Ultrafast MUTC Photodiodes with 230 GHz Bandwidth

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***Abstract*—Novel back-illuminated modified uni-traveling-carrier photodiodes (MUTC-PDs) are designed to achieve ultra-wide bandwidth. The fabricated 3-µm-diameter PDs demonstrate a 3-dB bandwidth of 230 GHz with a saturation power of –4.94 dBm @ 220 GHz.**

Keywords—millimeter-wave, inductive peaking, modified uni-traveling-carrier photodiode, high-speed.

I. INTRODUCTION

Photonics based millimeter-wave (MMW, 30 GHz-300 GHz) signal generation has been widely used in broadband MMW over fiber wireless communications, photonic MMW measurement instruments, spectroscopic imaging [1-3], due to its flexibility in frequency and power tuning. Uni-traveling carrier photodiodes (UTC-PDs) exhibit excellent performance in generation of high frequency and high power MMW signals. For instance, the evanescent-coupled UTC-PDs reported in [4] demonstrate a 3-dB bandwidth of 170 GHz, and an output power about −9 dBm at 200 GHz. Flip-chip bonded 4-µm-diameter modified UTC-PDs exhibit a 3-dB bandwidth up to 120 GHz as well as an unsaturated RF output power of −8.5 dBm at 160 GHz [5]. In our previous work, 4.5-µm-diameter photodiodes with a 3-dB bandwidth of 156 GHz and a saturation RF power of −0.53 dBm at 170 GHz are demonstrated [6].

In this work, a novel MUTC epitaxy structure with gradient p-doped thin absorption layer and optimized cliff layer is adopted to achieve high transit-time-limited bandwidth. Inductive peaking is implemented by high-impedance transmission line to enhance the RC-limited bandwidth. Meanwhile, reduced active area formed by electron beam lithography (EBL) helps further improve the bandwidth. The 3-µm diameter MUTC-PD exhibits a ultrawide bandwidth of 230 GHz, together with a high saturation output power of −4.94 dBm at 220 GHz.

II. DEVICE STRUCTURE AND DESIGN

The epitaxial layer structure of the proposed MUTC-PD is shown in Fig. 1(a). A gradient p-doped thin absorption layer of 80 nm and relatively thick InP depletion layer of 200 nm are used to attain an extremely wide transit-time-limited bandwidth. A 20-nm thick cliff layer with optimized doping concentration is inserted at the absorber/collector interface to reduce the transit time of electrons. As shown in Fig. 1(b), for the PD with an n-doped cliff layer of 3×10^{17} cm^{-3}, the electric field in the InP-depletion region is 20-40 kV/cm (indicated by the blue shade), which falls in the range for electron velocity overshoot [7]. The extracted transit time of electrons under different doping concentrations is plotted in Fig. 1(c). A transit time as low as 0.75 ps is secured with a cliff layer doping level of 3×10^{17} cm^{-3}.

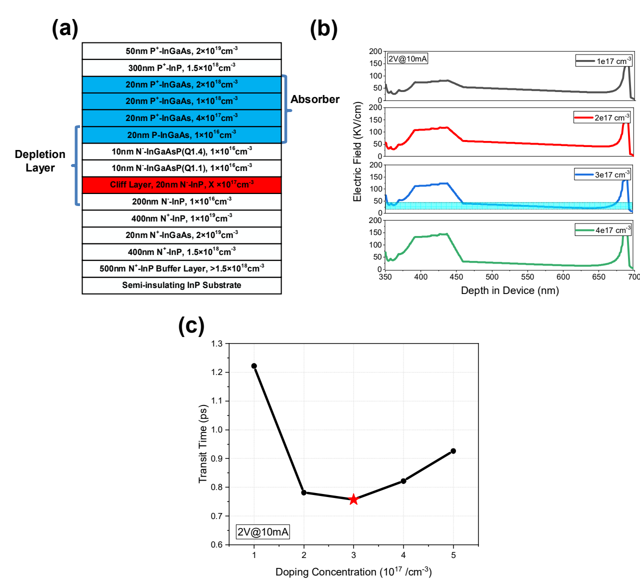

Fig. 1. (a) Epitaxy layer structure of proposed MUTC-PD. (b) Electric field and (c) transit time under different doping concentration.

