Inst. Phys. Conf. Ser. No 166: Chapter 6
Paper presented at 26th Int. Symp. Compound Semiconductors, Berlin, Germany, 22–26 August 1999

Photoresponse Dynamics of Uni-Traveling-Carrier and Conventional pin-Photodiodes

T. Furuta, H. Ito, and T. Ishibashi

NTT Photonics Laboratories, 3-1 Morinosato-Wakamiya, Atugi-shi, Kanagawa 243-0198, Japan

Abstract. The pulse photoresponse dynamics of InP/InGaAs uni-traveling-carrier photodiode (UTC-PD) and conventional pin-PD were studied. For UTC-PDs, the output peak voltage increases linearly and the response speed shows a slight increase at low to medium input energy region. At high input energy region, the output intensity tends to saturate and the response shows broadening due to the space charge effect. However, the pulse fall time decreases as the input energy increases because of the self-induced field effect. Thus, serious reduction of bandwidth was not found in a UTC-PDs. On the other hand, the response of pin-PDs, consisting of a fast response related to electrons and a slow one due to holes, shows different behavior. Even at a lower energy, due to the space charge effect, the hole response immediately exhibits significant broadening and the peak intensity tends to saturate, leading to a substantially reduced bandwidth and response linearity.

1. Introduction

For the applications of high-bit-rate fiber-optics communication and high-output microwave photonics, the PD's performances of high output level and broad bandwidth are required. One of the most important parameters which determine these characteristics is the carrier transit time. As shown in Fig. 1 (a), the electrons and holes are generated in the depletion layer in a conventional pin-PD. The electrons are quickly swept out of the depletion layer, however, the holes remain longer due to their lower mobility and saturation velocity than the electrons. Thus, the carrier transit time is determined by the hole transport. On the other hand, a UTC-PD [1], consisting of a neutral narrow-gap photoabsorption layer and a depleted wide-gap carrier collection layer (Fig. 1 (b)), exhibits different carrier transport. Namely, the minority electrons are generated in a photoabsorption layer and injected into the collection layer. The hole transport can be ignored because of its majority carrier nature. Hence, only electrons are active and the carrier transit time is determined by the drift and diffusion of electrons in the absorption layer, since the collector layer transit time is very fast due to the velocity overshoot effect.

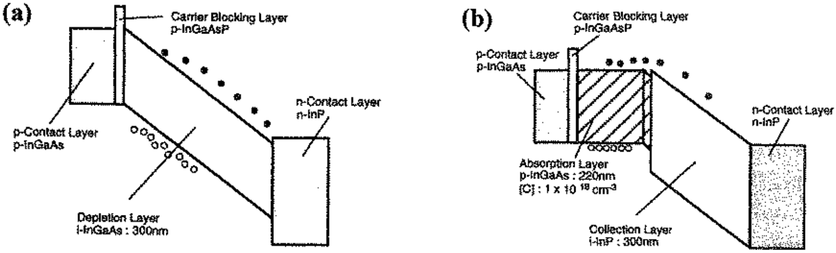


Fig. 1 Band diagrams of (a) conventional pin-PD and (b) UTC-PD.

Such a difference in the carrier transport of the two types of PDs is expected to be reflected in the difference of their performance such as output level and bandwidth characteristics. Previously, we reported the excellent performance of UTC-PDs (output peak current of 26 mA with 3dB reduction bandwidth (f_{3dB}) of 152 GHz [2] and 100 mA with f_{3dB} of 80 GHz [3]). However, experiments directly comparing the performance of a UTC-PD with that of a conventional pin-PD have not yet been done. In this work, we fabricated pin- and UTC-PDs with similar f_{3dB} and compared their photoresponses to clarify the difference in carrier dynamics and its effect on the output saturation characteristics.

