Improved process control, lowered costs and reduced risks through the use of non-destructive mobility and sheet carrier density measurements on GaAs and GaN wafers

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Improved process control, lowered costs and reduced risks can be realized through the use of non-destructive mobility and sheet charge density measurements during the fabrication of GaAs and GaN wafers. The results from this microwave-based technique are shown to agree with destructive van der Pauw Hall testing results to within +/- 5%. In addition, it has the ability to map wafer uniformity and provide separated 2DEG data for thick cap or multi-layered structures. As a result, this technique provides an efficient and cost-effective alternative to current process control metrology methods, while providing the user with important process control data.

Introduction

The successful manufacturing of compound semiconductor wafers is dependent upon the ability to collect meaningful process control data. In the fabrication of GaAs and GaN wafers, one typically uses the measurements of mobility, sheet carrier density and sheet resistance to monitor process control. The ability to gather this data quickly and accurately is vital to maintaining good process control, reducing product at risk, and lowering overall costs.

We will describe a new, non-destructive method for making mobility and sheet carrier density measurements based on microwave techniques. We will compare our test results with van der Pauw Hall data for the same wafers to demonstrate capability. Finally, we discuss the benefits of this new technique for semiconductor wafer and device manufacturers.

Background

The need for quick and accurate measurements on processed wafers has lead to the development of a variety of testing methods. Many of these techniques are based on van der Pauw Hall testing, which is described in detail in ASTM Standard F76. Typical Hall testing begins by dicing a square sample from the wafer to be measured. Ohmic contacts are prepared on the sample, and then leads are soldered on for connection. The sample is subjected to current-voltage measurements in a known magnetic field. The data can then be used to calculate the mobility and sheet carrier density of the sample. The drawbacks for this type of testing are that it is destructive, time-consuming and skill-dependent. In addition, on certain materials, such as GaN, it can be very difficult to make the good contacts required for reliable measurements.

Some manufacturers include testing sites and bond pads on their wafers as they are processed. However, this reduces the amount of wafer area that is available for saleable product, and also means that the process owner must wait for an extended period of time before getting important feedback information on his process. The cost of the product at risk could be significant, especially for GaN processing, where SiC (~$2500-$5000) and sapphire (~$300) substrates can be very expensive.

Magneto-conductive systems have also been developed. This technique relies on sheet resistance measurements at various magnetic fields to determine a mobility value.[1] One advantage of this method is that it is non-destructive. However, it requires one to do a complete calibration with multiple wafers of a given structure with known mobility values, and is not easily transferred over to other structures without additional testing and calibrating. An LEI Model 1400 was sold to Litton for measurement of GaAs pHEMT wafers and used their patented technique that required calibration and measurement at low temperature (77K).

The above techniques can be used for simpler, single-layer structures, such as some GaN applications. The addition of a cap layer, however, as is common for GaAs pHEMT processing, adds a level of complexity to the measurement. The cap layer is typically a highly doped layer that is approximately 200-300Å thick and has a mobility of its own. The mobility from this layer will then interfere with the measurement of the 2DEG layer mobility during standard Hall testing.

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To get around this problem, GaAs pHEMT manufacturers have to make a special reactor run in order to create a wafer which has the desired epi structure but also has only a thin cap layer (typically 20-50Å thick). The cap layer on this sample, which is only used for testing purposes, will be depleted and allow one to properly characterize the 2DEG layer only when performing the Hall test. These wafers are generally referred to as 'Hall' wafers. This method is commonly used because it provides the necessary information to maintain and control the reactor operation. However, it is also very costly because it uses up valuable substrates, requires labor to prepare the samples, and reduces the amount of time the reactor can be used for product wafers. Based on a facility that operates a 9-position reactor and must make a Hall run every other day, and assuming an average wafer selling cost of $750, a company would be losing over $800K in potential revenue each year.

