HIGH FREQUENCY PHOTODIODE WORK IN JAPAN

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ABSTRACT

The recent progress in the device performance of the uni-traveling-carrier photodiode (UTC-PD) is described. The UTC-PD utilizes only electrons as the active carriers, and this unique feature is the key to achieving excellent high-speed and high-output characteristics simultaneously. The achieved performance includes a record 3-dB bandwidth of 310 GHz, high-power photonic millimeter-wave generation with an output power of over +13 dBm at 100 GHz, high-output-voltage photoreceiver operation at bit rates of up to 80 Gbit/s, and demultiplexing operation at 200 Gbit/s using a monolithic PD-EAM optical gate.

INTRODUCTION

Photonics technology has been instrumental in realizing various broad-band communication systems, such as high-bit-rate fiber-optic communications systems and fiber-radio wireless communication systems. Photonic millimeter and sub-millimeter wave generation is also a promising approach for high-frequency measurements and radio astronomy. In these systems, opto-electronic devices, such as light sources, ultrafast optical modulators, and ultrafast photodetectors, are the key components. For the ultrafast photodetectors, a high saturation power level is important, because the combination of a high-saturation-power photodiode and an optical fiber amplifier can eliminate the post-amplification electronics and extend the bandwidth, and thus simplify the receiver configuration. A wide linearity range is also important, especially for analog applications. The uni-traveling-carrier photodiode (UTC-PD) [1], which has a unique mode of operation, is a promising solution for such requirements. In this paper, recent progress in InP/InGaAs UTC-PD technologies is described.

OPERATION OF UTC-PD

Fig. 1 shows the band diagram of the UTC-PD. Basically, the UTC-PD has a p-type narrow-gap absorption layer and an undoped (or a lightly doped n-type) wide-gap collection layer. Because the p-type absorption layer is quasi-neutral, majority holes respond very fast, within the dielectric relaxation time, by their collective motion. Therefore, only electrons are the active carriers, and their transport determines the total delay time. Since the electron velocity at overshoot is about one order of magnitude larger than the hole saturation velocity, the carrier transit time in the depletion layer can be much shorter and the space charge effect much smaller than in a conventional pin-PD. This feature results in both a higher 3dB bandwidth (f_{3dB}) and a higher output saturation current. In addition, the UTC-PD can provide high-power output with relatively low bias voltages. This is because the optimum electric field for obtaining a high electron velocity at overshoot in the InP collection layer is relatively small.

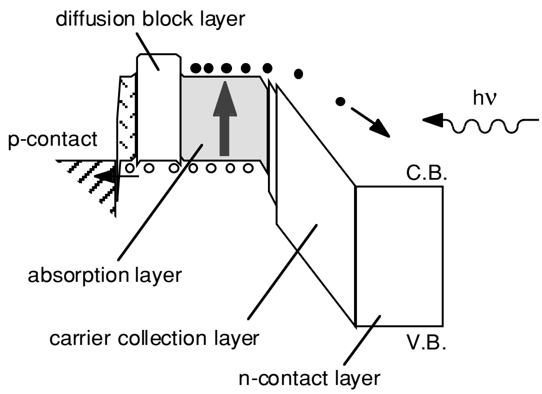


Fig. 1. Band diagram of a UTC-PD.

DEVICE CHARACTERISTICS

Fig. 2 shows the relationship between f_{3dB} and the absorption layer thickness (W_A) [2]. These results were obtained from the Fourier transform of the pulse photoresponse in a back-illuminated InP/InGaAs UTC-PD.

Data for conventional pin-PDs are also shown for comparison. The f_{3dB} increases as $1/W_A^2$ for the UTC-PD and as $1/W_A$ for the pin-PD. This difference comes from the difference in the carrier transport in the absorption layer; namely, the electron transport in the absorption layer is diffusive in the UTC-PD, which is in contrast to the drift motion of both carriers in the conventional pin-PD. The enhancement of f_{3dB} at high optical inputs (large signal outputs) is due to the effect of the self-induced field in the absorption layer [2].

Fig. 3 shows the pulse photo-response of a UTC-PD with an absorption layer thickness of 300 A [3]. The shortest pulse response of 0.97 ps was obtained with a very low bias voltage (V_b) of -0.5 V. The Fourier transform of this pulse response gives a 3-dB bandwidth of 310 GHz. This is the highest f_{3dB} ever reported for PDs operating at 1.55 µm. The device also exhibited a 10 dB down bandwidth of 750 GHz, and a 15 dB down bandwidth of over 1 THz.

