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Research Article

Reduced Turn-On Voltage for npn Graded-Base AlGaN/GaN Heterojunction Bipolar Transistors by Thermal Treatment

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A thermal treatment was employed to improve the DC performances of npn graded-base AlGaN/GaN heterojunction bipolar transistors (HBTs). Such HBTs without the thermal treatment exhibit a higher turn-on voltage of 6.45 V, a lower current gain of 0.84, and a lower collector current of 3.18×10^{-4} mA at V_{BE} of 4.5 V. The HBTs are examined by thermal treatment with rapid thermal process (RTP) annealing at various times and various temperatures. Experimental results reveal that the HBTs with the thermal treatment exhibit a lowest turn-on voltage of 3.90 V, a highest current gain of 9.55, and highest collector current of 112.2 mA at V_{BE} of 4.5 V. The thermal treatment brings forth the most remarkable improvements for the HBTs when the base parasitical Schottky diodes are modified.

1. Introduction

The npn heterojunction bipolar transistors (HBTs) have received more and more popularity in both wireless and wired consumer products due to the inherent superiority of bipolar devices compared to field-effect devices for linearity, efficiency, and output power, as well as the need for only a single positive power supply [1, 2]. Recently, the trend in portable electronics has been to achieve greater efficiency at lower bias conditions for longer battery life. Therefore, it has become one of the most important issues to reduce the HBTs base-emitter (B-E) turn-on voltage, $V_{BE,ON}$. Typically, two main approaches in reducing $V_{BE,ON}$ are (1) adoption of a narrower band-gap material for the base and (2) elimination of the effect of the conduction-band discontinuity (ΔE_C) at the B-E junction [3–10].

On the other hand, the GaN-based electronic devices are suitable candidate for high-temperature and high-power application due to their wide bandgap, higher critical electric field strength, and higher electron saturation drift velocity compared to other semiconductor materials. III-nitride technology has been advancing rapidly for several years [1, 2]. Concerning the adoption of a narrower band-gap material for III-nitride technology, GaN/InGaN HBTs [3–5] are first considered as candidates for the replacement to AlGaN/GaN ones [6–10]. However, a large spike at the B-E junction also severely limits the reduction of $V_{BE,ON}$. On the other hand, most p-InGaN-based HBTs are double-heterojunction ones. The blocking effect at base-collector (B-C) heterojunction results in a high knee voltage. Furthermore, the expected reduction of $V_{BE,ON}$ is usually insignificant due to increased ΔE_C. In brief, without proper design in abrupt B-E junction for widely studied HBTs, the reduction of $V_{BE,ON}$ is still limited.

In this work, we demonstrated grading growth of AlGaN/GaN at B-E junction of HBTs to eliminate the effect of ΔE_C. Typical measurements of HBTs are the Gummel plot (the collector and base currents, I_C and I_B, as a function of base-emitter voltage). The ideality factor of collector current (η_C) is near 1 because collector current is the domination of diffusion current. The base current (I_B) consider's the diffusion current and generation-recombination current, and the ideality factor of base current (η_B) takes on the values in the range of 1.0 to 2.0 [11, 12]. However, in previous reports, measurement results also give higher $V_{BE,ON}$ in Gummel plot, moreover; η_C and η_B are greater than 4 [5–10].

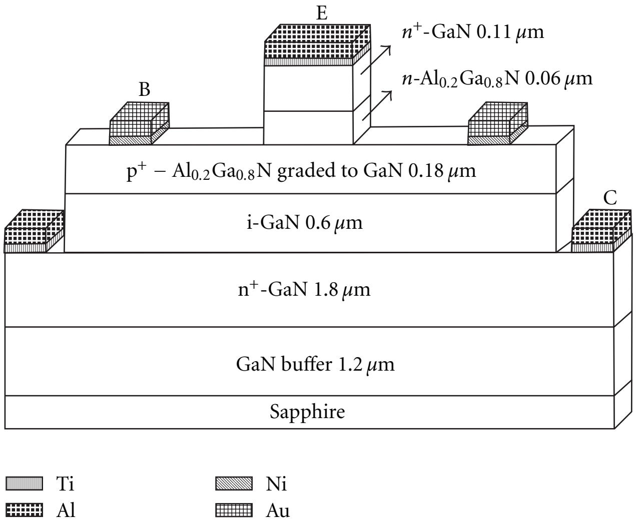


Figure 1: Schematic diagram of the studied npn graded-base AlGaN/GaN HBT's.

