RF Wafer Testing: An Acute Need, and Now Practical

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LEADING semiconductor producers have recently conceded that wafer level RF measurements are acutely needed to develop and produce advanced ICs. To a certain degree, this flies in the face of the 2003 recommendations by the ITRS Technical Working Group for Modeling and Simulation, which states, "The parameter extraction for RF compact models preferably tries to minimize RF measurements. Parameters should be extracted from standard I-V and C-V measurements with supporting simulations, if needed." The problem is that standard I-V and C-V measurements make the direct extraction of C_{OX} impossible for ultra-thin dielectrics due to high leakage currents and non-linearities. Yet, accurate parameter extraction for HF circuit modeling at 1–40GHz and for RF compact model verification has become essential. This challenge is increasing for high-performance/low-cost digital, RF, and analog/mixed-signal devices as the industry progresses toward the 65nm node and beyond.

The recommendations for minimizing the use of RF techniques are predicated on the assumption that they cannot be made effectively, particularly in a production environment, which may have been the case in the past. However, new parametric test systems now make fast, accurate, and repeatable RF parameter extraction almost as easy as DC testing. In fact, one system can take precise DC and RF measurements simultaneously, making it suitable for both lab and production use.

RF Testing Apps

Whether you are manufacturing RFICs on III-V wafers for cell phone modules or high performance analog on silicon-based technology, predicting final product performance and reliability requires wafer level RF s-parameter measurements in development and production. These measurements are an important addition to DC data in forming a complete picture of device characteristics. They also offer significantly more information with fewer measurements than a DC-only test suite.

Power amplifier RFICs are an obvious candidate for high frequency testing. They are extremely complicated, yet susceptible to end market pricing pressures. This makes them highly sensitive to testing costs in production, where functional tests are conducted under low bias conditions from 1GHz up to 40GHz, depending on their design and application. RF measurements have been limited to functional tests of packaged parts at the end of the line, as this testing is perceived as high cost and problematical in terms of repeatable, accurate results.

IC fabricators can also use RF wafer level measurements to extract figure of merit parameters on various high performance analog circuits at the 180nm node and beyond. SOCs that combine memory with RF, analog, and high speed digital devices have comparable RF test requirements.

Characterizing equivalent oxide thickness (EOT) on high-D gate dielectrics is critical in high performance logic devices at the 130nm node and beyond, in the development of new materials, and for continued scaling of future IC generations. For example, RF measurements can play an important role in accurate modeling of dielectrics and their behavior in MPU, ASIC, FPGA, and DSP devices. This has been done on prior generations of technology using multi-frequency capacitance measurements and with advancing technology there has been a shift to high-frequency capacitance (HFCV) measurements. However, HFCV is inadequate for ultrathin dielectrics, one reason being that the HFCV instrument (not the DUT) introduces a series resistance into the measurement.

Challenges In Standard I-V and C-V Measurements

RF parameters extracted from s-parameter data are included in compact simulation models used by design engineers during product development. However, manufacturers have taken wafer level s-parameter data only in device modeling labs, due to the complex nature of the measurements and associated cost. Even in a lab environment, accurate extraction of RF parameters has been a challenge due to the sensitivity of the measurement to probe contact resistance variation. To quickly make the large number of measurements required for production monitoring has seemed impractical, if not impossible.

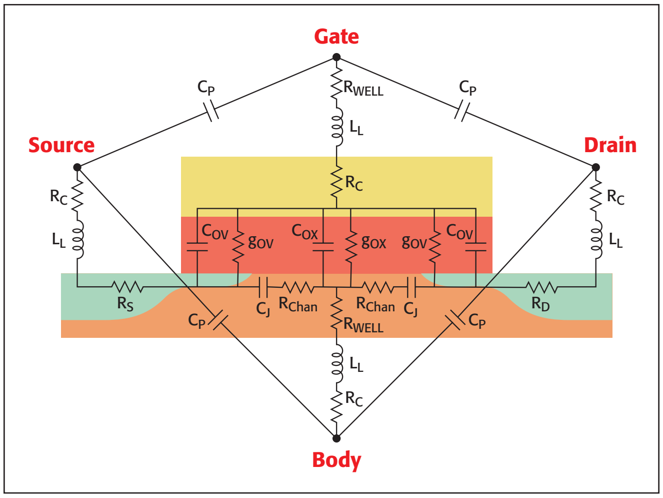


Figure 1. Simplified circuit model of a MOSFET DUT. The C_{OX} measurement factors to consider are parasitic capacitance between contact pads and leads (C_P), contact resistance (R_C), lead inductance (L_L), channel resistance (R_{Chan}), and overlap capacitance (C_{OV}).

