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Innovative ultra-BROadband ubiquitous Wireless communications through terahertz transceivers

iBROW

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First report on RTD photonic interfaces

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Contents

1. STATEMENT OF INDEPENDENCE ........................................................................... 7
2. ABBREVIATIONS ................................................................................................... 9
EXECUTIVE SUMMARY ..................................................................................................11
3. INTRODUCTION .......................................................................................................13
   3.1. Resonant tunnelling diodes .............................................................................. 14
   3.2. Optoelectronic applications of RTDs ................................................................. 16
   3.3. RTD-PD optical-to-mm-wave/THz transponder (download link) ..................... 18
   3.4. RTD-LD mm-wave/THz-to-optical transponder (upload link) ......................... 20
4. RTD-BASED PHOTO-DETECTOR ...........................................................................23
   4.1. Baseline DBQW-RTD optoelectronic properties ................................................. 23
   4.2. RTD optical waveguide photodetector ............................................................... 25
   4.3. RTD-PD design considerations ...........................................................................27
      4.3.1. Device configurations .................................................................................. 29
      4.3.2. Responsivity .............................................................................................. 29
      4.3.3. Frequency response ................................................................................... 32
      4.3.4. Epi-layer design ....................................................................................... 34
   4.4. RTD-PD fabrication and packaging .................................................................... 37
   4.5. RTD-PD on-wafer characterization .................................................................... 38
   4.6. RTD-PD optoelectronic high frequency characterization .................................... 48
5. RTD LASER DIODE PHOTONIC INTERFACE .......................................................49
   5.1. Laser diode direct modulation ........................................................................... 49
   5.2. Laser diode design, fabrication and packaging ................................................... 51
   5.3. Laser diodes characterization .............................................................................53
   5.4. RTD hybrid integration with a laser diode ......................................................... 54
   5.5. Alternative laser diode RTD based driving circuit configurations ..................... 59
   5.6. RTD electro-absorption modulator .................................................................... 60
6. RTD, RTD-PHOTODETECTOR, LASER DIODE (LD) AND RTD-LD MODELLING ........................................................................................................63
   6.1. RTD I-V curve modelling ..................................................................................... 63
   6.2. RTD-PD light response modelling ..................................................................... 68
   6.3. RTD oscillators as forced Liénard systems ....................................................... 70
   6.4. Laser diode rate equations ................................................................................ 73
   6.5. Laser diode simulation tools .............................................................................. 75
   6.6. RTD-LD modelling and simulation tools ........................................................... 77
7. CONCLUSIONS .........................................................................................................79
8. APPENDIX A: RTD-PD I-VS UNDER DARK AND LIGHT ILLUMINATION ..........81
9. REFERENCES .............................................................................................................83
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1. Statement of independence

The work described in this document is genuinely a result of efforts pertaining to the iBROW project: any external source is properly referenced.

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2. **Abbreviations**

AC – Alternating current
AlGaAs – Aluminium gallium arsenide
DBQW – Double barrier quantum well
DC – Direct current
Gbps or G/s – Giga bit per second
GaAs – Gallium arsenide
Ge – Germanium
GHz – Gigahertz
GSM – Global System for Mobile communications
IEEE – Institute of Electrical and Electronics Engineers
InAs – Indium arsenide
InGaAs – Indium gallium arsenide
InGaAlAs – Indium gallium aluminium arsenide
InP – Indium phosphide
I-V – Current voltage
J_p – Peak current density
LD – Laser diode
MOVPE – Metal organic vapour phase epitaxy
MMIC – Monolithic microwave/millimetre-wave integrated circuit
mm-wave – Millimetre-wave
NDC – negative differential conductance
NDR – negative differential resistance
OCEO – Optical controlled electronic oscillator
NDR – Negative differential resistance
PD – Photodiode
PDR – Positive differential resistance
PVCR – Peak to valley current ratio
RF – Radio frequency
RTD – Resonant tunnelling diode
RTD-EAM – Resonant tunnelling diode electro-absorption modulator
RTD-LD – Resonant tunnelling diode - laser diode
RTD-OW-PD – Resonant tunnelling diode optical waveguide photodiode
RTD-PD – Resonant tunnelling diode photo-detector
Si – Silicon
SMF - Single mode fiber
SSMF - Standard single mode fiber
THz – Terahertz
VNA – Vector Network Analyzer
Executive summary

The realisation of low cost high efficiency and high power mm-wave (e.g. around 90 GHz) and THz (e.g. around 300 GHz) sources is one of the major challenges towards the implementation of economically viable wireless short-range communication networks that take advantage of the fiber-optic supported base stations.

iBROW aims the development of low cost cell transponders with high efficient electrical and optical functionalities such as the above mm-wave and THz source and electrical-optical (E/O) and optical-electrical (O/E) transceivers based on the integration of resonant tunnelling diode (RTD) optoelectronic devices. The envisaged RTD-based optoelectronic transceivers consist of both receiver and transmitter functionalities that interface fibre-optic links with portable wireless devices operating up to THz frequencies.

The receiver part employs a monolithic RTD-photo-detector comprising of vertical epitaxial semiconductor layers consisting of a DBQW RTD structure embedded within light absorption regions where photo-generated electron-holes are created upon incident light. The transmitter part employs an RTD-laser/modulator where the RTD (circuitry) operates as a high-speed driver circuit simplifying the laser diode/modulator currently driving and amplifying circuitry typically based in traditional transistor circuits.

This report details the work on the development of resonant tunnelling diode photodetector (RTD-PD) and resonant tunnelling diodes laser diode (RTD-LD) optoelectronic circuits towards the implementation of efficient microwave/mm-wave-to-optical and optical-to-microwave/mm-wave signal converters. It comprehends the analysis of the RTD characteristics and functionalities, including a brief description of previously implemented RTD-PD and RTD-LD devices and circuits. The RTD-PD structure is analysed in detail, and the preliminary results of the optoelectronic characterization of implemented devices are presented and discussed. It was found that RTD-PDs comprising a 500 nm low doped In_{0.53}Ga_{0.47}As layer in the collector region show responsitivity up to 2 A/W. The preliminary optical-to-electrical conversion characterization experiments employed non-oscillating RTD-PD device acting as photo-detectors showed successfully data conversion at 1 Gbit/s. The preliminary results also show the ability of optically modulate RTD oscillators. The laser diodes implemented are discussed and the main characterization results presented. The laser diode characterization shows they can be used in 10 Gb/s systems. Finally, the modelling activities of the RTD, RTD-PD, LD and RTD-LD devices and circuits are presented and discussed.
3. Introduction

The demand for bandwidth in wireless short-range communications is doubling every 18 months [1]. The currently available wireless technology based on the use of the low frequency region of the microwave band cannot support the predicted growing demand for higher bandwidth much longer, essentially because it will require a substantially enhancement of spectral efficiencies over an order of magnitude, which is very difficult to achieve mainly because it will require substantially more complex systems and more power. TE-A technology is expected to achieve a spectral efficiency of 2.25 bit per second (bps) per Hz (bps/Hz); current LTE deployments have spectral efficiency of 1.4 bps/Hz [2]. As a consequence, there is a significant effort to develop new technology platforms that allow the use of much higher frequency spectrum regions, alleviating the spectrum scarcity and the bandwidth limitations of current microwave systems. The operation in the millimeter and terahertz bands will allow staying with moderate spectral efficiencies, but with much higher bandwidths that can go up to several tens of GHz, eventually with less power requirements.

iBROW targets the development of a unified technology that takes advantage of the resonant tunnelling diodes (RTDs) high frequency operation and simplicity. The project aims to develop RTD devices which can be the core of both ends of the THz wireless links, namely consumer portable devices and fibre-optic supported base-stations, enabling low cost ultra-broadband wireless communications for indoor and constrained outdoor environments. The targeted unified technology, which will enable the implementation of ultra-broadband THz wireless communications links, will be based on low power and low cost RTD solutions from two perspectives, Fig. 3.1:

1. All-electronic RTD circuitry suitable for integration into consumer wireless portable devices.

2. Optical-to-mm-wave/THz and mm-wave/THz-to-optical RTD transponders, consisting of monolithic integration of a RTD and a photo-detector (the RTD-PD) and of hybrid integration with a laser diode (the RTD-PD-LD), respectively, which will be suitable for integration into mm-wave/THz femto-cell base-stations connected to high-speed 40/100 Gbps fibre-optic networks.

![Fig. 3.1: Schematic representation of the iBROW RTD technology application scenarios, where the RTD-PD works as light receivers converting modulated light wave into an electrical signal, and the RTD-LD functions as a light transmitter converting a electrical signal into a intensity modulated light wave.](image)

The proposed RTD-based optoelectronic transceivers consist of both light receivers and light transmitters that interface the fibre-optic links with portable wireless devices. The receiver employs a
monolithic RTD-photo-detector consists of vertical epitaxial semiconductor layers comprising of a DBQW RTD structure embedded within light absorption layers where photo-generated electron-holes are created upon incident light. The transmitter employs an RTD-laser/modulator where the RTD (circuitry) operates as a high-speed driver circuit for the laser/modulator; the RTD features allow simplifying the currently laser diode/modulator driving and amplifying circuitry based in traditional transistor circuits. It is foreseen that the planned photonic transceivers based on RTD-photodetector structures and on hybrid integration of RTDs with laser diodes/optical modulators will be capable of handling both electrical and optical signals at tens of Gbps.

This proposal foresees a low-cost access point solution with no need of complex format and frequency conversion or complex electronic and optoelectronic circuitry. The main advantages of the RTD based technology are their capability of high frequency signal generation, circuit simplicity and low energy consumption, which makes them potential low-cost wireless transceivers. Few proposals employing the RTDs have been presented with some showing potential only for very short range wireless communication mainly because of the low power capability of the RTD technology being considered. Application at longer range will require the use of power amplifiers. Figure 3.2 presents schematically one of such proposals that allows wireless transmission at 300-GHz with data rate as high as 2.5 Gbit/s at transmission distance up to 1 meter [3][4].

Fig. 3.2: Experimental setup of wireless communication using two sets of RTD transceivers, together with schematic of transmitter and receiver operations which takes advantage of the RTD highly non-linear I-V [3][4].

3.1. Resonant tunnelling diodes

Generically, a resonant tunnelling diode (RTD) corresponds to a unipolar two terminal semiconductor device showing a pronounced N-shaped current-voltage characteristic at room temperature. The portion of its I-V characteristic exhibiting negative differential conductance (NDC) provides the electrical gain needed to implement very simple high frequency electrical oscillators and a myriad of other electronic and optoelectronic devices with new functionalities [5][6].

The RTDs object of study here consists of a vertical stacking of nanometric scale semiconductor layers consisting of a undoped indium gallium arsenide (InGaAs) layer sandwiched between two aluminium arsenide (AlAs) barrier layers, surrounded by undoped/low doped InGaAs spacer epilayers, forming a double barrier quantum well (DBQW). The final structure is completed with very high-doped InGaAs layers for ohm contact formation. The structure is normally realized on semi-insulating (SI) InP substrates, as illustrated in Fig. 3.3(a), but other substrates are possible such as SiGe. The charge carrier transport across the double barrier quantum well (DBQW) is mainly through electron resonant tunneling effect: the DBQW acts like a Fabry-Pérot etalon for the charge carriers’ wavefunctions, giving rise to peaks in the current-voltage characteristic when the energy of the incoming
carriers, which is a function of the applied voltages, coincides with the etalon charge transmission windows, Fig. 3.3(b), that coincides with the energy of the quantum well quasi-bounded energy level. This effect leads to an N-shaped current-voltage (I-V) characteristic as depicted in Fig. 3.3(c).

RTDs exhibit two key-features at room temperature when compared to other semiconductor devices: wideband negative differential conductance (NDC) and extremely high frequency operation reaching 1.9 THz [7]. The former leads to electric gain: when DC polarized in the NDC region the RTD produces RF signals whose frequency is determined by its intrinsic capacitance and by the equivalent inductance of the connecting circuitry. The latter, on the other hand, arises from the very thin (a few nanometers thick) DBQW structure along the direction of carriers' transport, which makes them the fastest pure solid-state electronic device operating at room temperature. The current and the voltage widths of the NDC region determine the RF power generated. Moreover, RTD operation frequency and generated power can be at certain extent controlled by the DC operating point. Since they show an N-shape I-V characteristic, changing the DC operating point within the NDC region can also change RTD oscillator circuits operating frequency and the generated RF power. These unique features make it possible for RTDs to operate at a certain extent as voltage controlled electronic oscillators (VCEOs). These functionalities can lead to significantly reduction in the number of elements required for realizing a given function such as very high frequency local oscillators. It can also provide an interesting solution for high-speed communications.

The main electrical characteristics of a RTD are: the peak current density ($J_p$), the peak to valley current ratio ($\text{PVCR}$), the peak voltage ($V_p$), the valley peak voltage difference ($\Delta V$), the valley peak current difference ($\Delta I$), and the estimated electrical power generated by a RTD oscillator operating well below device maximum oscillation frequency, $P_{LF}(f)$, where $f \ll f_{\text{max}}$. 

The power generated by the RTD at low frequency $P_{LF}(f \sim 0)$ can be estimated using [8][21]:

$$R_{LF}(f \sim 0) = \frac{3}{16} \frac{\Delta V \times \Delta I}{f}.$$  \hspace{1cm} (3.1)

The power generated by a RTD oscillating at frequency $f_{\text{os}}$ is given by [21]:

$$P_{RF}(f_{\text{os}}) = R_{LF} \left[ 1 - \left( \frac{f_{\text{os}}}{f_{\text{max}}} \right)^2 \right].$$ \hspace{1cm} (3.2)

The maximum oscillation frequency is given by [8][23]:

$$f_{\text{max}} = \frac{3}{16} \frac{\Delta V \times \Delta I}{L}.$$
\[ f_{\text{max}} = \frac{1}{2\pi R_n C_n} \sqrt{\frac{R_m}{R_s} - 1} = \frac{1}{2\pi C_n} \sqrt{\frac{1}{R_s R_n}} \quad (R_s << R_n) \]  

(3.3)

where \( C_n \) is the RTD self-capacitance of the device; \( R_n \) is absolute value of the (minimum) negative differential resistance of the device; and \( R_s \) accounts for the contact and device parasitic resistances. The oscillation frequency \( f_{\text{os}} \) corresponds to the frequency at which the imaginary part of the circuit impedance becomes zero, and is given by [8]:

\[ f_{\text{os}} = \frac{1}{2\pi} \sqrt{\frac{1}{L_s C_n} - \frac{1}{R_n^2 C_n^2}} \]  

(3.4)

where \( L_s \) represents the circuit equivalent inductance.

### 3.2. Optoelectronic applications of RTDs

The operation and functionality of a considerable number of novel optoelectronic devices and circuits based on III-V semiconductor compound materials can benefit from the integration with DBQW-RTDs taking advantage of the negative differential conductance (NDC) produced by the DBQW structures. Such optoelectronic devices include laser diodes, semiconductor optical amplifiers, photo-detectors, and semiconductor electro-refraction and electro-absorption modulators [5][6].

Optoelectronic applications of resonant tunnelling devices can be divided in two areas, optical and infrared, depending on the nature of the transitions: the optical applications utilize interband transitions (bandgap transitions), whereas the infrared region employs intersubband transitions (transitions within the same band). Among these optical modulation and photo-detection are the most promising applications [8].

Several optoelectronic applications of resonant tunnelling structures for light detection have been proposed [5][6]. Particularly, the integration of a DBQW with unipolar photodetectors by embedding the DBQW within or adjacent to the light sensitive region gives rise to a new device known, from now on, as resonant tunneling diode photodetector (RTD-PD). The RTD-PDs can be operated either in the steady state mode when polarized in one of the positive differential conductance (PDC) regions of the I-V curve, or in the oscillatory mode when polarized in the NDC region. These modes of operation and the RTD-PDs functionalities make them potential candidates for the implementation of low cost highly efficient optical-to-wireless interfaces capable of transferring electrical signals embedded in the optical carriers used in fibre optic communications to mm-wave/THz carriers. Moreover, when directly illuminated by intensity modulated optical signals the RTD-PD oscillators can lock to the optical signals subcarriers, with the RTD-PD electrical output power being merely determined by the NDC region characteristics.

When polarized in the PDCs but close to the NDC, the RTD circuits can behave as excitable systems [9]: when undisturbed RTDs remain in the quiescent (equilibrium) states, producing a small response to a “small” perturbation (stimulus) but fire a large transient response when the small perturbation (stimulus) exceeds a certain threshold then settling back to the quiescent point in what is called the refractory period, after which the RTDs can be excited again. Moreover, for small perturbations away from the equilibrium, the return is monotonic; however, for perturbations beyond a threshold value, the return is not monotonic, but undergoes a large excursion before settling down. The RTD-PD excitability properties makes intensity modulated optical signals capable to induce RTD-PD transition from the peak to the valley, producing electrical signals that mimic the optical signals subcarriers.
Excitability is a concept originally coined to describe the capacity of living organisms (or of their constituent cells e.g. nerves or neurons) to respond strongly to a relatively weak external stimulus that overcomes a well-defined threshold ([9] and references). If the system is perturbed from its rest state, it may relax back toward its steady state in two different ways. When the perturbation remains below the threshold, the relaxation will decay monotonically. For stimuli that overcome the threshold, the response consists of a pulse whose shape depends only on the excitable system but not on the details of the stimulus followed by a lapse, called the refractory time, during which the system does not respond to stimuli.

The intentional incorporation of light absorption layers into monolithic integrated electronic/photonic circuits comprising DBQW-RTD structures can also be used to implement electronic and optoelectronic devices and circuits whose behaviour can be controlled by both low power optical and/or RF signals. The integration of DBQW-PD structures with laser diodes (LDs) or with electro-absorption modulators (EAMs), such as the resonant tunneling diode electro-absorption modulator (RTD-EAM) [8], can give rise to novel electrical-to-optical transceiver interfaces making possible the implementation of novel compact ultra-broadband wireless-fibre communication transponders operating at tens of Gbps.

As mentioned before, when integrated with optoelectronic devices, such as LDs or EAMs and PDs, DBQW-RTDs can lead to devices with novel electronic and optoelectronic functionalities including optical bistability, and to new photonic circuits such as light and/or voltage controlled electronic/optoelectronic oscillators. For example, the RTD(-PD)-LD series integration adds novel nonlinear electronic and optical functionalities to laser diodes e.g. optical bistability [10]. When DC biased in the NDC region, the LD produces optical signals modulated by the RF oscillations produced by the RTD. Moreover, when biased in the NDC the applied DC voltage can be used to adjust the operating free-running frequency. This makes the RTD-LD behaving as an autonomous voltage controlled optoelectronic oscillator (VC-OEO) [6].

The RTD-LD VC-OEO can lock to injected RF signals (guided or broadcasted) with frequencies closed to its free-running or to its sub-harmonics/harmonics frequencies. As a consequence, the laser optical output is modulated by the NDC “amplified version” of the RF injected signal. It is expected that once synchronized the RTD-LD optical modulation index (OMI) will be almost independent of the RF injected signal power, being determined mainly by the RTD peak-to-valley current difference and by the DC operating voltage.

Indeed, novel optoelectronic oscillator (OEO) circuits operating in the multi-gigahertz range with electrical and optical input and output ports are easily obtain by the integration of RTD-PDs with LDs whose oscillations when perturbed by very low power optical or radio-frequency broadcasted signals lock to the incoming signals, with the power of the electrical output and the modulation depth of the laser output being mainly determined by the RTD-PD NDC extension and not by the magnitude of incoming signal above the locking level. Moreover, the locking range of theses RTD-PD-LD optoelectronic oscillators depends of the NDC characteristics of the RTD-PD and can allow the dynamic use of the spectra available. This light/voltage controlled optoelectronic oscillator concept has high potential to operate as microwave/mm-wave-to-lightwave interfaces converting low power optical or RF signals into amplitude modulated mm-wave or THz carriers and intensity modulated light-waves that then carry the information content of the optical or RF low power signals. The RTD-PD-LD circuits can also take advantage of the excitability property of RTD-PDs [11].
Next follows a brief description of the RTD-PD optical-to-mm-wave/THz and of the RTD-LD mm-wave/THz-to-optical transponders.

