Yield and Efficiency Improvements Using Multi-Field Hall Measurement for High Volume pHEMT Production

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Abstract

Maximizing yield in pseudomorphic high electron mobility transistors (pHEMT's) requires tight control of the electrical properties of the channel layer. Monitoring channel characteristics is therefore critical to keeping the process centered and screening out non-compliant material before the start of the costly fabrication process. The most common monitoring tools include non-contact sheet resistance and single-field Hall measurements. Unfortunately, these techniques provide an average value for the entire epi stack and cannot distinguish between the channel and heavily-doped cap of a typical pHEMT structure. In this paper we will describe the use of a commercially available multi-field Hall system for non-destructive testing of production material. This system is capable of separating the effects of multiple conducting layers, providing an effective monitor of the electrical characteristics of both the channel and cap layers.

BACKGROUND

Characterization of pHEMT electrical properties is complicated by the presence of multiple conducting layers in the epi stack. A schematic diagram of a typical pHEMT structure is depicted in Figure 1. In this case there are two main conducting layers, a high carrier density channel and a heavily-doped cap. Conventional non-contact sheet resistance and single-field Van der Pauw Hall measurements average the effects of these two layers and cannot distinguish between the high mobility carriers in the channel and the low mobility carriers in the cap. This complicates process control since a change in the electrical properties of channel cannot be distinguished from a change in the cap. This problem is commonly addressed by either etching away the cap layer of a production epiwafer before measurement, or growing a specially designed "thin-cap" calibration structure that allows direct measurement of channel properties. In both approaches care must to be taken to account for the carrier depletion layer that forms near the semiconductor surface due to Fermi level pinning. If the cap is too thin the depletion layer will extend into the channel and the measurement will under-estimate the channel carrier density. Conversely, if the cap is too thick it will contain residual carriers that will result in an over-estimation of channel carrier density.

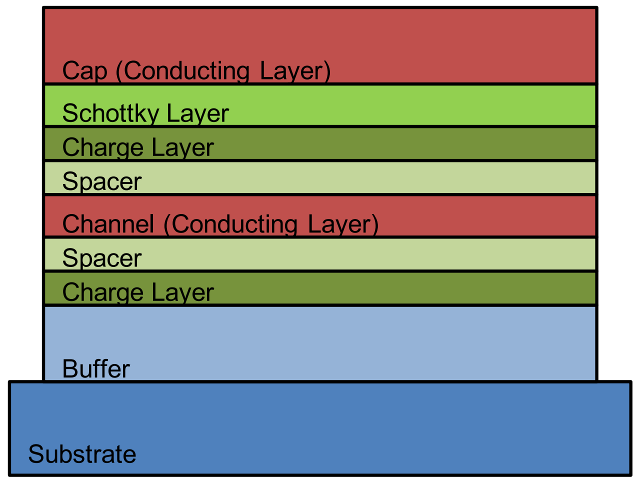

Figure 1: Schematic of a typical pHEMT structure highlighting the presence of two conducting layers.

Hall measurements carried out at multiple magnetic field strengths, combined with appropriate analysis, separate the effects of carriers of different mobility. This technique has been in use in research and development for several years, but has not been widely applied in manufacturing. Multi-field (MF) Hall measurements of whole wafers provide independent characterization of the channel and cap carriers. This eliminates the need for destructive testing of production wafers or the growth of additional calibration runs. The effectiveness of this technique can be seen in the single-field versus multi-field Hall data compared in Figure 2. Measurements were performed on a series of "thin-cap" pHEMTs, grown with cap thickness varying from 50Å to 250Å. Notice that the single-field sheet charge measurement monotonically decreases with decreasing cap thickness while the single-field mobility increases to a maximum value for the 150Å sample and remains constant for thinner caps. The thickness at which the mobility peaks is taken as the point at which the cap has just become fully depleted. Any thinner cap and depletion of carriers from the channel occurs. This results in the continuing decrease in overall carrier density. Compare this to the multi-field Hall results. With the channel and cap carriers separated it is easy to see the onset of channel depletion when the cap thickness drops below 150Å. In addition, both techniques agree on channel charge density and mobility for the 150Å sample. The data also show that the transition is fairly abrupt, demanding precise control of the cap thickness in order to minimize measurement error when using the single-field approach. This data clearly demonstrates the advantage of the multi-field Hall technique in the characterization of pHEMT structures.

