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Monolithic integration of UTC-PDs and InP HBTs using Be ion implantation

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1. Introduction

The uni-traveling-carrier photodiode (UTC-PD) provides higher saturation photocurrent than a conventional *pin* PD while maintaining an ultra-fast response [1]. The epitaxial layer structure of the UTC-PD is similar to that of the HBT with an InGaAs/InGaAsP/InP composite collector. Thus, monolithic integration of UTC-PDs and HBTs is a promising choice for developing ultra-high-speed optoelectronic integrated circuits (OEICs). Actually, by using Zn diffusion, UTC-PDs have been selectively fabricated from base-collector structures of composite-collector HBTs (CC-HBTs) [2].

This paper describes monolithic integration of UTC-PDs and HBTs using Be ion implantation, which can control dopant profiles more precisely. The UTC-PDs share the base and collector layers with the HBTs. A *p*-type photoabsorption layer for the UTC-PD is formed by Be ion implantation to the base and collector layers and rapid thermal annealing (RTA) is then performed to fully activate the Be atoms. In this work, we investigated the feasibility of the proposal technique by examining the performance of the UTC-PDs and HBTs fabricated on the same wafer.

2. Be ion implantation to base and collector layers of HBTs

An n^+-InP subcollector layer, a 410-nm-thick *ud*-InGaAs/ *n*-InGaAs/ *n*-InP collector layer, and a p^+-InGaAs base layer were grown on an InP substrate. Into these layers, 20-keV Be ions were implanted with a dose of $5\text{x}10^{13}$ cm^{-3}. After the implantation, RTA was performed at 650°C to electrically activate the implanted Be atoms. The depth profiles of Be atoms and carriers were determined by SIMS and *C-V* measurements, respectively.

Figure 1 shows the Be and hole depth profiles for the implanted samples. The depth profile of Be atoms before RTA shows a nearly gaussian-like shape. Although the Be atoms are redistributed by the RTA, most of the Be atoms remain in the InGaAs layers. An electrical activation of 100% is estimated from *C-V* measurements. The hole concentration is around 10^{18} cm^{-3} and the hole mobility is 130 cm^2/Vs, which indicates there is no significant degradation of crystal quality. Consequently, Be ion implantation is a useful technique for forming a *p*-type photoabsorption layer for the UTC-PD.

3. Device fabrication and characterization

An HBT layer structure was grown on a 3-inch InP substrate by MOVPE. The InGaAs base is 50-nm thick and doped with carbon to $4\text{x}10^{19}$ cm^{-3}. The collector is a 460-nm-thick InGaAs/InGaAsP composite collector. The use of the composite collector provides high-speed operation and high breakdown voltage simultaneously.

The UTC-PD shares the base and collector layers of the HBT. The photoabsorption layer is formed by Be ion implantation to the 50-nm-thick InGaAs base layer and 250-nm-thick InGaAs layer in the collector. Schematics of the layer structures of the HBT and UTC-PD are shown in Fig. 2. The fabrication sequence is the same as that for the HBT [3], except for the use of ion implantation and RTA. The fabrication starts with the formation of the emitter mesa structures. After the base surface is exposed, selective Be ion implantation (20 keV, $5\text{x}10^{13}$ cm^{-3}) and RTA are performed to convert the *ud*-InGaAs layer into the *p*-type layer. Next, collector mesas are formed and metals are lifted off. Each device is isolated and passivated with benzocycolbutene (BCB).

The fabricated UTC-PD exhibits good *I-V* characteristics. The ideality factor is 1.3 and the breakdown voltage is over 7 V. Figure 3 shows the photoresponse of the UTC-PD measured by an electro-optic (EO) sampling technique. The shape of the signal is symmetric, which is typical for the UTC-PD. From the Fourier transformation of the output pulse, a maximum 3-dB bandwidth of 105 GHz was obtained. The resposivity is 0.17 A/W. The performance of the UTC-PD is similar to that of reported UTC-PDs [4]. Figure 4 shows the output waveform of the UTC-PD operating at 100 Gbit/s, measured with a 65 GHz-bandwidth RF probe. The input RZ-optical data stream was generated by an optoelectronic pulse pattern generator (OE-PPG) as described in [5]. Clear eye opening was obtained with an output swing of 200 mV and a RMS jitter of 500 fs.

Figure 5 shows the common-emitter collector *I-V* characteristics for the HBT. The current gain, β, is 25 and the breakdown voltage, BV_{CEO}, is over 7 V. Figure 6 plots current-gain cut-off frequency f_t, maximum oscillation frequency f_{max}, and total collector junction capacitance C_{Tc}, as a function of collector current density J_C. The HBT provides a peak f_t of 150 GHz and a peak f_{max} of 250 GHz at J_C=100 kA/cm^2. The performance of the HBT is comparable to that of our baseline HBTs with a 300-nm-thick collector [3]. In conclusion, there is no serious degradation of the HBT performance associated with the RTA.

4. Conclusion

UTC-PDs have been fabricated from the HBT layer structure using Be ion implantation. The maximum 3-dB bandwidth of the UTC-PD is 105 GHz at a bias of -2 V. The fabricated HBTs exhibit reasonably high f_t and f_{max}. There is no serious degradation of the HBT performance associated with the RTA used for the UTC-PD fabrication. Be ion implantation is a promising technology for integrating UTC-PDs and HBTs.

