Implementation of Reduced Turn-On Voltage InGaP HBTs Using Graded GaInAsN Base Regions

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***Abstract*—InGaP/GaInAsN double heterojunction bipolar transistors (HBTs) with compositionally graded bases are presented which exhibit superior dc and radio frequency performance. Reducing the average base layer energy gap and optimizing the emitter–base (e–b) and base–collector (b–c) heterojunctions leads to a 100-mV reduction in the turn-on voltage compared to a baseline InGaP/GaAs process. Simultaneously grading the base layer energy band-gap results in over a 66% improvement in the dc current gain and up to a 35% increase in the unity gain cutoff frequency. DC current gains as high as 250 and cutoff frequencies of 70 GHz are demonstrated. In addition, the InGaP/GaInAsN DHBT structure significantly reduces the common emitter offset and knee voltages, as well as improves the dc current gain temperature stability relative to standard InGaP/GaAs HBTs.**

***Index Terms*—Bipolar transistor, GaInAsN, graded base, InGaP/GaAs, heterojunction bipolar transistors (HBTs), turn-on voltage.**

I. INTRODUCTION

GaAs-BASED heterojunction bipolar transistor (HBT) integrated circuits are an enabling technology for power amplifiers in wireless and high-speed digital ($>$10 Gbit/s) applications. Initial applications were based on AlGaAs/GaAs HBT technology, which is now being replaced by InGaP/GaAs HBTs due to improved reliability performance [1]. However, GaAs-based HBTs are approaching circuit design limitations in terms of turn-on voltage ($V_{\mathrm{be,\,On}}$), efficiency (i.e., offset and knee voltages—$V_{\mathrm{CE,\,sat}}$ and V_k), speed (i.e., f_t and $f_{\max}$) and temperature stability. Recently, several groups have demonstrated the potential of using lower energy band gap (E_{gb}) material in the base layer to reduce $V_{\mathrm{be,\,On}}$ in GaAs-based HBTs [2]–[6]. GaInAsN is a particularly attractive material system as it allows E_{gb} to be lowered while minimizing strain. However, GaInAsN materials typically display degraded minority carrier properties compared with GaAs, reducing dc current gain (β) and detracting from the frequency performance of the device [3], [4]. These unfavorable characteristics can be mitigated by compositionally grading E_{gb}, creating a quasielectric field that accelerates electrons across the base in an n-p-n bipolar device. The increased electron velocity decreases base transit time, thereby increasing β and improving RF performance, resulting in improved amplifier design flexibility for mobile and digital applications.

In this letter, we report on the use of a graded GaInAsN base in advanced GaAs HBT structures that achieve high base doping, superior dc current gains, and excellent radio-frequency (RF) performance. The use of GaInAsN as the base layer affords a way to simultaneously lower $V_{\mathrm{be,\,On}}$, reduce $V_{\mathrm{CE,\,sat}}$, improve V_k, and significantly decrease the β variation with temperature in GaAs-based HBT devices.

II. EXPERIMENT

Three different types of base structures were compared in this study: a conventional InGaP/GaAs HBT as well as constant and graded base composition GaInAsN DHBTs, referred to as c-GaInAsN and g-GaInAsN, respectively. Within each comparison set, the three structures are identical except for the base layer, ensuring emitter and collector breakdown voltages and resistances are comparable. Interfacial layers were inserted at the emitter–base (e–b) and base–collector (b–c) heterojunctions to suppress ΔE_c. The average E_{gb} for the g-GaInAsN is roughly matched to the E_{gb} of the c-GaInAsN in an attempt to equate the $V_{\mathrm{be,\,On}}$ values. The E_{gb} of the g-GaInAsN sample varies approximately 40 meV across the base, inducing an electric field of ~7 kV/cm.

All structures were grown on semi-insulating (100) GaAs using LP-MOCVD in an Aixtron 2400 multiwafer production reactor. Two sets of comparison structures were prepared for this study and are summarized in Table I. The GaInAsN base material has a composition of approximately 5% Indium and 0.3% Nitrogen. The two sets of structures differ primarily in collector design, yielding BV_{ceo} values of approximately 12 V and 8 V, respectively.

