High Uniformity 6” InGaP/GaAs Heterojunction Bipolar Transistors

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The growth of highly uniform, state-of-the-art InGaP/GaAs heterojunction bipolar transistors is demonstrated in a multi-wafer 6-inch configuration (AIX 2600). The uniformity of thickness, doping, composition, interface properties and minority carrier lifetime are assessed by electrical and structural characterization measurements, and shown to vary by less than ±3% across the wafer. The dc current gain versus base sheet resistance on a high gain structure, has a non-linear dependence on base sheet resistance, typical of high performance InGaP/GaAs HBTs.

Introduction

InGaP/GaAs based Heterojunction Bipolar Transistors (HBTs) are gaining wide acceptance in a variety of microwave and optical communication systems as power amplifiers and high-speed A/D converters. InGaP/GaAs HBTs are being developed because of numerous device improvements over AlGaAs emitter structures, including improved temperature stability of the peak dc current gain and enhanced reliability at high junction temperatures.[1]-[2] Currently a majority of HBT device production is based on 4” wafers, while 6” wafer processes are in development. In this work, 6” InGaP/GaAs HBTs with excellent structural and electrical uniformity are demonstrated. The electrical data from large area transistors are combined with photoreflectance measurements to examine layer thickness, doping and composition uniformity. In addition, Gummel plots and dc current gain results are shown. The dc current gain/base sheet ratio, measured at a base sheet resistance of 425 ohms/sq was 0.65, which is among the highest reported for any size InGaP HBT wafer.[3]

Experiments and Results

Device wafers were grown using low pressure MOCVD. The layering sequence from the top down featured a standard highly doped n^+-InGaAs contact layer followed by a 1200 Å thick GaAs ($4x10^{18}$ cm^{-3}) cap layer; a 500-800 Å thick lattice matched InGaP ($3x10^{17}$ cm^{-3}) emitter, and a 500 - 1000 Å thick C-GaAs base layer ($4x10^{19}$ cm^{-3}). This was followed by a 5000-10,000 Å thick GaAs ($1x10^{16}$ cm^{-3}) collector and a 5000Å GaAs ($4x10^{18}$ cm^{-3}) subcollector. Large area devices were fabricated (75 µm x 75 µm) and tested using an HP4145 parametric analyzer. Electrical parameters monitored radially across the 6” wafer include dc current gain, V_{be} turn-on voltages, breakdown voltage of the emitter and collector, base and emitter sheet resistances. The uniformity values quoted are calculated by dividing the difference of the maximum and minimum values by the average. The photoreflectance (PR) spectra were taken at the center, radial midpoint, and edge of the HBT and fit numerically to a theoretical expression in order to extract the emitter energy gap and electric field.[4]

Figure 1 shows the radial uniformity of several device electrical parameters across a typical 6” InGaP/GaAs HBT wafer. The electrical parameters, in combination with the PR data, allow individual layer uniformity to be assessed. In these samples, the breakdown of both the base-emitter and collector-base junctions is governed by the punch-through mechanism. Therefore, the breakdown voltage is proportional to the layer thickness. The emitter and collector breakdown voltages, and thus layer thickness, vary less than 2% across the 6” wafer. Figure 2 shows the photoreflectance spectra measured at the center, radial midpoint, and edge of the wafer. The emitter band gap (E_g), a function of the composition and ordering for an InGaP emitter, has a variation of less than 1%. The emitter electric field, which is related to the emitter doping, has a variation of approximately 1%. The emitter uniformity can be further studied via turn-on V_{be}, which is strongly dependent on the base-emitter interface. The turn-on V_{be} measured at a collector current density of 1.7 A/cm^2 is low, averaging 1.102V with a 3.0% variation. The low turn-on V_{be} indicates that the emitter-base interface was optimized to suppress the conduction band spike. The combination of PR and electrical measurements demonstrate that the emitter thickness, band-gap, doping, and interface uniformity vary less than 3% across the 6” HBT wafer.