### 3.3. RTD-PD optical-to-mm-wave/THz transponder (download link)

The RTD based optical-to-mm-wave/THz transponder consists of a “photoconductive detector” incorporating a double barrier quantum well structure (DBQW) close/adjacent to the light absorbing region(s), forming a resonant tunnelling diode photodetector (RTD-PD). The double barrier quantum well structure adds novel non-linear electronic and optoelectronic functionalities to the photoconductive structure, which can lead to an enhancement of photodetector sensitivity, responsivity, detection dynamic range, gain-bandwidth-efficiency product values, as well as low switching energies due to the RTD intrinsic electrical gain and the low voltage operation characteristics.

Recently, a GaAs/AlGaAs and InGaAs/AlAs RTD structures capable to operate at telecommunication wavelengths have been demonstrated [13-15]. A GaAs/AlGaAs RTD with a GaInNAs layer for light absorption in the third telecommunication window shows sensitivity (differential responsivity) as high as $10^3$ A/W [14]. A structure consisting of an In0.53Ga0.47As RTD with a low doped 600 nm In0.53Ga0.47As allows achieving a responsivity as high as $1.92 \times 10^4$ A/W [15]. The InGaAs/AlAs RTD heterostructure layers consisted of the following parts along the growth direction of the detector: a 300 nm In$_{0.53}$Ga$_{0.47}$As emitter with an n-type doping concentration of $2 \times 10^{18}$ cm$^{-3}$, a 7 nm In$_{0.53}$Ga$_{0.47}$As spacer to prevent scattering from the emitter to the upper layer, 3 nm AlAs, 6 nm In$_{0.53}$Ga$_{0.47}$As and 3 nm AlAs forming the DBQW, 600 nm In$_{0.53}$Ga$_{0.47}$As as the absorption layer, a 100 nm In$_{0.53}$Ga$_{0.47}$As collector with an n-type doping concentration of $2 \times 10^{18}$ cm$^{-3}$. These high sensitivity/responsivity values make RTD-PDs candidates for single photon detection needed by the evolving quantum communication field.

Although being remarkable, the above results refer to very low power optical signals and operation in the first PDC region typically far away from the NDC region. That is not the case of the photonic interfaces aimed by the iBROW project. As mentioned previously, the great advantage of the RTD-PD circuits is that when dc biased in the NDC or slightly below the peak voltage they can produce electrical signals that mimic the subcarrier of the incident lightwave, that is, the RTD-PDs are able to extract a modulated sub-carrier or baseband modulated optical signal arriving to the RTD-PD via free space or optical fibre, as schematically represented in Fig. 3.4. Moreover, when biased in the NDC the RTD-PD oscillator free-running frequency can be locked to the RF signal carried by an incident light wave if within the device locking range.
The RTD-PD main modes of operation to be considered in the iBROW can be described as follows:

(i) Non-oscillation mode: An intensity modulated lightwave incident upon a RTD-PD structure biased close to the negative differential conductance (NDC) produces photo-charges that reduce the series resistance, leading to a shift of bias quiescent operation point to the NDC region of the RTD I-V, which produces a mm-wave/THz-wave modulated by the lightwave subcarrier or baseband signal, Fig. 3.5.

(ii) Optical injection locking mode: when operating in the NDC region the RTD oscillations are locked to the optical signal sub-carriers within the RTD-PD oscillator locking range, Fig. 3.6.
3.4. RTD-LD mm-wave/THz-to-optical transponder (upload link)

The RTD-LD mm-wave/THz-to-optical transponder (electrical-to-optical converter) is based on the integration of a RTD (oscillator) with a laser diode (LD), where the LD is driven by the RTD oscillations. For operation beyond the LD bandwidth, a configuration integrating an optical modulator such as the RTD-EAM [5] can be considered. Two RTD-LD configurations are being considered:

(i) The RTD(-PD) and LD series integration: RTD(-PD) and LD are connected in series being both subject to the same current, as schematically represented in Fig. 3.7. The great advantage of RTD-LD series implementation is that it is a straight away of driving a LD.

(ii) RTD(-PD) and LD with independent basing circuits: in this case the LD acts as the RF load to the RTD(-PD) circuit, that is, the RTD and LD DC circuits are autonomous, with the RTD and LD being AC coupled with the RTD “generated” AC signals driving the LD. This configuration makes the LD quiescent operation point independently of the RTD I-V characteristic, as shown schematically in Fig. 3.8.
Fig. 3.8: Schematic representation of a RTD(-PD) driving circuit where the LD acts as the RF load. Also shown is a laboratory implementation where (d) corresponds to the RTD circuit and (c) is the LD circuit - the laser diode is shown in the microphotography inset. (e) is a circulator and (b) is the fiber arrangement to couple the LD light output.

The RTD(-PD)-LD modes of operation being considered can be summarized as follows:

(i) Non-oscillation mode: Broadcasted electrical signals (guided or wireless) coupled to an RTD-LD biased close to the negative differential resistance (NDC) can shift the bias quiescent operation point from the first positive differential resistance (PDC) to the NDC region producing a millimetre/THz wave modulated by the injected electrical pulses that are converted by the LD into an intensity modulated light wave that mimics the current flowing through the RTD and hence the injected/detected electrical pulses.

(ii) Electrical injection locking mode: when operating in the NDC the RTD oscillations are locked to the injected RF signals (guided or broadcasted) with the laser optical output being intensity modulated by the NDC “amplified version” of the injected/detected RF signal.

There are experimental evidences the RTD-LD can synchronize to a wireless signals and that the phase of the radio frequency subcarrier in the optical output follows the phase of the injected wireless signal [16-18]. It was demonstrated that the encoded digital information on the wireless signals by phase shift keying (PSK) schemes, as in most WiFi and GSM mobile systems, it is presented in the synchronized RTD-LD optical output subcarrier [16-18].
4. RTD-based photo-detector

A photo-detector is an optoelectronic device that absorbs optical signals and converts them into electrical signals. Photo-detectors are widely used particularly in optical communication systems. High-speed light-wave communication systems comprise a transmitter optoelectronic circuit employing a near-infrared light source and, for very high data bit rates, an optical modulator, where the light source carrier is modulated by an electric waveform embedding the coded information signal to be transmitted, a transmission media such as an optical fiber eventually utilizing in-line optical amplification, and a receiver optoelectronic circuit based on a photo-detector that recovers from the lightwave the electric waveform carrying the coded information signal [19]. The transmitter consists of an electronic driver circuit along with a semiconductor laser diode or a laser diode and an optical modulator. The receiver is a signal processing circuit coupled to a high speed photo-detector such as a photodiode, an avalanche photodiode (APD), a phototransistor or a photoconductor, which processes the photo-detected signal and recovers the electric waveform carrying the primitive information signal.

In high-speed optical communication applications detectors receive the transmitted optical pulses and convert them, with as little loss as possible, into electric pulses that can be then used by other devices connected at the receiving end. In general, the electrical output of a photo-detector has to go through an amplification stage. The performance requirements for the detectors are large responsivity, high sensitivity, low noise, wide bandwidth, high reliability, and low cost [19][20].

As mentioned previously, the iBROW RTD based optical-to-mm-wave/THz transponder consists of a unipolar semiconductor photoconductive detector that incorporates a double barrier quantum well (DBQW) structure close or adjacent to the low doped light absorbing region(s), forming a resonant tunnelling diode photo-detector (RTD-PD). The presence of the DBQW structure adds novel non-linear electronic and optical functionalities to photoconductive device: the inclusion of a DBQW in a unipolar photo-detector makes the built-in electrical field distribution across the unipolar structure a highly non-linear function of the applied voltage and of the incident light which can lead to a significant improvement on its sensitivity, responsivity, detection signal dynamic range, and gain-bandwidth-efficiency product values.

4.1. Baseline DBQW-RTD optoelectronic properties

Although the RTD-PD structures object of study in the iBROW project includes at least one intentional relatively thick light sensitive region, we started the RTD-PD work by investigating the optoelectronic properties of classical DBQW-RTD structures. By classical DBQW-RTD structure we mean the standard RTD structure with non-intentional light absorption layers, such as the one shown in Fig. 4.1, and do not benefited from the presence of proper access optical windows. The total thickness of the low doped light absorption layers in these devices is generally well below 100 nm. So, we expect no significantly optical response (very low responsivity) at moderate optical powers from such structures. Figure 4.1(a) presents a typical classical InGaAs/InP RTD epi-layer structure grown on Si-InP, and Fig. 4.1(b) shows the light coupling to the device through a lensed fiber and the electrical connection using high frequency ground-signal-ground probes that matches the device coplanar-waveguide (CPW) transmission line.
The optoelectronic characterization shows that the presence of light leads to the global shift of the I-V curve towards lower voltage, but the power levels needed to observe the effect are quite high (>0 dBm) as shown in Fig. 4.2(a). Figure 4.2(b) displays the generated RF power as function of the bias voltage when modulated light signals (λ=1550 nm, 14 dBm) with RF sub-carrier ranging from 100 MHz to 2 GHz are used. The results in the NDC region were discarded due to the intrinsic electrical gain and the oscillation effects. We observed for biasing in the 1st PDC region that the generated RF power increases as the bias voltage approaches to the peak and that for biasing in the 2nd PDR region it initially decreases reaching a minimum at a certain bias voltage, beyond which it starts to increase again. The drop in the RF output power due to the transition from the peak to the valley region is higher than 10 dB for 2 GHz modulation.

We are also investigating the optoelectronic response of standard DBQW-RTD with non-intentional light absorption layers but with intentional designed optical access windows.
4.2. RTD optical waveguide photodetector

The RTD-PD epi-layers with intentional added light absorbing regions investigated so far consisted of unipolar (isotype) III-V based semiconductor optical waveguide structures incorporating in its core a DBQW, as the one shown in Fig. 4.3(a). Firstly, the RTD-PDs were implemented in the optical waveguide photodetector configuration, Fig. 4.3(b), where light is butt-coupled to the facets of the waveguide. As shown in Fig. 4.3(a), the RTD-OW epi-layer was grown on a n+-InP substrate consisting of two In$_{0.53}$Ga$_{0.39}$Al$_{0.07}$As light absorbing layers (forming the waveguide core) 500 nm thick each side of the DBQW, initially designed to guide light of wavelength around 1550 nm and operate as electro-absorption modulators at around 1550 nm. The top InAlAs layer and the InP substrate acted as light confining layers allowing the coupled light to be guided along the DBQW plane, as schematically represented in Fig. 4.3(b).

![Fig. 4.3: (a) InGaAlAs/InP RTD-OW layer structure and (b) schematic RTD-OW die [5].](image)

When operated with light of energy higher than the material band-gap the structure can be used for photo-detection. We evaluated the potential of the optical waveguide (RTD-OW) to operate as a photo-detector (PD), from now on designed as RTD-OW-PD, using light with energy larger than the waveguide core material band-gap. The presence of the light leads to a global shift of the device I-V characteristic as a consequence of the built-in electrical field enhancement close to the collector barrier due to the accumulation of the light-generated holes in the collector absorbing layer. And since the RTD-OWPD structure also includes a light absorption layer in the emitter side the light-generated electron-holes in the emitter increases the amount of current flowing through the DBQW. Figure 4.4 shows a schematic representation of the principle of operation of the RTD-OWPD.

![Fig. 4.4: Schematic representation of the principle of operation of the RTD-OW photo-detector [13].](image)
The operation modes of the RTD-OWPD take advantage of the DBQW induced nonlinear electrical field distribution across the waveguide core. We have measured above 9 dB increase in the RTD-OWPD electrical response for light modulated up to 5 GHz, when the device operation point moved from the peak to the valley region (for more details see http://w3.ualg.pt/~jlongras/RTD-OWPD.htm - the results are not yet published). We have estimated responsivities up to 0.3 A/W at around 1550 nm for devices biased in the valley region [16], which is a quite significant value since the light energy is close or slightly lower than waveguide core band-gap energy.

RTD-OWPD circuits DC biased in or close to the NDC region can produce electrical signals that mimic the signals carried by incident modulated lightwaves, that is, they are able to extract a RF sub-carrier modulated or baseband modulated optical signals. When biased in the NDC region the RTD-OWPD oscillator free-running frequency can be locked to the RF signal carried by the incident lightwave, see e.g Refs [15-16]. That is, RTD-OWPDs can behave as autonomous optical controlled electronic oscillators (OCEOs). Moreover, well design RTD-PD structures when biased in the first PDC close to the peak can require low optical energy to induce the operation point transition either to the NDC region or to the second PDC. The characterization of the RTD-OW-PD response to butt-coupled intensity modulated optical signal also included [16]: (i) dark and illuminated current-voltage characteristics; (ii) estimation of responsivity-gain versus wavelength as a function of bias voltage; (iii) detection dynamic range.

We have also investigated the optoelectronic properties of RTD mesa structures with an optical waveguide epi-layer, as presented in Fig. 4.5(a). Figure 4.5(b) shows a master-slave oscillator implementations based RTD-PD, where the master circuit comprising a hybrid integration of a RTD(-PD) with a laser diode, and the slave circuit consisting of a RTD-PD oscillator. The RTD(-PD) self-oscillation in the master circuit drives laser diode, whose optical power is injected into the slave circuit through the RTD-PD via an optical fiber, as shown in Fig. 4.5(b). When within the locking range, the unidirectional synchronization leads to considerable phase noise reduction of the slave oscillations. Locking the master circuit to an external RF signal as low as -20 dBm, the slave oscillations shows a phase noise reduction of about 30 dB at 100 kHz carrier off-set when an optical power around 2.5 mW is injected into the slave circuit.

---

### Table 1: Layer Composition of RTD-OWPDs

<table>
<thead>
<tr>
<th>Layer no.</th>
<th>Material</th>
<th>Al Comp. fraction</th>
<th>Thickness</th>
<th>Doping type</th>
<th>Doping concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subst.</td>
<td>2&quot; n+ InP</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>In_{0.3}Ga_{0.7}As</td>
<td>0.067</td>
<td>500nm</td>
<td>n</td>
<td>Si: 5×10^{16} cm^{-2}</td>
</tr>
<tr>
<td>2</td>
<td>In_{0.3}Ga_{0.7}Al_{0.3}As</td>
<td>0.067</td>
<td>5nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>AlAs</td>
<td>1</td>
<td>1.7nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>In_{0.3}Ga_{0.7}As</td>
<td>-</td>
<td>5.1nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>AlAs</td>
<td>1</td>
<td>1.7nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>In_{0.3}Ga_{0.7}Al_{0.3}As</td>
<td>0.067</td>
<td>5nm</td>
<td>undoped</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>In_{0.3}Ga_{0.7}Al_{0.3}As</td>
<td>0.067</td>
<td>500nm</td>
<td>n</td>
<td>Si: 5×10^{16} cm^{-2}</td>
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<td>8</td>
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<td>600nm</td>
<td>n</td>
<td>Si: 2×10^{18} cm^{-2}</td>
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<td>In_{0.3}Ga_{0.7}As</td>
<td>-</td>
<td>40nm</td>
<td>n</td>
<td>Si: 2×10^{18} cm^{-2}</td>
</tr>
</tbody>
</table>
4.3. RTD-PD design considerations

Double barrier quantum-well (DBQW)-RTD structures are being considered for photo-detection due to potential high responsivities and gain-bandwidth-efficiency products, as well as low switching energies because of the NDC intrinsic gain and the low voltage operation characteristics. In order to improve photo-detection capabilities of RTDs a photoconductive layer is generally added to the DBQW-RTD structure. In conclusion, the RTD-PD consists of a monolithic integration of a RTD and a photo-detector structure (PD) capable to operate as an optical receiver with a built-in amplifier, which is able to extract a modulated RF sub-carrier or a modulated baseband from photo-detected optical carriers.

In previous work we had investigated RTD-PD epi-layers with intentional added light absorbing regions, as represented schematically in Fig. 4.3(a), consisted of unipolar (isotype) III-V based semiconductor structures grown on n⁺-InP substrates comprising a DBQW sandwiched between two 500 nm thick In₀.₅₃Ga₀.₃₉Al₀.₀₇As light absorbing layer, with a 300 nm thick top InAlAs layer. The 40 nm thick InGaAs top contact layer was a delta-doped. The photo-detection results were already discussed in the section dedicated to the RTD optical waveguide photodetector.

An updated version of the above epi-layer (wafer 905914A, IQE, Table 4.1) grown on semi-insulating (SI) InP substrate included two InGaAlAs light absorbing layer 200 nm and 500 nm thick each side of the DBQW, sandwiched between two InAlAs 600 nm layers; the top and bottom InGaAs contact layers were 40 nm and 300 nm thick. Unfortunately the fabricated devices did not show reliable I-V curves. RTD-PD mesa devices with a slightly different epi-layer structure, as described in the Table 4.2 (wafer 905675A, grown by IQE), with proper access optical windows and light absorption regions showed well-defined and stable I-V curves. The epi-layer comprises 1.7 nm AlAs barriers and a 5.7 nm quantum well, 500 nm In₀.₅₃Ga₀.₃₉Al₀.₀₇As light sensitive layers each side of the DBQW, and 300 nm InAlAs light layers. The RTD-PDs mesas were implemented with various optical windows sizes and shapes. The on wafer characterization of the RTD-PD devices from the IQE wafer 905675A is underway. The characterization includes: (i) I-V curves in dark; (ii) I-V curves under illumination at certain optical powers with and without an RF modulation component (1 GHz); (iii) frequency response – see next subsection.
Electronic oscillators operating at 17 GHz were implemented using 225 µm² RTDs with epi-layer structure similar to IQE wafer 905675A [21][22]. The oscillators required a 45 pH inductance to resonate the RTD intrinsic capacitance. It is expected that by using a reduced (and easily realisable) 2 pH inductance instead would have provided an 80 GHz oscillator. Therefore, mm-wave opto-electronic microwave/millimetre-wave oscillators should be realisable with such epi-layer structures.

Table 4.1: InGaAs/AlAs RTD-PD epi-layer structure with 200 nm collector and 500 nm emitter In\(_{0.53}\)Ga\(_{0.39}\)Al\(_{0.07}\)As-AlAs layers, IQE wafer 904664A.

<table>
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<tr>
<th>Layer</th>
<th>Type</th>
<th>Material</th>
<th>Group</th>
<th>Repeat</th>
<th>Mole Fraction (x)</th>
<th>Mole Fraction (y)</th>
<th>Strain (ppm)</th>
<th>PL (nm/Å)</th>
<th>Thickness (Å)</th>
<th>Dopant</th>
<th>CV Level</th>
<th>Comments</th>
</tr>
</thead>
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<td></td>
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<tr>
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<td>.52.1</td>
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<td></td>
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<td>Si</td>
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<td></td>
<td>Collector</td>
</tr>
<tr>
<td>11</td>
<td>N-</td>
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<td>.53.0</td>
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<td>8</td>
<td>i</td>
<td>In(x)GaAs</td>
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<td>.53.2</td>
<td></td>
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<td>20</td>
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<td></td>
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<td></td>
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<tr>
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<td>i</td>
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<td>Si</td>
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<td>Si</td>
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<td>Collector</td>
</tr>
</tbody>
</table>

Table 4.2: InGaAs/AlAs RTD-PD epi-layer structure with 500 nm collector and 500 nm emitter In\(_{0.53}\)Ga\(_{0.39}\)Al\(_{0.07}\)As-AlAs layers, IQE wafer 905675A.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Type</th>
<th>Material</th>
<th>Group</th>
<th>Repeat</th>
<th>Mole Fraction (x)</th>
<th>Mole Fraction (y)</th>
<th>Strain (ppm)</th>
<th>PL (nm/Å)</th>
<th>Thickness (Å)</th>
<th>Dopant</th>
<th>CV Level</th>
<th>Structure</th>
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<td>2.0e19</td>
<td>No</td>
<td></td>
<td>Collector</td>
<td></td>
</tr>
</tbody>
</table>

The optimized RTD-PD devices with appropriate access optical windows should lead to: (i) the improvement of the device optical response, namely maximizing the responsivity and sensitivity; (ii) the improvement of the photo-detection response/operation frequency higher as high as the equivalent electronic RTDs, well above 10 GHz. Currently, we are designing new RTD-PD epi-layers towards the improvement of devices performance, including:

a) Reduction of the optical power levels required to ensuring that RTD-PD oscillators can be driven by an optical sub-carrier RF signal (that is, to obtain larger light signal detection dynamic range);

b) Maximization of the optical-electrical power gain;

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c) Improved linearity and spectral response;
d) Enhanced sensitivity (differential responsivity) and responsivity-gain.