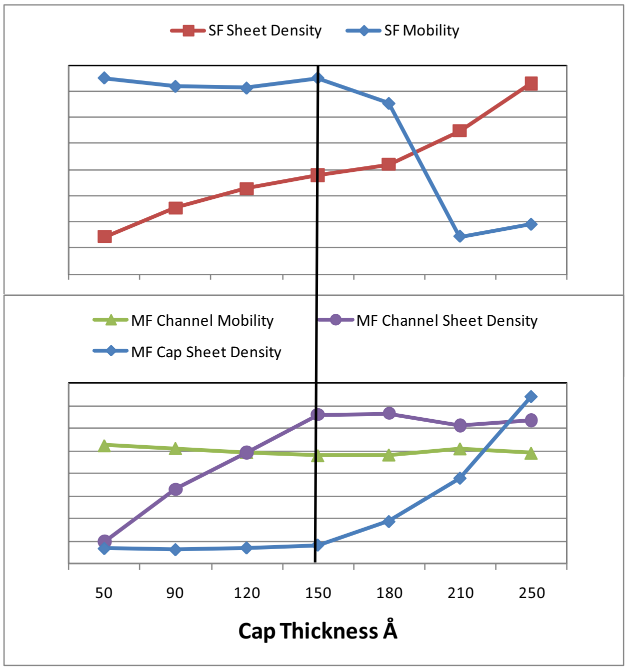

Figure 2: Single field vs. multi-field Hall measurements for "thin cap" pHEMT structures where the cap thickness is varied from 50 to 250Å. There is a clear transition in the data as the cap thickness drops below 150Å. This corresponds to the onset of carrier depletion in the channel.

EXPERIMENTAL

GaAs based pHEMT's were grown by MBE and characterized at room temperature on a Lake Shore 7612 multi-field Hall system. The magnetic field strength for the measurements varied from 3KG to 15KG. Measurements were carried out on whole six inch wafers contacted by spring loaded probe pins tinned with indium. Ohmic contact was achieved by "blasting" the contacts. This process involves applying 200V in 10, 100msec pulses to alternating pairs of contacts with a 100mA current limit. Data analysis was carried out using Lake Shore's QMSA [1] software for separation of channel and cap mobilities and sheet densities. Operating conditions were developed to minimize measurement variability and provide consistent ohmic contact at the edge of the wafer deposition area. In particular, the excitation (Hall) current was found to have a significant effect on the repeatability of multi-field Hall measurements. Figure 3 shows the improvement in measurement standard deviation observed with increasing excitation current. The data is based upon ten measurements of the same wafer at each excitation current. The wafer was removed from the system and then remounted for each measurement. Channel sheet charge density exhibited more variability than the other parameters at all excitation currents. However, the standard deviation is still well below 1% at 100µA and higher. Based upon this data, 300µA was chosen as the preferred excitation current. A more formal gage study was carried out using our optimized measurement conditions for channel sheet charge density. The study yielded a precision/tolerance ratio of ~26%. While not the best P/T ratio in our characterization suite, it is still below the 30% threshold that is typically considered acceptable in a manufacturing environment.

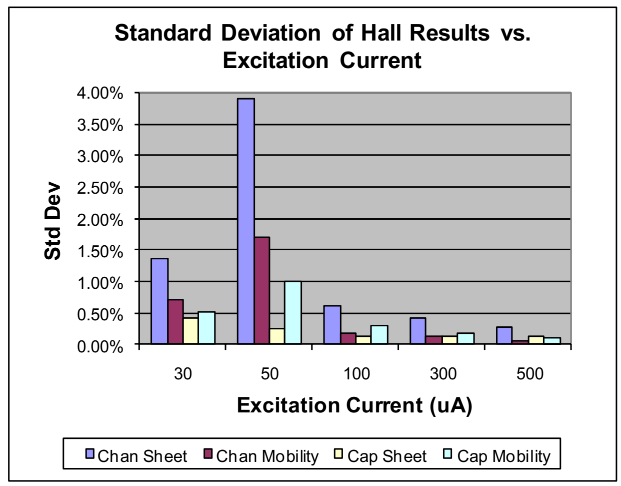

Figure 3: Room temperature multi-field Hall data variability is plotted versus the excitation current used for the measurement. Data is based upon ten measurements of the same wafer with the wafer removed from the sample holder between measurements.

