Characterization of InGaP/GaAs HBTs under Temperature and Current Stress

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Abstract

High-temperature bias stress tests on InGaP/GaAs HBTs are carried out at an emitter-base junction temperature ranging from 360 to 440°C and a collector current density of $1 \times 10^5$ A/cm$^2$. The drastic degradation of current gain is caused by the increase in the base current with an ideality factor close to 1, implying that the degradation results from the decrease of the minority carrier lifetime in the neutral base region. The variations in current-voltage characteristics of the emitter-base and base-collector junctions during stress testing reveal that the recombination centers continuously increase in the base layer near the emitter-base junction from the beginning of the bias testing. Both self-aligned HBTs and non-self-aligned HBTs have the same dependence of lifetime on the junction temperature with the same activation energy of 2.0 eV, suggesting that the current gain degradation is related to the intrinsic base region.

EXPERIMENTS

The epitaxial layers were grown on a semi-insulating GaAs (100) substrate by metalorganic chemical vapor deposition (MOCVD). The subcollector layer was a 600-nm GaAs doped to $5 \times 10^{18}$ cm$^{-3}$, and the collector layer was an 800-nm GaAs collector doped to $1 \times 10^{16}$ cm$^{-3}$. The base layer was a 70-nm C-doped GaAs base with a carrier concentration of $4 \times 10^{19}$ cm$^{-3}$. The InGaP emitter layer was 30 nm thick and the GaAs emitter layer was 200 nm thick, both of which were doped to $3 \times 10^{17}$ cm$^{-3}$. The emitter cap layers consisted of a 100-nm GaAs doped to $5 \times 10^{18}$ cm$^{-3}$ and a 100-nm InGaAs doped to $1 \times 10^{19}$ cm$^{-3}$.

Schematic cross-sections of the tested device structures are illustrated in Fig. 1. We fabricated both self-aligned HBTs and non-self aligned HBTs on the same wafer. The InGaAs and GaAs cap layers were etched by selective wet chemical etching using a WSi emitter electrode as an etching mask. Au/Pt/Ti/Mo/Ti/Pt metal was deposited on the InGaP as the base electrode and an ohmic contact was formed through the thin InGaP emitter layer by alloying. The base electrode was self-aligned to the emitter by using the undercut of the InGaAs and GaAs layers for the self–aligned HBTs [Fig. 1(a)]. The base electrode of the non-self-aligned HBTs, in contrast, was formed 1.5-μm apart from the emitter electrode by using a standard photolithographic process [Fig. 1(b)]. After the base mesa and the collector mesa were formed by wet chemical etching using a photoresist as an etching mask, a Au/Ni/W/AuGe collector electrode was deposited on the subcollector, lifted off, and alloyed. The device isolations were also formed by wet chemical etching. The fabricated HBTs with an emitter size $S_e$ of

INTRODUCTION

InGaP/GaAs heterojunction bipolar transistors (HBTs) are now identified as highly attractive devices for use in high-power microwave amplifiers and high-speed optical communication circuits due to their excellent high-frequency performance and ease of manufacture. To use HBTs for practical applications, it is essential to obtain high reliability and, thus, to understand the failure modes of the devices. However, little is known about degradation mechanisms in InGaP/GaAs HBTs [1, 2].

We have subjected InGaP/GaAs HBTs to high-temperature bias stress tests at an emitter-base junction temperature ranging from 360 to 440°C and a collector current density of $1 \times 10^5$ A/cm$^2$. We found that the current gain was decreased by increasing the base current with an ideality factor close to 1. We also found that the reverse current-voltage characteristics of the emitter base junction continue to increase from the beginning of the bias testing. Both self-aligned HBTs and non-self-aligned HBTs showed the same dependence of lifetime on the junction temperature with the same activation energy.
Fig. 1. Schematic cross-section of tested InGaP/GaAs HBTs: (a) self-aligned HBT; (b) non-self-aligned HBT.

2.5 x 20 μm² had a current gain of about 130 at a collector current density of 4 x 10⁴ A/cm².

We carried out bias stress tests on HBTs at a collector current density \( J_c \) of 1 x 10⁵ A/cm², a base-collector bias voltage \( V_{BC} \) ranging from 0 to 2.0 V, and a substrate temperature \( T_s \) ranging from 150 to 250°C. The emitter size \( S_e \) of the tested HBTs was 2.5 x 20 μm². The emitter-base junction temperature \( T_j \) was determined from the dependence of the current gain \( h_{FE} \) on the power consumption and \( T_s [3] \). The estimated \( T_j \) ranged from 360 to 440°C.