Unfortunately, that will lead to more power consumption. Therefore, we reported the npn graded-base AlGaN/GaN HBT employing thermal treatment to reduce the $V_{BE,ON}$ and ideality factor down to normal. We utilized the thicker base layer of 0.18 μm to avoid base Ni/Au electrode to penetrate into the collector layer during the thermal treatment.

2. Device Structure and Fabrication

The epitaxial layers were grown on c-plane (0001) sapphire substrate by metal-organic chemical vapor deposition (MOCVD). Growth was performed in H_2 ambient using trimethylgallium (TMGa) and trimethylaluminum (TMAl) as alkyl sources, and ammonia (NH_3) as the hydride source. Silane (SiH_4) and bis(cyclopentadienyl)-magnesium (Cp_2Mg) were employed as n-type and p-type dopants, respectively. Shown in Figure 1, a 1.2 μm GaN buffer was followed by a 1.8 μm n^+-GaN subcollector doped at 5×10^{18} cm^{-3}, a 0.6 μm n^--GaN doped at 1×10^{16} cm^{-3}, a 0.18 μm graded from p^+-$Al_{0.2}Ga_{0.8}N$ at the emitter-base junction to GaN at the base-collector junction and doped at 2×10^{18} cm^{-3}, a 0.06 μm n-$Al_{0.2}Ga_{0.8}N$ emitter doped at 5×10^{17} cm^{-3}, and finally a 0.11 μm n^+-GaN cap doped at 5×10^{18} cm^{-3}. For the device fabrication, the etching process was carried out by high-density plasma (HDP) system with RF power 200 W in RIE mode, in which photoresist was used as the etching mask instead of Ni metal. The chamber pressure was kept at 100 Torr and the employed gas sources are Ar (20 sccm), CH_4 (25 sccm), Cl_2 (50 sccm), and He (15 sccm). With those parameters, the etching rate is 150 nm/min. A double-mesa process, emitter mesa and base mesa formations, was employed to fabricate HBT's. One patterned photoresist was used as the mask to remove both the cap and emitter layers during the emitter mesa. The other larger patterned photoresist was used as the mask to remove both base and collector layers during the base mesa. Subsequently, the mesa-completed chip was deposited with Ti/Al bilayers and annealed in N_2ambient at 800°C for 30 s as the emitter and collector electrodes. For the fabrication of base metallization, Ni/Au bilayers were deposited on the graded base to form the base electrode. The base electrode spacing to the emitter mesa edge was 50-μm. The emitter area was $150 \times 300\,\mu m^2$.

3. HBT Performances and Discussion

To further investigate the effects of the thermal treatment on the output characteristics, the devices were proceeded with rapid thermal process (RTP) annealing at temperatures of 600°C and 700°C for annealing times of 30 s, 60 s, and 90 s. The TLM measurement was also performed for all RTP-annealing graded-base AlGaN/GaN HBT's (A-HBT) to verify contact resistance during the thermal treatment. The measured results indicate no variation occurring for the emitter and the collector contact resistances at such a low annealing time. Figure 2 shows the common-emitter *I-V*s for both N-HBTs and A-HBTs. The common-emitter *I-V*s for both A-HBTs and N-HBTs are similar and the collector-emitter offset voltage is about 0.2 V due to the neglected emitter, and collector contact resistances. The changes in *I-V*s between A-HBTs and N-HBTs are very small except the collector current with input base current above 15 μA. The enhanced current gain was obtained by RTP-annealing and details discussed in Figure 5. Besides, Gummel plot is the most typical measurement that is employed to characterize the performance of the HBTs [5–10, 13–16]. Figure 3 shows the Gummel plots for A-HBT. The Gummel plots for noneannealing graded-base AlGaN/GaN HBTs (N-HBTs) were included for comparison. The N-HBT has its η_B of 8.66 at low bias reduce to 5.72 at higher bias. It is similar to previous reports [5–10]. Whereas the entire A-HBTs exhibit an immovable η_B except that operate at high current injection. As the annealing temperature and the annealing time increases, η_B decreases gradually from 6.52 to 1.90. η_B of 1.90 is close to the ideality factor of generation-recombination current equal to 2 when annealing condition is at 700°C for 90 s.

