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Performance and Stability of MOVPE-Grown Carbon-Doped InP/InGaAs HBT's De-Hydrogenated by an Anneal after Emitter Mesa Formation

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1. Introduction

In order to improve InP/InGaAs HBT reliability, it is preferable to use carbon as a p-type base dopant. It is however known that carbon acceptors in InGaAs are unintentionally passivated due to the incorporation of hydrogen during MOVPE growth. Unfortunately, post-growth anneal of HBT epiwafers cannot alleviate this problem, because the n-type emitter layer acts as a barrier to the vertical diffusion of positively-charged hydrogen. In this study, in order to reverse the hydrogen passivation, we propose annealing HBT epiwafers after the formation of emitter mesa structures and investigate the feasibility of this approach in terms of fabricated-device performance. We also present the results of preliminary stress tests conducted to examine the stability of base-emitter (B-E) junctions.

2. Device Structures and Fabrication

Carbon-doped HBT's were grown on 3-in.-diam. (100)-oriented InP substrates by low-pressure MOVPE. Source materials were TMI, TEG, AsH_3, PH_3, Si_2H_6, and CBr_4. These HBT's consist of a 70-nm InP emitter, a 70-nm InGaAs base C-doped at 5×10^{19} cm^{-3}, and a 300-nm undoped InGaAs collector. The growth temperature was 520°C except for the base, which was grown at 450°C. The base hole concentration of as-grown epiwafers is about 1×10^{19} cm^{-3}.

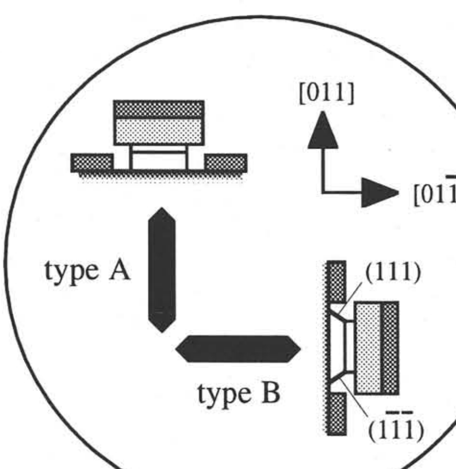
The devices were fabricated using a base-metal self-aligned evaporation technique [1]. The fabrication started with the formation of hexagonal WSi emitter electrodes. The electrode width is 1.2 μm and its area is 6 μm^2. After emitter mesa structures with undercuts were formed by dry and wet etching, the HBT epiwafer was annealed in nitrogen at 500°C for 5 min. During this heat treatment, hydrogen diffuses laterally in the base layer and dissociates from the layer at the uncapped external base region. It was confirmed from TLM measurements that nearly perfect de-passivation can be achieved when the emitter width is less than 2 μm. The high-temperature anneal simultaneously causes damage to the InP emitter sidewall. Therefore, the surface layer was slightly etched to remove the damaged region. Then, Pt/Ti/Pt/Au electrode metals were evaporated in a self-aligned manner to the emitter electrode. Conventional processes were used after the base electrode formation. We used BCB for passivation.

In order to investigate the high-temperature anneal effects on the InP sidewall surface, we prepared two types of HBT's: type A and type B. As shown in Fig. 1, the emitter orientation of type-A devices is perpendicular to the Major Flat while that of type B is parallel to the Major Flat. It is noticed that the etching profile of the InP mesa is different depending on the emitter orientation.

3. Device Performance and Stability

S-parameter measurements showed that at $V_{CE} = 1.2$ V the fabricated devices yield a maximum f_T of 126 GHz at $I_C = 5$ mA and a maximum f_{max} of 209 GHz at $I_C = 3$ mA. These values compare fairly well with those of Zn-doped HBT's with a similar base design [2]. This result is evidence that the high-temperature anneal after the emitter mesa formation is very effective in completely reversing the hydrogen passivation.

While the fabricated devices show excellent microwave performance, they generally exhibit current gain that is much lower than expected from the base design. Figure 2 plots current gain as a function of collector current density. The type-A HBT's typically exhibit maximum current gain of around 8, while Auger-recombination-limited gain is expected to be about 20. On the other hand, the type-B HBT's have a relatively large gain of 13. To find the reason for the lower current gain of the type-A HBT's, we divided their base recombination current into internal and periphery components using devices with various emitter widths (0.8-1.6 μm). The results are shown in Figs. 2 and 3. It can be seen that the type-A HBT's exhibit more than 10 times as much periphery current as the conventional Zn-doped-base HBT's [2] prepared for reference. The ideality factor of the periphery current is close to unity, and the maximum internal gain is as large as 14. Consequently, it is concluded that for the type-A HBT's, neutral-base recombination lifetime is significantly degraded especially at the emitter mesa periphery. Incidentally, we also found that the InP sidewall surface of the type-A HBT's is thermally unstable compared



Major Flat

Fig. 1 The crystallographic orientation of the emitter mesa structures prepared in this work.

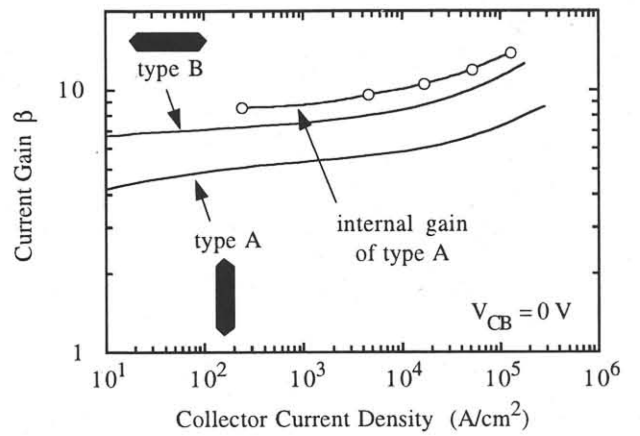


Fig. 2 Current gain vs. collector current density. Internal current gain for the type-A HBT's is also plotted.

