yet untapped THz properties.

For the electronic approach, a new type of InP-based Asymmetric Spacer Tunnel Diode (ASPAT) was investigated. The growth of the material was performed using molecular beam epitaxy (MBE) which can control very precisely the thickness of active layers (especially barrier) of the ASPAT down to a fraction of a monolayer. A key novelty in the SI InP based ASPAT studied here is the replacement of conventional GaAs with In$_{0.53}$Ga$_{0.47}$As. This produced a larger band discontinuity from spacer to barrier, thus ensuring tunnelling to be dominant rather than thermionic emission in the transport mechanisms.

The InGaAs-AlAs ASPAT diodes were designed to be used as zero bias detectors at high frequencies. The asymmetric InGaAs spacers sandwiching the AlAs barrier contributed to the asymmetric I-V characteristics and made this diode have a nonlinear region which is essential for detection.

This project dedicated efforts to not only mask designs and layouts but also developed optimised processes to achieved state of the art high-frequency performances from the fabricated devices. To simultaneously measure both DC and high frequency characteristics of the devices, the mask layout was designed to use a ground-signal-ground (GSG) contact structure with optimised strip width. An optimised process combining both wet and dry
etching methods was also developed. As the device was designed to use an air-bridge technique, this unique combination method with a precisely controlled time was used to achieve anisotropic etching and successful opening of the air-bridge to make small device mesa area and to allow the device to work at high frequencies.

After successful fabrication, the temperature dependence of the InGaAs-AlAs ASPAT diode was investigated and its I-V characteristics measured at various temperatures and compared with those of a Schottky diode (SBD) and a conventional GaAs-AlAs ASPAT diode respectively. These comparisons illustrate that the ASPAT diode’s characteristics have only a minor residual temperature dependence compared with SBDs and the currents in the InGaAs-AlAs ASPAT only marginally changed over the temperature range of 77K to 400K. When compared with the conventional GaAs-AlAs ASPAT, the new design showed an even better temperature stability due to its relatively higher barrier height. This property allows this type of diode to stably operate over a very wide range of temperature.

In addition, physical modelling of this new type of ASPAT diode was developed. This physical device simulation helped to give insight into the physics of this new zero bias detectors. The diode DC characterises can be simulated not only at room temperature, but also at various temperatures, and all simulated results showed excellent matching with measurements. The band diagram of the InGaAs-AlAs ASPAT showed a much higher conduction band discontinuity (around 0.5 eV) compared to that of GaAs-AlAs ASPAT diodes, thus the height of the barrier to electron transport is larger. This higher barrier limits even further the thermionic transport of elections and hence tunneling is the dominant mechanism in InGaAs-AlAs ASPAT. The simulation also helped to confirm that the properties of InGaAs-AlAs ASAPT diode lead to a much more temperature insensitive diode behaviour.

After successfully developing the DC model of ASPAT diode, the AC performances were extracted from SILVACO AC models. The junction capacitance, conductance and S-parameters of the intrinsic InGaAs-AlAs ASPAT diode were obtained. By using the ADS empirical model, the SILVACO simulated S-parameter results showed excellent matching with the RF measurements. From the RF measurements, the equivalent circuit which consists of the series resistance, junction capacitance and junction resistance of the InGaAs-AlAs ASPAT diodes can be extracted. At zero bias, the simulated junction capacitance of a 4×4 μm² InGaAs-AlAs ASPAT diode was found to be 18 fF which was
identical to the extracted value from the equivalent circuit and RF measurements. The detector circuit using 4×4 μm² devices for 100 GHz and 240 GHz detections were designed. These simulated results showed higher voltage sensitives than those of SBDs at both frequencies. In addition, from a simulation for the InGaAs-AlAs ASPAT detector at an operation temperature at 350 K, the simulated sensitivity only dropped by 120 V/W (≈ 1.5% change) over the 50 K temperature change while the change for the SBD was 800 V/W (27%) over 10 K temperature variations.

8.2 Further Work

This short section will suggest a number of new approaches to further improve the high frequency of devices

8.2.1 Photoconductive switches

By adding distributed Bragg reflector (DBR) layers below the active layers, optimised photoconductive materials excited at 800 nm and 1.55 μm can further improve the already efficient performance of the photoconductor. It is however worth checking the performance of these switches in continuous wave (CW) operating system. Such studies will bring the prospects for a truly portable and high efficient THz imaging system much closer to reality.

The Rigel 1550 Spectrometer has enormous potential and can also be extended to benefit different schools on the University of Manchester with collaborations with medical, biological, chemistry and other schools.

8.2.2 InGaAs-AlAs ASPAT diode

The key investigations of this newly designed InGaAs-AlAs ASPAT diode have been demonstrated in this work. The DC characteristics from 77 K to 400 K were studied and compared with SBDs and conventional GaAs-AlAs ASPAT diode. In addition, the RF performances of this type of ASPAT have been measured up to 40 GHz. The 100 GHz and 240 GHz zero bias detector circuit based on measured diode characteristics (4×4 μm² devices) were designed and their performances simulated.

