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Resonant Tunneling Diode Photodetectors for Optical Communications

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ABSTRACT

Resonant tunneling diodes (RTDs) have been extensively studied due to their potential applications in very high speed electronics, optical communications, and terahertz generation. In this work, we report the latest results on the characterization of the resonant tunneling diode photo-detectors (RTD-PDs), incorporating InGaAlAs light sensitive layers for sensing at the telecommunication wavelength of λ = 1310 nm. We have measured responsivities up to 28.8 A/W and light induced voltage shift of 204.8 V/W for light injection powers around 0.25 mW.

Keywords: Resonant tunneling diode, photodetector, negative differential conductance, optoelectronic, optoelectronic-integrated circuit

1. INTRODUCTION

Nowadays, most communication networks such as local area networks (LANs), metropolitan area networks (MANs), and wide area networks (WANs) have replaced or are about to replace coaxial cable or twisted copper wire with fiber optical cables. One of the reasons for this change is the demand for bandwidth in short-range communications, which is doubling every 18 months.[1] The currently available bandwidth based on the use of the low frequency region of the microwave band cannot support the predicted growing demand for higher bandwidth much longer. Therefore, there is a significant effort to develop new technologies that allow the use of higher frequency spectrum regions.

One of the approaches to reach this goal is to use light-wave communication systems which are based on a transmitter emitting visible or near-infrared wavelengths, whose light-carrier is modulated by the RF signal to be transmitted, a transmission media such as a fiber optics cable, eventually utilizing optical amplification, and a receiver based on a photo-detector that recovers the RF signal information content.[2,3] The transmitter circuit usually includes a semiconductor laser, and the receiver is based on a photo-detector such as a photodiode, an avalanche photodiode (APD), phototransistor or a photoconductor. Transmitter and receiver circuits are classical examples of optoelectronic integrated circuits (OEICs). OEIC technologies aim to emulate CMOS microelectronics technology by using integrated III-V electronic circuits with optoelectronic devices. Integrated III-V electronic circuits lead to superior speed, component density, reliability, complexity and manufacturability.[4] Approaches to light modulation, light detection and light generation at microwave and millimeter-wave frequencies have been investigated by combining double barrier quantum well (DBQW) resonant tunneling diodes (RTDs) with optical components such as photo-detectors,[5] optical waveguides,[6] and semiconductor lasers.[7]

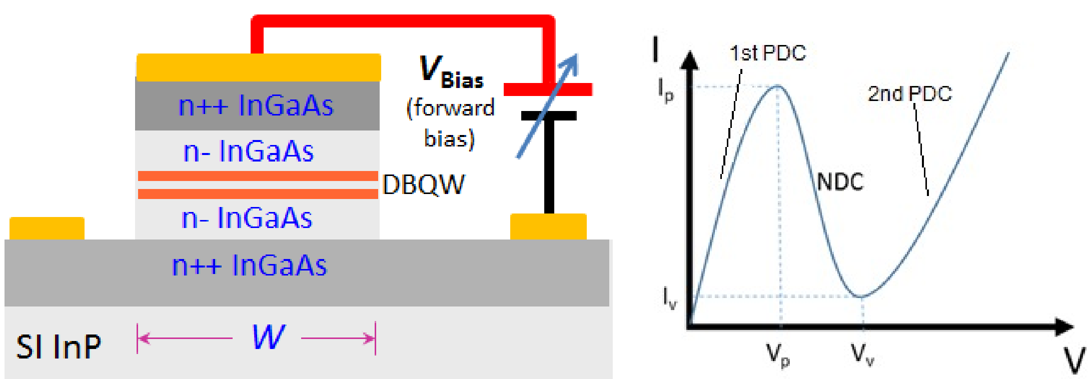
Third International Conference on Applications of Optics and Photonics, edited by Manuel F. M. Costa,
Proc. of SPIE Vol. 10453, 1045307 · © 2017 SPIE · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2271317