η_C for N-HBT equal to 4.32 is similar to previous reports [5–10]. η_C for A-HBT are 3.68, 4.51, 4.51, 1.09, 1.09, and 1.09 for annealing condition at 600°C for 30 s, 600°C for 60 s, 600°C for 90 s, 700°C for 30 s, 700°C for 60 s, and 700°C for 90 s, respectively. Clearly, η_C of 1.09 is close to ideality factor of diffusion current equal to 1 when annealing condition is at 700°C for 90 s. This phenomenon can also be found that the base parasitical Schottky diodes are modified. Detailed discussions have been demonstrated in next section. The ratios of η_B to its corresponding η_C are in the range of 1 to 2 for all A-HBT and N-HBT. It is found that base current considers the components of diffusion current and generation-recombination current at forward bias, and η_B is in the range of 1∼2.

On the other hand, the applied V_{BE} creating the condition of the I_C equals to 100 A/cm^2 and is defined as the turn-on voltage ($V_{BE,ON}$) and shown in Figure 4(a). The $V_{BE,ON}$ values of N-HBT are 6.45 V while they are 6.12, 5.97, 5.5,

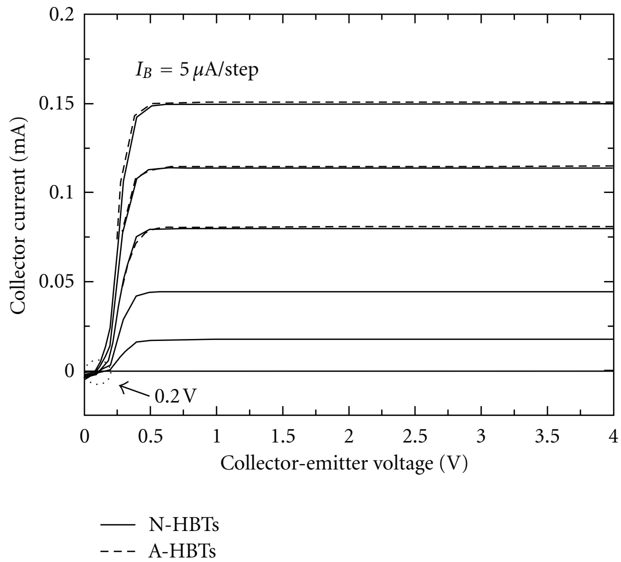


Figure 2: Measured collector current as a function of collector-emitter voltage for both N- and A-HBTs.