APPLICATION

Application of multi-field Hall measurements to the control of RFMD's pHEMT growth process begins with qualification of the MBE growth system. The initial calibration is based upon historical correlations between channel sheet charge density as measured by MF Hall and process pinch-off voltage (Vpo). MF Hall data is used in the initial calibration of the doping process by targeting the sheet charge which historically correlates to the Vpo target. By using this historical correlation, there is no need to send material for device processing during qualification. This approach can cut several days off the qualification process and also minimizes the number of calibration runs required. Once the pHEMT has all parameters within spec limits and the sheet charge on target, a series of three pHEMT runs centered on the initial calibration data is used to refine the sheet charge value to which the process will be controlled. At this point the system is considered qualified for pHEMT production.

Once a system is in production the electrical characteristics of the channel are monitored by running Hall measurements on three to four wafers per day.

RFMD's Hall technique is non-destructive. Therefore, measured wafers are delivered to the fab for processing. This allows a direct comparison between the Hall data and various DC performance characteristics. Figure 4 plots normalized Hall sheet charge and pHEMT Vpo versus run number from a single growth system over a period of several months. A five-point moving average was applied to the raw data for clarity. Note that these runs are not sequential but represent a sampling over time. Although a linear regression of multi-field sheet charge versus Vpo yields a relatively low R-squared of ~0.50, it is clear from the figure that room temperature multi-field Hall measurements provide a good prediction of trends in device Vpo.

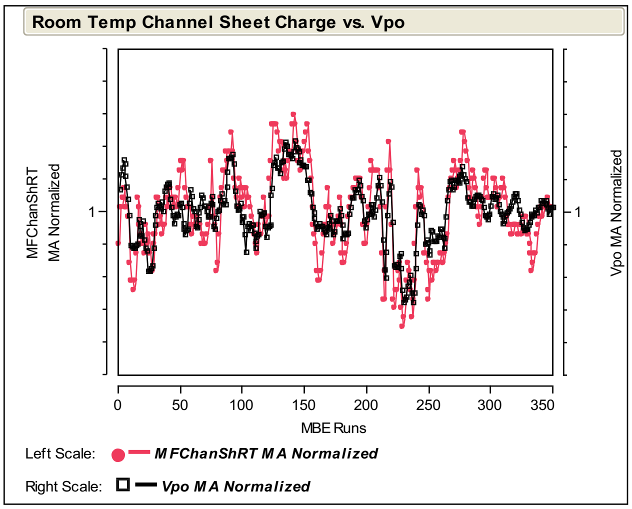

Figure 4: Normalized sheet charge and Vpo data versus run number. The data demonstrates that multi-field Hall measurement of channel sheet charge density closely tracks device pinch-off data, validating its use as a process monitor. Note that this is not a run chart and represents periodic sampling from a particular growth system over a period of several months. Also, the sign of the Vpo data has been flipped by the normalization process.

It can take several days for a wafer to complete enough processing for DC data to become available. In contrast, multi-field Hall data is collected within minutes after a wafer is unloaded from the growth system. This makes the Hall technique a much more effective monitor than feedback from the fab. Should a shift in the growth process be detected, wafers can be quarantined and corrective actions can be implemented immediately. This greatly reduces the risk of passing non-compliant material on to the fab, where the cost of scrapping a wafer escalates rapidly. An example of process control using multi-field Hall measurements is shown in Figure 5. The figure shows adjustments to the silicon effusion cell temperature in response to channel sheet charge density measurements, along with the Vpo values that were subsequently observed for processed devices. At the beginning of the sequence, the Hall data is below target and a series of increases in silicon cell temperature are implemented to re-center the process. Following a slight overcorrection, channel sheet charge and device Vpo are stabilized at their target values. In this example, device pinch-off did not go out of spec. However, the rapid feedback provided by Hall characterization greatly reduced the number of off-target wafers delivered for processing.

