Extended Abstracts of the 1997 International Conference on Solid State Devices and Materials, Hamamatsu, 1997, pp. 184-185

Improved Response of Uni-Traveling-Carrier Photodiodes by Carrier Injection

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1. Introduction

The uni-traveling-carrier photodiode (UTC-PD), which has a p-type photo-absorption layer and a widegap electron-collection layer, has been proposed as a device to provide a higher saturation output.[1)] Because of the high electron velocity in the collection layer, this device is capable of operating at high current densities while still keeping its ultrafast response. The fabricated InP/InGaAs UTC-PD showed an output voltage as high as 1.9 V with a 3-dB bandwidth (f_{3db}) of 115 GHz.[2)] The experimental results also indicated that electron transport in a p-type photo-absorption layer is of prime importance in maximizing the operating speed.

In this paper, we demonstrate that the response time of the UTC-PD's dramatically changes with the carrier injection level and the background hole density in the photo-absorption layer. The increase of f_{3db} is more pronounced in a structure with a lower hole density. This enhancement is attributed to the acceleration of electrons by the self-induced electric field associated with the hole current.

2. Experiments

The UTC-PD structures studied in this paper were grown on semi-insulating InP substrates by MOCVD. As shown in Fig. 1,

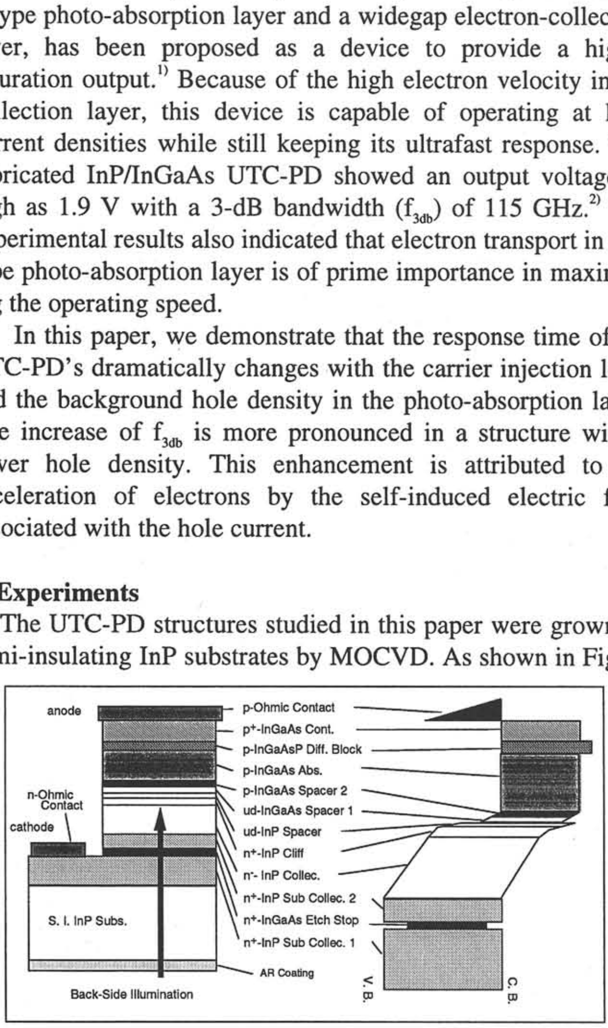

Fig. 1 Schematic cross-section and band diagram of the UTC-PD.

