Extended Abstracts of the 2003 International Conference on Solid State Devices and Materials, Tokyo, 2003, pp. 134-135

F-2-2

Extrinsic Base Regrowth of p-InGaN for Npn-type GaN/InGaN Heterojunction Bipolar Transistor

Toshiki Makimoto, Kazuhide Kumakura and Naoki Kobayashi[1]

NTT Basic Research Laboratories, NTT Corporation
3-1 Morinosato Wakamiya, Atsugi-shi, Kanagawa 243-0198, Japan
Phone: +81-46-240-3421 E-mail: makimoto@nttbrl.jp
[1] The University of Electro-Communications, Dept. of Applied Physics and Chemistry
1-5-1 Chofugaoka, Chofu-shi, Tokyo, Japan

1. Introduction

Much attention has been paid to nitride electronic devices, since they have large potentials for high power and high temperature applications. As one of them, nitride heterojunction bipolar transistors (HBTs) have several advantages such as high breakdown voltage, high current density, good linearity, low phase noise and good threshold voltage uniformity. Recently, we have reported that an AlGaN/InGaN HBT shows high breakdown voltage over 120 V and the corresponding electric field is as high as 2.3 MV/cm [1,2], which is much higher than those reported for HBTs composed of other materials such as Si/SiGe, InGaP/GaAs and InP/InGaAs. However, the reported nitride HBTs have two issues to be solved. One is their small current gain, while the other is their high offset voltages around 5 V in the common-emitter current-voltage (I-V) characteristics. These two issues are considered to be relating to their degraded p-type base ohmic contacts due to the etching damage generating during the HBT fabrication process, so several techniques have been tried to remove the influence of these damage. One of the techniques is the extrinsic base regrowth of p-GaN or p-GaAs on the exposed p-GaN intrinsic base surface [3,4]. This technique improved the base ohmic characteristics a little and the further improvement is needed. In this work, we have used the extrinsic base regrowth of p-InGaN instead of p-GaN and p-GaAs. Using the base regrowth of p-InGaN, the base ohmic characteristics have been significantly improved, resulting in high current gains and reduced offset voltages of nitride HBTs, so we report on these base ohmic characteristics along with GaN/InGaN HBT characteristics.

2. Experimental Procedures

The Mg-doped p-InGaN and p-GaN layers were grown at 780 ^{o}C on SiC substrates by metalorganic vapor phase epitaxy. To investigate the influence of the etching damage, the surface of the p-$In_{0.07}Ga_{0.93}N$ layer was intentionally etched by electron cyclotron resonance plasma etching. Then, a p-InGaN layer was regrown at 750 ^{o}C on the etched p-$In_{0.07}Ga_{0.93}N$. This regrown p-InGaN layer consists of 100-nm p-$In_{0.2}Ga_{0.8}N$ and 2-nm p-$In_{0.3}Ga_{0.7}N$ with a Mg concentration of $5x10^{19}$ cm^{-3}. Finally, Pd/Au metals were deposited for p-type ohmic contacts. Figures 1 and 2 illustrate the structure of the regrown p-InGaN layer and the corresponding band diagram, respectively. In this structure, the Piezoelectric charges are induced due to the strain between p-$In_{0.2}Ga_{0.8}N$ and p-$In_{0.3}Ga_{0.7}N$. The sign of these charges are negative, so the tunneling effect of holes are enhanced, resulting in the better ohmic characteristics [5]. Figure 3 illustrates the configuration for two rectangular electrodes for I-V measurements.

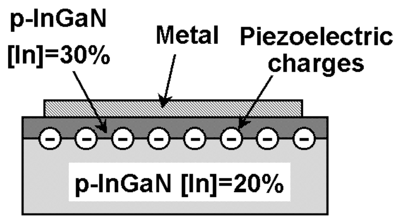

Fig. 1 Schematic illustration of the regrown layer.

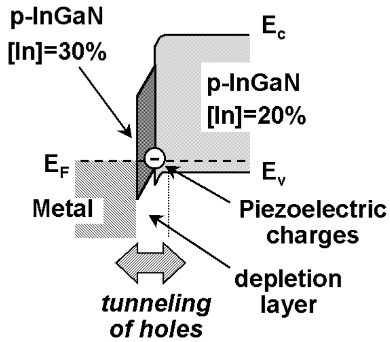

Fig. 2 Band diagram for the regrown layer.

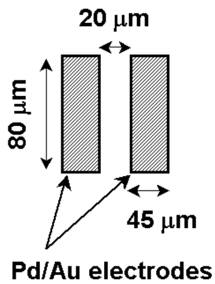

Fig. 3 Configuration for two Pd/Au ohmic electrodes to measure I-V characteristics.

3. Experimental Results

Figure 4 shows the I-V characteristics between two electrodes formed on the p-InGaN layer regrown on the etched p-$In_{0.07}Ga_{0.93}N$. For comparison, Pd/Au metals were also deposited directly on the etched p-$In_{0.07}Ga_{0.93}N$ and p-GaN layers. The Mg concentration for p-GaN was $5x10^{19}$ cm^{-3}, so the perfect ohmic characteristics were obtained for the as-grown p-GaN. However, the I-V characteristics for the etched p-GaN were much degraded, as reported previously. This is ascribed to the formation of a thick n-type conversion layer near the surface after etching, since the etching defects act as donors [6]. For the etched p-$In_{0.07}Ga_{0.93}N$, its I-V characteristics were improved, even though its Mg acceptor concentration is one fifth of that of p-GaN. This indicates that the surface n-type conversion layer becomes thin due to the effect of the In atoms in p-InGaN [6]. In contrast, the I-V characteristics were much improved by the regrowth of p-InGaN and showed almost perfect ohmic characteristics, which were better than those obtained by the regrowth of p-GaN or p-GaAs on the etched p-GaN. The following is a possible reason for the improved ohmic characteristics obtained in this work. The regrowth was performed on the etched p-InGaN layer, whose damage is less severe than that of p-GaN. Therefore, the n-type conversion layer near the etched surface may become thin enough to tunnel the holes after it is buried in the regrown p-InGaN. In addition to this effect, the etching damage may be recovered during the regrowth of p-InGaN.

