MBE Production of HEMT Material for Commercial Applications

Michael Wojtowicz, Thomas Block, Richard Lai, Michael Barsky, An-Chich Han,
and Dwight Streit
TRW Electronics and Technology Division
One Space Park, R6/2573, Redondo Beach, CA 90278

We report here the material monitoring aspects of TRW's high yield, high volume molecular beam epitaxy process. The uniformity, reproducibility, and reliability of MBE grown HEMT material have enabled the development of this commercial HEMT production line. Only a small set of all the possible epitaxial layer properties cause the majority of our device performance variations. They are channel width, channel In composition, Al barrier layer composition, and starting substrate. We will discuss how these parameters affect HEMT device performance and how they are monitored.

Low cost, high performance millimeter-wave power HEMT MMICs are required for many commercial as well as DoD system applications. These include wireless LANs, wireless cable broadcast transmitters and PCS microcell transponders for the commercial market and smart munitions and satellite crosslinks for DoD applications. Most of these applications are very cost driven, requiring superior millimeter-wave performance and a high yield. Reproducibility and control of the epitaxial material is critical to achieve the necessary yield and cost.

We report here the material monitoring aspects of TRW's high yield and high volume molecular beam epitaxy process for the production of HEMT epitaxial material. This material is grown to support TRW's HEMT production line. Control of all HEMT material properties such as layer thickness, alloy composition, material defect density, and surface morphology is essential to obtaining the uniformity, reproducibility, and reliability necessary in a HEMT production line. Extensive material characterization is necessary to monitor and control these parameters. At TRW we use a variety of characterization tools but are primary techniques are photoreflectance, photoluminescence, x-ray rocking curve, resistivity mapping, Hall effect, and surface scattering measurements.

To discuss the effects of all the material parameters on device performance and to detail the characterization tools would be a very lengthy paper. Instead, we have found that only a few HEMT material parameters cause the majority of device performance variations. They are channel thickness, channel In composition, barrier layer Al composition, and substrate material. Only these will be discussed here. Others parameters such as channel sheet charge and mobility are certainly important but they can be easily monitored and controlled through resistivity and Hall effect measurements.

In addition to the ability of characterizing the material properties, communication between the material growth, characterization, and processing groups is critical to establishing a reproducible process. Problems in the process area must be investigated without a preconceived bias as to the origin. Mistakes and process drift will occur throughout the production chain and must be correctly efficiently and quickly. At TRW all of our material is grown in-house so our materials, characterization, and processing groups are very integrated and issues are resolved quickly. This has been one of the keys to our production process.

Fig. 1 shows a schematic of a typical InGaAs/AlGaAs/GaAs HEMT device epitaxial layer structure. We also grow special structures identical to our device structure except the 50 nm GaAs n+ cap is replaced with a 5 nm GaAs undoped cap. This special structure is grown once per day as a material process monitor and is used for our Hall effect and photoluminescence (PL) measurements. The material overhead is very small but by removing the heavily doped cap our measurements are much more sensitive to material variations in the channel.

Typical 300K channel carrier concentrations are $3.5\text{x}10^{12}$ cm^{-2} with mobilities > 5,000 cm^2/V-s as measured by Hall effect. The processed devices feature 2 μm source-drain spacing, 0.15 μm gate widths, source vias, and airbridge gates. These devices show D.C. peak G_M > 550 mS/mm, F_T > 80, and gate-to-drain breakdown voltages > 9.5 V.

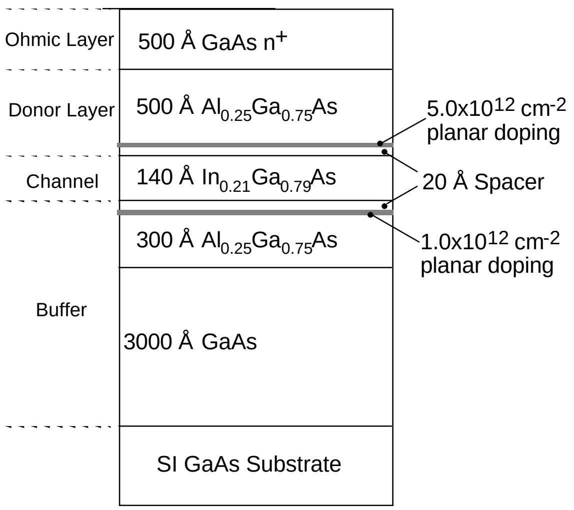

Fig. 1. Typical HEMT material profile.