The base layer uniformity was excellent as demonstrated by the dc current gain and base sheet resistance results. The dc current gain, measured at high current density, varies by approximately 3% across the wafer. This indicates that the minority carrier lifetime was consistent across the wafer. The base sheet resistance, which measures the doping mobility product, varied by 2.5%. The emitter sheet resistance, which is a measure of the doping-mobility product in the emitter cap and InGaAs contact

layers, was also excellent, with a variation of 6%. These results clearly indicate that 6” InGaP/GaAs HBT device wafers with layer thickness, composition, and doping uniformity of better than ±3% are possible in a high volume-manufacturing environment.

The Gummel plots overlaid in Fig. 3 include typical large area results from both a thick and a thin base layer device. The gain variation is the result of differences in the base current at high injection levels. The collector current is nearly identical in both devices, having an ideality factor of 1.01. In both cases the base current at low bias is small, indicating minimal space charge recombination. The difference in base current, and therefore current gain, is dominated by neutral base recombination, which is linear with base thickness. The higher base sheet sample has a thinner base resulting in reduced recombination and increased current gain.

The dc current gain (β) of large area HBT devices is an important figure of merit reflecting the material quality of the device. The current gain at low current density is limited by space charge recombination in the emitter. At high current density, the current gain is limited by neutral base recombination, which is controlled by the minority carrier lifetime of the electrons in the heavily doped p-type base layer. In the case where gain is limited by neutral base recombination, the gain is expressed as a function of the minority carrier lifetime in the base (τ), base thickness (w_b), and average minority carrier velocity in the base (υ) [5]

$$\beta \cong \upsilon\tau/w_b$$

Fig. 4 shows dc current gain as a function of base sheet resistance (R_{sb}) from two different series of InGaP/GaAs HBT’s measured at high injection levels (J_c = 1.0 kA/cm^2). In each series, the HBT structure is identical except for the base thickness. The dc current gains in this base sheet resistance range are consistent with state-of-the-art 4-inch InGaP/GaAs HBT wafers. The solid lines represent fits to the gain as a function of R_{sb}. The low gain series, (◊), exhibits a linear dependence on R_{sb}, as expected for structures where the base current is dominated by recombination in the neutral base.(see above discussion) The high gain series, (Δ), is best fit by a power function with a power exponent (m) exceeding 1.35. ($\beta=A_o R_{sb}^m$) The power law dependence of dc current gain on base sheet resistance is unexpected for HBTs limited by neutral base recombination. However, high performance GaAs-based HBTs have consistently shown such a dependence.[3][6] The non-linear behavior of the current gain suggests that the minority carrier lifetime may exhibit a thickness dependence. This could be explained if the minority carrier lifetime moves from a regime controlled by trap recombination to a regime where Auger recombination begins to play a role.

Conclusion

Production InGaP/GaAs 6” HBT wafers with individual layer thickness, composition, and doping variations of less than 5% have been demonstrated via electrical and photoreflectance measurements. A dc current gain of 280 at a base sheet resistance of 425 ohms/sq is shown, among the highest reported for this material system. Finally, the current gain displayed a power law dependence on base sheet resistance, typical of state-of-the-art InGaP HBTs.

References:

