Ultra-Wide Bandwidth and High Saturation Power Uni-Traveling Carrier Photodiodes

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Abstract: In this talk, we present our recent work on ultra-wide bandwidth (>100 GHz) uni-traveling-carrier photodetectors with high saturation power, by optimizing the photogenerated carrier transport and taking advantage of the inductive gain peaking effect. © 2024 The Author(s)

1. Introduction

Ultra-wide bandwidth photodiodes (PDs) with high saturation power are key components for millimeter-wave (MMW) photonic transmission and processing systems [1, 2]. Uni-traveling carrier PDs (UTC-PDs) have demonstrated broad bandwidth and high saturation performance due to the elimination of hole transportation in traditional PIN photodiodes. Recently, the increasing demand of MMW and sub-terahertz (THz) applications drives the need for PDs with bandwidth over 100 GHz [3-6]. Ultra-wide bandwidth UTC-PDs, especially modified UTC-PDs (MUTC-PDs), have been extensively investigated for high frequency optical-to-electrical conversion. However, high power performance of PDs at higher frequencies remains a challenge, due to their small size and the high charge density.

Recently, the effects of high-speed photogenerated carrier transport and inductive gain peaking have been investigated, and several new UTC-PD structures are proposed to realize both improved saturation characteristics and enhanced bandwidth simultaneously. In the talk, we present our recent work on ultra-wide bandwidth photodetectors with high saturation power.

2. Design, Fabrication and Performance of Ultra-wide Bandwidth (>100 GHz) Photodetectors

In UTC-PDs, the transport time of photogenerated electrons should be effectively reduced for enhanced device bandwidth. Higher electron speed results in lower carrier density, thus alleviating the charge screening effect and improving the saturation power. The internal electric field of UTC-PDs should be carefully tailored by optimizing the epitaxial structure.

On the other hand, higher bandwidth normally means smaller PD sizes. By adopting inductive coplanar waveguide (CPW) electrodes to enhance the frequency response at high frequencies, a larger PD size can be adopted for improved saturation performance while maintaining wide bandwidth. In this talk, different UTC-PD structures are presented for improved bandwidth and high saturation power.

2.1 100 GHz Bandwidth Dual-Drifting Layer (DDL) Structure UTC-PD with High Saturation Power

In the case of high power optical signal detection, there is a large voltage swing across the load resistor due to the large photocurrent. When the voltage swing is in the negative half cycle, the voltage across the depletion region of the PD is weakened, resulting in device performance degradation. In order to improve the saturation characteristics of the PD, it is necessary to reduce the load bias swing effect, e.g. by increasing the DC bias voltage. However, this will interfere with the velocity overshoot effect, resulting in a reduction in bandwidth.

To overcome the above issue, we proposed a dual-drifting layer structure UTC-PD [7] shown in Fig. 1(a), and experimentally verified its high saturation characteristics in the sub-THz frequency band. The double-drift layer structure consists of a velocity overshoot region and a velocity saturation region, with a 20 nm thick p-type InP layer in between, as shown in Fig. 1(b). By carefully designing the electric field profile in the depletion region, the photogenerated electrons in the velocity overshoot layer will travel at an overshoot velocity to reduce the carrier transport time. On the other hand, electrons travel at the saturation velocity in the velocity saturation layer. It also serves as the electric field loading region, ensuring that the device has the ability to operate under high bias conditions and effectively reduce the impact of the load bias swing effect for improved saturation characteristics without affecting the velocity overshoot. The fabricated 6-μm-diameter backside-illuminated DDL photodetector exhibits a responsivity of 0.17 A/W and a 3-dB bandwidth of 106 GHz under the reverse bias of 4 to 8 V, as shown in Fig. 1(c). According to Fig. 1(d), the output photocurrent of the device reaches 28 mA, which corresponds to an output RF power of 7.3 dBm and is the highest level among high-performance photodetectors under the same conditions.

