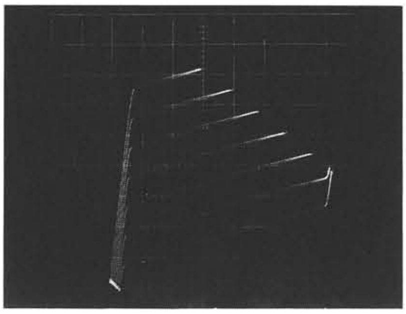
t_r was estimated as 1.5 ns. Although t_r was limited by the parasitic impedances, particularly by the emitter contact resistance (specific contact resistance was limited to $R_s \approx 5\times10^{-4}\ \Omega\mathrm{cm}^2$), it has been significantly reduced as compared to the diode-structured devices, whose switching times are typically on the order of several ns. Further technological improvements have to be searched for producing low ohmic contact resistances such as non-alloyed ohmic contacts [10], in order to achieve faster switching/ modulation speeds.



Vertical Axis, I_c	2mA/div
Horizontal Axis, V_{ce}	2V/div
Base Current Step	0.2mA

Fig. 5 Transistor characteristics measured in the common-emitter configuration.

4. Conclusions

We have presented device fabrication and measurement of optical modulation and electrical characteristics of a first GaAs/AlGaAs double-heterojunction bipolar transistor (DHBT) single-waveguide structure carrier-injected optical intensity modulator grown by molecular beam epitaxy.

The output light intensity increased almost linearly with the injection current caused mainly by the band-filling and plasma dispersion effects, and up to 43% optical modulation has been obtained at a pulsed emitter current of $I_e \approx 100$ mA. The switching time t_r of the transistor was determined to be about 1.5 ns and therefore, has been reduced significantly as compared to the diode-structured devices.

Finally, the authors would like to acknowledge Dr. S. Hirata of Sony Corp. for supplying the GaAs DFB laser diodes and Mr. Y. Tono-oka of NEC Corp. for supplying the photomasks used in this work. We are further indebted to Dr. H. Inoue and Dr. K. Ishida of Hitachi Ltd. for their valuable discussions and comments.

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S-C-7

Twin-PIN Photodiode with High-Speed Response at High Optical Input Power for Coherent Receiver

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A monolithic GaInAs twin-pin photodiode with high-speed response at high optical input power has been fabricated for coherent balanced optical receiver applications. The twin-pin photodiode has a very small capacitance of 80fF and a high quantum efficiency of 80%. Cutoff frequency of over 10GHz has been achieved at measurement conditions which maintain the high photodiode current of 7.2mA. These results indicate that the photodiode would greatly facilitate the creation of a high-sensitivity, high-speed coherent balanced optical receiver.

1.Introduction

The most important goal for a coherent optical receiver is that it achieves minimum detectable power close to the quantum noise limit while in a balanced configuration [1,2]. To achieve this possibility, we need a high power laser and two photodiodes with high speed and high power detection. In this paper, we discuss the photodiodes required for making high performance balanced optical receivers for operation at gigabit rates. The requirements are as follows: (1) simultaneous fulfillment of a detectable power of over several milliwatts and a high speed response of over 10GHz, and (2) a high quantum efficiency, a small capacitance and a high uniformity of response in the two photodiodes [3]. In the best of our knowledge, photodiodes that satisfy the above requirements, especially (1), have not been reported. We now report on a monolithic GaInAs twin-pin photodiode that satisfies both requirements. The photodiode was achieved through the study of the structure and the active layer thickness of the photodiode.

2.Study of structure and active layer thickness

Figure 1 illustrates the structure of the pin photodiode we chose as a basis for high speed and high power detection. With this structure, we can fabricate an extremely small pin-junction without any degradation from optical coupling losses, because a monolithic InP microlens is easily integrated. Because the p-region made by Zn-diffusion into the n^--InP layer can take p-contact metal on every surface, the contact resistance is less compared with a surface-illuminated structure. Therefore, we have studied the high-power and high-speed characteristics of this structure.