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References

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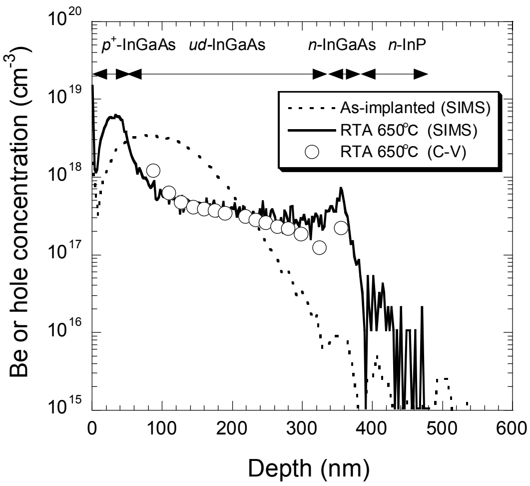

Fig. 1. Be depth profiles of the HBT layers before and after RTA. Carrier profile after RTA is also shown.

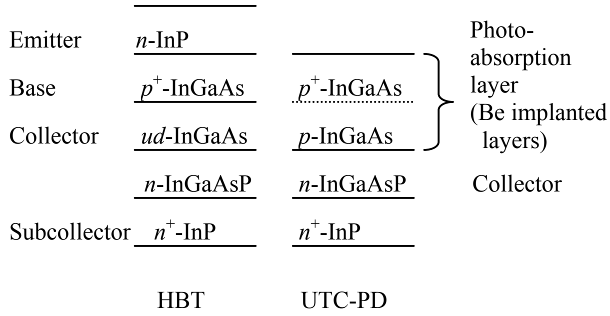

Fig. 2. Schematic layer structures of the HBT and UTC-PD.

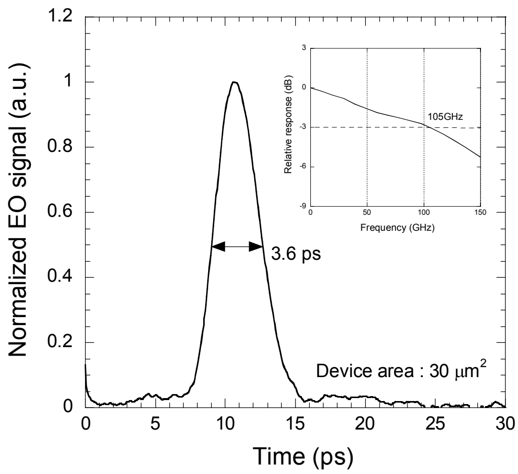

Fig. 3. Measured photoresponse of the UTC-PD with a 1.55 μm incident pulse at a bias of –2V. The power spectrum derived from the Fourier transform of the response is shown in the inset.

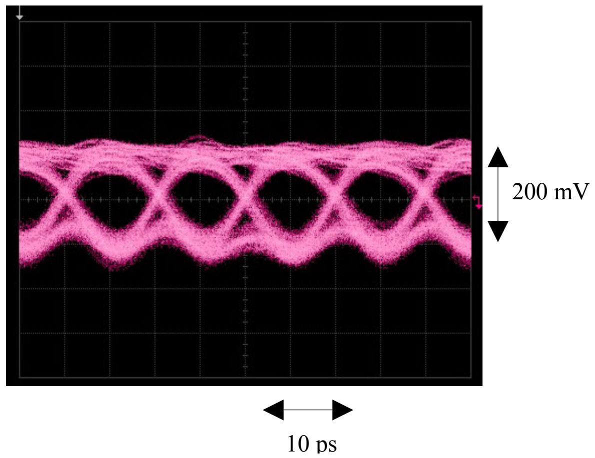

Fig. 4. Output eye pattern of the UTC-PD at 100-Gbit/s operation at a bias of –2 V. The PD area is 30 μm^2.

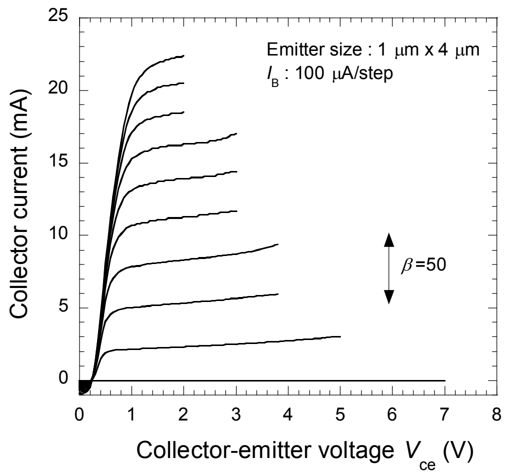

Fig. 5. Common-emitter *I-V* characteristics of the HBT with a 1 μm x 4 μm emitter.

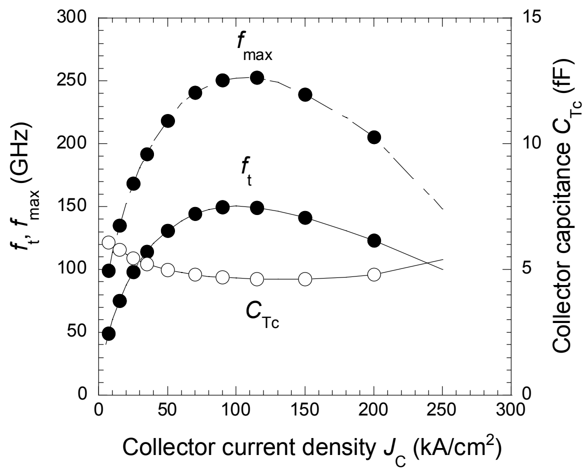

Fig. 6. Measured f_t, f_{max}, and total capacitance as a function of the collector current density.