A variation on the above technique is to measure a sample from a thick-cap production wafer by etching the cap layer away. Repeated measurements of the sheet resistance and Hall coefficient are made while removing small layers of the cap layer. A profile can be generated showing mobility and sheet carrier density as a function of etch depth. As the cap layer is etched away, the results will eventually reflect the parameters of the 2DEG layer only.[2] This procedure can be time-consuming and expensive, and the resulting 2DEG values may not be representative of the 2DEG layer before etching.[3]

A technique based on magnetic field-dependent Hall and resistivity data has also been developed. This method allows the user to determine the mobility and carrier concentration values for individual layers in a multi-layer structure. However, this method is still destructive, as it requires the attachment of leads to the measurement sample. The procedure involves taking Hall coefficient and resistivity measurements across a range of magnetic fields up to 12T and across a range of temperatures from 6 to 300K. A procedure known as Quantitative Mobility Spectrum Analysis (QMSA) can be used to extract the mobility and concentration for each carrier.[4]

Technique

A new technique, based on microwaves, has been developed that allows non-contact, non-destructive testing of wafers at room temperature while providing mobility and sheet carrier density measurements.

The station utilizes a 10GHz microwave source and a waveguide to direct the signal incident to the wafer surface. A circular waveguide, capable of propagating the TE_{11} mode, is utilized. Since in such a waveguide, any polarization of the TE_{11} mode is possible, one can have an incident wave in a given polarization and measure the reflected wave in the same polarization – thus obtaining a reflection coefficient and sheet resistance. The Hall effect, however, will launch a reflected wave in a polarization perpendicular to the former, and thus can be separately measured with a suitable coupler. The tooling allows the wafer to be held perpendicular to the end of the waveguide opening, and to be positioned within a magnetic field. For this case, a reversible electromagnet with a range of 0 to 10KGauss is used.

The process begins with some initial tuning and reference measurements. A copper short is placed in front of the waveguide to record an initial relative measurement of forward and reflected powers. After loading the sample, a movable short on the backside of the wafer is adjusted to present an open circuit to the back of the wafer. Finally, the Hall probe is mechanically adjusted and electrically balanced to zero out any signal from the incident polarization.

The sample is then positioned in the center of the magnet such that the wafer is perpendicular to the field. After making an initial zero magnetic field measurement, the wafer is subjected to a series of magnetic fields in the forward and reverse directions ranging from 0 to 10KGauss. At each field, the forward, reflected and Hall power signals are recorded.

A software conversion module has been developed to translate the microwave power readings into reflection coefficients, which can be used to calculate the σ_{XX} and σ_{XY} conductivity tensors. The Hall coefficient can then be calculated for each magnetic field as follows:

$$R_H = -\frac{1}{H} \times \frac{\sigma_{XY}(H)}{\sigma^2_{XX}(H) + \sigma^2_{XY}(H)} \quad [1]$$

From the Hall coefficient and conductivity tensors, one can determine the resistivity, (ρ), mobility (μ) and sheet carrier density (N_s) of a single-carrier structure as follows:

$$\rho(H) = \frac{\sigma_{XX}(H)}{\sigma^2_{XX}(H) + \sigma^2_{XY}(H)} \quad [2]$$

$$\mu = \frac{-R_H}{\rho(H)} \quad [3]$$

$$N_s = \frac{-1}{[e R_H]} \quad [4]$$

For a multi-carrier structure, the conductivity tensors are the sum of the individual conductivity tensors for each layer. Based on a technique developed by W.A. Beck[5], the software uses the data taken from the multiple magnetic field measurements to generate a mobility spectrum plot. The mobility spectrum plot determines the envelope of possible carrier distributions by plotting all of the viable conductivity versus mobility data points as determined by the measurements. The presence of multiple peaks in this plot is evidence of multiple carriers in the sample. The software also includes a multi-carrier fitting algorithm to calculate the mobility and sheet carrier density for the various possible configurations. For example, the two-carrier fit results can be used to separate the mobility of the 2DEG layer from the cap layer for a production GaAs pHEMT wafer.

Results

Initial testing was done to determine the repeatability and stability of the measurement system. A Repeatability & Reproducibility study consisting of 2 operators, 3 trials and 4 thin-cap GaAs pHEMT wafers from 3 different suppliers was conducted. The results are shown in Table 1.