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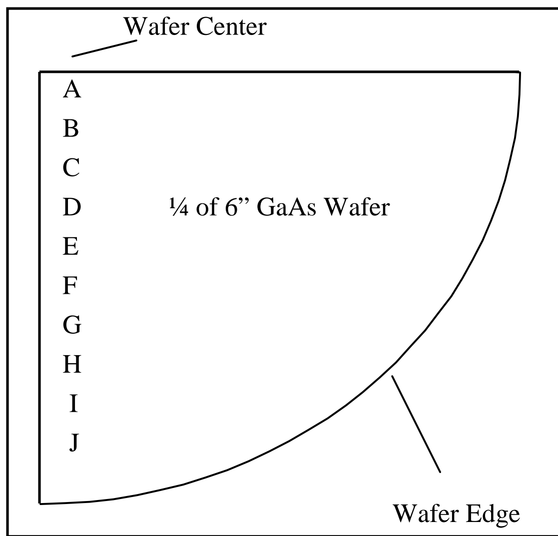
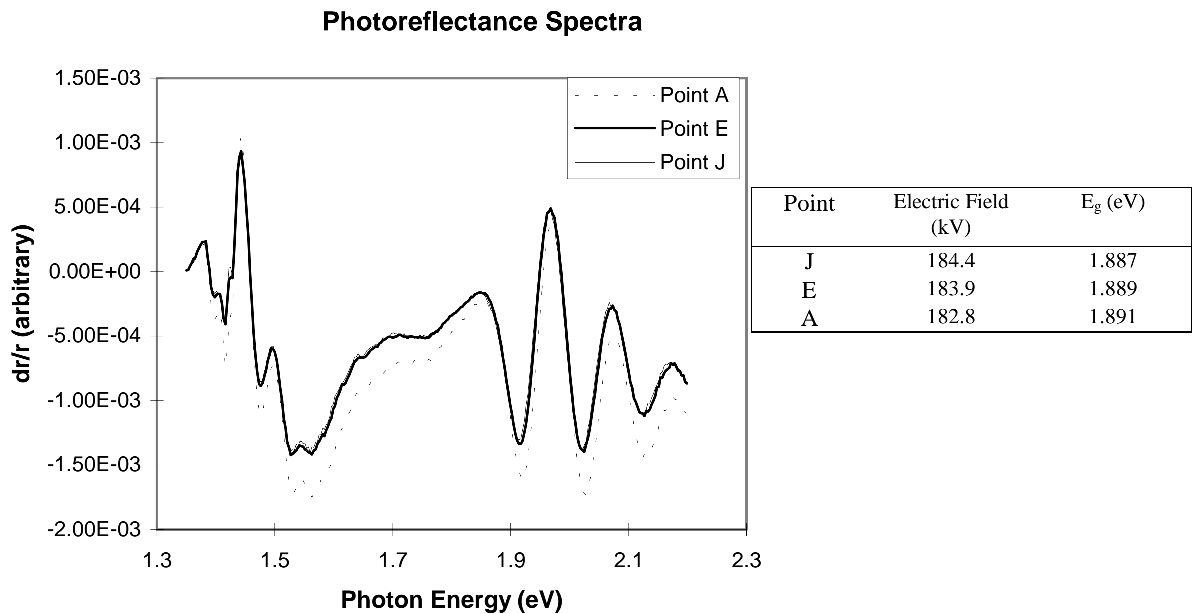


Data Point	Beta @ 1kA/cm2	Vbe @ 100mA	BVbeo (V)	BVcbo (V)	Base Cross (Ohms/sq.)	Emitter Cross (Ohms/sq.)
A	104.4	1.1031	7.22	17.8	237	33
B	103.4	1.1034	7.21	18.0	237	34
C	103.9	1.1033	7.22	17.8	237	33
D	104.5	1.1025	7.22	18.0	240	33
E	106.8	1.1006	7.22	18.0	238	34
F	103.4	1.1016	7.24	17.8	241	32
G	103.4	1.1025	7.24	17.8	241	32
H	103.6	1.1008	7.24	17.8	241	32
I	104.2	1.1004	7.22	17.8	242	33
J	105.6	1.1001	7.19	17.8	243	34
Mean	104.3	1.1018	7.22	17.9	239.7	33.0
Std. Dev.	1.1	0.0013	0.02	0.1	2.3	0.8

Figure 1. Large area device characteristics (L = 75 μm x 75 μm) taken in a radial direction on a 6” InGaP/GaAs HBT wafer. DC current gain, V_{be}, base sheet resistance, emitter sheet resistance, base-emitter breakdown voltage, and collector-base breakdown voltages are shown in the table.



Point	Electric Field (kV)	E_g (eV)
J	184.4	1.887
E	183.9	1.889
A	182.8	1.891

Figure 2. Photoreflectance spectra taken at the center, radial midpoint and edge of a 6” InGaP/GaAs HBT. The emitter electric field and band gap are shown in the table.

