Temperature dependence of current-voltage characteristics of *npn*-type GaN/InGaN double heterojunction bipolar transistors

Atsushi Nishikawa,[a] Kazuhide Kumakura, and Toshiki Makimoto
NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan

(Received 7 June 2007; accepted 13 September 2007; published online 28 September 2007)

We investigated the temperature dependence of the common-emitter current-voltage (*I-V*) characteristics of *npn*-type GaN/InGaN double heterojunction bipolar transistors. Although the current gain decreases with increasing measurement temperature, the current gain measured at 300 °C is still as high as 308. The reduction of the current gain with temperature is attributed not only to the hole back-injection current from the base into the emitter but also to the shorter minority carrier diffusion length due to the increase in the carrier concentration of the *p*-InGaN base. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2793819]

GaN-based electronic devices are expected to be advantageous for high-power and high-temperature operation compared with conventional GaAs or Si-based devices because of the wide band gap of GaN. Although most of the studies on the GaN-based electronic devices have been devoted to the high electron mobility transistors (HEMTs), the heterojunction bipolar transistors (HBTs) have inherent advantages over HEMTs, such as more uniform threshold voltages, higher linearity, normally off operation, and higher current densities. Therefore, we have focused on fabricating the *npn*-type GaN-based HBTs. One of the major problems in fabricating *npn*-type GaN-based HBTs is the high resistance of the *p*-type GaN base layer caused by the relatively deep Mg acceptor level (>160 meV). Early works on AlGaN/GaN HBTs, hence, reported the relatively low current gain (~10).[1–4] On the other hand, by adopting InGaN instead of GaN for the *p*-type base layer to increase the hole concentration[5,6] and reduce the dry etching damage,[7,8] and an extrinsic regrown *p*-InGaN base to improve the base Ohmic characteristics, we have succeeded in obtaining the high current gain of over 2000 (Ref. 9) and high-power characteristic of 270 kW/cm^2.[10] Our next target is to demonstrate the high-temperature operation of these GaN/InGaN double HBTs (DHBTs). For *pnp*-type AlGaN/GaN HBTs, we have reported high-temperature operation up to 590 °C with the current gain of 71 at 300 °C and 3 at 590 °C.[11,12] On the other hand, only a few reports have been examined for the temperature dependence of the *npn*-type GaN-based HBTs.[4,13,14] Some groups have reported an increase in the current gain from 1–3 at room temperature (RT) to 10 at 300 °C,[4,14] while another group has reported a decrease in the current gain from 20 at RT to 10 at 300 °C.[14] These studies were limited by a high base resistance. In this study, we investigated the temperature dependence of the common-emitter *I-V* characteristics of *npn*-type GaN/InGaN DHBTs with a regrown *p*-InGaN extrinsic base, whose current gain is larger than 2000 at RT.

The GaN/InGaN DHBT structure was grown on SiC substrates by using low-pressure metalorganic vapor phase epitaxy. Source gases were trimethylgallium, trimethylaluminum, and ammonia (NH_3) for the buffer and collector, and triethylgallium, trimethylindium, and NH_3 for the base and the emitter. The doping gases were bis-cyclopentadienyl magnesium and silane. The sample structure consists of a 40-nm-thick *n*-GaN emitter, a 100-nm-thick *p*-InGaN base, a 30-nm-thick graded InGaN layer, a 500-nm-thick *n*-GaN collector, a 1-μm-thick *n*-GaN subcollector, and an AlN buffer layer. The In composition of the *p*-InGaN base was 7%. The Mg concentration for the *p*-InGaN base was 2×10^{19} cm^{-3}, and Si doping concentrations for the *n*-GaN emitter, *n*-GaN collector, and *n*-GaN subcollector were 4×10^{19}, 1×10^{17}, and 4×10^{18} cm^{-3}, respectively. The regrown *p*-InGaN base consists of a 100-nm-thick *p*-$In_{0.2}Ga_{0.8}N$ and a 2-nm-thick *p*-$In_{0.3}Ga_{0.7}N$. The Mg concentration of these layers was 5×10^{19} cm^{-3}. Pd/Au and Al/Au metals were deposited for *p*- and *n*-type Ohmic contacts, respectively, by electron-beam evaporation. The emitter size was 50×30 μm^2. The *I-V* characteristics were measured with a curve tracer, and the Gummel plots were obtained with a Keithley 4200 semiconductor characterization system at temperatures ranging from RT to 300 °C.

