Effects of Temperature and Electrical Stress on the InGaP/GaAs Heterojunction Phototransistor: A Review

Than Hong Phuc*, Tran Thi Tra Vinh, Le Thi My Hanh, Than Quang Tho,
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Abstract—Although the effects of electrical stress and temperature on the performance of the InGaP/GaAs heterojunction bipolar transistors (HBTs) have been widely studied and published, little or none was reported for the InGaP/GaAs heterojunction phototransistors (HPTs) in the literature. In this study, we discuss the temperature-dependent characteristics of InGaP/GaAs HPTs before and after the high-temperature stress and assess the effectiveness of the emitter-ledge passivation, which was found to effectively keep the InGaP/GaAs HBTs from degrading at higher temperature or after an electrical stress. The emitter-ledge passivation is also effective in keeping a higher optical gain even at higher temperature. An electrical stress was given to the HPTs by keeping the collector current at $60\ \mathrm{mA}$ for 15 min at $420\ \mathrm{K}$. The high-temperature stress significantly decreased the current gain and optical gain of the HPT without emitter-ledge passivation. The current gain and optical gain of the HPT with emitter-ledge passivation were not affected by the high-temperature stress. The emitter-ledge passivation is found to be more effective than that in the HBTs.

Index Terms—Heterojunction Phototransistor (HPT), InGaP/GaAs, Emitter-ledge Passivation, Electrical Stress, Temperature Dependence.

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1. Introduction

PHOTODIODES such as PIN diodes and APDs have been commonly used as photodetectors in the photoreceiver OEIC [1]. Since the PIN diodes do not have the internal gain, the sensitivity to the weak input optical power is inferior. In the case of APDs, the avalanche breakdown produces the internal gain but sacrifices the noise figure [1], [2]. The HPTs are very attractive alternative to such devices since they have good compatibility with HBTs and provide a high optical gain without a high bias or an additional avalanche noise [2].

AlGaAs/GaAs based HPTs/HBTs have been often used as preamplifiers of the photoreceiver OEIC because of the mature technology [2]. However, the Al atoms of AlGaAs emitter and the exposed surface of extrinsic base provide the origins of degradation during operation [3]. Recently, the InGaP emitter has been actively employed to replace the AlGaAs emitter because of the superior physical properties of InGaP material. In addition, the InGaP emitter- ledge passivation layer as well as the emitter layer of InGaP/GaAs HBTs/HPTs can be easily formed to improve the performance because of high etching selectivity between the InGaP layer and the GaAs layer. Although there is a considerable interest in the InGaP/GaAs HBTs for the effects of electrical stress and temperature on the performances [4]–[7], there are few or no reports on the InGaP/GaAs HPTs have been published. In this paper, we investigate the temperature-dependent characteristics of InGaP/GaAs HPTs before and after the electrical stress and assess the effectiveness of the emitter-ledge passivation. The DC current gain and optical gain of the fabricated HPTs without and with the emitter-ledge passivation were measured in the temperature range of $300-400$ K before and after the electrical stress.

2. HPT Structure and Experiment

The InGaP/GaAs HPT epitaxial wafer was grown on S.I. GaAs (100) substrate using metal-organic chemical vapor deposition (MOCVD). The HPT epitaxial layer structure was described elsewhere [8]. The emitter and base structures consisted of 10 and 11 finger-shaped electrodes, respectively, each with a size of $4\mu\mathrm{m} \times 2100\mu\mathrm{m}$, as seen in Fig. 1. The emitter area was $300,000\mu\mathrm{m}^2$, which was larger by more than 3000 times than that of the normal HBTs.

The fabrication process of these devices included photolithography, vacuum evaporation, and chemical wet selective etching. The solutions of $\mathrm{H_3PO_4} : \mathrm{H_2O_2} : \mathrm{H_2O}$, $\mathrm{NH_4OH} : \mathrm{H_2O_2} : \mathrm{H_2O}$ and HCl were used to

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etch the GaAs, InGaAs and InGaP layers, respectively. Ti/Au and Ti/Pt/Au were evaporated to form the emitter ohmic contact and base ohmic contact, respectively. Following the base-contact formation, a multilayer of Ni/Au/AuGe/Au ohmic contact was formed for the collector.

