Continuous Improvement of Material Characterization Methodology through Gage R&R Studies

Mark Borek, Arun Chawla, Guoliang Zhou

Skyworks Solutions, Inc., 20 Sylvan Rd., Woburn, MA 01801, mark.borek@skyworksinc.com, Phone: (781) 376-3510

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Abstract

Reliable metrology data such as layer thickness and composition measured by X-ray diffraction (XRD), sheet resistance measured by Eddy current, and qualitative pHEMT epi parameters measured by photoluminescence (PL) are essential in a large-scale epitaxial wafer manufacturing process. In this paper, we present the use of ANOVA-based "Gage R&R" (repeatability and reproducibility) studies as the main analytical tool for the evaluation of our XRD, sheet resistance, and PL measurement processes. The results of early Gage studies for some of the measured material parameters revealed that the measurement process was only marginally reliable in the detection of product variation. We proposed experiments for the purpose of identifying the source(s) of the appraiser-to-appraiser measurement variation. Each experiment involved first hypothesizing a source of variation, followed by implementation of a Gage study with one or two variables to test the hypothesis. The series of Gage studies showed that enhancement of the x-ray incident beam intensity and increasing standardization of x-ray simulation procedures result in improved measurement reproducibility. For the case of sheet resistance measurement, by implementing an appropriate temperature compensation factor in the measurement process, the variation can be greatly reduced. For our PL measurement process, a preliminary Gage study revealed high appraiser bias for some of the measured peak parameters which allowed us to identify the need for improvement in our operator training system. After modifying the training system, a follow-up PL Gage study to test the effectiveness of the change showed significantly improved measurement repeatability.

INTRODUCTION

Continuous process control enhancement demands unremitting improvement in the effectiveness of measurement systems. One method of determining the capability of a measurement system is through a Gage R&R study (repeatability & reproducibility). Repeatability can be determined by measuring a part several times, effectively quantifying the variability in a measurement system resulting from the gauge itself. This can also be thought of as "within operator" variability [1]. Reproducibility is determined from the variability created by several operators measuring a part several times each, effectively quantifying the variation in a measurement system resulting from the operators of the gauge and environmental factors. This can also be thought of as "between operator" variation [1]. In order to determine the significant effects in our Gage study, we employ the analysis of variance (ANOVA) technique. An example of a Gage R&R ANOVA table is displayed in Table1. In Table1, the Repeatability (EV) %Contrib is the amount of the total variation that is accounted for by repeatability. The Reproducibility (AV) %Contrib is the amount of the total variation in the data that is accounted for by reproducibility. The Gage R&R %Contrib is the amount of the total variation that is due to repeatability & reproducibility. The Part to part %Contrib is the amount of the total variation in the data that is due to the product or process being studied. In general, a

Table I
Gage Study ANOVA Table

	Lower CL	5.15 Sigma	Upper CL	% of Total	% Contrib
Repeatability (EV)	0.29673	0.36416	0.47634	2.6271	0.069016
Reproducibility (AV)	0.5869	1.0578	2.5961	7.6311	0.58234
Part x Appraiser	0.18395	0.37537	0.62863	2.708	0.073331
Gage R&R	0.84928	1.18	2.6005	8.5127	0.72465
Part to part	7.9631	13.811	33.391	99.634	99.27

Gage R&R %Contrib <10 is considered to be a measurement that is capable of detecting variation, whereas a Gage R&R %Contrib between 10 and 30 suggests that the measurement system needs improvement. A Gage R&R %Contrib >30 indicates that the measurement system is unacceptable. An additional consideration when conducting a Gage study is sample selection. For a gage study, samples should be chosen so the ranges of values of the parameters that are to be measured are typical of the range of values that will be encountered in practice. As an example, if the study is to determine whether a measurement system is capable of measuring product variation across the entire tolerance range, then the samples that are selected should span the tolerance range for the parameter of interest. If the range of samples is too large, the gage study will improperly show that the measurement system is capable, conversely if the sample range is too narrow it will erroneously show that the measurement system is incapable.