This is the first attempt at RF design of complete receiver circuit, growth, fabrication and testing of InGaAs-AlAs ASPAT diodes. For further work, more wafers using the various
optimisations are worth growing and fabricating. Compared with the conventional design, InGaAs-AlAs ASPAT has a 0.5 eV higher barrier height making it a far more efficient tunnel device.

In order to work at even higher frequencies, devices with even smaller mesa sizes are needed. In addition, the mask schematic layout based on the detector circuit simulation should be fabricated and RF performances of fabricated circuits investigated. Furthermore, the integration of the detector with an antenna structure can be the next step for realising compact zero bias, zero power dissipating millimetre-wave and THz devices. Beyond these, the ASPAT can also be used for many other applications such as high-frequency mixers and multipliers. These will bring the ASPAT diode based applications one step closer to reality and make it an essential component of massive connectivity in the internet of thing (IoT) deployments.
Appendix A1: The preparation of Hall Effect samples

1. Cleave the sample in 7.5 mm × 7.5 mm size

2. Clean sample with NMP (1165) and DI Water and dry with N$_2$

3. Spin a layer of photoresist S1805, Time = 30 sec

4. Prebake in hotplate at 115 °C for 1 min

5. Place the metallic cloverleaf pattern on the sample and exposure using UV Eraser for 10 mins

6. Develop using MF319 for 2 mins, rinse with DI water and dry with N$_2$

7. Post bake in hotplate at 120 °C for 5 mins to harden the resist before etch

8. Etch using Ortho-phosphoric (3:1:50 of H$_3$PO$_4$;H$_2$O$_2$;H$_2$O) for 15 mins

9. Clean the sample with Acetone / IPA and dry with N$_2$ to remove the resist

10. Place four small cubic dots of pure Indium on the four square corners of the formed cloverleaf pattern

11. Anneal at 310 °C for 3 mins (InGaAs-InAlAs Samples) / 420 °C for 3 mins (GaAs Samples) under N$_2$ flow using the alloying jig
Appendix A2: The fabrication process of photoconductive antennas

<table>
<thead>
<tr>
<th>MESA</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample cleaning</td>
<td>NMP for 5 mins and Dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td>Resist coating</td>
<td>S1805 for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 120 °C for 1 min</td>
</tr>
<tr>
<td>Photolithography</td>
<td>Align the mesa mask and exposure for 20 sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 319 for 1 min, rinse with DI water and dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Post bake in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td>Etching</td>
<td>Calibration, etch calibrated sample for 20 sec using Orthophosphoric (H₃PO₄:H₂O₂:H₂O=2:1:2)</td>
</tr>
<tr>
<td>Sample cleaning</td>
<td>Calculate the etching time by considering the mesa height</td>
</tr>
<tr>
<td></td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
</tr>
</tbody>
</table>
## OHMICS

<table>
<thead>
<tr>
<th>Process</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with ( \text{N}_2 )</td>
</tr>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>AZnLOF (2μm) for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 110 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 5.5 sec</td>
</tr>
<tr>
<td></td>
<td>Post Exposure bake at 110 °C for 1 min</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 326 for 1 min, rinse with DI water and dry with ( \text{N}_2 )</td>
</tr>
<tr>
<td><strong>Metallisation</strong></td>
<td>Clean with HCL (HCL: ( \text{H}_2\text{O} )=1:1) for 1 min</td>
</tr>
<tr>
<td></td>
<td>Evaporate 2 cm Ti (50 nm) and 5.5 cm (150 nm) Au using thermal evaporator</td>
</tr>
<tr>
<td><strong>Lift-off</strong></td>
<td>Place the sample in NMP for 40 mins at room temperature</td>
</tr>
<tr>
<td></td>
<td>Clean the sample with Acetone / IPA, dry with ( \text{N}_2 )</td>
</tr>
<tr>
<td><strong>Annealing</strong></td>
<td>Anneal the contacts at 250 °C for 1 min under ( \text{N}_2 ) flow</td>
</tr>
<tr>
<td></td>
<td>using the alloying jig</td>
</tr>
</tbody>
</table>
## Appendix A3: The fabrication process of GaAs-AlAs ASPAT diodes

### OHMICS (TOP CONTACTS)

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<tr>
<th>Step</th>
<th>Process Details</th>
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<tbody>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>Spin AZnLOF (0.5μm) for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 110 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 12sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Post Exposure bake at 110 °C for 1 min</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 326 for 1 min, rinse with DI water and</td>
</tr>
<tr>
<td></td>
<td>dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Clean with HCL (HCL:H₂O=1:1) for 1min</td>
</tr>
<tr>
<td><strong>Metallisation</strong></td>
<td>Evaporate AuGe (100 mg), Ni (1.0 cm) and Au (15 cm)</td>
</tr>
<tr>
<td></td>
<td>using thermal evaporator</td>
</tr>
<tr>
<td><strong>Lift-off</strong></td>
<td>Place the sample in NMP for 40 mins at room temperature</td>
</tr>
<tr>
<td></td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
</tr>
</tbody>
</table>
### MESA (ISOLATION)

