Extended Abstracts of the 1993 International Conference on Solid State Devices and Materials, Makuhari, 1993, pp. 1059-1061

Analysis on the Stability of C-Doped AlGaAs/GaAs HBTs

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The reliability of C-doped and Be-doped AlGaAs/GaAs HBTs was investigated in terms of three factors, i.e. minority carrier injection characteristics, recombination characteristics, and parasitic ohmic characteristics, using a new approach. In forward-bias and high-temperature storage tests, the C-doped HBTs show no reduction in the intrinsic current gain which is dominated by the minority carrier injection characteristics. This result indicates that C is a stable base dopant without diffusion.

1. INTRODUCTION

AlGaAs/GaAs HBTs have received much attention as devices for high-speed and power applications. These practical uses of HBTs need stable device performance under high-current density operation. However, current-induced degradation has been reported for HBTs with Be as a p-type base dopant [1), 2)]. This degradation is considered to be caused by Be-diffusion into the wide band-gap emitter. Recently, it has been thought that carbon is a stable base dopant because it has a diffusion coefficient smaller than that of Be [3), 4)]. Thus, C-doped HBTs are being actively developed [5), 6)]. However, instability, such as reduction in current gain, is often observed even for C-doped HBTs under forward bias. This is because, as shown in Fig. 1, device performance depends on recombination characteristics and ohmic characteristics, as well as minority carrier injection characteristics which are greatly influenced by base-dopant diffusion. Therefore, to clarify the cause of the instabilities and evaluate the stability of carbon as a base dopant, we have isolated these three characteristics based on simple analysis of the I-V characteristics of each sample device, in combination with S-parameter measurements.

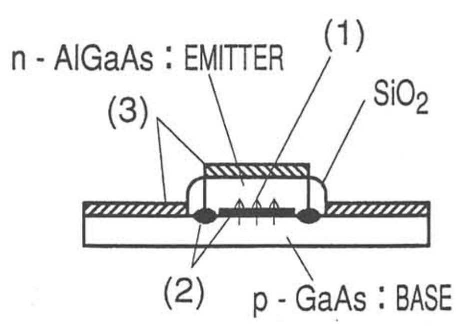

Fig. 1. Degradation factors: 1) the base-dopant diffusion, 2) the change in recombination current, and 3) the degradation of ohmic resistances.

2. EXPERIMENTS

The devices tested were MOCVD-grown C-doped HBTs and MBE-grown Be-doped HBTs with 80-nm-thick p-GaAs base layers doped to $4\times10^{19}cm^{-3}$. The emitter area was defined by RIBE, and a passivation film was made of CVD SiO_2. Three kinds of stress tests were carried out: 1) a short-term forward-bias test for 30 min under a constant collector current with stress current densities, J_S, ranging from 7×10^4 to $3\times10^5 A/cm^2$, 2) a long-term forward-bias test for 100 hrs with a J_S of $1.2\times10^5 A/cm^2$, and 3) a high-temperature storage test at 200 °C for 20 hrs in a nitrogen ambience.

3. APPROACH TO THE ANALYSIS

The minority carrier injection characteristics and the recombination characteristics are both reflected in dc characteristics. We isolated them from I-V characteristics using the following approach [7].

The base current is represented as the sum of two components,

$I_B = I_{Bi}\exp(qV_{BE}/n_i kT) + I_{Br}\exp(qV_{BE}/n_r kT)$, (1)

where n_i (≡1) and n_r (≡2) are ideality factors. The second term is the recombination current in the base-emitter space-charge region. By dividing eq. (1) by the collector current,

$I_C = I_{Ci}\exp(qV_{BE}/n_i kT)$, (2)

we can express current gain, h_{FE}, as

$1/h_{FE} = I_B/I_C = 1/h_{FEi} + K J_C^{\alpha-1}$, (3)

where h_{FEi} is intrinsic current gain, α is n_i/n_r, and K is a constant. These elements are determined from eq. (3), considering the correlation between h_{FE} and collector current density, J_C, as shown in Fig. 2.