III. RESULTS AND DISCUSSION

Fig. 1(a) compares the collector current density (J_c) for the conventional InGaP/GaAs HBT with those for the constant and graded base GaInAsN devices from sample set A. Both GaInAsN devices exhibited $V_{\mathrm{be,\,On}}$ reductions of approximately 100 mV when compared to the baseline GaAs HBT. All three structures display nearly identical ideality factors ($n \sim 1.05$). As designed, there is no appreciable difference in $V_{\mathrm{be,\,On}}$ between the two GaInAsN samples. Grading E_{gb} boosts the electron velocity in the GaInAsN base and, as seen in Fig. 1(b), increases β by a factor of 1.7 while retaining comparable $V_{\mathrm{be,\,On}}$ and R_{sb}. The improvement in β at high bias

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TABLE I

STRUCTURAL, DC, AND RF PARAMETERS FOR TWO COMPARISON SETS OF InGaP/GaInAsN DHBTs

Collector Design	Base Structure	Base Thickness (Å)	R_{sb} (Ω/□)	V_{be} (@ 1.75 A/cm²)	Device Size (μm²)	Peak β	Peak f_t (GHz)	BV_{ceo} (V)	$V_{on,offset}$ (mV)
A	constant GaInAsN	550	450	1.007	2 x 6	39	47.3	12.2	130
					2.4 x 25	43	61.0	12.9	145
	graded GaInAsN	550	450	1.014	2 x 6	65	52.4	12.1	170
					2.4 x 25	64	70.0	13.1	160
	GaAs	700	260	1.106	2 x 6	160	45.4	12.4	240
					2.4 x 25	157	52.0	11.8	250
B	constant GaInAsN	600	392	0.896	2 x 4 x 4	55	52.5	8.3	120
	graded GaInAsN	400	705	1.019	2 x 4 x 4	250	63.0	8.4	150
	GaAs	500	436	1.087	2 x 4 x 4	220	64.0	7.6	250

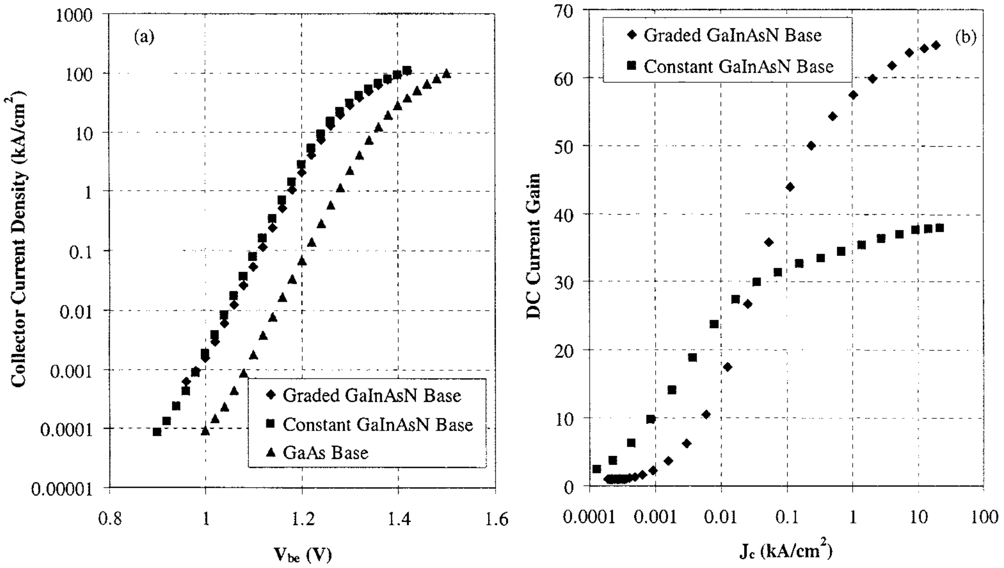

Fig. 1. (a) Collector current density from small area devices (2 × 6 μm²) on the three set-A structures discussed in the text. (b) DC current gain versus collector current density for the graded and constant composition GaInAsN DHBTs. The peak dc current gain of the set A standard GaAs HBT is 160 (not shown).