The HPT without and with an emitter ledge are referred to as the N-HPT and L-HPT, as seen in Fig. 2 and Fig. 3, respectively. The length and thickness of the InGaP emitter-ledge are 5 μm and 30 nm, respectively. The emitter-ledge passivation was formed by leaving a portion of the InGaP emitter in etching of InGaP, as shown in Fig. 4. The emitter ledge covers the surface of the external base at the emitter ledge and suppresses surface recombination near the emitter edge.

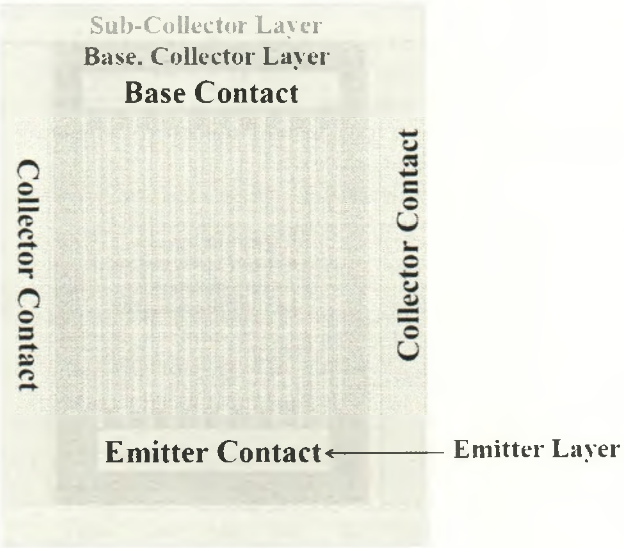

Fig. 1: Top view of the InGaP/GaAs HPT.

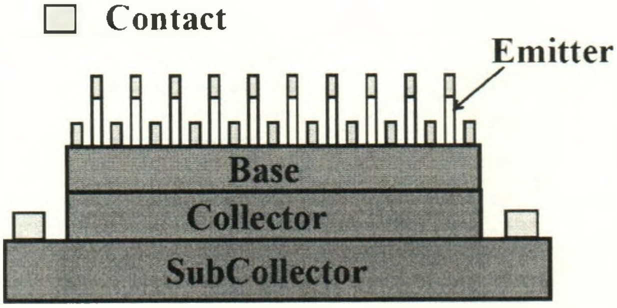

Fig. 2: Schematic cross section of Normal-HPT (N-HPT).

The common-emitter characteristics of the fabricated HPTs were measured by an HP4155A semiconductor parameter analyzer. The HPT performance is often characterized by the optical gain, which is defined as the number of electrons collected as the collector photocurrent, ΔIc, divided by the number of incident photons for monochromatic light. The optical gain is given by the following equation with assumption of 100% quantum efficiency.

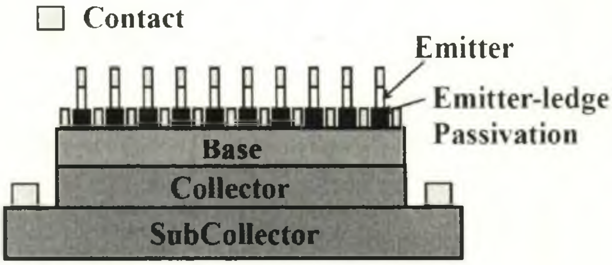

Fig. 3: Schematic cross section of Ledge-HPT (L-HPT).

