

Characterization and Control of Epitaxial Material for HBT Manufacturing

I. D. Calder, E.M. Griswold and G. Hillier

Advanced Technology Laboratory, Nortel Networks, P.O. Box 3511, Stn. C
Ottawa, Ontario, Canada K1Y 4H7

Phone: (613) 763-5442, e-mail: icalder@nortelnetworks.com Copyright © 1999 GaAs Mantech

ABSTRACT

An extensive toolkit of characterization techniques has been assembled to monitor epitaxial growth of GaAs and GaInP layers for HBT fabrication. Resistivity and particle count measurements are made on every wafer; photorefectance spectroscopy (PR) provides rapid feedback on composition and GaAs doping levels, and x-ray diffraction rocking curve analysis (XRD) of a grown-in superlattice structure supplies growth rate data. Selected wafers undergo SIMS and SEM analysis to determine thickness, doping, and composition of all layers. Thick GaInP and p+ GaAs calibration layers provide information on composition and carbon doping, through photoluminescence (PL), Hall effect, and XRD. Together, PL, PR, and XRD correlate GaInP ordering with reactor-to-reactor variations in material properties. This toolkit not only measures all important growth parameters, but also provides some redundancy to check measurement consistency, a basis for SPC, and correlations with device characteristics.

INTRODUCTION

GaAs HBT's are being manufactured with lattice matched GaInP emitters exhibiting cut-off frequencies in excess of 60 GHz [1]. They are used in high speed circuitry for Nortel Networks OC-192 (10 Gb/s) telecommunications system. GaInP emitters are preferred over the more traditional AlGaAs because of greatly improved reliability, as well as better device characteristics and easier processing.

Manufacturability of such an advanced technology, in particular the ability to obtain high yield, requires precise and reproducible epitaxy. This goal is accomplished by providing fast turnaround characterization of epitaxial growth using an extensive toolkit of analytical techniques. Thickness, composition, and doping levels throughout the structure are monitored on all wafers, as well as on some special calibration wafers, using a variety of techniques. The value of optical characterization in particular has been recognized for some time because of its precision and non-destructive nature [2].

EPITAXY

Epitaxial growth for our standard device consists of a 0.3 μm thick n⁺ sub-collector, a 0.4 μm thick collector, a 0.05 μm thick p⁺ base, a 0.05 μm thick GaInP n-type emitter, and a 0.2 μm thick n⁺ emitter cap layer. The doping levels are 5 $\times 10^{18}$ cm⁻³ for the sub-collector and emitter cap, 3 $\times 10^{16}$ cm⁻³

for the collector, 4 $\times 10^{19}$ cm⁻³ for the base, and 4 $\times 10^{17}$ cm⁻³ for the emitter. The n-type dopant is silicon and the base dopant is carbon. Material is routinely grown on an in-house MOCVD (metalorganic chemical vapor deposition) reactor and an in-house CBE (chemical beam epitaxy) system; MOCVD material is also obtained from an external vendor. There are systematic differences between wafers from different sources. Parameter targets are fine-tuned to reflect these differences.

CHARACTERIZATION

Our in-house MOCVD wafers include an 8 period 5 Å InAs / 295 Å GaAs superlattice grown into the first 2400Å of the subcollector. The superlattice period is measured by x-ray diffraction (XRD) and acts as a growth rate and uniformity monitor. A typical rocking curve is shown in Fig. 1. The peaks surrounding the intense narrow substrate peak are the result of the InAs/GaAs superlattice in the subcollector. Spacing between fringe peaks is inversely proportional to the combined InAs and GaAs layer thickness in the superlattice. Every wafer is also sent for resistivity

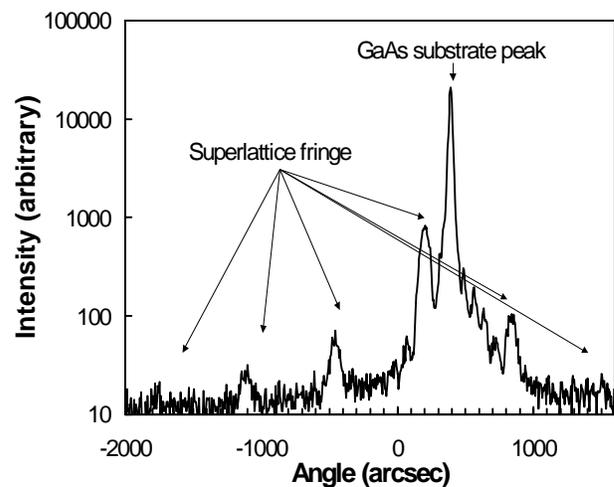


Figure 1. X-ray rocking curve from a full HBT structure. The peaks surrounding the intense narrow substrate peak are the result of the InAs/GaAs superlattice in the subcollector