they consisted of an n^+-InP/ $In_{0.53}Ga_{0.47}As$/InP subcollector layer, followed by a 208-nm InP collector layer (Si: 4 x 10^{16} cm^{-3}), a 10-nm InP cliff layer (Si: 2.5 - 3 x 10^{18} cm^{-3}), a 2-nm undoped (ud)-InP spacer layer, a 2-nm ud-$In_{0.53}Ga_{0.47}As$ first spacer layer, a 10-nm $In_{0.53}Ga_{0.47}As$ second spacer layer (C: 2.5 x 10^{18} cm^{-3}), a 210-nm $In_{0.53}Ga_{0.47}As$ photo-absorption layer, a 15-nm p^+-$In_{0.6}Ga_{0.4}As_{0.85}P_{0.15}$ barrier layer, and a 60-nm p^+-$In_{0.53}Ga_{0.47}As$ cap layer. Three structures with different hole densities in the photo-absorption layer, p = 2.5 x 10^{17}, 1.0 x 10^{18}, and 2.5 x 10^{18} cm^{-3} were prepared. The second spacer layer was inserted to keep the photo-absorption layer undepleted under operating conditions. The UTC-PD's were fabricated using conventional photolithography, wet chemical etching, and lift-off metallization techniques. After the devices were fabricated, back-side of the InP substrates was polished and an anti-reflection coat was finally deposited for back-side illumination. The external quantum efficiency was around 22 % for all three structures.

High-speed characterizations were made for UTC-PD's with the anode electrode diameter of 5.6 μm. The device was placed at the center of a 4-mm-long 50-Ω coplanar waveguide transmission line. The signal and ground lines were respectively connected to the anode and cathode electrodes of the device, where the load resistance (R_{load}) of the UTC-PD under test was equivalent to 25 Ω. The responses against the 790-fs width laser pulse at a 1.55-μm wavelengh and a repetition rate of 100 MHz were measured by using an electro-optic(EO)-sampling technique[3)] with an external CdTe probe tip. By calibrating the EO-signal intensity using a 50-GHz digital sampling oscilloscope, the UTC-PD output peak voltages (V_{out}'s) were derived. From the Fourier transform of the measured photoresponses, the f_{3db} of the devices was evaluated.

3. Results and Discussion

Figure 2 shows the laser pulse response of the UTC-PD with p = 1.0 x 10^{18} cm^{-3} when biased at -1.5 V. The observed V_{out} increases as the laser power increases, and it reached 1 V when the input laser power (P_{in}) was 0.99 pJ/pulse. In this condition, the full width at its half maximum and the f_{3dB} of the UTC-PD response were 5.1 ps and 70 GHz, respectively.

In Fig. 3, V_{out} was plotted as a function of P_{in} for three different absorption layer doping levels. Here, the bias voltage

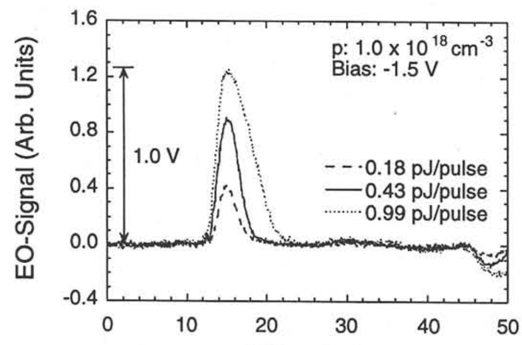

Fig. 2 Photoresponse of the UTC-PD.

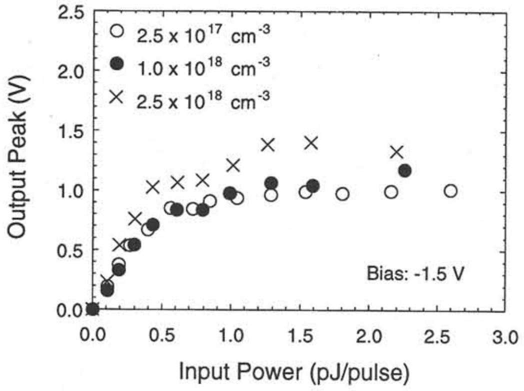

Fig. 3 Output peak voltage versus input laser power.

applied to the device was also -1.5 V. This figure shows that the V_{out} - P_{in} characteristic is divided into two regions: the linear region where P_{in} is small and V_{out} is proportional to P_{in}; and the saturation region where V_{out} scarcely changes with the increasing P_{in}. The saturation V_{out} is 1 V for the UTC-PD with $p = 2.5 \times 10^{17}$ cm^{-3}, and it increases slightly with the doping level.