for the graded base structure is due entirely to a reduction in the neutral base recombination component of the base current. It should be noted that the graded base set B sample (with a higher R_{sb}) achieved a peak β of 250 (J_c ~ 70 kA/cm²). In addition to increasing the β, grading E_{gb} improves the frequency response of the device. Extrapolated values for f_t and $f_{\max}$ plotted as a function of J_c for the GaInAsN DHBTs (set A) are illustrated in Fig. 2. For 2 × 6 μm² small area devices, the g-GaInAsN demonstrated a peak f_t of 52 GHz (at J_c of 42 kA/cm²). On larger 2.4-×-25-μm² devices, the same structure exhibited f_t values as high as 70 GHz.

The nearly identical f_t values from the c-GaInAsN and baseline samples in Fig. 2, despite the difference in base thickness (550 versus 700 Å), suggest a slight degradation of the electron mobility in the GaInAsN base. On the other hand, when the peak f_t values from the constant and graded GaInAsN DHBT samples are compared, the improvement in the electron base transit time is clearly evident and results in about a 10%–15% increase in the overall frequency performance. Similar performance enhancements are observed on structures fabricated from set B. As will be reported more fully elsewhere, this observed increase in peak f_t is consistent with a 1.7 increase in effective electron velocity as deduced from β. In comparing the $f_{\max}$, we note that the higher peak f_t of the g-GaInAsN structure can largely offset the higher R_{sb}(450 Ω/□ versus 260 Ω/□), and minimize the potential reduction in $f_{\max}$ due to higher base access resistance.

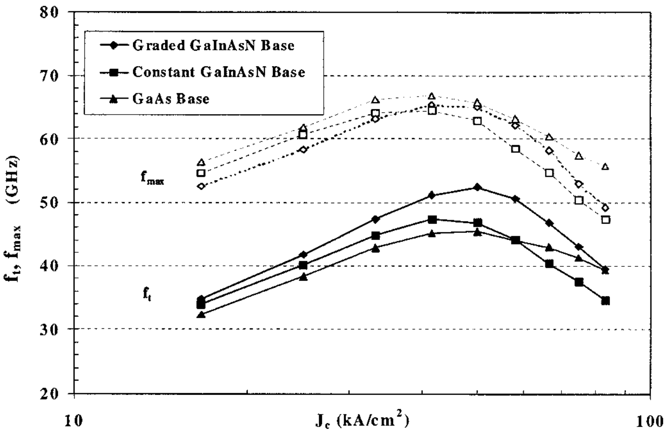

Fig. 2. Variation of current gain cutoff frequency (f_t) and maximum frequency of oscillation ($f_{\max}$) with collector current density for the three set A structures discussed in the text, all with a BV_{ceo} ~ 12 V. Measurements were made on 2 × 6 μm² devices at $V_{ce} = 3$ V, with f_t and $f_{\max}$ extrapolated using a −20 dB/decade slope of the small signal current gain (H_{21}) and unilateral gain (U), respectively.

