Mater. Res. Soc. Symp. Proc. Vol. 892 © 2006 Materials Research Society 0892-FF13-10.1

Reduction of Base Access Resistance in AlGaN/GaN Heterojunction Bipolar Transistors using GaInN Base Cap Layer and Selective Epitaxial Growth

Jay M. Shah[1], Thomas Gessmann[1], Hong Luo[2], Yangang Xi[2], Kaixuan Chen[2], Jong Kyu Kim[1], and E. Fred Schubert[1]
[1]Electrical, Computer, and Systems Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12180-3590, U.S.A.
[2]Department of Physics, Applied Physics, and Astronomy, Rensselaer Polytechnic Institute, Troy, NY 12180-3590, U.S.A.

ABSTRACT

One of the major challenges affecting the performance of Npn AlGaN/GaN heterojunction bipolar transistors (HBTs) is the high base access resistance, which is comprised of the base contact resistance and the base bulk resistance. A novel concept is proposed to reduce the base access resistance in Npn AlGaN/GaN HBTs by employing polarization-enhanced contacts and selective epitaxial growth of the base and emitter. In addition, this technique reduces the exposed base surface area, which results in a lower surface recombination current. Such a structure would enable better performance of AlGaN/GaN HBTs in terms of higher current gain and a lower offset voltage. Theoretical calculations on polarization-enhanced contacts predict p-type specific contact resistance lower than 10^{-5} Ωcm^2. Experimental results using transmission line measurement (TLM) technique yield specific contact resistances of 5.6×10^{-4} Ωcm^2 for polarization-enhanced p-type contacts and 7.8×10^{-2} Ωcm^2 for conventional p-type contacts.

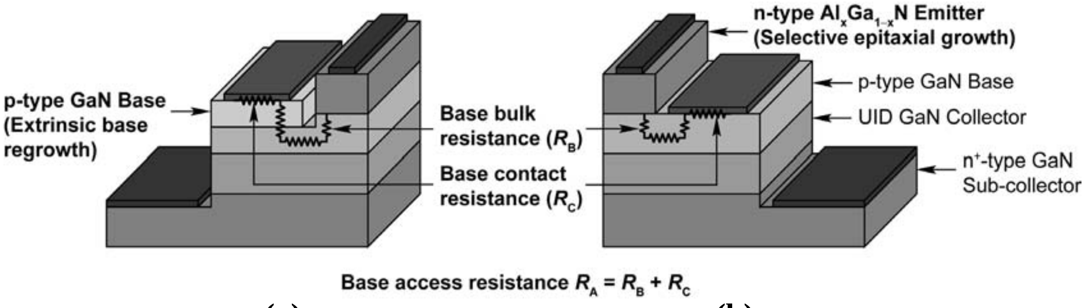
INTRODUCTION

The development of GaN-based HBTs is motivated by the demand for high-power and high-frequency electronic devices capable of working at temperatures greater than 100 ºC. GaN is desirable for electronic applications due to various advantages like large bandgap, large breakdown field, high projected saturation velocity, and the ability to form heterojunctions with AlGaN and GaInN alloys. However, there are several issues, mostly related to p-type GaN, that need to be resolved before obtaining high performance GaN-based HBTs. First, it is difficult to obtain a high hole concentration, because Mg is a deep acceptor in GaN. Second, the mobility of holes in GaN is low due to high hole effective mass. Low hole concentration and mobility result in low conductivity. This results in high base bulk and contact resistance, which in turn results in lower cut-off frequency, higher collector–emitter offset voltage, and lower transconductance. In addition, the lateral base resistance causes current crowding in the base-emitter junction. In this article, we propose a novel design to reduce the base access resistance in Npn AlGaN/GaN HBTs by using polarization-enhanced contacts and selective epitaxial growth. Reduction of the base access resistance in the proposed structure can be achieved by utilizing 2-dimensional hole gas (2DHG), generated by polarization-enhanced contacts, for lateral current transport in the base. We demonstrate that the specific contact resistance, of polarization-enhanced contacts, is lower than that of conventional contacts to p-type GaN, by more than two orders of magnitude.

