IN-LINE RF DEVICE TESTING FOR MONITORING A HIGH VOLUME GaAs HBT PRODUCTION LINE

Cristian Cismaru, Hal Banbrook, Peter J. Zampardi, Jing Li, James W. Penney, and Charles McGuire*

Skyworks Solutions, Inc., 2427 Hillcrest Drive, Newbury Park, CA 91320
cristian.cismaru@skyworksinc.com, 805.480.4663
*PrivaSys, Inc., Newbury Park, CA 91320

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Abstract

We demonstrate an RF test system calibration in the GHz frequency domain that utilizes calibration structures integrated on wafer along with test devices. The success of this method allowed us to develop very accurate, fully automated, in-line RF test systems and methodology, including a hybrid-pi device model extraction, suitable for a high volume GaAs HBT manufacturing facility.

INTRODUCTION

GaAs heterojunction bipolar transistors (HBT) are one of the major technologies used for manufacturing power amplifiers in wireless handset applications. While many HBT parameters can be directly measured using DC test algorithms, several important parameters and figures of merit, such as the transit time (related to cut-off frequency) and the power gain, cannot. As a result, monitoring the RF performance of these devices, in a production environment, is very desirable from circuit design, process control, and device modeling perspectives. While a number of papers have discussed model parameter extraction using AC measurements [1], few papers have discussed performing such measurements, on wafer, in a production environment [2-4]. The key differences for production testing, versus small sample device modeling, are the requirements for speed and simplicity, while maintaining data accuracy and integrity.

In this work, we discuss the RF process control (PCM) measurement infrastructure implemented at Skyworks Solutions. This infrastructure includes the measurement of RF parameters, DC parameters, and extracted HBT hybrid-pi [1] based parameters. We also discuss the steps taken to achieve a reliable automated on-wafer RF test, suitable for a high volume production environment starting from a manual, but accurate, laboratory measurement.

CALIBRATION

One of the most important considerations is equipment calibration. Unlike DC measurements, where the equipment is often calibrated once a year, RF measurements are performed at frequencies in the GHz range, and calibration is required at least once a day and validated before each batch of measurements (e.g. before each lot is measured). This requirement makes automatic on-wafer measurements extremely difficult. In this work we propose a calibration and de-embedding procedure that is suitable to automatic measurements.

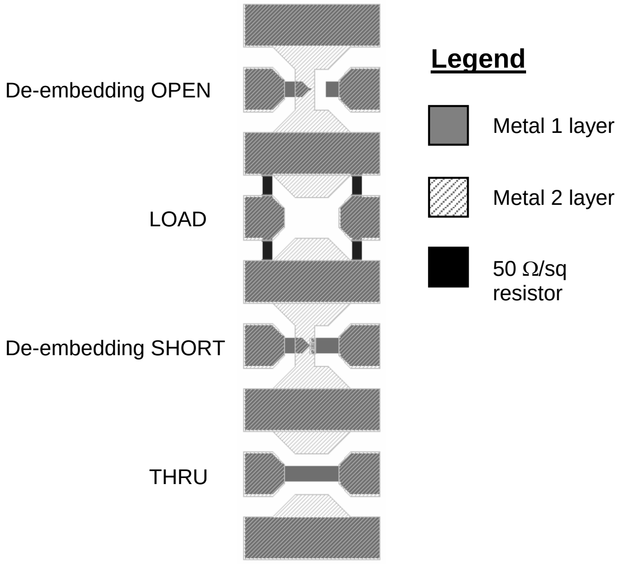


Fig. 1. On-wafer calibration and de-embedding structures

Typically, the calibration is done using an Impedance-Standard-Substrate (ISS) containing high-precision calibration standards, available from the RF probe manufacturers. However, this requires an operator to load a special ISS holder on the wafer prober and perform the calibration. While this method is used in a laboratory environment, time constrains make it unfeasible for high volume production. To satisfy the automation requirements in the latter case, on-wafer calibration structures need to be available on each reticle of the wafer.

In addition, since de-embedding structures are also needed to remove the measurement pad and interconnect parasitics from the measurement data, we need to consider a combination of calibration structures and de-embedding structures to minimize the real estate on the wafer. Fig. 1 shows the combination used in this work. This includes a de-embedding OPEN, a 50 Ohm LOAD, a de-embedding SHORT, and a THRU, for use with Ground-Signal-Ground (GSG) microwave probes with a tip pitch of 100 µm or 150 µm. The standards are built within any current GaAs HBT process by using two Au metal layers and a 50 Ohm/sq TaN resistor layer.