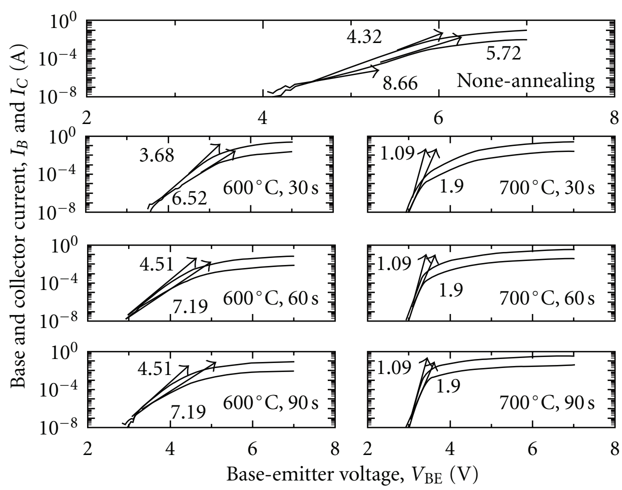
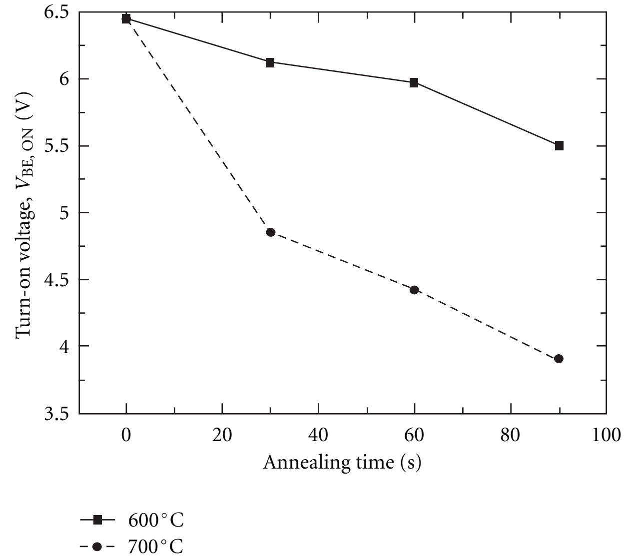
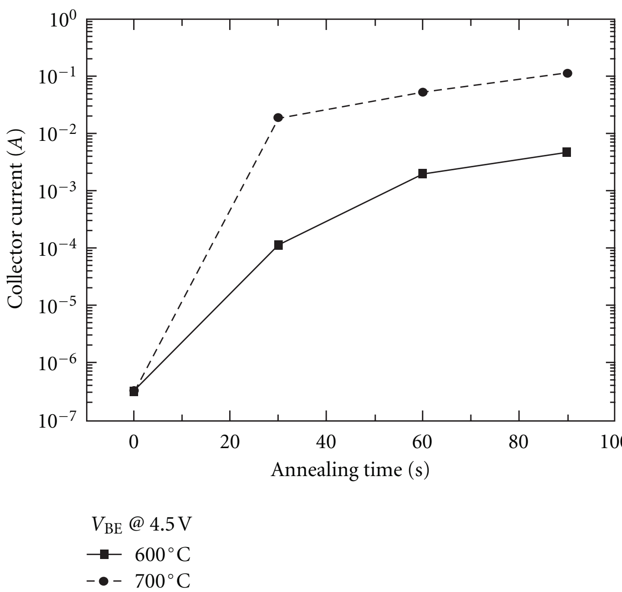


Figure 3: Gummel plots for all fabricated npn graded-base AlGaN/GaN HBT's.



(a)



(b)

Figure 4: (a) Turn-on voltage. (b) collector current as a function of annealing time for all fabricated npn graded-base AlGaN/GaN HBT's. A N-HBT's is also included for comparisons.

4.85, 4.42, and 3.90 V for A-HBT annealed at 600°C for 30 s, 600°C for 60 s, 600°C for 90 s, 700°C for 30 s, 700°C for 60 s, and 700°C for 90 s, respectively. Accordingly, we believe that a higher $V_{BE,ON}$ is resulted from a finite reverse-voltage drop occurring for the base parasitical Schottky diode. Figure 4(b) shows the collector current as a function of annealing time. The enhanced collector current was obtained by elevating the annealing temperature to 700°C. As the annealing time is increasing and applied V_{BE} is 4.5 V, the collector current increases from 3.18×10^{-4} mA to 112.2 mA at 700°C.

Figure 5 shows the current gain as a function of V_{BE}. We observe that the current gain gradually increases with V_{BE} and displays a high plateau at 700°C for 90 s. The enhanced current gain was obtained by elevating the annealing temperature from 600°C to 700°C. The current gain is enhanced at the same applied V_{BE} of 4.5 V after the thermal treatment. As the annealing time is increasing, the current gain increases from 9.10 to 9.55 at 700°C.

4. MSM Diodes Measurement

In order to further verify the behaviors in the studied A-HBTs by thermal treatment, when HBTs fabrication, metal-semiconductor-metal (MSM) diodes have been fabricated by evaporated Ni/Au bilayers on the graded-base layer. Figure 6 shown the measured current-voltage (I-V) curves for the noneannealing MSM diodes and the RTP-annealing ones