THEORY

Current designs of Npn AlGaN/GaN HBTs

The easiest approach to fabricate GaN-based HBTs is to grow the Npn structure, mesa etch the emitter and the base, and deposit the contact metals. However, the emitter mesa etch using a dry etching technique damages the underlying p-type GaN base resulting in poor contact adhesion and highly resistive contacts [1]. There are two techniques to circumvent this problem. In the first method, called extrinsic base regrowth, the entire Npn HBT structure is grown. The emitter is then mesa-etched using dry etching to reveal the base. Extrinsic base regrowth is performed on the damaged base surface by masking the emitter with a dielectric. This buries the etch damage inside the base and results in an as-grown p-type GaN surface for improved contacts [1,2]. The resulting structure is shown schematically in figure 1(a). In the second method, called selective epitaxial growth, the base-collector junction is grown without the emitter. The base is then masked with a dielectric and the emitter is selectively grown on the base [3]. This technique eliminates emitter mesa etching, thereby eliminating base surface damage. The resulting device structure is shown schematically in figure 1(b). It must be noted that even though the contacts to as-grown p-type GaN are more ohmic than those to etched p-type GaN, they are not as ohmic as desired for high efficiency electronic devices. Hence both the structures described above suffer from a high base *access* resistance (R_A) comprising of base *bulk* resistance (R_B) and base *contact* resistance (R_C) as shown in figure 1. Therefore, to reduce R_A, it is imperative to reduce R_B and R_C.

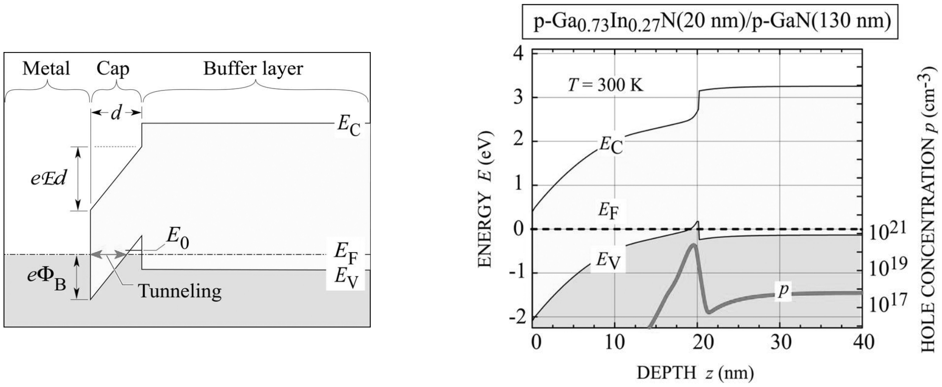


(a) (b)

Figure 1. Current designs of Npn AlGaN/GaN HBTs: (a) Extrinsic base regrowth HBT (b) Selective epitaxial growth HBT. Both designs suffer from high base access resistance.

New proposed design

Strain-induced piezoelectric as well as spontaneous polarization fields, in p-type GaInN contact layer on a bulk p-type GaN layer, result in band-bending that leads to the formation of 2DHG in the GaInN layer at the interface. Figure 2(a) shows the schematic band diagram of a polarization-enhanced contact employing a strained p-type III-nitride cap layer grown on a relaxed III-nitride buffer layer. Figure 2(b) shows the band diagram of an elastically strained, 20 nm thick *p*-type $Ga_{0.73}$ $In_{0.27}N$ cap layer on top of relaxed *p*-type GaN, self consistently calculated by solving the coupled Schrodinger Poisson equations in one dimension [4]. It is evident that the strong band-bending in the $Ga_{0.73}$ $In_{0.27}N$ cap layer, induced by the polarization fields, results in a peak of the hole distribution close to the GaInN/GaN interface, indicating the formation of a 2DHG. The polarization fields in GaInN enhance the depletion field, thereby reducing the tunneling distance and hence the contact resistance. Such polarization-enhanced contacts have been reported to have excellent ohmic characteristics compared to conventional contacts to GaN [4,5]. Theoretical calculations predict p-type specific contact resistances lower than 10^{-5} Ωcm^2 [5]. Although GaInN cap layers have been used to reduce the contact resistance in GaN/GaInN HBTs [2], they do not reduce the high base bulk resistance in AlGaN/GaN HBTs.