Since these on-wafer standards are not as "ideal" (i.e. more lossy) compared to an ISS [5], the calibration scheme has to be carefully considered. The two most popular methods are the LRRM (Line, Reflect, Reflect, Match) and the SOLT (Short, Open, Load, Thru). While both of these are available within proprietary software packages, such as Cascade's Wincal®, one would like to adopt a more cost effective solution. In addition, using proprietary software is not suitable for automated test. As a consequence, although we investigated the accuracy of both methods for use with on-wafer standards, we focused more on the latter, since SOLT is available within the equipment firmware for any network analyzer.

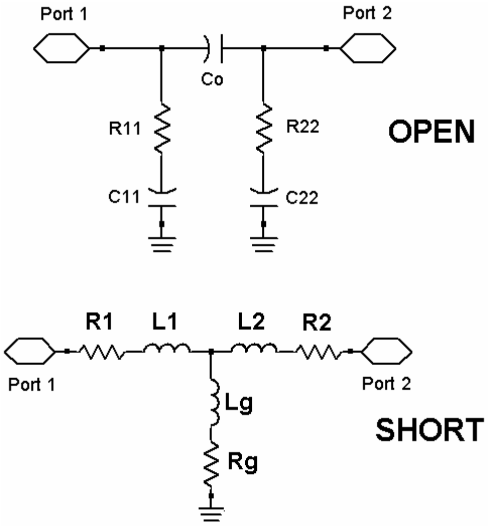
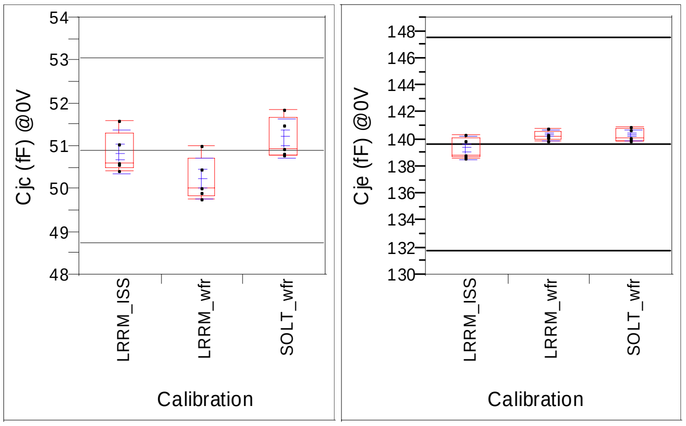


Fig. 2. Schematic of the equivalent circuit of the de-embedded OPEN and SHORT.

Our standard laboratory measurements involve using the LRRM method [6] in conjunction with the GSG ISS standards, as provided by Cascade Microtech, Inc. The accuracy of this method was demonstrated, [6] as this is an industry-wide, established calibration method for on-wafer RF and microwave measurements. Subsequent to the calibration, the de-embedding OPEN and SHORT structures (Fig. 1) are measured and a de-embedding parasitics equivalent model (Fig. 2) is extracted. Following the device S-parameter measurements, these models' 2-port parameter data is subtracted from the equivalent device measured data. Typical values for these parameters are (approximate): C11, C22 of 15 fF, R11, R22 of 40 Ohms, C0 of 1 fF, R1, R2, and Rg of 20 mOhms, L1, L2 of 20 pH, Lg of 3 pH.

In the case of on-wafer calibration, the OPEN (de-embedding) structure has a reflection coefficient far from ideal. Thus, for the on-wafer calibration methods, we use the air open as the OPEN standard (probes in air). Our on-wafer LOAD structure is a precise 50 Ohms (two 100 Ohm parallel resistors). For the LRRM calibration method, the load parasitic inductance is automatically determined [6] and, thus, not needed to be known. However, in the case of SOLT, this inductance does not influence the quality of the calibration since it is negligible (less than 1 pH). Furthermore, in the event that the fabricated load is not exactly 50 Ohms, this can be DC measured automatically before the calibration and the result transferred to the VNA as the actual LOAD impedance. The use of the SHORT standard with parasitic inductances (the de-embedding short) during the SOLT calibration makes the short de-embedding redundant. Last, the THRU standard's delay needed for the calibration was calculated by use of LineCalc® and also measured after performing a calibration on an ISS. Both methods returned a matching value of approximately 0.65 ps.



(a) (b)

Fig. 3. Device (60 µm^2) un-biased junction capacitances ((a) Cjc, (b) Cje) measured by using various calibration procedures (LRRM_ISS – LRRM on ISS substrate, LRRM_wfr – LRRM on wafer calibration structures, SOLT_wfr – SOLT on wafer calibration structures).

