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Heterojunction Bipolar Phototransistor with Monolithic Integrated Microlens

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1. Introduction

Heterojunction bipolar phototransistor(HPT) has been frequently used as a photodetector for optical communications because of its high internal gain. It is compatible with the fabrications and epitaxial structures of heterojunction bipolar transistors (HBTs). Optical oscillators and photoreceivers showing high-speed performance using InP/InGaAs HPT have been demonstrated [1-2].

Since light is incident on the top of the device in the conventional HPTs, theses top illumination type HPTs suffer from fiber coupling loss due to the blocking of lights by the contact metals and interconnection lines. Therefore, the lateral size of the HPT should be inevitably enlarged to obtain enough absorption area, which obstructs high-speed performance of the device. To enhance operation frequency, back-illumination methods have been tried by using transparent InP substrate at 1.55 μm wavelength [3-4]. The active size of the device could be reduced further in the back-illumination HPTs because the metals on the front surface didn't block the incident illumination.

The effects of the back-side lens were demonstrated in the case of p-i-n photodiode [5]. In this paper, we proposed a monolithic integration of a back-side microlens and an HPT to focus the lights to the small absorption area and to improve fiber alignment tolerance. The microlens was monolithically integrated on the back-side of InP substrate and the radius of curvature was optimized to focus light to the absorption layer. To confirm effects of microlens, two types of HPTs (back-illuminated HPTs with lens and without lens) were fabricated and their optical characteristics such as responsivity, quantum efficiency and fiber alignment tolerance were investigated.

2. Integration of HPT and Microlens

Fig.1 shows the schematic diagram of the HPT. Because light was incident on the back-side of substrate, we designed subcollector layer to be InP instead of InGaAs which was generally adopted for subcollector of InP/InGaAs HBTs. Doping level of InP subcollector was designed as high as 2×10^{19} in this HPT. It was reported that the contact resistance on the heavily doped InP($>10^{19}$) was as low as contact resistance on InGaAs($>10^{19}$) [6]. An 1μm thick InGaAs collector was undoped and acted as the absorption layer. Ti/Pt/Au layers were used for the emitter and collector contacts and Pt/Ti/Pt/Au layers were used for the base contact. Mesa structures were formed by using selective wet-etching process. $H_3PO_4/H_2O_2/H_2O$ was used for the etching of InGaAs and H_3PO_4/HCl was used for the etching of InP.

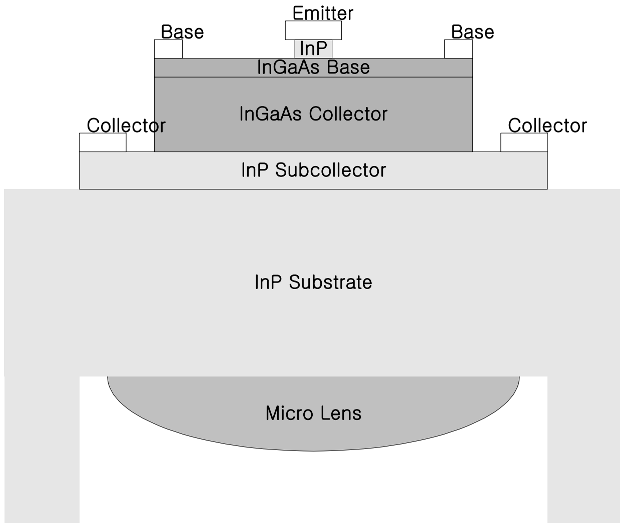

Fig. 1 Cross-sectional view of InP/InGaAs HPT.

The emitter size of the fabricated phototransistor is 11×11 μm^2. The absorption area is defined as 28.5×30.5 μm^2. The ideality factors of the base current and the collector current are 1.52 and 1.07, respectively. The ideality factor of 1.52 is ascribed to the large surface recombinations taking place at the emitter and base contact space [7]. Here, the separation between emitter and base contact is 4 μm.

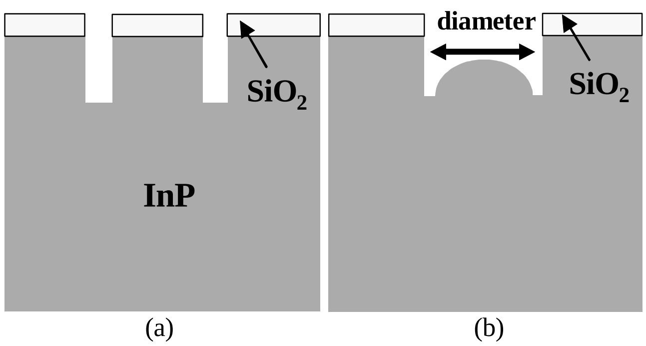

Fig. 2 Top view of the fabricated InP/InGAs HPT.