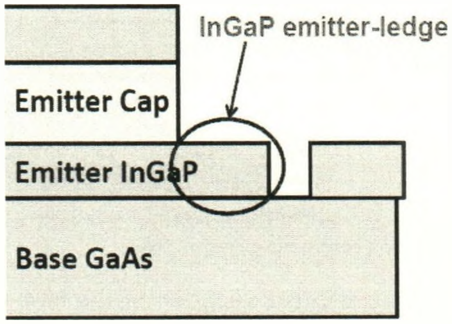

Fig. 4: Schematic cross section of the InGaP emitter-ledge passivation.

$$G = \frac{hc}{q\lambda} \cdot \frac{\Delta I_c}{P_{in}} \tag{1}$$

Where hc/λ is the photons energy, the ΔI_C is the collector photocurrent resulting from optical injection (the collector current difference between the operations under optical injection and in the dark), and P_{in} is the incident optical power. Optical measurements were performed using a green light laser operating at 532 nm. The intensity of the laser power was 0.35 mW with a beam diameter of 0.5 cm, and the exposed area of an HPT was 0.0275 cm^2. According to Gauss distribution, the incident optical power P_{in} of HPT was estimated to be 49μW. The electrical stress was given to the HPTs by keeping collector current at 60 mA, corresponding to a current density of 24 $\mathrm{A/cm}^2$, for 15 minutes at 420 K. Since the collector current density selected as an electrical stress is 24 $\mathrm{A/cm}^2$ and much smaller than the stress usually given to smaller HBTs as a stress test, the decreases in the DC current gain and optical gain were not observed when stressed at room temperature. In order to accelerate the degradation, the electrical stress was applied to the HPTs at 420 K. In order to avoid any serious damage to the HPTs, the electrical stress time was reduced to 15 min.

3. Results and Discussion

Fig. 5 shows the room-temperature common-emitter output characteristics of N-HPT and L-HPT, respectively, in the dark before the electrical stress. The collector current Ic was measured as a function of emitter-collector voltage V_{CE} and a current source was used to provide base current. The input base current I_B was varied from 5 to $25\mu A$ with $5\mu A$ per step. For each I_B. V_{CE} increased from 0 to 3.5 V. The collector currents of the L-HPT are higher than those of the N-HPT.

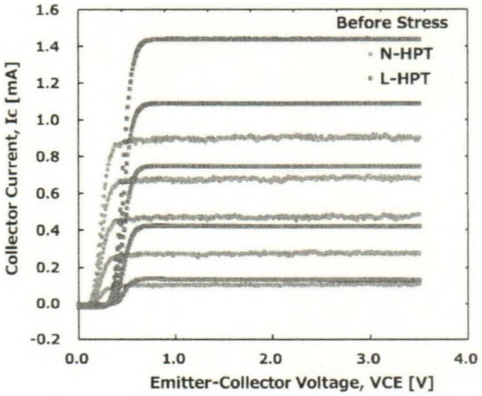

Fig. 5: Common-emitter I-V characteristics of N-HPT and L-HPT under illumination before the electrical stress.

The equivalent-circuit diagram of the base current-driven HPTs is shown in Fig. 6. R_E is the emitter resistance, R_B is the base resistance, Ic is the internal collector current, and I_{ph} is the photocurrent generated within the base-collector (B-C) depletion region and near the depletion edge. I_B will flow through R_E in the phototransistor operated in the dark and under illumination. The photocurrent I_{ph} will flow into node B' and then be shared by R_E and R_B. In the case of the phototransistor with a constant base current, I_{phb} is zero, and both I_B and I_{ph} flow through the base-emitter (B-E) junction.

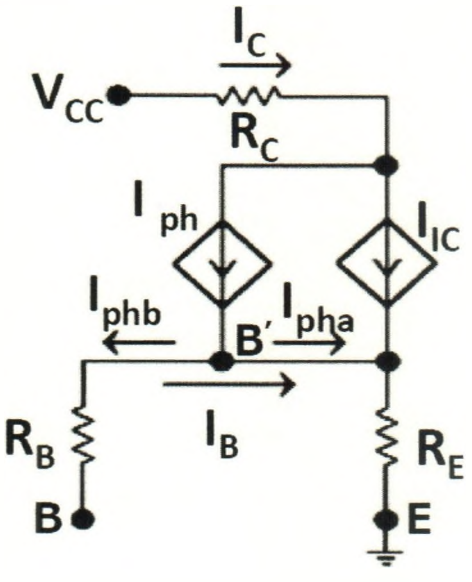

Fig. 6: Equivalent-circuit diagram of the HPTs with a current source.