Figure 1 shows the common-emitter *I-V* characteristics of the *npn*-type GaN/InGaN DHBT measured at RT and 300 °C. The base currents for the measurement at RT and 300 °C were 5 and 50 μA/step, respectively. The current gain, $\beta=\Delta I_C/\Delta I_B$, increases with increasing collector current and reaches its maximum at the collector current of about 20 mA in both cases. The maximum current gains measured at RT and 300 °C are 2450 and 308, respectively. The offset voltage is as low as 1 V, and it remains the same value in spite of an increase of the measurement temperature. Even though the higher base current is required to obtain the high-collector current at higher temperatures, the maximum collector current density obtained at 300 °C is as high as 5.55 kA/cm^2, which is similar to that obtained at RT. This indicates that the reduction of the current gain is due to an increase in the base current with increasing temperature. In general, the base current mainly consists of base-emitter junction space-charge recombination current (I_{Bscr}), surface recombination current (I_{Bsur}), base bulk recombination current (I_{Bbulk}), and hole back-injection current from the base into the emitter (I_{Bp}). In our device, the surface recombination current of the base layer can be neglected because the emitter area/perimeter ratio ($A/P=1500$ μm^2/160 μm) is

[a]Electronic mail: anishi@will.brl.ntt.co.jp

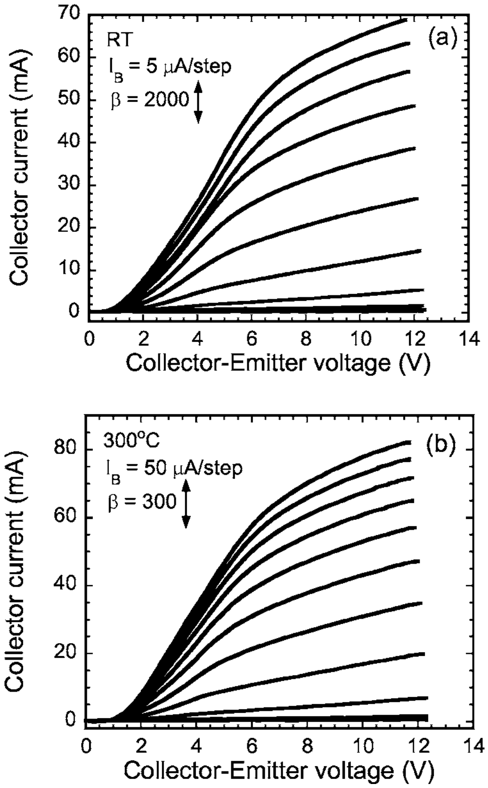

FIG. 1. The common-emitter *I-V* characteristics of the *npn*-type GaN/InGaN DHBT measured at (a) RT and (b) 300 °C.

large. In what follows, we will discuss the contributions of these components to the temperature dependence of the current gain.

Gummel plots are obtained at each temperature with the shorted collector-base junction ($V_{CB}=0$ V). Figure 2 shows the current gain as a function of the collector current at temperatures from RT to 300 °C. The maximum current gains at each temperature are lower than those obtained from the common-emitter *I-V* characteristics mentioned above. This is because the bias voltages of these two measurements are different,[9] but both measurements show the same tendency of the temperature dependence. At the low collector current region ($I_C < 10^{-3}$ A), the current gain increases with increasing collector current. The ideality factors were calculated to

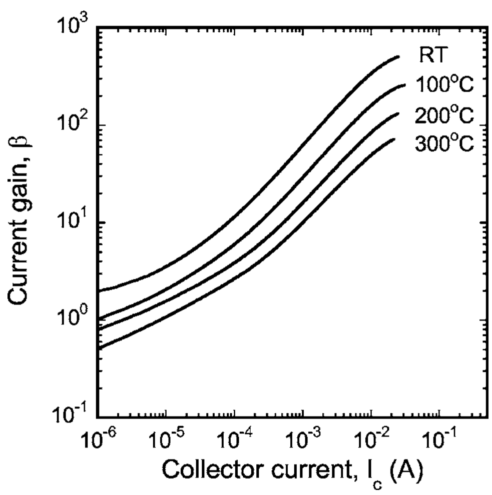

FIG. 2. Current gain as a function of the collector current at temperatures ranging from RT to 300 °C.