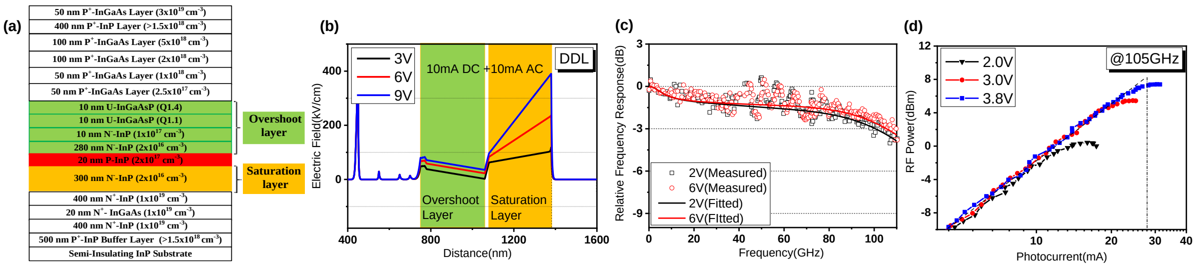

Fig. 1. (a) Epitaxial layer structure and (b) electric field profiles under different reverse biases of the DDL UTC-PD. (c) Bias dependent frequency response and (d) output RF power versus dc photocurrent of a 6-μm-diameter PD. [7]

2.2 100 GHz Bandwidth Double-cliff-layer (DCL) MUTC-PD with High Responsivity

In order to improve the responsivity of the PD, it is necessary to increase the thickness of the absorption region. However, this will increase the electron transit time, thus reducing the device bandwidth. We designed a novel epitaxial structure to simultaneously achieve high responsivity and large bandwidth by fine tuning the electric field in the depletion region.

A backside-illuminated double-cliff-layer MUTC-PD was designed and fabricated. As depicted in Fig. 2(a), an 850-nm-thick InGaAs absorption layer is adopted for high responsivity. The self-induced electric field in the graded p-doped absorption layer under high photocurrents facilitates electron drift out. Meanwhile, a depletion region with double-cliff layer is incorporated to tune the electric field distribution, thus mitigating the high-density electrons induced space charge screening effect and maintaining the overshoot electron velocity. As shown in Fig. 2(b), the electric field in the depletion region can be effectively elevated by the two n-doped cliff layers, thus improving the saturation performance of the PD.

An inductive CPW electrode with optimized length is employed to enhance the frequency response of the device [8]. The fabricated 6-μm-diameter DCL-UTC-PD exhibits a high responsivity of 0.51 A/W and a large 3-dB bandwidth of 102 GHz at a photocurrent of 10 mA, as plotted in Fig. 2(c). The saturation photocurrent at 100 GHz is measured to be 16 mA, corresponding to an RF power of 2.7 dBm.

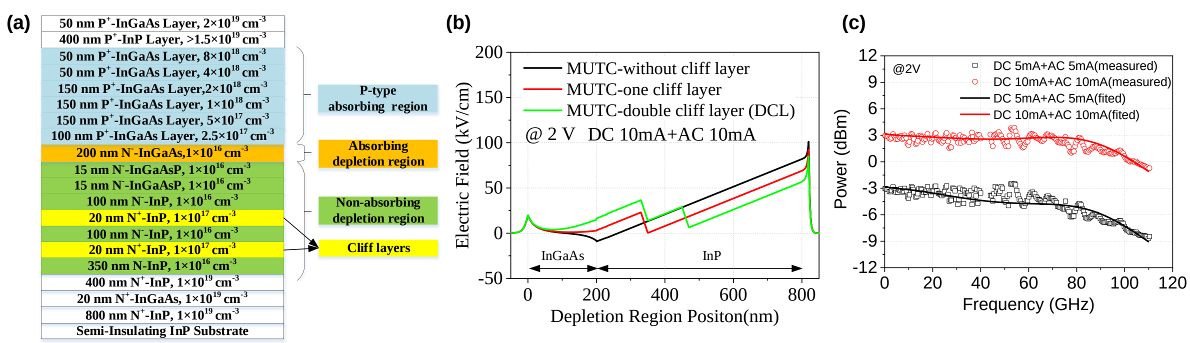

Fig. 2. (a) Epitaxial layer structure of the DCL-UTC-PD. (b) Electric fields within the depletion region of different types of MUTC-PDs. (c) 3-dB bandwidth of a 6-μm-diameter PD under different photocurrents.

