Improvements to a mm-Wave GaN MMIC Process with Comprehensive and Efficient Process Control Monitoring

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Abstract

As industrial demand grows for high frequency GaN MMICs, a greater emphasis should be placed on maintaining and improving quality along with the higher throughput. A necessary component to maintaining and improving quality with higher throughput is well-designed comprehensive process control monitoring of appropriate key performance parameters for efficient analysis of growing data sets. HRL has utilized a centralized PCM database and web-based visualization to improve designs with feedback, verify process control, improve performance through process technology comparison and resolve problems. This scalable process control monitoring approach is a part of the overall quality-control of HRL GaN MMICs as volume increases to meet growing demands.

INTRODUCTION

Industrial use of GaN-based MMICs has increased significantly in recent years due to the ability to deliver high RF power at high efficiency. GaN MMIC components can significantly reduce size, weight, power and cost requirements by delivering several times more power than competing technologies [1]. Production-level quantities are already being offered for low frequency GaN MMICs of less than 20 GHz [2]. However, there is a growing need for higher frequency, mm-wave parts up to 100 GHz.

HRL offers commercial mm-wave GaN MMICs that can achieve high output power at frequencies as high as 96 GHz [3]. HRL has seen demand for these high-frequency, high-power MMICs double in two years, and expects demand to continue to grow at this rate for some time. Therefore, HRL has established practices that will improve traceability, monitor processes, and improve efficiency, all while being scalable to meet the increasing demand. One of these practices, which will be covered in this paper, is a tightly controlled in-process wafer test plan with key performance parameter (KPP) screening and centralized process control monitor (PCM) data storage for quick and easy access for analysis.

DATA COLLECTION AND PROCESSING

HRL GaN MMIC wafers are tested in-process and in a cleanroom environment on automated probe stations at two processing steps. Wafers are tested just after FET gate fabrication, which is the first opportunity to probe devices that do not require airbridges. Wafers are then tested again at the end of frontside processing when devices that require airbridges and passive elements can be tested. Six to 11 discrete devices and over 40 passive elements are tested per reticle, and all wafer reticles are included in the test plan. The measurement definitions and test plans are setup and scripted in Microvue Wavevue software to achieve automated probe station testing. The software can control all probe stations and all measurement instruments, which allows seamless integration of test plans.

On-wafer automated testing at each process step includes both DC and RF measurements. DC testing is done on passive elements such as thin film resistors and capacitors, as well as active discrete FETs. DC and RF measurements are performed on the same devices, while the destructive breakdown tests are performed last. The following is a list of PCM tests performed and some data extracted from each measurement:

- **DC tests:**
    - Thin-film resistors: TLM measurements to extract sheet and contact resistance
    - Capacitors: Capacitance measurements, IV sweeps to extract breakdown voltage and estimate use-voltage lifetime
    - Epitaxial material: TLM measurements to extract sheet and contact resistance
    - FETs:
        - Transfer curve: Threshold voltage, peak transconductance, maximum drain current, leakage currents
        - Output characteristics: Device on-resistance, knee voltage
        - Forward-gate bias turn-on voltage
        - Catastrophic gate-drain 2-terminal and 3-terminal breakdown voltage

- **RF tests:**
  - S-parameter measurement up to 67 GHz: Ft, Fmax, maximum stable gain, etc.
  - Pulsed IV: Current collapse or DC-RF dispersion
  - Gain compression sweep of MMIC standard evaluation circuit: Linear and compressed gain, maximum output power, maximum power added efficiency

An example of raw IV data from a transfer curve measurement is shown in Figure 1. Also shown in the figure are parameters extracted from this measurement, including gate and drain leakage currents (I_{gl} & I_{dl}), pinch-off voltage (V_{po}), threshold voltage (V_{th}), peak transconductance (g_{mp}), voltage and current at g_{mp} (V_{peak}, I_{peak}), drain current at zero gate bias (I_{dss}) and maximum drain current (I_{max}).

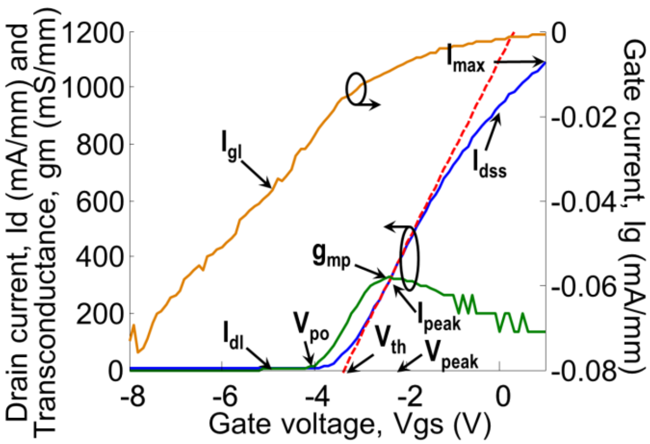

Figure 1: Example transfer curve data showing the extraction of parameters.