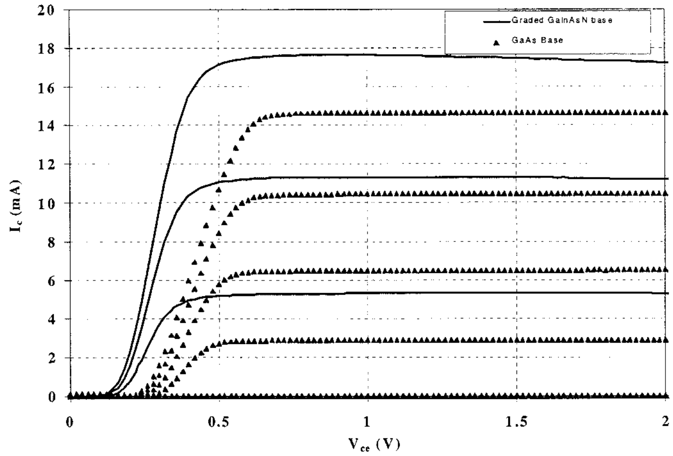

Fig. 3. Common emitter characteristics of a set B graded InGaP/GaInAsN DHBT ($R_{sb} = 705\ \Omega/\square$) and a typical InGaP/GaAs HBT ($R_{sb} = 436\ \Omega/\square$). These GaInAsN devices exhibited peak differential current gains of 250 while those for the baseline GaAs HBT are approximately 220 [7]. Measurements were made on $2 \times 4\ \mu\text{m} \times 4\ \mu\text{m}$ small area devices and the step of the base current was 25 μA.

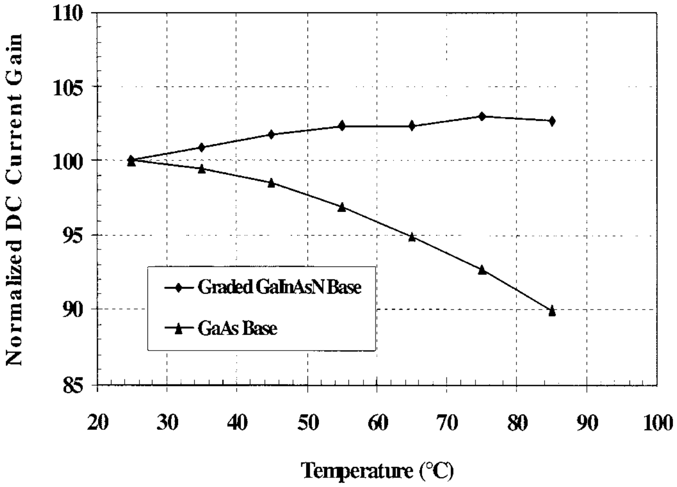

Fig. 4. Normalized dc current gain versus temperature for a graded InGaP/InGaAsN DHBT and a conventional InGaP/GaAs HBT measured at $J_c = 2$ kA/cm^2 on $2 \times 6\ \mu\text{m}^2$ set A devices.

Fig. 3 shows the common-emitter current–voltage (I–V) characteristics measured on the set B InGaP/GaAs and g-GaInAsN devices. The GaInAsN samples demonstrate significantly reduced offset and the knee voltages when compared to the baseline GaAs HBT. $V_{\text{CE, sat}}$ has been reduced to 150 mV from approximately 250 mV, and V_k is simultaneously reduced to approximately 400 mV from about 560 mV (at $J_c \sim 18$ kA/cm^2). To first order, this reduction in offset voltage may be expected due to the double heterojunction nature of the GaInAsN structures. The reduction can be better quantified by following the arguments presented by Mochizuki *et al.*, and noting that the $n = 2$ b–c diode currents of all three structures are nearly identical, while the e–b diode current is increased in the GaInAsN device, leading to better symmetry between the diode currents [8].

Fig. 4 compares the temperature dependence of β from g-GaInAsN and GaAs HBT structures. Typically, β in GaAs-based HBTs displays a negative temperature dependence that decreases as the difference in energy-gap between base and emitter is increased [9]. The GaInAsN devices, with a larger energy-gap differential, exhibit nearly constant temperature dependence (<3% variation from 25°C to 85°). The results obtained here on small area devices are consistent with those obtained on larger area devices of similar turn-on voltage [2].

IV. CONCLUSION

We have developed compositionally graded GaInAsN base DHBT structures that demonstrate improved dc and RF performance over that of similar constant composition GaInAsN devices. These advances pave the way for realizing reduced $V_{\text{be, On}}$ HBTs which are based on a mature GaAs technology platform and capable of being inserted into existing applications. The decreased electron base transit time associated with the graded base leads to a 1.7× increase in β compared to similar constant composition GaInAsN devices, and up to a 35% improvement in the cutoff frequency when compared with conventional InGaP/GaAs HBTs. Perhaps more important, the offset and knee voltages are reduced in GaInAsN structures. Finally, the GaInAsN DHBTs investigated here exhibit normalized gain variations of only 3% over a temperature range of 25 °C to 85 °C.

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