In the case of common-emitter, the DC current gain β is defined as I_C/I_B. Temperature-dependent DC current gain and optical gain of the HPTs before and after the electrical stress are shown in Figs. 7 and 8 , respectively. The HPTs were measured in the temperature range of 300 – 400 K. At any high temperature, the DC current gain and optical gain of both HPTs decreased even without the electrical stress. However, the DC current gain and optical gain of the L-HPT before and after the stress are higher than those of the N-HPT, and a difference is more enhanced in the optical gain. Since the photocurrent Iph generated in the base-collector junction increases the internal base current, the increased base current increases the current gain. The emitter-ledge passivation decreases the surface defect density and suppresses defect formation at the emitter perimeter, resulting in the increased current gain. According to the enhanced performance of the base-current driven phototransistor, a small difference in the dark is enhanced under illumination. There is no significant degradation of the L-HPTs' performance due to electrical stress. For the N-HPT, the electrical stress significantly degrades the characteristics of the N-HPT. The emitter-ledge passivation was found effective in suppressing the degradation when electrical stress was applied at 420 K [8]–[16].

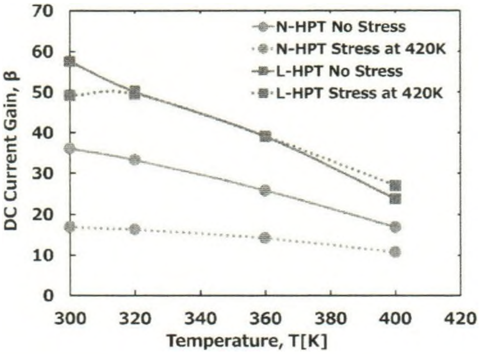

Fig. 7: Temperature-dependent DC current gain of the HPTs before and after the electrical stress.

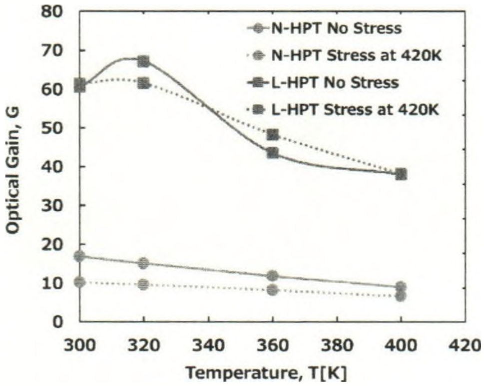

Fig. 8: Temperature-dependent optical gain G of the HPTs before and after electrical stress.

The degradation of the HPTs' performance at elevated temperature due to electrical stress is thought be associated with defect formation. There may be two types of defect formations; one is defect formation at the InGaP/GaAs heterointerface, and the other is defect formation at the emitter perimeter. The emitter-ledge passivation is effective in suppressing the defect formation at the emitter perimeter, but not at the InGaP/GaAs heterointerface. The stress time in this work may typically be too short for the defect formation at the InGaP/GaAs heterointerface. As the substrate temperature increased, the injection of holes from the base to the emitter increased. Hence, the space-charge. recombination via defects increased, resulting in the degradation of the HPTs' performance. By comparison of both HPTs' performance, L-HPT shows the improved reliability. The emitter-ledge passivation becomes more effective in the HPT performance than in the HBT performance, because a difference in the photocurrent generated within the B-C region is enhanced in the collector photocurrent [8]-[10].

4. Conclusion

The effects of temperature and electrical stress on the InGaP/GaAs HPTs were studied. In the entire temperature of range of 300 – 400 K, the HPT with the emitter-ledge passivation (L-HPT) has a current and optical gain higher than HPT without the emitter-ledge passivation (N-HPT). Due to the emitter-ledge passivation, thermal stability of current gain and optical gain even after electrical stress has been much improved. The emitter-ledge passivation is effective in minimizing the decrease of the DC current gain and optical gain with the increased temperature. The HPT with the emitter-ledge passivation showed improved performance and reliability. It is concluded that the emitter-ledge passivation is more effective in suppressing the degradation in the HPTs than that in the HBTs.

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