A Study on the Base Recombination Current in Direct-Growth *npn* GaN/InGaN DHBTs

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***Abstract* – We studied the impact of indium content on the base recombination current components for GaN/InGaN double-heterojunction bipolar transistors (DHBTs). With higher indium content in the base layer, the surface recombination current was reduced. The bulk recombination current, however, increases as the indium composition increases in the DHBTs. After the device burn-in, the GaN/$In_{0.05}Ga_{0.95}N$ DHBT demonstrated the current gain (h_{fe}) > 84 and collector current density (J_C) > 6.75kA/cm^2. This result stands as one of the highest performance reported on direct-growth GaN/InGaN DHBTs grown on sapphire substrates.**

Keywords: **InGaN, GaN, HBT, recombination, direct-growth**

INTRODUCTION

III-Nitride (III-N) heterojunction bipolar transistors (HBTs) have demonstrated great potential for high power switching and amplification applications [1-5]. For high power applications, it is desired for III-N HBTs to have high collector current density (J_C) and high d.c. current gain (β). However, only few reported III-N HBTs can achieve J_C >1kA with reasonable β values to date. It is largely due to the high base resistance and significant base recombination current components.

In our previous work, we have developed an *npn* GaN/$In_{0.03}Ga_{0.97}N$ double heterojunction bipolar transistor (DHBT) fabrication technique using a direct-growth approach[6]. The fabricated devices demonstrated β > 42 and J_C > 5.2 kA/cm^2. In this study, we investigated GaN/$In_{0.05}Ga_{0.95}N$ DHBTs with the same fabrication technique and studied possible approaches to the device performance improvements. In particular, the base current components were studied in greater detail for devices with different indium compositions in the InGaN base layers. We also found that the performance of fabricated GaN/InGaN DHBTs can also be improved through a constant current stressing to improve the free-hole concentration (i.e., the device "burn-in"). Using the 5% InGaN base layer design and the post-processing current stressing, we report a GaN/$In_{0.05}Ga_{0.95}N$ DHBT that can achieve β > 66 , h_{fe} > 84, and J_C > 6.75kA/cm^2.

LAYER STRUCTURE AND DEVICE FABRICATION

Two device structures ("Structure A" for GaN/$In_{0.05}Ga_{0.95}N$ and "Structure B" for GaN/ $In_{0.03}Ga_{0.97}N$ DHBTs) were investigated in this study. They have similar layer thicknesses and doping concentrations except for the base layer and the grading layer designs, as shown in Table 1. These wafers were grown on 2-inch *c*-plane sapphire substrates in a Thomas–Swam MOCVD system. The electron and hole concentrations were calibrated in test samples before each HBT epitaxial material growth runs, as reported in [7].

Two mesa etching process was developed using an inductively coupled plasma (ICP) etching system. The first etching step exposes the base layer and the second etching step stops at the sub-collector layer. The sub-collectors in fabricated DHBTs were not electrically isolated. After the etching process, the samples were treated in a diluted $KOH/K_2S_2O_8$ solution under ultraviolet illumination to remove the dry-etching-induced surface and sidewall damage [8]. Ni/Ag/Pt was patterned and annealed for the base contacts and Ti/Al/Ti/Au metal stacks were deposited for the emitter and collector electrodes. Fabricated samples in this study are not passivated with any dielectrics.

RESULTS AND DISCUSSION

Shown in Figure 1 are the common-emitter characteristics of the Structure A DHBT with emitter area (A_E) of 20×20μm^2. The device can achieve a $J_{C,MAX}$ = 4.9 kA/cm^2 at V_{CE} =10.4V and I_B =500 µA. Compared to our previously reported GaN/$In_{0.03}Ga_{0.97}N$ DHBTs (Structure B)[6], the knee voltage was reduced from 12.4V to 10.4V at similar current driving conditions. In the Gummel plot (not shown here), the collector current (I_C) and base current (I_B) crossed over at ~ 1 µA at V_{BE} = 4.5V. After the cross-over point, both the differential current gain h_{fe} ($=dI_C/dI_B$) and d.c. current gain β ($=I_C/I_B$) increase and reached 46.8 and 39, respectively. The current gain performance for 5%-InGaN-base devices (Structure A) didn't show better current gain when compared to 3%-InGaN-base designs (Structure B).