(a) **(b)**

Figure 2. (a) Schematic band diagram for a polarization-enhanced contact employing a strained p-type III-nitride cap layer grown on a relaxed III-nitride layer (b) Self-consistently calculated band diagram and free hole concentration *p* of a 20 nm thick *p*-type Ga$_{0.73}$In$_{0.27}$N layer grown pseudomorphically on *p*-type GaN with a dopant concentration of 10^{19} cm^{-3}. (Taken from [4])

The fundamental limitation of high resistance in p-type GaN necessitates the implementation of superior designs for better device performance. We propose a new design in which, the lateral current flow in the p-type base is realized by the 2DHG formed by polarization-enhanced contacts, thereby reducing the base bulk resistance. The proposed device structure is shown schematically in figure 3.

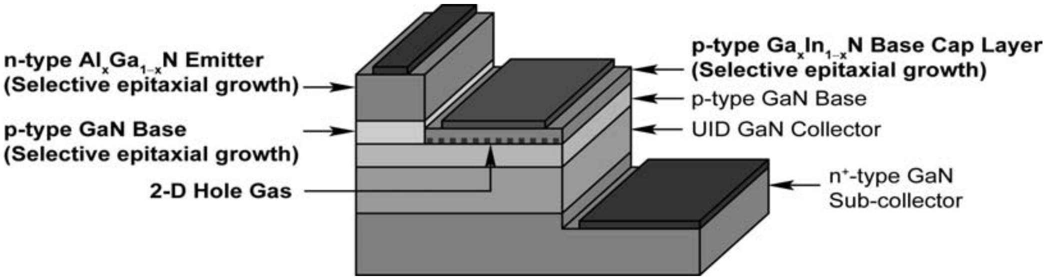


Figure 3. New proposed design of AlGaN/GaN HBT with polarization-enhanced contacts using GaInN base cap layer and selective epitaxial growth of emitter and base.

In addition to reducing the base contact resistance and base bulk resistance, this structure also reduces the exposed-base surface recombination current present in the most commonly used structure – extrinsic base regrowth HBT of figure 1(a). Lower contact resistance of the proposed structure would result in a lower ideality factor [6] of the base-emitter junction, thereby increasing the current gain. The dry etching damage to the base is also eliminated by using selective epitaxial growth technique.

Fabrication process flow

The detailed fabrication process flow is shown schematically in figures 4 and 5. The HBT structure is grown up to the base-collector junction without the emitter {figure 4(a)}. SiO_2 is then blanket-deposited {figure 4(b)} and patterned by photolithography and wet-etched by buffered oxide etch (BOE) to mask the emitter regions {figure 4(c)}. A thin p-type GaInN layer is then selectively and pseudomorphically grown on the p-type GaN base to facilitate polarization-enhanced contacts {figure 4(d)}. A Si_3N_4 layer, thin enough so as to not cover the SiO_2 layer completely, is blanket-deposited {figure 4(e)} and the SiO_2 layer is then wet-etched using BOE to expose the emitter regions {figure 4(f)}. A p-type GaN base layer thicker than the GaInN cap layer followed by a n-type AlGaN emitter layer are then selectively epitaxially grown in the emitter openings {figure 5(a)}. The Si_3N_4 mask is then wet-etched using hydrofluoric acid {figure 5(b)}. The sample is then patterned using photolithography and the base is mesa-etched using chemically assisted ion beam etching {figure 5(c)}. The photoresist is stripped off and the emitter, base, and collector are accessible for contact metallization {figure 5(d)}. Emitter and collector contacts are patterned using photolithography and metallization performed using electron-beam evaporation followed by rapid thermal annealing {figure 5(e)}. Finally, base contacts are patterned, deposited, and annealed to give the final device {figure 5(f)}.