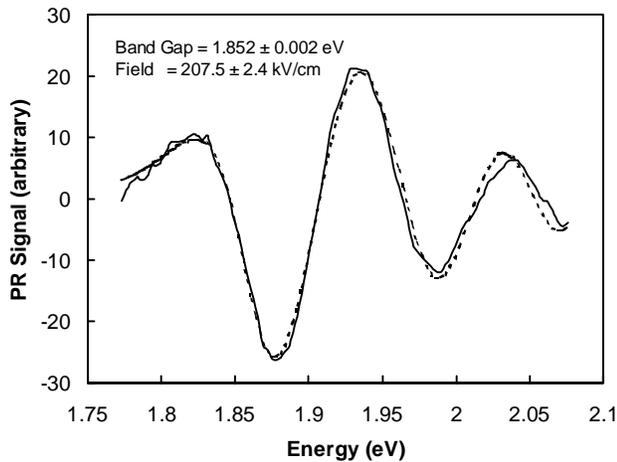


Figure 2. PR spectrum for the GaInP emitter near the emitter/base junction. The data are shown by the solid line, while the numerical fit is given by the dashed line. The parameters extracted from the fit are $E_g = 1.852$ eV and electric field = 207.5 kV/cm.

measurement to monitor the highly conductive emitter cap and sub-collector regions, for particle count measurements, and for analysis by photoreflectance modulation spectroscopy (PR) [3]. Selected wafers are analyzed destructively using secondary ion mass spectroscopy (SIMS) and scanning electron microscopy (SEM) in order to determine layer thicknesses and (SIMS only) composition and doping. Special calibration wafers are also produced that consist of a thick (0.5-2.0 μ m) GaInP layer on a GaAs wafer. These contain enough ternary material to enable photoluminescence (PL), Hall effect, and XRD measurements of bandgap, activated dopant, and lattice matching, respectively.

Photoreflectance

Photoreflectance is a non-destructive optical spectroscopic technique that provides a precise measure of transition energy and electric field in semiconductors. The dependence of optical reflectivity on illumination intensity provides insight into the dielectric function and hence into the material properties. PR is particularly sensitive at surfaces, junctions, or interfaces, and requires the presence of a (built-in or externally applied) electric field.

A typical PR spectrum for the GaInP emitter region (near the emitter/base junction) is illustrated in Fig. 2. The spectral line shape is fit numerically to a theoretical expression [4] in order to extract energy gap and electric field. This procedure accounts for contributions from transitions to all three valence bands. The GaAs portion of the PR spectrum arises mainly from the collector near the base/collector junction. Since the band gap of GaAs can be assumed, a somewhat simpler analysis is used here to obtain the electric field in the collector. The uncertainties in the extracted parameters and the consequent accuracy for determination of the related

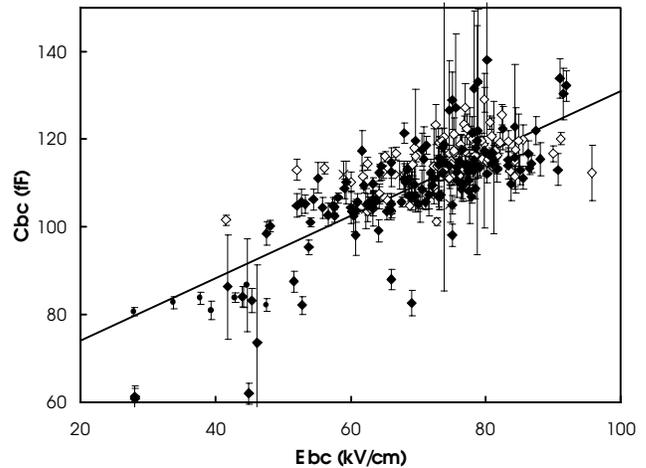


Figure 3. Correlation between base-collector field capacitance measured on finished devices, and the base-collector electric field as measured by PR after epitaxial growth.

physical properties of the semiconductor are summarized in Table I. To obtain the accuracy values, Vegard's Law is assumed for band gap, while the emitter and collector electric fields are assumed to vary as the square root of dopant concentration. In all cases the accuracy obtained is much smaller than the acceptance range of the particular property.