One of the main technical challenges in RF testing is accurate de-embedding of the DUT and measurement system. This is particularly true in the extraction of C_{OX} when characterizing ultra-thin gate dielectrics. ***Figure 1*** is a simplified circuit model of a real transistor that shows the components which complicate direct measurement of C_{OX}. These components include overlap capacitance between the gate contact and the source/drain well, gate resistance, lead inductance (from DUT to contact pads), contact resistance (between probe needle and contact pads), and channel resistance. These components must be segregated by the appropriate extraction after de-embedding. Correction algorithms are applied for contact resistance, lead inductance, and probe pad capacitance.

Reluctance In Adopting RF C-V

These difficulties have important implications in a production environment. Unreliable measurements can hinder yield management. A bad measurement result on a good device is referred to as alpha error. In a production environment, this may mean that a wafer has been improperly scrapped. The misleading ITRS information and the slow, painstaking process that many companies experience in their modeling labs combine to make engineers reluctant to adopt production RF measurements, believing they will have high alpha error. It is also perceived that throughput and operational costs will be unacceptable and that a high level of technical support is required to interpret results. Low throughput on prior generations of RF systems resulted from calibrations and measurements needing to be repeated due to contact resistance problems. Calibrations on these older systems also did not hold for different measurement frequency sets. High operational costs are associated with manual probing of gold calibration standards, which have soft pads and expensive RF probes that wear out quickly with over-scrubbing. There is also the false perception in the market that a special prober or chuck is required for wafer level s-parameter measurements. These factors result in a high perceived cost of ownership for RF C-V and reluctance by users to adopt the solution.

Succinctly put, the industry's overall perspective on wafer level RF testing has been that it is complicated and expensive. This is based on a view of RF measurements as black art and that implementing them in a high volume fab, run by a production floor operator, is fantasy. Additional concerns regarding RF measurements in production are that:

- extensive test structure changes are needed
- results are unstable, varying tool-to-tool, operator-to-operator, and day-to-day
- RF specialists must baby-sit every tool
- substantially different lot routing and operational workflow may be required
- it is doubtful this can be a real-time technique
- lab grade results are unlikely

Nevertheless, by maintaining the status quo based on these perceptions, fabs are "flying blind" in the implementation of new designs and processes for RFICs, new gate materials, and other advanced devices. The consequences are design and process iterations that greatly increase costs and time to market, accompanied by lower initial yields.

Third Generation Parametric Testers Provide a Solution

The key to making wafer level RF testing a production process control tool is fully automated measurements. This means that a robot delivers the wafer, the calibration standard, and the probe card to where they are needed. In other words, a major test system design goal is absolute data integrity without human intervention. If intervention is required, it should be accomplished by the fab host or the test controller, based on intermediate test results or operational requirements.

Third generation testers now available have features that allow this type of operation to 40GHz. Being designed specifically for a production environment, they avoid some of the attributes of testers designed for lab use. Lab instrument design focuses on optimizing the manual use-case and features other than those associated with production. However, users of these instruments pay for every extra GHz and other incremental features. There is no upgrade path to support changing needs from 6GHz to 65GHz as applications change. Third generation testers support this upgrade path.

Third generation testers address the need to automatically de-embed and extract the measurements according to the DUT characteristics, which is a major technical challenge in getting reliable C_{OX} results. These algorithms, coupled with improved interconnect technology and automated calibration procedures, allow fast and accurate RF parameter extraction from s-parameter measurements.

Correcting random measurement artifacts is a prerequisite to accurate de-embedding. For example, any change in contact resistance in a system with 50Ω characteristic impedance limits repeatability. Instrumentation manufacturers must identify all the sources of instability in RF measurements and design the test system to avoid them. Innovative design of the system interconnections is required to provide repeatable links between major system components.

Automatically measuring probe contact resistance and adjusting probe overdrive is another way an instrument manufacturer can assure repeatable measurements. By measuring the actual value of the contact resistance before RF measurements are taken, they can be corrected for the value of contact resistance, especially important for passive devices. Another benefit of actually measuring contact resistance is the ability to automatically initiate probe tip cleaning when the resistance gets too high due to contamination. Good overdrive control and cleaning only when needed will increase probe life significantly, which reduces a major consumable cost. (RF probes cost about $1000 each.) This should also be part of the statistical process control of the tester.

