SAND99-0612J

Growth and Fabrication of GaN/AlGaN Heterojunction Bipolar Transistor

J. Han, A. G. Baca, C. G. Willison, R. J. Shul and L. Zhang
Sandia National Laboratories, Albuquerque, NM 87185

F. Ren, A. P. Zhang and G. T. Dang
Department of Chemical Engineering, University of Florida, Gainesville, FL 32611

S. M. Donovan, X. A. Cao, H. Cho, K. B. Jung, C. R. Abernathy and S. J. Pearton
Department of Materials Science and Engineering, University of Florida, Gainesville, FL 32611

R. G. Wilson
Consultant, Stevenson Ranch, CA 91381

ABSTRACT

A GaN/AlGaN heterojunction bipolar transistor structure with Mg doping in the base and Si doping in the emitter and collector regions was grown by Metal Organic Chemical Vapor Deposition on c-axis Al_2O_3. Secondary Ion Mass Spectrometry measurements showed no increase in the O concentration ($2\text{-}3\times10^{18}$ cm^{-3}) in the AlGaN emitter and fairly low levels of C ($\sim4\text{-}5\times10^{17}$ cm^{-3}) throughout the structure. Due to the non-ohmic behavior of the base contact at room temperature, the current gain of large area (~90 μm diameter) devices was <3. Increasing the device operating temperature led to higher ionization fractions of the Mg acceptors in the base, and current gains of ~10 were obtained at 300 °C.

There is a strong interest in GaN-based electronics for applications involving high temperature or high power operation, based on the excellent transport properties of the III-nitride materials system.[1-7] Impressive advances in the performance of AlGaN/GaN high electron mobility transistors continue to be reported, due to in part to the formation of piezoelectrically-induced carriers in a 2-dimensional electron gas at the heterointerface.[5-16] There is also interest in the development of GaN/AlGaN heterojunction bipolar transistors (HBTs) to meet the linearity requirements of some future electromagnetic systems, particularly for military applications where ultrawide bandwidth and linearity are key issues. In these vertical device structures, minority carrier lifetime,[17] interface quality and doping control are important factors.[5]

There have been two recent reports on initial GaN/AlGaN HBTs.[18,19] In one case, extrinsic base regions were grown by Metal Organic Chemical Vapor Deposition (MOCVD) before base mesa etching to contact the collector. This was performed to overcome the high base resistance arising from the relatively low hole concentration (typically $\leq 10^{18}$ cm^{-3}) achievable in GaN (Mg).[18] Devices with 3×20 μm^2 emitters produced a dc current gain at 25 °C of ~3. In the other report, the active layer structure was grown by rf plasma-assisted Molecular Beam Epitaxy (MBE) on top of an MOCVD buffer.[19] Large area (90 μm diameter) devices were fabricated by a low damage dry etch process similar to that developed for GaAs/AlGaAs HBTs. The dc gain at 25 °C was in the range 1-3, but increasing the operation temperature to 300 °C produced a gain of ~10 by increasing the ionization efficiency of the Mg acceptors in the base layer.

In this letter we report on the growth by MOCVD of a graded emitter HBT structure, the measurement of typical background impurities (C, O, H) by Secondary Ion Mass

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, make any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Spectrometry (SIMS) since these could potentially have a strong influence on device performance, and finally on the dc characteristics of HBTs fabricated on this material.

The layer structure is shown schematically in Figure 1, and was grown at ~1050 °C following deposition of the GaN buffer at ~550 °C on the c-plane Al_2O_3 substrate. The growth system has been described in detail previously,[20] but in brief is a rotating (1200 rpm) disk MOCVD reactor. Ammonia (NH_3), trimethylgallium (TMGa) and trimethylaluminum (TMAl) were used as precursors, while silane (SiH_4) and bis-cyclopentadienyl-magnesium (Cp_2Mg) were employed for n- and p-type doping, respectively. High purity H_2 was used as the carrier gas. After growth the sample was annealed in the reactor at 850 °C for 20 min under 140 Torr of flowing N_2 to activate the Mg acceptors.

