Waveguide Uni-Traveling-Carrier Photodiodes for mmW Signal Generation: Space-Charge Impedance and Efficiency Limitations

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Overview

Photonic generation of mmW signals using high-speed photodiodes is promising due to the potential for ultra-wide bandwidth [1-3]. Uni-traveling carrier photodiodes (UTC-PDs) based on the InGaAs/InP material system have demonstrated measured RF output powers of 10 dBm, 6 dBm, and -2.2 dBm at frequencies of 100 GHz, 170 GHz, and 300 GHz respectively [4-6]. However, the power conversion efficiency (PCE) is a metric that has seen relatively little investigation and is important for practical applications [7]. The PCE is given by the output RF power, $\frac{1}{2}R_L I_{RF}^2$, divided by the sum of the input optical power, P_{opt}, and the DC power, $I_{ph} \cdot V_{Bias}$, applied to the diode. For the results in Refs. 4-6, the PCE is in the range of 1% to 10%. To investigate the efficiency limitations, we utilize the assumptions from Ref. 7 to write the PCE as $\eta_{RF} = \frac{1}{2} \cdot \frac{m^2 R_L}{I_{DC}^{-1}(V_{th} + 1/\mathcal{R}) + \alpha^{-1} + m(R_L + \alpha^{-1})}$ (1), where R_L is the load impedance, m is the optical modulation index, I_{DC} is the average photocurrent, V_{th} is the minimum bias to operate at high frequencies for low photocurrent, α^{-1} is the device series resistance, and $\mathcal{R}$ is the optical to electrical responsivity (A/W). The series resistance term, α^{-1}, includes resistances of the device such as contact resistance and sheet resistance, as well as an effective space-charge impedance. The space-charge impedance results from the electrical field of the photo-generated carriers in the junction that reduce the built-in field. Waveguide (WG) UTC-PDs were fabricated and here we characterize their space-charge impedance to demonstrate that this is the limiting factor for PCE and an important metric to quantify in state-of-the-art UTC-PDs.

Experimental Results

Fig. 1(a) shows a false colored SEM of the fabricated WG UTC-PD. A simulation of the optical mode along with the epitaxial structure is shown in Fig. 1(b) and 1(c). RF characterization of the device was completed using a 67 GHz Lightwave Component Analyzer. The frequency response of the device is shown in Fig 2(a) at a low (blue) and high (red) photocurrent level with a bias of -2 V. The 3-dB bandwidth under various photocurrents and bias voltages is shown in Fig. 2(b), demonstrating bandwidths of 45 GHz under low photocurrent (~90 μA) and increasing to 50 GHz under large photocurrent (~6 mA). We also measured S_{11} under low photocurrent for extracting the junction capacitance and series resistance of 27 fF and 5 Ω using the RC model shown at the inset of Fig. 2(b).

To extract the effective series resistance included in Eq. 1, the relative power measured at 60 GHz as a function of input photocurrent at different reverse biases is plotted in Fig. 3(a) along with the RF compression relative to the 50-Ω line (black dashed line in Fig. 3(a)) shown in Fig. 3(b). For each reverse bias, the photocurrent at which the compression reaches -1 dB is plotted in Fig. 3(c). The slope of this curve, 275 Ω, provides the total series resistance, $\alpha^{-1} + m(R_L + \alpha^{-1})$. For this measurement, the modulation index is around 0.1 resulting in a series resistance, α^{-1}, of 245 Ω. Comparing this to the series resistance obtained from fitting S_{11} shows that the major contribution to the effective series resistance is the space-charge impedance. Inserting the effective series resistance into Eq. 1 gives a maximum achievable efficiency of 4.6% for a modulation index of 1.

Conclusion

We fabricated and characterized a WG UTC-PD designed for mmW generation. The device characteristics were investigated to understand the effect of space-charge impedance on the PCE. This was shown to be the dominant factor in limiting the maximum achievable PCE. This result emphasizes the need for state-of-the-art photodiodes to be characterized for space-charge impedance in addition to bandwidth and RF output power at mmW frequencies. As was shown in Fig. 1(b), there is strong optical overlap with the absorbing region. The epitaxial and waveguide design are two important parameters that can be engineered to potentially obtain lower space charge impedance.