We also confirmed the reliability of UTC-PDs for 40 Gbit/s class applications through a bias-temperature stress test at 175-240 °C [4]. The dark current stayed almost constant, and no failure was observed for up to 1600 hours. The failure rate was then estimated assuming the random failure mode with an activation energy of 0.35 eV. The calculated failure rate at 25 °C is as low as 42 FIT for a confidence level of 60 %.

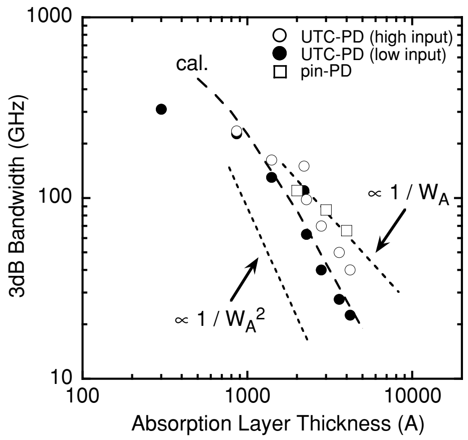


Fig. 2. Relationships between f_{3dB} and W_A for UTC-PDs and pin-PDs.

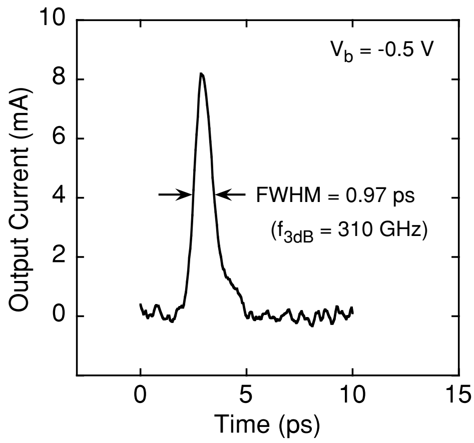


Fig. 3. Photoresponse of a UTC-PD with a W_A of 300 A.

APPLICATIONS OF HIGH-SPEED UTC-PDs

Promising analog applications of UTC-PDs are photonic microwave/millimeter-wave generators for fiber-radio wireless communications systems, high-speed measurement systems, microwave/millimeter-wave sensing, and radio astronomy [5]. The high linearity with the high output power of the UTC-PD can eliminate the electrical power amplifier in the O/E converter. High-power transmission of over +10 dBm in the millimeter-wave range [6] and a 2.5-Gbit/s data transmission at 120 GHz [7] have already been demonstrated. For practical applications, we have integrated a UTC-PD with an impedance transformer consisting of a coplanar-waveguide short-stub and a metal-insulator-metal capacitor.

Figs. 4 and 5 show a micrograph and the output power (P_{out}) characteristics of a device designed for operation at 100 GHz [8]. A wide linearity with a very high saturation output of +13 dBm at V_b of -3 V is obtained. This is the highest millimeter-wave output directly generated from a PD at frequencies in the W-band. Fig. 6 summarizes the reported maximum output powers against the operation frequency for UTC-PDs [8-12] and pin-PDs [13-16]. It is clear that UTC-PD can provide about two orders of magnitude higher millimeter-wave power than conventional pin-PDs. These results clearly demonstrate that the UTC-PD is a promising device for high-power photonic millimeter/sub-millimeter wave generation.

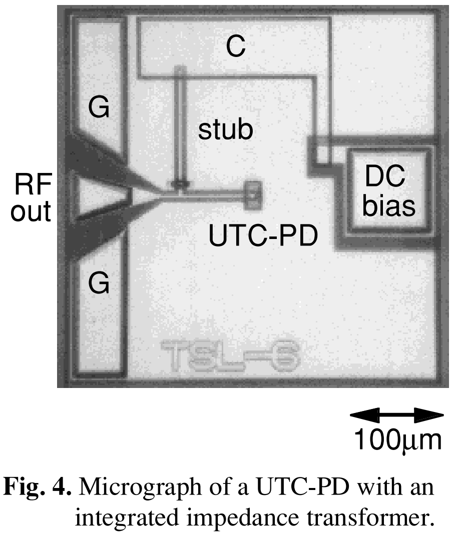
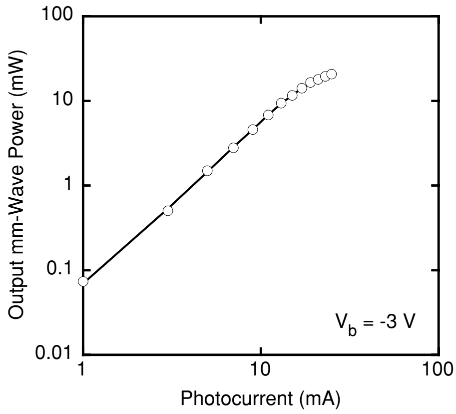


Fig. 4. Micrograph of a UTC-PD with an integrated impedance transformer.



