High Linearity and High Responsivity UTC Photodiode for Multi-Level Formats Applications

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Abstract *We present an evanescent waveguide InGaAs/InGaAsP UTC PD with respectively a bandwidth > 50 GHz, a responsivity of 0.55 A/W and an IP3 of 19.7 dBm at 10 mA and 20 GHz.*

Introduction

Optical receivers for ultra-high bit rate communication systems (40 and 100 Gb/s) use an optical preamplifier (in direct detection scheme) or a CW laser acting as a local oscillator (in coherent systems) which feed the photodiode with high optical power. For example, coherent receiver uses linear filters incorporated with DSP (digital signal processing) to reduce distortions occurring in the fibre. This implies a linear operation of the optical front-end receiver. UTC PD have demonstrated high power and high linearity operation[1-3] and are therefore a very promising structure for this application.

We recently reported an IP3 of 35 dBm at 20 GHz and 40 mA on a backside illuminated UTC with a bandwidth of 16 GHz[2]. However, detector saturation and linear operation degrade when the photodiode area is scaled down to increase the 3-dB bandwidth.

In this paper, we present a 4×15 µm² evanescent waveguide UTC PD with a bandwidth in excess of 50 GHz (suitable for 100Gb/s QPSK transmission) and a responsivity of 0.55 A/W with a very low TE/TM polarization dependence loss (0.1 dB). Very good linear operation is demonstrated using third-order intermodulation distorsion (IMD3) measurement and a third-order intercept point (IP3) of 19.7 dBm is achieved at 20 GHz, 10 mA photocurrent and -4V applied bias.

Design and fabrication

The evanescent waveguide UTC photodiode is grown using GS-MBE on InP-Fe substrate. This structure uses a thin p InGaAs absorption layer inserted between a P+ InP barrier layer and a N- InGaAsP (λ=1.3 µm) collector layer[1]. The multimode waveguide made with thin InGaAsP layers inserted in InP allows both high responsivity and a progressive absorption of light which allows high power operation[1]. The fabrication process uses mainly ICP dry etching for mesa realization, device isolation and waveguide input facet etching. SiN_x-CVD is used as a passivation layer and acts as an AR-coating layer. The dry etching of the waveguide input facet allows a precise control of the length of the multimode waveguide which becomes independant of the cleaving process. Fig.1 shows a SEM view of the waveguide UTC showing the monolithic lens achieved by dry etching of the mirror facet to improve optical coupling efficiency.

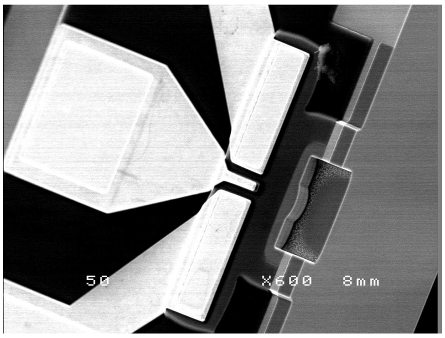

Fig. 1: SEM picture of a lensed facet waveguide UTC

Typical series resistance and capacitance extracted from S11 measurements up to 65 GHz are respectively 20Ω and 26 fF for a 4×15 µm² PD and 13Ω and 48 fF for a 4×30 µm² PD.

Results and discussion

Fig. 2 shows the frequency response of a 4×15 µm² UTC photodiode measured with a heterodyne setup at different photocurrents. 3-dB bandwidth increases from 35 GHz (responsivity of 0.51 A/W and 0.1 dB TE/TM loss) at a photocurrent of 0.1 mA to more than 50 GHz (responsivity of 0.55 A/W) at a photocurrent of 10 mA. For comparison, the bandwidth of a 4×30 µm² (0.62 A/W) photodiode increases from 35 GHz (Iph=0.1 mA) to 45 GHz (Iph=10 mA). Three main reasons can explain the bandwidth improvement of an UTC PD at high photocurrent level[2]:

- Reduction of the transit time in the absorption layer by the self-induced field: the majority hole current-density induces an internal electric field which accelerates electrons.

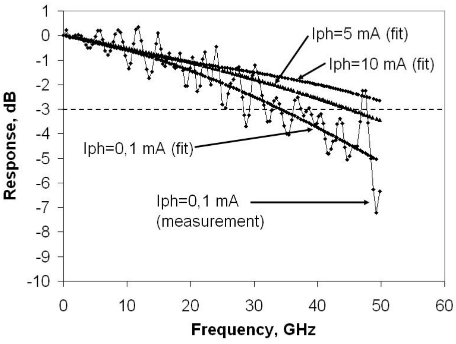

Fig. 2: Frequency response of a 4×15 µm² UTC photodiode for different output photocurrent at -3V applied bias

978-3-8007-3173-2

- Reduction of the transit time in the collector: under high electron injection, the electric field at the collector input is reduced which allows velocity overshoot of electrons.
- Reduction of the total capacitance by the subtraction of the differential capacitance Cdiff= Iph×$(d\tau_C/dV_{AC})$, where V_{AC} is the ac voltage.