In this work we report the latest results on resonant tunneling diode structures incorporating light sensitive layers, forming an RTD photo-detector (RTD-PD) capable of performing high-speed photo-detection. The structure under consideration incorporates an InGaAlAs layer capable of light sensing at the telecommunication wavelength of $\lambda = 1310$ nm. The implemented RTD-PDs are being characterized in terms of responsivity and voltage-shift sensitivity. Preliminary results indicate that the RTD-PD, when integrated in a telecommunication system, shows significant advantages in comparison to other commercial photo detectors, showing, superior bandwidth, high gain, low power consume and a compact structure. The wide range of applications that can take advantage of the RTD-PD new functionalities extend from optical control of high-frequency electronic circuits, to high frequency optoelectronic oscillator, clock recovery systems and seamless fiber-wireless interfaces. The work also aims to provide a comprehensive study on the nonlinear dynamics and potential applications of the optoelectronic-integrated circuit (OEIC) that incorporate RTD-PD structures suitable for integration into mm-wave/THz femtocell base-stations, under the EU H2020 iBROW project. [8]

The paper is organized as follows. In section 2, it is presented the theory behind the RTD-PD, describing the characteristic I-V curve, the main RTD-PD DC parameters under discussion on this paper and the possible applications of RTD-PDs. In section 3, the experimental results are presented, followed by the conclusions in section 4.

2. RESONANT TUNNELING DIODE PHOTODETECTOR

Generically, resonant tunneling diode (RTD) corresponds to a unipolar two terminal nanoscale semiconductor device consisting of double barrier quantum well (DBQW) structure made of a InGaAs quantum well sandwiched between two AlAs layers, as depicted in Figure 1(a), which shows a pronounced N-shaped current-voltage characteristic at room temperature, Figure 1(b); the RTD device is completed with highly doped InGaAs layer, lattice matched to InP substrate, for ohmic contact formation, Figure 1(a).



a) b)

Figure 1: (a) Typical RTD structure and (b) the corresponding I-V characteristic for forward polarization.

RTD's exhibit two main features at room temperature when compared to other semiconductor devices, wideband negative differential conductance (NDC) and an extremely high operating frequency reaching 1.92 THz.[9] The wideband NDC leads to electrical gain and when DC polarized in the NDC region the RTD produces a RF signal whose frequency is determined by its intrinsic capacitance and by the equivalent inductance of the connecting circuitry. The high operating frequency, on the other hand arises from the very thin DBQW structure, which makes the RTD the fastest pure solid-state electronic device operating at room temperature.[10] These unique features make the RTD possible to operate as a voltage controlled electronic oscillator (VCEO), providing and interesting solution for high-speed communications. Moreover, 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 countless of other electronic and optoelectronic devices with new functionalities.[11,12]

A wide number of optoelectronic devices and circuits based on III-V semiconductor compound materials can benefit from the integration with RTD's, taking advantage of the NDC produced by the DBQW structures. Such optoelectronic devices include laser diodes, semiconductor optical amplifiers (SOA), photo-detectors and electro-absorption modulators. The integration in the same epi-layer of an RTD with light sensitive region, gives rise to a device called from now on, resonant tunneling diode photodetector (RTD-PD). The RTD-PD's can be operated in two modes, steady state mode and oscillatory mode. The steady state mode is when the RTD-PD is polarized in one of the positive differential conductance (PDC) regions of the I-V curve. The oscillatory mode is when the RTD-PD is polarized in the NDC region of the I-V Curve. These operational modes make the RTD-PD a potential candidate for the implementation of low cost highly efficient photodetector, capable of transferring signals embedded in optical carriers used in fiber optic communications into electrical mm-wave/THz carriers.[11,12]

2.1 RTD-PD Design and Fabrication

It has been demonstrated, that resonant tunneling diodes (RTD) can operate as very high sensitive photodetectors. Different structures and geometries have been proposed to optimize the RTD photo detection for different optical wavelengths.[13–15] In order to enhance greatly the conversion from an optical signal into an electrical signal, an absorption layer must be incorporated in the RTD structure (Figure 2).

The studied group of RTD-PD were grown by molecular beam epitaxy (MBE) (wafer grown by IQE Inc.) and are based on an epi-layer structure that comprises a resonant tunneling structure (RTS) composed by a DBQW with a nearby and lattice-matched absorption layer, defined for light sensing. The epi-layer structure of the device presented on this paper incorporates a RTS region which is composed by an un-doped $In_{0.532}Ga_{0.468}As$ quantum well with 5.7 nm of thickness sandwiched between two un-doped AlAs barriers with 1.7 nm of thickness each. The structure is composed by two $5x10^{16}$ cm^{-3}: Si doped $In_{0.532}Ga_{0.394}Al_{0.076}As$ absorption layers, one in the emitter side and another in the collector side, both with a thickness of 500 nm.