The circuit model shown in Fig. 2(a) is adopted to estimate the frequency response of the PD [6]. The impact of the CPW inductance L_c on the frequency response of the 3-µm-diameter PD is shown in Fig. 2(b), and the maximum 3-dB bandwidth is obtained with L_c around 40 pH. The parameters for CPW optimization are the length L and the gap G of the high impedance line. It is found that the gap G has a significant effect on the inductance and the impedance of the transmission line. Therefore, firstly G is optimized with fixed L for better frequency response. As shown in Fig. 2(c), both the inductance and the impedance increase with the gap G. G = 60 µm is chosen to ensure L_c = 40 pH, and the corresponding impedance is 114 Ω. Then the maximum bandwidth is optimized by tuning L with fixed G = 60 µm, as shown in Fig. 2(d). For L = 20 µm, the 3-dB bandwidth is 238 GHz, about 86 GHz improvement over that of a PD with a standard 50 Ω CPW (indicated by the dashed line).

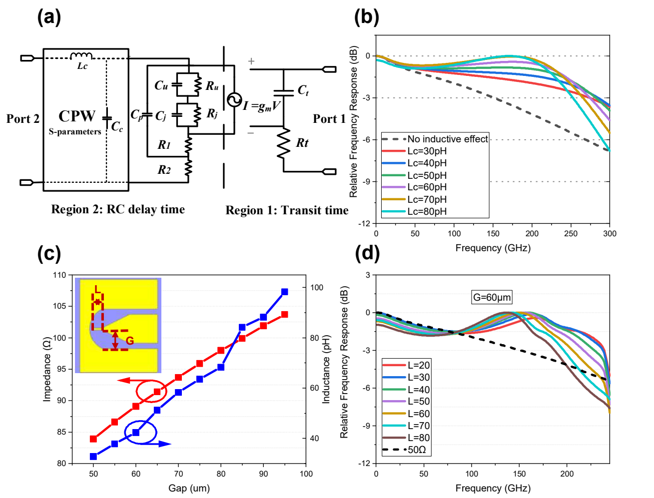

Fig. 2. (a) Equivalent circuit model for frequency response simulation. (b) Frequency responses with different CPW inductances. (c) Characteristics of high impedance line with different gaps. (d) Variation of the PD frequency response with the high impedance line length.

III. Experiment Results

For the fabrication of the 3-µm-diameter MUTC-PD, electron beam lithography is employed to define the p-electrode and the p-mesa to ensure accurate and consistent dimensions. The mesa is formed by a combination of plasma dry-etching and HCl wet-etching process. The microscopic photos of the fabricated 3-µm-diameter device are shown in Fig. 3(a). The frequency response of the device is measured with the heterodyne-beating system. The RF power from dc to 110 GHz is tested by a Keysight E4419B power meter. As for frequencies above 110 GHz, a VDI-Erickson power meter (PM5B) is used to record the RF power. The loss of the coaxial cables, the waveguide probes and the waveguide transitions are carefully calibrated out. The frequency response tested under 3 mA with a fixed reverse bias of 2 V are plotted in Fig. 3(b). The ultrafast PD exhibits a 3-dB bandwidth of 230 GHz. The output RF power versus photocurrent of the 3-µm-diameter MUTC-PD at 220 GHz with 2 V reverse bias is plotted in Fig. 3(c). The photocurrent at 1-dB compression is 5.85 mA, corresponding to an output power of −4.94 dBm at 220 GHz.

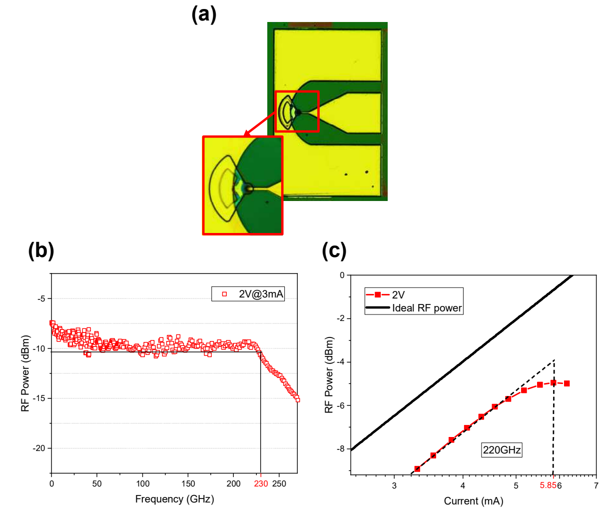

Fig. 3. (a) Microscopic photos of the fabricated PD. (b) Frequency response of 3-µm-diameter PD. (c) Output RF power versus output photocurrent at 220 GHz under 2V bias voltage.

Acknowledgements

This work was supported in part by National Key R&D Program of China (2018YFB2201701); National Natural Science Foundation of China (62235005, 62127814, 62225405, 61975093, 61927811, 61991443, and 61974080); and Collaborative Innovation Centre of Solid-State Lighting and Energy-Saving Electronics.

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