High-Speed Uni-Travelling Carrier Photodiodes for InP Photonic Integrated Circuits

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***Abstract*—We report on the design, growth and fabrication, and experimental assessment of Ultra-Fast InGaAsP/InP Uni-Travelling Carrier Photodiodes (UTC-PDs) suitable for active-passive monolithic integration with various Multiple Quantum Well (MQW) devices. The final Photonic Integrated Circuits (PICs) are expected to enable high bit rate (>10 Gbps) wireless transmission at a carrier frequency of 120 GHz. The proposed devices achieved a high 3-dB bandwidth of up to 110 GHz and a generated output power of more than 0 dBm (1 mW) at 120 GHz.**

Keywords—Uni-Travelling Carrier Photodiode (UTC-PD), Wireless Transmission, Monolithic Integration, Microwave Photonics, Millimeter-waves.

I. Introduction

The field of high speed wireless communications has seen a tremendous evolution recently driven by the demand for wireless bit rates over 1 Gbps [1]. The bandwidth being limited in the traditional bands, carrier frequencies in the millimetre-wave range have to be utilised, especially those above 60 GHz, where the bandwidth allocated would enable the required data rates. Recent work has shown the advantages of photonic techniques and components for that frequency range [2]. For the photonic solution, photomixing in a fast photodetector is the key technique to generate the carrier frequency.

Despite their great potential, most optoelectronic photomixing systems suffer from high power consumption that is the result of poor fibre-to-chip coupling and polarization dependent loss. Monolithic passive-active integration of Distributed Feedback (DFB) lasers with tunable sections [3], Electro-Absorption Modulators (EAMs), Semiconductor Optical Amplifiers (SOAs) and Multimode Interference (MMI) couplers in a single photonic integrated circuit (PIC) can offer a solution for efficient generation of an optical heterodyne signal that can be used as an input to a high bandwidth photodiode. Nevertheless, fast photodiodes are usually fabricated in a waveguide configuration with a thin absorber layer. Uni-Travelling Carrier Photodiodes (UTC-PDs) have been demonstrated as efficient Terahertz photomixers in [4] and [5]. In this paper we demonstrate high speed (f_{3dB} > 100 GHz) UTC-PDs based on epitaxial regrowth in a Multiple Quantum Well platform with generated output power of 1 mW at 120 GHz. Losses in passive sections and MMI couplers were also assessed. We expect this technology to lead to photomixing PICs suitable for 10 Gbps wireless transmission at 120 GHz.

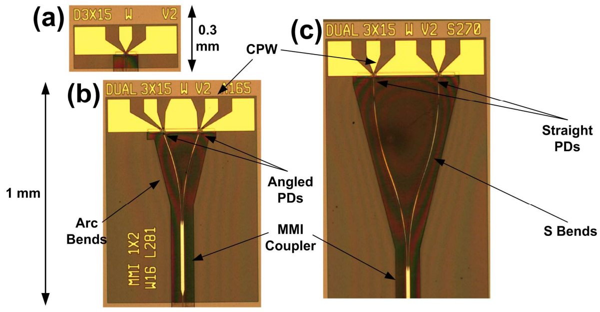

Figure 1: Images of chips with (a) Single UTC-PDs, (b) Dual angled UTC-PDs with Arc-Type bends and (c) Dual straight UTC-PDs with S-type bends.

II. UTC-PD Design Challenges

One of the main challenges is to design fast photodetectors despite the high series resistance that is introduced from the thick top cladding layer. This thicker layer is introduced to allow for both a strong passive waveguide section and to enable integration with laser structure where the InP contact layer is usually thick to avoid coupling of the optical mode into the strongly guiding layer just under the metal contact, also used as the p-contact layer for the photodiode. Light from passive waveguide sections is evanescently coupled into the photodiode absorber. An optimisation process based on a semi-analytical model [5], showed that the active area dimensions for maximum power generation at the target frequency of 120 GHz was 3×15 μm^2. In this simulation a constant level of optical power was considered at the input of the UTC-PD to account for the length-dependent responsivity.

III. Growth and Fabrication

The developed UTC-PDs are made on semi-insulating InP substrate using gas source molecular beam epitaxy. For the fabrication of these devices we implemented monolithic integration of passive waveguides and optical couplers, and photodiode (PD) active sections. This was done with two epitaxial growth steps. The process flow of our integrated UTC-PDs fabrication is then mainly based on dry and wet

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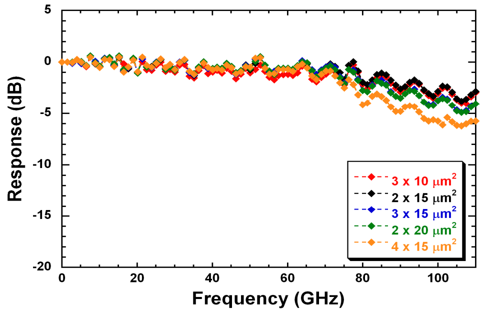

Figure 2: Frequency response up to 110 GHz from UTC-PDs with various active area dimensions.

