Characterization and Control of Epitaxial Material for HBT Manufacturing

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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; photoreflectance 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 0.3µm thick n⁺ sub-collector, a 0.4µm thick collector, a 0.05µm thick p⁺ base, a 0.05µm thick GaInP n-type emitter, and a 0.2µm thick n⁺ emitter cap layer. The doping levels are 5×10¹⁸ cm⁻³ for the sub-collector and emitter cap, 3×10¹⁸ cm⁻³ for the collector, 4×10¹⁹ cm⁻³ for the base, and 4×10¹⁷ 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.](image-url)
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 µm) 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 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>
<thead>
<tr>
<th>Parameter</th>
<th>Uncertainty</th>
<th>Property</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band gap</td>
<td>3 meV</td>
<td>GaInP composition</td>
<td>0.002</td>
</tr>
<tr>
<td>Emitter field</td>
<td>4 kV/cm</td>
<td>Emitter doping</td>
<td>4x10^{15} cm^{-3}</td>
</tr>
<tr>
<td>Collector field</td>
<td>8 kV/cm</td>
<td>Collector doping</td>
<td>2x10^{15} cm^{-3}</td>
</tr>
</tbody>
</table>

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 1.915 eV to ~1.44 eV [6]. At the same time, valence band splitting (VBS, the anisotropy between the [110] and [110] directions) increases from 0 to ~60 meV.

If the PR signal is measured with the incident light polarized first along the [110] and then along the [110]
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 $h = 0.39$. 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 $h = 0.23$. 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 $\frac{1}{2}(111)$, $\frac{1}{2}(311)$, $\frac{3}{2}(311)$
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 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.](image)

![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.](image)
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] > 4x10^{18} 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.

ACKNOWLEDGEMENTS

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REFERENCES


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

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