There are two important aspects to dopant and background impurity control in HBT structures. The first is that the p-type dopant should be confined to the base region, and not spill-over into the adjacent n-type emitter, where it could cause displacement of the junction and hence the loss of the advantage of the heterostructure. Figure 2 shows SIMS profiles of the Al marker, signifying the position of AlGaN emitter layer, and also the Mg doping profile in the adjacent base layer. It is clear that the reactor memory effect for Cp_2Mg has produced incorporation of Mg in the emitter, although the real situation is not quite as severe as it seems in the data because of "carry-over" of the matrix Al signal during the depth profiling. The fact that working HBTs can still be made on this material is due to the higher electron concentration in the emitter from the Si doping (Si ionization level is ≤30 meV, so that all of the Si will contribute an electron at 25 °C) relative to the hole concentration contributed by the Mg acceptors, whose ionization level is ≥ 170 meV in AlGaN.

The second aspect of impurity control is to minimize the concentration of O (which probably creates a shallow donor state in GaN), C (which may lead to compensated material) and H (which can passivate the Mg acceptors in the base). Figure 3 shows SIMS profiles for these elements, as well as for the intentional Si doping. Note that the C concentration throughout most of the structure is well below that of the Si, suggesting it will have no significant effect on the electrical properties of the material. The O concentration is also relatively constant and at a density well below that of the Si. It is clear that only a fraction of the oxygen is electrically active, since the base remains p-type even though the hole concentration from the Mg acceptors could be lower than the electron concentration from the O donors if all the oxygen was active. Note that residual hydrogen still decorates the Mg doping in the base, but since a reactivation anneal was performed, the hydrogen most likely is in the form of electrically inactive molecules or larger clusters, through the reactions:

$$(Mg\text{-}H)^{o} \rightarrow Mg^{-} + H^{+}$$

$$H^{+} + H^{o} \rightarrow H_2 + h^{+}$$

$$\text{or} \quad H^{o} + H^{o} \rightarrow H_2$$

These are in analogy with the behavior of hydrogen in other p-type semiconductors.[21] The concentrations of oxygen and carbon in GaN are a factor of 3-5 higher than that in comparable GaAs/AlGaAs HBTs.[22] It remains to be established as to the relative contributions of background impurities and structural defects to degradation of gain in GaN/AlGaN HBTs.

A Gummel plot from a 90 μm diameter device operated at 300 °C is shown in Figure 4. The maximum gain is ~10, similar to the previous report.[19] In general we could not obtain common-emitter characteristics, because the resistance of the extrinsic base region is too high to achieve modulation. The performance of the HBT is dominated by this high base resistance, and the resultant high specific contact resistivity of the ohmic metallization. At room temperature the alloyed (700 °C, 30 sec) Ni/Au is rectifying (Figure 5). However as the measurement temperature is increased the p-contact becomes ohmic, concomitant with the improved performance of the device. From separate transmission line measurements, we determined the specific contact resitivity to be in the 10^{-2} $\Omega \cdot cm^2$ range at 300 °C.

In conclusion, we have shown that even in high quality GaN/AlGaN heterojunctions with relatively low background concentration of C, O and H, the HBT device performance is dominated by the high base resistance; this should be a focus for future development work.

ACKNOWLEDGEMENTS

The work at UF is partially supported by a DARPA/EPRI grant (D. Radack and J. Melcher), no. MDA 972-98-1-0006, and by an ONR grant (N00014-98-1-0204) monitored by J. C. Zolper. Sandia is a multiprogram laboratory operated for the US Department of Energy by Sandia Corporation, a Lockheed-Martin company, under grant DEAC04-94-AL-85000.