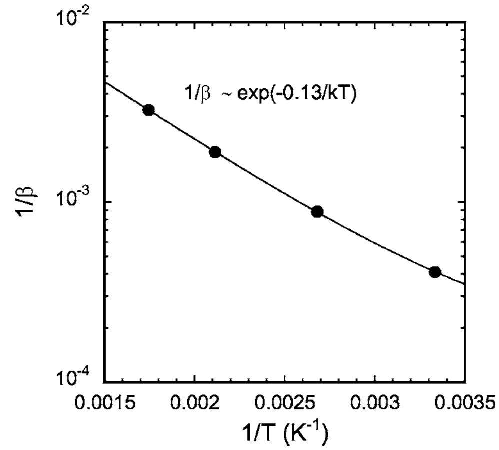

FIG. 3. Temperature dependence of the maximum current gain.

be about 2, indicating that the recombination current is dominant at the base-emitter junction.[12] The decrease in the current gain with increasing temperature also suggests that the current gain is dominated by the space-charge recombination current.[15] Even in the high-collector-current region, where the space-charge recombination current is negligible, the current gain decreases with temperature. To explain this behavior, we show the temperature dependence of the maximum current gain in Fig. 3. The maximum current gain as a function of temperature has an exponential dependence with an activation energy of 0.13 eV. In the case of the AlGaAs/GaAs HBTs, the activation energy obtained from the temperature dependence of the current gain corresponds to the valence band discontinuity in the base-emitter heterojunction.[16] However, in the case of the GaN/InGaN DHBTs, the value obtained here (0.13 eV) is higher than the valence band discontinuity (0.06 eV) estimated from the capacitance-voltage measurement,[17] which means that the hole backward injection current is not the only reason for the reduction of the current gain. In high-collector-current region, the base current consists of the hole backward injection current and the bulk recombination current. So, the reduction of the current gain is considered to be attributed to an increase in the bulk recombination current with increasing temperature. The base recombination current divided by the collector current is expressed by $I_{\mathrm{Bbulk}}/I_C = X_B^2/2D_B\tau = X_B^2/2L^2$, where X_B, D_B, τ, and L are the base thickness, the electron diffusion coefficient in the base, the minority carrier recombination lifetime, and the minority carrier diffusion length, respectively. For the AlGaAs/GaAs HBTs, the base bulk recombination current is relatively temperature independent, so that the hole back-injection current mainly contributes to the reduction of the current gain with temperature. On the other hand, in previous reports, we found that the hole concentration of Mg-doped $In_{0.06}Ga_{0.94}N$ monotonically increases with increasing temperature from 2×10^{18} cm^{-3} (RT) to 1×10^{19} cm^{-3} (280 °C),[6] and with increasing hole concentration, the minority carrier diffusion length becomes shorter for Mg-doped $In_xGa_{1-x}N$.[18,19] Therefore, the base bulk recombination current for the GaN/InGaN DHBTs contributes to the reduction of the current gain with temperature because of the shorter minority carrier diffusion length due to the increase in the carrier concentration of the p-$In_{0.07}Ga_{0.93}N$ base. Consequently, the reduction of the current gain with temperature for the GaN/InGaN DHBTs is larger than that for conventional AlGaAs/GaAs HBTs. However, the current gain at 300 °C is still as high as 308, indicating that the GaN/InGaN DHBTs have the capability to operate even at elevated temperatures. It is noteworthy that the current gain at RT after the measurement at 300 °C is similar to that before it, which indicates that there is no degradation of the crystal quality or Ohmic contact characteristics for each layer due to the high temperature of up to 300 °C.