TABLE I
ACCURACY OF PHOTOREFLECTANCE MEASUREMENTS

Parameter	Uncertainty	Property	Accuracy
Band gap	3 meV	GaInP composition	0.002
Emitter field	4 kV/cm	Emitter doping	$4 \times 10^{15} \text{ cm}^{-3}$
Collector field	8 kV/cm	Collector doping	$2 \times 10^{15} \text{ cm}^{-3}$

We have correlated PR measurements with device characteristics. For example, shown in Fig. 3 is a plot of base-collector capacitance compared with the collector field extracted from PR analysis.

BANDGAP CENTERING

The bandgap obtained from PR (or from PL) does not depend solely on the composition. GaInP in particular can experience atomic ordering within the Ga-In sublattice [5]. As the order parameter η varies from fully disordered ($=0$) towards fully ordered ($=1$), where the Ga and In atoms are on alternate planes of the sublattice, there is a band gap reduction (BGR) from 1.915eV to \sim 1.44eV [6]. At the same time, valence band splitting (VBS, the anisotropy between the [110] and $[\bar{1}\bar{1}0]$ directions) increases from 0 to \sim 60meV.

If the PR signal is measured with the incident light polarized first along the [110] and then along the $[\bar{1}\bar{1}0]$

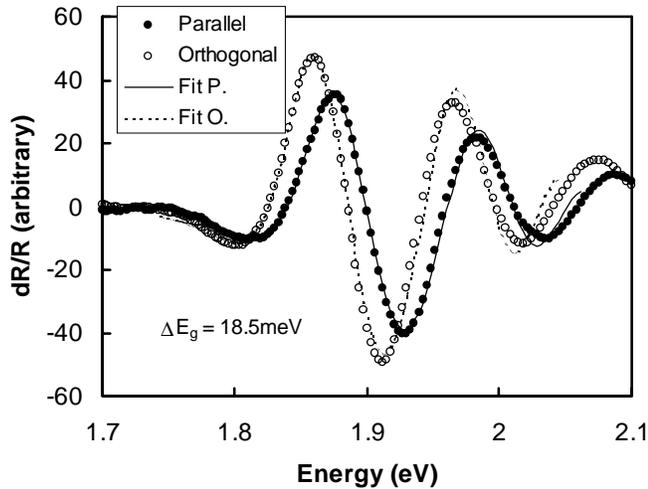


Figure 4. PR spectra for the same sample, with the incident polarized parallel and orthogonal to the [110] direction. The points show the measurements, while the fits are given by solid and dashed lines. The average band gap was 1.85eV.

directions, the difference in band gap between the two directions gives the VBS, which we then use to determine the degree of ordering [7]. Figure 4 shows the difference between two spectra taken on the same MOCVD-grown sample, but with light polarized in orthogonal directions. The VBS is 18.5meV, which indicates an order parameter η of 0.39. The corresponding BGR is then predicted to be 75meV, very close to the observed value of 70meV.

We also grow HBT structures by CBE. When the polarized PR technique was applied to a CBE wafer, the VBS was only 7meV, corresponding to $\eta = 0.23$. The equivalent theoretical BGR is 25meV, which again agrees well with the

observed reduction of 20 meV. These results imply that we are growing lattice matched material, since, within our uncertainties, we can account for the BGR through ordering alone. Figure 5 shows selected area diffraction patterns (SADP's) from [100]-oriented samples of our GaInP layers grown by MOCVD and CBE, as well as from a similar structure grown by MOCVD by an external supplier. All three SADP's contain the fundamental diffraction spots expected for a zinc-blende material. In the case of the Nortel MOCVD sample, and to a lesser extent the external sample, additional intensity is observed at $\frac{1}{2}(111)$, $\frac{1}{2}(311)$, $\frac{1}{2}(331)$ and higher order sites. These spots, and the absence of similar intensity in the corresponding [110] patterns, is representative of "Cu-Pt-type" atomic ordering [8]. Diffraction spots due to ordering are not observed in the CBE sample, corresponding to the lower degree of order in this material, as indicated by the polarized PR results.

Because the band gap of GaInP depends on the degree of ordering, which will depend on the deposition equipment even when all material is lattice matched, we cannot have a single target specification for band gap. For example, we have a difference of 30meV between the targets for our MOCVD and CBE material.