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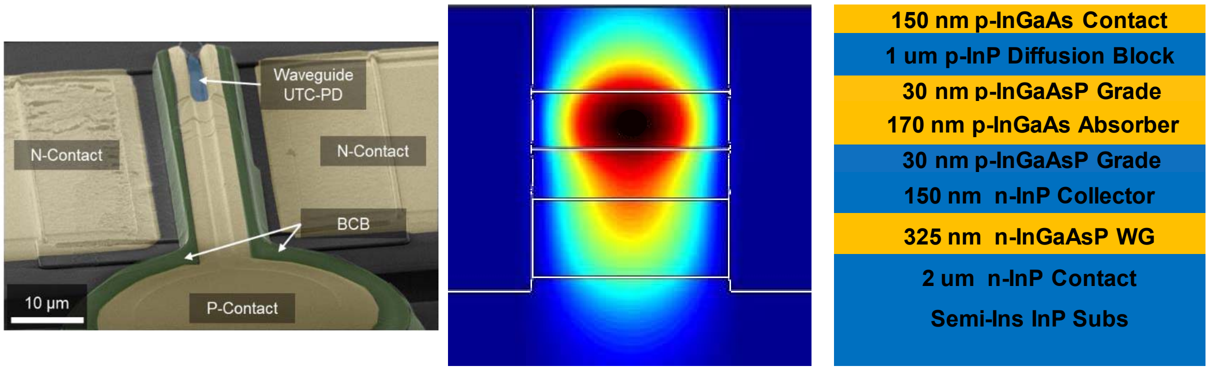
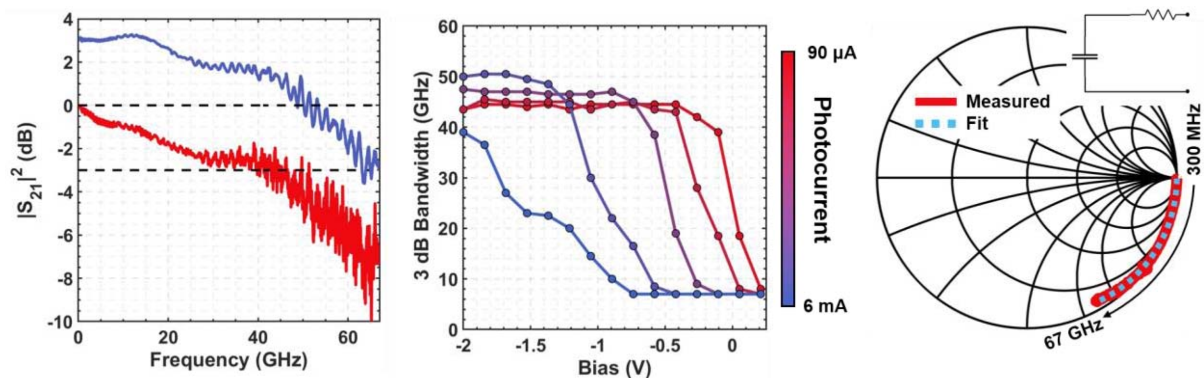


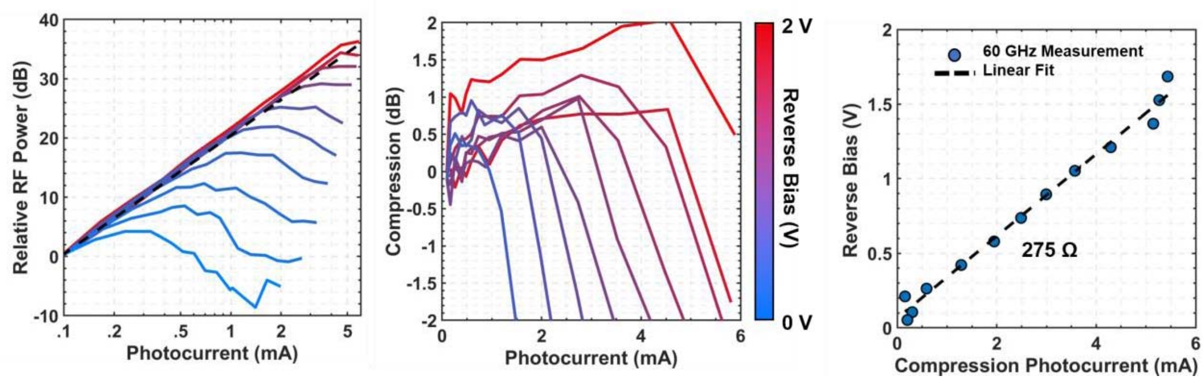
(a) (b) (c)

Fig. 1. (a) False colored SEM image of fabricated device. BCB was used to reduce parasitic capacitance. (b) Optical mode of the waveguide. (c) Epitaxial structure. The waveguide design, including both the physical layout and layer compositions, can be engineered to reduce the space-charge impedance.



(a) (b) (c)

Fig. 2. (a) Frequency response of device at -2 V bias showing 3-dB bandwidth of 45 GHz under low (red) and 50 GHz under high (blue) optical illumination. (b) 3-dB bandwidth for increasing photocurrent and bias ranging from 90 µA to 6 mA and 0.25 V to -2 V. (c) S_{11} from 300 MHz to 67 GHz at -2 V bias. Fitting to the model shown in the inset gives a total capacitance of 27 fF and series resistance of 5 Ω.



(a) (b) (c)

Fig. 3. (a) Relative RF power at 60 GHz as a function of DC photocurrent under various reverse biases. Black dashed line is 50 Ω line. (b) Compression from 50 Ω line as a function of photocurrent. The color legend applies to both (a) and (b). (c) Bias voltage at -1 dB compression for various photocurrents. The slope of the line, 275 Ω, gives the total series resistance.