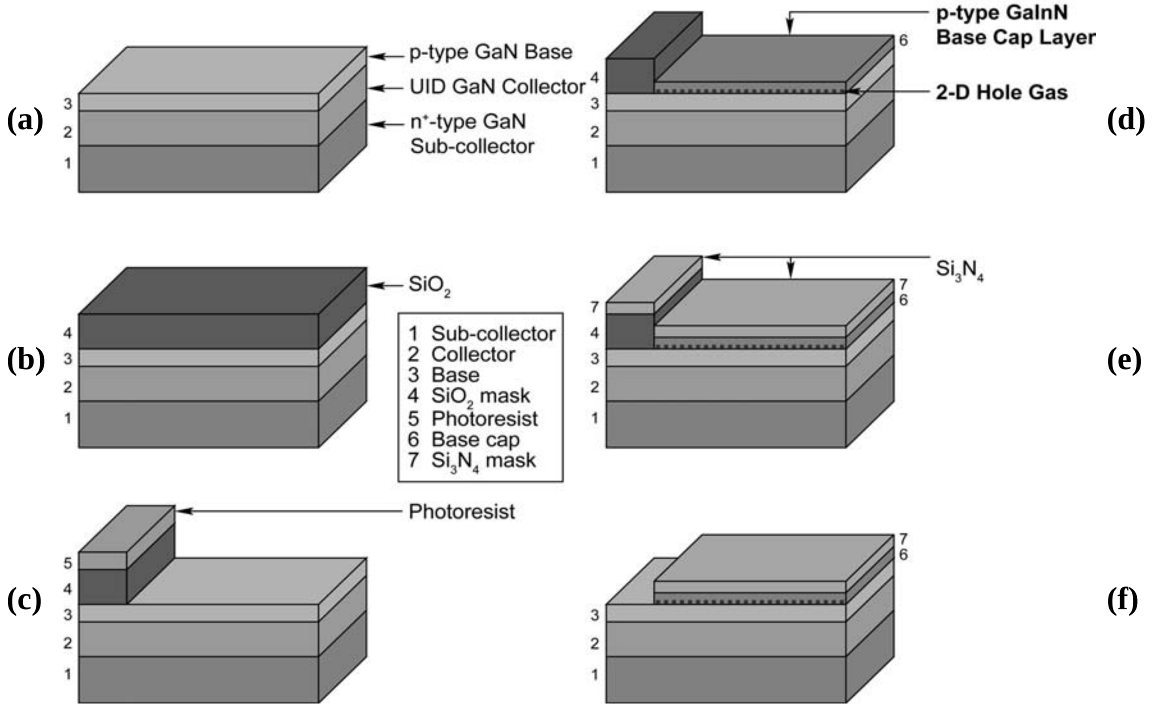


Figure 4. Device fabrication process flow for the new proposed design.

EXPERIMENT

Experiment involves the measurement of specific contact resistance using TLM method to compare conventional contacts to polarization-enhanced contacts. The conventional metal contacts consist of Ni (10 nm)/Au (30 nm) on 200 nm thick p-type GaN and the polarization-enhanced contacts consist of Ni (10 nm)/Au (30 nm) on p-type $Ga_{0.84}In_{0.16}N$ (3nm)/ GaN (200 nm). Both the contacts are annealed in oxygen at 450 ºC for 2 minutes. The specific contact resistance measured for the conventional contacts to p-type GaN is 7.8×10^{-2} Ωcm^2, while that measured for the polarization-enhanced contacts is 5.6×10^{-4} Ωcm^2 as shown in figure 6. Figure 7 shows the measured *I–V* characteristics of Ni/Au contacts to p-type GaInN/GaN before and after annealing. It is interesting to note that both sets of curves are linear and similar in magnitude. This indicates the presence of 2DHG.

