Optimized uni-traveling carrier photodiode and mushroom-mesa structure for high-power and sub-terahertz bandwidth under zero- and low-bias operation

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Abstract

In this paper, physically-based simulations are carried out to investigate and design uni-traveling carrier photodiode (UTC-PD) for high-power sub-terahertz wave generation at zero- and low-bias operation. The reliability of the physically-based simulation is demonstrated by comparing with our experimental result. Both the bandwidth and RF output power of the proposed UTC-PD is significantly improved by careful design the built-in electric field distribution under high-power input. For the optimized UTC-PD with the mesa diameter of 5 μm, its 3dB bandwidth large than 100 GHz even if the photocurrent reaches 6 mA under zero-bias operation. The device can reach a high bandwidth of 92.4 GHz, 105 GHz, and 119.5 GHz under the reverse bias of 0.5 V, 1 V, and 2 V, respectively, even the input photocurrent as high as 18.2 mA. The peak output-power of the device has enhanced at least 7 dB even at 170 GHz and zero- or low-bias operation. Besides, a novel design of mushroom-mesa UTC-PD (MM-UTC-PD) is proposed which with 4.3% improved high-speed performance. The MM-UTC-PD can trade-off between the external quantum-efficiency and bandwidth when miniaturized junction size is required.

1. Introduction

High efficiency, high speed, and high output-power photodiodes are critical components for optical communication systems. Typically, there is a trade-off between bandwidth and quantum efficiency for a p-i-n photodiode. The two major speed-limiting factors in p-i-n photodiodes that caused the compromise are the transit time and RC time. The RC time limit can be alleviated either by employing a smaller device area or by increasing the thickness of the depleted photo-absorption layer, thereby decreasing the junction capacitance. However, an increased depletion width consequently increases the transit time. On the other hand, a smaller device area and thinner absorption layer will reduce the external efficiency of p-i-n photodiodes. Unlike conventional p-i-n photodiode, the uni-traveling carrier photodiode (UTC-PD) consists of a p-type neutral absorption layer and a wide-gap depleted collection layer [1, 2]. This means that the thickness of the depleted collector can be designed to be independent of the thickness of the absorber. Therefore, the RC delay time is decreased by increasing the thickness of the collector with ignoring the impact on the carrier transit time to a certain extent. The carrier transit time is decreased by downscaling the thickness of the absorber with ignoring the impact on the RC delay time to a certain extent. However, the increased collector thickness will lead to an increased reverse bias to maintain its depleted state. The increased bias voltage results in an increased self-heating effect because the Joule heat is equal to the bias voltage multiplied by the output current [3]. Hence, the more miniaturized size of the active area in UTC-PD will result in the broader bandwidth from dc to sub-terahertz [4–8]. However, this could lead to difficulty in optical coupling, exhibiting small external efficiency, ease of self-heating, and eventually thermal failure under high-power operation [7–9].
mechanisms limiting the performance of UTC-PD are RC delay time, carrier transit time, space-charge effects, self-heating, etc [10].

One possible solution to mitigate the self-heating is the flip-chip bonding of photodiode onto a heat sink [8, 9, 11, 12]. Another method is to make the UTC-PD worked under zero bias [3]. For zero bias operational UTC-PD, the bias circuit can be omitted, thus optimizing the trade-off between compact photonic integration and high baud rate transmission. This is because the signal crosstalk must be avoided when designing the high data rate transmission and high-density photonic integration technologies for millimeter-wave transmitter [13, 14]. Besides, the packaging can be simplified, energy-consumption and dark-current can be reduced, and noise can be restrained, when the device is working at bias-free.

It is well known that the space charge effect can be suppressed by a higher bias voltage. Accordingly, the 3dB bandwidth and RF output-power of photodetector contain some penalty under zero-bias operation. However, for a zero-bias operational UTC-PD, the space-charge screening effect can be restrained to some extent via optimization the doping profile in the absorber, spacer and collector, and the thickness of spacer and collector [15]. In particular, a fixed distribution of background dopants in the collector can be used to repress the effect [16]. In this paper, by introducing and improving a graded doping profile rather than a uniform doping profile [6, 17, 18] in the depletion region of UTC-PD, the built-in electric field at the location where it will tend toward zero under high photocurrent density operation can be preconditioned to be higher. Consequently, the device can achieve high output-power with a broadband coverage from dc to sub-terahertz under zero- and low-bias operation, without the associated failure caused by increased thermal loading from higher reverse bias. The optimal epitaxial layer parameters of the device are acquired simultaneously.

Utilizing one of the advantages of UTC-PD, we can independently design the thickness of the absorption layer and the collection layer to alleviate the contradiction between quantum efficiency and RC time. In this work, by reducing the area of the collection layer while keeping the size of the active layer unchanged, a novel mushroom-mesa UTC-PD (MM-UTC-PD) structure is formed. Thereby, if it’s RC delay time is reduced, then its bandwidth can be improved. Compared with the mushroom-mesa PIN-PD structure [19], the MM-UTC-PD structure does not reduce the area of the absorption layer. Therefore, with the suggested structure, the bandwidth can be enhanced without the external quantum efficiency being affected. However, the proposed MM-UTC-PD structure maybe bring other adverse aspects, if the photogenerated carriers in the suspended part of absorption layer cannot be collected quickly and effectively, a significant disadvantage effect on the bandwidth and responsivity. Consequently, it is necessary to verify the feasibility of this structure.