Table 1: R&R Results for LEI 1610

	Sheet Res (ohms/sq)	**Mobility** (cm2/Vs)	**Density** (cm-2)
Repeatability	2.259	31.66	1.365E10
Reproducibility	1.667	39.97	0
Total R&R	2.807	50.99	1.365E10
5.15 Std Dev	14.46	262.57	7.030E10
~ Sample Ave	370	5700	3.08E12
+ / - Range	+/- 7.23	+/- 131.3	+/- 3.51E10
As % of Ave	+/- 1.9%	+/- 2.3%	+/- 1.1%

Further testing was done to demonstrate the ability to measure mobility values across a large range. A variety of GaAs and GaN structures on various substrates have been successfully tested. Tables 2 and 3 below shows a series of wafers tested for Northrop Grumman and compares the measured value from van der Pauw testing to the value measured on the LEI 1610. The table shows that the accuracy is ~10% or better for mobilities ranging from 100 to 18,000 cm2/V-s and sheet densities ranging from the E11 to the E14 cm-2.

Table 2: Comparison of Mobility Measurements on LEI 1610 to Expected Values

Structure	**Mobility** (cm2/V-s)		**% Delta**
	Expected	Measured	
InAs pHEMT	18300	17043.4	**6.9%**
Si-doped GaAs on GaAs	6600	6248.4	**5.3%**
Si-doped InP on InP	3918	3845.4	**1.9%**
Si-doped InP on InP	3458	3270.0	**5.4%**
undoped InP on InP	3554	3209.9	**9.7%**
Si-doped GaAs on GaAs	3106	2768.8	**10.9%**
Be-doped GaAs on GaAs	120	126.0	**-5.0%**
Be-doped GaAs on GaAs	94	102.3	**-8.9%**

Table 3: Comparison of Sheet Carrier Density Measurements on LEI 1610 to Expected Values

Structure	**Sheet Density** (cm-2)		**% Delta**
	Expected	Measured	
InAs pHEMT	1.74E+12	1.85E+12	**-6.1%**
Si-doped GaAs on GaAs	6.93E+11	6.79E+11	**2.0%**
Si-doped InP on InP	7.85E+12	7.81E+12	**0.6%**
Si-doped InP on InP	1.75E+12	1.68E+12	**4.1%**
undoped InP on InP	1.14E+12	1.16E+12	**-2.1%**
Si-doped GaAs on GaAs	6.70E+13	6.60E+13	**1.4%**
Be-doped GaAs on GaAs	2.38E+14	2.28E+14	**4.2%**
Be-doped GaAs on GaAs	5.40E+14	4.90E+14	**9.3%**

Data was also collected to evaluate the performance of this technique relative to destructive Hall testing. To help evaluate this technique, typical Hall testing was done by Northrop Grumman with GaAs pHEMT wafers over a two-month period. The samples were also non-destructively tested on the LEI 1610 prior to the Hall testing. The measurements for mobility and sheet carrier density were then compared. The normal probability plot in Figure 1 shows the percent difference between the two test methods. The plot indicates that the non-destructive method is equivalent to within 5% of the destructive Hall method.

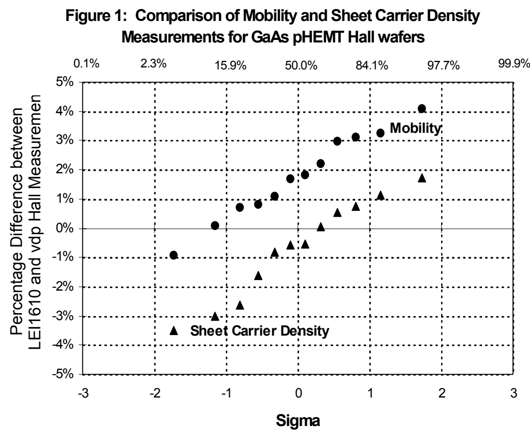
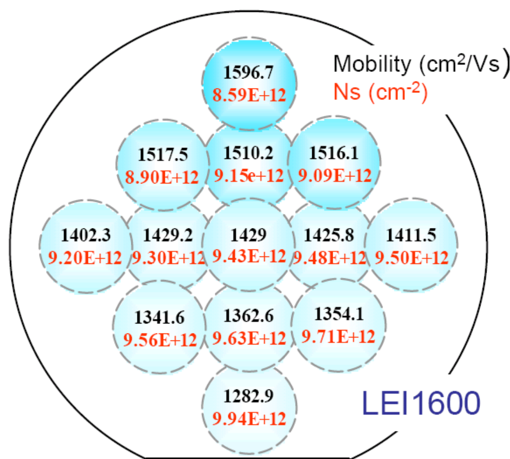