Under these conditions, the use of either LRRM or SOLT calibration with air open, on-wafer 50 Ohm load, on-wafer short, and on-wafer thru, coupled with a device parasitic de-embedding scheme provides data accuracy on par with carefully performed laboratory measurements. Fig. 3 shows junction capacitance measurements of an unbiased device across one wafer demonstrating a difference of less than 1 fF among the three calibration methods (LRRM on ISS, LRRM on wafer, and SOLT on wafer).

RF MEASUREMENTS

The objective of the in-line on-wafer device RF test is two-fold. First, the test is used as a PCM (process control monitor) to provide information on key parameters to process and device engineering. Second, device figures of merit, such as RF gain, device transit time, and f_T together with the hybrid-pi model parameter are reported and used in defining statistical device models as well as wafer-specific device models, a very valuable tool for product design. Finally, the hybrid-pi model parameters are very useful during device design studies.

The devices regularly used as RF PCMs for in-line monitoring are GaAs HBTs with emitter areas between 60 μm^2 to 170 μm^2. These devices are manufactured in several process generations. First, the devices are measured DC to determine the necessary bias points for the subsequent RF tests. Several DC parameters are extracted as well (DC gain, turn-on voltages, saturation parameters, etc.). Once the desired bias points are defined, a full frequency sweep S-parameter measurement is recorded at the selected bias. The frequency sweep has to be between the low end of the network analyzer and the highest desired device operating frequency (e.g. 5.8 GHz in the case of wireless standard, ignoring harmonics). Based on this measurement, figures of merit [7] are extracted (e.g. unilateral gain, MSG/MAG, stability factor) at various frequencies of interest. In addition, these measurements are the basis for the extraction of the hybrid-pi model parameters (see Fig. 4).

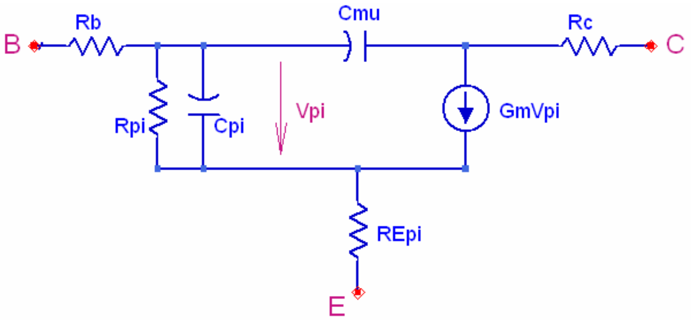


Fig. 4. Schematic of the hybrid-pi model.

Prasad [1] was used as a reference for the model extraction routine. Fig. 5 shows a typical comparison between measured s-parameters and calculated s-parameters, the latter based on the extracted hybrid-pi model, which demonstrates a good matching. Although the hybrid-pi parameters are not identical to the related parameters in the compact device model, they provide quick and reliable insight on the device quality and RF performance. For example, the device base resistance R_b affects f_{max} and consequently the RF gain at higher frequencies (e.g. 5.8 GHz). Fig. 6 shows the extracted base resistance of a 60 μm2 device, biased at a 0.1 mA/um^2 current density and Vce of 3.5 V, measured across all wafers in a production lot.

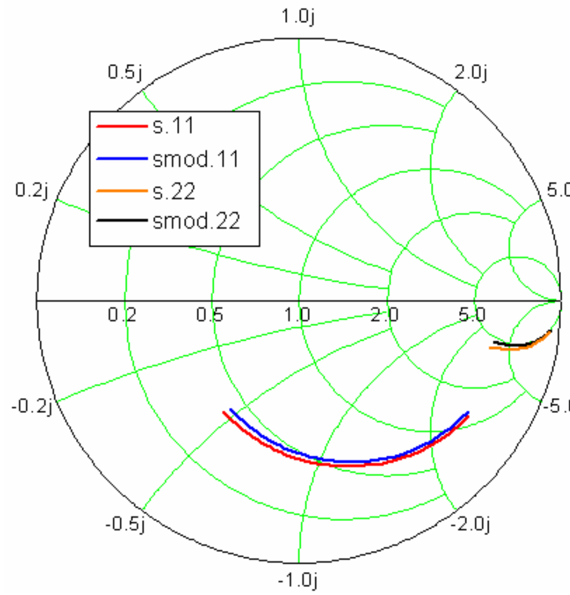


Fig. 5. Example of comparison between measured s-parameters and hybrid-pi modeled s-parameters (s.11, s.22 are measured data; smod.11 and smod.22 are hybrid-pi computed s-parameters) normalized to 50 Ohms.

In addition to full frequency sweep s-parameter measurements, an RF spot frequency (4 GHz) measurement is performed at various device current densities to determine f_T at each bias and subsequently the device transit time. Device junction capacitances are also measured with the device unbiased (“cold”).