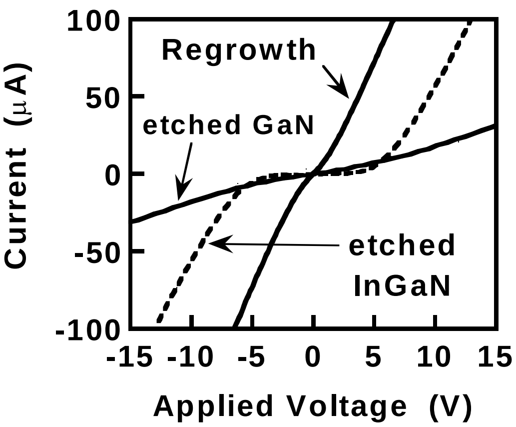

Fig. 4 I-V characteristics between two electrodes on the regrown p-InGaN, the etched p-InGaN and p-GaN.

We have applied this regrowth technique to the base layer of GaN/InGaN HBT with an emitter area of 50 μm x 30 μm. The In mole fraction in the base layer and its thickness in the intrinsic base were 0.07 and 100 nm, respectively. The Mg doping concentration of the intrinsic base was $1x10^{19}$ cm^{-3} and its hole concentration is estimated to be $1x10^{18}$ cm^{-3}. The n-GaN emitter layer has a high Si doping concentration of $4x10^{19}$ cm^{-3}, since the emitter ohmic characteristics were not obtained for lower doping concentrations. Figure 5 shows the common-emitter I-V characteristics at room temperature. From this figure, the current gain increased up to 2000 and the offset voltage decreased to around 1 V [7], while the maximum current gain was 20 and the offset voltage was 5 V for the GaN/InGaN HBT without a regrown extrinsic base layer. Therefore, it was found that the base ohmic characteristics are closely related to the nitride HBT characteristics.

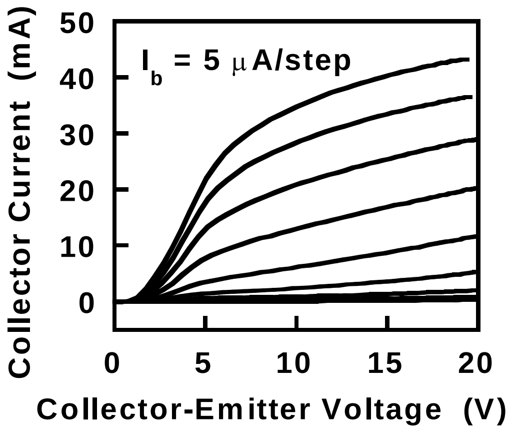

Fig. 5 Common-emitter I-V characteristics of GaN/InGaN HBT with a regrown base layer.

4. Conclusions

We have applied the regrowth of p-InGaN to the extrinsic base layer. Using this technique, the base ohmic characteristics have been significantly improved. As a result, high current gains up to 2000 and reduced offset voltages were obtained for the nitride HBTs. These results show that p-InGaN is a promising material for the intrinsic base layer and that the extrinsic base regrowth of p-InGaN is an effective way improve nitride HBT characteristics.

Acknowledgements

We would like to thank Mr. M. Kashiwa, Mr. T. Kido, and Prof. N. Matsumoto in Shonan Institute Technology for the device fabrication. We are grateful to Dr. Y. Hirayama and Dr. S. Ishihara for their encouragement throughout this work.

References

[1] T. Makimoto, K. Kumakura, and N. Kobayashi, phys. stat. sol. (c), **0**, No.1, 95 (2002).

[2] T. Makimoto, K. Kumakura, and N. Kobayashi, *29th International Symposium on Compound Semiconductors 2002 (ISCS 2002),* Th-C-4, Lausanne, Switzerland (2002).

[3] L. S. McCarthy, P. Kozodoy, S. P. Denbaars, M. Rodwell, and U. K. Mishra, *25th International Symposium on Compound Semiconductors (ISCS 1998)*, We2A-1, Nara (1998).

[4] K. P. Lee, A. P. Zhang, G. Dang, F. Ren, J. Han, S. N. G. Chu, W.S. Hobson, J. Lopata, C. R. Abernathy, S. J. Pearton, and J. W. Lee, Solid-state Electron., **45**, 243 (2001).

[5] K. Kumakura, T. Makimoto, and N. Kobayshi, Appl. Phys. Lett. **79**, 2588 (2001).

[6] T. Makimoto, K. Kumakura, and N. Kobayashi, J. Cryst. Growth **221**, 350 (2000).

[7] T. Makimoto, K. Kumakura, and N. Kobayashi, to be presented in *The Fifth International Conference on Nitride Semiconductors (ICNS-5)*, Nara (May, 2003).