High-Power Performance of Type-II GaInAsSb/InP Uniform Absorber Uni-Traveling Carrier Photodiodes

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Abstract: We report the first power performance of Type-II GaInAsSb/InP UTC-PDs. The UTC-PDs attain a zero-bias output power of -14 dBm at 100 GHz, one of the highest reported for any zero-bias photodiodes.

1. Introduction

Interest in applying Millimeter-waves (MMWs) and Terahertz (THz) waves for broadband communications has increased to meet the demand for higher data rates. One of the challenges is the development of solid-state signal sources in this frequency range. Photonic techniques have proven to be an excellent alternative to the conventional electronic systems to generate signals in the MMW and THz range [1]. Therefore, an optical-to-electrical (O/E) signal interface, such as high-bandwidth photodiodes is one of the key elements of such systems. In addition, the high-power capability of a PD is crucial as it eliminates the need for high-bandwidth post-amplification electronics, thus extending the bandwidth of the entire system [2].

Uni-travelling carrier photodiodes (UTC-PD) are good candidates for high-bandwidth and high-power operations as it involves the transport of fast-moving carriers (electrons) through the absorber and collector layers. This avoids the long tail response and space charge effect associated with hole drift transport taking place in PIN-PDs. UTC-PDs with heavily p-doped absorber and lightly n-doped collector layer are also promising candidates for bias-free operation [2, 3]. 3-dB bandwidths of 310 GHz [4] and output power extending 20 mW at 100 GHz [2] have been demonstrated for UTC-PDs with a graded GaInAs absorber layer. Zero-bias bandwidth of 170 GHz and output power of -11.3 dBm at 170 GHz has been demonstrated for a Type-II ($GaAs_{0.5}Sb_{0.5}$/InP) UTC-PD with a modified graded collector layer of InP and $In_{0.52}Al_{x}Ga_{0.48-x}As$ [3].

The conduction band discontinuity of $\Delta E_C = 0.25$ eV between a GaInAs absorber and an InP collector, impedes electron transport from the absorber to the collector. Regardless of various schemes e.g., step-grading [4] or chirped-superlattice [5], the travelling space charge of electrons at high excitation eventually leads to the collapses of the electric field in the collector and limits the final performance of the device. Type-II UTC-PDs with a GaAsSb absorber are good candidates for high-power operations, but the bandwidth is limited due to the low electron mobility in GaAsSb [6]. We have demonstrated better electron transport properties of GaInAsSb alloy for application in UTD-PDs than GaInAs and GaAsSb [7]. The addition of In- to GaAsSb alloy was shown to increase the mobility of minority electrons by raising the L-valley compared to GaAsSb. This reduces the population of slower electrons in the L-valley and eliminates the L-valley blocking effects at the heterojunction with InP while maintaining the type-II band alignment with InP [8].

The simpler epitaxial structure enables reproducible growth and fabrication process leading to stable device performance. This work goes beyond our previous work and demonstrates that GaInAsSb is an advanced absorber material for high-bandwidth and high-power UTC-PDs. The UTC-PDs show a transit-time limited bandwidth of 274 GHz [7] and a linear RF response beyond 15 mA at 100 GHz. The devices have a record zero-bias bandwidth of 78 GHz for a 50 μm^2 device [9] and attain a saturation photocurrent of 7 mA and RF power of -14 dBm for an 80 μm^2 device.

2. Device Fabrication and Results

The detailed epitaxial structure of GaInAsSb/InP UTC-PDs can be found in [7]. The design includes a 225 nm InP collector layer n-doped at 6×10^{16} cm^{-3} and a 100-nm uniform quaternary $Ga_{0.81}In_{0.19}As_{0.65}Sb_{0.35}$ absorber p-doped at 1.36×10^{18} cm^{-3}. Fig.1 shows the simulated equilibrium band diagram for uniform GaInAsSb UTC-PDs at 300 K. Photodiodes with different sizes were fabricated by optical lithography and wet etching [7].

DC characterization of the photodiodes was performed using an HP4156B semiconductor parameter analyzer. The room temperature I-V characteristics of the PDs show a dark current smaller than 10 nA up to a reverse bias of -5 V [7]. The measured responsivity for larger area devices was 0.1 A/W at -3 V when the collector was fully depleted.