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>Spin S1813 for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 120 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 2 mins (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 319 for 1 min, rinse with DI water and dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Post bake in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Etching</strong></td>
<td>Calibration, etch calibrated sample for 2 mins using Orthophosphoric (H₃PO₄:H₂O₂:H₂O=3:1:50)</td>
</tr>
<tr>
<td></td>
<td>Calculate the etching time by considering the mesa height</td>
</tr>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
</tr>
</tbody>
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## MESA (MESA ETCH)

<table>
<thead>
<tr>
<th>Sample cleaning</th>
<th>NMP for 5 mins and Dry with N\textsubscript{2}</th>
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</thead>
<tbody>
<tr>
<td>Preheat</td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td>Resist coating</td>
<td>S1805 for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 120 °C for 1 min</td>
</tr>
<tr>
<td>Photolithography</td>
<td>Align the mesa mask and exposure for 20 sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 319 for 1 min, rinse with DI water and dry with N\textsubscript{2}</td>
</tr>
<tr>
<td></td>
<td>Post bake in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td>Etching</td>
<td>Calibration, etch calibrated sample for 20 sec using Orthophosphoric (H\textsubscript{3}PO\textsubscript{4}:H\textsubscript{2}O\textsubscript{2}:H\textsubscript{2}O=2:1:2 and 3:1:50)</td>
</tr>
<tr>
<td>Sample cleaning</td>
<td>Calculate the etching time by considering the mesa height</td>
</tr>
<tr>
<td></td>
<td>Clean the sample with Acetone / IPA, dry with N\textsubscript{2}</td>
</tr>
<tr>
<td><strong>BOTTOM CONTACTS</strong></td>
<td></td>
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<tr>
<td>---------------------</td>
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<tr>
<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with N₂</td>
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<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>AZnLOF (2 μm) for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 110 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 5.5 sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Post Exposure bake at 110 °C for 1 min</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 326 for 1 min, rinse with DI water and dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Clean with HCL (HCL:H₂O=1:1) for 1min</td>
</tr>
<tr>
<td><strong>Metallisation</strong></td>
<td>Evaporate AuGe (100 mg) and Au (15 cm) using thermal evaporator</td>
</tr>
<tr>
<td><strong>Lift-off</strong></td>
<td>Place the sample in NMP for 40 mins at room temperature</td>
</tr>
<tr>
<td><strong>Annealing</strong></td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Anneal the contacts at 420 °C for 2 mins under N₂ flow using furnace</td>
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</tbody>
</table>
### DIELECTRIC LAYER

<table>
<thead>
<tr>
<th>Sample cleaning</th>
<th>NMP for 5mins and Dry with N₂</th>
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<tbody>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
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<tr>
<td>Resist coating</td>
<td>S1805 for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 120 °C for 1 min</td>
</tr>
<tr>
<td>Photolithography</td>
<td>Align the mesa mask and exposure for 20 sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 319 for 1 min, rinse with DI water and dry with N₂</td>
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<tr>
<td></td>
<td>Hard bake in hotplate at 250 °C for 30 mins</td>
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## DIELECTRIC BRIDGE

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<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
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<tr>
<td></td>
<td>Prebake in hotplate at 110 °C for 1 min</td>
</tr>
<tr>
<td></td>
<td>Align the mesa mask and exposure for 5.5 sec (0.9mW i-line)</td>
</tr>
<tr>
<td>Photolithography</td>
<td>Post Exposure bake at 110 °C for 1 min</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 326 for 1 min, rinse with DI water and dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Clean with HCL (HCL:H₂O=1:1) for 1min</td>
</tr>
<tr>
<td>Metallisation</td>
<td>Evaporate Ti (1cm) and Au (15 cm) using thermal evaporator</td>
</tr>
<tr>
<td>Lift-off</td>
<td>Place the sample in NMP for 40 mins at room temperature</td>
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<tr>
<td></td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
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</table>
## Appendix A4: The fabrication process of InGaAs-AlAs ASPAT diodes

### OHMICS (TOP CONTACTS)

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<th>Process</th>
<th>Procedure</th>
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<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with N₂</td>
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<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>Spin AZnLOF (0.5μm) for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 110 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 12 sec (0.9mW i-line)</td>
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<tr>
<td></td>
<td>Post Exposure bake at 110 °C for 1 min</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 326 for 1 min, rinse with DI water and dry with N₂</td>
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<tr>
<td><strong>Metallisation</strong></td>
<td>Clean with HCL (HCL:H₂O=1:1) for 1 min</td>
</tr>
<tr>
<td></td>
<td>Evaporate Ti (1 cm) and Au (15 cm) using thermal evaporator</td>
</tr>
<tr>
<td><strong>Lift-off</strong></td>
<td>Place the sample in NMP for 40 mins at room temperature</td>
</tr>
<tr>
<td></td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
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### MESA (ISOLATION)

