Photodetectors for Classic and Quantum Communication with 39 GHz Bandwidth and 66% Quantum Efficiency

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Abstract *We present a coherent receiver chip based on flipped uni-travelling carrier (UTC) photodiodes. The UTC photodiodes allow for better linearity with up to 1.2 dBm RF output power and a bandwidth of 39 GHz. By flipping the active structure, the quantum efficiency is maximized for QKD applications.*

Introduction

Coherent communication systems are widely deployed for long haul and metropolitan data transmission due to their high capacities [1]. Beyond high-speed and the capability of transmitting signals over long distances, it enables quantum cryptography to be expanded using the existing telecommunication infrastructure. This includes the established fibre networks, but also the use of existing photonic components to realize scalable and cost-effective quantum secure networks [2, 3]. Still, the improvements of particular components and the increase of their integration level is a driving factor in order to make quantum key distribution (QKD) accessible for protecting government services, enterprises and the critical infrastructure.

The photonic integrations targets versatile quantum secure devices, which are usable both for classical telecommunication and for continuous variable quantum key distribution (CV.QKD). For the receiver this implies high responsivity, linear behaviour at high optical local oscillator powers, and low noise electronics without sacrificing the device bandwidth. Therefore, a new type of a UTC photodiode with a down-lying p-side (pSd UTC) has been developed, accomplishing high responsivity, linearity and bandwidth. Further, the photodiode is configured for coherent detection by combining two pairs of evanescently coupled dual photodiodes with a 90° optical hybrid monolithically integrated on an InP chip. The chip enables coherent detection in classical transmission and CV-QKD schemes and additionally represents a generic technological enhancement for the fabrication of photodiodes and other opto-electronic components on InP.

Design and Fabrication

UTC photodiodes, compared to PIN photodiodes, have the potential to achieve superior bandwidth and linearity. . This is a consequence of a fast carrier transport due to the suppression of the slow holes drifting in the absorbing InGaAs region [4]. These characteristics result from the

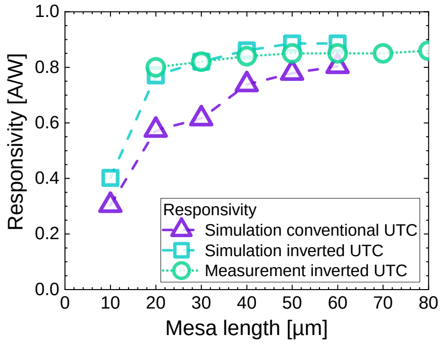


Fig. 2: Simulation and measurement of the responsivity for the waveguide integrated UTC photodiode

specific epitaxial layer structure. Basically, it combines an at least partially p-doped absorbing region, being made of InGaAs, and a collection layer being formed of InP with an bandgap grading and a slightly doped cliff layer in between to adjust the electric field inside this active region. This active region is cladded with highly doped transparent contact layers (see Fig. 1), where the

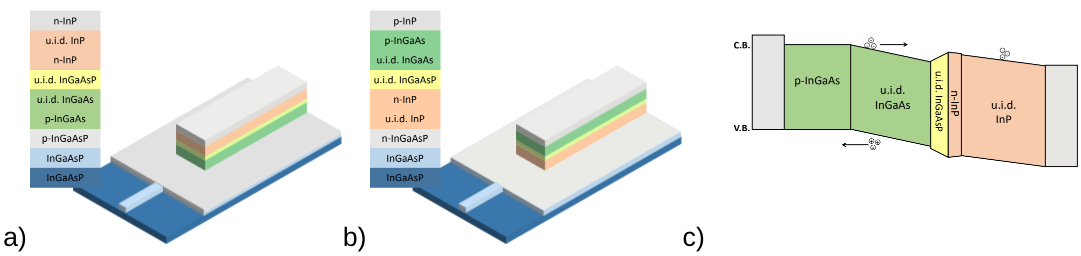


Fig. 1: Epitaxial layer structure of inverted UTC photodiode (a) and conventional design (b) and band diagram (c)

p-contact needs to be placed adjacent the absorbing region and the n-contact aside the collection layer. Inherently, a placement of the n-contact at the bottom of the structure and the p-contact at the top impedes the evanescent coupling due to the refractive index contrast of the layer structure.