### 4.3.1. Device configurations

The implementation of efficient low cost optical-to-mm-wave/THz transceivers requires a detailed investigation of the epi-layers optoelectronic properties, particularly the effect of the localization of the light absorption layers. So far the relevant wafer epi-layers object of study included absorption layers both sides of the DBQW structure – see, for example, Tables 4.1 and 4.2. It is fundamental to investigate epi-layer structures with just one light absorbing layer in order to study the effect of the light-generated electron-hole pairs on the optical response of the devices, namely on the responsivity, on the sensitivity and on the photo-detector bandwidth.

In simple terms, an RTD-PD structure corresponds to the monolithic integration of a DBQW with a photo-conductive detector. A photo-conductive detector is a device where incident light leads to the increase of the number of charge carriers in the active area, thus decreasing the global resistance of the device, unlike standard photodiode which produce a current when exposed to light. Figure 4.6(a) shows the schematic diagram of a basic DBQW-RTD structure, where the layer(s) between the DBQW and the high-doped emitter and collector contact regions normally are few tens of nanometer thick; Fig. 4.6 (b) displays the diagram of a RTD-PD mesa structure, where there is at least one low doped light sensitive region several hundred nanometer thick between the DBQW and the emitter or collector contact layers. Figure 4.6(c) shows a RTD-PD in an optical waveguide configuration, where the light is butt-coupled to the waveguide facets.

![Baseline RTD, RTD-PD mesa, and RTD-PD optical waveguide implementations](image)

Fig. 4.6: (a) Schematic diagrams of the baseline RTD; RTD-PD (b) mesa and (c) optical waveguide implementations.

Generally speaking, a RTD-PD operates in photoconductive mode. However, the position of the light absorbing layer(s) relatively to the DBQW will determine the effect of the light-generated electron-holes pairs on its I-V characteristic and on its optoelectronic response to light. The discussion of different optoelectronic functionalities dependent on the light-sensitive layer position will be address in the section dedicated to device and circuit simulation.

### 4.3.2. Responsivity

Ultrafast photodetectors are optimized mainly with respect to high bandwidth-quantum efficiency product, sensitivity (lowest detectable light level) and high-output saturation power (responsivity). In an
ideal photodetector every photon produces one electron-hole pair, which is transferred without losses to the contact electrodes of the photodiode giving rise to the light-generated current, that is, the photodetector quantum efficiency is equal to one.

The efficiency of a photodetector as an optical-electrical converter is normally characterized by its responsivity, which is defined as the ratio of generated photocurrent and incident (or sometimes absorbed) optical power, determined in the linear response region [19][20]. The photodetector responsivity is usually defined for the steady state. The term responsivity should not be confused with sensitivity; the latter is the lowest detectable light level, which is typically determined by detection noise and significantly influenced by the required detection bandwidth [19][20].

A photo-detector should ideally be operated in a spectral region where its responsivity is not far below the highest possible value, because this leads to the lowest possible detection noise and thus to a high signal-to-noise ratio and high sensitivity (the lowest detectable light level). For photodetectors that have voltage rather than current outputs, its responsivity can be defined as the ratio of the output voltage and optical power, with units of volt per watt (V/W). If a photodetector is combined with some electronics generating a voltage output, the output voltage is the photocurrent times the transimpedance of the electronics. In the simplest case, one uses a shunt resistor, and the transimpedance is the shunt resistor resistance.

The optical response of the RTD-PD will be characterized in the steady state or stationary mode and in the dynamic mode. The former corresponds to the RTD-PD response to incident continuous wave (constant intensity) optical signals. The latter deals with the RTD-PD response to intensity modulated optical signals. The RTD-PD steady (stationary) state responsivity $R_{cw}(\lambda)$ is defined as the ratio of the current difference under illumination and dark conditions, $I_{light}(V) - I_{dark}(V)$, and the continuous-wave optical power $P_{light}(\lambda)$ incident on the device, this is:

$$R_{cw}(\lambda, V) = \frac{I_{light}(V) - I_{dark}(V)}{P_{light}(\lambda)}.$$  

(4.1)

The RTD-PD dynamic responsivity $R_{f}(\lambda)$ is defined as the ratio of the photocurrent amplitude and the modulated optical power $P(\lambda, f)$ incident on the device, this is:

$$R_{f}(\lambda, V, f) = \frac{I_{ph}(f)}{P(\lambda, f)}.$$  

(4.2)

In the above equations, $\lambda$ and $f$ represent the wavelength and the frequency of modulation of the lightwave. Next we will discuss, in general terms, the responsivity of a photoconductive detector, although we have always in mind the RTD-PD.

In what follows we assume the detector operates in the photoconductive mode under a given applied voltage. When illuminated with an optical power $P(\lambda)$ the detector will generate a photocurrent $I_{ph}$, and responsivity is given by:

$$R_{\lambda} = \frac{I_{ph}}{P(\lambda)} = \eta_{ph} \left( \frac{e\lambda}{hc} \right) = \eta_{ph} R_{\lambda}.$$  

(4.3)
where $\eta_{ph}$ represents the photo-detector external quantum efficiency, defined as the fraction of photons creating electron-hole pairs; $\mathcal{R}_\lambda = \left( \frac{e\lambda}{hc} \right)$ represent the ideal responsivity, that is, the maximum responsivity for a given wavelength; $e$, $h$ and $c$ are the elementary charge, the Planck constant and the speed of light in the vacuum, respectively.

For wavelengths 1310 nm and 1550 nm the ideal (maximum) responsivity values are 1.048 A/W and 1.25 A/W, respectively. As we will see it is of critical importance the light absorbing material to have as large absorption coefficient as possible. The wavelength dependence of the absorption coefficient for several materials is shown in Fig. 4.7(a). In the case of photodiodes and photoconductive devices, the responsivity reaches its maximum value typically in the wavelength region where the photon energy is somewhat above the bandgap energy, declining sharply when the energy of the photons lays within in the region of the semiconductor bandgap, where the absorption decreases, as shown in Fig. 4.7(b) for In$_{0.53}$Ga$_{0.47}$As.

Fig. 4.7: (a) Absorption coefficient $\alpha$ as function of the wavelength $\lambda$ for several semiconductor materials [19][20]; (b) Spectral response of a In$_{0.53}$Ga$_{0.47}$As photodetector [39].

Several effects and loss mechanisms lead to reduction of responsivity. The photo-detection quantum efficiency value is reduced by the limited absorption in finite absorption layers thickness, residual optical reflection of the incident light at semiconductor surface, losses due to fiber-chip coupling, losses in internal contact layers and carrier recombination (before the contacts are reached). Moreover, the photocurrent generated in the high frequency range operation will be smaller than the stationary state value because of bandwidth limiting effects such as RC time and transit time constraints.

The RTD-PD photo-detection external quantum efficiency $\eta_{ph}$ is dependent on the bias voltage, on light wavelength since the material absorption coefficient $\alpha$ depends on the wavelength $\lambda$ and on the applied voltage $V_{DC}$, and on the light coupling efficiency $\kappa$ to the detector. The photo-detection external quantum efficiency $\eta_{ph}$ can be written (from Eq. 4.4) as:

$$\eta_{ph} = \frac{I_{ph}}{P(\lambda)} \left( \mathcal{R}_\lambda \right)^{-1}$$  (4.4)
Considering the RTD-PD optical window facet (Fresnel) reflectance $R_{\text{ref}}$, due to refractive index mismatch between the air and the semiconductor material, and the finite dimension(s) of light sensitive layer(s) $L$, the external quantum efficiency $\eta_{\text{ph}}$ can be approximated by the product of the light coupling factor $\kappa$ (dependent on the size and shape of the optical window and on the mode profile of the optical fiber used to coupled light into the RTD-PD) multiplied by the material absorbance [20]:

$$
\eta_{\text{ph}}(V, \lambda, L) = \kappa(1 - R_{\text{ref}})\left(1 - e^{-\alpha(V, \lambda)L}\right)
$$  \hspace{1cm} (4.5a)

$$
\eta_{\text{ph}}(V, \lambda, L) = \kappa(1 - R_{\text{ref}})\alpha(V, \lambda)L, \text{ for } \alpha(V, \lambda)L << 1
$$  \hspace{1cm} (4.5b)

where $R_{\text{ref}} = \left[(n-1)/(n+1)\right]^2$ is the facet (Fresnel) reflectivity (n is the semiconductor refractive index), $\alpha(V, \lambda)$ is the material absorption coefficient at the wavelength $\lambda$ and at the bias voltage $V = V_{\text{DC}}$, and $L$ is the photo-detector absorbing active region thickness. Therefore, the RTD photo-generated current $I_{\text{ph}}(\lambda)$ in response to an incident optical signal $P(\lambda)$ will be dependent on wavelength and on the applied bias:

$$
I_{\text{ph}}(\lambda, V) = \Re_{\lambda}(V, \lambda)P(\lambda) = \eta_{\text{ph}}(V, \lambda)\Re_{\lambda}(V, \lambda)P(\lambda)
$$  \hspace{1cm} (4.6)

Let’s consider the RTD-PD mesa structure shown in Fig. 4.6(b), where the relevant light absorption layer with thickness $L$ is made of low doped (n-) 500 nm In$_{0.53}$Ga$_{0.47}$As (with refractive index 3.5, $R_{\text{ref}} = 0.31$), which has an absorption coefficient of $\sim 1 \times 10^4$ cm$^{-1}$ for $\lambda = 1310$ nm. The expected external quantum efficiency of a 500 nm In$_{0.53}$Ga$_{0.47}$As layer is 0.27, assuming $\kappa = 1$, which results in a responsivity as high as 0.29 A/W. Ignoring the Fresnel reflection, the responsivity would be 0.41 A/W.

### 4.3.3. Frequency response

As mentioned above, the photo-detector response typically falls off for intensity modulated signal frequencies above some detection bandwidth. There are basically three factors that limit the speed of a photodetector: diffusion of carriers, drift transit time in the depletion region, and capacitance of the depletion region. The slowest of the three processes is the diffusion of carriers to the high-electric field depletion region from outside that region. To minimize this slow effect, carriers should be generated near or in the depletion region. Reducing the ratio between the diffusion length and the drift length of the device results in a greater proportion of the generated current being carried by the faster drift process. Diffusion of the carriers generated outside the depletion region is a slow process — caused by the optical absorption in the diffusion regions outside of the high-field depletion region (diffusion current can last as long as the carrier lifetime), they lead to the formation of a long tail in the impulse response of the photodiode, which results in a low-frequency falloff in the frequency response. The diffusion time $\tau_{\text{diff}}$ for carriers to diffuse a distance $L$ can be estimated using equation below [20]:

$$
\tau_{\text{diff}} = \frac{L^2}{2D}
$$  \hspace{1cm} (4.7)

where $D$ is the minority carrier diffusion coefficient. For InGaAs electron and hole diffusion coefficients are of the order of 150 cm$^2$/s and 5.5 cm$^2$/s [20], respectively, which, for $L = 500$ nm, gives a hole diffusion time $\tau_{\text{diff}}$ around 227 ps.
The 3-dB electrical frequency (frequency where the collected current has decreased by $\sqrt{2}$)\(^1\) of a photoconductive detector limited by the carrier-diffusion time can be estimated using equation [37]:

$$f_{3dB_{dif}} = \frac{3.5}{2\pi} \frac{1}{\tau_{dif}}$$  \(\text{(4.8)}\)

Using the value of $\tau_{dif}$ it gives a 3-dB frequency $f_{3dB_{dif}} \approx 3.3$ GHz). For a high-speed photodetector, this diffusion mechanism has to be eliminated (by reducing the photo-generation of carriers outside the depletion layer through an improved design of the device structure, such as including advanced heterojunctions).

The second process, the transit time, is the time required for the carriers to drift across the depletion region and get swept out of the device. For higher frequency operation the photo-generated carriers, particularly the electron, transit time across the structure must be small, which implies that $L$ must be minimized and the photo-generated carriers’ velocities, particularly the electron velocity, in the semiconductor must be maximized. With sufficient bias, electrons and holes will drift at their saturation velocities. The 3-dB electrical frequency of a photoconductive detector limited by the carrier-transit time can be calculated using equation [37]:

$$f_{3dB_{tt}} = \frac{3.5}{2\pi} \frac{v}{L}$$

$$v^{-4} = \frac{1}{2} \left( v_e^{-4} + v_h^{-4} \right)$$  \(\text{(4.9)}\)

where $v_e$ and $v_h$ are the electron and hole saturation velocities, respectively. For very high bandwidth (thin) photo-detectors, the bandwidth-efficiency product $f_{3dB_{tt}} \times \eta_{ph}$,

$$f_{3dB_{tt}} \times \eta_{ph} = \frac{3.5}{2\pi} v \kappa(1 - R_{ref}) \kappa(V, \lambda)$$  \(\text{(4.10)}\)

is independent of design parameters.

The expected intrinsic carrier-transit time limited 3-dB frequency $f_{3dB_{tt}}$ of the RTD-PD mesa structure shown in Fig. 4.7(a), with a light absorbing layer of $L = 500$ nm, is of the order of 60 GHz, using $v = 5.3 \times 10^6$ cm/s (from electron and hole velocities in InGaAs, $v_e = 6.5 \times 10^6$ cm/s and $v_h = 4.8 \times 10^6$ cm/s, respectively [20][37]). It corresponds to a transit time is around 10 ps.

Here we have assumed the absorbing layer thickness is equal to the depleted (high electric field) intrinsic/low-doped layer thickness. This assumption is quite ambitious and do not takes into account that the depletion region is bias dependent, while the intrinsic layer thickness is fixed by the epi-layer design.

For mesa type photodetectors (that is, structures where the absorbing layer is perpendicular to the illumination), several compromises in designing have to be considered with respect of the thickness of

---

\(^1\) The 3-dB optical frequency corresponds to the frequency where the current has decreased by 2.
the active photon-absorbing layer. The ideal bandwidth-quantum efficiency product for perpendicular illuminated photodetectors depends on the operating wavelength. A large absorption layer thickness is needed to achieve high quantum efficiency and hence high responsivity. However, a large absorbing layer results in longer carrier drift time. As a numerical reference and assuming single-pass absorption, it is estimated that for an absorbing coefficient of the order of $1 \mu m^{-1}$ the ideal bandwidth-efficiency product will be below 20 GHz and 35 GHz in the third and second optical communication windows, respectively [37].

Lastly, the capacitance of the device determines its RC time constant (here, $R$ represents the device/circuit load resistance, usually 50 $\Omega$). To maximize a photodiode response, the transit time and diffusion time are typically designed to be comparable but smaller to the RC time constant. For instance, given the saturation velocity for InGaAs, a 10 ps transit time, for example, requires that the depletion layer be 0.5 $\mu m$ thicker at most. For a comparable RC time constant in a 50 $\Omega$ system, the capacitance must be less than 200 fF. Assuming the capacitance $C$ can be estimated using the parallel plate approximation,

$$C = \varepsilon \frac{A}{d} \quad (4.11)$$

where $d$ is the dielectric thickness (here the depleted region), here $d=0.5 \mu m$, $A$ is the active area of the device, and $\varepsilon$ is the dielectric relative electrical permittivity ($\varepsilon=13$ for InGaAs). Considering the numerical values above, we find the device active area must be less than $870 \mu m^2$ (equivalent to disc with a diameter smaller than 35 $\mu m$). However, it is highly unlikely that the RTD-PD 500 nm absorbing layer become completely depleted unless it is designed as an intentional un-doped or very low-doped layer. If we assume a 100 nm collector depleted region, the maximum area must be lower than 170 $\mu m^2$ (equivalent to a circular optical window diameter smaller than 15 $\mu m$).

### 4.3.4. Epi-layer design

The iBROW optical-to-wireless RTD-based transceiver consists of an RTD-PD structure obtained by embedding a DBQW within the low doped region of an isotype semiconductor $N_E - n - N_C$ heterojunction, where $N_{E,C}$ and $n$ represent the high-doped emitter/collector layers and the moderately doped layer of the isotype structure, respectively. That is, the RTD-PD corresponds to a semiconductor $N_E - n_E - DBQW - n_c - N_C$ heterojunction, where $N_E$ and $n_E$ represent the high-doped and the low-doped emitter layers of the structure, respectively, while $n_C$ and $N_C$ represent the low-doped and the high-doped collector layers of the structure, respectively. In the $N_E - n_E - DBQW - n_c - N_C$ heterojunction both $n_E$ and $n_C$ regions can be designed to act as light absorbing layers for a given wavelength range, as schematically represented in Fig. 4.8.

Ultrafast RTD-PDs need to be designed to achieve high bandwidth-quantum efficiency product, high sensitivity (lowest detectable light level) and high-output saturation power (responsivity). From the electrical point of view, the epi-layer design must aim to maximize performance in terms of generated power and operation frequency. Considering the expected optoelectronic performance the RTD-PD epi-layer design needs to accomplish high sensitivity, high-output saturation power and high bandwidth.
Although the epitaxial layer design guidelines for RTDs and photodetectors (PDs) are well described in the literature, see e.g. [1]-[3],[19],[20], much design is still done empirically with the help of simulation tools that provide qualitative assessments of the devices performance. Taking into consideration the knowledge gained with previous and on-going work several changes in the RTD-PD epi-layer need to be applied in order to achieve, or at least approach to the realization of devices delivering the expected performance. The first change relatively to the wafer #905675A is the replacement of the In$_{0.53}$Ga$_{0.39}$Al$_{0.07}$As by In$_{0.53}$Ga$_{0.47}$As, allows achieving higher responsivity at 1550 nm, close to the responsivity obtained currently at 1310 nm, due to the superior value of the In$_{0.53}$Ga$_{0.47}$As absorption coefficient at 1550 nm as shown in Fig. 4.7(b). Another crucial modification deals with the reduction of the importance of the light generated carrier diffusion current components by diminishing the thickness of the low-doped InGaAs layers.

The first RTD-PD epi-layer design attempt aimed to investigate the performance of RTD structures with high peak current densities, and high responsivity and sensitivity. A high peak current density epi-layer (iBROW RTD-PD#1 on SI-InP; DB RTD-PD 01B, IQE growth #421168A) that comprised a considerably thick (1000 nm) InGaAs layer on the collector/top side for light detection was ordered: its DBQW consisted of 1.1 nm thick AlAs barrier and 4.5 nm thick In$_{0.80}$Ga$_{0.20}$As quantum well. Table 4.3 details the epi-layer structure.

Unfortunately, because the high peak current density the device area of the RTD-PD implemented (>100 um$^2$) give rise to peak currents higher than 200 mA. Such current levels result in overheating, which shortens the device lifetime and prevents a proper characterization. The devices were designed with active areas that allow the presence of proper optical access windows, in order to achieve considerable high light couple efficiency with standard single mode optical fibers that have typical mode field diameters around 9 micrometers [40].

We have also designed moderate peak current density RTD-PD structures grown on both InP and Ge/Si substrates, as described in table 4.4. The devices on Ge/Si substrate were non-functional and so investigations are on-going to establish its causes.