References

1. See S. N. Mohammad and H. Morkoc, Prog. Quantum Electron. 20 361 (1996).
2. Q. Z. Liu and S. S. Lau, Solid-State Electron. 42 667 (1998).
3. M. S. Shur, Solid-State Electron. 42 2131 (1998).
4. J. C. Zolper, Solid-State Electron. 42 2153 (1998).
5. M. S. Shur and M. A. Khan, in High Temperature Electronics, ed. M. Willander and H. L. Hartnagel (Chapman and Hall, London 1996). pp 297-321.
6. S. C. Binasi, J. Redwing, G. Kelner and W. Kruppa, Electron. Lett. 33 242 (1997).
7. Y. -F. Wu, B. P. Keller, P. Fini, S. Keller, T. Z. Jenkins, L. T. Kehias, S. P. DenBarrs and U. K. Mishra, IEEE Electron. Dev. Lett. 19 50 (1998).
8. B. E. Foutz, L. F. Eastman, U. V. Bhapkar and M. S. Shur, Appl. Phys. Lett. 70 2849 (1997).
9. E. R. Brown, Solid-State Electron. 42 2119 (1998).
10. P. M. Asheck, E. T. Yu, S. S. Lau, G. J. Sullivan, J. Van Hove and J. Redwing, Electron. Lett. 33 1230 (1997).
11. G. J. Sullivan, M. Y. Chen, J. A. Higgins, J. W. Yang, Q. Chen, R. L. Pierson and B. T. McDernott, IEEE Electron. Dev. Lett. 19 198 (1998).
12. P. Kozodoy, J. P. Ibbetson, H. Marchand, P. T. Fini, S. Keller, J. S. Speck, S. P. DenBaars and U. K. Mishra, Appl. Phys. Lett. 73 975 (1998).
13. N. X. Nguyen, C. Nguyen and D. E. Grider, Electron. Lett. 34 811 (1998).
14. Q. Chen, J. W. Yang, R. Gaska, M. A. Khan, M. S. Shur, G. J. Sullivan, A. L. Sailor, J. A. Higgins, A. T. Ping and I. Adesida, IEEE Electron. Dev. Lett. 19 44 (1998).
15. Z. Fan, C. Lu, A. Botchkarev, H. Tang, A. Salvador, Ö. Aktas, W. Kim and H. Morkoç, Electron. Lett. 33 814 (1997).

16. L. F. Eastman, K. G. Chu, J. Smart and J. R. Shealy, Mat. Res. Soc. Symp. Proc. 512 3 (1998).

17. Z. Z. Bandic, P. M. Bridger, E. C. Piquette and T. C. McGill, Appl. Phys. Lett. 72 3166 (1998).

18. L. S. McCarthy, P. Kozodoy, S. P. DenBarrs, M. Rodwell and U. K. Mishra, 25th Int. Symp. Compound Semicond., Oct. 1998, Nara, Japan.

19. 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).

20. J. Han, M. H. Crawford, R. J. Shul, J. J. Figiel, M. Banas, L. Zhang, Y. K. Song, H. Zhou and A. V. Nurmikko, Appl. Phys. Lett. 73 1688 (1998).