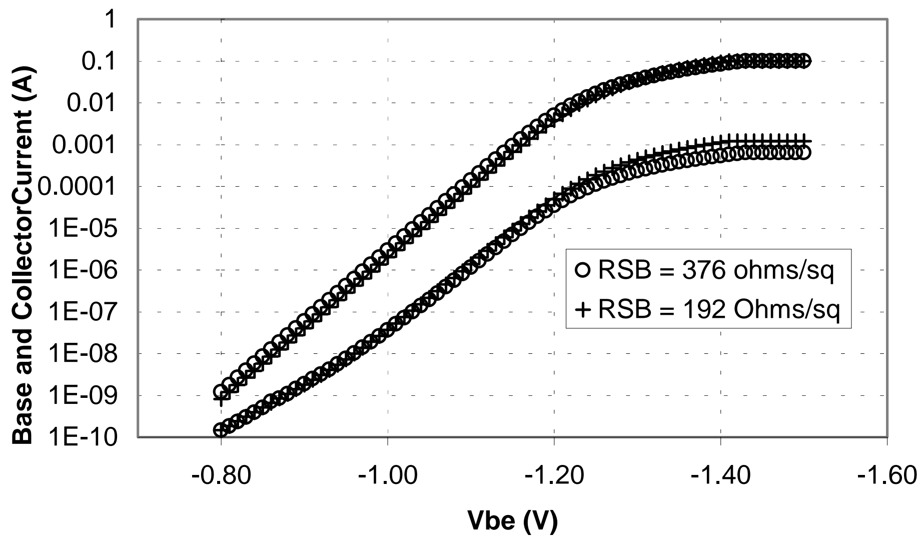


Figure 3. Gummel plots of a low and high gain InGaP/GaAs HBT (L = 75 μm x 75 μm) are shown. The base current at low V_{be} is very low, a characteristic of InGaP HBTs. (Base thickness = 500 and 900 Angstroms, respectively)

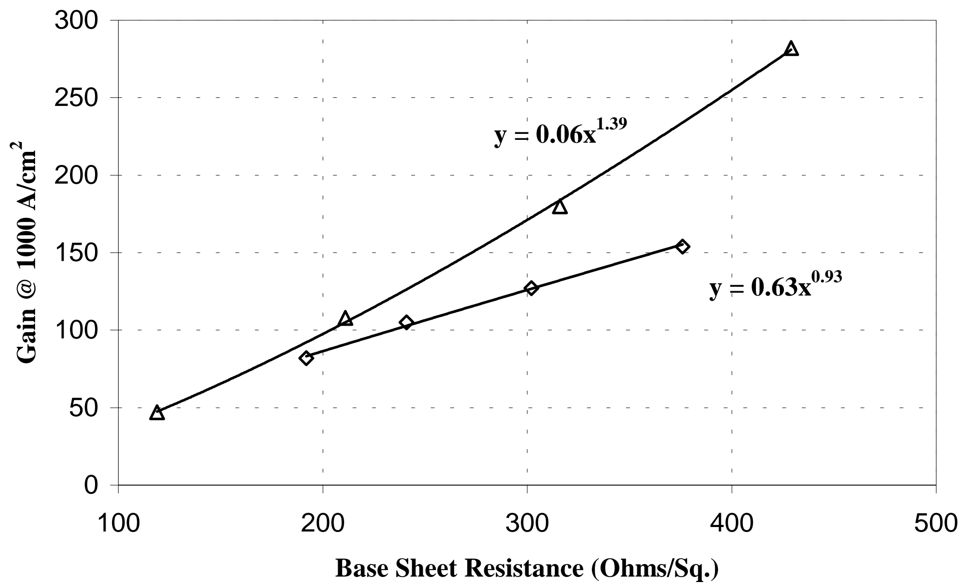


Figure 4. The DC current gain measured at 1 kA/cm^2 in large area devices (L = 75 μm x 75 μm) as a function of base sheet resistance. The solid lines represent power fits to the data series. The base thickness was changed to yield varying sheet resistance.