Since the RTD maximum oscillator output power is given by $P_{\text{max}} = (3/16) \Delta V \times \Delta I$ [21][22], where $\Delta V$ and $\Delta I$ are the peak-to-valley current and voltage differences, respectively, high power oscillators require large $\Delta I$ and $\Delta V$. The adoption of thicker barriers and a wider quantum well gives rise to moderate peak current densities (10 – 100 kA/cm$^2$) and large peak-to-valley current ratios (PCVRs), and therefore large $\Delta I$. Therefore, for the RTD-PD oscillator realisation an epi-layer design approach that increases $\Delta V$ at moderate current densities (and large PCVR) could be desirable.
Another aspect, related with the previous ones and that needs to be considered is the device sizing for which $|\Delta V_\text{DC}| \approx 50$ and the optical access windows, whose size should assure light coupling factor $\kappa$ close to 1 (that is, all the light exiting the optical fiber is coupled to the RTD-PD – we will address this issue in the section dedicated to the device packaging). As a rule of thumb the optical window size should be at least equivalent to the mode-field diameter of the optical fiber (standard or lensed single-mode fiber) being used to couple light to the RTD-PD.

Table 4.3: In$_{0.80}$Ga$_{0.20}$As/AlAs RTD-PD epi-layer with a 1 µm thick light sensitive region.

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Thickness (Å)</th>
<th>Semicond. Composition</th>
<th>Doping (cm$^{-3}$)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>450</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E19 : Si</td>
<td>Collector</td>
</tr>
<tr>
<td>11</td>
<td>250</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E18 : Si</td>
<td>Collector</td>
</tr>
<tr>
<td>10</td>
<td>10000</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td></td>
<td>Absorption</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>Un-doped</td>
<td>Spacer</td>
</tr>
<tr>
<td>8</td>
<td>11</td>
<td>AlAs</td>
<td>Un-doped</td>
<td>Barrier</td>
</tr>
<tr>
<td>7</td>
<td>45</td>
<td>In$<em>{0.80}$Ga$</em>{0.20}$As</td>
<td>Un-doped</td>
<td>Well</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>AlAs</td>
<td>Un-doped</td>
<td>Barrier</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>Un-doped</td>
<td>Spacer</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>2E16 : Si</td>
<td>Spacer</td>
</tr>
<tr>
<td>3</td>
<td>250</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E18 : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>2</td>
<td>4000</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E19 : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
<td>InP</td>
<td>Un-doped</td>
<td>Buffer</td>
</tr>
</tbody>
</table>

Substrate | Si : InP |

Table 4.4: RTD-PD Baseline #1A epi-layer grown on both InP (NC1800352) and Ge/Si.

<table>
<thead>
<tr>
<th>Layer #</th>
<th>Thickness (Å)</th>
<th>Semicond. Composition</th>
<th>Doping (cm$^{-3}$)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>450</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E19 : Si</td>
<td>Collector</td>
</tr>
<tr>
<td>11</td>
<td>800</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E18 : Si</td>
<td>Collector</td>
</tr>
<tr>
<td>10</td>
<td>5000</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>5E16 : Si</td>
<td>Absorption</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>Un-doped</td>
<td>Spacer</td>
</tr>
<tr>
<td>8</td>
<td>17</td>
<td>AlAs</td>
<td>Un-doped</td>
<td>Barrier</td>
</tr>
<tr>
<td>7</td>
<td>47</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>Un-doped</td>
<td>Well</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
<td>AlAs</td>
<td>Un-doped</td>
<td>Barrier</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>Un-doped</td>
<td>Spacer</td>
</tr>
<tr>
<td>4</td>
<td>200</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>2E16 : Si</td>
<td>Spacer</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E18 : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>2</td>
<td>4000</td>
<td>In$<em>{0.53}$Ga$</em>{0.47}$As</td>
<td>3E19 : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
<td>InP</td>
<td>Un-doped</td>
<td>Buffer</td>
</tr>
</tbody>
</table>

Substrate | Si : InP / Ge/GeSi |

Having in mind the above considerations, the RTD-PD Baseline #1A epi-layer, as described in table 4.5, was proposed. This epi-layer must fulfill all or the most relevant features that will allow the realization of high performance RTD-PDs. It is expected that RTD-PD devices with RTD-PD Baseline #1B epi-layer (Table 4.5), will show a substantial reduction in the diffusion and transit time constants, $\tau_{\text{diff}}$ and $\tau_{\text{transit}}$, respectively. Using $\tau_{h,\text{diff}} = L^2/2D_h$ (for holes) and $\tau_{l} = L/v$ (for both carriers), we estimate the hole-diffusion time constant will be around 82 ps ($f_{\text{dB},h,\text{diff}} = 0.55 / \tau_{h,\text{diff}} \approx 6.7$ GHz, where $f_{\text{dB}}$ is the 3 dB bandwidth of the RTD-PD and $\tau_{l} = L/v$ is the light propagation time through the device. This estimation is based on the assumption that the device is operated at room temperature and that the optical fibers used are single-mode fibers with mode-field diameters of 5-7 µm. If broader bandwidths are required, it would be necessary to use fibers with larger mode-field diameters or to employ multi-mode fibers which can support higher bandwidths. Nevertheless, this simple estimation shows the potential of RTD-PD devices for high-speed optical communications. The reduction in the transit time constant is also significant and will contribute to the overall performance of the devices, allowing for faster data transmission rates.
using $D_h = 5.5 \text{ cm}^2/\text{s}$ and the carriers transit time will be in the order of 6 ps ($f_{3dBtt} = 0.55/\tau_{tt} \sim 90$ GHz). The estimated diffusion time of holes represents the worst-case scenario since we are assuming that the hole-diffusion current becomes the most relevant current component in the device. The estimated electron-diffusion time ($\tau_{e,\text{diff}} = L^2/2D_e$, with $D_e = 150 \text{ cm}^2/\text{s}$) is 3 ps ($f_{3dB,e,\text{diff}} = 0.55/\tau_{e,\text{diff}} \sim 183$ GHz).

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (Å)</th>
<th>Semicond. Composition</th>
<th>Doping (cm$^{-3}$)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>450</td>
<td>$\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$</td>
<td>$3 \times 10^{19}$ : Si</td>
<td>Collector</td>
</tr>
<tr>
<td>11</td>
<td>800</td>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.48}\text{As}$ or InP</td>
<td>$3 \times 10^{18}$ : Si</td>
<td>Collector</td>
</tr>
<tr>
<td>10</td>
<td>3000</td>
<td>$\text{In}<em>{0.55}\text{Ga}</em>{0.45}\text{As}$</td>
<td>$2 \times 10^{16}$ : Si</td>
<td>Absorption</td>
</tr>
<tr>
<td>9</td>
<td>20</td>
<td>$\text{In}<em>{0.50}\text{Ga}</em>{0.47}\text{As}$</td>
<td>Un-doped</td>
<td>Spacer</td>
</tr>
<tr>
<td>8</td>
<td>17</td>
<td>$\text{AlAs}$</td>
<td>Un-doped</td>
<td>Barrier</td>
</tr>
<tr>
<td>7</td>
<td>47</td>
<td>$\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$</td>
<td>Un-doped</td>
<td>Well</td>
</tr>
<tr>
<td>6</td>
<td>17</td>
<td>$\text{AlAs}$</td>
<td>Un-doped</td>
<td>Barrier</td>
</tr>
<tr>
<td>5</td>
<td>20</td>
<td>$\text{In}<em>{0.50}\text{Ga}</em>{0.47}\text{As}$</td>
<td>Un-doped</td>
<td>Spacer</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>$\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$</td>
<td>$2 \times 10^{16}$ : Si</td>
<td>Spacer</td>
</tr>
<tr>
<td>3</td>
<td>800</td>
<td>$\text{In}<em>{0.52}\text{Al}</em>{0.48}\text{As}$ or InP</td>
<td>$3 \times 10^{18}$ : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>2</td>
<td>4000</td>
<td>$\text{In}<em>{0.53}\text{Ga}</em>{0.47}\text{As}$</td>
<td>$3 \times 10^{19}$ : Si</td>
<td>Emitter</td>
</tr>
<tr>
<td>1</td>
<td>2000</td>
<td>InP</td>
<td>Un-doped</td>
<td>Buffer</td>
</tr>
<tr>
<td></td>
<td>Substrate</td>
<td>$\text{SI : InP} / \text{Ge/GeSi}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### 4.4. RTD-PD fabrication and packaging

At UGLA, there is a developed fabrication process based on photolithography and wet etching to realise RTD devices and integrated circuits. It uses polyimide passivation and vias in the polyimide to the device contacts. It has been successfully used to realise device sizes greater than 3×3 µm$^2$ [21-24]. Two other processes, one based on the planarising benzocyclobutene (BCB) and the other on electron-beam lithography are being developed for the realisation of smaller devices and for process robustness among other things. Some details of these processes are also available in deliverable D3.3 and in Refs. [21-24].

The RTD-PD devices are being fabricated in a mesa configuration (with square, rectangular or circular shapes) with optical windows with equivalent diameters ranging from 10 um to 20 um to allow high light coupling efficiency with single mode optical fibers. The devices are being fabricated as individual RTD-PDs and as RTD-PD oscillators on wafer samples with around 1 cm$^2$. The samples are then backside polished to reduce their thickness, making them easier to cleave. The sample is cleaved along crystal planes to create bars. Each bar contains an array of many chips, which are then diced into individual dies with typical dimensions not much larger than 1 mm$^2$. This size will also help the cleaving process. The dies are now ready for testing and packaging.

The process of packaging begins with die bonding, which is the attachment of the chip to a ceramic sub-mount. The RTD-PD with mesa configuration would be first die-bonded onto a sub-mount allowing illumination access to the RTD-PD upper mesa window. After the die bonding process, electrical contact is made to the chip by bonding gold wires from the chip to bond pads located on the sub-mount. The sub-mount would then be placed inside the package, which might contain a transfer lens.
design (e.g. using aspherical or ball lens) to efficiently couple light from the optical fiber to the RTD-PD chip and aligned to maximize the top illumination light coupling efficiency.

The RTD-PD sub-mount being considered is similar to those sub-mounts used to for the vertical-cavity surface-emitting lasers (VCSELs). The sub-mount design should lead to a configuration that minimizes the parasitic effects due to long wire bond and layout interconnections. Minimizing the wire bond lengths helps to prevent signal distortion which can degrade the multi-Gbps signals. Figure 4.8 shows schematically two possible approaches for the RTD-PD packaging module.

Fig. 4.9: Possible approaches for the RTD-PD packaging module. (a) Light coupling with the help of a collimating lens; (b) light coupling using lensed or tapered fibers [26].

The RTD-PD electrical signal output will depend on the light coupling efficiency, as well as on the responsivity. It is expected that optimized devices will have responsivities close to 0.8 A/W, reaching values higher than 1 A/W if anti-reflection (AR) coatings are used to reduce optical reflections at the optical window increasing the amount of light coupled to absorption region of the RTD-PD.

The RTD-PDs being designed operate around 1 V with peak current up to 50 mA. A maximum DC operating power for the RTD-PD is projected to be 50 mW. It is expected that optimized devices will operate at lower voltages with smaller peak currents. In the oscillator mode the power generated by the RTD-PD oscillator is expected to be in the range 0 dBm to 10 dBm at 10GHz. RTD-PD transponder storage temperature it is expect to be -50 ºC and 100 ºC, and working temperature to be supported are between -20 ºC and 70 ºC.

4.5. RTD-PD on-wafer characterization

Here, we report the preliminary results on low frequency optoelectronic characterization of RTD-PDs from wafers #905914A (WOWi), #905675A (WOWi) and #NC1800352 (RTD-PD Baseline #1A on InP). The #905914A epi-layer is described in Table 4.1, and includes 200 nm and 500 nm In$_{0.53}$Ga$_{0.39}$Al$_{0.07}$As collector and emitter layers, respectively; the #905675A epi-layer is defined in Table 4.2, and includes two 500 nm In$_{0.53}$Ga$_{0.39}$Al$_{0.07}$As layers each side of the DBQW; the #NC1800352 epi-layer is described in Table 4.3.

The electrical characterization analysis includes the extraction of the following RTD-PD electrical parameters:

- Peak current density $J_p$ [kA/cm$^2$];
- Peak voltage $V_p$ [V];
- Valley-peak voltage difference $\Delta V_{V-P}$ [V];
- Peak to valley current ratio $PVCR$;
- Estimated RTD-PD generated power at low frequency $P_{LF}$ [mW].
The setup used for the optoelectronic characterization is shown schematically in Fig. 4.10. The consortium member Compound Semiconductor Technologies Global Ltd (CST) provided the laser diodes used in the characterization. They are biased through a bias tee to allow modulating the intensity of the laser by an injected RF signal. The RTD-PDs were biased also through a bias tee using a Keithley source meter/power supply unit (PSU). The RTD-PD photo-generated RF signal was monitored using both an Anritsu 40 GHz spectrum analyzer and a Keysight wide-bandwidth oscilloscope. The devices were probed using a ground-signal-ground probe, through which the DC bias was applied and the photo-generated RF signal was collected.

**Fig. 4.10:** Schematic of the setup used to characterize the low frequency response of RTD-PDs.

We investigated the optical response using non-modulated light, i.e., using constant intensity or continuous-wave (CW) light and employing intensity modulated light. The laser diode light is coupled to RTD-PDs using a cleaved bare standard single mode optical fiber (SSMF), in an arrangement shown in Fig. 4.11, which presents photographs of the setup used for the low frequency optical response characterization (up to few gigahertz), with a closer view of the fiber optic light coupling to the RTD-PD. As we will see, the RTD-PD photo-detection response depends on the state of the light-wave intensity. We started the characterization with the evaluation of the response of the RTD-PDs to non-modulated light signals.

**Fig. 4.11:** Photographs of the setup used to characterize the RTD-PD devices. The close look gives a view of the fiber optic light coupling procedure.

The RTD-PDs low frequency optoelectronic characterization includes measurement of the devices I-V characteristics under different illumination conditions, and of the devices response to modulated optical signals, to determine the devices responsivities and sensitivities:

- Devices I-V characteristics in dark;
- I-V curves under illumination for different optical powers;
- I-V characteristics for light modulated at around 1 GHz;
• Responsivity;
• Sensitivity.

Here, the responsivity represents the ratio between the photo-generated current and the optical power being detected; the sensitivity is the lowest detectable light level, which is typically determined by detection noise and significantly influenced by the required detection bandwidth [19][20].

Four samples with typical size of 1 cm$^2$, three of them comprising single RTD-PDs, and one sample with single RTD-PDs and RTD-PD oscillators, were characterized. Next we present and discuss the main results obtained.

**Epi-layer #905914A characterization – RTD-PD samples #1 & #2**

The first RTD-PD sample from epi-layers #905914A did show a minute light response mainly we believe that was due to the poor quality of the optical windows – this sample corresponded to the first production of RTD-PD devices under iBROW. The RTD-PDs from a second sample of epi-layers #905914A showed light response but far from the levels we were expecting. The RTD-PD photo-detected power was under -50 dBm for a 1 mW injected optical power. From the measured photo-generated power we estimate a maximum responsivity for the best performing devices of the order of 0.01 A/W, well below the target of 0.6 A/W.

**Epi-layer #NC1800352 characterization – RTD-PD sample #3, block A**

Figure 4.12(a) shows the schematic and a photograph of sample #3 layout, comprising different blocks of RTD-PDs. The geometrical characteristics of the different blocks are summarized in Fig. 4.12(b). The nomenclature used to identify the RTD-PDs is as follows, first the letter identifying the block, then the number of the row and at last the number of the column: as an example, the RTD-PD A25 is encircled by the green rectangle represented in the Fig. 4.12(a).

Fig. 4.12: (a) Layout and microphotography of sample #3 (RTD-PD wafers #NC1800352). (b) Resume of the geometrical characteristics of the devices on each block. Block A is confined in the red rectangle. Device A25 is encircled by the green rectangle.
Several optical window shapes and sizes were implemented. Figure 4.13 shows the schematically the geometry of the optical windows used to investigate the influence of the windows shape and size on the device performance.

Fig. 4.13: The geometrical shape of the RTD-PDs optical windows employed.

The first row of each block has no intentional defined optical window. The optical window of the second row corresponds to the collector-exposed area between the reddish metal strips, which form the collector contact. The optical window in the third rows corresponds to the bluish rectangle as shown in Fig. 4.13. The fourth-row optical window is the white rectangle enclosed by the reddish collector contact. The circular collector contact of the fifth row of each block has no intentional defined optical windows. The optical window of the sixth row corresponds to the white disc in the interior of the ring-shaped reddish collector contact.

**RTD-PD low frequency electrical characterization**

The results presented and discussed next are from RTD-PDs of block A, which comprises 36 devices. From the NDC point of view we can say that block A has a yield of around 78%, meaning that 22% of the devices do not show stable or any sign of NDC for the voltage range used in the characterization.

<table>
<thead>
<tr>
<th>Block A</th>
<th>Peak Current Density ($J_p$)</th>
<th>PVCR</th>
<th>Peak Voltage ($V_p$)</th>
<th>$\Delta V$</th>
<th>Power Generated ($P_{LF}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>50 kA/cm$^2$</td>
<td>3.3</td>
<td>0.27 V</td>
<td>0.17 V</td>
<td>1/5</td>
</tr>
<tr>
<td>A3</td>
<td>33 kA/cm$^2$</td>
<td>1.5</td>
<td>0.17 V</td>
<td>0.17 V</td>
<td>1/5</td>
</tr>
<tr>
<td>A5</td>
<td>50 kA/cm$^2$</td>
<td>3.3</td>
<td>0.27 V</td>
<td>0.17 V</td>
<td>1/5</td>
</tr>
</tbody>
</table>

Most of the operating devices show peak current densities of 50 kA/cm$^2$, PVCRs up to 3.3, and valley-peak voltage differences ($\Delta V$) as high as 0.27 V. All the working devices from the third row (devices denoted as A3X) have peak current densities $J_p$ around 33 kA/cm$^2$, well below 50 kA/cm$^2$, which should be related to the large optical window and the contact configuration; the PVCR is around 1.5, which is also below the PVCR of the devices without optical window such as A5X; the values of the valley peak voltage difference ($\Delta V$) is around 0.17 V, also substantially smaller to the values for A5X devices. As consequence, A3 RTD-PDs maximum theoretical AC output power estimated from I-V characteristic ($P_{LF}$), using Eq. (3.2), corresponds to one fifth of the potential power generated by the A5 devices. Some devices from rows A4 and A6, with optical windows, show identical electrical characteristics to the best performing A5 devices (including peak current density $J_p$, peak to valley
current ratio \((P_{VCR})\), valley peak voltage difference \((\Delta V)\), and hence power generated at low frequency, Eq. (3.2).

Table 4.6: Electrical properties of RTD-PDs of block A, sample #3 (wafers #NC1800352).