The relation between f_{3dB} and V_{out} is shown in Fig. 4 for three types of UTC-PD's. The observed f_{3dB} increases first with V_{out} up to a maximum. The highest f_{3dB} = 150 GHz was obtained for the device with $p = 2.5 \times 10^{17}$ cm^{-3}. After reaching its maximum, f_{3dB} decreases with V_{out}. This f_{3dB} enhancement is more prominent for a lower doping level. It was confirmed that f_{3dB} determined by the CR-time constant was estimated to be 360 GHz for these devices at the bias voltage of less than -1.0 V. So, the difference in V_{out} dependence of f_{3dB} is attributed to the difference in carrier traveling time in the devices.

When the photo-absorption layer doping level decreases, the minority electron mobility is expected to increases. This can reduce the carrier transit time in the absorption layer and thus increase f_{3dB}. This effect, however, does not explain the enhancement of f_{3dB} with the increasing V_{out}. As the photo-excited electrons are flowing toward the cathode, a hole current is

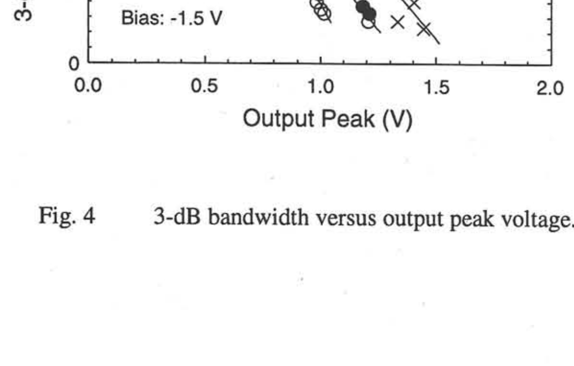

Fig. 4 3-dB bandwidth versus output peak voltage.

induced in the photo-absorption layer. Ignoring the hole diffusion component, the hole current density J_h is approximated as

$$J_h = qp_0\mu_h E \, , \tag{1}$$

where q, p_0, μ_h, and E are elemental charge, the hole mobility (~150 cm^2/Vs), the background hole density in the photo-absorption layer, and the electric field, respectively. Equation (1) suggests that a self-induced electric field E, which simultaneously acts on electrons, is higher for a lower p_0. It can effectively accelerate the photo-excited electrons toward the cathode electrode. Assuming that the electron current is dominated by the diffusion current in the photo-absorption layer, the potential difference over the photo-absorption layer at the output peak due to the electric field E

$$\Delta\phi_{eff} = \int E dx$$

is related to V_{out} as

$$\Delta\phi_{eff} \approx \frac{V_{out} W_A}{2q\mu_h p R_{load} S} \, , \tag{2}$$

where, W_A and S are the photo-absorption layer thickness and the device active area, respectively. From eq. (2), $\Delta\phi_{eff}$ is respectively estimated to be 60, 15, and 6 meV for $p = 2.5 \times 10^{17}$, 1.0×10^{18}, and 2.5×10^{18} at V_{out} = 0.4 V. As predicted in the previous paper,[1] a static potential gradient of even 50 meV can considerably improve f_{3dB}. Although the self-induced electric field appears instantaneously, the f_{3dB} enhancement observed can basically be attributed to a similar mechanism.

4. Conclusion

The photoresponse of InP/InGaAs UTC-PD was systematically investigated by changing the photo-absorption layer doping level from 2.5×10^{17} to 2.5×10^{18} cm^{-3}. Fabricated devices generated the saturation output voltage of up to 1 V at a bias voltage of -1.5 V. From the behavior of 3-dB bandwidths vs. output voltage, we found the enhanced bandwidth as a result of the self-induced electric field in the photo-absorption layer.

Acknowledgments

The authors would like to thank M. Koyama for his help in MOCVD growth, H. Sato for his help in the device fabrication, T. Nagatsuma and M. Yaita for their valuable discussions about the EO-sampling measurement, and Y. Imamura for his encouragement.

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