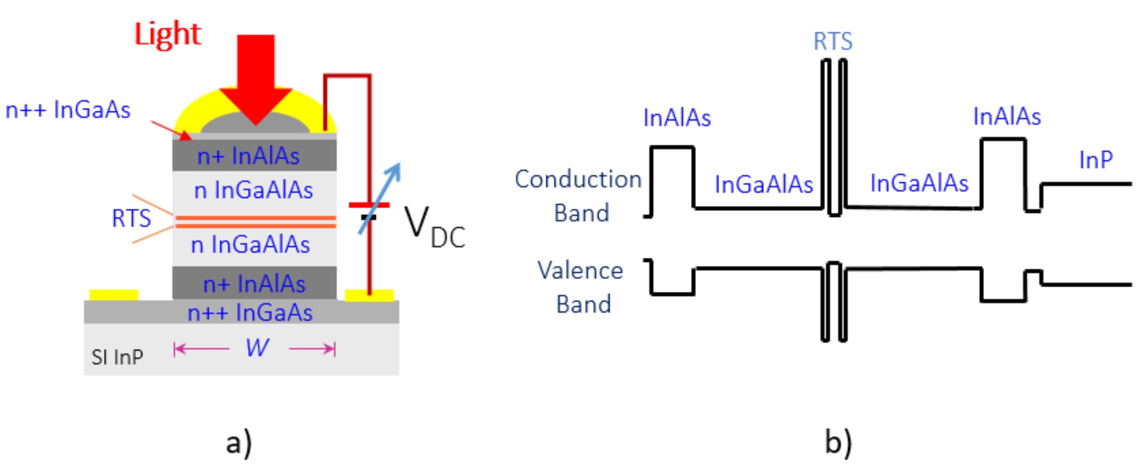


Figure 2 a) Schematic of the RTD-PD epi-layer structure; b) RTD-PD band profile, showing the conduction band and valence band when no bias is applied

The RTD-PD optical window at the top allows the injected of light to be absorbed in the low doped InGaAlAs layer, photo-generating electron-hole pairs which become separated by the built-in electric field due to the applied voltage, with the photo-generated electrons moving towards the collector side while photo-generated holes move in the emitter direction. The injection of light into the RTD-PD leads to a current rise and to a global I-V voltage shift.

2.2 RTD-PD DC responsivity and light induced voltage shift

The optical response of the RTD-PD discussed here will be characterized in the steady state or stationary mode, which corresponds to the RTD-PD response to an incident continuous lightwave (constant intensity optical signal). The RTD-PD steady (stationary) state responsivity $\mathcal{R}_{cw}(\lambda, \mathrm{V})$, usually measured in A/W is defined as:

$$\mathcal{R}_{cw}(\lambda, \mathrm{V}) = \frac{I_{light}(\mathrm{V}) - I_{dark}(\mathrm{V})}{P_{light}(\lambda)} = M(\mathrm{V}).\eta_{ph}\left(\frac{e\lambda}{hc}\right) \quad (1)$$

Where $I_{light}(\mathrm{V}) - I_{dark}(\mathrm{V})$ is the current difference under illumination and dark conditions, and $P_{light}(\lambda)$ is the continuous-wave optical power incident on the device; $M(\mathrm{V})$ accounts for the internal current gain effect (due to electron-holes pair generation and/or impact ionization mechanisms, or other phenomena not yet investigated), η_{ph} is the external quantum efficiency and e, h, c are the elementary charge, Planck constant and the speed of light in vacuum, respectively.

The RTD-PD steady (stationary) state light induced voltage shift $Vs_{cw}(\lambda, \mathrm{I})$, usually measure in V/W is defined as the ratio of voltage difference under illumination and dark conditions, $V_{light}(\mathrm{I}) - V_{dark}(\mathrm{I})$, and the continuous-wave optical power $P_{light}(\lambda)$ incident on the device, this is:

$$Vs_{cw}(\lambda, \mathrm{V}) = \frac{V_{light}(\mathrm{I}) - V_{dark}(\mathrm{I})}{P_{light}(\lambda)} \quad (2)$$

Under light elimination the presence of the absorption layer leads in a pronounced shift in the I-V curve. This pronounced shifts in the RTD I-V curve for small optical powers can lead to large responsivities, that can be exploited for different proposes.[14,15]