<table>
<thead>
<tr>
<th>RTD #</th>
<th>(J_p) (kA/cm²)</th>
<th>(P_{VCR})</th>
<th>(V_{fe}) (V)</th>
<th>(\Delta V) (V)</th>
<th>(P_V) (mW)</th>
<th>RTD #</th>
<th>(J_p) (kA/cm²)</th>
<th>(P_{VCR})</th>
<th>(V_{fe}) (V)</th>
<th>(\Delta V) (V)</th>
<th>(P_V) (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A11</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>A21</td>
<td>49.7</td>
<td>2.97</td>
<td>-1.33</td>
<td>0.133</td>
<td>0.82</td>
</tr>
<tr>
<td>A12</td>
<td>46.9</td>
<td>2.70</td>
<td>-1.21</td>
<td>0.211</td>
<td>1.17</td>
<td>A22</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A13</td>
<td>53.1</td>
<td>3.35</td>
<td>-1.37</td>
<td>0.161</td>
<td>1.12</td>
<td>A23</td>
<td>16.4</td>
<td>3.25</td>
<td>-1.40</td>
<td>0.169</td>
<td>1.18</td>
</tr>
<tr>
<td>A14</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>A24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A15</td>
<td>14.9</td>
<td>0.90</td>
<td>-0.715</td>
<td>0.807</td>
<td>0.24</td>
<td>A25</td>
<td>50.5</td>
<td>2.99</td>
<td>-1.16</td>
<td>0.239</td>
<td>1.30</td>
</tr>
<tr>
<td>A16</td>
<td>19.4</td>
<td>1.18</td>
<td>0.904</td>
<td>0.631</td>
<td>0.35</td>
<td>A26</td>
<td>49.6</td>
<td>2.90</td>
<td>-1.26</td>
<td>0.168</td>
<td>1.00</td>
</tr>
<tr>
<td>A31</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>A41</td>
<td>43.0</td>
<td>3.29</td>
<td>-1.44</td>
<td>0.120</td>
<td>0.87</td>
</tr>
<tr>
<td>A32</td>
<td>30.3</td>
<td>1.56</td>
<td>-1.21</td>
<td>0.160</td>
<td>0.34</td>
<td>A42</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A33</td>
<td>30.5</td>
<td>1.52</td>
<td>-1.12</td>
<td>0.176</td>
<td>0.34</td>
<td>A43</td>
<td>54.5</td>
<td>3.35</td>
<td>-1.08</td>
<td>0.267</td>
<td>1.91</td>
</tr>
<tr>
<td>A34</td>
<td>32.6</td>
<td>1.44</td>
<td>-1.16</td>
<td>0.169</td>
<td>0.32</td>
<td>A44</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A35</td>
<td>32.9</td>
<td>1.49</td>
<td>-1.11</td>
<td>0.183</td>
<td>0.37</td>
<td>A45</td>
<td>54.7</td>
<td>3.34</td>
<td>-1.13</td>
<td>0.239</td>
<td>1.72</td>
</tr>
<tr>
<td>A36</td>
<td>32.8</td>
<td>1.45</td>
<td>-1.08</td>
<td>0.190</td>
<td>0.36</td>
<td>A46</td>
<td>26.7</td>
<td>3.28</td>
<td>-1.43</td>
<td>0.127</td>
<td>0.90</td>
</tr>
<tr>
<td>A51</td>
<td>51.3</td>
<td>3.37</td>
<td>-1.08</td>
<td>0.267</td>
<td>1.82</td>
<td>A61</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>A52</td>
<td>51.6</td>
<td>3.35</td>
<td>-1.18</td>
<td>0.211</td>
<td>1.43</td>
<td>A62</td>
<td>52.0</td>
<td>3.29</td>
<td>-1.21</td>
<td>0.183</td>
<td>1.24</td>
</tr>
<tr>
<td>A53</td>
<td>51.0</td>
<td>3.33</td>
<td>-1.09</td>
<td>0.267</td>
<td>1.79</td>
<td>A63</td>
<td>51.9</td>
<td>3.27</td>
<td>-1.22</td>
<td>0.176</td>
<td>1.18</td>
</tr>
<tr>
<td>A54</td>
<td>48.7</td>
<td>3.19</td>
<td>-1.10</td>
<td>0.274</td>
<td>1.72</td>
<td>A64</td>
<td>51.9</td>
<td>3.36</td>
<td>-1.12</td>
<td>0.239</td>
<td>1.63</td>
</tr>
<tr>
<td>A55</td>
<td>51.4</td>
<td>3.37</td>
<td>-1.09</td>
<td>0.260</td>
<td>1.76</td>
<td>A65</td>
<td>46.5</td>
<td>3.25</td>
<td>-1.36</td>
<td>0.140</td>
<td>0.93</td>
</tr>
<tr>
<td>A56</td>
<td>50.4</td>
<td>3.34</td>
<td>-1.09</td>
<td>0.260</td>
<td>1.72</td>
<td>A66</td>
<td>51.6</td>
<td>3.35</td>
<td>-1.16</td>
<td>0.218</td>
<td>1.48</td>
</tr>
</tbody>
</table>

**RTD-PD optoelectronic response to non-modulated light**

Figure 4.14 shows the typical optical response of RTD-PDs for 0.1 mW and 1 mW CW optical power levels at the wavelengths (a) 1310 nm and (b) 1550 nm; also shown is the I-V under dark conditions.

Fig. 4.14: Typical response of RTD-PDs for different optical power levels at the wavelengths (a) 1310 nm and (b) 1550 nm.

Analyzing the RTD-PDs response for the two wavelengths, we observe that the devices are more responsive to 1310 nm. That can be explained by the larger value of the absorption coefficient of the
light sensitive low doped InGaAs region, when compared with the absorption coefficient at 1550 nm [see Fig. 4.7(b)]: \(\alpha \sim 1.1 \times 10^4 \text{ cm}^{-3} (1310 \text{ nm})\) and \(\alpha \sim 0.75 \times 10^4 \text{ cm}^{-3} (1550 \text{ nm})\). The 1310 nm light also induces a larger voltage shift towards lower voltage and a larger increment of peak and valley currents as the bias voltage approaches peak and valley regions. All characterized devices show stronger response to optical light in the first PDC region than in the second PDC region. The photocurrent generation in the first PDC leads to a responsivity of 7 A/W at 1310 nm for 1 mW optical power; for light at 1550 nm the responsivity goes up to 5 A/W for the same optical power level. The ratio of the light absorption in the semiconductor at 1550 nm and at 1310 nm can be estimated using 
\[
\frac{1-e^{\alpha_{1310}L}}{1-e^{\alpha_{1550}L}},
\]
that gives 1.4, and which compares with the measured values. Appendix A displays a set of I-V characteristics for dark and under illumination.

In practice, there are several physical effects, such as incomplete absorption, recombination, reflection from the semiconductor surface \((R)\), coupling losses (estimated from the light coupling efficiency \(\kappa\)), and contact shadowing, which reduce the optical response and hence the responsivity. If the light coupling losses are substantially reduces by employing optical windows with diameters larger than the single mode fiber mode field diameter, which is around 9.2 \(\mu\)m at 1310 nm, it would give rise to coupling efficiencies close to 1, assuming that the reflectivity at the semiconductor surface is greatly reduced (i.e., \(R \sim 0\)). [Here, the mode field diameter (MFD) represents a measure of the transverse extent of distribution of the irradiance, i.e., the optical power per unit area, across the end-face of the single-mode fiber. When the fiber single mode irradiance has a Gaussian profile the mode field radius corresponds to the radial points at which the irradiance drops to \(1/e^2\) from its maximum value at the fiber axis.] For achieving RTD-PD with light coupling efficiency close to 1 the light exiting the fiber should produce a spot size less than the size of the RTD-PD optical active area (here corresponding to the optical window area). Spot sizes less than 10 microns are ideal for allowing the fabrication of RTD-PDs with area (and hence capacitance) compatible with very high speed transmission rates.

As a first approximation, we can estimate the light coupling efficiency as the ratio between the optical window useful area and the fiber mode field equivalent area. If we consider the case of the A6 RTD-PDs, which have circular optical windows with diameter of 4 \(\mu\)m (giving a light absorbing area of \(\sim 12.6 \mu\text{m}^2\)) and the 9.2 \(\mu\)m mode field diameter of the fiber used in the experiment (equivalent to a light “emitting” area of \(\sim 63.6 \mu\text{m}^2\)), the coupling efficiency would be around 30%. For A3 (5x10 \(\mu\)m\(^2\)) devices we estimate a coupling efficiency of around 80%. Combining the above corrections (assuming a coupling efficiency \(\kappa = 1\), and all the optical power is transmitted to the semiconductor, that is, there is no reflection of the light from the surface of the semiconductor, \(R = 0\)), we would expect a correction factor of 1.8 \([1/(0.69x0.8)]\) for A3 devices, and we would be achieving responsivity values up of to 12.7 A/W (7 A/W measured) and 9 A/W (5 A/W measured), for 1 mW of light at 1550 nm and at 1310 nm, respectively. As referred above, the light coupling efficiency \(\kappa\) can be estimated, as first approximation, as the ratio of the optical window useful area and the single mode fiber mode field equivalent area, and for the optical windows shapes and sizes under consideration (see Fig. 4.12(b) and Fig. 4.13), we estimate: \(\kappa_{A2} (4 \times 10 \mu\text{m}^2) \approx 0.65\), \(\kappa_{A3} (5 \times 10 \mu\text{m}^2) \approx 0.8\), \(\kappa_{A4} (4 \times 4 \mu\text{m}^2) \approx 0.35\), \(\kappa_{A6} (r = 2 \mu\text{m}) \approx 0.3\).

**RTD-PD optoelectronic response to modulated light at around 1 GHz**

The RTD-PDs operation as a photodetector was evaluated by characterizing their response to intensity modulated light. The most basic function of a photo-detector is to convert light to an electric current; this is evaluated in terms of the responsivity expressed in ampere per watt (A/W) or by the external quantum efficiency \(\eta_{ph}(\lambda, V)\) (the fraction of free carriers collected by the external circuit...
relative to the number of incident photons). Once the photons have entered the semiconductor, the photo-detection process consists of absorption and collection of the photo-generated electron-hole pairs. In an ideal photo-detector, each incident photon would result in the charge of one electron flowing in the external circuit. The responsivity $\mathcal{R}$ of a photodetector operating as an optical-electrical converter, with a light absorption layer of thickness $L$ and absorption coefficient $\alpha$, defined as the ratio of photocurrent $I_{\text{ph,RF}}$ and incident optical power $P_{\text{light}}(\lambda)$, can be written as [see Eq. 4.3]:

$$\mathcal{R}(\lambda, V) = \frac{I_{\text{ph,RF}}(\lambda, V)}{P_{\text{light}}(\lambda)} = \frac{\lambda [\mu m]}{1.24} \eta_{\text{ph}}(\lambda, V) = \frac{\lambda [\mu m]}{1.24} \kappa (1 - R) (1 - e^{-\alpha(\lambda, V)L}).$$ (4.12)

For the devices being considered, where the absorption(s) layer(s) is made of In$_{0.47}$Ga$_{0.53}$As the absorption coefficients at 1310 nm and 1550 nm are $\sim 3.1 \times 10^4$ cm$^{-3}$ and $\sim 5.5 \times 10^4$ cm$^{-3}$, respectively; the power reflection coefficient from the semiconductor surface is $R \sim 0.31$.

Figure 4.15 presents the A3 RTD-PD devices output photo-generated RF power (photo-generated electrical power) as a function of the applied bias, with the injected 1310 nm optical power intensity modulated at around 1 GHz as a parameter. Inset is shown an oscilloscope trace of the RTD-PD electrical response to the injected light. From the output RF power we estimated responsivity in the valley region greater than 1.12 A/W, which would be superior to 2 A/W if compensated by the reflectance at the air-semiconductor interface and assuming a light coupling efficiency close to 1. The estimated responsivity of A3 devices in the valley of 2 A/W is considerable superior when compared the peak value around 0.8 A/W (compensated as above); in terms of photo-generated power the difference between valley and peak is -8 dBm. The above responsivity estimation values assumed the impedance of the measurement equipment (oscilloscope and spectrum analyzer) is 50 ohm.

![Figure 4.15: RTD-PDs photo-detected power as function of applied bias, for different optical power levels modulated at 1 GHz; the wavelength of the light was 1310 nm. Inset is shown the photo-detected signal trace in the oscilloscope: the peak-to-peak voltage is 20 mV.](image)

We have made the comparison between the responses of RTD-PDs and of a commercial photodetector [Thorlabs DET08CFC - 5 GHz InGaAs, 800 - 1700 nm - its spectral response is shown in Fig 4.7(c)]; for the range of optical powers employed the measured responsivity of this photodetector is within the 0.8-0.9 A/W range. Considering the light coupling arrangement used and the characteristics of the optical windows, the responsivity of the best performing RTD-PD devices is considerable superior to the currently used InGaAs p-in photodetectors.
Figure 4.16 displays the oscilloscope traces corresponding to A3 RTD-PDs photo-generated current signals in the peak and in the valley regions - green traces - for two values of optical power, 0.2 mW and 0.87 mW, both modulated at 1 GHz. Also shown are the DET08CFC photo-generated signals (yellow traces) for 2 mW [(a) and (b)] and 0.87 mW [(c) and (d)]. Figures 4.16(a) and (b) show the RTD-PD oscilloscope traces for 0.2 mW optical power illumination (the DET08CFC illumination was 2 mW), corresponding to responsivities at peak and valley around 0.81 A/W (1.47 A/W when corrected as above) and 1.51 A/W (2.7 A/W when corrected as above), respectively; Figs. 4.16(c) and (d) display RTD-PD and DET08CFC traces for 0.87 mW optical power illumination, which corresponds to RTD-PD responsivity at peak and at valley of 0.43 A/W (0.78 A/W when corrected as above) and 0.94 A/W (1.7 A/W when corrected as above), respectively.

Fig. 4.16: Oscilloscope traces of the RTD-PD photo-generated signals for: 0.2 mW light illumination at (a) peak and (b) valley; and for 0.87 mW light illumination at (c) peak and (d) valley. The DET08CFC illumination levels are 2 mW and 0.87 mW, respectively. Green traces: RTD-PDs photo-generated electrical response. Yellow traces: DET08CFC photodiode electrical response.

RTD-PDs from row 4 (A4, 4x4 µm² optical window), e.g., have responsivities up to 0.8 A/W (3.3 A/W, when corrected as above, assuming $\kappa_{A4} = 0.35$) in the peak, and 0.4 A/W (1.66 A/W, when corrected as above) in the valley.

The best performing A2 (A4, 4x10 µm² optical window) devices show responsivity values, after the above reflectance and coupling efficiency corrections, up to 0.67 A/W (1.5 A/W, when corrected as above, assuming $\kappa_{A2} = 0.65$) in the peak region, and 0.07 A/W (0.156 A/W, when corrected as above) in the valley region.
RTD-PDs from row A6 (\(\kappa_{A6} \approx 0.3\)) show lower values of responsivity, which we attributed to the smaller effective area of their optical windows – the designed optical windows correspond to circles of 2 \(\mu\)m radius.

One aspect that differentiates A3 RTD-PDs from the other devices is their stronger optical response (higher responsivity) in the valley region than in the first PDC. Devices from rows A2, A4 and A6 show stronger performance in the first PDC region (peak region).

The reason(s) why devices from row A3 show higher response in the valley (second PDC), and the other devices have stronger response in the first PDC rather than in the second PDC is not yet well understood. Eventually, it is due to the contact configuration which leaves a considerable portion of the collector-exposed with light illuminating the RTD-PDs mesas side-walls and/or the emitter contact layers (bottom highly doped InGaAs layer corresponding to the layer 2 of Table 4.4) that are not covered by the metallization. The contacts configuration also can lead to current spreading effects making the carrier transport through resonant tunneling less efficient, with less voltage dropped across the depleted region in the collector.

As mentioned, several optical windows shapes and sizes were implemented, as schematically represented in Fig. 4.13. The A3 devices (they correspond to 10 \(\mu\)m x 10 \(\mu\)m mesa RTDs with 5 \(\mu\)m x 10 \(\mu\)m optical windows, the largest area optical window in the block A) show considerable inferior electrical response when compared with the devices from other rows (see Table 4.6), showing also higher optical response in the second PDC region than in the first PDC region of the DC I-V curves.

Devices from rows A4 and A6 show lower measured responsivity, however this can be explained by the smaller effective area available to couple light into the devices. Apart of devices from row A3, all electrical working devices from block A show similar electrical properties, as displayed in Table 4.6.

The combination of the electrical and the optical response performances seems to indicate that optical windows identical to the ones of rows 4 and 6 but larger in size would be the best options to implement RTD-PDs with larger external quantum efficiency. Square optical windows seem to be more favorable at this stage due to the lift-off process employed in the optical windows formation. Tapered and lensed fibers offer an additional and convenient way to improve optical coupling between single mode optical fiber and few micrometer size active area photodetectors.

Devices from blocks B, C, D, E and F are being tested in order to investigate to proceed with the study of the effect of the optical window size and shape on the devices performance.

**Epi-layer IQE#905675A characterization - RTD-PD sample #4, blocks A and B**

The epi-layer IQE#905675A, see Table 4.2, includes two 500 nm In\(_{0.53}\)Ga\(_{0.39}\)Al\(_{0.07}\)As light sensitive layers designed to have a bandgap wavelength below 1550 nm - this epi-layer was designed and growth previously to the project iBROW approval. Most of the useful area of sample #4 is occupied by RTD-PD oscillator circuits, but it includes two blocks of single RTD-PDs (devices surrounded by the green rectangle in the left top side of Fig. 4.17): devices A and B are 10x10 \(\mu\)m\(^2\) and 15x15 \(\mu\)m\(^2\), respectively. There are two sets of A devices (10x10 \(\mu\)m\(^2\)) regard less to optical window sizes and shapes: (i) rectangular windows with 3x8 \(\mu\)m\(^2\) (\(\kappa(3\times 8\mu m^2) \approx 0.46\)); and (ii) square windows of 6x6 \(\mu\)m\(^2\) (\(\kappa(6\times 6\mu m^2) \approx 0.7\)). All B devices (15x15 \(\mu\)m\(^2\)) have optical windows 5x10 \(\mu\)m\(^2\) (\(\kappa(5\times 10\mu m^2) \approx 0.8\)).

Figure 4.17 displays a partial view of the layout of sample #4 and a sample’s microphotograph. Figure 4.18 shows the optical window geometries employed and the devices I-V characteristics. Table 4.7 summarizes the devices main electrical characteristics.
Fig. 4.17: Partial view of sample #4 layout (RTD-PD wafers #905675A). The devices surrounded by the green line are single RTD-PD devices.

Fig. 4.18: Optical windows employed and devices I-V characteristics.

Table 4.7: Summary of main electrical characteristics of the sample #4 devices.

<table>
<thead>
<tr>
<th>Device size</th>
<th>Optical window</th>
<th>ΔV* (V)</th>
<th>ΔI* (mA)</th>
<th>Estimated Power (mW)</th>
<th>Gn (mS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 µm²</td>
<td>3x8 µm²</td>
<td>1.2</td>
<td>7.4</td>
<td>1.7</td>
<td>9.3</td>
</tr>
<tr>
<td>100 µm²</td>
<td>6x6 µm²</td>
<td>0.8</td>
<td>9.7</td>
<td>1.5</td>
<td>18.2</td>
</tr>
<tr>
<td>225 µm²</td>
<td>5x10 µm²</td>
<td>1.0</td>
<td>18.5</td>
<td>3.5</td>
<td>27.8</td>
</tr>
</tbody>
</table>

*: negative bias voltage

A large number of RTD-PD devices show very small response to optical light (low responsivity). The responsivity for non-modulated light is below 5 A/W. The highest measured responsivity values in the first PDC region were 0.6 A/W for 0.2 mW@1310 nm light modulated at 1 GHz. When compensated by the reflectance of the semiconductor material (0.31) and by the coupling efficiency ($\kappa(6\times6\,\mu m^2) = 0.7$), the expected responsivity would be as high as 1.24 A/W. In the second PDC region the responsivity reached values up to 0.2 A/W (0.41 A/W, when corrected as above).

RTD-PD devices of sample #4 (epi-layer #905675A) show lower responsivity when compared with devices of sample #3 (epi-layer #NC1800352). That can be (at least partially) due to the expected smaller light absorption coefficient of the In$_{0.53}$Ga$_{0.39}$Al$_{0.07}$As layers of #905675A wafer. The quality of the optical windows and some sort of contact shadowing can also contribute to lower the responsivity values obtained.
4.6. RTD-PD optoelectronic high frequency characterization

High frequency optoelectronic response characterization of RTD-PD mesa devices and RTD-PD oscillators is underway on wafer devices and oscillator circuits. Individual diced RTD-PD oscillator circuits designed to operate within the microwave and millimeter-wave bands are also ready to be characterized. The characterization includes DC bias frequency tunneling range, electrical and optical locking range, light induced switching times, spectral sensitivity and responsivity, and data transmission evaluation. The time domain characterization also includes eye diagram measurements.

By embedding data within the lightwave being injected into the RTD-PDs, data can be retrieved from the RTD-PD photo-generated response and shown in the form of eye diagrams. The preliminary characterization employed non-oscillating RTD device acting as photo-detectors, and data was successfully received at a data rate of 1 Gbit/s. The preliminary results also show the ability of optically modulate RTD oscillators.

The on-going high frequency characterization will allow identifying the equivalent circuit of the single RTD-PD including all parasitic elements, namely the series resistance and the RTD-PD intrinsic capacitance, which combined with the transit time analysis will allows to determine the optoelectronic transfer function (opto-electronic (O/E) conversion function) of the RTD-PD.