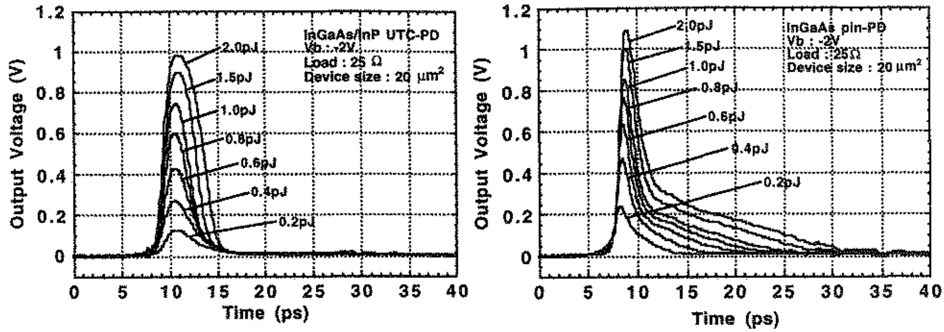
2. Device Design and Fabrication

The PD's structures were designed so that the f_{3dB} under small signal condition of the UTC-PD is similar to that of the pin-PD. To determine the layer parameters, the f_{3dB} was calculated based on the drift-diffusion model [4]. The thicknesses of InGaAs depletion layer of pin-PD and InP collection layer of UTC-PD were designed to be 300 nm to produce the same junction capacitance. For the pin-PD, the calculated f_{3dB} is about 100 GHz assuming the electron and hole velocities to be 4×10^7 cm/s [5] and 5×10^6 cm/s [6], respectively. For a UTC-PD, the intrinsic response is dominated by the photoexcited minority electron transport in p-InGaAs. From our previous results [2], [3], the minority electron mobility of 4000 $cm^2/V{\cdot}s$ was used for calculation. Also included was the self-induced electric field effect which enhances the electron velocity [7]. The obtained thickness of p-InGaAs which satisfies the f_{3dB} of 100 GHz is 220 nm, with the hole concentration of 1×10^{18} cm^{-3}.

The epitaxial layer structures were grown on semi-insulating InP substrates by MOCVD. Si and C were used for the n- and p-type dopants, respectively. The PDs were fabricated using a conventional process with junction area of 20 μm^2, where the f_{3dB} limited by CR time constant is 500 GHz. Thus, the response of each PD is mostly determined by the carrier transport through the device. Each device was connected to two 50Ω coplanar waveguides (an equivalent 25Ω load). The back side of the InP substrates was polished and then anti-reflection films were deposited for back-side illumination. The responsivities measured at 1.55 μm were 0.2 and 0.24 A/W for the UTC-PD and pin-PD, respectively. This difference is due to the difference of their absorption layer thicknesses.

3. Results and Discussion

To study the photoresponse of PDs, electro-optic-sampling (EOS) measurement was performed with the wavelength, full width at half maximum (FWHM), and repetition rate of 1.55 μm, 400 fs, and 100 MHz, respectively. An external CdTe crystal was used for probing the response



(a) (b)

Fig. 2 Photoresponses of (a) UTC-PD and (b) conventional pin-PD.

signal on coplanar signal line.

Figure 2 shows the photoresponse of a UTC-PD (a) and a conventional pin-PD (b) at V= -2 V with the input energies as a parameter. The input energy versus output voltage is also shown in Fig. 3. For a UTC-PD, the output voltage linearly increases as the input energy increases up to 1.0 pJ/pulse (linear region). After this point, the output voltage gradually saturates and reaches about 1 V at 2 pJ/pulse, which corresponds to the peak current of 40 mA. The FWHM shows a little decrease at the linear region (3.5 to 2.8 ps). Near output saturation, it shows gradual increase (2.8 to 4.4 ps) above 1.0 pJ/pulse. This response broadening and peak intensity saturation is basically due to the space charge effect in the collection layer. Here, it should be noted that the fall time becomes monotonically faster (2.3 to 0.6 ps) as the input energy increases. This behavior is explained by the self-induced field effect in the absorption layer [7]. For example, roughly estimated electric field at 1.0 pJ/pulse is about 3.5 kV/cm, which makes the electrons drift toward the collection layer and then, the fall time becomes faster. Therefore, it is expected that this self-induced electric field effect improves f_{3dB} characteristics at higher input energy.

The photoresponse shape dependence on input energy of pin-PD, on the other hand, is quite different from that of UTC-PD as shown in Fig. 2 (b). The waveform consists of two current components, i.e., a fast component that appears at the initial time stage and is attributed to electron transport and a subsequently appearing slow one due to hole transport. With increasing input energy,

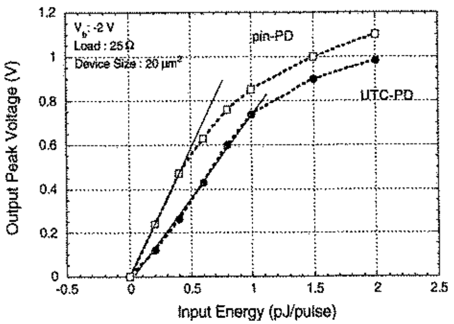


Fig. 3 Input vs output characteristics.