In order to confirm the validity of this approach, we must directly measure the degree of lattice matching for our GaInP and compare it with band gap over a reasonable range of compositions. We use XRD to measure lattice mismatch and then plot that against PL bandgap. By interpolating to zero mismatch we can directly compare the centre points for each method. Plotted in Fig. 6 are data for Nortel MOCVD, CBE, and externally grown material. Bulk GaInP samples are typically produced after source or system changes to guarantee material compliance and system calibration. These samples are 0.5 to 2 μm thick and doped with $4 \times 10^{17} \text{ Si/cm}^3$. An XRD measurement will return a precise measurement of

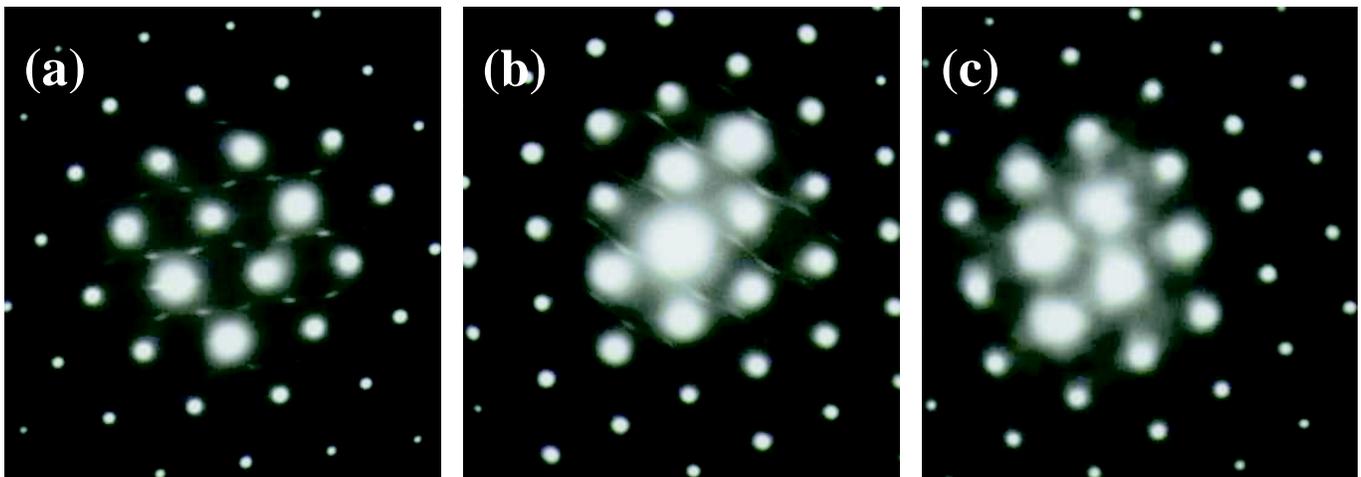


Figure 5. Selective area diffraction patterns of GaInP emitter regions, taken with a transmission electron microscope. The three samples are from material grown by (a) MOCVD at Nortel, (b) MOCVD at an external supplier, and (c) CBE at Nortel. Superlattice diffraction spots (halfway between the bright spots) are clearly seen in the MOCVD sample from Nortel, while a much longer exposure was required to make them visible in the MOCVD grown externally. They cannot be seen at all in the CBE sample.

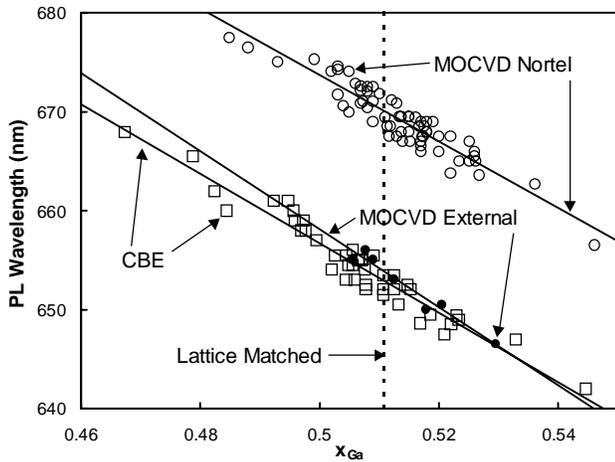


Figure 6. Bulk GaInP sample correlation for material grown in house—MOCVD Nortel, CBE, and externally—MOCVD external.

epi mismatch which, assuming Vegard's Law, can then be converted to a Ga composition fraction. Note that coherent GaInP layers, lattice matched to GaAs, will be composed of 51.1% Ga. Plotting these data along with room temperature photoluminescence, the composition for the three sources of material are compared. The increasing target PL bandgaps of 1.851 eV, 1.897 eV, and 1.899 eV for MOCVD (Nortel), MOCVD (external), and CBE correspond to the decreasing degree of order observed by PR and TEM.

CARBON DOPED GAAS BASE MATERIAL

Without the aid of SIMS or some sort of large area device process, the determination of a correctly doped base is elusive. Therefore it is prudent to produce a bulk carbon doped GaAs calibration sample from time to time. Nortel has performed resistivity, XRD, SIMS and Hall measurements on these samples to help guarantee consistent material quality.