To overcome this constraint, the absorption can be increased by flipping the structure above the passive waveguide. Therefore, the p-doped contact layer is designed to have a higher refractive index than the underlying waveguide layer while being highly doped for a low contact resistance. The top contact is realized with a wide-bandgap material in order to achieve a high confinement in the absorbing region. The resulting structure layer for the absorbing region as well as for the InP region of same thickness is considered for a responsivity estimation. At a mesa width of 4 µm the length is varied between 10 µm and 60 µm. For a maximum mesa length of 60 µm, the external responsivity is up to 0.89 A/W, being an enhancement of 10% compared to a conventional UTC structure. This enhancement is still much more significant for shorter mesa geometries as for the 4x30 µm² mesa, showing a responsivity of 0.83 A/W, being 33% larger than for the same structure with a bottom n-contact. While not very important for CV-QKD operation, a short mesa length is enabling data transmission at high baud rates due to the reduction of parasitics and thereby increasing the bandwidth. The results are presented in Fig. 2.

The full device structure is grown in a single step on 3” semi insulating InP substrate. Standard photolithography and e-beam direct photography in combination with various dry and wet etching processes are applied for structuring of the passive and active elements. The fabrication flow is compatible with the HHI foundry process and allows the presented technology development to be transferred to multi project wafers as well [5].

Device characterization

Full characterization was carried out by measuring the DC and RF characteristics of single photodiodes as well as the DC characteristics of a fully integrated coherent receiver chip. RF characteristics of the coherent of the latter are still under investigation. The dark current was measured in a voltage range up to -5V and is below 4 nA (see Fig. 3) in that reverse bias regime, indicating a low noise contribution. The responsivity of the pSd-UTC PD is above 0.8 A/W over the whole c-band and reaches 0.83 A/W at a wavelength of 1550 nm,

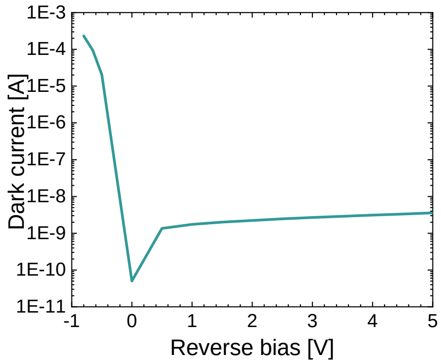


Fig. 3: Dark current of the fabricated waveguide integrated inverted UTC device

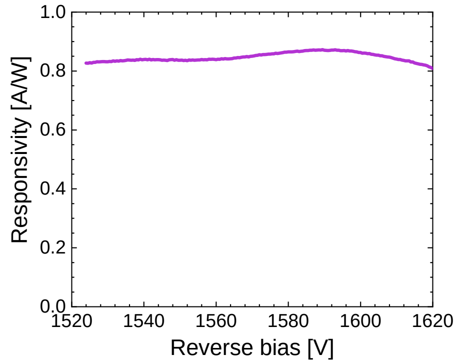


Fig. 4: Responsivity of the fabricated waveguide integrated inverted UTC device

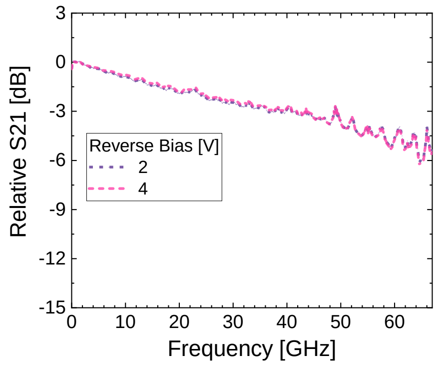


Fig. 5: Bandwidth of the fabricated waveguide integrated inverted UTC device

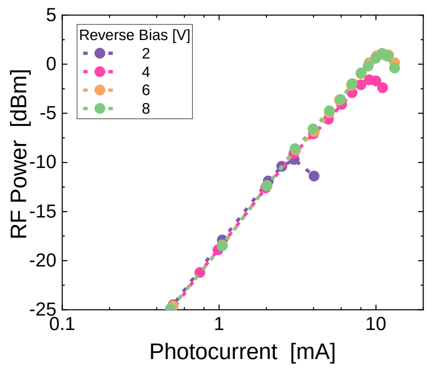


Fig. 6: Linearity of the fabricated waveguide integrated inverted UTC device at a frequency of 20 GHz