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<th>Sample cleaning</th>
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<td>Resist coating</td>
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<tr>
<td></td>
<td>Prebake in hotplate at 120 °C for 1 min</td>
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<tr>
<td></td>
<td>Align the mesa mask and exposure for 2 mins (0.9mW i-line)</td>
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<td>Photolithography</td>
<td>Develop in MF 319 for 1 min, rinse with DI water and dry with N₂</td>
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<tr>
<td></td>
<td>Post bake in hotplate at 120 °C for 5 mins</td>
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<tr>
<td></td>
<td>Calibration, etch calibrated sample for 2 mins using Orthophosphoric (H₃PO₄:H₂O₂:H₂O=3:1:50)</td>
</tr>
<tr>
<td>Etching</td>
<td>Calculate the etching time by considering the mesa height</td>
</tr>
<tr>
<td>Sample cleaning</td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
</tr>
</tbody>
</table>
## MESA (MESA ETCH)

<table>
<thead>
<tr>
<th>Step</th>
<th>Procedure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>Spin S1805 for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 120 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 20 sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 319 for 1 min, rinse with DI water and dry with N₂</td>
</tr>
<tr>
<td></td>
<td>Post bake in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Etching</strong></td>
<td>Calibration, etch calibrated sample for 10mins using dry</td>
</tr>
<tr>
<td></td>
<td>etching method (CH₄ and H₂) 10 mins, and O₂ polymer removal for 10mins</td>
</tr>
<tr>
<td></td>
<td>Calculate the etching time by considering the mesa height</td>
</tr>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>Clean the sample with Acetone / IPA, dry with N₂</td>
</tr>
</tbody>
</table>
## MESA (AIR BRIDGE OPENING)

<table>
<thead>
<tr>
<th>Step</th>
<th>Process Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with N(_2)</td>
</tr>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>Spin S1805 for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 120 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 20 sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 319 for 1 min, rinse with DI water and dry with N(_2)</td>
</tr>
<tr>
<td></td>
<td>Post bake in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Etching</strong></td>
<td>Calibration, check the test structures to extracted the undercut ratio ( (\text{H}_3\text{PO}_4:\text{H}_2\text{O}_2:\text{H}_2\text{O}=3:1:50) )</td>
</tr>
<tr>
<td></td>
<td>Calculate the etching time by considering the undercut ratio</td>
</tr>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>Clean the sample with Acetone / IPA, dry with N(_2)</td>
</tr>
</tbody>
</table>
## BOTTOM CONTACTS AND BOND PAD

<table>
<thead>
<tr>
<th>Process</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sample cleaning</strong></td>
<td>NMP for 5 mins and Dry with N(_2)</td>
</tr>
<tr>
<td></td>
<td>Preheat in hotplate at 120 °C for 5 mins</td>
</tr>
<tr>
<td><strong>Resist coating</strong></td>
<td>AZnLOF (2μm) for 30 sec</td>
</tr>
<tr>
<td></td>
<td>Prebake in hotplate at 110 °C for 1 min</td>
</tr>
<tr>
<td><strong>Photolithography</strong></td>
<td>Align the mesa mask and exposure for 5.5 sec (0.9mW i-line)</td>
</tr>
<tr>
<td></td>
<td>Post Exposure bake at 110 °C for 1 min</td>
</tr>
<tr>
<td></td>
<td>Develop in MF 326 for 1 min, rinse with DI water and dry with N(_2)</td>
</tr>
<tr>
<td></td>
<td>Clean with HCL (HCL:H(_2)O=1:1) for 1 min</td>
</tr>
<tr>
<td><strong>Metallisation</strong></td>
<td>Evaporate Ti (1cm) and Au (15cm) using thermal evaporator</td>
</tr>
<tr>
<td><strong>Lift-off</strong></td>
<td>Place the sample in NMP for 40 mins at room temperature</td>
</tr>
<tr>
<td><strong>Annealing</strong></td>
<td>Clean the sample with Acetone / IPA, dry with N(_2)</td>
</tr>
<tr>
<td></td>
<td>Anneal the contacts at 280 °C for 2 mins under N(_2) flow using furnace</td>
</tr>
</tbody>
</table>
Appendix B: The instruction of the Rigel 1550 THz spectrometer

Figure B1 shows the Rigel 1550 THz spectrometer.