RESULTS AND DISCUSSIONS

At the initial stage of the bias testing, the current gain \( h_{FE} \) was degraded by 10-15%. Then it remained stable and, finally, it decreased rapidly and drastically. Figure 2 shows Gummel plots of a self-aligned HBT measured at a room temperature before and after bias stress testing at \( T_j \) of 375°C for 20 h. The base current \( I_B \) drastically increased after the bias stress test. On the contrary, the collector current \( I_C \) showed almost no change. This result indicates that the drastic reduction in \( h_{FE} \) is entirely caused by the increase in \( I_B \). The ideality factor of the increased \( I_B \) is close to 1, implying that the \( I_B \) increase originates in the decrease of the minority carrier lifetime in the neutral base region. This ideality factor is not the same as those reported for AlGaAs/GaAs HBTs [4-6] and InGaP/GaAs HBTs [2], which have ideality factors nearly equal to 2 or much larger. This suggests that the mechanism of the \( h_{FE} \) degradation in our HBTs is different from those of previously reported HBTs. We also subjected an HBT only to thermal stress. However, the current gain was not decreased. Therefore, the degradation in \( h_{FE} \) is influenced by minority carrier injections, which probably generate recombination centers by recombination-enhanced defect reactions.

Figure 3 shows measured forward and reverse current-voltage characteristics of both the emitter-base junction and the base-collector junction of the HBT during stress testing. Only the reverse current at the emitter-base junction significantly increased, indicating that recombination centers increase in the base layer near the heterojunction interface. Furthermore, the reverse current continuously increased during the bias testing. This result implies that the recombination centers start to increase from the beginning of the bias testing. We suppose that the recombination centers decrease the minority carrier lifetime in the neutral base region, and that the degradation in \( h_{FE} \) appears after the recombination centers dominate the lifetime of minority carriers.
We defined the lifetime of the HBTs as the time taken for $h_{\text{FE}}$ to reduce by 10% after the initial change. Figure 4 shows Arrhenius plots of the dependence of lifetime on $T_i$ of self-aligned HBTs and non-self-aligned HBTs. Both types of HBTs showed the same dependence of lifetime on $T_i$ with the same activation energy $E_a$ of 2.0 $\pm$ 0.2 eV. Since lifetime does not depend on the emitter-base spacings, the degradation in $h_{\text{FE}}$ is related to the intrinsic base region. Consequently, we conclude that the degradation in current gains with $E_a$ of 2.0 eV is ascribed to the decrease of the minority carrier lifetime due to the increase of the recombination centers in the intrinsic base region near the emitter-base junction. The previously reported reliability results of InGaP HBTs are also shown in Fig. 3 [2, 5]. The $E_a$ of our HBTs is almost the same as that in Ref [5].

In order to analyze the degradation mechanism structurally, we observed the cross-sections of the HBTs after the stress testing by transmission electron microscopy (TEM). However, we did not find any
dislocations, microtwin-like defects, or precipitates related to carbon [1, 6, 7]. We thus suspect that the recombination centers are related to point defects or dangling bonds activated by the minority carrier injections in the base layer.

CONCLUSIONS

We carried out high-temperature bias stress tests on InGaP/GaAs HBTs with an emitter size of 2.5 × 20 μm$^2$ at an emitter-base junction temperature $T_J$ ranging from 360 to 440°C and a collector current density $J_C$ of $1 \times 10^5$ A/cm$^2$. We found that the current gain was decreased by increasing the base current with an ideality factor close to 1. We also found that the reverse current-voltage characteristics of the emitter base junction start to increase from the beginning of the bias testing. Both self-aligned HBTs and non-self-aligned HBTs showed the same dependence of the lifetime on $T_J$ with the same activation energy $E_a$ of 2.0 eV. These results suggest that the degradation of current gain is attributed to the decrease of the minority carrier lifetime due to the increase of recombination centers activated by minority carrier injections in the intrinsic base region near the emitter-base junction.

ACKNOWLEDGEMENT

We would like to thank the process staff of the compound semiconductor group at Hitachi Central Research Laboratory for their contributions to the device fabrication.

REFERENCES