Up to 40 GHz the RTD-PD generated power is measured using a spectrum analyzer. For higher frequency measurement a power meter with sensor heads for V- and W-bands will be used. The frequency response of the RTD-PD modules for a range of optical power and for different values of the DC bias voltage will be determined. The characterizations will also give insights towards the heterostructure optimization, namely the effective absorption layer thickness and the device parasitic elements.

The characterization will also employ RTD-PD dies packaged in appropriate housing modules with fiber pigtail and output high frequency electrical connector.
5. RTD laser diode photonic interface

Generically, a high frequency fiber-communication transmitter comprises a driver circuit, a laser diode or a CW laser diode and an optical modulator (for operation at frequencies beyond the maximum bandwidth a laser diode can be directly modulated) that converts the electrical driving signals carrying the information into an intensity modulated lightwave. For operation up to the laser diode resonant frequency, novel alternatives to traditional laser diode transistor-based driver circuits have been proposed. The one being considered in the iBROW project is based on a hybrid integration of a RTD with a laser diode [5][6]. Because of its NDC, RTD circuits can act as voltage-controlled oscillators and switches, and low voltage digital-like signals can be able to switch a RTD between on (peak current) and off (valley current) states. In what follows we summarize the work done so far to implement RTD-LD based transceivers. We start by making some considerations related to the maximum bandwidth that a laser diode can be directly modulated. It follows a brief explanation of the LD implementation including design, fabrication, packaging and characterization. The latest results on the hybrid integration of RTDs with LDs are also discussed. Finally, we present the resonant tunnelling diode electro-absorption modulator (RTD-EAM) that can be an alternative for the implementation of electrical-to-optical transceiver operating beyond the laser diode direct modulation maximum bandwidth.

5.1. Laser diode direct modulation

Laser diode direct current modulation is a convenient highly effective way to achieve high-speed intensity modulation of lightwave carriers, and so current modulation is widely used in optical communication systems to transfer information from the electrical domain to the optical domain at Gbps. A detector at the receiving end converts the modulated light back into current, transferring the information from the optical domain back to the electrical domain.

Suppose the laser is biased with current $I_B > I_{th}$ (threshold current, the minimum current needed to achieve laser emission) and the corresponding output power is $P(I_B)$. The laser diode output power can be intensity modulated in a straightforward by superimposing a current signal (modulating signal) $s(t) = i(t)$ into the DC injected current $I_B$, Fig. 5.1,

$$I(t) = I_B + i(t) = I_B[1 + m\cos(\pi f_m t)]$$

and the optical output power becomes:

$$P(t) = P(I_B) + P(i(t)) = P(I_B)[1 + m\cos(\pi f_m t)]$$

where $m = \Delta I/(I_B - I_{th})$ represents the optical modulation index (or depth).

But how fast can the laser diode optical output be modulated?

For a given LD structure, the frequency response is flat in the low-frequency range reaching a peak at the vicinity of a characteristic frequency, known as laser relaxation oscillation frequency $f_R$ [20], decreasing steeply for frequencies higher than $f_R$. The relaxation oscillation frequency $f_R$ is a
characteristic of the LD that depends on the optical and electrical properties of semiconductor materials, on the geometrical parameters of the laser structure, and on the steady state operating conditions (injected DC current $I_B$). Because the relaxation oscillation frequency $f_R$ increases with the DC injected current, high bandwidth operation of laser diode based transceivers requires, in principle, a quiescent current well above the LD threshold current $I_{th}$.

Fig. 5.1: Schematic representation of direct modulation of a laser diode [19][20][27].

The maximum frequency at which the laser diode optical output power can be current modulated is called the 3-dB frequency $f_{3-dB}$, that corresponds to the frequency at which the optical power decreases from its value at zero frequency (or low frequency) by 3 dB (that is, the optical power decreases by a factor of $2$). The relaxation oscillation frequency $f_R$ sets therefore the scale for the maximum frequency at which a laser can be current modulated. Therefore, increasing the DC current will increase the frequency $f_{3-dB}$. However, as the current is increased at some point the relaxation oscillation peak disappears. If the current is increased beyond this point the frequency $f_{3-dB}$ decreases instead of increasing. The maximum value of the laser 3-dB frequency $f_{3-dB}$ is related to the inverse of the photon lifetime $\tau_p$ in the cavity [20][27]:

$$f_{3-dB}\mid_{\text{max}} = \frac{1}{\sqrt{2\pi}\tau_p}$$  \hspace{1cm} (5.3)

The inverse of photon lifetime sets the upper limit on the modulation speed of semiconductor laser diode. However, in most of the LD structures the laser current modulation response is determined by the LD equivalent circuit parasitics: a resistor (representing the resistance of the top quasi-neutral region and the top contact) and the capacitance between the top metal contact and the substrate. At high frequencies, the capacitance between the top metal contact and the substrate can short out the active region and decrease the laser current modulation response. Therefore, careful attention must be paid to circuit parasitics when optimizing laser diodes for high speed operation. Since a typical Fabry-Perot laser has a multimode lasing behavior (the number of lasing modes can be as high as few tens) which can be disadvantageous in high-speed optical communications, it is important to employ FP laser structures that support few lasing modes or adopt single mode laser structures such as distributed feedback (DFB) lasers.
Generally speaking, well design laser diodes based transmitter can employ directly current modulation up to the laser diode relaxation frequency, which for well-designed Fabry-Pérot laser diode structures can be higher than 10 GHz.

Although, there are further advanced laser diode structures that can reach higher speed operation than FP LDs, they are more difficult to implement leading to higher cost solutions. Such LD structures include [28]: buried heterostructure lasers with regrown reversed biased junctions that can reach 10-15 GHz; polyimide planarized laser structures which can overcome 15 GHz; semi-insulating InP based mushroom configurations that can go up to 25 GHz; and co-planar strip line laser with mushroom structures which are capable to achieve 30 GHz.

5.2. Laser diode design, fabrication and packaging

The iBROW uplink mm-wave/optical transponder will employ laser diodes (LDs) with the capacity to transmit up to 10 Gbps data. Both Fabry-Pérot (FP) lasers operating at 1310 nm and 1550 nm, and distributed feedback (DFB) lasers operating at 1310 nm are being object of investigation. It is expected that DFB lasers would show improved wavelength and modulation bandwidth performances without needing complex cooling.

Fabry-Pérot laser are easy to fabricate and can be directly modulated at high data rates (specific configurations can go higher than 10 Gbps) with wavelength dispersion tolerable for short-range optical-fiber links. The active volume of the lasers being considered is formed by a stack of strained InGaAlAs-InP quantum wells. Specifically, the laser hetero-structures are grown using the metalorganic vapor phase epitaxy technique and the epi-layer is formed by several controlled growth sections [29]: a highly p-doped (Zn) GaInAs electrode; an InP p-doped cladding structure; an AlGaInAs p-doped (Zn) transition layer; an active region consisting of tensely strained AlGaInAs quantum barriers and compressively strained AlGaInAs quantum wells; AlGaInAs n-doped (Si) transition layers; and the semi-conductor n-doped (Si) InP substrate. The total thickness of the p-electrode and cladding layer is approximately 1.8 µm. The total thickness of the un-doped active region is 145 nm.

The number and thickness of quantum wells and barriers has been optimized to increase the differential gain of the laser, while taking account carrier transport across the separate confinement heterostructures, which effectively reduce the differential gain and effectively increase the differential carrier lifetime. To achieve high speed operation the optical confinement factor provided by the active layers, which is obtained by the use of a high number of quantum wells, was maximized. The development of an optimized epitaxial structure is still an on-going process.

The FP LDs used in this work consist of ridge waveguides processed to produce single laser diode dies that are 200 µm long and 100 µm wide [29]. The ridge forms a waveguide that confines the laser generated light between the claddings maximizing the light field overlap with the strained MQW AlGaInAs active layers. The nominal ridge width used in this study is 2 µm. A gold metallization pattern covers the ridge and forms the p-electrode that allows achieving pumping and laser action using an electrical injection current. The n-electrode is formed with a backside metallization, which forms an electrical contact with the n-doped InP substrate. An etched trench on each side of the ridge allows electrical isolation of the p-electrode contact from the rest of the die surface. Each facet of the ridge can be coated with either anti-reflective or highly reflective (HR) layers that allow control of lasing action parameters such as the current threshold, the wavelength and the optical power output of the
device. For most of the measurements described in this report, the lasers light output was coupled to a lensed fibre aligned to one of the ridge waveguide facets.

In order to be able to separate the many laser diode chips on the processed wafer samples, the wafers/samples are first backside polished to reduce their thickness, making possible cleaving them along crystal planes creating laser diode bars. Each bar contains an array of several chips. The bars are then prepared for precision facet coatings. The coated bars are then diced becoming ready for subsequent testing and packaging. The process of packaging begins with die bonding on an AlN ceramic high frequency sub-mounts, Fig. 5.2. The sub-mounts are designed for efficient heat removal and the thermal expansion coefficient matches to the laser diode material. After the die bonding electrical contact is made to the chip by bonding gold wires from the chip bonding pads to sub-mount bond pads. The sub-mount design should lead to a configuration that minimizes the parasitic effects due to wire bond and layout interconnections. Moreover, minimizing the wire bond lengths helps to prevent signal distortion which can degrade the multi-Gbps signals.

![Fig. 5.2: Laser chip on AlN sub-mount design used for high speed characterization.](image)

The sub-mounts are then placed inside the high frequency butterfly packages being considered, Fig. 5.3. These packages can incorporate transfer lens arrangements (such as aspherical or ball lens) to efficiently couple light from the laser diode chip to the optical fiber. Since the semiconductor devices can be particularly sensitive to humidity and environmental changes, hermetic sealing in an inert atmosphere (such as dry-nitrogen) is being considered for long-term stability and reliability. The LD/RTD-LD transponder expected storage temperature range is from -50 °C to 100 °C, and the working temperature is between -20 °C and 70 °C. However, at the prototyping stages the hermetic sealing is not mandatory.

The packaging configurations to be used to control the operation conditions of the iBROW transponder components are being developed by Optocap. Figure 5.3 shows from the left to the right a generic blueprint of the package, two assembled laser packages for the cases where the lasers are wire bonded directly to the input RF signal transmission line or wire bonded after a thin film resistor (for matching impedance) placed in series with the input RF signal transmission line, and last a microphotograph showing the LD sub-mount placed inside the package.
5.3. Laser diodes characterization

The laser high speed operation was first investigated utilising industrial standard 10G drivers. The laser diodes are being biased with a DC current between 30 mA to 60 mA, which for an 11 ohm load its equivalent to power consumption between 40 mW and 90 mW. The expected maximum driving current (as high as the biasing current) is 85 mAp-p at 10 GHz. The optical output power from the lasers at an operation current of 40 mA (the estimated average bias quiescent point) can reach up to 15 mW (both at 1550 nm and at 1310 nm). The beam far field full width at half maximum (FWHM) divergence angles for the 1310 nm laser are 23° for the “slow axis” and 40° for the “fast axis; for the 1550 nm laser the slow and fast axis divergence angles are 24° and 30°, respectively.

The laser diodes have been object of a detailed characterization and evaluation by CST, INESC and UGLA. The results show that error-free optical data transmission can be achieved at the data rate of 10 Gbps, Fig. 5.4.

Several activities are on-going towards the realization of optimized solutions to achieve improved LDs and RTDs, and to the assembly and characterisation of butterfly package RTD-LD components, in order to be able to delivery qualified components for both laboratory and demonstration test-beds.
5.4. RTD hybrid integration with a laser diode

Few attempts to monolithic integrate a DBQW-RTD with laser diodes have been described in the literature. The most relevant efforts targeted the incorporation of DBQW structures in AlGaAs/GaAs and on InGaAs/InGaAlAs laser diode epi-layers [5]. The latter [10] aimed the monolithic integration of a DBQW-RTD with an optical communication laser operating at 1550 nm, with the device consisting of a vertical integration of a DBQW on an InGaAs/InGaAlAs multiple quantum well laser structure. In principle, such integration is straightforward as the DBQW section requires only the growth of four to six extra epilayers on the n-type region of the laser junction. A detailed description of a device structure and fabrication can be found in [10]. The RTD-LD current-voltage characteristic emulates the RTD non-linear I–V curve, hysteresis and bistability. Although operating at low temperature, the results demonstrated the feasibility of monolithically integrated RTDs with LDs.

However, the realization of monolithic RTD-LD structures capable of operating at room temperature is more difficult than initially expected [10]. As consequence, the efforts were concentrated on the development of hybrid integrated circuit (HIC) approaches based on the integration of DBQW-RTDs with commercial prototype laser diodes mounted on high frequency sub-mounts. In what follows we describe shortly the recent developments on RTD-LD hybrid integrated circuit (HIC) approaches for operation in the 1300 nm and 1550 nm optical communication windows.

Hybrid RTD-LDs are easy to implement and allow studying the behaviour of both components separately [30]. In such implementations, the RTD die can be either bonded on or outside the LD sub-mounts. In the implementation bonded on the LD sub-mounts the RTD is connected to the LD circuitry through bonding wire, as schematically represented in Fig. 5.5. We have also integrated RTD-PDs with laser diodes, Fig 5.5 and Fig. 5.6, to implement a light and voltage controlled optoelectronic oscillator circuits, as shown in Fig 5.7.

![Fig. 5.5: Examples of hybrid integration of RTDs with laser diodes.](image-url)

As displayed in Figs. 5.5 and 5.6, the RTDs/RTD-PDs were mounted on or close to the LD sub-mounts with the collector contacts being wire-bonded to a 50 Ω copper microstrip transmission line (coupled to a SMA connector) laminated onto the non-conductive PCB substrate and the emitter wire-bonded to the signal pad of the laser diode sub-mount. The DC bias and RF signals were applied via a wideband bias-tee through a resister-capacitor shunt attached as close as possible to the RTD(-PD)-
LD components. The shunt input port was designed to reduce the spurious oscillations acting as a short circuit for the RF signals generated by the RTD(-PD)-LD.

Fig. 5.7: Hybrid RTD-PD-LD circuit implementation and the “package” used for the experimental evaluation.

Adding a laser diode to the RTD circuit does not change the basic shape of the RTD’s nonlinear I-V characteristic. Typically, it just shifts the peak and valley regions to higher voltages (a shift corresponding to the voltage drop across the laser p–n junction), while the current values are left almost unchanged, see Fig. 5.7(d). [Figure 5.7 shows the schematic of an optoelectronic oscillator comprising a RTD-PD, a laser diode (LD) that is driven by the RTD-PD.] Therefore, if the LD series resistance is small, the nonlinearity of the RTD is preserved in the laser output and the RTD provides a dynamical bias control for the laser diode. In such configuration the RTD can reduce significantly the laser driving circuits’ complexity by taking advantage of its high nonlinear current-voltage (I-V) characteristic, with the NDC region providing electrical gain to the laser diode driving circuit. Then it is possible to operate the RTD-LD as an autonomous voltage controlled optoelectronic oscillator (VC-OEO), with the operating frequency determined by the DC bias voltage. Taking advantage of the resonant tunnelling diode photo-detector (RTD-PD) functionality, high frequency electronic and optoelectronic circuits controlled by both electrical and optical signals are implemented, Fig. 5.7(a). Because RTD bistability the RTD-LD optical output is also be bistable which can be of particularly convenience for non-return to zero (NZR) digital modulation [13].

Fig. 5.7: (a) Schematic representation of RTD-PD-LD integration; (b) Equivalent electric circuit. (c) Diagram of the RTD-PD-LD optoelectronic circuit and characterization set-up; (d) I-V curves of the individual components [12].
As mentioned above, taking advantage of the RTD-PD light response, high functionality, high frequency electronic and optoelectronic circuits capable to be controlled by both electrical and optical signals can be implemented. Figure 5.8 shows the diagrams of single and dual loop optoelectronic oscillators (OEOs) with optical fiber delayed feedback comprising an RTD-PD, a LD and optical fiber delay lines with both optical and electrical input and output ports. The laser optical output (optical output port) was coupled to a lensed fibre connected to the optical fiber loop used to couple a fraction of the light produced by the LD back into the RTD-PD.

These RTD-PD based optoelectronic oscillators, with optical fiber delayed feedback paths in a ring configuration, can produce stable and low-phase noise microwave signals with attractive applications in microwave-photonic systems. The lasers employed were ridge waveguide commercial prototype devices supplied in high frequency sub-mounts by Compound Semiconductor Technologies Global Ltd (CST) designed for emission at around 1550 nm with a bandwidth of 10 GHz and a threshold current $I_{th}$ around 6 mA, which is slightly inferior to used RTD-PDs valley current $I_v$. When DC biased in the NDR region, the LDs work well above the threshold current. Figure 5.9 shows optical output of the RTD-OEO single and dual loop configuration operating at around 1.1211 GHz, showing a clear reduction of spurious oscillations in the dual loop configuration (side mode suppression ratio of 60 dB) with a considerable phase-noise reduction.
We are working towards the improvement of RTD-LD hybrid circuits to make them capable of operating at modulation rates, well above 10 Gbit/s: the oscillation frequency goes up by solving the instabilities associated to the DC bias circuitry, making possible the RTD-LD operation as an autonomous voltage controlled optoelectronic relaxation oscillators in the 10 GHZ-range. The investigation will also explore its operation in the injection mode based on the injection of low power periodic and phase modulated electrical and optical signals. These oscillators can find many applications such as in generation of random numbers, novel spread spectrum, ultra-wide bandwidth, and optical communication schemes.

Using similar RTD-PD-LD circuits we have implemented optoelectronic oscillators with the RTD-PD set in an excitable regime and used to driving the on-chip laser diode (LD), as shown in Fig. 5.10. The RTD-PD electrical response to external perturbations drives the laser diode such that pulses in the RTD-PD current lead to the production of optical pulses by the LD. The RTD-PD provides a non-monotonic current-voltage (I-V) curve with a region of negative differential conductance which allows it behaving as an excitable system [11].

![Fig. 5.10: (a) Schematic of the RTD-PD and LD chips forming the RTD-LD excitable optoelectronic device. Inset is the cross-section showing the epi-layer structure of the RTD. (b) Experimental I-V characteristics of LD, RTD-LD, and I-V model fit. (c) Equivalent electrical model of the RTD-LD circuit. (d) Excitable pulses in both the electrical and the optical RTD-LD outputs triggered by either a square or a pulse input signals at $V_{dc} = 2.9$ V [11].](image)

The circuit works as follows. When the RTD-PD is biased in the first positive differential conductance (PDC) region slightly below the peak, it responds to weak external perturbations by emitting excitable pulses in both electrical and optical outputs when the perturbation exceeds a given threshold. We observed spiking behavior with identical shape and intensity triggered by either a square input signal or a train of pulses with amplitude levels, $V_{in}$, ranging from 100 mV to 450 mV, and pulse widths, $W$. 

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from 100 ns to 200 ns, Fig. 5.10(d). The period of the injected signals was kept well above the circuit lethargic time value. The time traces of Fig. 5.10(d)(top) show upward electrical spikes of identical shape with typical full width half maximum (FWHM) values of 13 ns triggered due to RTD-LD transitions from the peak-to-valley regions. The downward electrical pulses correspond to the valley-to-peak transitions before the RTD-LD system returns to its quiescent point. The LD intensity output, Fig. 5.10(d)(bottom), follows the electrical current switching induced by the RTD-LD with a sequence of downward pulses of identical shape and typical FWHM of √200 ns. If operated in the second PDC region, the direction of the electro-optical pulses would be reversed. We verified the existence of a critical threshold below which there is no response. The estimated critical value of the perturbation is 9 V ns when d.c. biased at 2.9 V, e.g. a 100 ns square whose plateau is 90 mV.

Using the above hybrid device we implemented an RTD-PD-LD optoelectronic oscillator that can operate as regenerative memories if an optical delay line (propagation loop) is included in the circuit to re-injected part of the laser output into the RTD and provide the temporal buffer memory that store the bits of information as light intensity pulses. Figure 5.11 shows the schematic of the RTD-PD-LD time-delayed neuromorphic photonic resonator in which the optical output is re-injected after a time delay due to the propagation into an optical fiber [9].