The channel is the most important material region since the carriers and transport are primarily confined to this region. Both In composition and channel width can affect the final device performance. The In composition affects device performance primarily through the dependence of mobility and saturation velocity on In composition. Channel mobility affects the performance by increasing the source and drain resistances. However, channel mobility and channel sheet charge are easily and directly monitored through Hall effect measurements. This is an important measurement but is very well known so it will not be discussed here. The following two simple charge control derived equations for G_M and maximum frequency of oscillation (F_T) show the relationship to saturation velocity clearly.

$$g_m = \frac{\partial I_{ds}}{\partial V_{gs}} \approx \frac{C_{gs}}{\tau_{ds}} = \frac{\varepsilon_o \varepsilon_r v_s}{(d+\Delta d)}$$

$$f_t = \frac{v_s}{2\pi L_g} = \frac{g_m}{2\pi\left(C_{gs}+C_{gd}\right)}$$

Channel width also affects device performance through the Δd term. This term is a measure of the distance between the delta doping layer and the average electron concentration. Increasing channel electron confinement minimizes this term. Wider channels provide better confinement by reducing the energy levels in the channel. Fig. 2 shows a plot of device F_T and peak G_M as a function of channel width. Device performance increases from 10 to 20 nm and then suddenly degrades. Misfit dislocations running in one direction, <110> occur for channel widths > 14 nm. However, the performance does not degrade until the channel strain becomes large enough to form an orthogonal set of dislocations. This occurs at a channel width of 20 nm.

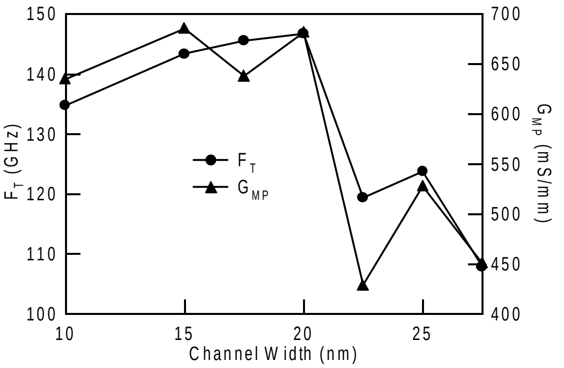

Fig. 2. F_T and G_M as a function of channel thickness.

Fig. 3 shows a plot of the channel conductivity and wafer surface haze as a function of channel width. The channel conductivity decreases slightly for channel widths from 10 to 25 nm then decreases rapidly past 25 nm. Channel mobility decreases as the channel width increases past 14 nm but the channel sheet concentration increases, countering the affect of the decreasing mobility. The benefit of increased confinement outweighs the mobility degradation. The device performance is more sensitive to channel width for lower electron effective masses, e.g. high In composition, because of the strong energy level dependence on the effective mass.

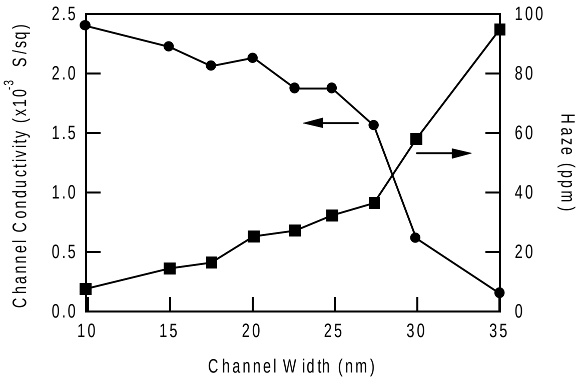

Fig. 3. Channel conductivity and wafer surface haze as a function of channel width.