2. UTC-PDs under zero-bias operation

We get a modified zero-bias operational UTC-PD (PD1), which has acollector with a uniform doping profile in our previous work [15], and the detailed parameters of the structure is illustrated in table 1. The frequency response (I(ω)) of bias-free operational UTC-PD with large-signal (100% modulation depth) input is calculated by a commercial software of Silvaco Atlas. In this process, we use the Fermi–Dirac carrier statistics model together with the drift–diffusion model for carrier transport. The experimental test parameters of InP and In0.53Ga0.47As materials in the models of concentration dependent mobility (CONMOB) and parallel electric field mobility (FLDMOB) are available in the report of [20]. The models of carrier recombination in our simulation include Shockley–Read–Hall (SRH), concentration-dependent SRH, and Auger recombination models [21]. Numerical solutions are obtained using the Newton method in a three-dimensional model. Then, the normalized responsivity (τ(ω)) and RF output power (Pout(ω)) of the device are calculated as follows [22], with the ideal load impedance (RL = 50 Ω), the series resistance (RS = 15 Ω) and parasitic capacitance (CP = 5 fF) of the device,

\[ \tau(\omega) = 10\log_{10}\left(\frac{I(\omega)}{I(0)}\frac{1}{1 + \omega^2(R_S + R_L)^2(C_P + C_f)^2}\right)^2 \]  

\[ P_{out}(\omega) = \frac{I(\omega)}{\sqrt{1 + \omega^2(R_S + R_L)^2(C_P + C_f)^2}} R_L \]  

where ω is angular frequency, and I(0) = I(ω)|ω→0. The 3-dB bandwidth is defined as the frequency f3dB at which the responsivity drops by 3-dB with respect to the DC value. The junction capacitance (Cf) of the photodiode is extracted from the C-V curve via Atlas simulation. The parasitic capacitance and the series resistance respectively caused by the interaction of electrodes and the contact of metal-semiconductor were taken into account [23]. The physical model obtaining the bandwidth and output power of the UTC-PD includes the effects of the series resistance, parasitic capacitance, external load impedance, and the detailed parameters of
Table 1. Epitaxial layer parameters of the zero- and low-bias operational UTC-PDs.

| Layer/Thickness (nm) | Doping (cm⁻³)/Type | PD1 | PD2 | PD3 | PD4 | PD5 | PD6 |
|----------------------|---------------------|-----|-----|-----|-----|-----|-----|
| In₀.₃₅Ga₀.₆₅As       | P-Contact/50        | 1e15/P |   |     |     |     |     |
| In₀.₃₅Ga₀.₆₅As:In₀.₇³Ga₀.₂₇P₀.₂₄₅ | Electron Barrier/20 | 8e18/P |   |     |     |     |     |
| In₀.₃₅Ga₀.₆₅As       | Absorber/200        | 3e17 → 5e18/P(1) |   |     |     |     |     |
| In₀.₃₅Ga₀.₆₅As       | Spacer1/10          | 1.3e18/P |   |     |     |     |     |
| InP → In₀.₃₅Ga₀.₆₅As | Spacer2/13(0)       | 1e15/N |     |     |     |     |     |
| InP (Spacer3) or Cliff/10 |   | 1.5e18/N |     |     |     |     |     |
| InP (Collector)/300 | 1e14                 |     | 1e17 | 2e17 | 4e16 | 4e16 |     |
| /N                  | 1e14                |     | 1e14 | 1e14 | 1e14 | 1e14 |     |
| /N(6)               | 1e14                |     | 1e14 | 1e14 | 1e14 | 1e14 |     |
| /N(6)              | 1e14                |     | 1e14 | 1e14 | 1e14 | 1e14 |     |
| InP (Subcollector)/50 | 1e17/N              |     |     |     |     |     |     |
| In₀.₃₅Ga₀.₆₅As:In₀.₇³Ga₀.₂₇P₀.₂₄₅ | Etch-Stop-1/20 | 1e18/N |     |     |     |     |     |
| InP (N-Contact)/1000 | 1e19/N              |     |     |     |     |     |     |
| In₀.₃₅Ga₀.₆₅As:In₀.₇³Ga₀.₂₇P₀.₂₄₅ | Etch-Stop-2/20 | 1e19/N |     |     |     |     |     |
| InP/50              |                     |     |     |     |     |     |     |

* The PD1, PD2, PD3, PD4, PD5, and PD6 with same epitaxial layer parameters but the doping profile in the collector. (1) 3e17 → 5e18/P means the P-type doping concentration varies linearly from 3 × 10¹⁷ cm⁻³ (near the Spacer1 layer side) to 5 × 10¹⁸ cm⁻³ (near the electron barrier layer side) in the absorption layer. (2) InP → In₀.₃₅Ga₀.₆₅As (Spacer2)/13 means the 13 nm thick Spacer2 is a graded bandgap layer which changes linearly from In₀.₃₅Ga₀.₆₅As (near the Spacer1 layer side) to InP (near the cliff layer side). (3) 1e16 → 1e14/N, (4) 1e17 → 1e14/N, and (5) 2e17 → 1e14/N means the N-type doping concentration varies linearly from 1 × 10¹⁶ cm⁻³, 1 × 10¹⁷ cm⁻³, and 2 × 10¹⁷ cm⁻³ (near the subcollector layer side) to 1 × 10¹⁴ cm⁻³ (near the cliff layer side) in the collection layer, respectively. (4) The doping profile in the collector of PD5, near the spacer side a uniform doping of 4 × 10¹⁶ cm⁻³ with a thickness of 100 nm, and near the N-contact side a uniform doping of 1 × 10¹⁴ cm⁻³ with a thickness of 200 nm [24]. (5) The doping profile in the collector of PD6, near the spacer side a uniform doping of 4 × 10¹⁶ cm⁻³ with a thickness of 150 nm, and near the N-contact side a uniform doping of 1 × 10¹⁴ cm⁻³ with a thickness of 150 nm [25].

the structure. In section four, the reliability of the physics-based simulation is demonstrated by compared with our experimental result.