![Photo of Rigel 1550 THz spectrometer](image)

Figure B 1 Photo of Rigel 1550 THz spectrometer

The main body of the spectrometer is only 70 cm×50 cm×90 cm. All the key elements are shown in Figure B2 and listed in Table B-1.
Figure B.2 Photo of Rigel 1550 THz spectrometer (a) sensor heads
(b) front panel and (c) back panel

Table B-1 Key elements of Rigel 1550 THz spectrometer (respects to number in Figure B.2)

<table>
<thead>
<tr>
<th>Numbers respect to Figure B1</th>
<th>Component</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Optical Delay module</td>
</tr>
<tr>
<td>2</td>
<td>Onefive ORIGAMI Femtosecond Laser</td>
</tr>
<tr>
<td>3</td>
<td>Shaker electronic controller</td>
</tr>
<tr>
<td>4</td>
<td>Laser driver</td>
</tr>
<tr>
<td>5</td>
<td>Linear stage for slow scan</td>
</tr>
<tr>
<td>6</td>
<td>Lock-in amplifier</td>
</tr>
<tr>
<td>7</td>
<td>NI DAQ for data acquisition</td>
</tr>
<tr>
<td>8</td>
<td>Square wave generator</td>
</tr>
<tr>
<td>9</td>
<td>USB Hub</td>
</tr>
<tr>
<td>10</td>
<td>Shaker power supply</td>
</tr>
</tbody>
</table>
The different optical delay scan units allow the adjusted distance between photoconductive modules to be up to 1 metre, making the system capable of characterising samples under different situations. The plano-convex lenses also help collimate the THz beam easily onto the samples under test.

The experimental procedure steps for the Rigel 1550 THz spectrometer are as follows:

i. Connection checking: Before turning on the PC and spectrometer, the connection of the transmitter and the receiver must be checked. The connection of the USB from PC to the spectrometer cabinet for electrical components must be in position.

ii. Self-test: In this step, the interface between PC and spectrometer is checked by using NI-DAQ driver version 9.3.

iii. Shaker moving: Run Shaker.exe until the serve position goes to the center and activates the shaker to be in the middle position.

iv. Align: Run Show_Signal.exe and adjust the position of transmitter and detector. By doing this, stronger THz signal can be achieved.

v. Setting: under the setting options, click ‘Go Home’ every time before each scan. This signals to the software that a new run is going to begin.

vi. Scan: set start position to 2 mm, motor speed to 0.1 mm/s. The scan width for Rigel 1550 THz spectrometer is up to 50 mm, after setting these parameters, the stop position can be automatically calculated by Rigel.exe.
Appendix C: Introduction and specification of SILVACO

As shown in Figure C1, ATLAS simulation allows two kinds of inputs: the structure files which contain definitions of the structure and the text file using syntax commands to allow ATLAS to execute. The input part allows users to define/model structure, materials and the physical characteristics of the designed devices. Three types of output are provided by ATLAS. The runtime output, where the warning and error messages are shown, illustrates the progress of simulations. Log files act as the storage for all terminal information from the device analysis and the solution files store two or three-dimensional data of the solution variables of the device. The simulated data of the process contains the numerical and model analysis of the device and these results are then plotted by the visualization tool called TonyPlot.

Figure C 1 ATLAS inputs and output [166]

Simulations follow the same process independently of the specific information of devices. The general steps of SILVACO simulation are shown in Figure C 2.
Structure specification

(1) Mesh

Mesh statement works to define the two or three dimensional Cartesian grids of the structure. The default unit for all coordinates is micrometer to improve the accuracy and precision of the analysis.

The mesh should be carefully defined throughout the device structure. For example, the main part which includes the area slightly before and after the AlAs barrier in the ASPAT structure, needs to be set to more points in order to achieve accurate calculations. The device mesh structure for InGaAs-AlAs ASPAT diode with a mesa size of 4×4 μm² is shown in Figure C 3.
Figure C 3 Device mesh structure for InGaAs-AlAs ASPAT with a mesa size of 4×4 μm²

(2) Region

Region statement is used to define the isolated location of the device. By using ‘Region’, the initial mesh statement is separated into distinct blocks. The material parameters of each block will be set by the referred region number. The region number must be ordered from the lowest to highest region and mesh must be assigned to a region.

(3) Electrode

The next statement after defining the device region is electrode. Electrodes need to be defined on the selected device area for electrical analysis. The following syntax is the electrodes define statements used in this work:

#electrodes

Electrode name=anode top

Electrode name=cathode bottom

Material Models Specification
(1) Materials

Material is associated with physical parameters with materials in the mesh. In ATLAS, all the default parameters are set for silicon properties as SILVACO was first developed for Silicon based devices. However, users are able to define materials such as GaAs, InGaAs, InAlAs, etc. with the pre-established names in the region statements. Normally, the user-defined material parameters are required especially for their energy band gap, effective masses, permittivity, and effective density of states etc. It is important that all required parameters are checked and clearly defined in the section material parameters; it is also necessary to check parameters which are required in the correspond models. This is because that if the required parameters are not defined in this statement, SILVACO will automatically use the default Silicon parameter instead.