TABLE I

LAYER STRUCTURE OF NPN INGAN/GAN DHBTS

LAYER	Material		THICKNESS (nm)	FREE CARRIER CONCENTRATION (cm^{-3})
	5%-INGAN DHBT (Structure A)	3%-INGAN DHBT (Structure B)		
Emitter cap	GaN	GaN	70	$n = 1 \times 10^{19}$
Emitter grading	$In_xGa_{1-x}N$ (x = 0–0.05)	$In_xGa_{1-x}N$ (x = 0–0.03)	30	$n = 1 \times 10^{19}$
Base	$In_xGa_{1-x}N$ (x = 0.05)	$In_xGa_{1-x}N$ (x = 0.03)	100	$p = 2 \times 10^{18}$
Collector grading	$In_xGa_{1-x}N$ (x = 0.05–0)	$In_xGa_{1-x}N$ (x = 0.03–0)	30	$n = 1 \times 10^{18}$
Collector	GaN	GaN	500	$n = 1 \times 10^{17}$
Subcollector	GaN	GaN	1000	$n = 3 \times 10^{18}$
Buffer layer	GaN	GaN	2500	UID
Sapphire Substrate				

The device results may suggest that the base resistance was improved with the higher indium content in the base layer. However, higher indium content in the base layer did not seem to increase the current gain and the maximally achievable collector current density. To understand the impact of higher indium content on the device performance, a surface-leakage-current assessment was used to compare the base recombination current components on both Structure A and Structure B.

Using the linear regression fitting on the J_C/β against the emitter perimeter/area ratio (L_E/A_E), the surface-recombination-related current component ($K_{B,surf}$) and bulk-related current (J_{Bulk}) can be extracted for constant J_C's [9]. It should be noted that J_{Bulk} consists mostly of the defect-related recombination current in the bulk region as the base resistance is relatively high and the emitter crowding effect is significant in III-N HBTs. As shown in Figure 2, $K_{B,surf} = 6.1 \times 10^{-4}$ A/cm is extracted for DHBTs with Structure A. This value is about one third of that for the DHBTs with Structure B. It may indicate that higher indium content in the base layer may be preferable in achieving lower surface recombination in DHBT designs. However, J_{Bulk} increases significantly from 3.78 A/cm^2 to 6.36A/cm^2 when one compares Structure A (5%-InGaN base) to Structure B (3%-InGaN base). It suggests that more recombination centers were presented in the higher indium content base layer, possibly due to a larger lattice mismatch in the InGaN base layer with higher indium compositions. For $GaN/In_{0.05}Ga_{0.95}N$ DHBTs with A_E = 20×20 µm^2, the bulk-related current contribute to 84% of the base current. The reduction of bulk recombination centers may become an effective approach to increase the current gain in InGaN HBTs.

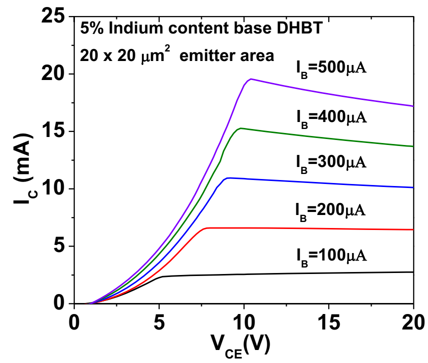


Figure 1. Common-emitter characteristics of a fabricated $GaN/In_{0.05}Ga_{0.95}N$ DHBT with $A_E = 20 \times 20$ μm^2

It is well-known that the hydrogen passivation may be significant in as-grown p-type layers in conventional III-V HBTs using MOCVD approaches. The hydrogen passivation effect can be reduced through electric current stressing, or the device burn-in. To explore further device performance enhancement in fabricated GaN/InGaN HBTs, we applied a constant base current stressing (I_B = 200uA) and set V_{CE} at 15V on DHBTs with Structure A design. The collector current (I_C) and the base voltage (V_{BE}) were monitored every 5 seconds for 50 minutes, as shown in Figure 3.

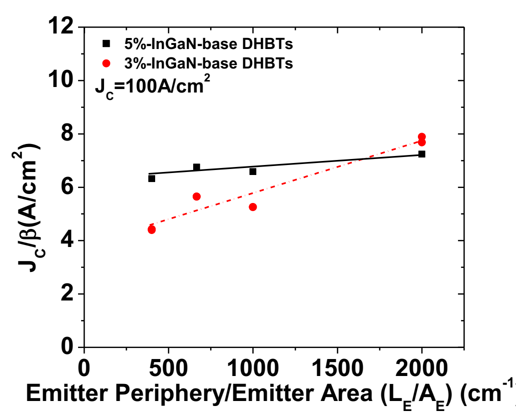


Figure 2. J_C/β plotted against the emitter perimeter-to-area ratio (L_E/A_E) for J_C = 100 A/cm^2 for 3%-InGaN-base and 5%-InGaN-base DHBTs.

As seen in the plot, the collector current increased and reached the saturation around 9.7 mA as the time evolves. The β increases from 32 to 47 after 30 minutes of stressing correspondingly. A clear device burn-in effect on InGaN-based DHBTs was observed.