Figure 1 shows the built-in electric field distribution of the UTC-PDs with various doping profile in the collection layer under zero-bias operation. As illustrated in table 1, the PD1, PD2, PD3, and PD4 with same epitaxial layer parameters but the doping profile in the collector. The collector of PD1 has a uniform doping profile of 1 × 10¹⁴ cm⁻³, the collector of PD2, PD3, and PD4 with a linear graded doping profile are changing from 1 × 10¹⁴ (near spacer side) to 1 × 10¹⁶ cm⁻³, 1 × 10¹⁷ cm⁻³, 2 × 10¹⁷ cm⁻³ (near N-contact side), respectively. As plotted in the figure 1, the electric field intensity of the spacer and the input-side of the collector decreases at the higher input power [26], and the intensity of the output side of the collector will increase at the same time [25]. Distinctly, due to the linear gradient doping in the UTC-PD, the electric field intensity of the input side of the collector, the spacer and the output side of the absorber is stronger while the output side of the collector decreases. Compared with the uniform doping profile [6, 16–18], the built-in field at the location where it will tend toward zero under high input power operation can be preconditioned to be higher by the graded doping profile. In addition, as shown in figure 2, the increasing rate of junction capacitance of the devices with the gradient doped collection layer gets slower with the input power enhancement. Therefore, under zero biased operation, despite the bandwidth of the devices reduces as the input power goes up [27, 28], this value decreases much slower, resulting from the large gradient of the doping in the collector, as illustrated in
As illustrated in figure 1, for PD3, the small electric field in the output side of the collector layer (−0.3 to −0.17 μm) is exhibited to 1.3 kV cm$^{-1}$ under a low input power. However, the acquired acceleration of the electron will be higher at the initial segment and then travels through the structure because the electric field of the absorber, the spacer and the input-side of the collector are enhanced by the graded doping [18]. Besides, the electric field at the output side of the collector layer goes up to 5 kV cm$^{-1}$ under the high input power. That’s why, for PD3, as the input photocurrent increased from 1.2 to 10 mA, the 3dB bandwidth is around 100 GHz, and output-power exhibition good linearity, under zero-bias operation. For the device with uniform doping of 1 × 10$^{14}$ cm$^{-3}$ in the collector (PD1), under the high input power, the electric field in the input-side of the collector and the output-side of the absorber tends to zero and dramatically decreases in the spacer synchronously [26], but the high charge compensated device has a different situation [25]. The junction capacitance strongly depends on the photocurrent for PD1, about three time’s increase of the capacitance as the input photocurrent rising from 1.2 to 10 mA (from depletion state to non-depletion state). However, the junction capacitance only increased by 40% for PD3 correspondingly. In reference [6], the capacitance of the photodiode with an active diameter of 5 μm is changed about three times as the reverse voltage descending from 2 to 0 V even when the input power is zero. Therefore, as shown in figure 2(a), when the input photocurrent is above 6 mA, the 3dB bandwidth of PD3 is broader than that of PD1. For PD1, the bandwidth is decayed about 31 GHz (versus 50 GHz [27] and 35 GHz [28]) as the input photocurrent increases from 2 to 5 mA. The output-power of the device is −4.95 dBm at 100 GHz and the corresponding photocurrent of 3 mA (versus −7 dBm [23]). As illustrated in table 2, for PD1 the peak output-power at 100 GHz is 1.63 dBm (versus −18.6 dBm [14]) and the corresponding photocurrent of −9.79 mA (versus 2.5 mA [14]). Its peak output-power at 160 GHz and 170 GHz is −1.76 dBm and −2.28 dBm (versus −13.9 @ 160 GHz with a 70% modulation depth [27] and −11.3 dBm @ 170 GHz with a 60% modulation depth [28]), respectively, both of the corresponding photocurrent of
about 9.2 mA (versus 8 mA \cite{27, 28}). Nevertheless, for PD3, the output-power is \(-5.74\) dBm at 100 GHz and 3 mA, and the peak output-power at 100 GHz, 160 GHz, and 170 GHz of 8.8 dBm, 5.25 dBm, and 4.75 dBm, respectively, and the corresponding photocurrent is approximately 15 mA, 27.6 mA, and 28.2 mA.

Figure 3 shows the bandwidth of PD3 change with the thickness of the collector under various input power. The 3dB bandwidth of the PD3 is ascended and descended under a low (<6.07 mA) and a high (>18.2 mA) input power, respectively, as the collector becoming thickens (from 300 nm to 800 nm). The device has relatively thin collector, can achieve high linearity, and has the advantage of high speed in the case of high input power, which is consistent with the reported results \cite{7, 31, 32}. There are four main causes for the above phenomenon. Firstly, the transit time of the photogenerated carrier is inverse to the collector thickness. Secondly, the built-in electric field of the device is collapse significantly under high input power \cite{26}. Thirdly, the intensity of the electric field is reverse to the thickness of the collector due to the built-in potential is constant. Finally, under low input power, the junction capacitance of the device depends on the thickness of the collector and then will be saturated in this region due to the built-in potential with a small constant at zero-bias operation. Hereby, the thickness of the collector is set to 300 nm to obtain the trade-off between the transit time and RC time \cite{32}. According to figure 2(a), when the input photocurrent is over than 1 mA under zero-bias operation, the bandwidth of the UTC-PD with the proposed doping profile will be improved, compared with that of the reported doping profile (PD5 and PD6) \cite{24, 25}. Then we obtained epitaxial parameters of the charge compensated zero-bias operational UTC-PD (CC-UTC-PD, PD3), as illustrated in table 1. For the CC-UTC-PD (PD3), the output power in the linear region and the peak RF output power dwindled and enhanced by 0.8 dB and 7.2 dB, respectively, and its bandwidth will be improved when the photocurrent is over 6 mA, compared to that of the UTC-PD with the uniform doping of \(1 \times 10^{14} \) cm\(^{-3}\) in the collection layer.
3. UTC-PDs under low-bias operation