(2) Models

Models used in SILVACO refer to the physical equations used in the device analysis. In order to accurately simulate the device, model statements need to be carefully chosen to specify the particular phenomenon otherwise it will require different mathematical models, and physical mechanisms.

(3) Contact

The purpose of defining the contact statement is to specify the physical attribute of the electrodes. In SILVACO, the default for the metal-semiconductor is the perfect Ohmic contact. The name of contact is used to identify each electrode property.

(4) Numerical methods selection

Methods are used to discretise the problem and then estimate the solution. There are three different numerical methods available in ATLAS which can be used to solve the semiconductor device equations.

- “Newton” is widely used for linearizing the non-linear problem. In Newton, all unknowns are put together to solve the total system. Users should be careful in defining the mesh since the wrong definition of mesh will cause Newton to fail to converge. Compared to other methods, Newton usually converges since it automatically adjusts the step size to find the solution, but as a result takes a longer processing time.
• “Gummel” is a decoupled numerical method to solve each unknown in turn keeping all other variables as constant. It is useful to the system with equations weakly coupled and only works for linear convergence. In order to avoid non-convergence, Gummel will truncate the over range results.

• “Block” is a method which is able to produce a quick simulation, but at the expense of accuracy compared to the other two methods. This method is recommended for devices that require analysis of energy balance and lattice heating.

Generally, the simulation can first choose to use the Gummel method then switch to Newton to complete the solution. These numerical methods specifications are provided in the method statements of the input file. For ASPAT diodes, Newton method is used to achieve faster converges compared with Gummel, but requires a longer calculation time per step.

(5) Solution specification

To obtain solutions, SOLVE must be invoked. At the start of the solution statement, SOLVE INIT can make the first solution under equilibrium conditions. Users need to define voltages on the electrode defined previously in the structure specification. The bias steps need to be well defined to obtain the desired results accuracy and reduce the processing time.

(6) Results stored

Log files are used to obtain and store the results and these results are plotted by “TonyPlot”. The plotted results can be then exported to other file types. In the case of the ASPAT diode simulation code, the log file includes the DC or AC data generated by the solve statement.
Appendix D: The DC simulation code of InGaAs-AlAs ASPAT diodes

GO ATLAS

# Thicknesses
#----------------------------------------------------------------------------------------

#Structure parameter definition (Constants) values in 'um'
#----------------------------------------------------------------------------------------

## Thicknesses
set t_contact1=0.1
set t_ohmic1=0.3
set t_emitter=0.035
set t_spacer1=0.005
set t_barrier=0.00283
set t_spacer2=0.2
set t_collector=0.035
set t_ohmic2=0.4
set t_etch=0
set t_contact2=0.1

## Doping concentrations
set d_ohmic1=1.5e19
set d_emitter=1e17
set d_collector=1e17
set d_ohmic2=1.5e19
set d_gap=1.5
set d_mesa=7.9
set d_device=20

## Layers
set I=$t_{contact1}$
set A=I+$t_{ohmic1}$
set B=A+$t_{emitter}$
set C=B+$t_{spacer1}$
set D=C+$t_{barrier}$
set E=D+$t_{spacer2}$
set F=E+$t_{collector}$
set G=F+$t_{ohmic2}$

# Mesh generator

## The x.mesh and y.mesh specifies the location 'loc' of mesh grid lines along the respective
## axis. 'spacing' determines the mesh spacing in microns at the position specified by 'loc'
## parameter. The mesh spacing from one mesh statement to the next is gradually changed
## and is managed by the simulator itself.

mesh diag.flip width=8
x.mesh location=0 s=0.5
x.mesh location=$d_{mesa}$ s=0.5
x.mesh location=$d_{device}$ s=0.5

# Ohmic1
y.mesh l=0.000 s=0.005
y.mesh l=I s=0.005
y.mesh l=A s=0.005
y.mesh l=B s=0.005
y.mesh l=C s=0.003
y.mesh l=D s=0.0001
# SECTION 2: Structure Specification

region num=1 name=contact1 material=Gold y.min=0 y.max=$I
region num=2 name=ohmic1 material=InGaAs x.comp=0.47 y.min=$I y.max=$A
region num=3 name=emitter material=InGaAs x.comp=0.47 y.min=$A y.max=$B
region num=4 name=spacer1 material=InGaAs x.comp=0.47 y.min=$B y.max=$C
region num=5 name=barrier material=AlAs y.min=$C y.max=$D x.min=0 x.max=$d_mesa calc.strain qtregion=1
region num=6 name=spacer2 material=InGaAs x.comp=0.47 y.min=$D y.max=$E
region num=7 name=collector material=InGaAs x.comp=0.47 y.min=$E y.max=$F
region num=8 name=ohmic2 material=InGaAs x.comp=0.47 y.min=$F y.max=$G
region num=10 name=etch material=Air y.min=0 y.max=$F+$t_etch x.min=$d_mesa x.max=$d_device

electrode num=1 name=anode x.min=0 x.max=$d_mesa y.min=0 y.max=$I material=Gold
electrode num=2 name=cathode x.min=$d_mesa+$d_gap x.max=$d_device y.min=$F+$t_etch-$t_contact2 y.max=$F+$t_etch material=Gold
# Doping
#--------------------------------
doping uniform n.type conc=$d_ohmic1 Region=2
doping uniform n.type conc=$d_emitter Region=3
doping uniform n.type conc=$d_collector Region=7
doping uniform n.type conc=$d_ohmic2 Region=8