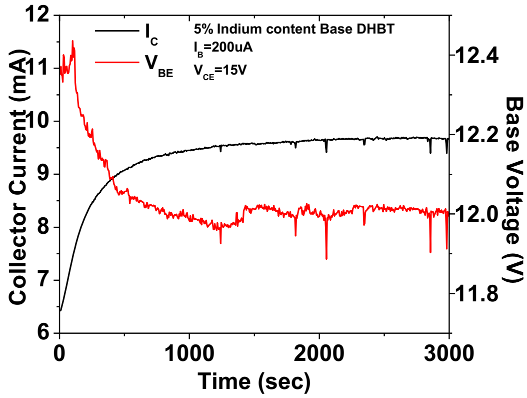


Figure 3. The measured collector current and base voltage during constant base current stressing (I_B = 200 uA)

The device burn-in effect may be due to the reduced hydrogen passivation in the Mg-doped InGaN base layer. After the electric current stressing, the free-hole concentration in the base layer is increased and the bulk-related recombination centers can be reduced. This scenario is similar to that being observed in conventional MOCVD-grown III-V HBTs.

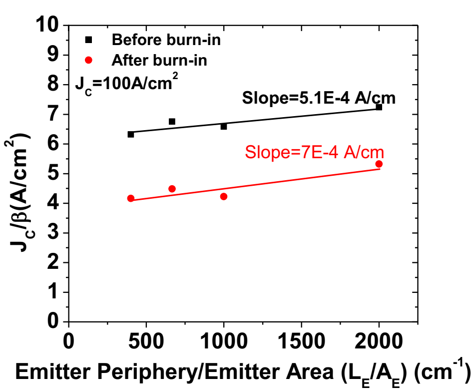
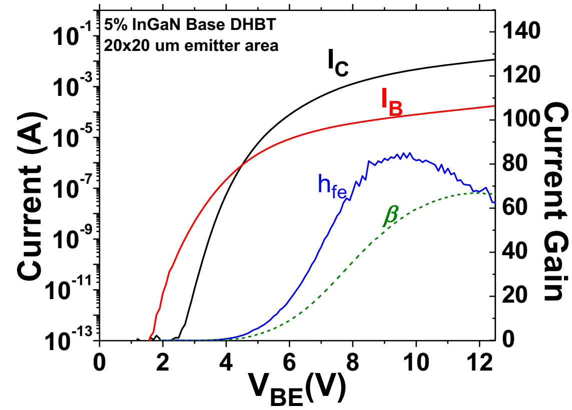
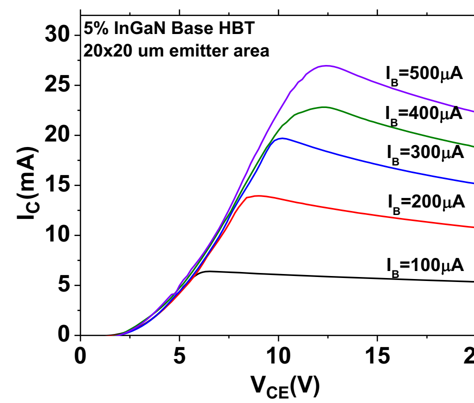


Figure 4 J_C/β plotted against the emitter perimeter-to-area ratio (L_E/A_E) before and after burn-in.

As shown in Figure 4, the linear regression fitting of J_C/β against the L_E/A_E were plotted to evaluate the leakage current components in Structure A devices before and after the current stress. The evaluation was done with at J_C=100A/cm^2. The surface recombination current remains approximately unchanged before and after the current stressing. On the other hand, the bulk recombination current was reduced from 6.2 to 3.8A/cm^2, indicating that the bulk recombination centers are reduced. The increase in the free-hole concentration can also be verified with the reduction of V_{BE} at the same current drives after the device burn-in, as seen in the Gummel plot (Figure 5(a)).



(a)



(b)

Figure 5. A Gummel plot and a common-emitter characteristics of a fabricated GaN/In$_{0.05}$Ga$_{0.95}$N DHBTs with A_E = 20 × 20 μm^2 after base current stressing.

Shown in Figure 5 are the I-V characteristics of a DHBT (Structure A) after a 50-minute base current stressing experiment. The device shows β > 66 and h_{fe} >84 at V_{BE} =12V and V_{BE} =9.5V, respectively. $I_{C,MAX}$ is also increased to 27mA (J_C = 6.75kA/cm^2) at I_B=500uA. These results, to our best knowledge, are the best performance of GaN/InGaN DHBT on sapphire substrate reported to date.

CONCLUSIONS

In summary, we investigated the influence of the indium content in the base layer and report an enhanced device performance after the device burn-in procedure. The data showed that the surface recombination current can be reduced using a higher indium content in the base layer. However, higher bulk defect density the higher indium-containing base layer may undermine the achievable current gain. On the other hand, the device burn-in may effectively reduce the bulk recombination current and the base resistance, possibly due to the reduction in the hydrogen passivation effect in the Mg-doped base layer. Using the 5% InGaN base layer design and post-processing current stressing, we report a state-of-the-art GaN/InGaN DHBT that is capable of achieving $\beta > 66$, $h_{fe} > 84$ and $J_C > 6.8\text{kA/cm}^2$.

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ACRONYMS

DHBT: Double-Heterojunction Bipolar Transistor