As the bandwidth at 0.1 mA photocurrent is the same for a 4×15 µm^2 PD and a 4×30 µm^2 PD, 3-dB bandwidth is mainly limited by transit time under low optical power injection. As a result, the bandwidth improvement can be explained by the self induced field in the absorption layer and the velocity overshoot effect in the collector. Using a gradual doping in the absorption layer produces a quasi-field which increases electron velocity in the absorption layer, as the self-induced field at high photocurrent, which improves 3-dB bandwidth at low injection level. First results with the same structure and a gradual doping allowing an internal potential of 20 mV in the absorption layer show a bandwidth improvement from 35 GHz to 42 GHz at 0.1 mA photocurrent for a 4×15 µm^2 PD.

IMD3 measurements were made with a two-tone setup[2] for different diodes areas. Two DFB lasers are externally modulated at f_1=20GHz and f_2=20.1 GHz. The signals are combined, amplified in an EDFA, and then attenuated to control the optical power. The Mach-Zehnder modulators used for the external modulation of optical signals are biased at the quadrature point to minimize their second harmonic contribution to the measured IMD3. The modulation index m is tuned between 2.5% and 8%. Fig.3 shows the result of IMD3 measurements for a 4×15 µm^2 PD at different reverse bias voltages of respectively 2, 3 and 4V. IP3 are extrapolated from the fundamental signal (line of slope 1) and the IMD3 signal (line of slope 3). Table 1 presents a summary of the results for the different PD sizes.

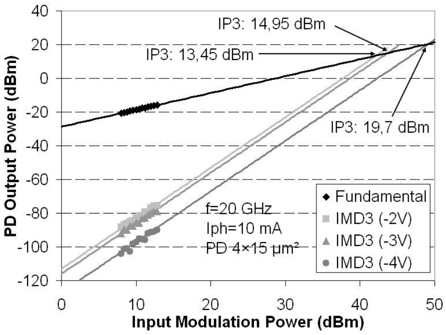

Fig. 3: IMD3 measurements for a 4x15 µm^2 photodiode at 20 GHz and 10 mA photocurrent

From Fig 3, it appears that the linearity is improved with increased applied bias. Increasing reverse bias prevents from space charge effect and allows a more linear operation. A limited improvement of 1.5 dB is observed when the reverse bias is increased from 2V to 3V. However, an improvement of more than 4.7 dB is achieved for a reverse bias of 4V. Table 1 confirms this behavior for a 4×25 and a 4×30 µm^2 PD which reaches an IP3 of 23.3 dBm at -4V applied bias which is compatible with the output power levels of the local oscillator used in coherent receivers (around 13 dBm[4]).

Tab. 1: IP3 of UTC photodiode at 20 GHz and 10 mA photocurrent

Diode size	IP3 (dBm)		
	V=-2V	V=-3V	V=-4V
4 × 15 µm^2	13.45	14.95	19.7
4 × 25 µm^2	13.95	15.15	21.6
4 × 30 µm^2	15.25	16.4	23.3

Worth noting is the degradation of IP3 under large reverse bias (4V) when the photodiode size decreases probably due to an internal thermal heating. Fig. 4 confirmed this limitation with the bandwidth degradation occurring for the 4×15 µm^2 PD when the applied reverse bias increases from 3V to 4V and 4.5V.

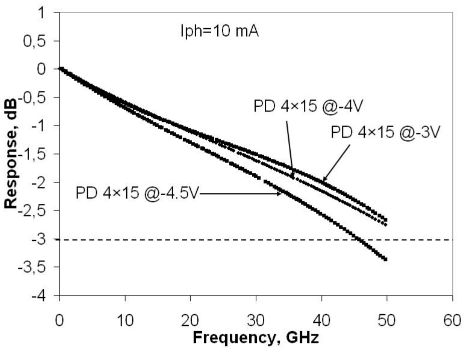

Fig. 4: Frequency response of a 4×15 µm^2 UTC PD at 10 mA photocurrent and different bias voltage

Conclusions

In this paper, we presented a photodiode with high responsivity (0.55A/W), high bandwidth (>50 GHz) and high linearity (IP3=19.7 dBm) under high output photocurrent (10 mA). Under moderate bias voltage, reducing the size of UTC diode has a limited effect on its linearity (only 1.45 dB penalty between 60 and 120 µm^2 PD at -3V). Increasing the applied bias to -4V improves considerably linearity with IP3 reaching 23.3 dBm for 120 µm^2 PD and 19.7 dBm for 60 µm^2 PD as needed for highly linear receivers operating at high bit rates.

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