The RF performance of the PDs was characterized using a Thorlabs MX70G electrical-to- optical converter at λ = 1550 nm and a PNA-X vector network analyzer from 0.2 to 60 GHz. An off-wafer LRRM (line/reflect/reflect/match) calibration followed by a fixture de-embedding in the PNA-X brings the reference plane to the end of the RF cable in the input port and to the tip of the RF probe at the output port. The modulator's frequency response was de-embedded from the measurement.

For power measurements at 100 GHz, a laser heterodyne beating system at λ = 1550 nm was used with a W-band RF probing system and a W-band RF power meter. The modulation depth was 65%. An Erbium-Doped Fiber Amplifier (EDFA) was used to amplify the optical power up to 25 dBm. The RF power reported here has been carefully de-embedded considering the insertion loss of about 1.3 dB of the WR-10 waveguide probes. The modulated light signal was then coupled into the top-illuminated PDs using a single-mode optical fiber with a spot diameter of ~ 9 μm.

The frequency response of the devices has been reported both at -2.5 V and at 0 V [7, 9]. For a 50 μm^2 device, zero-bias $f_{3\text{-dB}}$ bandwidth of 78 GHz was determined, which increased to 100 GHz when the collector was fully depleted at -2.5 V [9]. Figs. 2 and 3 show the relative S_{21} photoresponse plotted against frequency for GaInAsSb UTC-PDs of different sizes at 0 V and -3 V, respectively. Light traces represent measured data, while bold traces show the equivalent circuit model fit, as detailed in [7]. For the 80 μm^2 device, the $f_{3\text{-dB}}$ cut-off is 45 GHz at 0 V and is more than 60 GHz at -3 V, which is beyond the capabilities of our measurement setup. As the devices are RC-limited, the equivalent circuit model allowed us to distinguish between the contributions of the RC-delay and transit-delay to the $f_{3\text{-dB}}$ cut-off frequencies. A transit-time limited cut-off frequency of f_T = 274 GHz was extracted for the GaInAsSb absorber [7].

In this report, the 100 GHz power performance of GaInAsSb UTC-PDs at 0 V and -3 V is discussed. Fig. 4 shows the measured photogenerated RF output power versus the photocurrent obtained with the beating setup. The ideal RF power under a 50 Ω load is also plotted against the averaged photocurrent for reference. The RF power of 80 μm^2, 100 μm^2, and 115 μm^2 devices is plotted at 0 V and -3 V at 100 GHz. The devices show a linear response up to a high photocurrent of 15 mA and an RF power over 0 dBm. Clearly, the saturation photocurrent is well beyond 15 mA and was beyond the measurement setup capability.

At zero-bias, the 80 μm^2 devices show a saturation photocurrent of 7 mA and an RF power of -14 dBm. The 100 μm^2 and 115 μm^2 devices begin to saturate at 10 mA with an RF power of -15 dBm. Table I compares the zero-bias device performance of our device with the reported zero-bias UTC-PDs. The devices presented in this work show comparable power performance to Type-II ($GaAs_{0.5}Sb_{0.5}/InP$) UTC-PDs with a modified graded collector layer of InP and $In_{0.52}Al_xGa_{0.48-x}As$, which is designed for a zero-bias performance and flip-chip bonded for better output power [3]. Our devices show better performance compared to Type-II MUTC with a saturation photocurrent of 2 mA and an RF power of -15 dBm [10] and Type-I GaInAs based UTC-PD with a saturation photocurrent of 2 mA and an RF power of -18.6 dBm [11]. This performance is among the highest reported for any zero-bias photodiode.

The present study highlights the interest in GaInAsSb absorbers for UTC-PDs due to their better electron transport properties. The transit-time limited cut-off as well as the power performance of our quaternary UTC-PDs can be further improved by composition and/or doping grading schemes. Future work will focus on improving the overall responsivity with resonant cavity structures and/or conversion to a waveguide architecture [1, 12].