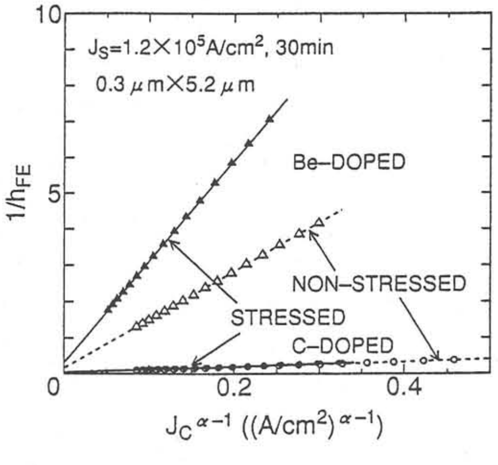

Fig. 2. Plots of $1/h_{FE}$ as a function of $J_C^{\alpha-1}$. Current gain h_{FE} measured is described as $1/h_{FE} = 1/h_{FEi} + K J_C^{\alpha-1}$, where h_{FEi} is the intrinsic current gain and obtained from the intercept with the y-axis.

The intrinsic current gain, h_{FEi}, is dominated by the minority carrier injection characteristics. Therefore, the base-dopant diffusion is evaluated from the h_{FEi}. The recombination current is evaluated as $K J_C^{\alpha} S_{EB}$, where S_{EB} is the area of the base-emitter junction. We employed this approach on sample devices to investigate changes in these characteristics after the above stress tests.

On the other hand, the ohmic characteristics are reflected in the rf characteristics. We evaluated them from measured S-parameters using equivalent circuits [8), 9)].

4. RESULTS AND DISCUSSION

Fig. 3 shows the dependence of the intrinsic current gain, h_{FEi}, on the stress current density, J_s, in the short-term forward-bias tests. The h_{FEi} of the C-doped HBTs showed no degradation for J_S up to $3\times10^5 A/cm^2$, while h_{FEi} degradation was seen in the Be-doped HBTs for J_S above $1\times10^5 A/cm^2$. Fig. 4 shows the changes in the h_{FEi} during the long-term forward-bias tests. The h_{FEi} of the Be-doped HBTs decreased to half the initial value in 30 min. However, the h_{FEi} of the C-doped HBTs showed no degradation for 100 hrs. Since the h_{FEi} reflects the minority

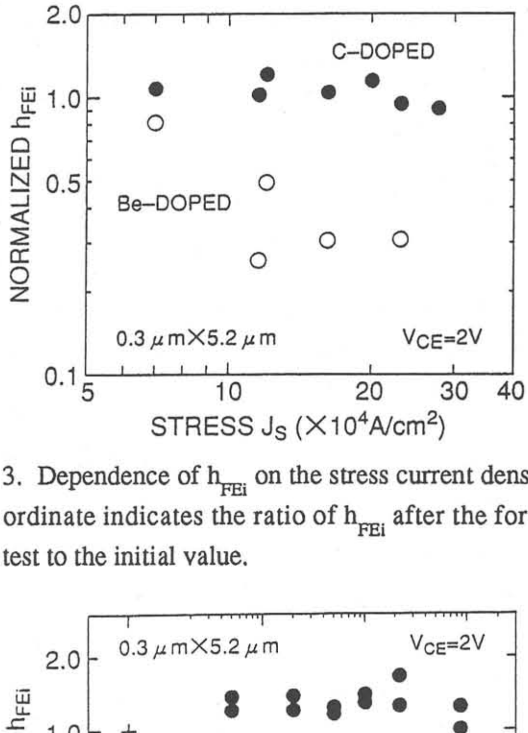

Fig. 3. Dependence of h_{FEi} on the stress current density J_S. The ordinate indicates the ratio of h_{FEi} after the forward-bias test to the initial value.

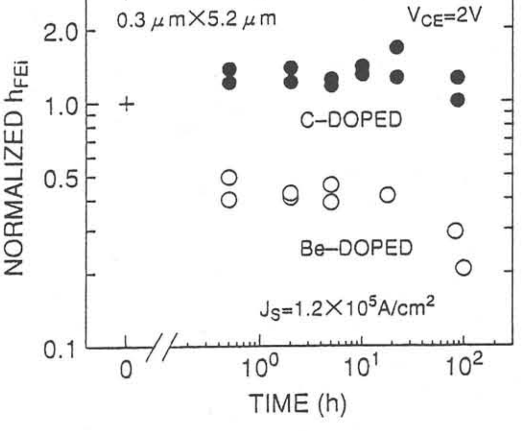

Fig. 4. Dependence of h_{FEi} on the stress duration. The stress current density was kept at a constant value of $1.2\times10^5 A/cm^2$.