In summary, we investigated the temperature dependence of the common-emitter *I-V* characteristics of *npn*-type GaN/InGaN DHBTs with a regrown *p*-InGaN extrinsic base. Although the current gain decreases with increasing temperature from RT to 300 °C, the current gain measured at 300 °C is still as high as 308. The reduction of the current gain with temperature is attributed not only to the hole back-injection current from the base into the emitter but also to the shorter minority carrier diffusion length due to the increase in the carrier concentration of *p*-InGaN base layer.

The authors would like to thank Dr. K. Torimitsu and Dr. J. Yumoto for their encouragement throughout this work.

[1] L. C. McCarthy, P. Kozodoy, M. J. W. Rodwell, S. P. DenBaars, and U. K. Mishra, IEEE Electron Device Lett. **20**, 277 (1999).
[2] H. Xing, M. Chavarkar, S. Keller, S. P. DenBaars, and U. K. Mishra, IEEE Electron Device Lett. **24**, 141 (2003).
[3] D. J. H. Lambert, J. J. Huang, B. S. Shelton, M. M. Wong, U. Chowdhury, T. G. Zhu, H. K. Kwon, Z. Liliental-Weber, M. Benarama, M. Feng, and R. D. Dupuis, J. Cryst. Growth **221**, 730 (2000).
[4] J. Han, A. G. Baca, R. J. Shul, C. G. Willison, L. Zhang, F. Ren, A. P. Zhang, G. T. Dang, S. M. Donovan, X. A. Cao, H. Cho, K. B. Jung, C. R. Abernathy, S. J. Pearton, and R. G. Wilson, Appl. Phys. Lett. **74**, 2702 (1999).
[5] K. Kumakura, T. Makimoto, and N. Kobayashi, J. Cryst. Growth **221**, 267 (2000).
[6] K. Kumakura, T. Makimoto, and N. Kobayashi, J. Appl. Phys. **93**, 3370 (2003).
[7] T. Makimoto, K. Kumakura, and N. Kobayashi, J. Cryst. Growth **221**, 350 (2000).
[8] T. Makimoto, K. Kumakura, and N. Kobayashi, Phys. Status Solidi A **188**, 183 (2001).
[9] T. Makimoto, K. Kumakura, and N. Kobayashi, Appl. Phys. Lett. **83**, 1035 (2003).
[10] T. Makimoto, Y. Yamauchi, and K. Kumakura, Appl. Phys. Lett. **84**, 1964 (2004).
[11] K. Kumakura, T. Makimoto, and N. Kobayashi, Phys. Status Solidi A **194**, 443 (2002).
[12] K. Kumakura and T. Makimoto, Extended Abstract of the 2005 International Conference on Solid State Device and Materials, 2005 (unpublished).
[13] F. Ren, C. R. Abernathy, J. M. Van Hove, P. P. Chow, R. Hickman, J. J. Klaassen, R. F. Kopf, H. Cho, K. B. Jung, J. R. La Roche, R. G. Wilson, J. Han, R. J. Shul, A. G. Baca, and S. J. Pearton, MRS Internet J. Nitride Semicond. Res. **3**, 41 (1998).
[14] D. H. Keogh, P. M. Asbeck, T. Chung, J. Limb, D. Yoo, J.-H. Ryou, W. Lee, S.-C. Shen, and R. D. Dupuis, Electron. Lett. **42**, 661 (2006).
[15] W. Liu, *Handbook of III-V Heterojunction Bipolar Transistors* (Wiley, New York, 1998), p. 184.
[16] W. Liu, S. K. Fan, T. Henderson, and D. Davito, IEEE Trans. Electron Devices **40**, 1351 (1993).
[17] T. Makimoto, K. Kumakura, T. Nishida, and N. Kobayashi, J. Electron. Mater. **31**, 313 (2002).
[18] K. Kumakura, T. Makimoto, N. Kobayashi, T. Hashizume, T. Fukui, and H. Hasegawa, Appl. Phys. Lett. **86**, 052105 (2005).
[19] K. Kumakura, T. Makimoto, N. Kobayashi, T. Hashizume, T. Fukui, and H. Hasegawa, J. Cryst. Growth **298**, 787 (2007).