Optimization of MUTC-PD Cliff Layer Design under High Optical Power Injection

Zhangwan Peng
College of Information Science and Electronic Engineering
Zhejiang University
Hangzhou, China
pengzhangwan@zju.edu.cn

Ruoyun Yao
College of Information Science and Electronic Engineering
Zhejiang University
Hangzhou, China
yaoruoyun@zju.edu.cn

Weiwei Pan
College of Information Science and Electronic Engineering
Zhejiang University
Hangzhou, China
weiweipan@zju.edu.cn

Wanshu Xiong
College of Information Science and Electronic Engineering
Zhejiang University
Hangzhou, China
xiongwanshu@zju.edu.cn

Chaodan Chi
Research Institute of Intelligent Networks
Zhejiang Lab
Hangzhou, China
chicd@zhejianglab.com

Chen Ji
College of Information Science and Electronic Engineering
Zhejiang University
Hangzhou, China
chen.ji@zju.edu.cn

***Abstract*—We analyzed and optimized doping concentration in the cliff layer of a Modified Uni-Traveling-Carrier Photodiode (MUTC-PD) to alleviate the space charge effect, achieving 310 GHz intrinsic 3-dB bandwidth under 15 mW/µm² optical power density.**

Keywords—terahertz, MUTC-PD, cliff layer, high optical power

I. Introduction

Terahertz radiation,with frequency range from 0.1 to 10 terahertz (THz), has been extensively researched owing to its various applications in medical imaging, security detection and wireless data transmission communication system [1-3]. In the application of optical heterodyne, the InGaAs Uni-Traveling-Carrier Photodiode (UTC-PD) is regarded as a key optoelectronic device for continuous terahertz wave generation due to its unique high operating bandwidth. To improve the responsivity of a UTC-PD without degrading its high frequency response, a MUTC-PD which has a hybrid absorber structure has been introduced. The absorber of the MUTC-PD consists of a highly p-doped layer and a lightly n-doped layer. During operation, the n-doped absorption layer will be depleted to create an electric field that allows electrons to transit at a fast drift speed. The heavily n-doped cliff layer inside the device which was first introduced in [4]. Although the incorporation of a cliff layer in the MUTC-PD has been reported to contribute to high-saturation-current [5], there has been limited quantitative investigation into the underlying device physics. In this work, we simulated for the first time quantitatively the carrier transport physics behind bandwidth degradation of MUTC-PD under high optical power injection, in particular the surprisingly critical role played by relatively small variation in cliff layer doping concentration and its strong effect on UTC-PD carrier transport, and proposed an optimized MUTC-PD design achieving a high 310 GHz intrinsic 3-dB bandwidth at 15 mW/µm² optical power density.

II. Device Structure and Simulation Results

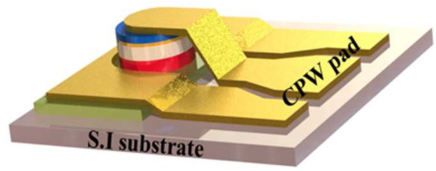
A. Design Structure

Fig.1(a) shows the baseline epitaxial structure of a bottom-illuminated MUTC-PD design, which includes a 60 nm N-contact, a 185 nm InP collector, a 5 nm cliff layer, a 10 nm transition layer, a 120 nm hybrid InGaAs absorber, a 15 nm block layer and a 60 nm P-contact growing on a semi-insulating (SI) substrate sequentially. The hybrid absorption layer includes a 60 nm heavy p-doped InGaAs (un-depleted) region and a 60 nm light n-doped InGaAs (depleted) region for high speed intrinsic response. In our baseline design, a 5 nm thin n-doped (2e18) InP cliff layer is placed immediately underneath the 10 nm InGaAsP transition layer. Fig. 1(b) shows the schematic diagram of the MUTC-PD in Fig.1(a), depicting the etched mesa and coplanar waveguide electrode [illegible]ures on SI substrate.

(a)

Layer	Material	Thickness (nm)	Doping (cm^{-3})	Type
P contact	$In_{0.53}Ga_{0.47}As$	60	$>2\times10^{19}$	P^+
Block layer	$In_{0.6}Ga_{0.4}As_{0.85}P_{0.15}$	15	2×10^{19}	P^+
P+ absorber	$In_{0.53}Ga_{0.47}As$	60	2×10^{18}	P^+
N- absorber	$In_{0.53}Ga_{0.47}As$	60	2×10^{16}	N
Transition layer	InGaAsP	10		i
Cliff layer	InP	5	2×10^{18}	N^+
Collector	InP	185	2×10^{16}	N
N-contact	InP	60	$>2\times10^{19}$	N^+
Semi-Insulating substrate	InP			

(b)



(c)

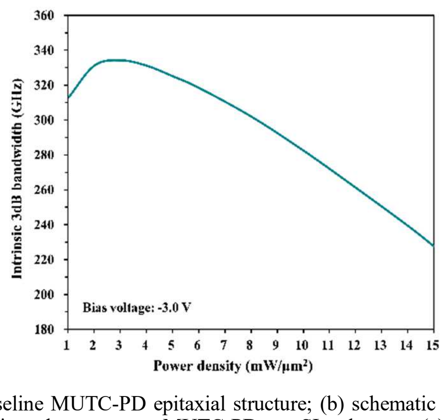


Fig.1 (a) Baseline MUTC-PD epitaxial structure; (b) schematic diagram of bottom-illuminated mesa type MUTC-PD on SI substrate; (c) simulated intrinsic 3-dB bandwidth under different optical power density.