XRD Gage Studies

X-ray diffraction is a critical tool in the characterization of pHEMT epi wafers. Through the measurement of a $\theta - 2\theta$ scan over the appropriate angular range followed by simulation of the collected data with a theoretical model, the compositions and thickness of the layers in a pHEMT epi wafer can be determined. For all XRD Gage studies, sample data was collected with a Philips MRD system configured with a five crystal X-ray diffractometer. All data collections and simulations were performed with the Philips X'pert software. For the initial XRD gage study, four appraisers measured five samples and performed two simulations on each sample. The parameters measured for each X-ray sample were Al composition, In composition, InGaAs channel thickness and Cap layer thickness. The %R&R contributions for Al composition, In composition, InGaAs channel thickness and cap layer thickness were 22.3, 10.8, 26.2, and 4.0 respectively. Because 3 out of 4 of the parameters have %R&R contributions > 10, the measurement needs improvement. Inspection of the Xbar-R chart for Al composition in Figure 1 indicates the presence of operator bias and repeatability. When considering how to further improve the measurement process we considered two possible causes for the high %R&R values. Inspection of the collected data revealed that there was a considerable difference in the intensity of the collected and simulated data. At the time of the study the X-ray tube was near the end of its life, so for the next Gage study we re-measured the samples after the X-ray tube was replaced. We also chose a different

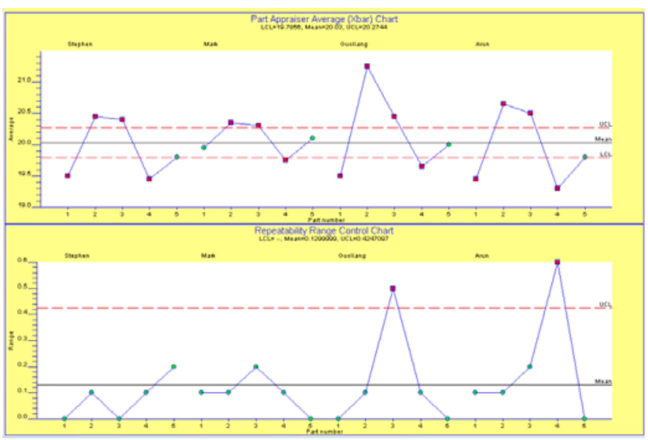

Figure 1: Xbar-R chart for Al composition from initial XRD Gage Study

set of samples that were more representative of the range that we were interested in studying, i.e. in this case samples that span the tolerance range rather than a narrow portion of this range. Once these changes were implemented, we performed a new Gage study, this time the same four appraisers measured six samples and performed two simulations on each sample. For this Gage study, the Al composition %R&R improved to 9.8, the In composition %R&R improved to 2.5 and the InGaAs thickness %R&R improved to 13.7, however the Cap thickness %R&R increased to 18.5. The improvement in operator bias and repeatability for Al composition in this study are evident in the Xbar-R chart in Figure2. We attributed the increase in the Cap thickness %R&R to be due to sample selection, i.e. for these new samples the Al composition, In composition and InGaAs thickness now spanned the tolerance range, however the range for the GaAs cap thickness was actually considerably reduced. With this improvement in %R&R, we considered

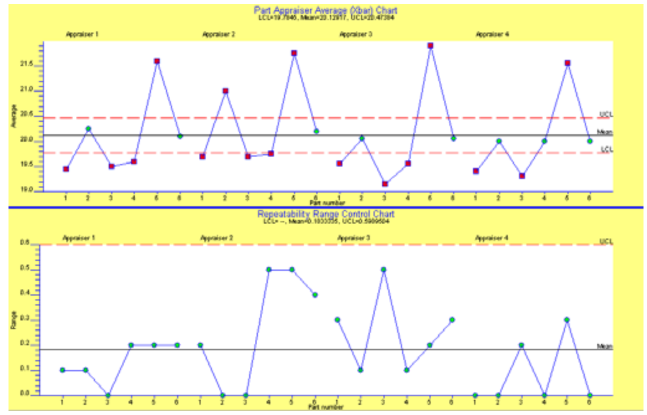

Figure 2: Xbar-R chart for Al composition from XRD Gage Study after increasing X-ray beam intensity.