#--------------------------
#Interface
#--------------------------
interface s.c y.min=$I y.max=$I
interface s.s y.min=$A y.max=$A
interface s.s y.min=$B y.max=$B
interface s.i y.min=$C y.max=$C
interface s.i y.min=$D y.max=$D
interface s.s y.min=$E y.max=$E
interface s.s y.min=$F y.max=$F
interface s.c y.min=$F+$t_etch y.max=$F+$t_etch x.min=$d_mesa+$d_gap x.max=$d_device
interface tunnel region=5 dy.tunnel=0.001

#--------------------------
#Contacts
#--------------------------
contact name=cathode
contact name=anode

#------------------------------------------
# SECTION 3: Material & Models Definitions
## The physical parameters for the materials are defined in the following three subsections

### AlAs

material material=AlAs eg300=2.83 affinity=3.5
# align=0.684
# InGaAs x.comp=0.47
material material=InGaAs permittivity=13.876 eg300=0.74 affinity=4.51 nc300=1.55e18

#### INITIAL BAND DIAGRAM ####

output t.quantum band.param qfn qfp val.band con.band charge polar.charge flowlines
solve init
save outf=XMBE326_INITIAL.str
tonyplot XMBE326_INITIAL.str

#### ANALYSIS ####

models sis.el sis.ho sis.nlderivs qtregion=1 print
intrap acceptor structure=top e.level=0.2 density=3.5e11 degen.fac=1 sign=1e-19 sigp=1e-17

#DC ANALYSIS

log outf=XMBE326_BIASED.log
solve init
solve vanode=-1.5 name=anode vstep=0.01 vfinal=1.5
save outf=XMBE326_BIASED.str
log off

tonyplot XMBE326_BIASED.str
tonyplot XMBE326_BIASED.log

quit
Appendix E: The AC simulation code of InGaAs-AlAs ASPAT diodes

GO ATLAS

# Thicknesses
#---------------------------------------------------------
#Structure parameter definition (Constants) values in 'um'
#---------------------------------------------------------

## Thicknesses
set t_contact1=0.1
set t_ohmic1=0.3
set t_emitter=0.035
set t_spacer1=0.005
set t_barrier=0.00283
set t_spacer2=0.2
set t_collector=0.035
set t_ohmic2=0.4
set t_etch=0
set t_contact2=0.1

## Doping concentrations
set d_ohmic1=1.5e19
set d_emitter=1e17
set d_collector=1e17
set d_ohmic2=1.5e19
set d_gap=1.5
set d_mesa=4
set d_device=15

## Layers
set I=$t_{contact1}$
set A=$I+$t_{ohmic1}$
set B=$A+$t_{emitter}$
set C=$B+$t_{spacer1}$
set D=$C+$t_{barrier}$
set E=$D+$t_{spacer2}$
set F=$E+$t_{collector}$
set G=$F+$t_{ohmic2}$

#-----------------------------
# Mesh generator
#-----------------------------

## The x.mesh and y.mesh specifies the location 'loc' of mesh grid lines along the
## respective
## axis. 'spacing' determines the mesh spacing in microns at the position specified by 'loc'
## parameter. The mesh spacing from one mesh statement to the next is gradually changed
## and is managed by the simulator itself.

mesh diag.flip width=4
x.mesh location=0 s=0.5
x.mesh location=$d_{mesa}$ s=0.5
x.mesh location=$d_{device}$ s=0.5

# Ohmic1
y.mesh l=0.000 s=0.005
y.mesh l=$I$ s=0.005
y.mesh l=$A$ s=0.005
y.mesh l=$B$ s=0.005
y.mesh l=$C$ s=0.003
y.mesh l=$D$ s=0.0001
y.mesh l=$E s=0.005
y.mesh l=$F s=0.005
y.mesh l=$G s=0.005