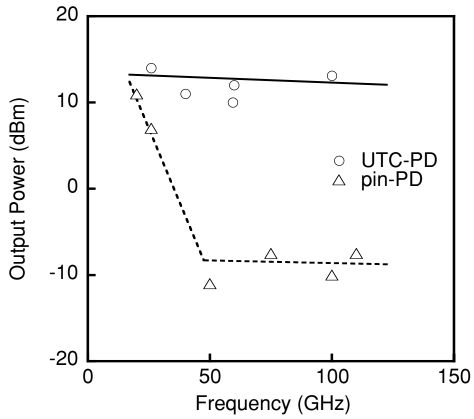
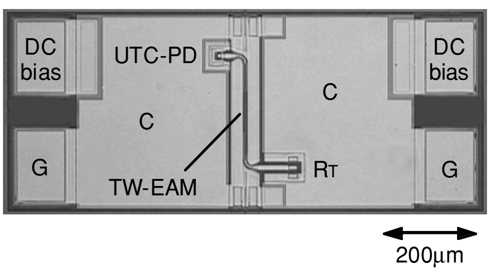


Fig. 5. Relationship between P_{out} and diode photocurrent at 100 GHz.

Fig. 6. Relationship between P_{out} and operation frequency for UTC-PDs and pin-PDs.

UTC-PDs are also advantageous in digital applications, such as high-bit-rate optical transmission systems operating at or over 40 Gbit/s. This is because a UTC-PD acts as a photo-receiver that can drive the decision circuit directly without post amplifiers. The operation of a UTC-PD at up to 80 Gbit/s with an output voltage of 0.8 V_{pp} has been demonstrated [17]. A UTC-PD can also directly drive an electro-absorption modulator, providing an ultrafast optical gate [18]. Fig. 7 shows a micrograph of a PD-EAM optical gate. Here, a UTC-PD, traveling-wave EAM, terminal resistor, and a bias circuit are monolithically integrated. In this device, the EAM is directly driven by the high-speed and high-output signals generated from the UTC-PD. This configuration can eliminate the speed-limiting electrical driver amplifiers. Fig. 8 shows the experimental results of the optical de-multiplexing operation using the PD-EAM [19]. Optical data pulses with 5-ps period corresponding to 200 Gbit/s, shown on the right, were fed into the EAM, and the UTC-PD was driven by an optical clock pulse. Then, every signal pulse was clearly de-multiplexed by adjusting the timing between the input data pulses and the clock pulse. The on/off ratio was more than 18 dB.



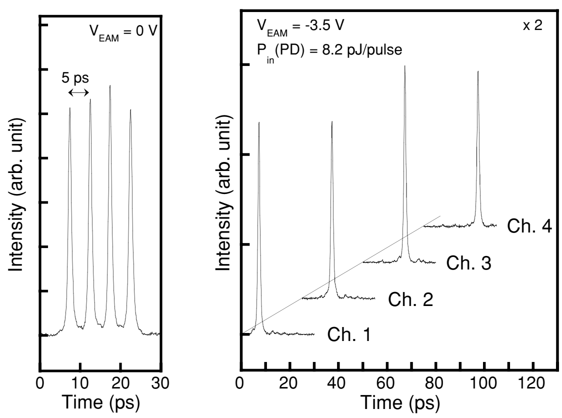


Fig. 7. Micrograph of a monolithic PD-EAM optical gate.

Fig. 8. Input and output waveforms of a 200 Gbit/s DEMUX operation.

SUMMARY

The uni-traveling-carrier photodiode has a fast response and is capable of high output, and low voltage operation. UTC-PDs exhibit excellent bandwidths of over 300 GHz, and an excellent reliability. We have already demonstrated high-power millimeter-wave generation without using electrical power amplifiers at up to 100 GHz with a maximum output power of over +10 dBm. Such a simple configuration will be used in future wireless communication systems, high-speed measurement systems, and radio astronomy. We also demonstrated photoreceiver operation without electrical amplifiers at 80 Gbit/s, and an optical DEMUX function with the PD-EAM optical gate at 200 Gbit/s. These results clearly indicate that the UTC-PD is a promising key component for future ultra-high-speed photonic systems.

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