21. M. Stavola, in Properties of Si, INSPEC Data Review, ed. R. Hall (IEE, London 1999).

22. C. R. Abernathy, Mat. Sci. Eng. Rep. R14 203 (1995).

Figure Captions

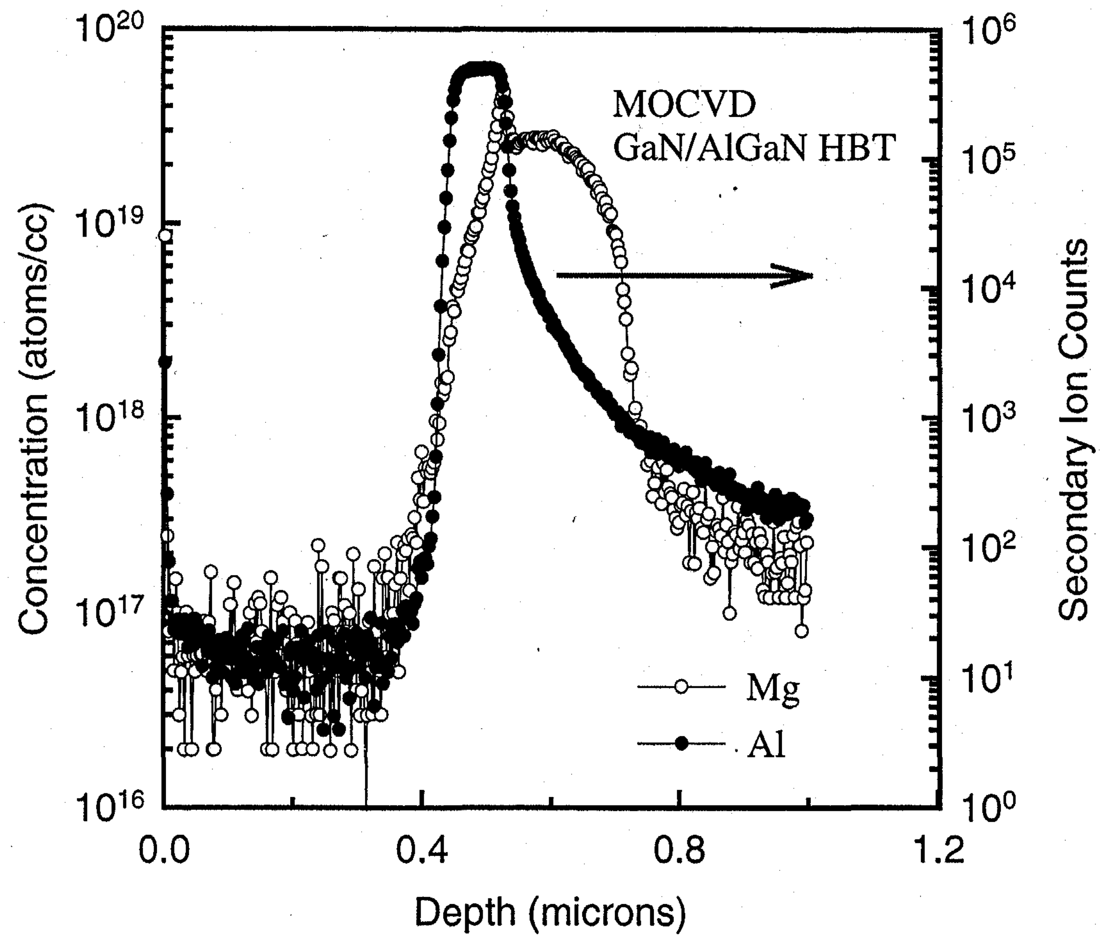
Figure 1. Schematic of GaN/AlGaN HBT structure.

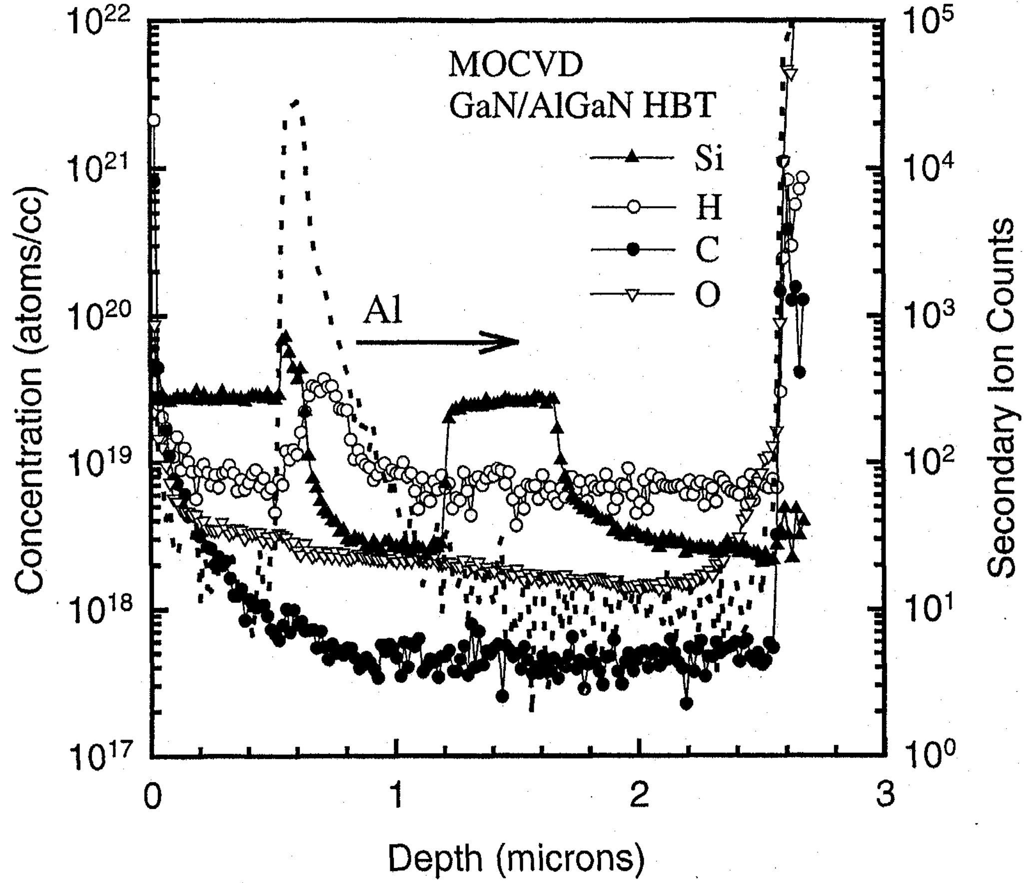
Figure 2. SIMS profiles of Mg in the GaN/AlGaN structure.