There are two additional affects that will limit the benefits of increasing channel width. As the channel becomes wide enough the quantum confinement effects will be reduce. At a certain width the channel will no longer be a quantum confined system and the device performance will degrade because the electron confinement is being reduced. Also, for small gate widths the benefit of a wide channel will be reduced because of fringing field affects, i.e. aspect ratio, will limit the ability of the gate to control the channel charge.

Channel monitoring is accomplished through photoluminescence and x-ray rocking curve measurements. Fig. 4 shows the PL spectra for channel widths from 10 to 35 nm. Both the intensity and peak positions change with channel width. In addition, the channel In composition will also affect the peak energies making it very problematic to separate the two effects. In addition, low temperature PL is considered a destructive measurement and cannot be performed on device wafers.

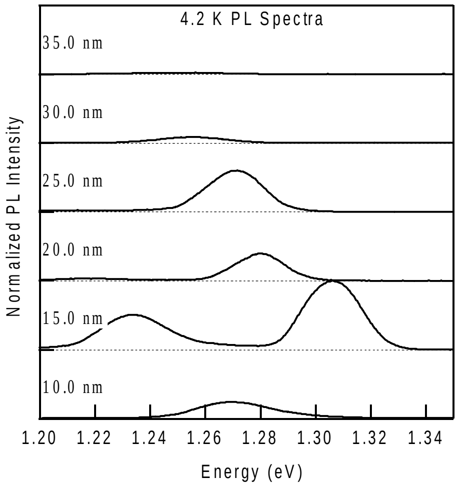

Fig. 4. PL spectra of HEMTS with varying channel widths.

X-ray rocking curve measurements, on the other hand, are non-destructive and can separate the effects of channel thickness and In composition. Fig 5 shows a plot of two rocking curves for different channel widths and compositions which clearly shows a shift and change in width of the broad peak, -2000 to –5000 arcsec, corresponding to the InGaAs channel. The problem with x-ray curves is that they must be fit to yield the channel width and composition. This can be a very labor intensive task not suited for a production process. However, recently a major x-ray equipment manufacturer has developed a rapid, robust automated fitting software routine which can allow these x-ray measurements to part of the production process.

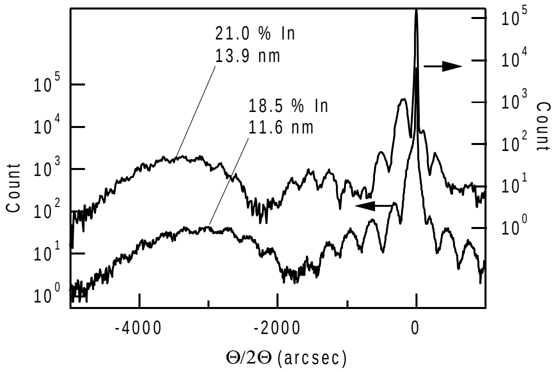

Fig. 5. X-ray rocking curve measurements illustrating the affect of channel width and In composition on the spectra.

The Al composition of the barrier layers affects device performance by changing the confiment of charge in the channel and by affecting the device processing. As seen in the case of wide channels, carrier confinement provided by the barrier layers is very important to device performance. Greater Al composition provides more confinement and variations in the Al composition will cause device performance variations. In addition to the direct confinement affect, the Al composition affects the gate recess etch. The etch is peroxide based and for high Al the etch proceeds slower which increases the amount of lateral etching. This causes changes in the final gate recess width. In this material system the breakdown voltage is dependent on the recess width as shown in Fig. 6. The reason is due to the strong surface pinning of the AlGaAs exposed in the recess depleting electrons from the channel region. This provides a resisitive region that can drop some of the applied bias. This effect also causes a reduction of the frequency performance due to affective widening of the gate. In other material systems where the surface pinning is less (InAlAs/InGaAs/InP) there is significantly less dependence of breakdown on the recess width. Large variations of the donor layer thickness will also lead to breakdown voltage varitions due to changes in the etch times.