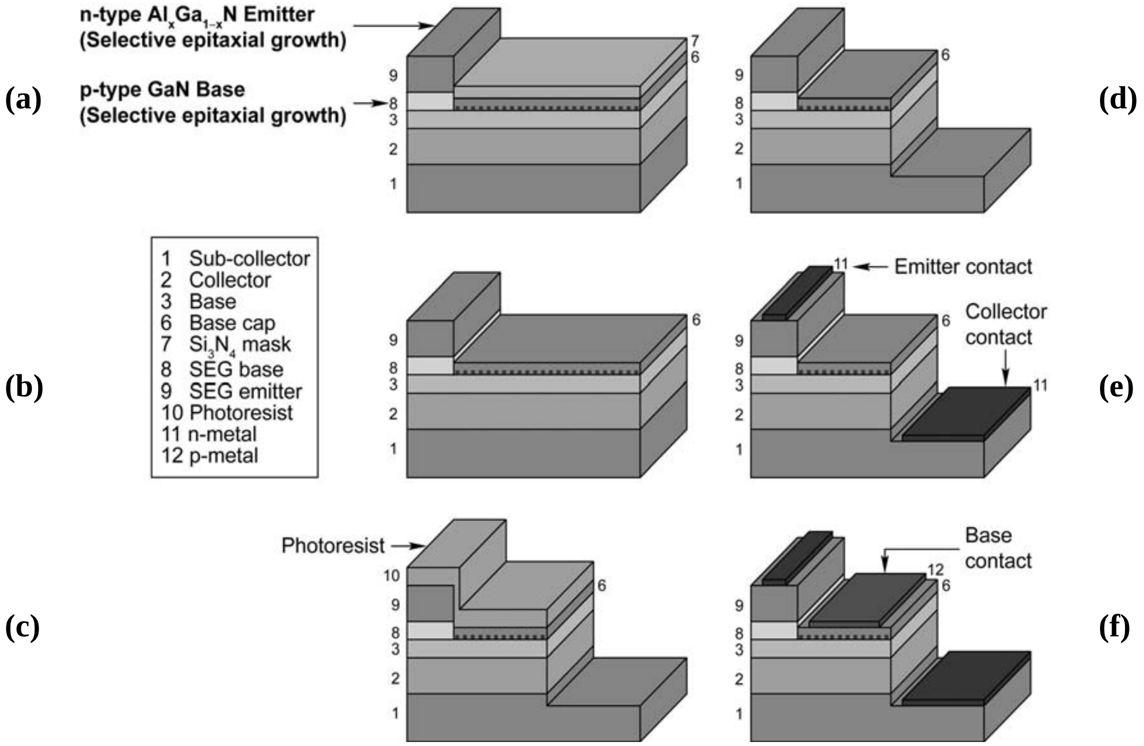


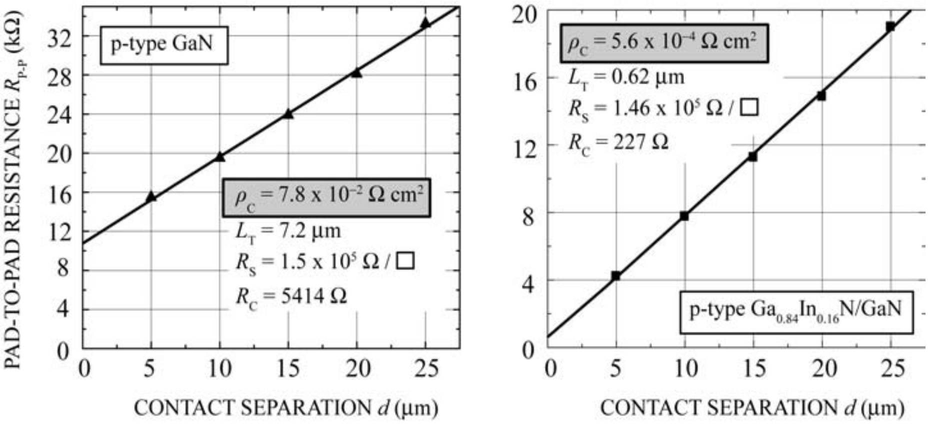
Figure 5. Device fabrication process flow for the new proposed design (cont’d from figure 4).