Figure 3. SIMS profiles of Si, C, O and H in the GaN/AlGaN structure.

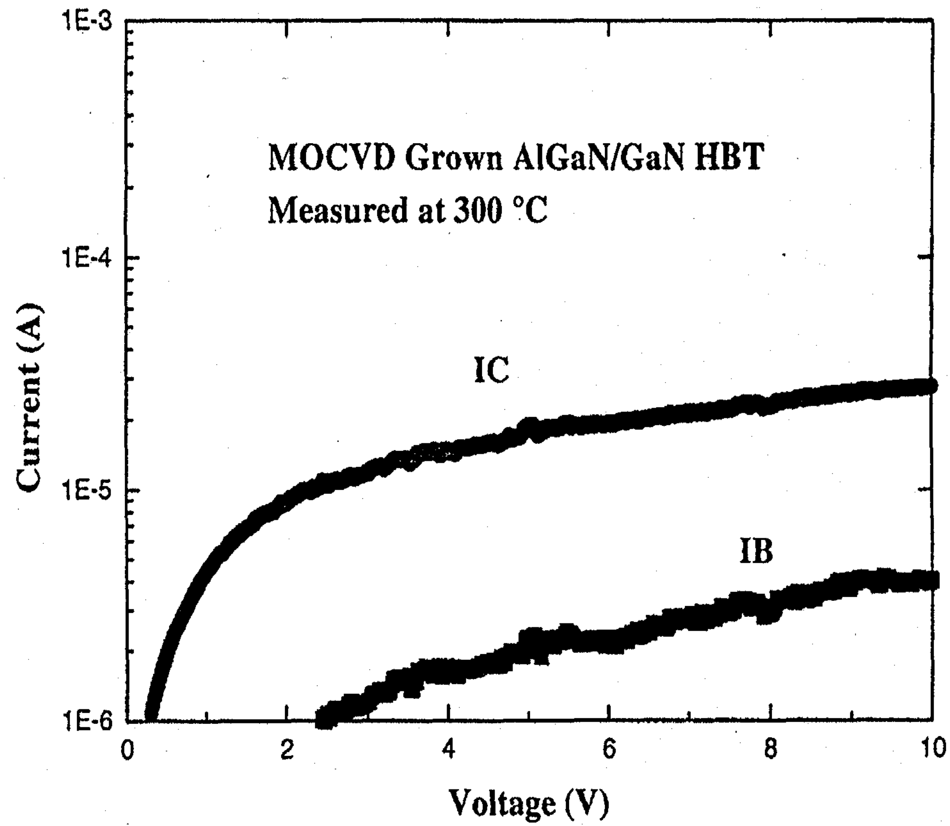
Figure 4. Gummel plot of GaN/AlGaN HBT measured at 300 °C.

