Ultra Compact High responsivity Photodiodes for >100 Gbaud Applications

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Abstract *We demonstrated ultra-compact waveguide UTC photodiode with bandwidth efficiency product of 37 GHz on 50Ω load and above 55 GHz on 25Ω load, which allows to reach a bandwidth above 110 GHz with 0.6 A/W responsivity.*

Introduction

The fast increase of cloud services leads to a continuous increase of data traffic and transmission experiments are now done at 100 Gbaud and even 200 Gbaud. High bandwidth receiver are of primary importance to limit the complexity of digital signal processing and are widely studied[1-4]. A classical method to have an improved HF response is to use a matching load resistor to reduce RC time constant and reflection due to impedance mismatch. Using this technique, a receiver module using matching load resistor (resulting in 25Ω effective load) to improve HF response has been demonstrated recently with 145 GHz bandwidth[1] but at the price of a reduced responsivity and a high PDL (>4 dB). Using the same approach, a bandwidth of 120 GHz with 0.51 A/W responsivity[2] and 100 GHz with 0.66 A/W responsivity[responsivity [3] has been achieved. When looking at intrinsic PD performance, without 50Ω matching resistor, ≈0.5 A/W with 75 Ghz bandwidth has been demonstrated[4]. These diodes however suffer from the length of the input taper (≈1 mm) which increase the overall size of the device.

We have demonstrated in the past short multimode waveguide photodiodes with 0.58 A/W responsivity and an intrinsic 3-dB bandwidth of 50 GHz[5]. In this paper, we will demonstrate very short photodiodes (0.4×0.5mm² chip size) with a responsivity up to 0.8 A/W for >45 GHz intrinsic bandwidth and 85 GHz on 25Ω load and up to 0.6 A/W for 70 GHz intrinsic bandwidth and >110 GHz bandwidth with matching resistor.

Photodiode design and fabrication

The photodiode (PD) is grown on a semi-insulating substrate using MOVPE (metal organic vapor phase epitaxy) The structure comprises P doped InGaAs absorption layer (0.2 µm) with a inserted between a p+ InP barrier layer (0.5 µm) and a n- InGaAsP collector layer (0.4 µm). This structure, derived from the one described in[5], used a multimode diluted waveguide to allow an efficient coupling with a lensed optical fiber. The input facet is etched using ICP dry etching, which allows to realize on wafer AR coating and define a lens[6] to increase the lateral coupling tolerance.

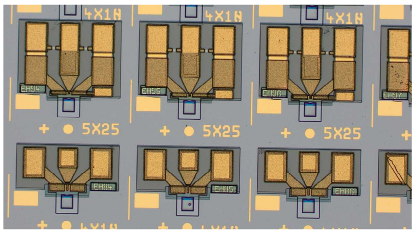

Fig. 1: Optical microscope photograph of UTC wafer with standard photodiode (bottom line) and photodiode with biasing circuit (top line)

The photodiode junction is etched using a mixed of ICP dry etching and wet etching. The main improvements compared to[5] are optimized epitaxial design with a gradient doping profile in P InGaAs absorber to decrease transit time, an improved process to increase responsivity and decrease parasitic capacitance and the optional implementation of biasing circuit comprising a decoupling capacitor and a matching resistor (Fig.1). The photodiodes are very compact (0.4×0.5 mm² even for devices including integrated biasing circuit) which allows to decrease the individual cost of a photodiode.

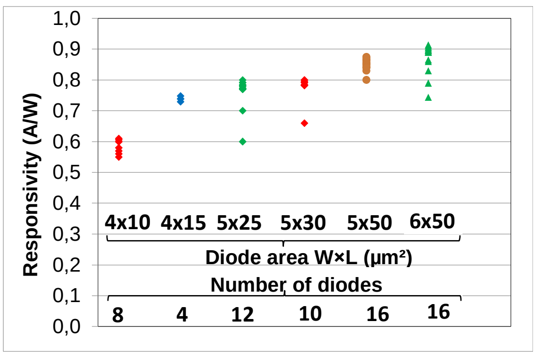

Fig. 2: Responsivity of the UTC photodiode at 1550 nm with the number of diode measured for each geometry

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Photodiode characteristics

We implement photodiodes with various dimensions from 4×10 µm² to 6×50 µm². Typical dark current at -2V bias is few nA for all diode size which shows the quality of the passivation of the junction using ICP-SiN$_x$ deposition.