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B. Simulation Results

We used a commercial 3D finite element semiconductor device simulator Apsys to calculate the frequency response of the MUTC-PD design, the calculated intrinsic 3-dB bandwidth of the baseline design is shown in Fig. 1(c) under varying optical power density at -3V bias voltage. As the optical power density varies from 1 mW/μm² to 3 mW/μm², the 3-dB bandwidth increases gradually to a maximum value of 330 GHz. This initial bandwidth increase with optical power is unique to UTC-PD and can be explained by the self-induced E-field effect accelerating electron transport in the depleted absorber region[5], demonstrating the accuracy and sophistication of the simulator in modeling complex carrier transport effects. When the optical power injection increases further, the bandwidth drops rapidly reaching 227 GHz at 15 mW/μm². This phenomenon can be explained by the large amount of photocarriers generated under high optical input power conditions and cannot be swept out efficiently, which creates a space charge effect, directly leads to the high speed response degradation.

III. OPTIMIZATION RESULTS

To understand quantitatively MUTC-PD bandwidth reduction under high optical power input, we analyzed electron population distribution, electric field, and intrinsic high frequency response at -3V DC bias under high optical power input (15mW/μm²). Fig. 2 shows the effect of 2e18, 3e18 and 5e18 cm^{-3} n-type cliff layer doping respectively, which turns out to be a highly sensitive parameter. For the 2e18 cliff layer doping (baseline) case (blue square dotted curve), a high photo-electron concentration accumulates at the undoped InGaAsP transition layer, creating a strong negative E field gradient in the transition layer, and lowers the E field in the depleted absorber region, reducing electron drift speed inside the absorber and intrinsic 3-dB bandwidth to 228 GHz.

At 3e18 cm^{-3} (orange solid curve), E field gradient in the depleted cliff layer raises the depleted absorption layer E field level further, significantly reduces electron accumulation, improving intrinsic 3-dB bandwidth is to 310 GHz. When the cliff layer doping concentration increases to 5e18 cm^{-3} (green dashed curve), the stronger cliff layer E field gradient pushed up the E field level in the depleted absorption layer even further as expected.

However counter intuitively in Fig. 2 (c) the intrinsic 3-dB is actually reduced to 162 GHz. The root cause can be seen in Fig 2(a) where a very strong electron accumulation (3.5e17) is observed in the InP collector to the cliff layer interface (0.245 μm), this electron accumulation produces a sharp E field gradient at the interface where the E field level actually becomes negative (i.e. strongly opposing) and dramatically slows down electron transport toward the collector. Overall we see that a slight variation in n-doped cliff layer doping can modify the carrier and internal E field distribution of a MUTC-PD in a nonlinear and complex way, with a dramatic effect on device carrier transport properties at high optical power.

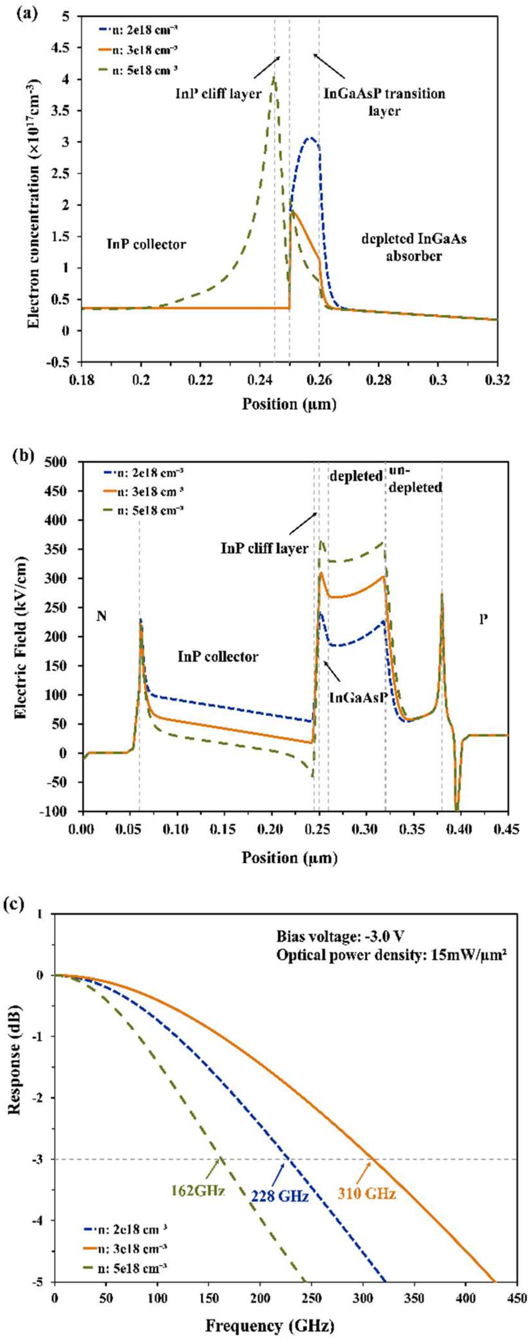

Fig. 1. (a)Electron population, (b) Electric field distribution inside a MUTC-PD and (c) calculated intrinsic 3-dB bandwidth vs variation in cliff layer n-doping concentration (2, 3, 5e18 cm^{-3}) under high optical power input (15mW/μm²) at -3V bias voltage.

IV. CONCLUSION

In this paper, we simulated a MUTC-PD design under high optical power injection condition systematically for the first time. We discovered the cliff layer doping concentration has a very sensitive effect on the device OE intrinsic bandwidth, the carrier transport effect was quantified by analyzing in detail the carrier concentration and internal electric field distributions. An optimized design with 310 GHz intrinsic 3-dB bandwidth at 15 mW/μm² optical power density has been demonstrated, which we believe should prove to be highly useful for the future commercial deployement of high power MUTC-PD for free space THz communication links, in order to overcome strong atmospheric THz signal attenuations.

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