The electrical and optical excitable response of these RTD(-PDs) ensures the regeneration and the rectification of the signal as a special nonlinear node along the propagation loop. The erbium doped fiber amplifier (EDFA) was inserted in the loop to control the amount of feedback coupling and compensate weak optical response of the RTD as a photodetector and the losses associated to the coupling and decoupling of light from the RTD-PD and LD dies, respectively. We believe the use of an RTD-PD with intentional light absorption layer(s) will eliminate the need of the EDFA. The photonic circuits works as follows: Initially the bits of information corresponding to electrical pulses are injected into the circuit electrical input port, inducing RTD-PD switching which makes the laser to produces light pulses that mimic the electrical pulses. The light pulses re-injected into the RTD-PD triggers after the round-trip in the fiber a new electrical response, thereby repeating the cycle with a period close to the optical pulse propagation time in the fiber.
Although the present proof-of-concept photonic memory operates in the Mb/s range, lethargic times at tens of ps can be achieved by reducing the parasitics of the hybrid integrated circuit. This will dramatically increase the attainable bit rate up to Gb/s as predicted by the simulations, paving the way for a new class of high-speed neural-inspired photonic memories.

The RTD-PD high-speed excitable response capability makes possible to foresee promising applications in photonics – for more details see, e.g., [9]. The preliminary results demonstrate the RTD-PD-LD optoelectronic oscillator is capable of generating electrical and optical pulses at telecommunication wavelengths (1550 nm), Fig. 5.10(d). The RTD-PD transitions provide a dynamical bias current control for the laser diode conferring to this optoelectronic circuit configuration the necessary conditions to operate as an excitable system with high speed response and quadruple electronic and optical input/output functionalities. It is worth mentioning that this setup can be transposed and adapted to other types of semiconductor laser devices and systems like e.g. VCSELs or mode-locked devices.

The RTD-PD-LD operation in the “excitable” mode has potential to work as an efficient optical-to-mm-wave/THz transceiver for ultra-broadband wireless communications seamlessly integrated with high-speed fibre-optic networks. For the RTD-(PD)-LD operation as a transmitter/receiver, the magnitude of the DC bias and the amplitude AC modulation voltages need to be carefully adjusted so that the RTD quiescent point moves to the NDC region or switches to the valley region.

5.5. Alternative laser diode RTD based driving circuit configurations

In the RTD-LD arrangement discussed above, the LD is connected in series with the RTD. In this configuration the DC current flowing through the RTD also flows through the laser diode, the RTD I-V is shifted to higher voltage due to laser diode resistance. The RTD I-V characteristic determines the laser diode quiescent point current range, which imposes some constrains to the RTD I-V parameters such as the peak and valley current allows values. To minimize distortion, for example, it is recommended that the RTD peak current it is approximately 2/3 of the laser diode maximum allowed bias current and the valley current stays above the laser diode threshold current.

Other configurations are being considered which comprehends separate DC biasing circuits for the RTD and for the LD, with only the RF component of the current generated by the RTD being used to drive the laser diode. A possible configuration that makes the LD quiescent operation point independent of the RTD I-V characteristic is represented schematically in Fig. 5.12. The RTD and LD DC circuits are autonomous, with the RTD and LD being AC coupled, that is, a part of the RTD generated AC drives the LD.
Fig. 5.12: Schematic representation configuration of a RTD-LD implementation that makes the LD quiescent operation point independent of the RTD I-V characteristic, where both devices use different DC biasing circuitry [16].

5.6. RTD electro-absorption modulator

So, for RTD based mm-wave/THz-to-optical transponder (electrical-to-optical converter) operating at beyond the modulation bandwidth of the LD being considered in the iBROW project, a low power configuration integrating an optical modulator such as the RTD-EAM [5][8] can be considered.

In previous work, we investigated the optoelectronic properties of semiconductor optical waveguide incorporating a DBQW in the waveguide core, aiming the implementation of novel optical modulators and photodetectors with new functionalities due to the non-linear and high speed and wide bandwidth properties of DBQW-RTDs. The structure, known as RTD optical waveguide (RTD-OW), was first implemented in GaAs/AlGaAs material system to operate at 900 nm, and then using the InP/InAlGaAs material systems to operate at 1550 nm (see e.g. [8]). The AlGaAs/GaAs material system is able of absorbing/detecting light signals of wavelengths ranging from 600 nm to 900 nm. This range covers the 850 nm fiber optic communications wavelength window. The InGaAlAs quaternary compound is able of absorbing/detecting light signals of wavelengths ranging from 700 nm to 1650 nm. This range covers all the wavelengths of interest nowadays in fiber optic communications: 850 nm, 1300 nm, and 1550 nm.

Figure 5.13 shows schematically the InGaAlAs/InP RTD optical waveguide conduction band profile and the I-V of a RTD-OW with a 6 nm InGaAs quantum well and 2 nm AlAs barriers DBQW, two InGaAs layers 500 nm thick each side of the DBQW, forming the waveguide core, and two InAlAs cladding layers to allow light confinement along the direction of the DBQW plane.

The RTD electro-absorption modulator (RTD-EAM) operates at a wavelength slightly higher than the waveguide core material band-gap, Fig. 5.14. The electro-absorption modulation is a consequence of the Franz-Keldysh effect that leads to an increase of the semiconductor absorption coefficient for light with energy slightly smaller than the core band-gap energy due to the built-in electric field enhancement when the RTD operation point switches from the peak to the valley region, Fig. 5.14(b): the RTD switching leads to an enhancement of the electric field across the collector region (since there is an increase in the applied voltage with a simultaneously reduction of the current) that leads to the rise of the absorption coefficient. The electric field switching speed is determined by the RTD bandwidth.
FIG. 5.14: Schematically representation of the InGaAlAs/InP RTD-EAM principle of operation indicating the change in the waveguide light transmission.

The RTD-OW die and the packaging for electrical and optoelectronic characterizations is schematically represented in Fig. 5.15.

FIG. 5.15: RTD-OW die and packaging for electrical and optoelectronic characterization.

In both cases the main objective of the work was to demonstrate that RTD optical waveguides could operate as electro-absorption modulators with on/off driving voltages as low as few hundred of millivolt. Electro-absorption modulation due to relaxation oscillation operation up to 14 GHz with modulation depth up to 18 dB was demonstrated with AlGaAs/GaAs devices. The initial results with InGaAlAs/InP devices showed direct electro-absorption modulation up to 26 GHz at 1550 nm with modulation depth higher than 10 dB for RF driving power around 7.7 dBm. Moreover, some devices showed 5 dB changes in the light transmission for bias voltage increments as low as 1 mV [5].
6. RTD, RTD-photodetector, laser diode (LD) and RTD-LD modelling

The iBROW wireless-to-optical and optical-to-wireless transceivers will be based on the integration of RTDs with laser diodes (RTD-LD) and on the use of unipolar photodetectors incorporating DBQW structure, respectively. The objective is to implement very simple, low cost and energy efficient photonics interfaces for ultra-broadband terminal base stations based on hybrid fibre-wireless systems, aiming to demonstrate at least 10 Gbps wireless communications employing simple modulation formats, seamlessly interfaced to fibre optic networks.

The experimental activities are realized in parallel with the development of computational models of RTDs, RTD-LDs and RTD-PDs devices and associated circuits which are suitable for system level and link level simulations towards the study and evaluation of ultra-broadband RTD-based communication architectures, including the study of the impact of RTD based RF-to-optical and optical-to-RF transceiver impairments on the systems performance.

As mentioned before, RTDs can be monolithically integrated on the same chip with conventional electronic and photonic devices, e.g. transistors, optical waveguides, photodetectors and laser diodes, with potential to provide low cost single chip solutions, including reduced power consumption and increased functionality, speed and circuit reliability, without losing any advantage of using optical devices. However, although monolithic RTD-LDs are expected to show many advantages, unforeseen effects in the monolithic devices related to the material growth (e.g. lattice mismatch leading to defects or incorrect doping levels), particularly in the case of LDs, can compromise their expected performance. Therefore, considering the uplink data rates up to 10 Gbps, we anticipated that the implementation of hybrid versions of the microwave-to-optical RTD-LD based transceivers will provide higher flexibility allowing an extensive study of circuits’ performance, assuming a compromise between high-speed operation restrictions due to packaging, and great flexibility in the implementation and testing. Therefore, the wireless-optical transceiver discussed here employs a hybrid RTD-LD configuration where the RTD circuit operates as a high-frequency driver replacing the currently based-transistor laser diode driving and signal amplifying circuits.

The RTD-LD configurations under investigation take in consideration both the RTD and the LD nonlinear dynamic behaviours using in the case of RTDs the Liénard oscillator approach and for the LD the rate equations for the carrier and photon densities. The simulation packages under development benefit from the experimental characterization of RTD devices and circuits, of laser diodes and RTD-PD circuits being realized throughout the project. The extraction of several physical parameters from the experimental data is used to validate the above mentioned numerical models and evaluate the performance of the simulation tools.

Next we present the working towards the development of the RTD-PD and RTD-LD circuit simulation packages. The discussion below is an extended version of section 5 of the Deliverable 4.1 - First report on system-level simulations.

6.1. RTD I-V curve modelling

The resonant tunnelling diodes (RTDs) object of study within the iBROW framework consists of a double barrier quantum well (DBQW), realized with an indium gallium arsenide (InxGa(1-x)As) layer few nanometre wide sandwiched between two aluminium arsenide (AlAs) nanometre thick layers, with adjacent undoped or moderately doped layers followed by highly doped InGaAs thick layer each side.
of the DBQW where the electrical contacts are applied. Due to the embedded double-barrier quantum well there are only certain energy levels (resonant levels) for which the electrons have high probability to tunnel through the structure that leads to N-shape current-voltage characteristics exhibiting regions of high non-linear negative differential conductance (NDC) surrounded by regions of positive differential conductance (PDC). Since the RTDs are nanometre size and very compact, they are capable of ultra-high-speed operation because the quantum tunnelling effect through the double barrier quantum well is a very fast process and the electrons transit time through the remaining nanometre size layers can be quite small. One of the most relevant active areas of research is the implementation of ultra-high frequency oscillators and switching devices that can operate at terahertz frequencies.

The RTD inherent high speed operation, up to terahertz frequency, the pronounced N-shape non-linear current-voltage (I-V) characteristic, the wide-bandwidth negative differential conductance (NDC), the structural simplicity, the flexible design, the relative ease of fabrication, and the versatile circuit functionality, make them excellent candidates for nanoelectronic circuit applications. In order to take advantage of the full potential of RTD devices several attempts have been made to incorporate the full RTD characteristics into circuit simulators such as SPICE-like and ADS CAD tools [31]. Being able to simulating a circuit’s behaviour before its implementation can lead to a great overall cost reduction in particular for monolithic micro-wave/mm-wave integrated circuits because it can greatly improve design efficiency and provide insight into the expected functionalities.

Since a quantum mechanics based model that includes all the RTD features is not yet available, a number of empirical models have been advanced. Most models describe the RTD by small-signal equivalent circuits consisting of a voltage dependent capacitance $C(V)$, resulting from charging and discharging of electrons at the DBQW and depletion regions, in parallel with a voltage depend current source $I = F(V)$, together with a series resistance $R$, arising mainly from the ohmic contacts, and an inductance $L$ due to connections (wiring, wire bonding and transmission lines) [5][6]. The voltage dependent current source $F(V)$ can be implemented as polynomial or piecewise functions. However, this is not completely satisfactory if a detailed circuit description of the circuit is needed.

A useful RTD non-linear I-V characteristic representation has to consider a wide variety of device structures and materials available, i.e., a proper modelling of the I-V characteristics has to be based as much as possible on the RTD physical parameters such as material properties, DBQW energy levels, dopant concentration across the structure, and device geometry. Significant efforts have been devoted to the development of relatively simple analytic RTD models sufficiently accurate to closely relate essential RTD physical parameters with measured I-V characteristics capable to be directly called from device/circuit simulators such as SPICE-like tools.

iBROW addresses this problem by revising the most preeminent physics-based RTD current-voltage characteristic numerical representations. Based on previous experience we are adopting the physics-based RTD current-voltage equation proposed by Schulman et al. [32]. They derived a mathematical function that provides a satisfactory fitting of the I-V shape characteristic of the InGaAs and GaAs RTD based devices. The $I = F(V)$ mathematical function contains physical quantities that can also be treated as empirical parameters for fitting purposes. In their analysis the resonant tunnelling current density is expressed within the effective mass approximation [20], which includes nonzero temperature, Fermi-Dirac statistics and the charge carrier transmission coefficient $T(E, V)$ through the DBQW [32]:

$$I = F(V)$$
where \( E = E_r - qV/2 \) is the energy measured up from the emitter conduction band edge, \( E_r \) is the energy of the resonant level relative to the bottom of the well at its centre, and \( \Delta E_r \) is the resonance width. The parameters \( q \) and \( k_B \) are the unit electric charge and the Boltzmann constant, respectively.

Equation (6.1) can be rewritten as:

\[
J_{RT}(V) = A\ln\left(1 + \frac{\sqrt{B-C+n_tV}}{1 + e^{\frac{B-C+n_tV}{k_BT}}}\right) \times \frac{\pi}{2} + \tan^{-1}\left[\frac{C-n_tV}{D}\right]
\]  

(6.2)

where the parameters \( A, B, C, \) and \( D \), and \( n_t \) can be used to shape the curve to match the positive differential portions of the measured I-V characteristic, having at the same time a well-defined physical interpretation: \( A \) and \( B \) are related, among other factors, with energy resonance width \( \Delta E_r \) and Fermi level energies, and allow to adjust RTD peak current; \( C \) and \( n_t \) determine essentially the RTD peak voltage, correlated with the energy of the resonant level relative to the bottom of the well and with the transmission coefficient; finally, \( D \) is related with the resonance width \( \Delta E_r \), allowing to adjust the peak to valley current ratio (PVCR) and the peak to valley voltage ratio (PVVR).

Equation (6.2) gives good estimations of the peak current and the NDC region of current-voltage characteristic. In order to represent the increasing valley current due to tunnelling through higher resonances or thermal excitation over the barriers and other leakage current effects, an additional current density component, identical to the classical diode current, the non-resonant term \( J_{NR}(V) \), have to be included:

\[
J_{NR}(V) = \frac{q}{2\pi} \ln\left(1 + e^{\frac{C-n_tV}{k_BT}}\right)
\]

(6.3)

The final form of the RTD current-voltage (I-V) curve is then given by:

\[
I(V) = I_{RT}(V) + I_{NR}(V) = M[J_{RT}(V) + J_{NR}(V)]
\]

(6.4)

where the multiplying factor \( M \) is used to scale Equation (6.4) in order to take into account the devices area. The analytic expression \( I = F(V) \) given by Eq. (6.4) when fitted to the experimental RTD I-V characteristic is integrated in the circuit models that represent RTD circuits. Though it
comprises six independent parameters related to DBQW-RTD physical structure, the fitting procedures we have implemented are quite simple and not much time consuming.

A MATLAB package capable of obtaining quite satisfactory I-V fittings with reduced intervention of the operator was developed. Figure 6.1 shows a summary of the sequential operation of the MATLAB RTD I-V autofitprogram developed package. Figure 6.1(a) displays the autofitprogram starting window; (b) represents the loaded experimental I-V considered for the fitting; (c) shows the “Auto Fit” option; (d) illustrates the possibility to fine adjust each of the physical related parameters to obtain the fitting that best suits the operator request; and finally, as shown in Fig. 6.1(e), it is possible to save the final fitting parameters (Variable.txt, saved in the working folder) and obtain a plot showing the experimental and the fitting curve that can then be copied and exported.
Fig. 6.1: Sequential operation of the MATLAB RTD I-V autofitprogram package.

The electronic circuits incorporating RTD devices are, in general, represented by their lumped-element versions, where, as mentioned previously, the RTD is usually modelled as a voltage dependent capacitor $C(V)$ in parallel with a voltage dependent current source $I = F(V)$; the capacitance $C(V)$ results from the DBQW and the depletion region that is created across the collector region adjacent to the DBQW. So, the analysis methodology of an RTD circuit starts with the determination of the six independent parameters that leads to the fitting curve $I = F(V)$ of the experimental RTD I-V, and with the estimation of the device capacitance, together with equivalent resistance, capacitance and inductance of associated the circuitry. For the frequencies in consideration (up to 300 GHz), the lumped elements represent also other non-ideal intrinsic aspects of the device, such as device and contact resistances, inductance and capacitance, arising mainly from the ohmic contacts and the remaining electrical circuitry. In the case of MMIC RTD oscillator circuits the inductance represents also the effect of the coplanar waveguide (CPW) transmission lines, which in the case of the circuits being implemented (up to 300 GHz) are quite short (a few micron).

Current electronic circuit simulators, such as SPICE\(^2\), can use the above analytic fitting function $I = F(V)$ to simulate circuits incorporating DBQW-RTD structures. We have simulated several RTD circuits using the PSPice\(^3\) software package to verify if the fitting curves were a good representation of the experimental RTD I-Vs. The results show that the fitting curves given by the autofitprogram were able to mimic quite well the experimental I-Vs since the simulated circuits show identical behaviour to that of the experimental circuits. As an example, the PSPice code shown in Fig. 6.2 corresponds to an RTD oscillator operating at around 300 GHz – the circuit configuration is identical to circuits developed by UGLA within iBROW and considers an RTD with an area of 18 µm\(^2\) and a capacitance of 72 fF, where the CPW line was equivalent to an inductance of 3.8 pH. Within the iBROW consortium, UGLA and NOKIA are also using the Advanced Design System (ADS), an electronic design automation software system developed by Keysight EEs of EDA, for circuit simulation.

Besides the use of the Schulman et al. physics-based RTD current-voltage equation, we have also investigated the representation of the NDC region of the experimental I-V by the Van der Pol cubic approximation, $I = F(V) = bV^3 - aV$ where $a$ and $b$ are positive parameters, where the point $V=0$ V corresponds to the middle of the NDC region \[21\]. The voltage dependent current source $I = F(V) = bV^3 - aV$ only represents the I-V characteristic in the NDC and in the valley and the peak neighbouring regions \[22\]. Contrary to the Schulman representation that can be used for the large and small signal analysis (that is throughout the full I-V characteristic), the Van der Pol cubic approximation is only appropriate for the small signal analysis. Other analytic and numerical representations of the RTD I-V are also being object of study in order to determine its range of applicability \[33\].

\(^2\) SPICE is an acronym for Simulation Program with Integrated Circuit Emphasis.

\(^3\) PSPICE is an acronym for Personal Simulation Program with Integrated Circuit Emphasis.
6.2. RTD-PD light response modelling

Light absorption induces a NDC shift to lower voltage and a current increase, dependent on the optical power levels being absorbed. Moreover, due to the internal electrical field dependence the device responsivity (the ratio of the photocurrent generated by the optical power absorbed) is a function of the bias voltage. The results show clearly a higher responsivity close to the peak region.

Double barrier quantum well RTD based photo-detectors are also very interesting alternatives for single photon detection when compared with traditional approaches such as avalanche photo-detectors due to the built-in electrical gain arising from highly non-linear current-voltage (I-V) characteristic which shows at least a region of negative differential conductance (NDC). Moreover, under bias the generated photo-excited electron-hole pairs modulate the internal electric field across the DBQW, which can lead to RTD-PDs with responsivities higher than $10^3$ A/W [14]. By taking advantage of these effects, RTD-PD structures can be used to implement light-by-light switching and optically switched RTD photo-detectors. Early demonstrations of such optically switched devices have shown potential for high-speed transmission communications at Gb/s rates with very low electrical power dissipation [13-15]. Demonstration of single photon detectors were also achieved combining DBQW-RTDs and quantum dot structures [34].

The injection of light into the RTD-PD mesa gives rise to a global shift of its I-V characteristic as a consequence of the built-in electrical field enhancement close to the collector barrier mainly due to the accumulation of light-generated holes in the collector absorption layer. Figure 6.3 shows the schematic diagram of an RTD-PD mesa with an epi-layer identical to the RTD-OWPD object of discussion in the next section; also shown are the current-voltage characteristics under dark and illuminated conditions, showing the light absorption leads to a global shift of the I-V to lower voltage, and the responsivity of the devices as function of the applied voltage. The light induced RTD-PD peak to valley switching gives rise to a current change equivalent to the peak-to-valley current difference which can lead to absolute responsivities of tens of A/W.