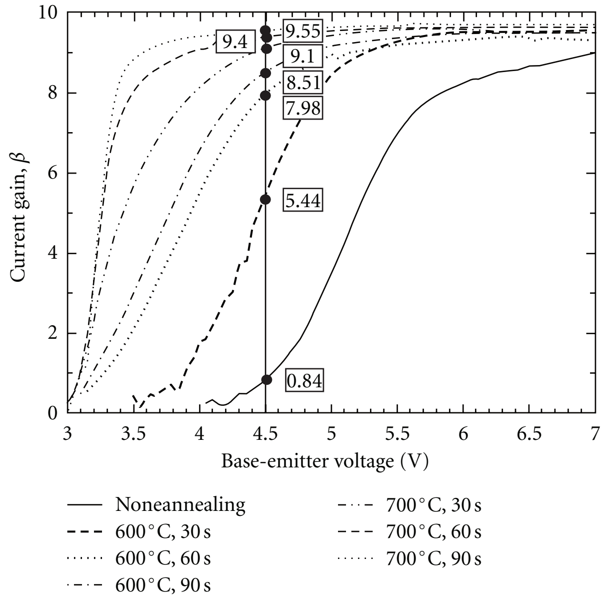


Figure 5: Current gain as a function of base-emitter voltage for all fabricated npn graded-base AlGaN/GaN HBT's. A N-HBT's is also included for comparisons.

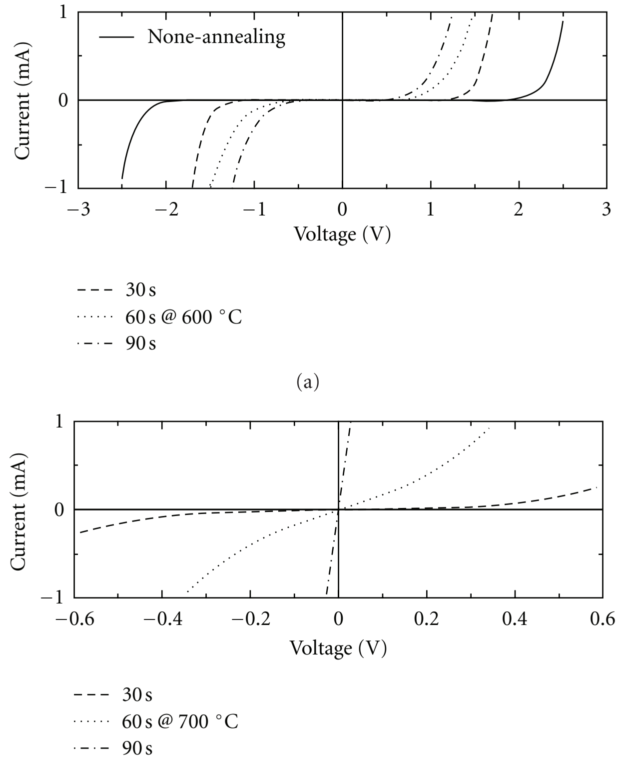


Figure 6: Measured currents of MSM diode as a function of applied voltage for noneannealing and RTP-annealing.

with the same chip and the same device dimension. Figures 6(a) and 6(b) are measured at 600°C and 700°C, respectively, for 30 s, 60 s, and 90 s. *I-V* curves for noneannealing MSM diodes are also included for comparisons. As increase the annealing temperature and the annealing time, the measured *I-V* curves for MSM diode are gradually into the Ohmic contacts. Furthermore, the curve at the annealing conditions of 700°C for 90 s exhibits the better characteristics of an Ohmic contacts, and the value is 27 Ω. All results and comparisons discussed indicate that the thermal treatment can really eliminates the base parasitical Schottky diodes. Accordingly, the base metallization in previous reports [5–10] certainly has the base parasitical Schottky diode.

5. Conclusion

In conclusions, we report on the characterization and comparison between AlGaN/GaN graded-base N-HBTs and A-HBTs and then demonstrate what improvements annealing can yield in this work. Such N-HBTs exhibits a higher turn-on voltage of 4.55, a lower current gain of 0.84, and lower collector current of 3.18×10^{-4} mA at V_{BE} of 4.5 V. To study the effects of thermal treatment on device performances, experimental results also reveal that the A-HBTs exhibit a lowest turn-on voltage of 3.09, a highest current gain of 9.55, and highest collector current of 112.2 mA at V_{BE} of 4.5 V. For the device fabrication, HBTs and MSM diodes performed on graded base layer were simultaneously fabricated on the same chip. Actually, the characteristics of MSM diodes can well describe those of HBTs at the base. Therefore, the base metallization certainly has the base parasitical Schottky diode. The base parasitical Schottky diodes cause the higher $V_{\mathrm{BE,ON}}$ and the greater ideality factor. The thermal treatment brings forth the most remarkable improvements for the HBTs when the base parasitical Schottky diodes are modified.

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