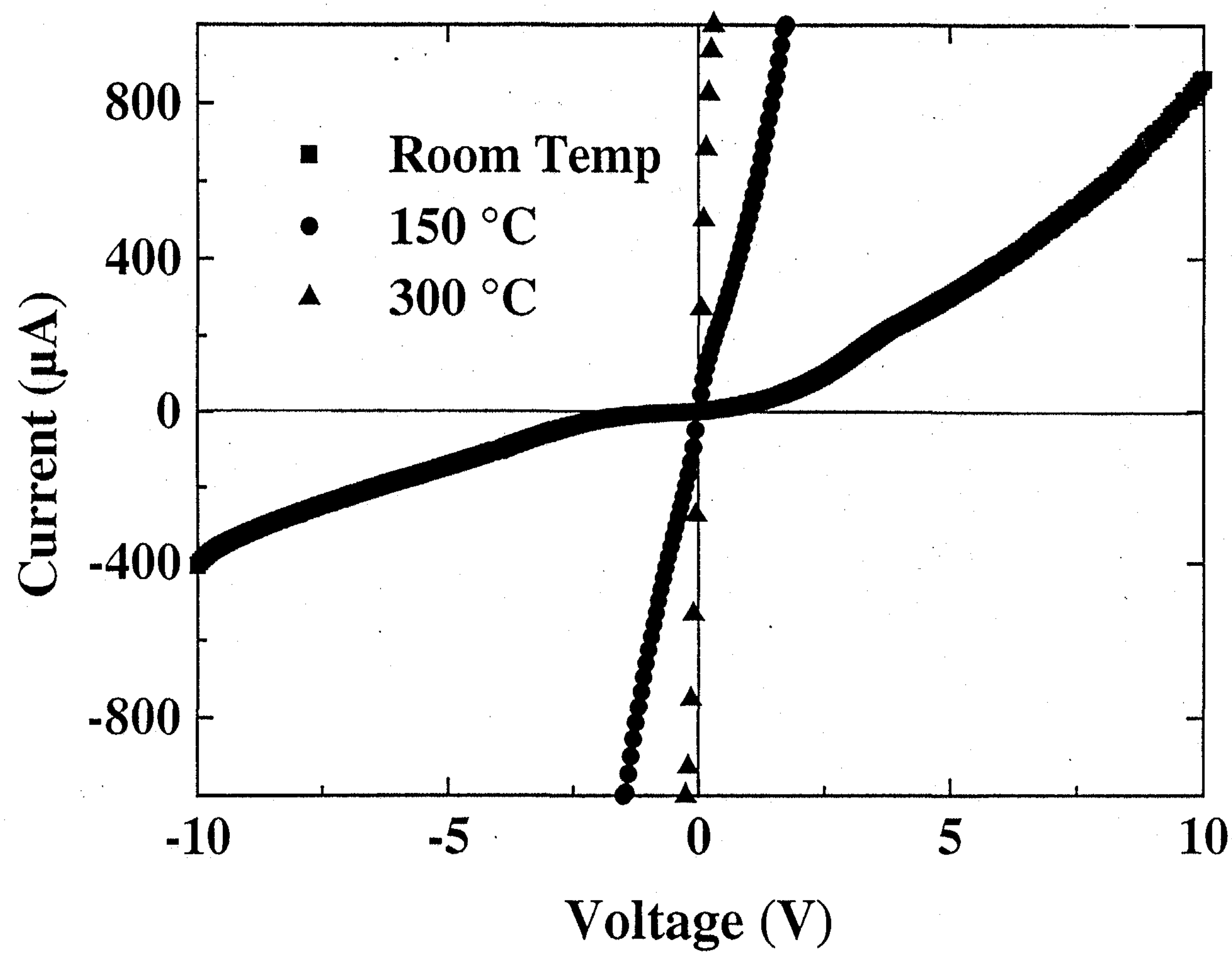
Figure 5. I-V characteristics for Ni/Au base contact at different measurement temperatures.