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Fig. 6.2: PSPice implementation of an RTD circuit that mimics the circuits presented in [EW].

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Because of the interest in applying RTDs for optical modulation, optical switching and photo-detection, there is a demand for RTD optoelectronic models that describe its response under light excitation. In order to fully represent the I-V characteristic of RTD-PD under illumination, and to be able to model the optical response of the RTD-PD structure we are currently investigating a physics-based RTD current-voltage equation that takes into consideration the RTD-PD light absorption effects [35]. We extended the physics-based model of Schulman et al. to include the effect of illumination, namely the photoconductive and charge accumulation effects close to the DBQW, which are materialised through the introduction of two new terms in the Schulman et al. physics-based model, equation (6.1). The proposed physics-based model of RTD I-V under illumination becomes [35]:

\[
J(V, L) = A \ln \left( \frac{1 + e^{\frac{q}{k_B T} \left( \frac{B-C+n_1(V+V_{pc}+V_{ph})}{k_B T} \right)}}{1 + e^{\frac{q}{k_B T} \left( \frac{B-C-n_1(V+V_{pc}+V_{ph})}{k_B T} \right)}} \right) \frac{\pi}{2} + \tan^{-1} \left( \frac{C-n_1(V+V_{pc}+V_{ph})}{D} \right) + H \left( \frac{(V+V_{pc}+V_{ph})}{k_B T} \right) - 1, \tag{6.5}
\]

where \( V_{ph} \) is the photo-induced voltage shift due to the charge accumulation effect; and \( V_{pc} \) accounts for the photoconductive effect. The quantities \( q \) and \( k_B \) are the unit electric charge and the Boltzmann constant, respectively. As before, the parameters \( A, B, C, \) and \( D, \) and \( n_1 \) can be used to shape the curve to match the positive differential portions of the measured I-V characteristic. The analytic expression of the RTD I-V characteristic \( I=F(V, L) \), comprises previous (dark) six independent parameters related with the RTD physical structure, and two new parameters associated to the illumination response. The light \( (L) \) and voltage \( (V) \) dependent current source \( I=F(V,L) \) under investigation will be incorporated in the previously discussed RTD modelling MATLAB tools.

The quantities \( V_{ph} \) (the photo-induced voltage shift due to the charge accumulation effect) and \( V_{pc} \) (which accounts for the photoconductive effect) are being calculated in terms of the optical power coupled to the RTD-PD and semiconductor material and device parameters. When proper validated and tested the above equation will be then integrated in the RTD-PD circuit models.
6.3. RTD oscillators as forced Liénard systems

It is well known that a single-port device that has a negative differential conductance (NDC) in a portion of its operating range may be used as the basis of a bistable or multistable circuit, and can also be used to form astable circuits (relaxation oscillators), monostable circuits (single-pulse generators), and sine-wave generators. A simple way to implement a RTD oscillator is to couple a RTD, DC biased in the NDC, to a resonant tank circuit or to a resonant cavity that provides frequency stability (the coupling location in the cavity can serve to partially match its impedance to that of the RTD). Such oscillator corresponds to a relaxation oscillator system since it operates by sequential transitions between unstable states. Tuning the DC bias across the NDC changes the RTD impedance and as consequence tunes the relaxation oscillation frequency making the circuit operate as a voltage controlled oscillator (VCO). Generally speaking, to have a wide DC operating range and therefore large tunability, a wide negative conductance region (a large difference between the peak and valley voltages) is required.

Since an RTD is a voltage-dependent current source device that can present a quite considerable NDC, when connected to resonant tank circuit and biased in the NDC portion of its I-V characteristic produces oscillations at the tank circuit characteristic frequency [36]. Typical RTD switching times are in general dominated by the effects of current densities and capacitances, i.e., by the circuit RC time constants [36]. Figure 6.4 represent a microphotography of a MMIC RTD oscillator and its AC equivalent circuit [24], with the RTD being represented by a capacitance $C$ in parallel with a voltage dependent current source $I = F(V)$. The inductance $L$ accounts for the CPW transmission line and the resistor $R$ for the device and contacts resistance.

In order to understand the origin of the circuit self-oscillations induced by the RTD we consider the equivalent circuit of Fig. 6.4(a), shown in Fig. 6.4(b). By applying Kirchoff’s laws (using Faraday’s law) to the circuit of Fig. 6.4(b), the voltage $V$ across the capacitor $C$ and the current $I$ through the inductor $L$ are given by the following set of two first-order non-autonomous differential equations [6]:

$$\dot{V} = \frac{1}{C(V)} [I - F(V)] \quad (6.6)$$
The solutions of above equation for a configuration where the RTD is DC biased in the NDC, corresponds relaxation oscillations due to the sequential transitions between the two positive differential conductance regions of the device I-V. Tuning the DC bias across the NDC changes the RTD impedance and as consequence the relaxation oscillation frequency is also tuned making the circuit to operate as a voltage controlled oscillator (VCO). Generally speaking, to have a wide DC operating range and therefore large tunability, a wide negative conductance region (a large difference between the peak and valley voltages) is required.

The circuit of Fig. 6.4 with the RTD DC biased in NDC produces relaxation oscillation at a frequency around $f(V) \approx \left(\frac{2\pi \sqrt{L \cdot C(V)}}{R}\right)^{-1}$, the circuit characteristic frequency, whenever the series $R$ is smaller than the RTD negative differential resistance (NDR) at the circuit quiescent point. From the application point of view the wideband NDC of RTD leads to low frequency oscillations instabilities that are detrimental. A most common source of instability arises from the DC source circuitry by introducing in the circuit an equivalent inductance, which together with RTD capacitance leads to oscillations at around few megahertz (Figueiredo, 2000; Slight, 2006). A common method for eliminating these low frequency oscillations and allowing circuit operation at much higher frequency is to place a shunt capacitor across the terminals of the device [21]. The inductance is now only due to the connection from the shunt capacitor to the RTD.

If subject to an external perturbation the RTD circuit of Fig. 6.4(a) can be numerically studied using the equivalent circuit shown in Fig. 6.4(b) and now reproduced in Fig. 6.5.

Fig. 6.5: RTD lumped circuit including an injected AC driving signal $V_{AC} \sin(2\pi f_{in} t)$.

Starting from Equations (6.6) and (6.7), and after some algebra, the circuit behaviour can be represented by a second-order differential equation, usually referred as one of the generalized nonlinear Liénard systems subjected to a time-dependent signal $V_{AC} \sin(2\pi f_{in} t)$ [6]:

$$\ddot{V} + H(V)\dot{V} + G(V) = V_{AC} \sin(2\pi f_{in} t)$$

(6.8)

where $G(V) = \left(\frac{V}{LC(V)} + \frac{R}{LC(V)}F(V) - \frac{V_{DC}}{LC(V)}\right)$ is a nonlinear force, and $H(V) = \left(\frac{R}{L} + \frac{1}{C(V)}\dot{F}(V)\right)$ is a damping factor.

Most of the RTD circuits can be described as Liénard oscillator systems, which are represented by the two first order differential Equations (6.6) and (6.7) [6] or by the second order-differential Equation (6.8). In the Liénard oscillator representation the RTD is replaced by a capacitor in parallel with a voltage dependent current source given by $I = F(V)$. As a first approximation the RTD capacitance can
be estimated using the parallel plate approximation – a more precise approximation can include a capacitor with a voltage dependent capacitance $C(V)$.

As mentioned previously, in a more simplified approach, circuits containing RTDs can be described as Van der Pol oscillators [21][22], which is a simplified version of the Liénard oscillator where the voltage-controlled current source $I = F(V)$ is modeled by a cubic polynomial with the zero voltage point shifted to the center of the NDC region:

$$I = F(V) = -aV + bV^3.$$  \hfill (6.9)

In a yet more simplified version, the RTD voltage-controlled current source can be replaced by a small-signal negative conductance $-g_n$.

Making use of the RTD I-V autotfitprogram package we developed in MATLAB a robust and user-friendly RTD basic circuit simulator tool capable of simulating electronic circuits containing several RTDs in parallel. At the present status, the RTDs have to be identical (that is, they have the same characteristics: same I-V and capacitance – the global capacitance is the sum of RTD capacitances). Figure 6.6 shows the front end of the MATLAB RTD circuit simulation package (a) and a typical output (b). The operator can choose the circuit parameters ($R$, $L$, $C$, $F(V)$), and the type of RF input signal – pulsed, square or sinusoidal. It is possible to load new I-V curves, save the current setting parameters, among other possibilities. The typical outputs include the RF driving signal, the voltage across the RTD, the current flowing through the RTD, and the circuit power spectrum.

(a) Front end of the MATLAB RTD circuit simulation package.
So far, the MATLAB and SPICE implementations of RTD circuits allowed us to investigate the operation of the RTD circuits as voltage controlled oscillators, allowing the characterization in terms of:

- Voltage waveform across the RTD / Load;
- Current waveform through the RTD / Load;
- Power generated;
- Output power;
- Self-frequency tuning range:

6.4. Laser diode rate equations

The iBROW uplink transmission capabilities will depend on the performance of RTD-LD system, particularly of the laser diode frequency response. Since the RTD-PD wireless-to-optical interface will be realized via hybrid integration of RTDs with LDs, it is of fundamental importance to characterize the laser diode dynamics. As such, in parallel with the investigation of RTDs, we need to study in detail LDs both experimental and analytical/numerical. Numerical and computational simulation packages have been implemented to gain deeper insight into LD nonlinear dynamic behaviour. It is important to have an accurate model allowing for the performance assessment within the targeted application scenarios, including the RTD-LD appropriate implementations and functionalities, aiming at finding the right devices, circuit configurations and parameters that maximize the electrical to optical conversion. Of particular relevance are the laser diode structures and parameters that better respond to RTD electrical functionalities in order to achieve efficient electrical to optical conversion namely maximize circuit bandwidth and the optical modulation index.

In order to be able to investigate the features of the possible configuration scenarios of the combination of RTDs with LDs, both components, the laser diode and the RTD, need to be properly modeled. Moreover, because of its nonlinear dynamic behavior the LD needs to be modelled
accurately for the assessment of the impact of distortion in the performance of the applications scenarios.

The most common and effective method to analyze the characteristics of laser diodes is based on the rate equation analysis. The LD rate equations represent the time dependent variation of carrier density $N$ and photon density $S$ inside the laser diode active layers. The carrier density $N$ rate equation gathers information of simulated and spontaneous emission recombination, and current injection; photon density $S$ rate equation considers the stimulated emission, the decay of phonons and spontaneous emission. These processes depend on the carrier lifetime, injected current density, thickness of the active layers, photon lifetime. Assuming the laser oscillates in a single mode and the population inversion is homogeneous, the laser rate equations for photon density $S$ and carrier density $N$ are \[20][38]:

\[
\frac{\dot{N}}{Q} = \frac{I}{qV_{ar}} - \frac{N}{\tau_n} - g_0(N-N_0)\frac{S}{1+\varepsilon S} \tag{6.10}
\]

\[
\dot{S} = \Gamma g_0(N-N_0)\frac{S}{1+\varepsilon S} - \frac{S}{\tau_p} + \frac{\beta N}{\tau_n} \tag{6.11}
\]

where $I$ is the total current flowing through the laser diode, which in the case of the RTD-LD series implementation is given by the generalized Liénard’s system, Eqs. (6.6-6.7) or Eq. (6.8), plus the DC bias current; $q$ is the electron charge, $V_{ar}$ is the laser active region volume, $\tau_n$ and $\tau_p$ are the spontaneous electron and photon lifetimes, respectively; $\beta$ is the spontaneous emission factor; $g_0$ is the gain coefficient, $N_0$ is the minimum electron density required to obtain a positive gain, $\varepsilon$ is the value for the nonlinear gain compression factor, and $\Gamma$ is the optical confinement factor \[20].

The laser optical output power is given by \[20][38]:

\[
P(t) = \frac{\eta \frac{hc}{\lambda}}{21\tau_p} S(t) \tag{6.12}
\]

where $h/c/\lambda$ represent the photon energy.

The numerical analysis employed extracted parameters of the laser diodes, as described in. Table 6.1 resumes the typical parameters of LDs being object of investigation in the iBROW.

<table>
<thead>
<tr>
<th>Table 6.1: Typical parameters of iBROW laser diodes.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Parameter</strong></td>
</tr>
<tr>
<td>Active region volume</td>
</tr>
<tr>
<td>Optical confinement factor</td>
</tr>
<tr>
<td>Electron lifetime</td>
</tr>
<tr>
<td>Photon lifetime in the cavity</td>
</tr>
<tr>
<td>Gain slope constant</td>
</tr>
<tr>
<td>Gain compression factor</td>
</tr>
<tr>
<td>Spontaneous emission factor</td>
</tr>
<tr>
<td>Internal quantum efficiency</td>
</tr>
<tr>
<td>Carrier density at transparency</td>
</tr>
<tr>
<td>Threshold current</td>
</tr>
</tbody>
</table>
6.5. Laser diode simulation tools

The LD modeling based on the rate equations for the carrier and photon densities, which has been shown to provide accurate description of laser diode structures, is being realized in close articulation between UALG, UGLA, INESC and CST. An LD simulation packaged is being implemented in MATLAB and validated with data gathered from experimental characterization of the LDs fabricated by CST, which includes the extraction of laser parameters package parasitics, namely of laser material and geometrical parameters relevant to the rate equation (Table 6.1), a topic where INESC and CST/UGLA have considerable experience. A more extensive simulation packaged can include the contribution of the laser package parasitics. The characterization work aims at the determination of the LDs threshold current, input impedance and transfer function, as well as bandwidth.

Figure 6.7 (a) shows the front end of the MATLAB laser diode simulation package being developed. The MATLAB laser diode tool is in final phase of the validation and test. The laser diode simulation tool allows us to investigate the laser diode operation, producing the following outputs, Fig. 6.7(b):

- Current-voltage (I-V) characteristic;
- Light-current (L-I) characteristic;
- Laser diode frequency transfer function;
- Laser diode light output response to a driving RF current signal.

(a) Front end of the MATLAB laser diode simulation package.
Figure 6.8 shows the simulated light-current (L-I) characteristic and frequency transfer function for a laser diode operating at 1550 nm: in the left is light-current (L-I) characteristic (obtained using parameters from Table 6.1); in the right is laser diode frequency transfer function.

To describe and predict the electrical and optical behaviour of RTD-LD circuits we coupled Liénard oscillator system [Eqs. (6.6-6.7) or Eq. (6.8)] to the LD rate equations that governs the interrelationship between carrier density $N$ and photon density $S$. The RTD-LD simulation outcomes include the prediction of devices and circuit responses, both in time and frequency domains. This provides insights to improve LD and RTD structures, RTD-LD circuit layouts and correspondent circuitry parameters, giving guidelines that allow the maximisation of the operation bandwidth and optical modulation index. Several configurations of LD and RTD connections are being investigated. The simulation tool allows also a detailed study of the different RTD-LD operation modes.
6.6. RTD-LD modelling and simulation tools

The transmitter component of the RTD-based optoelectronic transceiver employs an RTD-laser/modulator where the RTD (circuitry) operates as a high-speed driver circuit and the laser diode/modulator converts the electrical signal containing the information into an optical modulated signal which is propagated through optical fiber network. The RTD-LD/modulator wireless-to-optical transceiver interface incorporates an antenna that picks up and feeds the wireless signals into the RTD which then modulate the laser output. It must be noted that the laser diode is not directly modulated by mm-wave/THz signals. Depending on the modulation scheme, the wireless signal is frequency down converted at the RTD (e.g., by employing optical beat techniques) or by taking its envelope or baseband signal. This is a simple low-cost method to transfer analogue/digital information from the wireless domain to the optical domain. High-speed optical

The RTD mm-wave/THz-to-optical transponder (electrical-to-optical converter) is based on the integration of a RTD oscillator with a LD, where the LD is driven by the RTD oscillations. The RTD-LD series integration adds novel non-linear electronic and optical functionalities to laser diodes. The great advantage of RTD-LD series circuit is that when dc biased the NDR region the LD produces optical signals modulated by the current oscillations produced by the RTD. Moreover, when biased in the NDR the applied dc voltage can be used to adjust the free-running frequency. This makes the RTD-LD behaving as an autonomous voltage controlled optoelectronic oscillator (VC-OEO).

The RTD-LD optoelectronic simulation tool will help the design of the RTD-LD circuits, and will allow the circuit operation study, producing several outputs, including:

- Laser light-current (L-I) characteristic;
- Laser diode frequency transfer response;
- Laser diode optical output in the time domain.

The MATLAB RTD-LD implementation allows the simulation of circuits where the LD DC bias is decoupled from the RTD biasing circuit.

Figure 6.9(a) shows the front end of the RTD-LD simulation package, which is in the validation and test phase. Figures 6.9(b) and 6.9(c) show the typical outputs for RTD-LD oscillating at 3.1 GHz and 9.9 GHz, respectively.
Fig. 6.9: Front end of the MATLAB RTD-LD simulation package of a RTD connected in series with a laser diode. (a) Front end of the RTD-LD simulation package. The LD parameters are given in table 6.1. (b) Simulation of a RTD-LD oscillating at 3.1 GHz; the LD DC current is 30 mA. (c) Simulation of a RTD-LD oscillating at 9.9 GHz; the LD DC current is 15 mA.
7. Conclusions

This report describes the work on the development of low cost high efficiency electrical-optical (E/O) and optical-electrical (O/E) transceivers based on the integration of resonant tunnelling diode (RTD) optoelectronic devices. A detail description of resonant tunnelling diode photodetector (RTD-PD) is presented with a discussion of the relevant design parameters in order to be able to achieve high frequency operation and high responsivity.

RTD-PD mesa devices of different areas and optical window geometries where implemented. The preliminary characterization results of RTD-PD devices were presented and discussed: RTD-PDs comprising a 500 nm low doped In$_{0.53}$Ga$_{0.47}$As layer in the collector region show responsivity up to 2 A/W for 1 GHz sinusoidal intensity modulated lightwaves with 0.2 mW power. Devices comprising 500 nm low doped In$_{0.53}$Ga$_{0.39}$Al$_{0.07}$As layers in emitter and collector regions showed responsitivity up to 0.6 A/W for identical excitation. The preliminary optical-to-electrical conversion characterization experiments employed non-oscillating RTD-PD device acting as photo-detectors showed successfully data conversion at 1 Gbit/s. The preliminary results also show the ability of optically modulate RTD oscillators.

The main characterizing results can be summarized as: (i) when illuminated, the device current increases, particularly in the first PDR region; (ii) the peak and the valley current occurs at lower voltages (iii) the responsivity decreases with the optical power; (iii) when polarized in the valley region the devices show superior responsivity to standard vertical illuminated photodiodes. The guidelines for new epi-layer designs and for fabrication of a new set of devices were presented and discussed.

The resonant tunnelling diodes laser diode (RTD-LD) optoelectronic circuit configurations were also discussed and a brief presentation of the laser diode being characterized is present together with the work to implement packaged RTD-PD modules.

Finally, a comprehensive presentation and discussion of the simulation software packages being developed is made. The on-going work comprehends the high frequency characterization of the RTD-PD devices and oscillator circuits, the implementation of the RTD-LD modules, together with a new batch of RTD-PD devices and circuits with superior performances, as envisaged in project proposal.
8. Appendix A: RTD-PD I-Vs under dark and light illumination

Next are displayed the current-voltage characteristics of the devices from sample #3 (NC1800352) that respond better to the incident light of wavelength 1310 nm, that is, devices that shows the highest current enhancement, voltage shift and responsivity.
The characterization allowed identify the optical window geometries that give the best performance. The optical window that seems to lead to higher photo-detection is the one corresponding to windows of row 3 (half of the RTD-PD mesa uncovered), which are the ones with bigger area. On the other hand, the rows where the devices show similar electrical properties are 5th and 6th (A5X and A6X). The remaining blocks are currently being tested.
9. References