It would not be difficult to design a high-speed, high quantum efficiency pin photodiode to handle low input optical power. However,problems arise when we attempt to design a high-speed pin photodiode with high optical input power for coherent balanced optical receiver applications. The most important effect which should be taken into account in the present design is the space charge effect. If high optical power with high-speed modulation is input, the electric field in the active layer is distorted by a localized electric field produced by the large number of photo-carriers. Some photo-carriers are forced to stay in the active layer because the localized electric field opposes the external applied electric field. This causes degradation of high-speed response. The effect is closely related with the active layer thickness since the electric field is a function of this thickness.

From above consideration, we used a simple equation presented by G.Lucovsky et al. [4] to calculate the high power effect to -3dB cutoff frequency of the photodiode. Figure 2 shows the calculated results of -3dB cutoff frequency as a function of the active layer thickness. The calculation was done in a twin-pin structure. The parameter is the average photo-current of the pin photodiode. We assumed that the external applied field was 70kV/cm throughout the active layer, and the junction diameter was 20 μm. Electron velocity(v_e) and hole velocity(v_h), which both depend on the external electric field(E), were taken to be the following: v_e is 70000 $\times$E for under 3kV/cm, 315828$\times E^{-0.35772}$ for over 3kV/cm, and v_h is 1300$\times$E for under 50kV/cm, 6.5 $\times 10^4$ for over 50kV/cm. Velocity has the unit [m/s] and electric field has the unit [kV/cm]. The space charge effect reduces the electric field. The carrier velocity was determined from this effect, and the -3dB cutoff frequency of back-illuminated pin photodiodes was calculated.

In figure 2, the decrease of the -3dB frequency in the range of the active layer thickness below 1 μm is due to the CR limitation. The decrease in the thicker region is influenced by the space charges and the transit time of the carriers depended on the active layer thickness. From this figure, we can estimate the space charge effect and the active layer thickness for high power detection. We see that the active layer thickness is a very important factor.

3.Fabrication of twin-pin photodiode

We reported on the use of monolithic integration of two photodiodes in a previous paper [5]. In the above section, we studied the thickness of the active layer. From the results of these studies, we fabricated monolithic twin-pin photodiodes with acive layer thicknesses of 1.4 μm and 2.8 μm. Figure 3 illustrates the structure of our back-illuminated twin-pin photodiode and its circuit. The junction diameter of each photodiode was 20 μm. The center to center spacing between the two photodiodes was 125 μm which is suitable for optical fiber coupling. On the rear surface of this twin-pin photodiode, an InP-microlens was integrated to obtain a large coupling tolerance for the optical fiber [6]. An optical signal(S) and a local laser power(L) was fed as shown in this figure. The metal bumps are for flip-chip bonding. The circular bump is for electrical signal output. To obtain a good uniformity of layer thickness, the layers of the photodiode were grown by metalorganic vapor phase epitaxy(MO-VPE) on a semi-insulating(SI) InP substrate with (100) plane. A mesa structure was formed for electrical isolation by Ar ion-beam etching. Au/AuGe n-contacts were formed on the mesa slope. Figure 4 is a photograph of the twin-pin photodiode which was flip-chip bonded directly onto 2 μm thick Au-bonding pads formed on a ceramic mount of 0.9 $\times$1.5mm^2. The two integrated InP microlenses were 80μm in aperture diameter. The chip size was 300 $\times$250 μm^2.

Figure 5 is the photosensitivity profile measured using a single mode fiber. The single mode fiber used was a tapered fiber with a hemispherical lens with a radius of curvature of 20 μm at the fiber tip. As is clearly shown in this figure, a significantly large profile was obtained. The fiber alignment tolerance which permits a 0.5dB coupling loss is estimated to be as large as 60 μm.