ways in which to further improve the measurement process. Because our X-ray simulations are manual, i.e. parameters in the simulated curve are adjusted by the appraiser until the simulated and raw data curves match, we next decided to standardize the simulation procedure between the evaluators. Once the simulation procedure was standardized between all evaluators, we repeated the Gage study. For this gage study, the same four appraisers performed two simulations on the same six samples that were used in the previous study. The results of this study showed significant improvement, as the Al composition %R&R was 1.9, the In composition %R&R was 1.5, the InGaAs thickness %R&R was 3.5, and the Cap thickness %R&R was 14.2.

Contactless Resistance Gage Studies

The sheet resistance of a pHEMT wafer is determined by the bulk resistivity of the individual layers in the epilayer structure as well as the sheet charge and mobility of the high mobility channel and the various layer thicknesses. Changes in Rs can be an indicator of changes in these critical parameters and thus accurate determination of changes in Rs is of vital importance. For the Rs Gage study, five operators measured five samples and performed two measurements on each sample. All contactless resistance measurements were conducted with a Lehighton 1510C-RS system. Samples selected for this study were representative of the natural process variation. The %R&R contribution for this study was 6.84, which indicates that the measurement system is capable of adequately detecting sample variation. In spite of the acceptable results of the Gage R&R study, we continued to try to improve the contactless resistance measurement process because we discovered a significant amount of variation in the daily measurement consistency check. For a daily measurement consistency check of Rs, we use an MBE-grown epi-wafer that consists of a single layer of moderately doped GaAs. Because there is minimal operator involvement in the Rs measurement, rather wafers are handled by a robot, we instead considered the influence of external factors. By recording the ambient temperature and humidity during the daily measurement consistency check, we were able to determine that there was a significant correlation between lab temperature and Rs as displayed in Figure3. These results indicate that for every 1C change in temperature, there is a corresponding .5% change in Rs (ohm/sq).

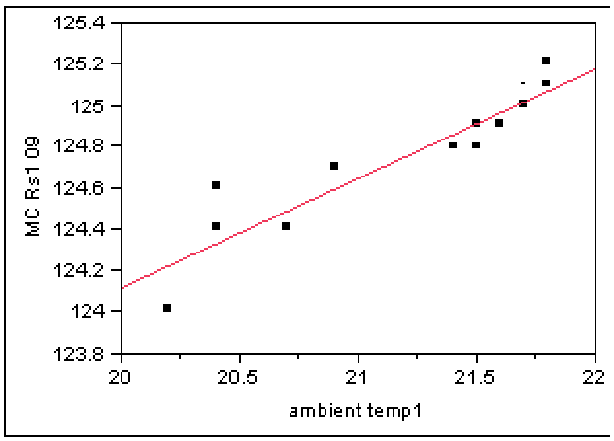

Figure3: Linear fit of correlation between ambient temperature and Rs of GaAs measurement consistency standard.

The Lehighton 1510C measurement software has a temperature compensation feature available, so for comparison we created an additional recipe for measurement of the daily consistency check that utilizes the temperature compensation feature. We collected 25 data points of the measurement consistency standard wafer with both measurement recipes, i.e. with and without the temperature compensation function. In order to eliminate any other potential interactions, both measurements were conducted back-to-back. Standard XmR charts were created for these two data sets and the measurements that were conducted with the temperature compensation feature had a 33% reduction in the 3 sigma limits relative to the standard measurement recipe. The reduction in variation of the Rs measurement consistency wafer is displayed in Figure 4. Based on the reduction in variation of the measurement consistency wafer after implementing the temperature compensation in the measurement recipe, we implemented this change in all pHEMT measurement recipes as well. Once the temperature compensation was implemented for all Lehighton measurement recipes, we repeated the previous Gage R&R study with the same operators and same samples. With the addition of the temperature compensation in the measurement recipe, the %R&R contribution for this second study was reduced to .725.