Figure 4 shows the bandwidth and junction capacitance of the devices dependence of input power under low reverse bias operation. Generally, the reverse voltage can enhance the internal electric field of a photodiode, so the space-charge effect and the depletion layer can be suppressed and broadened, respectively. Consequently, the transit time and RC-delay time limited bandwidth is improved, the RF output power is also enhanced. The reverse voltage improves the bandwidth of all types photodiode compared with the zero-bias operation, as described in figures 2(a) and 4. As plotted in those figures, the junction capacitance is reduced obviously as the reverse bias increases [6], especially under high input power. The junction capacitance of the devices with a depleted drift layer is reasonable tends to 7 fF under the photocurrent of 1.2 mA and the reverse bias of 2 V [6, 23]. For PD1, the capacitance at 15.7 mA is dwindled by half as the reverse voltage changing from 0.5 to 2 V. However, the electric field around the spacer of the device with a severe collapse under high input power [26], as shown in figure 1, which is not conducive the traveling of electrons from the absorber to the collector. Therefore, the bandwidth of the device is less significant improved as the voltage increases from 0.5 to 2 V when the photocurrent large than 13 mA. For the charge compensated structures, its bandwidth is significantly improved when the voltage increased. The bandwidth of the proposed CC-UTC-PD (PD3) is greater than PD1 when the input photocurrent bigger than 6.0 mA, 4.85 mA, and 2.6 mA under a reverse bias of 0.5 V, 1 V, and 2 V, respectively. The advised device can reach a high bandwidth of 92.4 GHz, 105 GHz, and 119.5 GHz at a reverse bias of 0.5 V, 1 V, and 2 V, respectively, when the input photocurrent is as high as 18.2 mA. Besides, its bandwidth is only attenuated about 10 GHz (versus 50 GHz [27] and 35 GHz [28]), 7.5 GHz (versus 20 GHz [28]), and 7.5 GHz (versus 8 GHz [28]) under the reverse bias of 0 V, 0.5 V, and 1 V, respectively, as the input photocurrent increases from 2 to 5 mA. For the suggested CC-UTC-PD (PD3), the bandwidth of 135 GHz is obtained under the photocurrent of 5 mA and the reverse bias of 1 V. This result is comparable with the reports by Jhih-Min Wun et al when the active diameter of 3.2 μm and 6 μm, the bandwidth of their devices with a 160 nm absorption layer is 140 GHz [27] and 165 GHz [28], respectively. The bandwidth of the proposed structure (PD3) is 112 GHz, 124 GHz, and 138 GHz at the photocurrent of 10 mA under the reverse bias of 0.5 V, 1 V, and 2 V (versus 112 GHz @ 4 V [6]), respectively.

### Table 2. The performance of the UTC-PDs under zero-bias operation.

| References | 100 GHz | 160 GHz | 170 GHz |
|------------|---------|---------|---------|
| [14]       | – 18.6 and 2.5 |        |         |
| [27]       | – 13.9 and 8   |        | – 11.3 @ 8 |
| PD1        | 1.63 and 9.79  | – 1.76 @ 9.2 | – 2.28 @ 9.2 |
| PD3        | 8.8 and 15     | 5.25 @ 27.6 | 4.75 @ 28.2 |

![Figure 3. The bandwidth of PD3 changed with the thickness of the collector under various input power.](image)
As plotted in figure 4, the bandwidth of PD6 is greater than CC-UTC-PD (PD3) under a lower input power operation when the bias is above 1 V. Therefore, the RF output-power characteristics of them need a comparison. Figure 5 reveals the RF output-power depends on the input photocurrent for the UTC-PDs under low-bias operation. As shown in figures 2(b) and 5, with the increase of bias, the output power of the devices increases [7, 27, 28, 31] and the output power of CC-UTC-PD is larger than that of PD6 and much larger than that of PD1. Besides, the output power of the devices decreases as the increase of the frequency [6]. In the linear region, PD1 with higher RF output power than CC-UTC-PD (PD3) when the operation frequency around 160 GHz and the reverse bias smaller than 0.5 V. This is due to the bandwidth of PD1 is higher than PD3 under above conditions.

As illustrated in figure 5 and table 3, the peak output-power of the CC-UTC-PD (PD3) is large than PD1, PD6, and the experimental results [6, 14, 27, 28, 31, 33–38], under same conditions. The peak output-power of
PD1, CC-UTC-PD, and PD6 is $-0.78 \text{ dBm}$, $7.17 \text{ dBm}$, and $5.13 \text{ dBm}$ at $170 \text{ GHz}$, respectively, under the reverse bias of $0.5 \text{ V}$ (versus $-8.5 \text{ dBm}$ [28]), and the corresponding photocurrent of $9.2 \text{ mA}$, $28.6 \text{ mA}$, and $20.7 \text{ mA}$.

When the bias of $1 \text{ V}$, the corresponding peak output-power is $0.283 \text{ dBm}$, $8.92 \text{ dBm}$, and $6.94 \text{ dBm}$ at $160 \text{ GHz}$ (versus $-9.83 \text{ dBm}$ [27]), and the photocurrent of $9.2 \text{ mA}$, $29.4 \text{ mA}$, and $21.3 \text{ mA}$ (versus $9 \text{ mA}$ [27]), respectively. For CC-UTC-PD, the RF output power under $100 \text{ GHz}$, $120 \text{ GHz}$, $160 \text{ GHz}$, and $170 \text{ GHz}$ peaked at $13.7 \text{ dBm}$ (versus $-5 \text{ dBm}$ [14], and $11.3 \text{ dBm}$ [35]), $12.5 \text{ dBm}$ (versus $5.5 \text{ dBm}$ @ $110 \text{ GHz}$ & $3 \text{ V}$ [6]), $10.2 \text{ dBm}$ (versus $7.8 \text{ dBm}$ [38]), and $9.64 \text{ dBm}$ (versus $6.12 \text{ dBm}$ [7, 31]), respectively, when the reverse voltage of $2 \text{ V}$. The improvement of the RF output power is about $9.4 \text{ dB}$ and $2.4 \text{ dB}$, respectively, compared with PD1 and PD6.