Figure 6 is a graph of the -3dB cutoff frequency as a function of the average pin photodiode current. Experimental points marked by solid circles were measured with a twin-pin photodiode with an active layer thickness of 1.4 μm at a bias voltage of 10V. Experimental points marked by open circles were measured with a twin-pin photodiode with an active layer thickness of 2.8 μm at a bias voltage of 20V. The solid lines show the calculated results for the experimental conditions. Quantum efficiency was 80% for the photodiode with the 1.4 μm active layer thickness and 93% for the photodiode with the 2.8 μm active layer thickness. Capacitance was 80fF for the photodiode 1.4 μm and 50fF for the photodiode 2.8 μm. We find, that there is a great difference between the -3dB cutoff frequencies of the two photodiodes. The photodiode 1.4 μm in active layer thickness achieved 12GHz at 8 mA in photocurrent. A discrepancy from the calculation (16GHz) is due to slight impedance mismatch in the measurement setup. In the case of the photodiode 2.8 μm in active layer thickness, experimental points conformed well to the calculated result. Therefore, the main cause of degradation of the cutoff frequency corresponding to the photo-current comes from the space charge effect.

Figure 7 is a graph of the frequency response of the twin-pin photodiode with active layer thickness of 1.4 μm. The applied bias voltage was $\pm$10V. The load resistance of the photodiode was 50 Ω. The average photocurrent of 7.2mA was maintained by feeding a high optical power with 1.55 μm in wavelength onto the microlens surface. The cutoff frequencies shown in figure 7 are 14GHz and 12GHz. This difference in cutoff frequency was due to the asymmetrical metal pattern on the ceramic mount. These results show that the present device will facilite the fabrication of high-performance and compact balanced optical receivers having sensitivity close to the quantum noise limit.

5.Conclusion

We studied the high optical power characteristics of a photodiode based on the back-illuminated struture and pointed out importance of the active layer thickness. From a design based on these results, a monolithic GaInAs twin-pin photodiode with high speed at high optical input power was fabricated. A cutoff frequency over 10GHz at a photocurrent over 7mA was achived for the first time with our twin-pin photodiode. These results demonstrate that the present device is well suited for a high-performance coherent balanced optical receiver with sensitivity close to the quantum noise limit.

Acknowledgements

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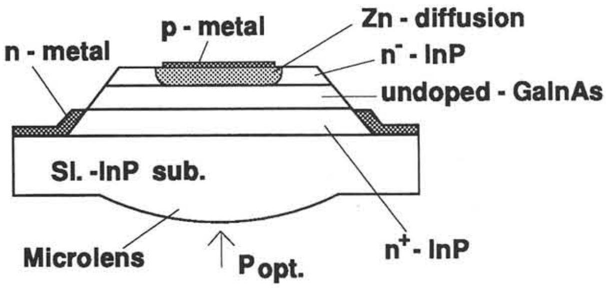