#-----------------------------------
# SECTION 2: Structure Specification
#-----------------------------------
#-----------------------------------
# Regions definition
#-----------------------------------
region num=1 name=contact1 material=Gold y.min=0 y.max=$I
region num=2 name=ohmic1 material=InGaAs x.comp=0.47 y.min=$I y.max=$A
region num=3 name=emitter material=InGaAs x.comp=0.47 y.min=$A y.max=$B
region num=4 name=spacer1 material=InGaAs x.comp=0.47 y.min=$B y.max=$C
region num=5 name=barrier material=AlAs y.min=$C y.max=$D x.min=0 x.max=$d_mesa calc.strain qregion=1
region num=6 name=spacer2 material=InGaAs x.comp=0.47 y.min=$D y.max=$E
region num=7 name=collector material=InGaAs x.comp=0.47 y.min=$E y.max=$F
region num=8 name=ohmic2 material=InGaAs x.comp=0.47 y.min=$F y.max=$G
region num=10 name=etch material=Air y.min=0 y.max=$F+$t_etch x.min=$d_mesa x.max=$d_device
#-----------------------------------
# Electrodes
#-----------------------------------
electrode num=1 name=anode x.min=0 x.max=$d_mesa y.min=0 y.max=$I material=Gold
electrode num=2 name=cathode x.min=$d_mesa+$d_gap x.max=$d_device y.min=$F+$t_etch-$t_contact2 y.max=$F+$t_etch material=Gold
#-----------------------------------
# Doping
#-----------------------------------
doping uniform n.type conc=$d_{ohmic1} Region=2

doping uniform n.type conc=$d_{emitter} Region=3

doping uniform n.type conc=$d_{collector} Region=7

doping uniform n.type conc=$d_{ohmic2} Region=8

#--------------------------

#Interface

#--------------------------

interface s.c y.min=$I$ y.max=$I$

interface s.s y.min=$A$ y.max=$A$

interface s.s y.min=$B$ y.max=$B$

interface s.i y.min=$C$ y.max=$C$

interface s.i y.min=$D$ y.max=$D$

interface s.s y.min=$E$ y.max=$E$

interface s.s y.min=$F$ y.max=$F$

interface s.c y.min=$F$+$t_{etch}$ y.max=$F$+$t_{etch}$ x.min=$d_{mesa}$+$d_{gap}$ x.max=$d_{device}$

interface tunnel region=5 dy.tunnel=0.001

#--------------------------

#Contacts

#--------------------------

contact name=cathode

contact name=anode

#--------------------------

# SECTION 3: Material & Models Definitions

#--------------------------

# AlAs

material material=AlAs eg300=2.83 align=0.684
# InGaAs x.comp=0.47

material material=InGaAs permittivity=13.876 eg300=0.74 affinity=4.5 nc300=1.55e18

#------------------------------------------

##### INITIAL BAND DIAGRAM #####

#------------------------------------------

output t.quantum band.param qfn qfp val.band con.band charge polar.charge flowlines

solve init

#------------------------------------------

##### ANALYSIS #####

#------------------------------------------

models sis.el sis.ho sis.nlderivs qtregion=1 print

intrap acceptor structure=top e.level=0.2 density=3.5e11 degen.fac=1 sign=1e-19 sigp=1e-17

#AC ANALYSIS

# AC ANALYSIS

method climit=1e-4 itlimit=50 maxtraps=20

method newton gummel

solve

solve vcathode=0 local

method carr=2

log outf=XMBE326_AC.log s.param y.param z.param abcd.param inport=cathode outport=anode

solve vanode=0 ac.analysis direct frequency=4e4 fstep=4e9 nfsteps=20

tonyplot XMBE326_AC.log

quit
REFERENCES


REFERENCES


[21] I. Kostakis and M. Missous, "Optimization and temperature dependence characteristics of low temperature In_{0.3}Ga_{0.7}As and In_{0.53}Ga_{0.47}As-In_{0.52}Al_{0.48}As semiconductor terahertz photoconductors," AIP Advances, vol. 3, p. 092131, 2013.


REFERENCES


REFERENCES


[111] J. Mangeney and P. Crozat, "Ion-irradiated In_{0.53}Ga_{0.47}As photoconductive antennas for THz generation and detection at 1.55 μm wavelength," *Comptes Rendus Physique*, vol. 9, pp. 142-152, 2008.
REFERENCES


[114] M. Zawawi, "Advanced In$_{0.6}$Ga$_{0.4}$As/AlAs Resonant Tunneling Diodes for Applications in Integrated mm-waves MMIC Oscillators," 2015.


[120] I. Mehdi and G. Haddad, "Lattice matched and pseudomorphic In$_{0.53}$Ga$_{0.47}$As/In$_{1-x}$Al$_x$As resonant tunneling diodes with high current peak to valley ratio for millimeter wave power generation," *Journal of applied physics*, vol. 67, pp. 2643-2646, 1990.


[128] Y. Wang, M. R. R. Abdullah, J. Sexton, and M. Missous, "Temperature dependence characteristics of In$_{0.53}$Ga$_{0.47}$As/AlAs asymmetric spacer-layer tunnel (ASPAT) diode detectors," in *Millimeter Waves and THz Technology Workshop (UCMWT)*, 2015 8th UK, Europe, China, 2015, pp. 1-4.


REFERENCES