CONCLUSIONS

AlGaN/GaN HBT performance is currently limited by the high base access resistance. We propose a new design to reduce the base access resistance by employing polarization-enhanced contacts and selective epitaxial growth technique. Theoretical calculations and experimental results confirm that polarization-enhanced contacts are much more ohmic compared to conventional contacts. Analysis of the proposed device design suggests improved base access resistance due to polarization-enhanced contacts and utilization of 2DHG for lateral current transport.

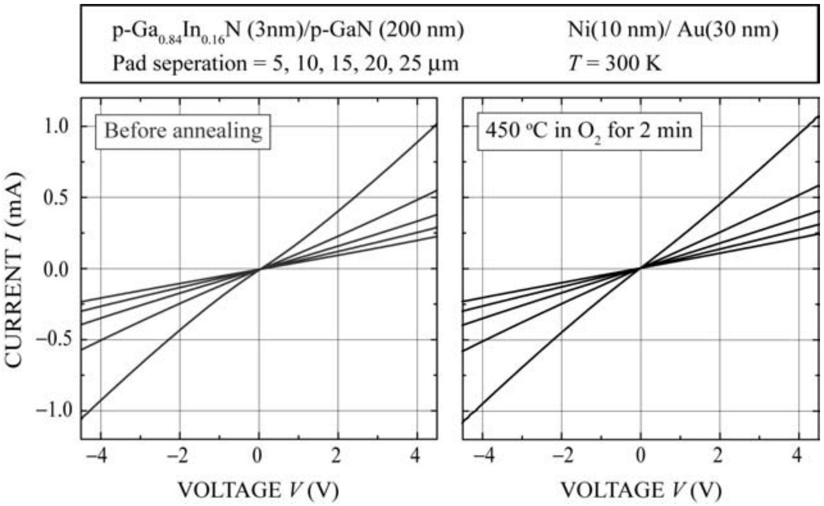
ACKNOWLEDGEMENTS

The authors are grateful for support by the US Office of Naval Research (ONR) and the National Science Foundation (NSF).



(a) **(b)**

Figure 6. Evaluation of specific contact resistance of Ni/Au contacts to (a) p-type GaN (b) p-type GaInN/GaN.



(a) **(b)**

Figure 7. Measured *I*–*V* characteristics of Ni/Au contacts to p-type GaInN/GaN (a) before annealing and (b) after annealing.

REFERENCES

1. L. S. McCarthy, P. Kozodoy, M. J. W. Rodwell, S. P. DenBaars, and U. K. Mishra, IEEE Electron Device Lett. **20** (6), 277 (1999).
2. T. Makimoto, K. Kumakura, and N. Kobayashi, Jpn. J. Appl. Phys. **43** (4B), 1922 (2004).
3. J. B. Limb, L. McCarthy, P. Kozodoy, H. Xing, J. Ibbetson, Y. Smorchkova, S. P. Denbaars, and U. K. Mishra, Elec. Lett. **35** (19), 1671 (1999).
4. T. Gessmann, Y.-L. Li, E. L. Waldron, J. W. Graff, E. F. Schubert, and J. K. Sheu, Appl. Phys. Lett. **80** (6), 986 (2002).
5. Y.-L. Li, E. F. Schubert, and J. W. Graff, Appl. Phys. Lett. **76**, 2728 (2000).
6. J. M. Shah, Y.-L. Li, Th. Gessmann, and E. F. Schubert, J. Appl. Phys. **94** (4), 2627 (2003).