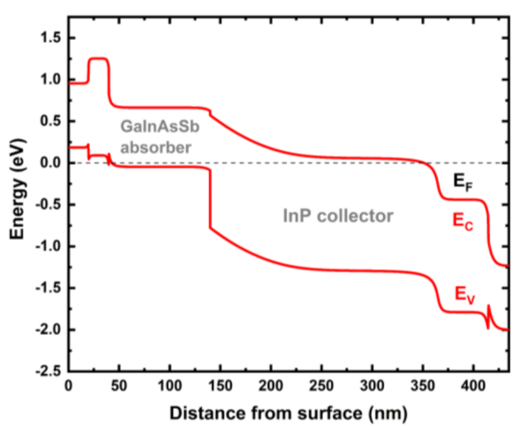

Fig 1: Simulated equilibrium band diagram for quaternary GaInAsSb absorber UTC-PD at 300K

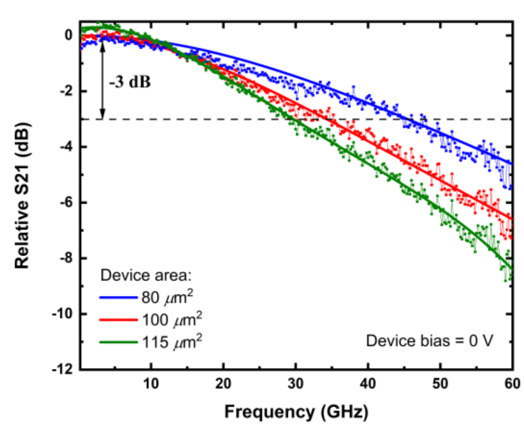

Fig 2: Measured (thin traces) and equivalent circuit model fitted (bold traces) frequency response of GaInAsSb absorber based UTC-PDs at 0V.

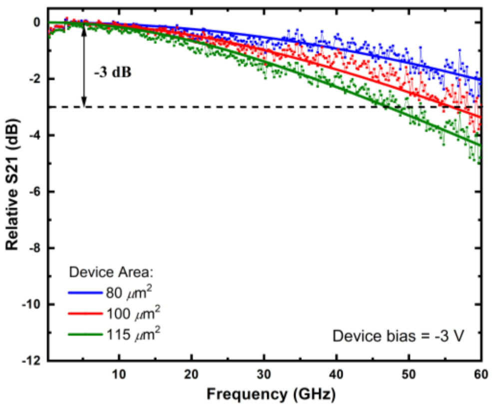

Fig 3: Measured (thin traces) and equivalent circuit model fitted (bold traces) frequency response of GaInAsSb absorber based UTC-PDs at -3 V.

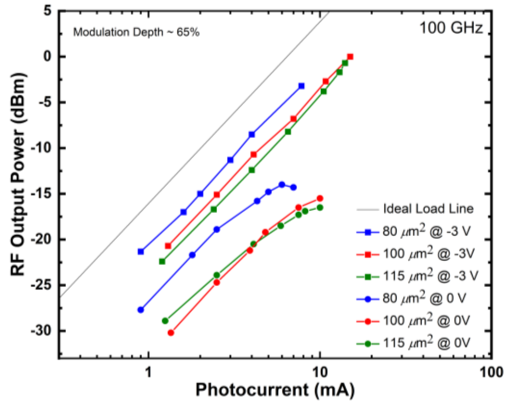

Fig 4: The RF output power dependence of photocurrent at 100 GHz for UTC-PD at 0 V and -3 V at 65% modulation depth.

Table I: Performance comparison for zero-bias photodiodes

Ref	Structure	Type	Size (μm^2)	Responsivity (A/W)	Zero-bias Bandwidth (GHz)	Zero-bias saturation current (RF power)
[3]	Graded GaAsSb/InP/ $In_{0.52}Al_xGa_{0.48-x}As$	Flip – Chip bonded	28	0.09	170	8 mA (-11.3 dBm) @ 170 GHz
[10]	Graded GaAsSb/InAlGaAs	Waveguide	16	0.14	66	2 mA (-15 dBm) @ 100 GHz
[11]	GaInAs/InP	Back illuminated	80	0.2	110	2 mA (-18.6 dBm) @ 100GHz
This work	Uniform GaInAsSb/InP	Top illuminated	80	0.1	45	7 mA (-14 dBm) @ 100 GHz

3. Conclusion

We have demonstrated the power performance of GaInAsSb as an absorber for high-power photodiodes. Linear response without RF output saturation was observed for a high photocurrent of 15 mA and RF power over 0 dBm. The 80 μm^2 devices showed saturation photocurrent of 7 mA and an RF power of -14 dBm. The 100 μm^2 and 115 μm^2 devices showed saturation photocurrent above 10 mA and an RF power above -15 dBm. Improving the overall performance of UTC-PDs by scaling down the device size and optimizing the epitaxial layers is currently underway.

4. Reference

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