Uni-Traveling Carrier Photodiodes with Type-II $GaAs_{0.5}Sb_{0.5}/In_{0.53}Ga_{0.47}As$ Hybrid Absorbers Integrated with Substrate Lens in 400 Gbit/sec DR-4 System

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Abstract: UTC-PD with type-II $GaAs_{0.5}Sb_{0.5}/In_{0.53}Ga_{0.47}As$ hybrid absorber integrated with substrate lens is demonstrated with high responsivity (0.95A/W) and wide O-E bandwidth (33GHz) at 1310 nm wavelength. High-sensitivity (-10dBm OMA) is realized in 400G lens-free DR-4 platform.

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I. Introduction

The continuous reduction of gate length of CMOS transistor drives the increase in data rate per channel in the communication system. This leads to higher bandwidth requirement for both transmitter (Tx) and receiver (Rx). In the newly developed 400 Gbit/sec Ethernet system (DR-4) with 4 fiber channels, the corresponding data rate per channel is 112 Gbit/sec [1]. In order to attain such high data rate, one of the possible solutions is to utilize the pulse-amplitude modulation-4 (PAM-4) format with a 56 Gbaud per channel. A high-responsivity p-i-n photodiode operated at 1310 nm wavelength with a 3-dB optical-to-electrical (O-E) bandwidth over 30 GHz and a large aperture size to meet the required alignment tolerance in device package, serves as the key component in the receiver end of the aforementioned Ethernet system. However, there is engineering trade-off among speed, responsivity, and device active area in the design of high-speed PD. To enlarge the photo-absorption constant in the active layer of PD is one of the most effective ways to fundamentally mitigate these trade-offs [2,3]. Furthermore, in order to further reduce the cost in the newly developed DR-4 system, it is necessary to integrate the Tx and Rx in the same platform [1]. Such compact co-package inhibits the use of external glass lens for the focus of the launched optical signal onto PD in the Rx side. In this work, we demonstrate the back-side illuminated uni-traveling carrier photodiode (UTC-PD) with a type-II hybrid absorber (p-$GaAs_{0.5}Sb_{0.5}$/i-$In_{0.53}Ga_{0.47}As$) and a backside lens fabricated on the InP substrate. With flip-chip bonding package, such device exhibits wide 3-dB O-E bandwidth (33 GHz), large diameter of active mesa (20 μm), high responsivity (0.95 A/W), and high-sensitivity (-10 dBm OMA) in the platform of DR-4 package, which has no lens inside.

II. Device Structure

Figures 1 (a) shows the simulated band diagram of our demonstrated device structure. Our epi-layer structure was grown on the semi-insulating (S.I.) InP substrate in a molecular-beam epitaxy (MBE) chamber. From top to bottom, it is composed of the p^+-$In_{0.53}Ga_{0.47}As$ contact layer, p^+-$Al_{0.3}Ga_{0.7}As_{0.5}Sb_{0.5}$ electron blocking layer, p-type hybrid absorber, InP collector layer, and n^+ InP contact layer. The detailed thickness and doping are specified in this figure. Here, the hybrid absorption region with a type-II band alignment ($GaAs_{0.5}Sb_{0.5}/In_{0.53}Ga_{0.47}As$) is comprised of two major parts. The first is the p-type $GaSb_{0.5}As_{0.5}$ absorption layer with a thickness of 300 nm and a graded doping profile (top: 1×10^{19} cm^{-3} to bottom: 5×10^{16} cm^{-3}) designed to accelerate the electron diffusion process. The second is an intrinsic $In_{0.53}Ga_{0.47}As$ layer with a thickness of 400 nm. The un-doped $In_{0.53}Ga_{0.47}As$ layer is inserted in the p-type absorption region of the traditional UTC-PD to minimize the electron recombination process. As shown in Figure 1 (a), the type-II band alignment between the interface of the $GaAs_{0.5}Sb_{0.5}$ and $In_{0.53}Ga_{0.47}As$ layers narrows the effective bandgap to 0.5 eV (~2.4 μm cut-off wavelength [4]), which can further enhance the absorption process under 1.55 μm (0.8 eV) wavelength excitation. Due to the narrowing of the bandgap and enhancement of the photo-absorption process at the type-II interface, our device with a top-illuminated structure shows an over 16.7 % improvement in the responsivity as compared to that of UTC-PD with the same thickness of pure $In_{0.53}Ga_{0.47}As$ absorber (0.7 μm) [3]. The InP collector layer thickness (1.2 μm) is optimized to balance the RC-limited and internal transient time limited bandwidths in our device [3]. Figure 1 (b) and (c) shows the picture of top-view of demonstrated PD before and after flip-chip bonding. As can be seen, there is a backside lens fabricated on the InP substrate side of our demonstrated PD [5,6]. The measured DC responsivity of our demonstrated PD under -2V bias and 1310 nm wavelength excitation is around 0.95 A/W. This number is as high as most of the reported InP based PD for 10 Gbit/sec operations. In addition, such responsivity (0.95 vs. 0.7 A/W) is higher than that of the top-illuminated PD reported in our previous work [3], which has the same epi-layer structure. This is because that the topmost contact metal can serve the reflector and fold the optical absorption path in the backside-illuminated PD.