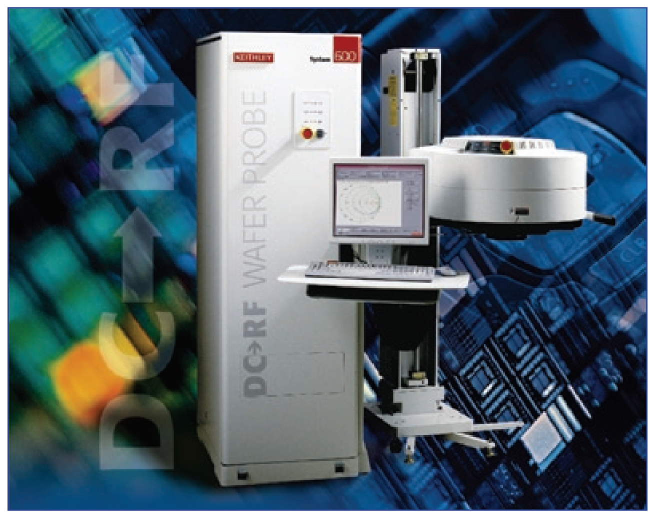
With stable and known parasitics, the Smith chart curves generated from collected data are free of artifacts; there is no need for specialists to analyze and interpret results. In older systems, an expert in RF measurements was required to monitor data (i.e. curve traces of every measurement set), look for strange or unexpected results, and then analyze those results to make sure they represented process variations, instead of measurement anomalies.

Improved logic in third generation parametric testers makes continuous monitoring of RF measurement quality a reality and reduces or eliminates the need for support by RF specialists. With these systems, different production floor operators can get repeatable real-time results across a wide range of products and production tools. RF measurements are almost as easy as making DC measurements, which are also required to completely characterize wafer devices. In fact, one third generation system can make DC and RF measurements simultaneously. (See sidebar.) This system contains a number of other refinements that speed up throughput, making it practical to do high volume wafer level testing for process monitoring and control. These same features speed up measurements in the modeling lab without sacrificing lab grade results, thereby shortening the development cycle and time to market. All this can be done without purchasing special probers, through easy system upgrades. When the calibration standard is stored on the prober, the operational work flow is identical to DC-only testing and is changed only during periodic maintenance cycles.

Innovative Designs for RF Testing

For many years, RF parametric testing at the wafer level was the province of “big iron” ATE systems limited to 6GHz or less or lab systems that were not capable for production use. Both were impractical for statistical process characterization and monitoring. To solve these and other problems associated with existing systems, in 2001 Keithley introduced its DC/RF series of parametric testers.

With these systems DC and RF testing can be done in parallel, asynchronously. This means that DC tests can be run in the background as RF testing is performed or visa versa, depending on which type of testing has the more complex attributes. As soon as either set of measurements is complete, the system is ready to perform more tests. Empirical data shows that neither DC nor RF test results are affected by running all test types in parallel. Since DC and RF measurements can be made simultaneously with a single prober insertion, throughput is greatly increased. System software provides real-time de-embedding and parameter extraction, while its mature point-and-click GUIs are unmatched by other systems in their ease of use.



The Keithley system design was influenced by a successful collaboration with several customers, resulting in innovations in interconnect and VNA integration, as well as adapting the parametric tester invented by Keithley to accommodate RF measurement needs. Since then there has been continuous improvement in all aspects of these systems, and in July 2003, Keithley received the Attendees Choice award at SEMICON-West for the 300mm production capability that was added.

Recently, Keithley introduced the third generation of these DC/RF parametric testers and already has several application successes with prominent semiconductor fabs. In these applications it was demonstrated that different technicians using the same system in a production facility could get the same results; in the past, this hasn’t even been possible in the lab on other vendor’s tools. When used in the lab, the Keithley tools provide excellent correlation with measurements made in production, even though the lab test suites are far more complex.

From the outset, a design objective was to make DC/RF parametric test systems that were usable by fab equipment operators to get high quality RF measurement results. Now it’s possible for ordinary operators to push a wafer boat into the test system and get lab-grade results without specialized RF training. All the operator has to know is the name of a parameter; they do not need to be concerned about calibration, de-embedding, or parameter extraction techniques. This can all be done at high production throughput, not at rates normally associated with lab measurements.

These capabilities are the result of patented and patent pending calibration procedures, interconnect technology, and de-embedding algorithms. Included with each system is the industry’s largest RF parametric extraction library.

The Keithley systems are the only production solutions available for RF C-V measurements to meet the needs of the 65nm node and beyond, and those solutions have been qualified for 300mm production environments. At this writing, they are qualified for RF production test at seven companies in the US, Europe, and Asia. These applications include on-wafer RF functional testing of IC devices at two different manufacturers of cell phones chips. Keithley is the only RF test system supplier qualified for production measurements above 6GHz. Four different probe cards have been qualified for these systems.