**Figure 5.** The RF output power dependence of the input photocurrent for the UTC-PDs at various frequency under a reverse bias of $0.5 \text{ V}$ (a), $1.0 \text{ V}$ (b), and $2.0 \text{ V}$ (c). The PD1, PD2, PD3, PD4, PD5, and PD6 with same epitaxial layer parameters but the doping profile in the collector, as illustrated in table 1.
Through the analyses above, the proposed CC-UTC-PD is a benefit structure to high-power sub-Terahertz wave generation at zero- and low-bias operation.

4. Experimental results

The UTC-PD7 and UTC-PD8 epitaxial layers were grown on semi-insulating single-side-polished InP substrates by Solid Source Molecular Beam Epitaxy. The epitaxial layer parameters are illustrated in Table 4. The UTC-PD7 is a traditional structure, while the UTC-PD8 is a simpler structure which gets from PD1. Back-illuminated cylindrical mesa structure was fabricated by wet-chemical etching and traditional photolithography procedures. The TiAu layer was deposited on P- and N-contact layers by magnetron sputtering system and lift-off process in different steps. The TiAu P-contact electrode was fully covered the active area and act as a mirror under back-illumination. Afterwards, the wafer was annealed at 420°C for 2 min under a nitrogen atmosphere to form P-type and N-type Ohmic electrode. Then, the wafer covered with polyimide and annealed for pre-passivation in nitrogen ambient. Subsequently, the top window was opened for microwave GSG coplanar pads connections to the N- and P-contact electrodes, and anneals it for passivation again. The GSG coplanar pads were deposited on polyimide for high-speed measurements.

The frequency responses of the UTC-PDs were measured using a 40-GHz Agilent network analyzer under 300 K. Light with a wavelength of 1550 nm modulated by Mach–Zehnder modulator was used as input light. The normalized S21 of the UTC-PDs is plotted in Figure 6. In the measurement, the UTC-PD8 with 24 μm mesa diameter demonstrated 11.8 GHz and 10 GHz 3dB bandwidth at 0.05 mA and 1 mA photocurrent, respectively, under zero-bias operation. However, the 3dB bandwidth of the UTC-PD7 is only 6.2 GHz under the same conditions.

As shown in Figure 7, the 3dB bandwidth of the UTC-PD8 with 20 μm and 14 μm mesa diameter can achieve 20.8 GHz and 40 GHz (versus 13 GHz with 40 × 5 μm² active area [39], 21.5 GHz with 15 × 4 μm² active area [40]), respectively, under zero-bias operation. The bandwidth of the UTC-PDs with reduced mesa diameter is significantly improved because the bandwidth is mainly limited by RC-time. When the reverse bias of 1 V, the 3dB bandwidth of the device with 20 μm mesa diameter can achieve 36.6 GHz, while the 3dB bandwidth of the device with 14 μm mesa diameter is larger than 40 GHz.

As illustrated in Figures 6 and 8, under bias-free and small input power operation, the bandwidth of the UTC-PD8 almost twice than the UTC-PD7, when both of the structure with same junction area. This is because the built-in electric field in the absorber, spacer and collector layers of the modified UTC-PD8 is larger than UTC-PD7 under the same conditions. Therefore, the UTC-PD8 is a benefit structure to achieve high-speed
under these conditions. This result is consistent with the previously reported zero-bias operational UTC-PD design, the device with lower doping concentration in the collector can achieve high-speed response \cite{14, 15, 23, 28}. Nevertheless, under zero-bias operation, the bandwidth of the UTC-PD8 is significantly decreasing as the increased photocurrent. The main reason for this trend is that with the increase of input power, the electric field decreases and the energy band flattens. The report of \cite{14} also suggest that the UTC-PD with a uniform doping concentration of $3 \times 10^{14}$ cm$^{-3}$ in the collector result in a small saturated photocurrent. As plotted in figures 7 and 8, the frequency responses of the devices are obviously improved with an applied reverse bias of 1 V. The bandwidth of UTC-PD8 is insensitive to photocurrent under the reverse bias operation compared to zero bias operation. Thus, the major reason for the UTC-PD8 sensitive to photocurrent under zero bias operation is space charge effect. As shown in figures 7 and 8, the simulation results agree well with the experimental results. Therefore, the obtained numerical solutions in this paper are reliable, and it is expected that the proposed CC-UTC-PD can repress the bandwidth attenuated with the increase of photocurrent under zero bias operation.

| Layer                        | Thickness (nm) | Doping (cm$^{-3}$) | Type         |
|------------------------------|----------------|--------------------|--------------|
| In$_{0.53}$Ga$_{0.47}$As (P-contact) | 50 and 2e19/P   | 50 and 2e19/P      |              |
| InGaAsP (Q1.24) (Electron barrier) | 20 and 5e18/P   | 20 and 8e18/P      |              |
| In$_{0.53}$Ga$_{0.47}$As (Absorber) | 220 and 2e18/P  | 220 and 3e17 → 5e18/P$^{(1)}$ |
| In$_{0.53}$Ga$_{0.47}$As (Spacer) | 20 and 1e16/P   | 10 and 1.5e18/P    |              |
| InGaAsP (Q1.4) (Spacer)       | 10 and 1e16/N   | 12 and 1e15/N      |              |
| InGaAsP (Q1.1) (Spacer)       | 10 and 1e16/N   | 10 and 1.5e18/N    |              |
| InP (Cliff)                   | 10 and 1e18/N   | 10 and 1.5e18/N    |              |
| InP (collector)              | 400 and 1e16/N  | 350 and 1e15/N     |              |
| InP (Subcollector)           | 50 and 5e18/N   | 50 and 1e17/N      |              |
| In$_{0.53}$Ga$_{0.47}$As (Etch stop2) | 10 and 1.5e19/N | 15 and 1e18/N      |              |
| InGaAsP (Q1.24) (Etch stop2) | 15 and 1e18/N   | 900 and 1e19/N     |              |
| InP (N-Contact)              | 10 and 1.5e19/N | 100 and 1e19/N     |              |
| Semi-insulating InP Substrate |                | 5e18/P$^{(1)}$     |              |