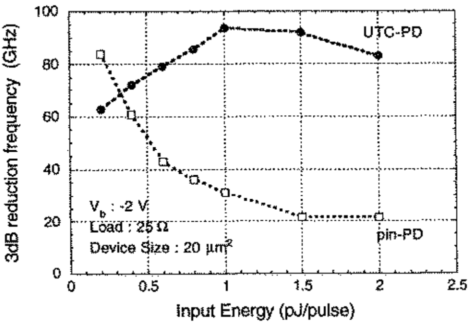


Fig. 4 f_{3dB} vs input energy.

the peak voltage shows linear increase at the narrow input energy range (up to 0.4 pJ/pulse). When the input energy exceeds this region, the output voltage tends to saturate and reaches about 1.1 V at 2.0 pJ/pulse. Concerning with the photoresponse, the fast component shows a little broadening, while the full width of hole response drastically increases (6 to 25 ps) as the input energy increases. This large broadening and peak saturation is attributed to the space charge effect, which appears even at low input energy. In a pin-PD, the electrons and holes are generated in the depletion layer. Here, much slower response of holes produces hole accumulation and band flattening around the cathode region. This causes further slower hole transport with the input energy increases and then, electrons are not swept out completely from the depletion layer. Contrarily, in a UTC-PD, only electrons are active and their fast drift velocity suppress the space charge effect in the collection layer. In addition, the self-induced electric field effect enhances the electron velocity. Consequently, a UTC-PD exhibits the wide linearity and high output level maintaining the broad bandwidth.

To clarify the photoresponse difference quantitatively, we analyzed the waveforms by the Fourier transform method. In Fig. 4, the obtained f_{3dB} is plotted as a function of the input energy. It can be seen that the UTC-PD shows broad bandwidth characteristics (63~94 GHz) with full input energy range (up to 2 pJ/pulse). The enhancement of f_{3dB} is attributed to the self-induced electric field. On the other hand, the pin-PD's one drastically decreases with increasing input energy (85 to 21 GHz) due to the space charge effect. Similar results were also confirmed under different bias conditions (-1 to -4 V).

4. Conclusions

The photoresponse dynamics of a UTC-PD and a conventional pin-PD with similar small-signal f_{3dB} bandwidth were investigated. The f_{3dB} of the pin-PD degrades quickly with increasing input energy, while that of the UTC-PD keeps its wide bandwidth property due to less space charge effect. In addition, the self-induced electric field helps to accelerate the electron motion, leading to a velocity enhancement and increasing f_{3dB}. This clearly demonstrates that the UTC-PD can yield a high output and maintain a broad bandwidth even at low operation voltage. Thus, the UTC-PD is a promising device for the application of optical communication and microwave photonics.

Acknowledgements

The authors would like to thank N. Watanabe for epitaxial growth, T. Nagatsuma for EOS measurements, Y. Royter, S. Kodama and H. Fushimi for fruitful discussions, and S. Mitachi, K. Yamazaki, and Y. Matsuoka for their continuous encouragement.

References

[1] Ishibashi T, Shimizu N, Kodama S, Ito H, Nagatsuma T, and Furuta T, 1997 Tech. Dig. Ultrafast Electronics and Optoelectronics, Incline Village, Nevada, 166

[2] Shimizu N, Watanabe N, Furuta T, and Ishibashi T, 1998 IEEE Photonics Tech. Lett. **8**, 412

[3] Ishibashi T and Shimizu N, 1999 UEO, pp106-108

[4] Ishibashi T, Kodama S, Shimizu N, and Furuta T, 1997 Jpn. J. Appl. Phys. **36**, 6263

[5] Kurishima K, Nakajima H, Kobayashi T, Matsuoka Y, and Ishibashi T, 1994 IEEE Electron Devices **41**, 1319

[6] Hill P, Schlafer J, and Emmans R B, 1965 J. Appl. Phys. **35**, 622

[7] Shimizu N, Watanabe N, Furuta T, and Ishibashi T, 1997 Ext. Abs. 1997 Int. Conf. on SSDM, 184