Responsivity measurements are made using a lensed fiber with a mode field diameter (MFD) of 5.5 µm and are presented on Fig.2 at 1550 nm. We can notice that the photodiodes presents a high responsivity, up to 0.6 A/W for 4×10 µm² PD to 0.91 A/W for 6×50 µm² PD. For 4×15 µm² PD, the responsivity is already significantly improved compared to 4×10 µm² PD and reach 0.73 A/W which is very promising to reach simultaneously high bandwidth along with high responsivity. Responsivity variation over C-band is below 7 %.

These measurements, made on several photodiodes (4 to 16 depending on diode geometry, as shown in the graph), also show a good reproducibility of the results. The polarization dependence loss (PDL) is very low for all design and stay below 0.2 dB which is, to our best knowledge, state of the art result for such small photodiodes.

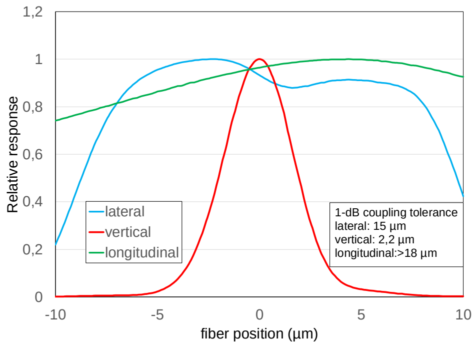

Fig. 3: Coupling tolerance measurements

The use of an integrated lens allows a broad alignment tolerance of 15 µm in the lateral direction which simplify the packaging of the photodiode. The tolerance is 2.2 µm in the vertical direction and above 18 µm in the longitudinal direction (Fig. 3).

We then measure the frequency response of our photodiodes using a heterodyne setup. A DC-110 GHz powermeter was used to measure the output HF power of the diode allowing doing a continuous measurement from 0 to 110 GHz. S-parameter based correction using the full S parameters of the photodiode, the probe+bias tee and the powermeter, is used to remove the losses of the probe and bias Tee used for the measurement but also to remove the ripple due to the reflection between the photodiode and the powermeter. We first show on Fig. 4 the frequency response of the photodiodes without matching resistor to find the intrinsic bandwidth of

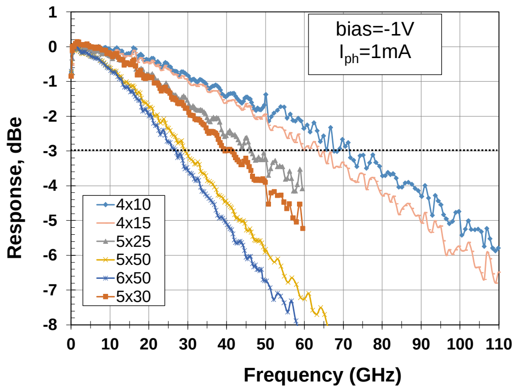

Fig. 4: Influence of the photodiode size on the frequency response

the photodiode on 50Ω load. The measurement was done at 1 mA photocurrent and -1V bias. We can notice that the smallest photodiode (4×10 µm²) present a wide 3 dB bandwidth of 70 GHz with a responsivity of 0.6 A/W, resulting in a wide bandwidth-efficiency product of 34 GHz on 50Ω load. The 4×15 µm² one demonstrates an even higher bandwidth-efficiency product of 37 GHz with a 3 dB bandwidth of 63 GHz and a responsivity of 0.73 A/W. Our photodiode design is very versatile as we obtain on the same wafer 0.8 A/W responsivity and 46 GHz bandwidth with 5×25 µm² PD and even the bandwidth of very large 6×50 µm² PD is still above 25 GHz.

S-parameter measurement allows to extract series resistance and capacitance of the different photodiodes which are respectively 27.8Ω and 16.6 fF for 4×10 µm² photodiode (123 GHz RC cut off), 19.5Ω and 23.1 fF for 4×15 µm² photodiode (99 GHz RC cut off), 11.5Ω and 42.8 fF for 5×25 µm² photodiode (60 GHz RC cut off). From these measurements, we assess an equivalent frequency corresponding to transit time around 80-85 GHz, which is known to be the limiting factor for small diodes. This transit time can easily be improved by reducing collector thickness which is the bandwidth limiting factor.

Fig. 5 presents the influence of the bias voltage on the bandwidth. We can see that even at 0V bias, a wide 3-dB bandwidth of 45 GHz is achieved without responsivity degradation compared to a -1V bias. This is very interesting to simplify photodiode packaging. Then the optimal bias voltage is -1V with 62 GHz bandwidth and the bandwidth decrease to 57 GHz and 53 GHz with respectively -2 and -3V bias voltage. This may results from the electron velocity decrease in III-V semiconductor for electric field is above ≈10 kV/cm. This confirms that the transit time in the collector is the major photodiode bandwidth contribution and that the it could be further increased by reducing the collector thickness.