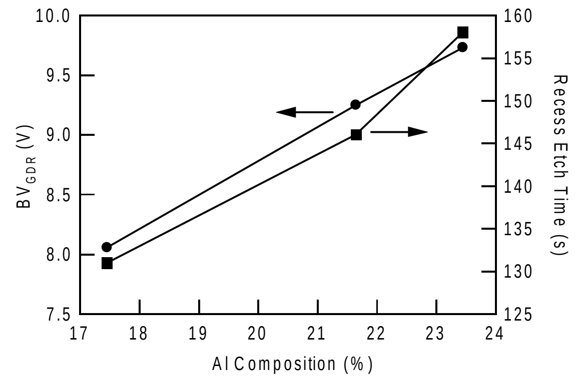

Fig. 6. Gate-to-drain reverse breakdown and recess etch times as a function of Al composition.

The Al composition is measured by photoreflectance. This technique is non-destructive and can be applied to device material. X-ray rocking curve measurements are not very usefull for Al composition monitoring because they are not very sensitive to the Al composition in the HEMT structures. Fig. 7 shows a typical PR response of the HEMT. Spectral response is seen from all regions of the HEMT. However, there are major limitations to the usefullness of most of these spectral features. The primary use is to determine the Al composition.

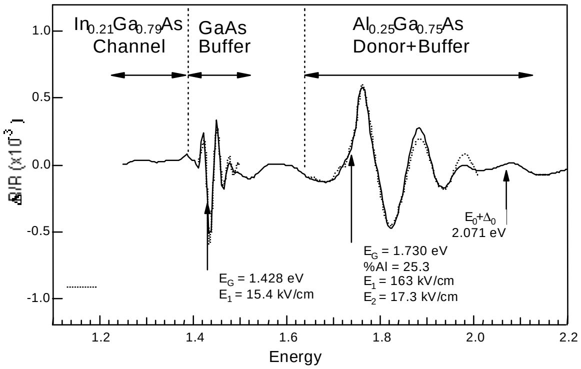

Fig. 7. Typical PR HEMT PR response.

In addition to all the epitaxial material effects, we have found a correlation between HEMT device performance and GaAs substrates. Vertical gradient freeze (VGF) grown substrates allow us to grow thicker channels than liquid encapsulated Czochralski (LEC) grown substrates. Fig. 9 shows the peak G_M and F_T for a series of channel widths from 14 nm to 16 nm. As channel width increases from 14 to 15 nm G_M and F_T increase for both substrate types. From 15 to 16 nm the devices grown on VGF substrates continue to show increasing performance while devices grown LEC substrates show decreaseing performance. The exact cause of this dependence has not been established. We have also seen a dependence of device performance on the x-ray rocking curve FWHM average of the substrate. VGF material shows a lower average FWHM than LEC material. The performance dependence could be due to excess strain or defects in the LEC material causing excess strain in the channel which generates a higher concentration of misfit dislocations.

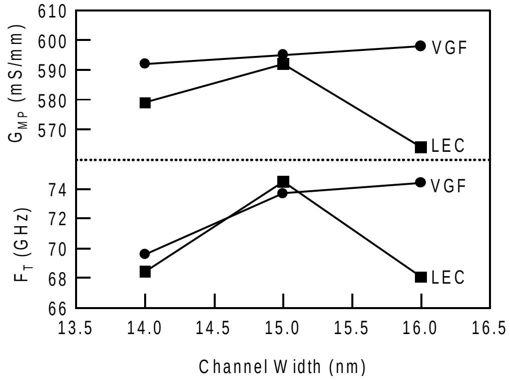

Fig. 9. F_T and peak G_M as a function of channel width for LEC and VGF grown GaAs susbtrates.

In conclusion, we have described the affect of variations in some key HEMT epitaxial material properties on device performance and how we monitor those material properties. The ability to identify the key material properties and monitor them has enabled the development of TRW's HEMT production line. For other production lines the important material parameters may be somewhat different due to different processing techniques. Therefore each line must identify its own set of material parameters. To accomplish this proper analytical tools must be used but of equal importance is the ability to integrate and promote open communication between the epitaxial growth, material characterization, and device processing groups. Without effective communication the key material parameters will not be identified or effectively controlled.