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Statistical Process Control of Wireless Device Manufacturing Requires Production Worthy S-Parameter Measurements

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Whether you are manufacturing RFICs for cell phone modules on III-V wafers or DSPs on a silicon-based technology, predicting final product performance and reliability requires s-parameter measurements at the wafer level to complement the DC data. This is only practical when calibration and de-embedding of the s-parameters is automated, along with probe cleaning. Cost of consumables and overall cost of test must also be comparable to the traditional DC process monitor operation. The ideal case is to have a single test operation collect the DC and s-parameter data.

RF Process Monitoring – Who Needs It?

Almost without exception, semiconductor device manufacturers use DC data for statistical process control of their manufacturing operations. They have traditionally taken s-parameter data only in device modeling laboratories due to the complex nature of the measurements and associated cost. RF parameters are extracted from the s-parameter data and included in the simulation models used by design engineers during product development. RF parameters for modeling and DC data for production was a working paradigm until product performance approached the gigahertz range. Process control for gigahertz devices requires RF parameter sampling to meet the Known Good Die goals of RFICs for cell phone modules, guarantee the frequency performance of DSP chip level interconnect, and monitor gate dielectrics with complex material properties. As device performance improves to meet the demands of the wireless market, component manufacturers are struggling to improve test coverage without unacceptable increases in test cost. Several

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leading manufacturers have attempted to migrate the RF parametric measurement capability from their device modeling labs to manufacturing operations with little success and high levels of frustration.

Traditional Methods of RF Parameter Testing

As might be expected, RF testing began in product development to describe device performance in terms of familiar transmission line characteristics, such as 2-port/4-terminal s-parameters (s_{11}, s_{12}, s_{21}, and s_{22}) and noise parameters (NF, 1/f Noise). The instruments used for microwave device testing were added to equipment racks containing DC test equipment to allow measurements from DC to RF frequencies. However, these rack-and-stack test systems have traditionally required multiple probe insertions on the wafer for both calibration and measurements. A large number of individual measurements are required to characterize a device fully at DC and RF frequencies, so this type of system design results in extremely long test times. For example, with a Vector Network Analyzer, it can take from several minutes to a few hours just to complete the initial calibration of the system. Measurements are rarely made after only a single calibration with these types of setups.

The long calibration and test times associated with traditional rack-and-stack systems are a result of manual methods that require substantial operator intervention to verify test system performance. Although the RF test methodology is well established, actual implementation is complicated and may require a practitioner with Ph.D. credentials to obtain accurate calibrations and measurement results. It can take several days to complete a full battery of tests using traditional equipment and methods. This may be tolerable during product development for initial device characterization, but is not practical in a process monitoring environment. (See Table 1.)

Table 1. Characteristics of a traditional rack-and-stack DC/RF parametric test system.

Special prober and chuck required.
No test executive; each test program is usually created in BASIC.
Multiple manual calibrations needed; low repeatability.
Manual de-embedding[1] prone to probe variations due to contamination (resonance).
Slow measurements, data transfers, and extractions.
Expert user required to extract RF parameters from s-parameter data.
Low data integrity leads to repeat measurements and low productivity.
High cost of consumables (e.g., probe tips).
Not practical for production monitoring, only device characterization.

1 De-embedding refers to a calibration procedure that removes the effects of parasitic impedance associated with probe pads and interconnections. These effects can include the generation of resonant frequencies that obscure RF measurements at certain frequencies.

Fortunately, there are no fundamental impediments to automating RF parametric test algorithms. With appropriate instruments and probe hardware, plus test executive software, calibration and test times can be shortened dramatically. By pushing individual measurement times down to the millisecond domain, RF parameter extraction becomes practical for process monitoring.

Automated Probe Package Hardware and Software

To ensure high reliability and repeatability, the probes, probe cards, and interconnect used with the automatic probe station must exhibit low loss and reflections from DC to the highest frequency of interest. With today's wireless devices, that upper limit may be 40GHz. For such broadband semiconductor testing, the interconnection scheme typically uses precision miniature 50Ω coaxial cable from the probe tips to the connector interface. This coaxial design provides lower loss and less radiation than coplanar designs, plus measurement repeatability with about –80dB isolation.

Repeatability also is a function of stable calibration, which is related to VNA architecture, probe design and probe package software. Independently spring-loaded beryllium-copper or tungsten probe tips assure repeatable contacts at the probe points, minimize circuit damage, and increase probe life. The best designs allow 300,000 or more touchdowns before repair is required. The probe control algorithm used with this hardware should automatically provide a small amount of overdrive so the probe point does not over-scrub the connection pad surface, but makes a reliable contact that is free of dust, dirt, and oxide contamination. The slight scrubbing and ability to view the exact contact area eases probe positioning and allows the precision necessary for good calibrations. For enhanced data integrity, some probe card algorithms include a burnishing routine that supports automated cleaning of probe tips.

With an automated calibration algorithm in the test executive, a system level calibration can be as short as two minutes. By calibrating the instruments, interconnects, probe card, probe card adapter, and calibration substrate as a complete system, the highest overall accuracy is assured. This also eliminates the need to recalibrate for changes in test frequency or the number of data points, which consumes a lot of time with manual calibrations.

Use of a VNA for RF Measurements

The heart of the s-parameter measurement system is the Vector Network Analyzer (VNA). The primary considerations for this VNA are noise floor (<–90dBm), how the sweep is synthesized (lock on every frequency point), high speed data transfer, internal mass storage, software initiated calibration, and high MTBF (>50,000 hours). A VNA can provide a high level of precision in auto-reversing s-parameter measurements of active and passive multi-port devices at microwave frequencies. Within 350ms, the VNA can collect 100 or more data sets with 1kHz resolution. If the test executive contains an appropriate library of RF macros, the VNA s-parameters can be used to extract corrected RF parameters quickly (ft, fmax, fmin, Q, C, Rb, L, Load Pull, and many other RF characteristics. These can be presented in tabular form, as Smith charts, X-Y plots, etc. See ***Figures 1*** and ***2***.