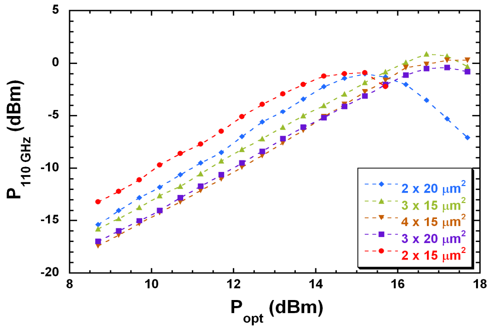

Figure 3: Power saturation at 110 GHz for various UTC-PDs with different active area dimensions. The reverse bias voltage was 3 V.

etchings for the realisation of shallow ridge waveguides, PD mesa, and PD isolation. Finally, a BCB planarization step is performed, followed by a metallisation step for electrodes interconnection. This process flow uses fabrication steps that are compatible with the integration of MQW active sections and the realisation of shallow ridge laser and SOA waveguides.

IV. Single Photodiodes

The mask that was designed for these devices included various types of UTC-PDs with different passive sections. The performance of the UTC-PDs was first measured on chips with single devices (Fig 1(a)). The responsivity at 1.55 µm of devices with a short waveguide (70 µm) was found to be 0.35 A/W despite the fact that the waveguide was not designed for coupling from a fiber and the absence of an anti-reflection coating. The frequency response from the single UTC-PDs was assessed using two external cavity lasers, coplanar probes and a microwave power meter. The frequency response for devices with various dimensions can be seen in Fig. 2. A 3-dB bandwidth between 80 and 110 GHz was measured depending on the device active area dimensions. The generated RF power at 110 GHz as a function of the optical input power was measured to investigate saturation effects. The results are shown in Fig. 3. The maximum output power was generated by a device with an active area of 3×15 µm^2. Devices with smaller active area dimensions suffer from stronger saturation while the larger devices have a limited frequency response due to a higher capacitance.

V. Dual Photodiodes

Chips with dual photodiodes and 1×2 MMI couplers were also assessed (Fig. 1(b), 1(c)). Single photodiodes with the

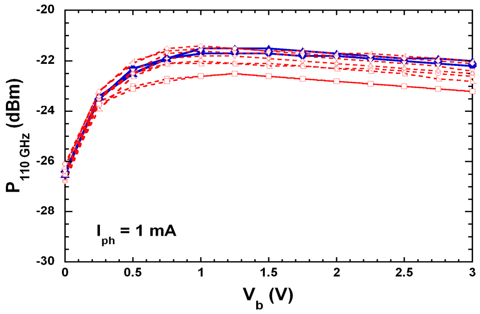

Figure 4: Generated power at 110 GHz for straight (blue) and angled (red) UTC-PDs.

same chip length were also included in the mask in order to evaluate the propagation loss independently from the insertion loss introduced from the MMI coupler and the S-type and Arc-type waveguide bends. The responsivity at 1.55 µm of devices with chip lengths varying from 770 µm to 1170 µm was compared to the one found from single devices with a short input waveguide (70 µm). An average propagation loss of 2.6 dB/mm was found from these measurements.

Three types of dual 3×15 µm^2 photodiode chips were assessed. The first one included Arc-type bends and angled photodiodes to minimize the chip area and the other two included S-type bends and angled and straight photodiodes respectively. The total insertion loss (MMI + bends) was found to be 3.2 dB, 3.6 dB and 4.3 dB respectively by comparing the measured responsivity with the one from single devices with the same chip length.

In order to investigate the effect of the angled photodiodes and coplanar waveguides on the frequency response of the UTC-PDs, the generated output power at 110 GHz (Fig. 4) was measured from straight and angled photodiodes at the same photocurrent level (1 mA). An additional average loss of only 0.5 dB at 110 GHz was measured from the angled photodiodes, proving that they are a viable solution for the demonstration of a monolithically integrated heterodyne source.

Acknowledgement

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References

[1] H.-J. Song, and T. Nagatsuma, “Present and Future of Terahertz Communications,” IEEE Transactions on Terahertz Science and Technology, vol. 1, no. 1, pp. 256–263, 2011.

[2] A. Stöhr et al., “Millimeter-Wave Photonic Components for Broadband Wireless Systems,” IEEE Transactions on Microwave Theory and Techniques, vol. 58, no. 11, pp. 3071–3082, 2010.

[3] F. van Dijk et al., “Monolithic dual wavelength DFB for narrow linewidth heterodyne beat-note generation,” Proc. IEEE Intl. Topical Meeting Microw. Photon. (MWP), 2011, pp. 73–76.

[4] E. Rouvalis, C. C. Renaud, D. G. Moodie, M. J. Robertson, and A. J. Seeds, “Travelling-Wave Uni-Travelling Carrier Photodiodes for continuous wave THz generation,” Optics Express, vol. 18, no. 11, pp. 11105–11110, 2010.

[5] E. Rouvalis, C. C. Renaud, D. G. Moodie, M. J. Robertson, and A. J. Seeds, “Continuous Wave Terahertz Generation From Ultra-Fast InP-Based Photodiodes,” IEEE Transactions on Microwave Theory and Techniques, vol. 60, no. 3, 2012.