MBE Grown NPN GaN/InGaN HBTs on Bulk-GaN Substrates

CNF Project Number: 2443-16

Principal Investigators: Huili Grace Xing, Debdeep Jena

User: Kazuki Nomoto

Affiliation: School of Electrical and Computer Engineering, Cornell University

Primary Source of Research Funding: NSF, AFOSR

Contact: grace.xing@cornell.edu, kn383@cornell.edu

Primary CNF Tools Used: Autostep i-line stepper, Heidelberg mask writer DWL2000, P7 profilometer, FilMetrics, AFM Veeco Icon, Zeiss SEM, PT770, Oxford 81, Oxford PECVD, odd-hour evaporator, AJA sputter deposition, RTA AG610

Abstract:

In this work, we demonstrate MBE grown GaN/InGaN/GaN *n-p-n* HBTs on bulk single-crystal GaN substrates with a low leakage current in each *p-n* junction. Good current saturation of the collector current with the collector-emitter voltage was observed. The common-emitter current gain is ~ 1.5 (V_{CB}=0V). Visible light emission was observed from the B-C and E-B junctions at forward-bias from 3.5 to 7 V. Two EL peaks at 3.2 eV and 2.9 eV are seen. The origin of this photon peak at 3.2 eV is related with band to band radiative transition in the $In_{\sim 0.04}Ga_{\sim 0.096}N$ base. Though recombination in the base of an HBT hurts its gain and performance, if the recombination is radiative, it also offers potential ways to cool the device, and to communicate with other devices. This first demonstration of an MBE-grown HBT paves the way towards HBT based power electronic devices and circuits in the future.

Summary of Research:

The wide bandgap GaN-based semiconductors are excellent candidates for high-power switching applications. Recently a large number of GaN-based high power switching transistors were reported with high-quality epitaxial growths on bulk-GaN substrates by MOCVD. Buried *p*-type structures are prevalent in GaN vertical power transistors, offering capabilities including reverse blocking, avalanche and reduce surface field. However, it is well-known that *p*-GaN gets passivated by hydrogen in MOCVD grown materials. Furthermore, it is quite difficult to activate the doped-Mg in buried *p*-GaN structures. MBE growth on the other hand enables efficient (Mg) acceptor doping for buried *p*-type layers that do not require activation annealing. In addition to a high degree of control of alloy compositions and heterostructures, the ability to grow buried *p*-layers is a significant advantage of MBE over MOCVD for HBTs, where the *p*-base is critical. And bulk-GaN crystals are necessary to reduce vertical leakage currents.

In this work, we demonstrate MBE grown GaN/InGaN/GaN *n-p-n* HBTs on bulk single-crystal GaN substrates with a low leakage current in each *p-n* junction. High-quality GaN/InGaN epi-layers were successfully grown on a bulk-GaN substrate (TDD~2×10^7/cm^2). The In composition in the graded collector-base (C-B) and base-

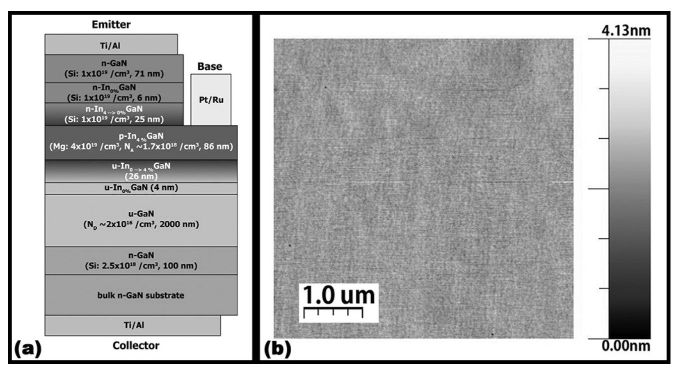

Figure 1: (a) A schematic cross section of MBE grown InGaN/GaN HBTs on bulk-GaN substrates. (b) AFM image of the as-grown InGaN/GaN HBT structure.

emitter (B-E) junctions was graded from 0% to 4% and from 4% to 0% by linearly decreasing and increasing the Ga flux, respectively. A high base hole concentration of $p \sim 1.7\times10^{18}$/cm^3 was determined by Hall effect measurement.

Figure 1(a) shows a schematic cross section image of a fabricated GaN/InGaN HBT. A very smooth as-grown epi-surface was confirmed by AFM, as shown in Figure

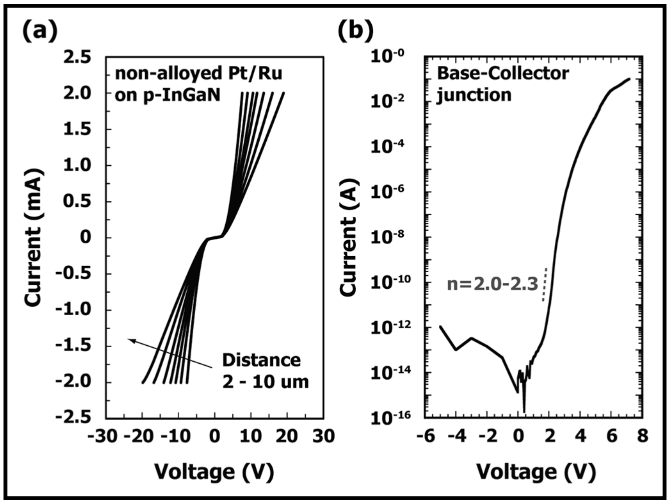

Figure 2: (a) Representative TLM I-V *characteristics of Pt-based ohmic contacts on* p-*InGaN. (b) Forward bias I-V characteristic for a base-collector* p-n *junction diode.*