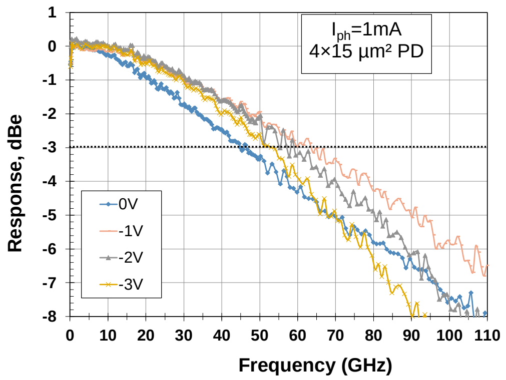

Fig. 5: Influence of the voltage on the frequency response

UTC are well known for their improved bandwidth under high photocurrent condition, due to negative differential capacitance and electrons overshoot velocity. We measured the frequency response for various photocurrent under -1, -2 and -3 V bias. Fig.6 shows the results under -2V which are the most interesting: the bandwidth increase from 57 GHz at 1 mA to 80 GHz at 5 and 6 mA photocurrent. Interestingly, at 6mA photocurrent, the responsivity increase by 17% compared to 1 mA photocurrent at 0.85 A/W due to increased temperature in InGaAs absorber.

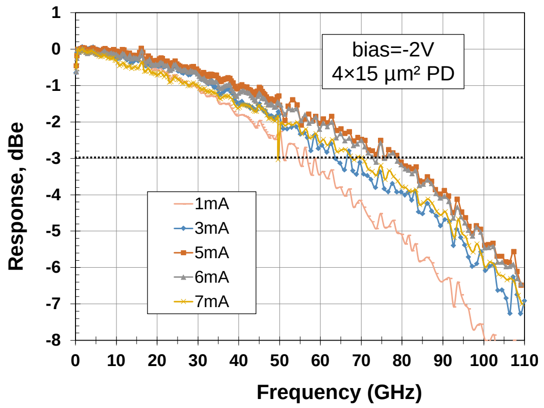

Fig. 6: Influence of the photocurrent on the frequency response

We implement biasing integrated circuit on samples of 5×25 and 4×10 µm². Fig.7 shows their frequency response at 1 mA photocurrent and of the 4×10 µm² PD at 3 mA. We can notice that due to a 25Ω effective load (50Ω matching resistor in parallel with 50Ω input impedance of the powermeter) the bandwidth is greatly enhanced and is now above 86 GHz for 5×25 µm² PD and above 110 GHz for 4×10 µm² PD which give records bandwidth-efficiency product of respectively 55 GHz and above 54 GHz on 25Ω load. With less than 2-dB losses at 110 GHz at 1 mA and only 1 dB losses at 3 mA, we expect a 3-dB bandwidth of at least 120 GHz for small 4×10 µm² photodiode.

We observe a small overshoot in the frequency response (around 50 GHz for 5×25 µm² PD, around 80 GHz for 4×10 µm² PD) which could be due to a transmission line inductive behaviour and can explain that we obtain a 3-dB bandwidth above the transit time limit.

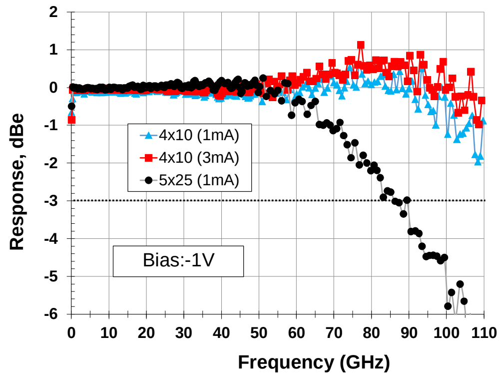

Fig. 7: Frequency response of photodiodes with integrated biasing circuit

Conclusions

In this paper, we have demonstrated an optimized waveguide UTC design allowing obtaining ultra compact photodiode with very low PDL below 0.2 dB and a very high efficiency-bandwidth product of 37 GHz on 50Ω load and at least 55 GHz on 25Ω load. This allows us to realize high speed photodiode with 0.6 A/W responsivity and 70 GHz bandwidth on 50Ω load. This bandwidth is expanded above 110 GHz bandwidth on 25Ω load which also allow a very high 0.8 A/W responsivity with 86 GHz bandwidth. This is a promising building block for future communication above 100Gbaud and high speed instrumentation equipment.

Acknowledgements

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