corresponding an external quantum efficiency of 66.4 % (see Fig. 4). By measuring the S21 parameter in a frequency range of up to 67 GHz at reverse bias voltages of 2 V and 4 V, the f3dB-bandwidth is found to be 39 GHz (see Fig. 5). These measurements shows barely no voltage dependency. To evaluate the linearity, a heterodyne signal at a carrier frequency of 20 GHz is generated and varied in its optical power. At a reverse bias voltage of 2 V, the maximum output power is -10.0 dBm corresponding to a photocurrent of 3 mA. When increasing the operation voltage up to 8 V, the maximum RF output is up to 1.2 dBm at an photocurrent of 11.2 mA. This allows for optical input powers up to 13.5 mW beneficial for coherent detection both for classical communication and for CV-QKD, where the input power of the local oscillator needs to be orders of magnitude higher to improve the signal-to-noise ratio.

Next to single photodiodes, the flipped UTC structure is arranged in a coherent photodetector chip including a spot size converter, the optical

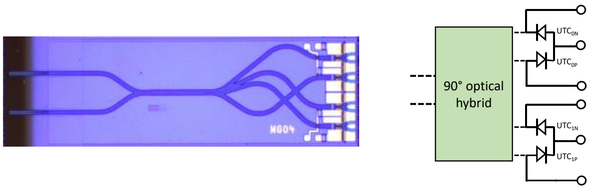
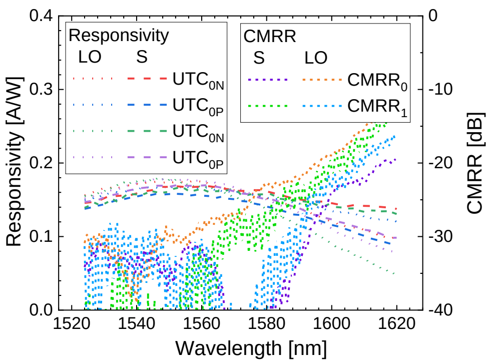


Fig. 7: Coherent photodetector chip including spot size converter, MMI and 2 pairs of balanced photodiodes

90° hybrid and two pairs of dual photodiodes. The responsivity of each photodiode was measured independently when coupling light through the signal path (S) as well as through the path for the local oscillator (LO).



s

Fig. 8: DC characteristics of coherent receiver chip based on inverted UTC photodiodes

The external responsivity including the 6 dB inherent loss of the 90° optical hybrid is above 0.15 A/W for all photodiodes. The resulting CMRR for the two channels (0 and 1) is better than -25 dB over the c-band. The results prove the capability of the presented chip for its application in a sophisticated coherent receiver.

Conclusion

The demonstrated waveguide integrated pSd UTC photodiodes show an excellent performance with the dark current below 4 nA, responsivity up to 0.83 A/W and RF characteristics. Its high linearity for optical input powers up to 13.5 mW and its bandwidth of 39 GHz are important credentials for coherent photodetectors in classical communication and CV-QKD. Next to the application of an inverted epitaxial layer structure on UTC photodiodes, this technological enhancement is applicable to other devices and photodiodes and of particular interest for evanescent coupling photodiodes as in [6], since the optical coupling and the epitaxial design can be decoupled. The contact resistance, the optical losses in the coherent photodetector as well as the photodiodes active region show potential to be improved, but fitting the requirements for diverse coherent detection schmes. For a system integration a dedicated TIA development is needed. However, to our knowledge this the first demonstration of p-side down photodiodes on an evanescent coupling waveguide structure pathing the way to more performant photonic integrated circuits.

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