The raw measurement data are automatically imported into a MS SQL database. A Matlab script is applied to process the raw measurement data and extract parameters. 20 key performance parameters and 148 total parameters are extracted from the raw data, which are also stored in the database. Parameters include standards such as I_{dss}, peak transconductance and threshold voltage, but also leakage currents (process-sensitive), current collapse (trap-sensitive), and actual sacrificial breakdown voltage (performance-sensitive). Key performance parameters are automatically evaluated against pre-defined lower and upper specification screening limits to determine part failure and wafer yield. Overall process capability metrics (C_p, C_{pk}) are also evaluated based on the KPP specification limits.

DATA VISUALIZATION AND APPLICATION

The raw or extracted parameter data can then be viewed on-demand by all process engineers and staff through a web-browser-based user interface built using Visual Studio/C#. Data can be filtered and displayed in any of these formats:

- **Lot summary table:** Shows statistical data of extracted parameters of each wafer in a lot, including average, standard deviation, min/max, median, 25%/75% quartiles, individual parameter yield and overall wafer yield.
- **Wafer maps:** Shows a color-scale wafer map of a particular extracted parameter for an individual wafer (see example in Figure 2).
- **Trend chart:** Shows a statistical box-plot of a particular extracted parameter across several lots and/or wafers, and data can be color grouped by lot, technology, etc. (see example in Figure 3).
- **IV curves:** Plots raw IV data from measurements, which can be color grouped by lot, wafer, etc.
- **Yield analysis:** Shows yield across several lots and/or wafers based on KPP screening criteria, along with failure mode analysis in the form of a Pareto chart.
- **Part list table:** Shows a table of all individual parameter values of parts on a wafer.
- **Correlation analysis:** Allows correlation study of two extracted parameters from a selected data set.

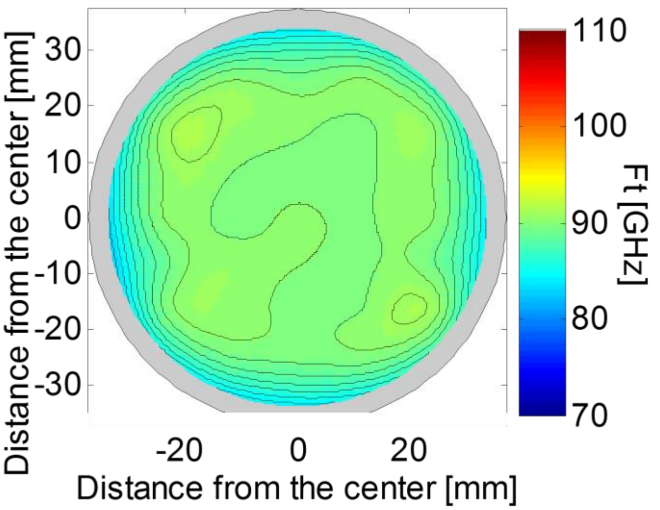

Figure 2: A color-scale wafer map of Ft from an example wafer in the Figure 3 trend chart.

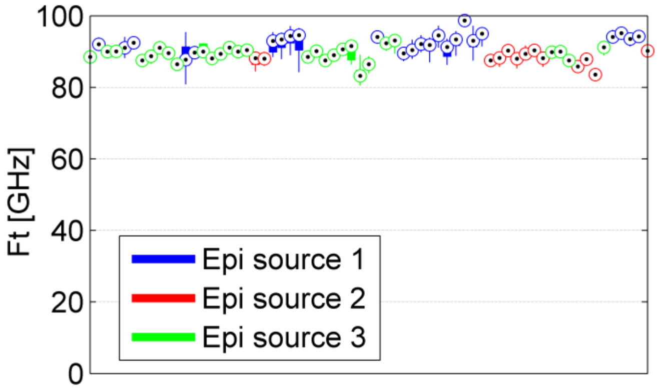

Figure 3: A trend chart box plot of Ft showing statistical box plots. Each column represents a wafer's statistical distribution. Black dots indicate the median and the thin lines cover approximately 99.3% of the data distribution. Many thin lines are not visible in this plot due to the tight parameter distribution.

This large amount of data has been useful for improvements through design feedback, process control verification, process technology comparison and problem troubleshooting. The statistical characteristic data are fed back into MMIC models for refinement and iterative design improvement. The empirical data feedback allows designers to verify or improve model parameters that are estimated before MMIC fabrication. As process variability is quantified and reduced through the statistical PCM data feedback, designers can also push the designed performance further as they need to accommodate less variability. Figure 3 shows an example of process control verification from a trend chart of Ft for recent wafers. The wafers are color-grouped by different epitaxial material sources, showing the stability of the process independent of source material. The average Ft was 90 GHz, and the average wafer standard deviation was 1 GHz. Figure 2 also shows a wafer map of Ft from one of the wafers included in the trend chart, showing an example of the excellent wafer uniformity.