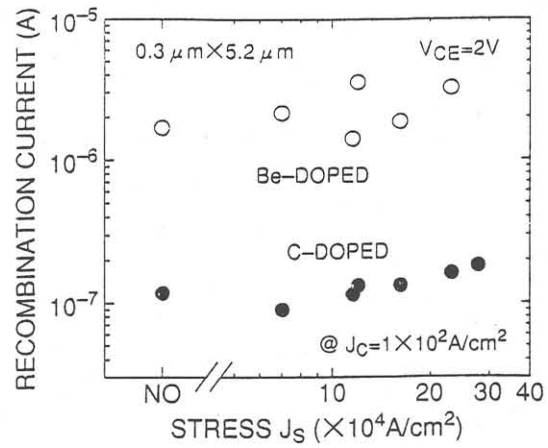

Fig. 5. Dependence of the recombination current on J_S.

carrier injection characteristics, the stable h_{FEi} of the C-doped HBTs means that C does not diffuse under forward bias. The reductions in the h_{FEi} of the Be-doped HBTs are well explained by the current-induced diffusion of Be into the wide band-gap emitter. Change in the h_{FEi} was not seen for the C-doped HBTs in the high-temperature storage test. This suggests that C is stable for thermal stress as well as for current stress.

The other factors, recombination current and ohmic resistance, showed some changes. Fig. 5 shows the dependence of the recombination current on J_s in the short-term forward-bias tests. The recombination

	INTRINSIC		EXTRINSIC
	INTRINSIC CURRENT GAIN	RECOMBINATION CURRENT	OHMIC RESISTANCE
(1)	C : stable for $Js<3\times10^5$ A/cm^2 Be: degraded for $Js>1\times10^5$ A/cm^2	C : increased for $Js>2\times10^5$ A/cm^2 Be: increased for $Js>7\times10^4$ A/cm^2	R_{EE} : changed (±30%) R_B : changed (±15%)
(2)	$Js=1.2\times10^5$ A/cm^2 C : stable for 100 hrs Be: degraded during 30min	$Js=1.2\times10^5$ A/cm^2 C : increased by 330% Be: increased by 700%	
(3)	C : stable for 20 hrs	C : stable for 20 hrs	R_{EE} : increased by 200% R_B : increased by 150%

Table 1. Summarized results of the stress tests: (1) the short-term forward-bias test (30 min), (2) the long-term forward-bias test (100 hrs), (3) the high-temperature storage test (200°C). (C: C-doped HBTs, Be: Be-dcped HBTs, R_{EE}: emitter series resistance, R_B: base resistance)

current increased for the Be-doped and C-doped HBTs, as J_s increased. Ohmic resistance showed significant changes in the forward-bias tests and the high-temperature storage tests, as shown in Table. 1. These changes in recombination current and ohmic resistance cause the unsteadiness of device performance and remain to be stabilized.

5. CONCLUSION

Changes of the characteristics under forward-bias and high-temperature storage tests were evaluated for the C-doped and Be-doped HBTs. The C-doped HBTs showed no reduction in the intrinsic current gain, h_{FEi}, under these stress conditions, suggesting that carbon is a suitable base dopant without diffusion by current-stress or thermal-stress. On the other hand, recombination current and ohmic resistance showed significant changes. They must be stabilized for achieving stable device performance.

ACKNOWLEDGMENTS

The authors would like to thank N. Hayama, Dr. N. Goto, and H. Takahashi for device fabrication, and H. Toyoshima for the growth of the epitaxial layers. They also wish to thank Y. Ueda and K. Iioka for their support in device processing, and N. Nagano for his advice about S-parameter measurements. Thanks are also due to Dr. T. Nozaki for his continuous support.

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