$^{(1)}$ 3e17 → 5e18/P means the P-type doping concentration varies linearly from $3 \times 10^{17}$ cm$^{-3}$ (near the Spacer1 layer side) to $5 \times 10^{18}$ cm$^{-3}$ (near the electron barrier layer side) in the absorption layer.
5. Mushroom-mesa UTC-PD

The epitaxial parameters of the MM-UTC-PD are same as those of CC-UTC-PD. As plotted in figure 9, the schematic cross-sectional view of the cylindrical mesa of the MM-UTC-PD. By the process of reactive ion etching and selective wet-chemical etching the structure can be fabricated. In the figure, the $D_A$ and $D_C$ indicate the diameter of the absorption and collection layer of the device, respectively. The beneficial of the structure can be indicated and the optimum ratio between $D_A$ and $D_C$ can be obtained by changing the diameter of absorber and collector. Figure 10(a) shows the frequency response of the UTC-PDs with various junction area. As plotted in the figure, the transit time limited bandwidth decreases and the RC time limited bandwidth increases as the reduction of the $D_C/D_A$. Thus, the bandwidth of the device raises first and then dwindles as the $D_C/D_A$ changes from 1 to 0.8. When the $D_C/D_A$ equals 0.9, the 3dB bandwidth of the MM-UTC-PD is 116.25 GHz under zero-bias operation, improved by 4.3% compared with the traditional structure. Figure 10(b) shows the RF output power of the UTC-PDs at 100 GHz under zero-bias operation. As illustrated in the figure, for devices with an active diameter of 5 $\mu$m, the output power is attenuated as $D_C/D_A$ diminishes. The peak RF output power of the devices is 8.8 dBm, 7.9 dBm, and 5.76 dBm as the $D_C/D_A$ of 1.0, 0.9, and 0.8, respectively, the corresponding input power of 92.3 mW, 86.4 mW, and 78.5 mW. The saturated input power descends as the $D_C/D_A$ decrease, due to the mushroom structure with larger current density under same input power which causing more serious space charge effect. The output power in the linear region of the device faded by 0.7 dB, compared with the traditional structure under the same conditions when the $D_C/D_A$ equals 0.9.
The transit time limited bandwidth and the output-power attenuated as the $D_C/D_A$ diminish is major due to the photogenerated carriers in the suspended part of the absorption layer cannot be collected quickly and effectively. The suspended part of the absorber should be less than one diffusion length of the electron for the sake of avoiding the above detrimental effects to some extent. The average minority carrier mobility and lifetime in the Zn-doped absorption layer of ~$120$ cm$^2$ V$^{-1}$ s$^{-1}$ and ~$260$ ps [41], respectively, leading to the corresponding diffusion length only of ~$280$ nm. Thus, for an MM-UTC-PD with an active diameter of 5 $\mu$m, the $D_C/D_A$ should be more than 0.888 is consistent with the above simulation results, and the diffusion length determines the best $D_C/D_A$ of the MM-UTC-PDs with different active size. Therefore, we proposed MM-UTC-PD with junction diameter ($D_J$) of 4.5 $\mu$m when the active diameter ($D_A$) of 5 $\mu$m. If the proposed structure with the junction diameter of 4.5 $\mu$m and 3 $\mu$m, then its active area will be 1.26 and 1.4 times the traditional structure,
respectively, when the two type structures have same junction capacitance, so the suggested structure is expected to achieve higher external quantum efficiency and to compensate its smaller loss of the output power.

As shown in figure 10(b), when the active diameter of the traditional UTC-PD is 4.5 μm, the RF output power under 100 GHz peaked at 8.41 dBm with an illumination beam diameter of 5 μm, and the corresponding input power is 98.1 mW. Although the peak output power of the traditional structure is improved by 0.34 dB compared to the suggested structure, the required corresponding input power of the former more than the latter as high as 11.8 mW, which contrary to the advocated of low power consumption. In the linear region, the output power of the proposed structure is 0.6 dB higher than the traditional UTC-PD, when both structures have the same junction diameter of 4.5 μm. Considering that the need to achieve broadband coverage from dc to sub-terahertz, a miniaturized size of the junction area is typically required [4–8]. Nevertheless, this miniaturization will cause some adverse effects, such as difficulty in optical coupling, exhibiting small external quantum-efficiency and larger contact-resistance, ease of self-heating and eventually thermal failure under high-power operation [7–9]. In addition, the P-contact resistance is proportional to the metal-semiconductor contact area, and the larger P-contact area facilitates heat dissipation. Therefore, the proposed MM-UTC-PD can be used to trade-off the above contradiction to a certain degree.

6. Conclusion

The properties of the proposed CC-UTC-PD are simulated, and these simulations indicate it’s a benefit structure to high-power sub-terahertz wave generation at zero- and low-bias operation. The physically-based simulation successfully predicted that the performance of the UTC-PD varies with the change of its structural parameters and the external conditions, and the simulation results agree well with our experimental results. This indicates that the physically-based simulation is reliable, and it can be used to design and analysis the UTC-PDs. For the CC-UTC-PD with the mesa diameter of 5 μm, its 3dB bandwidth large than 100 GHz even if the photocurrent reaches 6 mA under zero-bias operation. The device can reach a high bandwidth of 92.4 GHz, 105 GHz, and 119.5 GHz under the reverse bias of 0.5 V, 1 V, and 2 V, respectively, even the input photocurrent as high as 18.2 mA. The attenuation of the device’s bandwidth is suppressed when the input photocurrent increased comparing to other structural or experimental results. Besides, the proposed structure has enhanced at least 7 dB in peak output-power compared to the device with a uniformly doped collection layer, even at 170 GHz and zero- or low-bias operation. Although the MM-UTC-PD with a little punishment in peak output power, its bandwidth is improved by 4.3%, compared with the traditional structure. This suggested structure can realize the trade-off between the external quantum-efficiency and bandwidth when miniaturized junction size is required. The above proposed structures may find applications in next-generation optical interconnect or coherent fiber communication systems, where is greatly desirable for broadband high-power photo-receiver with low power consumption and high-density integration. Our future work is to fabricate photodetectors with the proposed structures and further verify the proposed design.