Figure 4 shows an example of how the database was exploited to compare process technology changes and improve device characteristics. A new gate process was exercised on a subset of wafers. Using the database of test data, over 1000 data points from the new gate process (Process B in Figure 4) were compared to thousands of data points from the original gate process (Process A in Figure 4). Percentage change in key performance parameters was analyzed to evaluate the new gate process. As shown in Figure 4, the only parameters that were significantly affected by the new gate process were gate leakage, drain leakage and DC-RF dispersion, or current-collapse. Furthermore, all of these significant changes were improvements: lower leakage and lower DC-RF dispersion. Therefore, by using the test database, the new gate process was statistically determined to be superior to the original gate process.

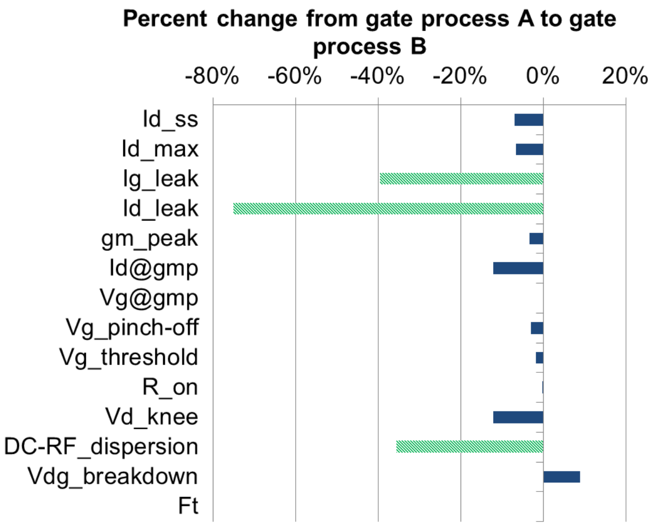

Figure 4: A bar chart comparing the percentage change of key performance parameters from the original gate process (A) to the new gate process (B). Striped bars highlight significant changes. Only leakage currents and DC-RF dispersion were significantly affected by the processing change, and they were all improved.

Finally, the database has been employed to troubleshoot problems and diagnose issues. For example, at one time, device drain leakage current was increasing to undesirable levels. However, the leakage change was not consistent from wafer-to-wafer, which made the issue difficult to diagnose. The database was utilized to investigate drain leakage correlation with all other parameters both graphically and numerically, which resulted in finding a strong relationship between device drain leakage current and epitaxial buffer leakage current. Furthermore, because X-ray diffraction data are gathered for all wafers, the database was then leveraged to find a correlation between epitaxial buffer leakage current and epitaxial layer composition. Figure 5 shows how buffer leakage current changed with deviation of epitaxial material composition from the target value. Using this data, the epitaxial material screening criteria was tightened to minimize variation from the target epitaxial material composition.

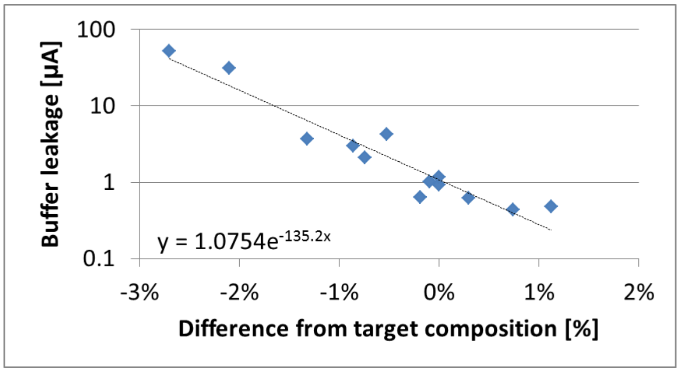

Figure 5: Correlation between wafer buffer leakage current and the difference from target epitaxial material composition, showing a strong relationship and fit with an exponential equation. This data was exploited to improve epitaxial material specification limits.

SUMMARY

HRL's comprehensive GaN MMIC process control monitoring approach results in massive amounts of data collection. To support product quality improvement with increasing demand, a custom solution was created to store, process and visualize the growing PCM data. The entire software infrastructure employed in this solution is with off-the-shelf products and customization was added through development of database design and script programming. Using a database, back-end script and front-end web-based visualization, this solution has allowed HRL to do the following:

1. Verify process stability, as shown by an example Ft trend-chart in Figure 3.
2. Improve performance through statistical process comparison, as shown by an example of a gate fabrication process improvement in Figure 4.
3. Find the root cause of problems to develop a resolution, as seen by the example relationship found between buffer leakage and difference from target epitaxial composition in Figure 5.
4. Feedback characteristics to MMIC designs for further improvements.

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ACRONYMS

GaN: Gallium Nitride
MMIC: Monolithic microwave integrated circuit
KPP: Key performance parameter
PCM: Process control monitor
FET: Field effect transistor
MS: Microsoft
SQL: Structured query language
Idss: Drain current at zero gate bias
Cp, Cpk: Process capability metrics
C#: C Sharp programming language