While these systems were designed primarily for a process integration interface, where modeling meets parametric test in the fab, their high precision, data integrity, and throughput makes RF measurements practical for modeling labs, parametric production monitoring, and end-of-line functional testing. For instance, one modeling lab using the Keithley system reported that data collection and analysis that formerly took up to 13 weeks could be completed in as little as one 8-hour work shift. The large quantity of high quality data being collected effectively closes the "model-to-measurement" gap that has previously existed. It is now possible to verify new RF process models in less than a week, compared to more than two months using older RF solutions.

High speed, high quality data collection is largely the result of self-monitoring features in these systems. For example, they monitor for human triggered events, such as an undocked test head, any change in equipment due to movement or reconnections, and calibration not being initiated at the proper interval (usually, a three day span). In all cases, the system recalibrates itself automatically, which only takes about two minutes.

A Soft-Touch (automatic Z adjustment) control feature results in superior RF measurements and lower consumables cost. In the past, the technique has been to overdrive the probe to scrub through contact surface resistance, but you still didn't know the magnitude of that resistance. The Keithley systems measure the contact resistance and limits the amount of overdrive and probe wear. Additionally, the value of contact resistance is used to correct the measurements.

The result of overdriving is shorter probe life; in other systems, the best achievable RF probe life is about 3000 touchdowns. This is drastically improved with Soft-Touch control. In one application the customer is getting a useful life of up to 300,000 touchdowns; in another, the user is getting up to 4 million touchdowns on a set of RF probes. In the latter case, the savings from fewer probe replacements over a six month period repaid the cost of an RF upgrade to a DC only system.

Another aspect of Keithley's probe control is better utilization of prober overhead time, resulting in higher throughput. While the prober is indexing and the needles are in the air, the system makes s-parameter measurements to determine if needle tips are getting contaminated. If so, the probes are moved to the cleaning pads for cleaning. The ability to automatically trigger probe tip cleaning and calibration as needed, within a single test execution thread or single command from a 300mm host, is unique to Keithley's third generation systems. Moreover, this function is executed without requiring a unique configuration in the test program, without any delay or disruptive communication with the 300mm host, and without the robot having to do anything. The system also does data extraction while the needles are in the air. The only thing it does when the probes are down is make measurements. Thus, no CPU cycles are wasted.

Probe card change-outs have long been a problem in many parametric test systems, and the cards must be changed every time there is a new type of wafer (different product) coming through the fab line. These problems are exacerbated in the case of RF testers, where mechanical damage during change-out is a frequent occurrence. For example, in many of these systems mechanical interconnections require the use of a cumbersome torque wrench. This frequently results in accidental damage as the wrench is dropped on probes, or due to over-torque damage, or inaccurate calibration occurs due to under-torqued connections. Even without these problems, a technician's hands can come in contact with the probes and bend them or damage other probe card parts.

These problems are avoided in the Keithley system: an operator simply pushes a button, the probe card comes out and is removed, and a new one is dropped into the slot, all of which can actually be accomplished by a robot instead of the operator. All the while, the test head stays docked, so calibration is often not affected for most probe types. Automatic probe card change for 40GHz measurements is another unique feature of the Keithley systems.

Another common problem in older wafer level RF testers has been oversized bias tees. These tees are used as part of a Kelvin connection to supply DC bias to the probe. Some of these tees are as big as a fist, making them hard to fit them into a probe head, and prone to interconnection problems that lead to measurement error. Working with Anritsu, Keithley developed a miniature Kelvin bias tee that can be located in the test head for stable connections with minimum parasitics.

With the flexibility to upgrade Keithley legacy systems going back almost 20 years and utilize most production probers up to 40GHz, Keithley's DC/RF system design provides the lowest cost of ownership available. Even a new system provides an attractive cost of ownership because of its initial price, high throughput, low operational/support costs, and low consumables cost.

Beyond the hardware and software in its DC/RF parametric testers, Keithley engineers work closely with customers to apply these innovative systems and RF measurement techniques to particular applications. Keithley develops extraction libraries that accommodate particular device and fab operation subtleties, helping users really understand what RF measurements mean in terms of semiconductor device processes. Keithley systems are also being used in labs to create statistical models much faster by collecting an extraordinary amount of reliable data in a much shorter time than ever thought possible. All this is being done with DC femtoamp precision, and RF measurements up to 40GHz.

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Carl Scharrer is the Principle Industry Consultant for Keithley Instruments, Inc., Cleveland. He has spent over 20 years working on product and process development for US semiconductor manufacturers.

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