3. RTD-PD MEASUREMENTS

Under dark conditions, the RTD-PD devices being object of study, the RTD-PD F21, show negative differential conductance (NDC) of 142.4 mS, peak-to-valley current ratio (PVCR) of 1.26, peak-to-valley voltage ratio (PVVR) of 0.82. The estimated generated RF power at low frequency (P_{LF}) is of the order of 0.63 mW. Figure 3 shows the I-V curve of the RTD-PD F21 for forward bias (top under positive polarization) for dark conditions (blue line), for 0.25 mW optical power (red line), 0.5 mW optical power (yellow line) and 1 mW optical power (purple line). A Fabry-Perot laser emitting light at a wavelength of 1310 nm was used as light source.

Concerning the RTD-PD photo-detection parameters, the RTD-PD F21 shows: a responsivity of 28.8 A/W and 15.1 A/W on the first and second PDC, respectively, for illumination with 0.25 mW optical power, 24.4 A/W and 13.5 A/W on the first and second PDC, respectively, with 0.5 mW optical power, 19.7 A/W and 10.8 A/W on the first and second PDC, respectively, at 1 mW optical power. A light induced voltage-shift sensitivity of 204.8 V/W and 408.4 V/W on the first and second PDC, respectively, for 0.25 mW optical power, 144.4 V/W and 318 V/W on the first and second PDC, respectively, using 0.5 mW optical power, 102.2 V/W and 262 V/W on the first and second PDC, respectively, for 1 mW optical power.

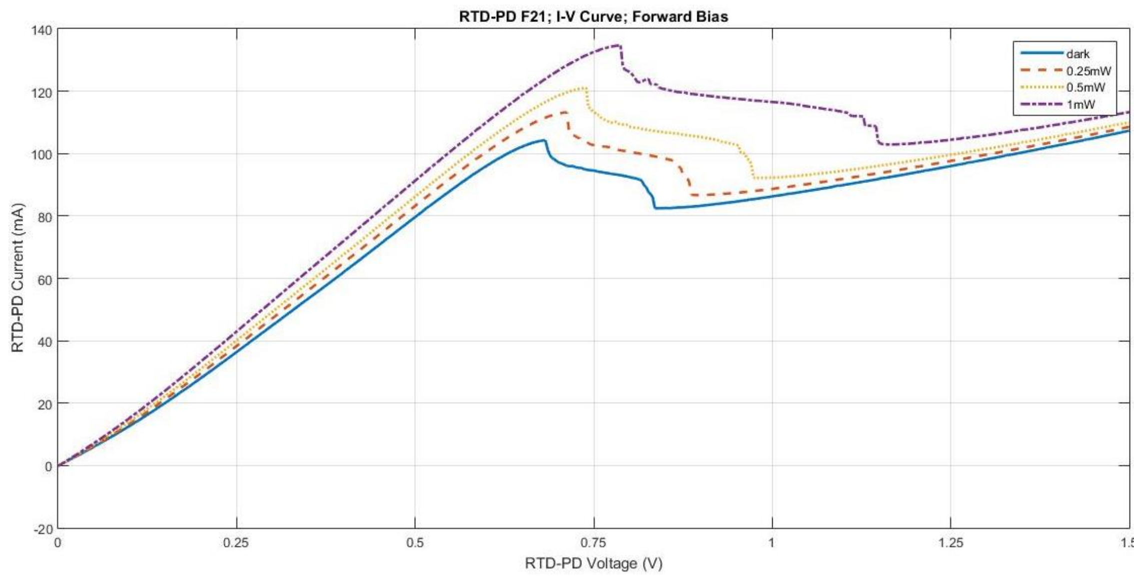


Figure 3 RTD-PD F21 I-V curve (forward bias or positive polarization) under dark conditions (blue line), with 0.25 mW of optical power (red line), 0.5 mW of optical power (yellow line) and 1 mW of optical power (purple line)

Figure 4 shows the I-Vs curve of the RTD-PD F21 under reverse bias (top at negative polarization), under dark conditions (blue line), for 0.25 mW optical power (red line), 0.5 mW (yellow line) and 1 mW optical power (purple line). Under dark conditions, the RTD-PD F21 DC characteristics show a negative differential conductance (NDC) of 122.8 mS, a peak-to-valley current ratio (PVCR) of 1.26, a peak-to-valley voltage ratio (PVVR) of 0.81. The estimated generated RF power at low frequency (P_{LF}) is of the order of 1.54 mW.