III.Measurement Result:

Figures 2 (a) and (b) shows the measured bias-dependent O-E frequency responses of device under low (0.1 mA) and high (1.5 mA) output photocurrents at 1.31 μm wavelength, respectively. Evidently when the reverse bias is over -2 V, the measured 3-dB O-E bandwidths of demonstrated PD is around 33 GHz. Furthermore, regardless of high or low output current, the measured 3-dB O-E bandwidths remain unchanged. This measurement result clearly indicates the good linearity of our device, which is a critical issue in the performance of PAM-4 receiver. Figure 3 shows the measured photo-generated microwave power versus output photocurrent for the demonstrated PD obtained under different reverse biases (-2 to -5V). The measurement frequency chosen was around the 3-dB O-E bandwidth at 30 GHz. The ideal relation between the microwave power and averaged photocurrent (solid line) with a 100% optical modulation depth under a 50 Ω load is also plotted for reference. We note that even under -2 V bias, the saturation currents can be as high as around 4 mA. Such high output current can satisfy the required overload optical power (+4.5 dBm; around 2.5 mA photocurrent) for the 400 Gbit/sec receiver with PAM-4 modulation format. Figure 4 (a) shows the photo of our demonstrated PD packaged in the DR-4 platform. Figure 4 (b) shows the measured sensitivity at 112 Gbit/sec with a PAM-4 modulation format. A very-high OMA sensitivity (-10 dBm) under BER=2×10^{-4} can be achieved, far exceeding the required spec. for DR-4 system (-4.6 dBm OMA). Table 1 shows the benchmark of commercial available PDs for DR-4 application. With the 3-dB bandwidths as high as 35 GHz, our PD exhibits superior performances in terms of responsivity and saturation current to those of reported ones.

IV.Summary:

In conclusion, we demonstrate the UTC-PD structure with a novel design in its hybrid absorber (p-$GaAs_{0.5}Sb_{0.5}$/i-$In_{0.53}Ga_{0.47}As$) integrated with a substrate lens for flip-chip bonding package and the application of Rx in DR-4 system. Such device can achieve a very-high responsivity (0.95 A/W), wide O-E bandwidth (33 GHz), high saturation current (4 mA), and high-sensitivity (-10 dBm OMA) without using any external lens in our package.

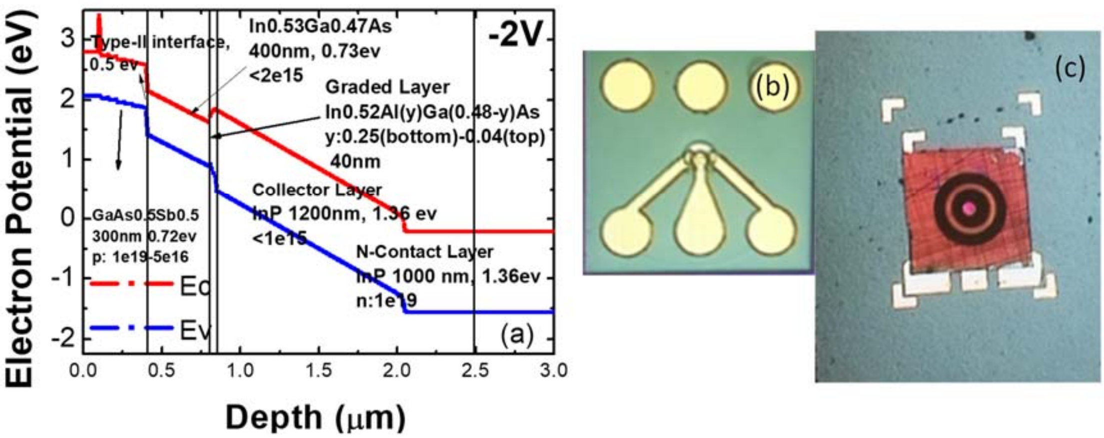

Fig. 1(a). Simulated band diagram of the demonstrated hybrid-absorber UTC-PDs under -2 V bias voltage. The unit for doping density in each layer is cm^{-3}. Photo of top-view of the fabricated devices (b) before and (c) after flip-chip bonding.

