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 × 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.

INTRODUCTION

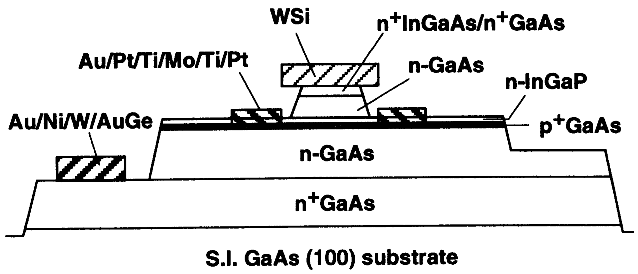
InGaP/GaAs heterojunction bipolar transistors (HBTs) are now identified as highly attractive devices for use in high-power microwave amplifiers and high-speed optical communication circuits due to their excellent high-frequency performance and ease of manufacture. To use HBTs for practical applications, 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 × 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.

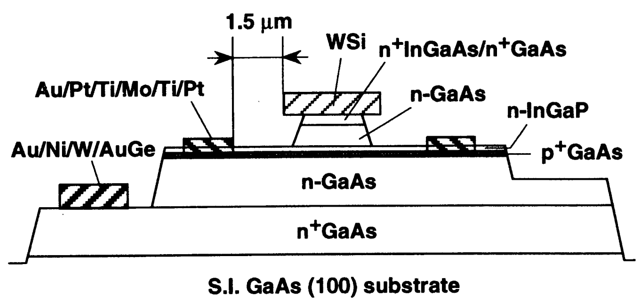
EXPERIMENTS

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 × 10^{18} cm^{-3}, and the collector layer was an 800-nm GaAs collector doped to 1 × 10^{16} cm^{-3}. The base layer was a 70-nm C-doped GaAs base with a carrier concentration of 4 × 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 × 10^{17} cm^{-3}. The emitter cap layers consisted of a 100-nm GaAs doped to 5 × 10^{18} cm^{-3} and a 100-nm InGaAs doped to 1 × 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



(a)



(b)

Fig. 1. Schematic cross-section of tested InGaP/GaAs HBTs: (a) self-aligned HBT; (b) non-self-aligned HBT.

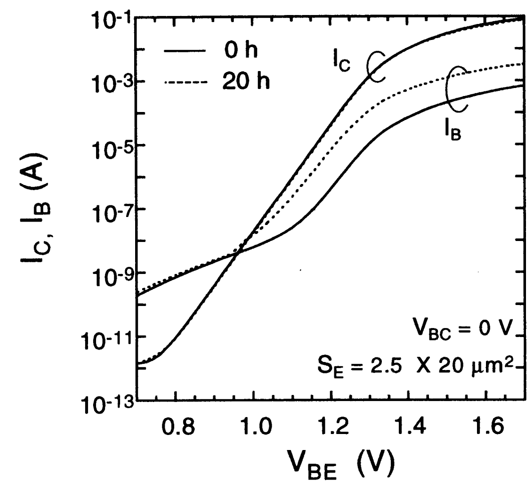


Fig. 2. Gummel plots of an self-aligned InGaP/GaAs HBT measured at a room temperature before (solid lines) and after 20-h-long bias testing (dashed lines) at T_j of 375℃ and J_c of 1×10^5 A/cm².

2.5×20 μm² had a current gain of about 130 at a collector current density of 4×10^4 A/cm².

We carried out bias stress tests on HBTs at a collector current density J_c of 1×10^5 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 2.5×20 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.