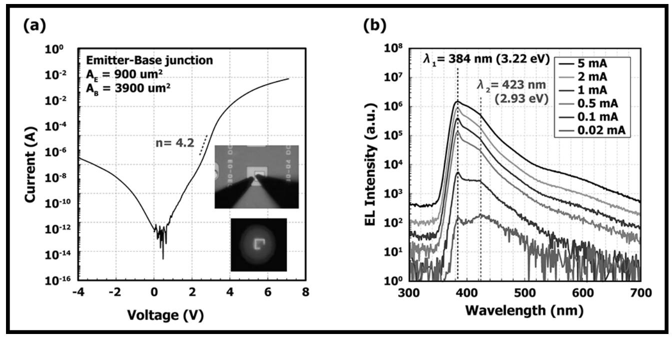

Figure 4: (a) Forward bias I-V *characteristic for a base-emitter* p-n *junction in HBT. Inset figure shows the visible light emission during the measurement. (b) Electroluminescence spectrums of a base-emitter* p-n *junction in HBT with a forward bias voltage from 3.5 V to 7 V.*

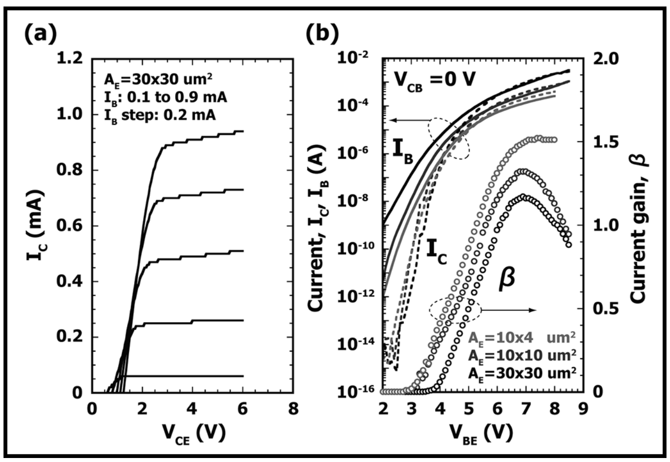

Figure 3: (a) The family curves of a GaN/InGaN n-p-n *HBT with* $A_E = 30\times30\ \mu m^2$ *and (b) Gummel plots with various emitter sizes at* $V_{CB} = 0V$.

1(b). Device fabrication started with a two-step mesa etching process for the emitter mesa and device isolation by the Cl-based ICP etching. The base ohmic contacts were formed with Pt/Ru = 20/50 nm by electron beam evaporation. Figure 2(a) shows representative *I-V* characteristics of ohmic contacts on *p*-InGaN. For the emitter contacts, Ti/Al metal stacks were deposited and have a contact resistance of $1.7\times10^{-4}\ \Omega\cdot cm^2$. Finally, Ti/Al stacks were evaporated on the backside of the *n*-type bulk GaN without patterning as the collector contact.

The representative B-C junction forward/reverse *I-V* characteristic is shown in Figure 2(b) in log scale. The junction shows rectifying behavior with a low leakage current, 10^{14} on/off ratio and the ideality factor 2, which means that the Shockley-Read-Hall recombination current dominates in the junctions [1]. Good current saturation of the collector current with the collector-emitter voltage was observed, as shown in Figure 3(a). Gummel plots for the HBTs with various emitter sizes are shown in Figure 3(b). The common-emitter current gain ($\beta \equiv I_C/I_B$) is ~ 1.5 (V_{CB}=0V).

In order to improve the current gain, the base resistance needs to be decreased since the measured sheet resistance of the InGaN base layer is > 100 kΩ/sq. Visible light emission was observed from the B-C and E-B junctions at forward-bias from 3.5 to 7 V. The measured electrical forward-bias *I-V* characteristic and electroluminescence (EL) spectra for the E-B junction are shown in Figures 4 (a,b). Two EL peaks at 3.2 eV and 2.9 eV are seen. The origin of this photon peak at 3.2 eV is related with band to band radiative transition in the $In_{\sim0.04}Ga_{\sim0.096}N$ base. The broad EL spectrum after the highest peak comes probably from deep donor-acceptor transition in highly Mg doped layer [2]. The inset in Figure 4(a) shows the visible strong emission even at a low forward voltage of 3.5 V. This result indicates high-quality material and confirms radiative recombination in the *p-n* junctions. Though recombination in the base of an HBT hurts its gain and performance, if the recombination is radiative, it also offers potential ways to cool the device, and to communicate with other devices. This first demonstration of an MBE-grown HBT paves the way towards HBT based power electronic devices and circuits in the future.

References:

[1] Z. Hu, K. Nomoto, D. Jena, H. Xing, et al., APL, vol. 107, pp. 243501-1-243501-5, Dec. 2015.

[2] U. Kaufmann, M. Kunzer, H. Obloh, C. Manz, et al., Physical Review B 59 (1999) 5561-5567.