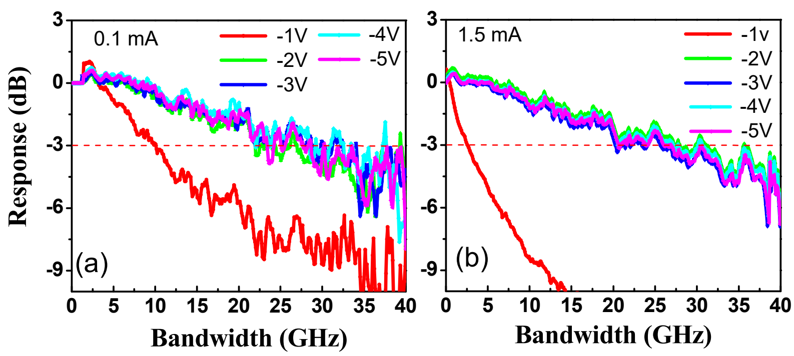

Figure 2. The measured bias dependent O-E frequency responses under different output photocurrents (a) 100 μA and (b) 1.5 mA at 1.31 μ m wavelength.

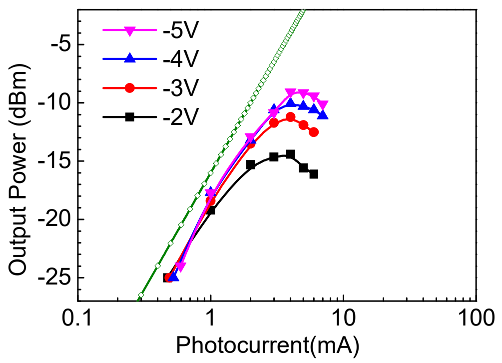

Figure 3. The measured photo-generated microwave power versus photocurrent for device under sinusoidal signal excitation and with different reverse biases at operating frequencies of 30 GHz. The open symbol line shows the ideal trace for a 100% optical modulation depth and 50 Ω load.

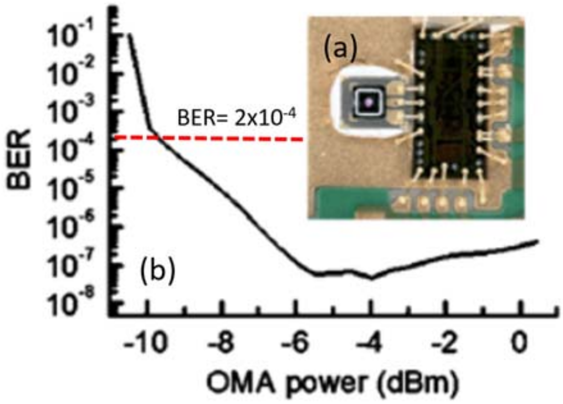

Figure 4. (a) The photo of our demonstrated p-i-n PD packaged in the DR-4 Rx platform. (b) The measured bit-error-rate (BER) vs. OMA power of such modules.

TABLE I
KEY PERFORMANC METRICS IN 56G PD

Parameters	**NTT**	**GCS D0480_16 µm**	**Hamamatsu 56 GB BT**	**Broadcom LPD 3035-DS 100**	**Albis PD40X1**	**UTC-PD with type-II hybrid absorber**
Reference	7	8	9	10	11	**(This Work)**
Type	Backside illumination	Top illumination	Backside illumination	Backside illumination	Backside illumination	**Backside illumination**
Mesa Size	19 µm	20 µm	16 µm	16 µm	12 µm	**20 µm**
Responsivity	0.8 A/W (1310 nm)	0.77 A/W (1310nm)	0.85 A/W (1550 nm)	0.9 A/W (1310 nm)	0.8 A/W (1310nm)	**0.95 A/W (1310nm)**
C_P		80 fF	50 fF	70 fF	40 fF	**40fF**
Bandwidth	35 GHz (-2V)	36 GHz (-3V)	30 GHz (-2V)	29 GHz (-2V)	35 GHz (-2.5V)	**33 GHz (-2V)**
Saturation Current	4 mA (-2V)					**4 mA (-2V)**

V. Reference:

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