Highly carbon doped ($[C] > 4 \times 10^{18} \text{ cm}^{-3}$) GaAs is a pseudomorphic material due to the lattice contraction caused by the small carbon atom on the group V lattice site. In addition to the lattice contraction, hydrogen, which is suspected to be chemically bonded to carbon, causes a relative lattice expansion. Care must be taken to appropriately anneal the sample of hydrogen prior to analysis.

The effect of annealing p-GaAs is a relative shift to higher strain for a given total amount of carbon. Figure 7 illustrates this effect by comparing active (Hall) and total (SIMS) carbon in the lattice for samples prior to an *in situ* anneal step, with Hall data after an anneal step was introduced into the recipe. The differences in the Hall data are not statistically significant.

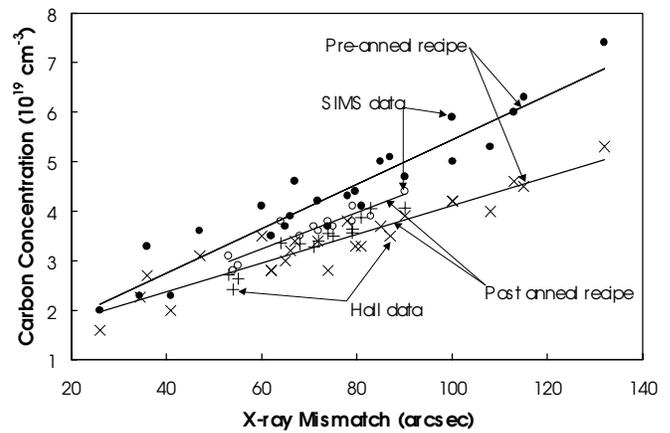


Figure 7. Correlation of lattice parameter with total (SIMS) and active (Hall) carbon in GaAs before and after anneal process was introduced...

To simplify p-GaAs calibration measurements, it is possible to use the above correlation to XRD data along with sheet resistance to ensure proper layer thickness and doping level. If this calibration procedure is used between batches of runs, we can guarantee HBT material compliance to spec.

ACKNOWLEDGEMENTS

We wish to thank Deborah Clark and Richard Arès for providing the CBE samples, Rick Streeter for the SIMS measurements, and Scott Campbell for the PL.

REFERENCES

- [1] R. Surridge and T. Lester, "GaInP/GaAs HBT Manufacture for 10 Gb/s Telecommunications Applications", *Proc. 1998 GaAsMANTECH*, pp. 97-10, 1998.
- [2] P.B. Smith, W.M. Duncan, and A.A. Allerman, "Optical Characterization of Heterojunction Bipolar Transistors", *IEEE J. of Selected Topics in Quantum Electronics*, pp. 1011-1016, 1995.
- [3] F.H. Pollak, W. Krystek, M. Leibovitch, and H. Qiang, "Contactless Room Temperature Analysis of Heterojunction Bipolar Transistor Wafer Structures using Photoreflectance", *Proc. Int. Workshop on Semicond. Char.: Present Status and Future Needs*, pp. 669-672, 1995.
- [4] D.E. Aspnes and N. Bottka, "Electric-Field Effects on the Dielectric Function of Semiconductors and Insulators", *Semiconductors and Semimetals Vol. 9, Modulation Techniques*, ed. By R.K. Willardson and A.C. Beer, Academic Press, New York, pp. 457-543, 1972.
- [5] A.G. Norman, "Transmission Electron Microscopy and Transmission Electron Diffraction Studies of Atomic Ordering in Group III-V Compound Semiconductor Alloys", *Proc. NATO Advanced Workshop on the Evaluation of Advanced Semiconductor Materials by Electron Microscopy*, pp. 233-253, 1988.
- [6] P. Ernst, C. Geng, F. Scholz, and H. Schweizer, "Band-Gap Reduction and Valence-Band Splitting of Ordered GaInP₂", *Appl. Phys. Lett.* **67**, pp. 2347-2349, 1995.
- [7] Y.-S. Huang, W.D. Sun, F.H. Pollak, J.L. Freeouf, I.D. Calder, and R.E. Mallard, "Contactless Electoreflectance Characterization of GaInP/GaAs Heterojunction Bipolar Transistor Structures", *Appl. Phys. Lett.* **73**, pp. 214-216, 1998.
- [8] Y.-E. Ihm, N. Otsuka, J. Klem, and H. Morkoç, "Ordering in GaAs_{1-x}Sb_x Grown by Molecular Beam Epitaxy", *Appl. Phys. Lett.* **51**, pp 2013-2015, 1987.