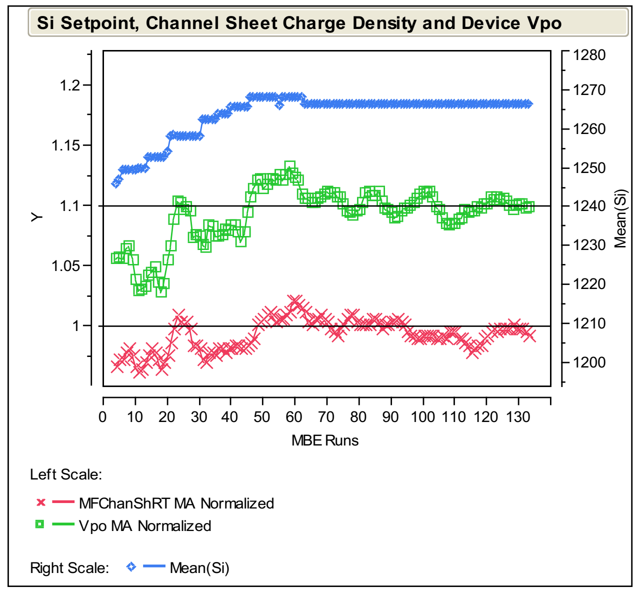

Figure 5: The rapid feedback provided by multi-field Hall measurement makes it an effective tool for process control. In this figure, adjustments to the temperature of the silicon cell are guided by channel sheet charge measurements and are successful in re-centering device Vpo. The hall and Vpo data points are five-wafer rolling averages. The sign of the Vpo data has been flipped by the normalization process.

Thus far, the focus of this paper has been primarily on the electrical properties of the pHEMT channel. An additional benefit of the multi-field Hall technique is that it also provides electrical data for the heavily doped cap layer. While not as critical to device performance, changes in the properties of the cap provide an additional monitor for detecting variations in the growth process. Figure 6 compares epilayer sheet resistance as measured during device processing (RsEpi), with non-contact sheet resistance (Rs) and multi-field Hall data collected immediately after wafer growth. The Hall data depicted in the figure is the sheet charge density of the pHEMT cap. A step change in RsEpi is seen to coincide with an increase in cap sheet charge. Notice that no corresponding change is observed in the Rs data. It was ultimately determined that a small error had occurred in the calibration of the non-contact resistivity systems. As a result, Rs appeared to shift by about 2%. Since channel sheet charge was controlled independently by channel Hall data, Rs was moved back to target by increasing the doping level in the cap layer. Since this adjustment was made shortly after the calibration error occurred, no clear step appeared in the Rs data. However, the multi-field Hall data from the cap clearly shows the increase in the doping level. As a result, a drop in RsEpi was observed once device testing of wafers from this time period commenced. This was a fairly subtle shift that was not observable by any other characterization method. Furthermore, single-field Hall techniques that require thin-cap or etched wafers would not have detected the problem since they can only provide data for the channel layer. Only multi-field Hall measurements were able to detect the shift in epilayer properties and provide a means to trouble-shoot the problem.

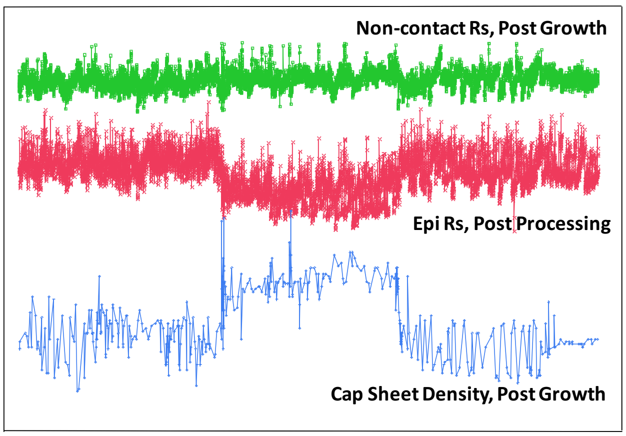

Figure 6: Post growth sheet resistance and post processing epilayer resistance are compared with post growth cap sheet density as measured by the multi-field Hall technique. A shift in the doping level of the cap layer is clearly seen in the sheet charge measurement made by multi-field Hall. A corresponding drop in epilayer sheet resistance is observed in test data collected during device processing.

CONCLUSIONS

Multi-field Hall measurements have proven to be an effective means of controlling and trouble-shooting our pHEMT production process. The technique provides rapid feedback of the electrical properties of the channel and cap layers of the pHEMT structure. The ability to separate the effects of these two conduction layers eliminates the need to spend time and resources growing specialized calibration structures. Because the test is non-destructive, measurements are carried out on production wafers that can then be delivered for processing. These features result in improvement in the efficiency of the growth process and an increase in overall wafer yield.

ACKNOWLEDGEMENTS

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REFERENCES

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ACRONYMS

MBE: Molecular Beam Epitaxy
pHEMT: pseudomorphic High Electron Mobility Transistor
MF: Multi-Field
QMSA: Quantitative Mobility Spectrum Analysis