2.3 230 GHz Bandwidth MUTC-PD with High Saturation Power

Improving the RC-limited bandwidth requires reduced device size, but this leads to an increase in the current density and the accumulation of carriers inside the device. With an aim to improve the performance of small-size devices, we carefully designed the epitaxial structure so that the electric field in the depletion region can facilitate electron velocity overshoot.

An MUTC-PD with miniaturized device diameter of 3 μm was demonstrated in our recently work. The epitaxial structure of the MUTC-PD is shown in Fig. 3(a). The total thickness of the gradient-doped absorption region is 80 nm, which is used to form a self-induced electric field, so as to reduce the transit time of electrons. In addition, a 20 nm cliff layer is inserted between the absorption layer and the depletion layer to adjust the electric field distribution inside the device. We carefully designed the doping concentration of the n-type cliff layer. As shown in Fig. 3(b), when the doping concentration of cliff layer is 3×10^{17}cm^{-3}, the electric fields in the absorption layer and depletion layer are 120 kV/cm and 20-40 kV/cm, respectively. The latter falls exactly within the electron velocity overshoot range, thus ensuring a reduced transition time for the photon generated electrons.

A PD with a mesa diameter of 3 μm were fabricated with inductive CPW electrode specially designed to further extend the bandwidth [9]. We tested the frequency response and saturation characteristics of under a 2 V bias voltage. A bandwidth of up to 230 GHz at 3 mA is recorded in Fig. 3(c). The photocurrent at the 1-dB compression point reaches 5.85 mA, corresponding to a saturated output RF power of –4.94 dBm at 220 GHz. The results show that our PD achieves both large bandwidth and high output power.

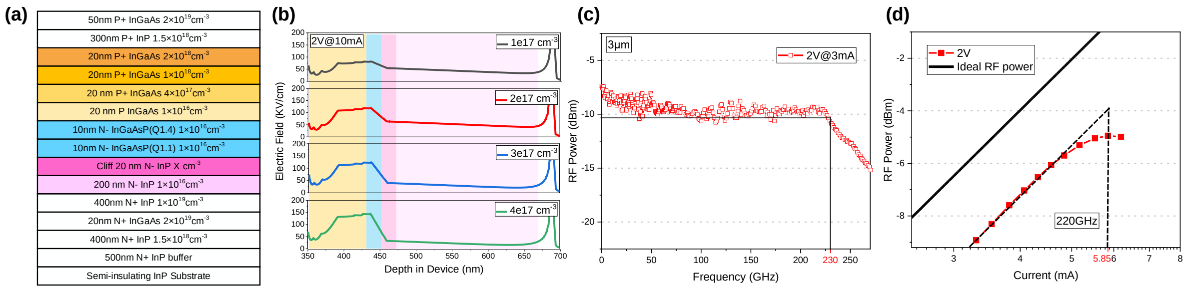

Fig. 3. (a) Epitaxy layer structure and (b) electric field within the depletion region of the MUTC-PD. (c) Frequency response under 2 V reverse bias and (d) output RF power versus output photocurrent of the 3-μm-diameter PD [9]

3. Conclusions

In this talk, our recent progress in ultra-wide bandwidth photodetectors with high saturation power are discussed. The effects of high-speed photogenerated carrier transport and inductive gain peaking have been investigated, and several new structure UTC-PDs devices are proposed and fabricated for 100 GHz and 200 GHz applications. To further increase the saturation output power, flip-chip bonding can be employed to facilitate heat dissipation.

4. Acknowledgements

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