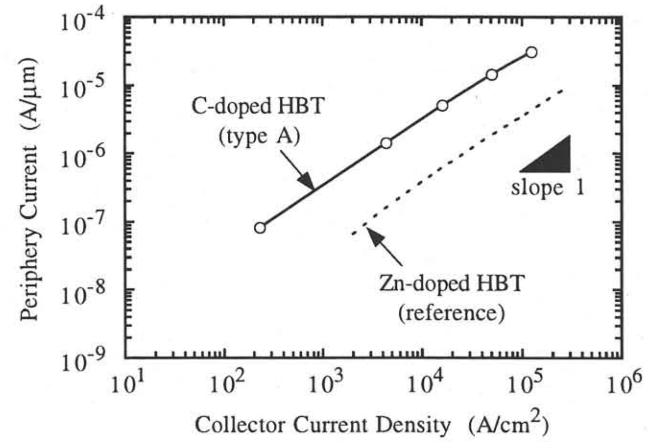


Fig. 3 Periphery recombination current vs. collector current density for the type-A HBT's. For comparison, periphery current for conventional Zn-doped-base HBT's is also shown.

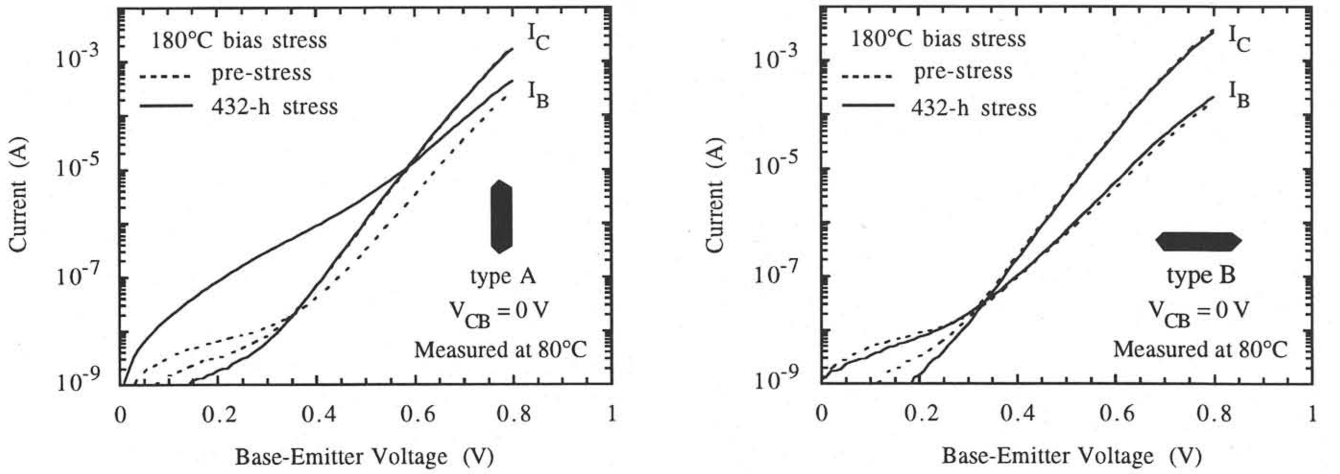


Fig. 4 Gummel plots before and after 432 hours bias stress at 180°C. For the stress experiments, discrete devices were mounted on packages.

with that of the type-B HBT's. We therefore speculate that especially in the type-A HBT's, a much larger number of point defects are generated at the InP sidewall during the anneal and propagate into the base, where they degrade the crystal quality. It may be necessary to optimize the anneal conditions in order to apply the proposed technique to type-A devices.

To investigate the stability of B-E junctions, preliminary bias stress tests were performed at an ambient temperature of 180°C. In the stress experiments, the transistors were forward biased at V_{BE} = 0.72 V to force a current density of about 60 kA/cm^2. Figure 4 compares Gummel plots before and after 432 hours of stress. For the type-A device, the base current is significantly increased after stress while the collector-current turn-on voltage remains almost unchanged. In sharp contrast, the Gummel plots for the type-B device show only a small change in both base and collector currents. It is interesting that the stability of the B-E junction also depends on the surface orientation of the InP emitter mesa. Such dependence suggests that the increase in the base current observed for the type-A device is due to excess leakage current generated at the InP emitter sidewall. Presumably, in the type-A devices, defects build up at the InP emitter sidewall during stress, which in turn create an "electron injection channel" from the emitter sidewall to the external base.

4. Conclusions

A high-temperature anneal after emitter mesa formation has been shown to be useful in reversing the hydrogen passivation of carbon acceptors. However, this technique causes damage to the InP emitter sidewall and possibly degrades current gain. In order to avoid such undesirable effects, we have to carefully optimize the anneal conditions and/or select the optimum emitter mesa orientation. The preliminary stress tests have revealed that the device stability also depends on the emitter orientation. Promising results are obtained from the devices whose emitter orientation is parallel to the Major Flat.

References

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2) K. Kurishima, H. Nakajima, S. Yamahata, T. Kobayashi, and Y. Matsuoka: IEICE Trans. Electron. **E79-C** (1995) 1171.