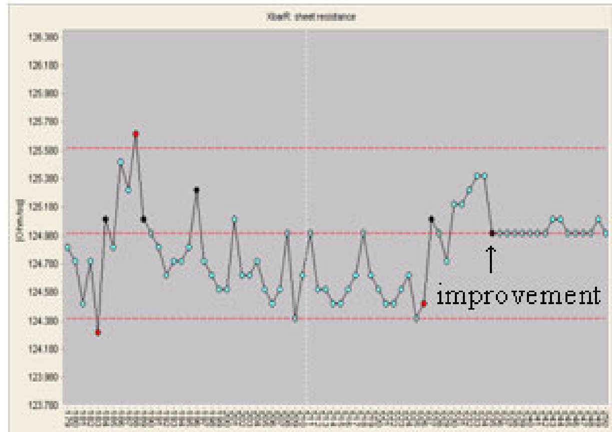

Figure 4: SPC chart of measurement consistency standard Rs before and after including temperature compensation in measurement recipe

Photoluminescence Gage Studies

The PL measurement can be utilized to gather much qualitative information about a pHEMT epi-wafer. The material quality, channel layer composition and thickness can be correlated with the respective peak intensity, peak wavelength and full width half maximum (FWHM) values obtained from the PL measurement. It is therefore of great interest to ensure that any changes in these measured values are due to actual changes in the material rather than a result of changes that might be generated by the measurement process. For the PL system Gage study, nine operators performed measurements on five pHEMT wafers, and each measurement was replicated twice. All PL wafers were measured with a Philips PLM-100 system. The results of this Gage study were quite favorable, as the %R&R contribution for the FWHM and Peak wavelength were 2.55 and .42 respectively, whereas the %R&R contribution for the Peak intensity was 17.9, which indicates a need for improvement. Inspection of the corresponding Xbar-R charts for peak intensity and FWHM, as displayed in Figure 5 and Figure 6,