Figure 1: Comparison of Mobility and Sheet Carrier Density Measurements for GaAs pHEMT Hall wafers

One distinct advantage of the non-destructive aspect of this testing method is that it can generate a wafer 'map' by taking multiple measurements across the wafer. This allows the user to look at the uniformity of the mobility or sheet carrier density measurement across the wafer. Users have begun to use mapping as an effective method to study their epi uniformity and monitor their processes.[6] Figure 2 shows an example of a 13-point 'map' for mobility and sheet carrier density for a GaN HEMT structure on a 2-inch sapphire substrate; this data is provided courtesy of Professor T. Suzuki, Nippon Institute of Technology/Epitec.

Figure 2: Mapping of Mobility and Sheet Carrier Density for a 2 inch GaN HEMT wafer



This non-destructive testing method also has the ability to separate mobility and sheet carrier density measurements for the 2DEG layer from the cap layer when testing thick-cap production wafers. Data was collected from a series of thick-cap wafers, and compared to the LEI 1610 measurements from the companion Hall wafers. The results indicated that there was an average offset of ~15% +/-10% between the separated 2DEG mobility value and the measured mobility from the Hall wafer.

Discussion

The need for good process control measurements is obvious. The LEI 1610 has demonstrated the range and capability to be a viable alternative to the existing van der Pauw Hall testing methods.

The fact that this method is also non-destructive makes it even more attractive. The key benefits of a non-destructive mobility system are the abilities to increase sample populations and detect process problems quickly, and to offer this improved process control at lower costs than existing methods.

Proper process control can lead to improved uniformity, which will ultimately lead to higher yields and more stable processes. Mapping carrier mobility and sheet carrier density on process wafers is an important step toward proper process control, and could gain widespread popularity, much like the non-contact sheet resistance mapping that is so common today. Because the method is non-destructive, wafer mapping can enable the comparison of downstream device-level results back to epi-level measurements. This feedback loop can be used to make further process improvements that will impact device performance.

One area of great opportunity is the ability to provide separate measurements for multi-layer structures. Specifically, the ability to measure the 2DEG layer of production GaAs pHEMTs and GaN HEMTs could eliminate the need for dedicated Hall-wafer reactor runs. The current results are very promising. The difficulty arises in trying to compare thin-cap results with thick-cap results. It has been suggested that comparing the mobility and sheet carrier density values of a device with a thick cap to a Hall measurement – or to a measurement based on etching the cap layer off – will not be accurate.[3] For the 1610, the non-destructive data was on average approximately 15% higher than the expected value as measured from companion Hall wafers. The reason for the offset may, in fact, be due to the existence of the cap layer.

Furthermore, the lack of any traceable standards for mobility-type measurements makes comparisons difficult. The ASTM International F1.15 Compound Semiconductor Subcommittee's Mobility Round Robin may result in the development of material similar to the NIST Sheet Resistance/Resistvity SRMs.

More important, however, is the need for repeatable measurements. Current testing shows repeatability of ~5-10% and further work is underway to improve this capability.

Conclusions

The need for good testing to maintain process control in the manufacture of semiconductor wafers is well understood. We have presented information that describes a new, non-destructive method to test mobility and sheet carrier density based on microwave measurements. This method has the measurement range and accuracy that make it desirable for monitoring GaAs and GaN wafer processing. The non-destructive aspect of the method provides the added benefits of allowing multi-point wafer mapping, and 2DEG layer separation. These lead to decreased costs and effective yield improvement.

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