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References

[1] Pearall T P, Piskarski M, Brochet A and Chevrier J 1981 A Ga0.47In0.53As/InP heterophotodiode with reduced dark current IEEE J. Quantum Electron. QE-17 255–9
[2] Ishibashi T, Kodama S, Shimizu N and Furuta T 1997 High-speed response of uni-traveling-carrier photodiodes Japan. J. Appl. Phys. 36 6263–8
[3] Chen H, Beling A, Pan H and Campbell J C 2009 A method to estimate the junction temperature of photodetectors operating at high photocurrent IEEE J. Quantum Electron. 45 1357–41

[4] Shimizu N, Watanabe N, Furuta T and Ishibashi T 1998 InP-InGaAs uni-traveling-carrier photodiode with improved 3-dB bandwidth of over 100 GHz IEEE Photon. Technol. Lett. 10 1412–4

[5] Ito H, Furuta T, Nakajima Y, Yoshino K and Ishibashi T 2005 Photonic generation of continuous THz wave using uni-traveling-carrier photodiode J. of Lightw. Technol. 23 4016–21

[6] Li Q, Li K, Fu Y, Xie X, Yang Z, Beling A and Campbell J C 2016 High-power flip-chip bonded photodiode with 110 GHz bandwidth Journal of Lightw. Technol. 34 2138–44

[7] Shi J-W, Kuo F-M and Bowers J E 2012 Design and analysis of ultra-high-speed near-ballistic uni-traveling-carrier photodiodes under a 50-O load for high-performance power performance IEEE Photon. Technol. Lett. 24 533–5

[8] Wun J-M, Wang Y-W and Shi-J W 2018 Ultrafast uni-traveling-carrier photodiodes with GaAs, Sb, s/InGaAs, As type-II hybrid absorbers for high-power operation at THz frequencies IEEE J. Sel. Topics Quantum Electron. 24 8500207

[9] Shi J-W, Kuo F-M, Wu C-I, Chang C-L, Liu C-Y, Chen C-Y and Chyi J-I 2010 Extremely high saturation current-bandwidth product performance of a near-ballistic uni-traveling-carrier photodiode with a flip-chip bonding structure IEEE J. Quantum Electron. 46 80–86

[10] Feiginov M N 2007 Analysis of limitations of terahertz p–i–n uni-traveling-carrier photodiodes Appl. Phys. 102 Art. no. 084510

[11] Wun J-M, Lai C-H, Chen N-W, Bowers J E and Shi J-W 2014 Flip-chip bonding packaged THz photodiode with broadband high-power performance IEEE Photon. Technol. Lett. 26 2462–4

[12] Cross A S, Zhou Q, Beling A, Fu Y and Campbell J C 2013 High-power flip-chip mounted photodiode array Opt. Exp. 21 9967–73

[13] Angkaew A, Umezawa T and Kawanishi T 2014 Crosstalk reduction for large scale photonic integrated circuits Presented at the Int. Topical Meeting Microwave Photonics (Japan: Sendai) Art. no. TuEB-9 (https://doi.org/10.1109/MWP.2014.6994150)

[14] Umezawa T, Akahane K, Yamamoto N, Inagaki K, Kanno A and Kawanishi T 2015 Zero-bias operational ultra-broadband UTC-PD above 110 GHz for high signal rate PD-array in high-density photonic integration Presented at Optical Fiber Communications Conf. and Exhibition (CA, USA: Los Angeles) Art. no. MSCP.7.ieeeexplore.ieee.org/document/7121553 (https://doi.org/10.1364/ OFC.2015.MSCP.7)

[15] Liu T, Huang Y, Niu H, Fei J, Ma X, Wu G, Liu K, Duan X and Ren X 2018 Design of bias-free operational uni-traveling-carrier photodiodes for terahertz wave generation Opt. Quantum Electron. 50 Art. no. 284

[16] Williams K J and Esman R D 1999 Design considerations for high-current photodetectors J. Lightwave Technol. 17 1443–54

[17] Li X, Demiguel S, Zheng X, Campbell J C, Tulchinsky D A, Williams K J, Ishikita T, Kinsey G S and Sudharsans R 2004 High-saturation-current charge-compensated InGaAs-Inp uni-traveling-carrier photodiode IEEE Photon. Technol. Lett. 16 864–6

[18] Xie X, Zang J, Beling A and Campbell J C 2017 Characterization of amplitude noise for photo noise washout in charge-compensated modified uni-travelling carrier photodiodes J. Lightwave Technol. 17 1718–24

[19] Duan X, Wang J, Huang Y, Liu K, Shang Y, Zhou G and Ren X 2016 Mushroom-mesa photodetectors using sub wavelength gratings as focusing reflectors IEEE Photon. Technol. Lett. 28 2273–6

[20] Huang Y-L and Sun C-K 2000 Nonlinear saturation behaviors of high-speed p–i–n photodetectors J. Lightwave Technol. 18 203–12

[21] 2016 (Santa Clara, CA, united States of America: ATLAS User’s Manual) Cited in 3rd Chapter

[22] Ghione G 2009 Semiconductor Devices for High-Speed Optoelectronics (United States of America: by Cambridge University Press) Ch. 4