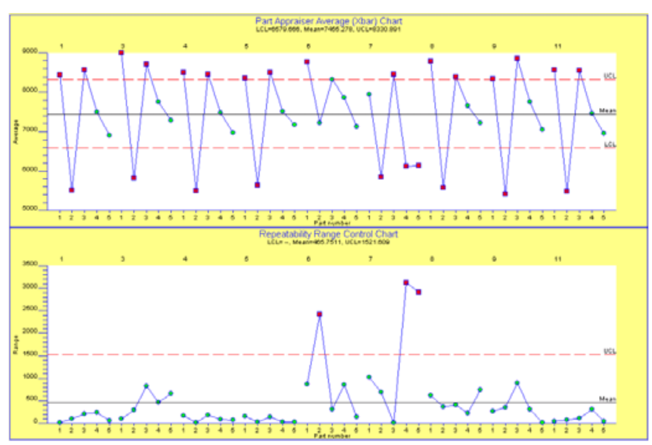

Figure 5: Xbar-R chart of peak intensity for initial PL Gage study

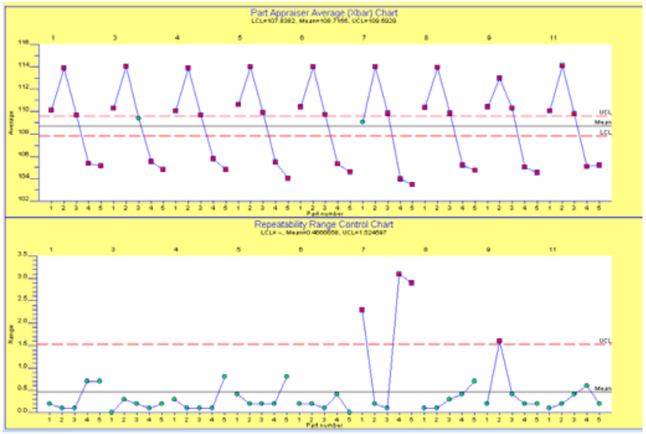

Figure 6: Xbar-R chart of FWHM for initial PL Gage study

reveals that two of the operators had poor repeatability for these parameters. Because there is minimal difference in the actual PL system operation between measurements, we decided to focus on the operating procedure as a potential source of the repeatability problem. Based on this information, we re-trained all operators that were involved in this study in order to ensure that the same operating procedures were being carried out by all participants. Once the training was completed, we repeated the PL gage study with the same group of operators measuring the same set of samples. As displayed in Figure 7 and Figure 8, retraining the operators resulted in significant improvement in the

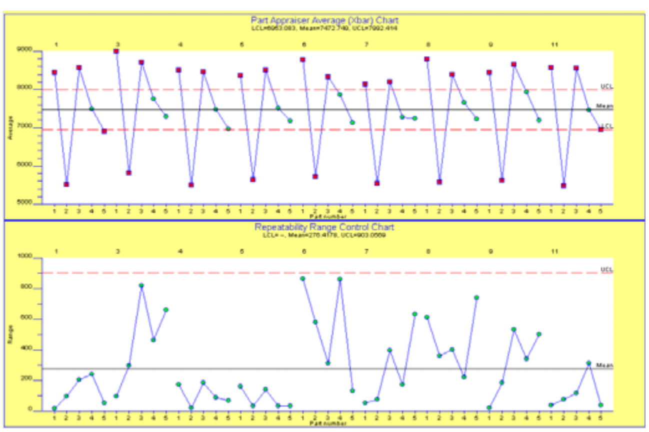

Figure7: Xbar-R chart of peak intensity for second Gage study after re-training of appraisers on PL operating procedures.

repeatability of the peak intensity and FWHM as all of the points in the Range chart are in control, and the %R&R contribution for both of these parameters improved to 5.4 and .86, respectively and the %R&R contribution for the peak wavelength remained unchanged.

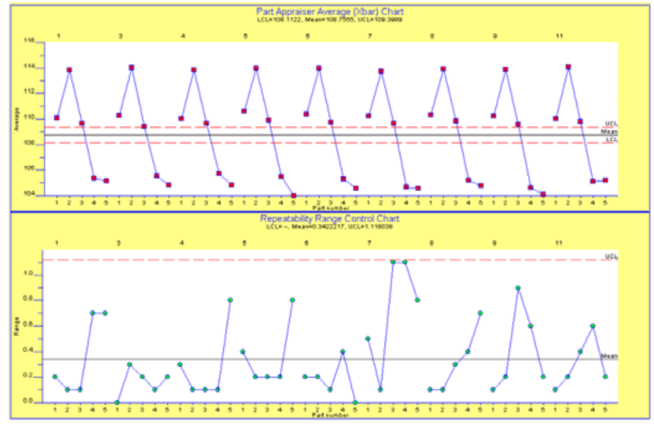

Figure 8: Xbar-R chart of FWHM for second Gage study after re-training of appraisers on PL operating procedures.

CONCLUSIONS

When characterizing the material properties of pHEMT epi wafers, it is critical to ensure that the measurement system is capable of detecting product variation. At Skyworks, we utilize Gage R&R studies to improve the capability of our MBE measurement systems. In order to improve measurement capability, we first hypothesize a source of variation and then perform a Gage study with one or two variables to test the hypothesis. By following this procedure, we have been able to improve the capability of our X-ray diffraction, photoluminescence and contactless resistance measurement systems.

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ACRONYMS

XRD: X-ray diffraction
PL: photoluminescence
Rs: sheet resistance
ANOVA: analysis of variance
pHEMT: pseudomorphic high electron mobility transistor
MBE: molecular beam epitaxy
FWHM: full width half maximum