Design Optimization of InGaAsN-based *Pnp* Heterojunction Bipolar Transistors for Low-Power Applications

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The Heterojunction Bipolar Transistor (HBT) technology with the InP/InGaAs material system has demonstrated good potential for low-power electronic applications with the use of a small band-gap material in the base for an advantageous lower turn-on voltage V_{ON}. The high-cost and concerns over breakage have limited the commercial application of this InP technology. Progress in (In,Ga)(As,N) material quality has motivated the development of new bipolar transistors using this alloy as the base layer. By incorporating a proper amount of N and In into GaAs simultaneously, a quaternary material lattice-matched to GaAs can be obtained with a significant energy band-gap reduction.

Recently, we demonstrated a *NpN* InGaP/InGaAsN/GaAs double heterojunction bipolar transistor (DHBT) with V_{ON} significantly lower than in corresponding GaAs-based HBTs, showing the potential of InGaAsN-based HBTs for low power applications [1]. The focus of this present work is the optimization of *Pnp* InGaAsN HBT, which in conjunction with the *N-p-N* InGaAsN based HBT technology, would allow the low-power InGaAN-based complementary heterojunction bipolar transistor (CHBT) technology to take advantage of the matured and cost-effective GaAs foundry technology. The CHBT technology has the potential for enhanced circuit performance for digital, linear, and microwave applications compared to circuits using only *N-p-n* HBTs.

The InGaAsN material is lattice-matched to GaAs with an E_G of approximately 1.2 eV. When stacked next to AlGaAs (to be initially used as the emitter), the resulting band alignment is especially suitable for *Pnp* HBT applications with almost 0.5 eV of the band conduction discontinuity ΔE_C to suppress majority carrier electrons to be back injected into the emitter while a small valence band discontinuity ΔE_V of 0.15 eV facilitates hole transport from the emitter to the base.

The original experimental work consists of replacing the conventional GaAs material used for the base and the collector in traditional *Pnp* AlGaAs/GaAs HBTs by InGaAsN. While the AlGaAs/InGaAsN SHBT device seems to be penalized in terms of DC current gain β compared to the GaAs-based HBT, it shows however advantageous features for the turn-on voltage V_{ON}, which is ~ 0.2 V lower (0.77 V compared to 1.05 V) than the GaAs HBT. A possible cause may be the presence of recombination centers in the InGaAsN base, resulting in high levels of recombination current. The paper reviews several design configurations to improve initial performances. The use of GaAs as a collector of an AlGaAs/InGaAsN/GaAs double heterojunction bipolar transistor (DHBT) is examined to take advantage of better breakdown properties and improved collector characteristics. This design does not require the use of any exotic grading junction since an almost perfectly aligned valence band configuration is expected at the B/C junction. Because a GaAs emitter will have better material properties from that of AlGaAs, performances of an aluminum-free GaAs/InGaAsN/GaAs PnP DHBT device are also addressed. The impact of a quasi-electric field in the InGaAsN base on transport properties, by grading the base doping concentration, is analyzed. The InGaAsN DHBTs show functional current gain greater than 45 on small area devices (emitter area of 3x25 μm^2), a sufficient gain value for many circuits applications. A DC gain as high as 100, very comparable to the one from the AlGaAs/GaAs *Pnp* HBT, is found for the InGaAsN HBT with graded base doping, with a tremendous improvement of the transit time across the base. A comparison of base ideality factor, knee voltage, offset voltage, and breakdown voltage is addressed to highlight the most optimized design for the *Pnp* InGaAsN-based transistor. High frequency characteristics are analyzed for the various HBT designs previously defined in terms of hole transport and base layer resistivity. A f_T value ~ 13 GHZ, very comparable from that of GaAs HBT is found for both InGaAsN DHBTs since the hole transport is not too affected by the single InGaAsN base layer. f_{MAX} values similar to f_T are obtained due to the InGaAsN base resistance still higher than in a similar *p*-type GaAs base layer. New solutions to overcome this limitation will be examined.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract DE-AC04-94AL85000.

[1] Chang P. C., Baca A. G., Li N. Y., Xie X. M., Hou H. Q., Armour E., *Appl. Phys. Lett.* 2000, 76: 2262-2264.