[23] Umezawa T, Kanno A, Kashima K, Matsumoto A, Akahane K, Yamamoto N and Kawanishi T 2016 Bias-free operational UTC-PD above 110 GHz and its application to high baud rate fixed fiber communication and W-band photonic wireless communication J. Lightw. Technol. 34 5138–47

[24] Chitioui M, Carpentier D, Bernard S, Rousseau B, Lelarge F, Pommerace F, Jaryy C, Enard A and Achouche M 2009 Thick absorption layer uni-traveling-carrier photodiodes with high responsivity, high speed, and high saturation power IEEE Photon. Technol. Lett. 21 429–31

[25] Chitioui M, Enard A, Carpentier D, Bernard S, Rousseau B, Lelarge F, Pommerace F and Achouche M 2008 High-performance uni-traveling-carrier photodiodes with a new collector design IEEE Photon. Technol. Lett. 20 1163–5

[26] Wun J-M, Liu H-Y, Zeng Y-L, Pan C-L, Huang C-B and Shi J-W 2015 High-power THz-wave generation by using ultra-fast (315 GHz) uni-traveling-carrier photodiode with novel collector design and photonic femtosecond pulse generator Presented at Optical Fiber Communications Conf. and Exhibition (CA, USA: Los Angeles) paper MSCP.6.ieeeexplore.ieee.org/document/7121553 (https://doi.org/10.1364/ OFC.2015.MSCP.6)

[27] IhH-Min Wun Y-L, Zeng and Shi J-W 2016 GaAs, Sb, s/InP UTC-PD with graded-bandgap collector for zero-bias operation at Sub-THz regime Presented at Optical Fiber Communications Conf. and Exhibition (California, USA: Anaheim) paper Tu2D.4 (https://doi. org/10.1364/OFCC.2016.Tu2D.4)

[28] Wun J-M, Chao R-L, Wang Y-W, Chen Y-H and Shi J-W 2017 Type-II GaAs, Sb, s/InP uni-traveling-carrier photodiodes with sub-terahertz bandwidth and high-power performance under zero-bias operation J. Lightwave Technol. 35 711–6

[29] Davis G A, Weiss R E, LaRue R A, Williams K J and Esman R D 1996 A 920–1650-nm high-current photodetector IEEE Photon. Technol. Lett. 8 1573–5

[30] Maloney T and Frey J 1977 Transient and steady-state electron transport properties of GaAs and InP Appl. Phys. 48 781–7

[31] Shi J-W, Kuo F-M, Rodwell M and Bowers J E 2011 Ultra-high-speed (270 GHz) near-ballistic uni-traveling-carrier photodiode with very-high saturation current (17 mA) under a 50-O load Presented at IEEE Photonic Society 24th Annual Meeting (VA, USA: Arlington) paper MSCP.6.ieeeexplore.ieee.org/document/7121553 (https://doi.org/10.1109/PHO.2011.6110405)

[32] Chitioui M, Enard A, Carpentier D, Bernard S, Rousseau B, Lelarge F, Pommerac F and Achouche M 2008 High-power high-linearity uni-traveling-carrier photodiodes for analog photonic links IEEE Photon. Technol. Lett. 20 202–4

[33] Kuo F-M, Shi J-W, Chiang H-C, Huang H-P, Chiou H-K, Pan C-L, Chen N-W, Tsai H-P and Huang C-B 2010 Spectral power enhancement in a 100 GHz photonic millimeter-wave generator enabled by spectral line-by-line pulse shaping IEEE Photon. J. 2 719–27

[34] Ito H, Nagatsuma T, Hirata A, Minomori T, Tatsuka A, Hirota Y and Ishibashi T 2003 High-power photonic millimeter-wave generation at 100 GHz using matching-circuit-integrated uni-traveling-carrier photodiodes Proc. Inst. Elect. Eng. Optoelectron. 150 138–42

[35] Ito H, Hirota Y, Hirata A, Nagatsuma T and Ishibashi T 2001 11 dBm photonic millimetre-wave generation at 100 GHz using uni-travelling-carrier photodiodes IEEE Electronics Letters 37 1225–6

[36] Hirata A, Harada M and Nagatsuma T 2003 120-GHz wireless link using photonic techniques for generation, modulation, and emission of millimeter-wave signals J. Lightwave Technol. 21 2145–53

[37] Ito H, Ito T, Muramoto Y, Furuta T and Ishibashi T 2003 Rectangular waveguide output uni-traveling-carrier photodiode module for high-power photonic millimeter-wave generation in the F-band J. Lightwave Technol. 21 3456–62
[38] Wan J-M, Liu H-Y, Lai C-H, Chen Y-S, Yang S-D, Pan C-L, Bowers J E, Huang C-B and Shi J-W 2014 Photonic high-power 160 GHz signal generation by using ultra-fast photodiode and a high-repetition-rate femtosecond optical pulse train generator IEEE J. Sel. Topics Quantum Electron. 20 3803507

[39] Yang H, Daunt C L M, Gity F, Lee K-H, Han W, Corbett B and Peters F H 2010 Zero-bias high-speed edge-coupled unitraveling-carrier InGaAs photodiode IEEE Photonics Technol. Lett. 22 1747–9

[40] Sun S, Liang S, Xu J, Zhang L, Guo L, Xie X, Zhu H and Wang W 2017 Evanescently coupled waveguide InGaAs UTC-PD having an Over 21 GHz bandwidth under zero bias IEEE Photonics Technol. Lett. 29 1155–7

[41] Cui D, Hubbard S M, Pavlidis D, Eisenbach A and Chelli C 2002 Impact of doping and MOCVD conditions on minority carrier lifetime of zinc- and carbon-doped InGaAs and its applications to zinc- and carbon-doped InP/InGaAs heterostructure bipolar transistors Semicond. Sci. Technol. 17 503–9