A microlens was monolithically fabricated on the back-side of InP substrate using two-step dry/wet etching. The procedure of fabricating a microlens is shown in Fig. 3. Dry etching was performed using reactive ion beam etching with Ar/Cl_2 gases under patterned SiO_2 mask layer. After removing SiO_2 mask, the mesa was shaped into a lens by etching in a solution of $HBr/H_3PO_4/(0.5M)K_2Cr_2O_7$ which simultaneously smoothed the surface of lens like mirror. The radius of curvature of microlens is determined by the dry etched depth, wet etching time and the diameter of the lens so as to focus the light to the area of InGaAs absorption layer. To increase the numerical aperture of lens while maintaining the diameter of lens constant, the substrate was thinned and polished.

The measured radius of curvature and the diameter of the fabricated microlens are 176 μm and 120 μm, respectively. Since the microlens is in the well shown in Fig. 2 (b), it can be safely protected from surface scratches.

3. DC Mesurements

The photo-responses of the back-illuminated HPTs with lens and without lens were measured. The optical power at the end of the multimode fiber used for the illumination was 120 μW, and the collector-emitter bias voltage was 2.0 V with floating base.

Fig. 3 shows measured photo-response results. The optical gain of HPT with micolens was 31.4 and the gain of HPT without microlens was 9.5 at the incident light of 120 μW and 2.0 V of V_{CE}.

In a PD mode, emitter and base are shorted. The responsivity of the HPT with microlens was 0.61 (A/W) while the responsivity of the HPT without microlens was 0.18 (A/W) at the reverse bias of 3 V. Quantum efficiency has improved from 14.4 % to 49.2 % by using a microlens.

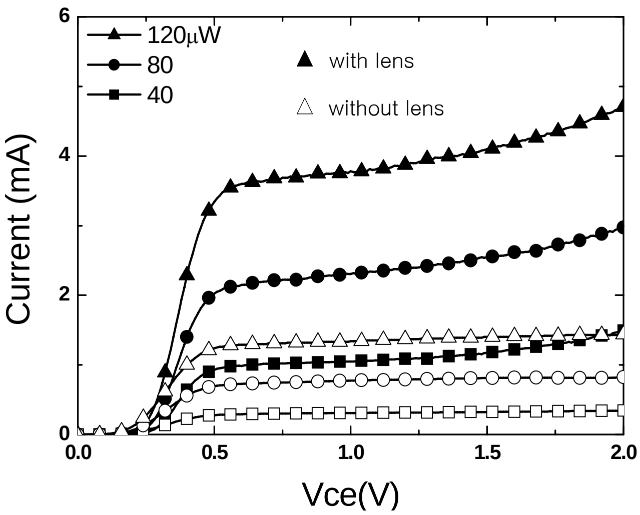

Fig. 3 The photo-current characteristics of back illuminated HPT with and without lens.

To investigate the fiber alignment tolerance, we moved the fiber laterally with 1 μm steps and the photocurrents of HPTs were measured. Fig. 4 shows measured fiber alignment tolerance results. Each measured photocurrent was normalized to its maximum current. At 3 dB point below its maximum photo-current, the fiber alignment tolerance of

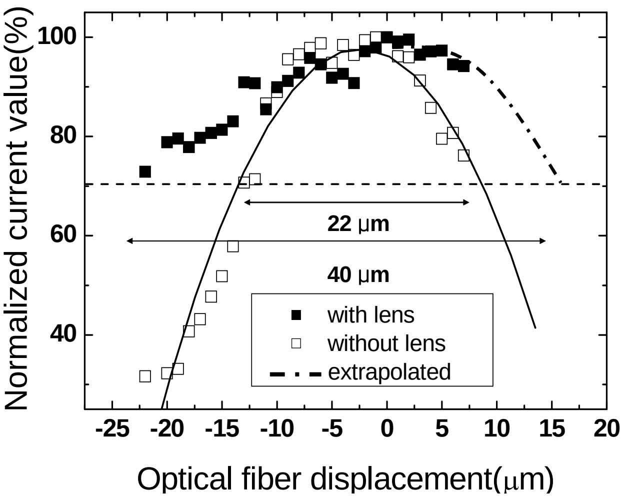

Fig. 4 Fiber alignment tolerances for the back-illuminated HPTs. Each value is normalized to its maximum photo-current.

HPT increased from 22 μm to 40 μm by using microlens. This gives about 180 % improvement of fiber coupling range. The coupling range of 38 μm was estimated by extrapolation.

4. Conclusions

Heterojunction bipolar phototransistor with a monolithically integrated microlens has been fabricated. The coupling efficiency of back-illuminated HPT has been increased by 34.8 % by using a microlens which was formed by using two-step dry/wet etching. The HPT with a microlens showed almost 3 times increased optical gain and about 180 % expanded fiber coupling range. Therefore, the HPT with a back-side microlens would be a good candidate for high-speed photodetector even with a small active area.

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