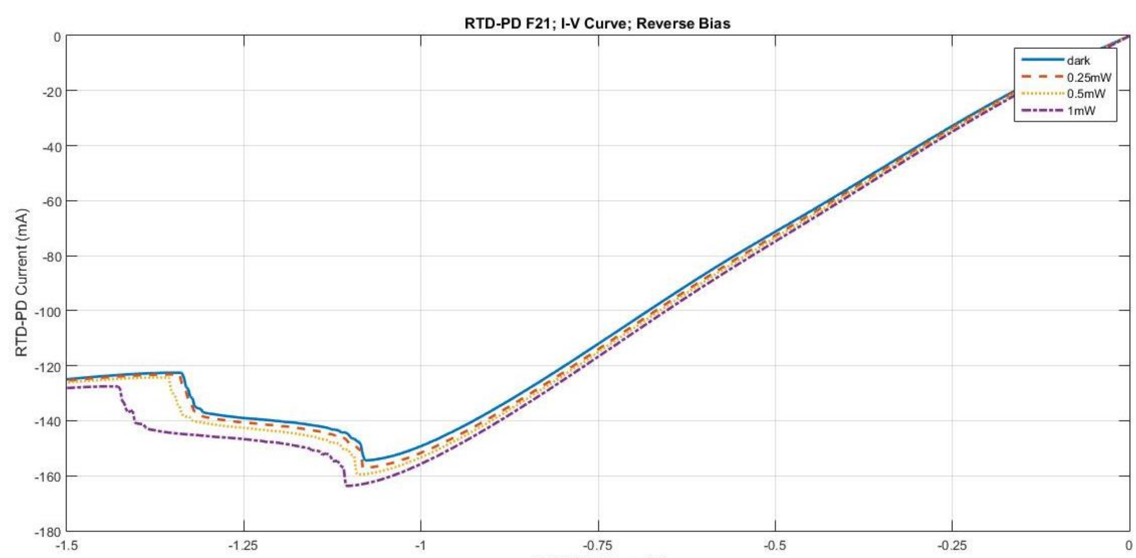


Figure 4 RTD-PD F21 I-V curve (reverse polarization) under dark conditions (blue line), with 0.25 mW of optical power (red line), 0.5 mW of optical power (yellow line) and 1 mW of optical power (purple line).

Concerning the RTD-PD photo-detection under reverse bias, the RTD-PD F21 show the following behavior: A responsivity of 10.8 A/W and 2.4 A/W on the first and second PDC, respectively, using 0.25 mW optical power, 10 A/W and 3.6 A/W on the first and second PDC, respectively, for 0.5 mW optical power, 8.5 A/W and 4.2 A/W on the first and second PDC, respectively, under 1 mW optical power illumination. A light induced voltage-shift sensitivity of 204 V/W and 180 V/W on the first and second PDC, respectively, when using 0.25 mW optical power, 138 V/W and 216 V/W on the first and second PDC, respectively, for 0.5 mW optical power, 84 V/W on the first PDC when illuminated with 1 mWoptical power.

As can be seen by the figures 3 and 4 the light induced an I-V curve shift towards higher voltages as the optical power is increased. This global shift of the device I-V characteristic can be exploited in terms of signal modulation. The work continues with more detailed study and also by investigating the RTD-PD frequency response.

4. CONCLUSION

An RTD-PD with high responsivity was described in this paper. So far we have measured responsivities up to 28.8 A/W and light induced voltage shifts up to 204.8 V/W for 0.25 mW optical power. We have also observed that due to their high nonlinear current-voltage characteristic nature, which incorporates a negative differential conductance (NDC) region, the RTD-PDs optoelectronic response is also highly nonlinear. The properties are being considered for implementation of opto-electrical converter for ultra-wideband communication systems.

ACKNOWLEDGMENTS

This work is partially supported by the Fundação para a Ciência e a Tecnologia (FCT) under the project UID/Multi/00631/2013, by the European Structural and Investment Funds (FEEI) through the Competitiveness and Internationalization Operational Program (COMPETE 2020), by National Funds through FCT under the project ALG-01-0145-FEDER-016432/POCI-01-0145-FEDER-016432 and by the European Commission under the project iBROW (grant agreement no. 645369).

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