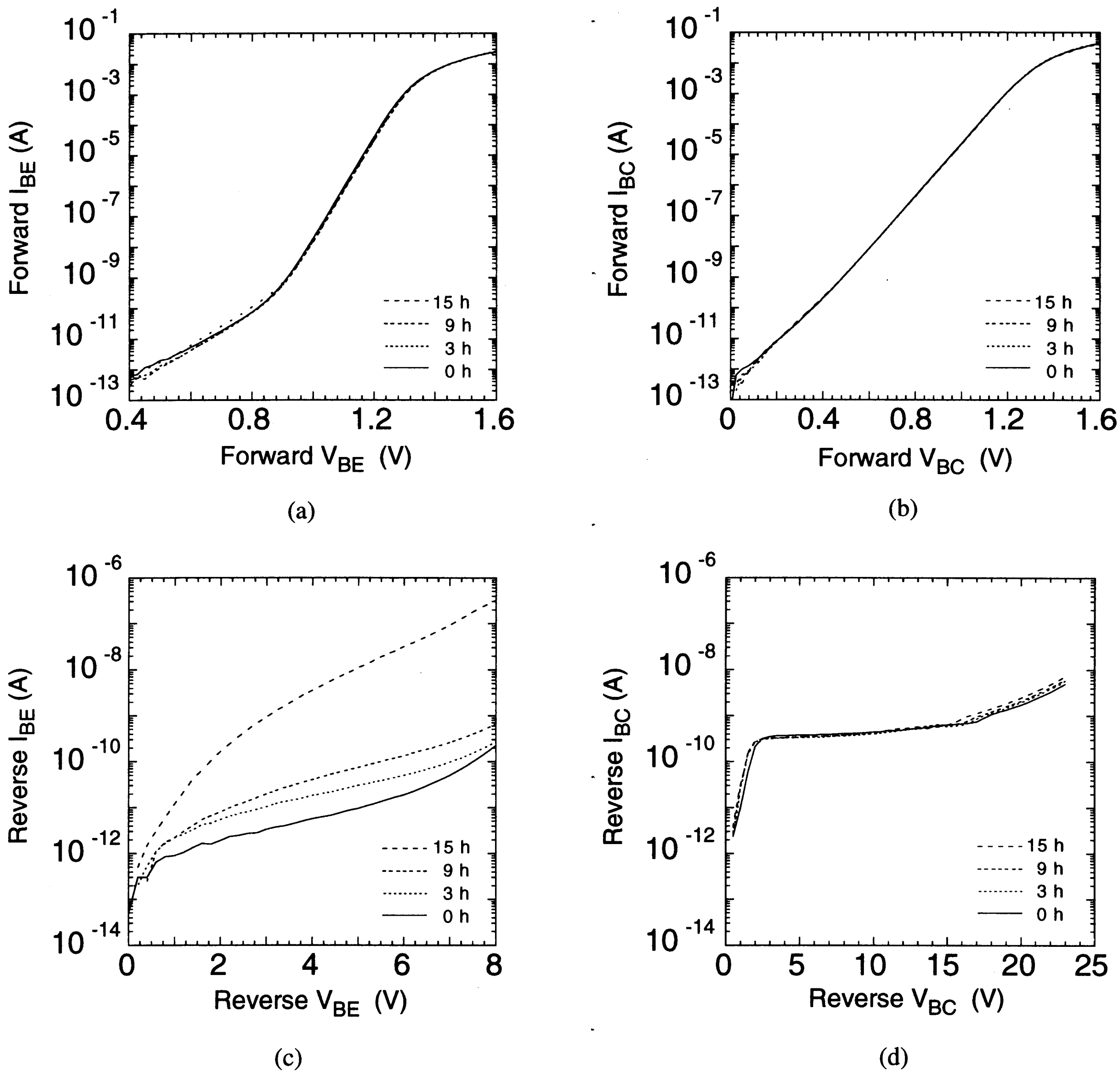


Fig. 3. Current-voltage characteristics of emitter-base and base-collector junctions for an HBT before and after bias stress testing at T_j of 375℃ and J_c of 1×10^5 A/cm^2: (a) forward characteristics at emitter-base junction; (b) forward characteristics at base-collector junction; (c) reverse characteristics at emitter-base junction; (d) reverse characteristics at base-collector junction.

We defined the lifetime of the HBTs as the time taken for h_{FE} to reduce by 10% after the initial change. Figure 4 shows Arrhenius plots of the dependence of lifetime on T_j of self-aligned HBTs and non-self-aligned HBTs. Both types of HBTs showed the same dependence of lifetime on T_j with the same activation energy E_a of 2.0 ± 0.2 eV. Since lifetime dose not depend on the emitter-base spacings, the degradation in h_{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

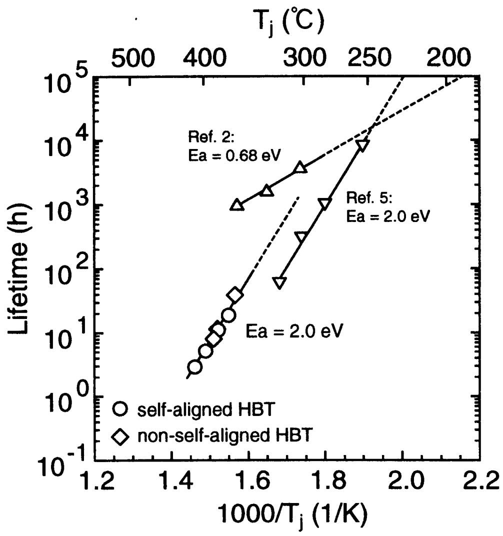


Fig. 4. Arrhenius plots of the lifetime of self-aligned HBTs (○) and non-self-aligned HBTs (◇). Also shown are the results reported in references [2, 5].

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 1×10^5 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.

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