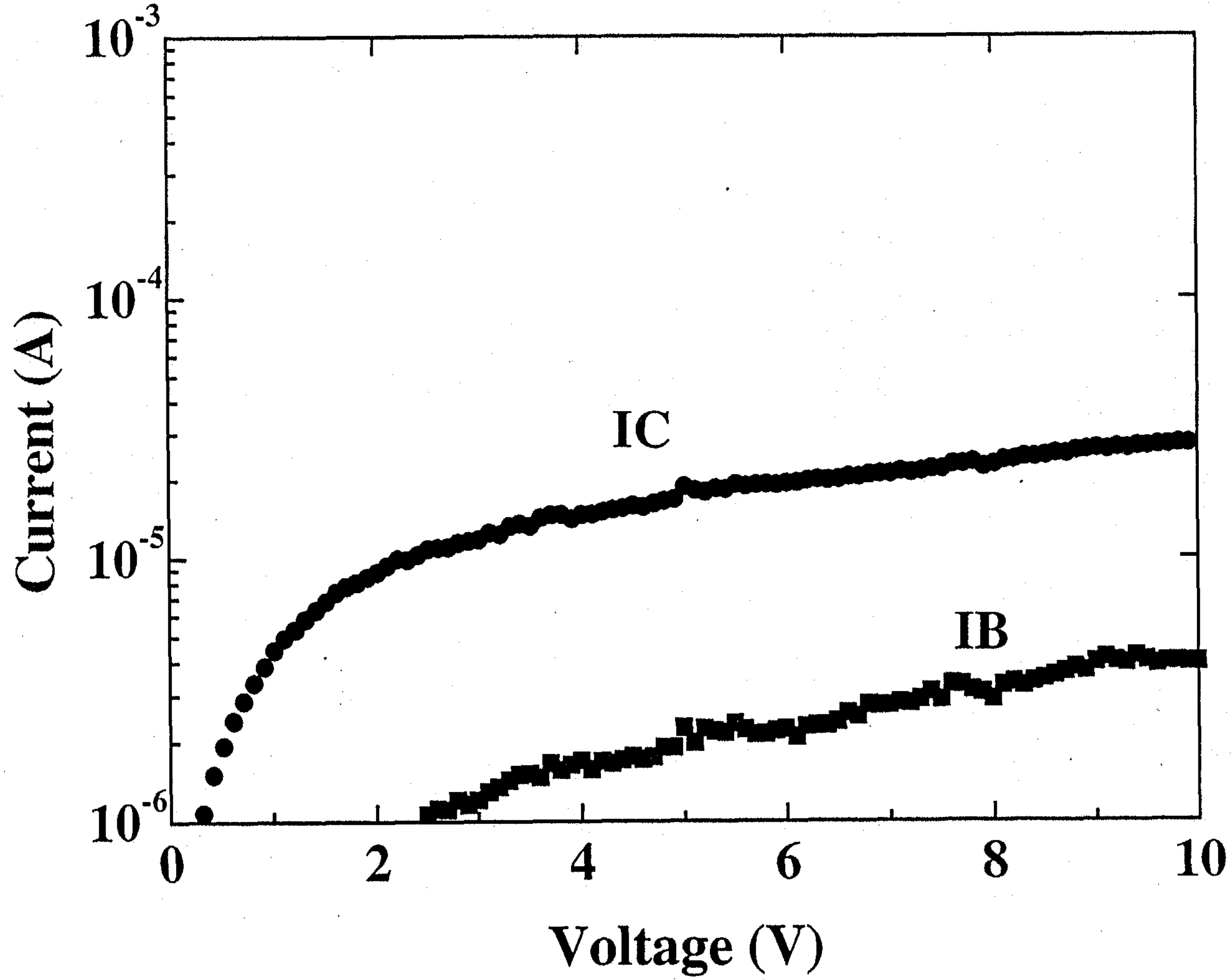

MOCVD
GaN/AlGaN HBT
Mg
Al
Concentration (atoms/cc)
Secondary Ion Counts
Depth (microns)
0.0
0.4
0.8
1.2



MOCVD
GaN/AlGaN HBT
Si
H
C
O
Al
10^22
10^21
10^20
10^19
10^18
10^17
Concentration (atoms/cc)
10^5
10^4
10^3
10^2
10^1
10^0
Secondary Ion Counts
0
1
2
3
Depth (microns)


MOCVD Grown AlGaN/GaN HBT
Measured at 300 °C
IC
IB
1E-3
1E-4
1E-5
1E-6
Current (A)
0
2
4
6
8
10
Voltage (V)


Room Temp
150 °C
300 °C
800
400
0
-400
-800
Current (μA)
-10
-5
0
5
10
Voltage (V)



Current (A)
10^-3
10^-4
10^-5
10^-6
0
2
4
6
8
10
Voltage (V)
IC
IB