Figure 1. Structure of pin-PD for high-speed and high-power detection

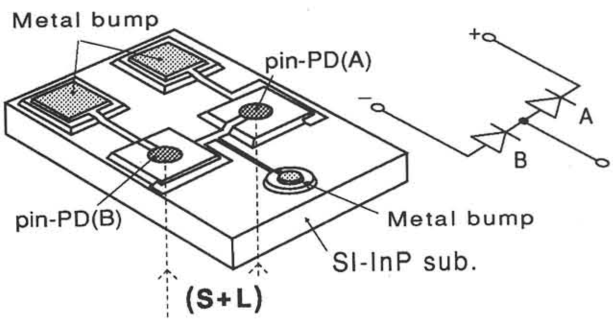

Figure 3. Structure of twin-pin photodiode and the circuit

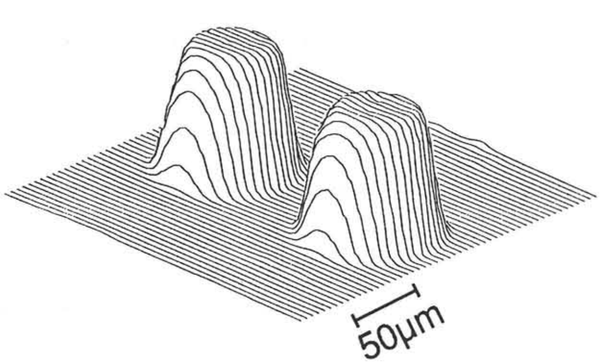

Figure 5. Photosensitivity profile of twin-pin-PD

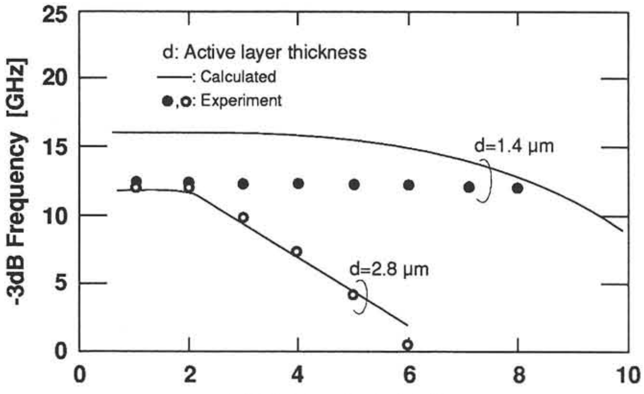

Figure 6. Experimental results of -3dB cutoff frequency as a function of average pin photocurrent

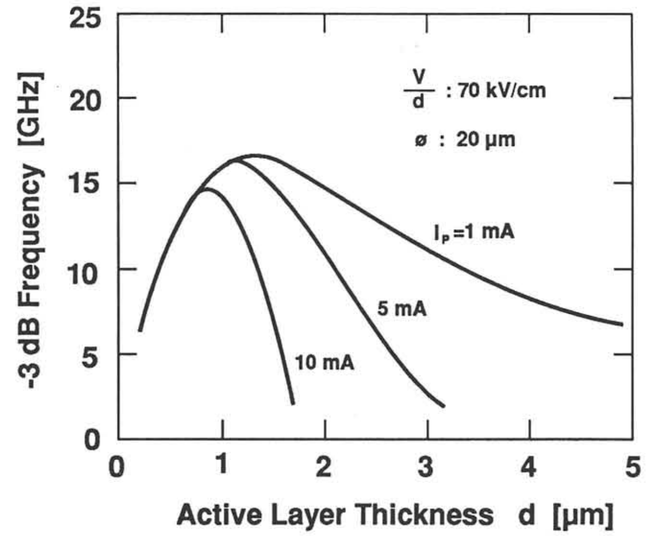

Figure 2. Calculation of -3dB cutoff frequency as a function of active layer thickness of pin-PD

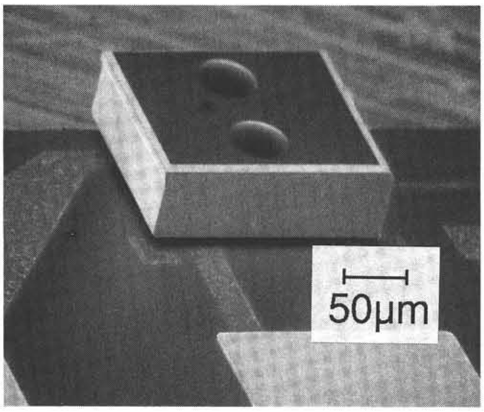

Figure 4. Twin-pin-PD directly bonded on ceramic mount

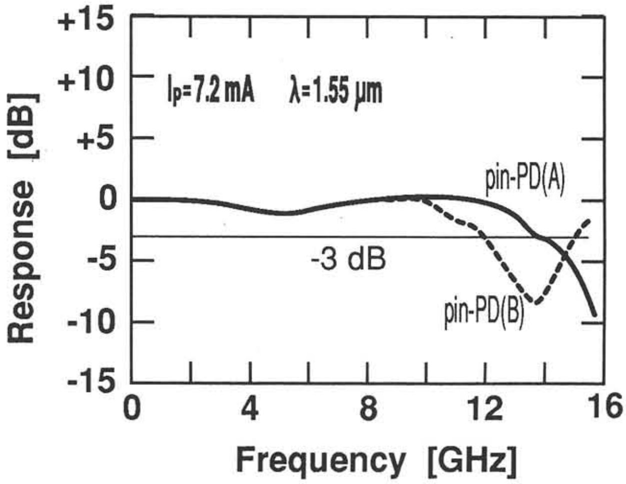

Figure 7. Frequency response of twin-pin-PD