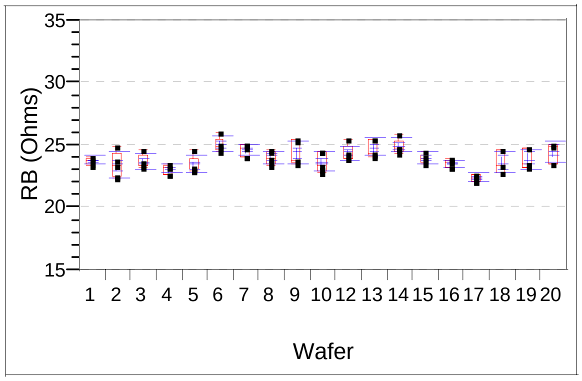


Fig. 6. Full-lot base resistance R_b as extracted from the hybrid-pi model (60 μm^2 device, biased at a 0.1 mA/μm^2 current density and Vce of 3.5 V).

AUTOMATED TEST

Two implementations of the automated RF test were developed. The first was derived from the laboratory, manual test discussed in the previous section. This test used an Agilent vector network analyzer 8510C and a 4142B power supply. The wafer was tested on a manual Cascade 10K probe station with Picoprobe GSG 40 GHz probes. The test equipment was controlled by a PC running Agilent ICCAP device characterization and modeling software. To fully automate the test, the prober was changed to a cassette-to-cassette automatic Electroglass EG2001X and all the corresponding automation was programmed within the test plan in ICCAP. Although this setup has many advantages, such as ICCAP modeling interface, it requires expensive software licensing and it creates an undesirable dependence on one software package. Nevertheless, this is an excellent choice for speedy RF measurements in a laboratory environment. As a less expensive alternative, the second implementation is based on an in-house control and analysis software, developed in C code, and, since the RF measurement is not performed at higher frequencies than 10 GHz, a less expensive vector network analyzer, an Agilent 8722 is employed. Nevertheless, both systems are capable of providing very reliable and accurate data. Fig. 7 shows a multiple-lot sample of RF gain at 2.4 GHz, with a standard deviation of only 0.07 dB, while Fig. 8 displays the corresponding device transit time.

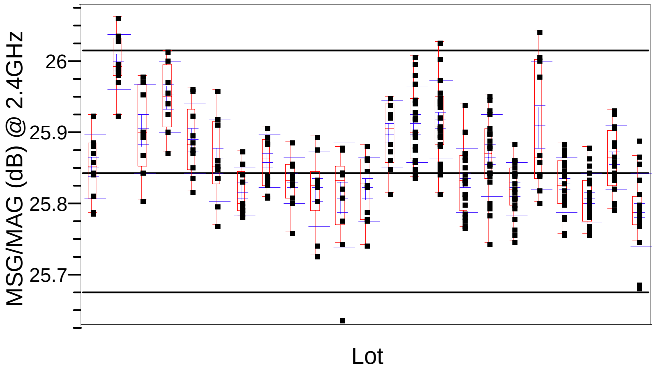


Fig. 7. Multiple-lot sampling of device small signal gain at 2.4 GHz (60 μm^2 device, biased at a 0.1 mA/μm^2 current density and Vce of 3.5 V).

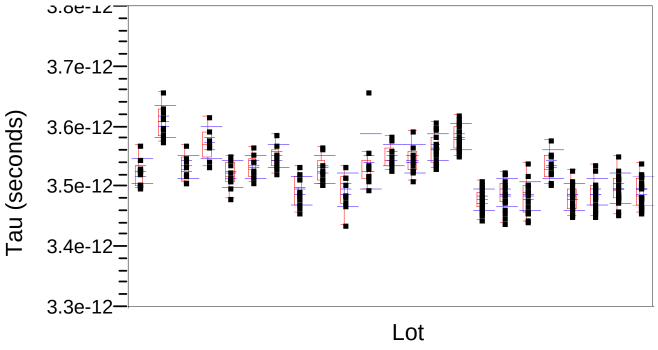


Fig. 8. Multiple-lot sampling of device transit time (60 μm^2 device, biased at a 0.1 mA/μm^2 current density and Vce of 1.5 V).

CONCLUSIONS

In conclusion, we investigated and demonstrated an RF test system calibration in the GHz frequency domain that utilizes calibration structures integrated on wafer along with the devices to test. The success of this method allowed us to develop very accurate, fully automated, in-line RF test systems and methodology, including a hybrid-pi device model extraction, suitable for a high volume GaAs HBT manufacturing facility.

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ACRONYMS

HBT: Heterojunction Bipolar Transistor
PCM: Process Control Monitor
ISS: Impedance Standard Substrate
LRRM: Line Reflect Reflect Match
SOLT: Short Open Load Thru
VNA: Vector Network Analyzer