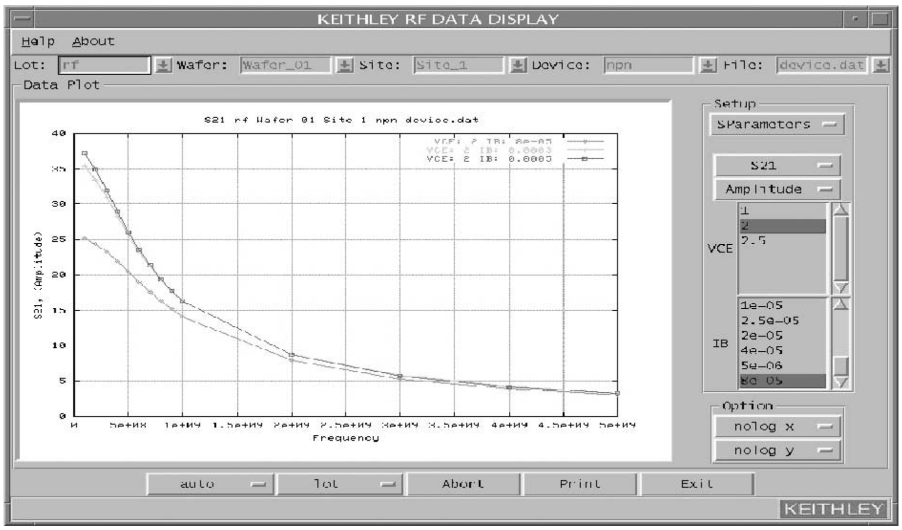

Figure 1

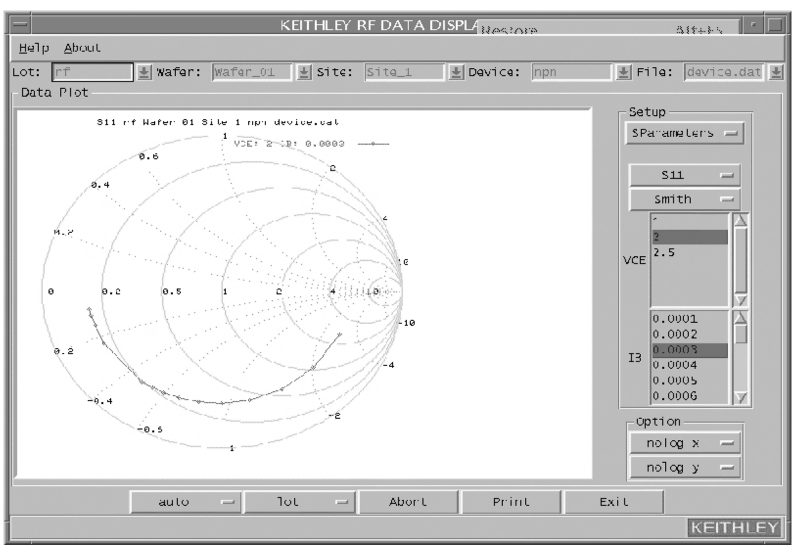

Figure 2

Keithley Sx00DC/RF Series

Just as Keithley Instruments was the first to bring low current DC measurements to the production test environment, we have used the design approach described in this paper in the new Keithley Sx00DC/RF APT Systems for process monitoring. In partnership with Anritsu Corporation and GGB Industries, Keithley developed a low cost, merged DC/RF test solution based on the best technologies available. Key performance features include:

- Keithley Sx00 APT based DC test system with solid state transfer switch and Anritsu VNA technology for fast RF measurements with 1kHz frequency resolution, stable auto-calibration, and a modular upgrade path from 20–110GHz.
- Anritsu VNA includes integrated fast sweeping source, auto-reversing s-parameter test set, and four-channel receiver.
- GGB self-leveling G-S-G probe technology provides measurements from DC to 200GHz. with 300,000 or more touchdowns (a 100× increase over older systems).
- Keithley System 41 RF Switch technology is an option for multiple DUTs for measurements up to 20GHz.
- Both single and segmented limits can be used for PASS/FAIL testing; 1 to 4096 averages can be performed on the data.
- Full factory automation, efficient test programming, and high productivity tools provide high measurement throughput and accuracy for all DC and RF parameters.

This APT system design can be used with any automatic prober, and provides fully automated single-pass calibration that is quickly executed during testing—without the need for human verification. The calibration includes automatic de-embedding of probe pad/interconnect impedance that would impair data integrity, and can be completed in approximately two minutes. (The manual calibration procedures of traditional rack systems take up to four passes and two hours. Furthermore, manual de-embedding is prone to probe variations due to contamination, resulting in low data integrity that leads to repeat measurements and reduced productivity.) Automation of probe tip cleaning is also accomplished with this system.

Sx00DC/RF test functions are integrated with the Keithley Test Environment (KTE) production productivity tools. With the KTE User Library of RF Macros, even novice users can quickly extract RF parameters. The result is 3× better raw measurement speed with realtime data extraction and binary transfers to file or a plant network. A data-driven programming environment and KTE's User Access Points allow easy program adaptation, even during test. With the fast RF auto-calibration (which is unique to the Keithley system), overall system throughput can be increased by 10× compared to traditional rack system designs.

This high speed and repeatability makes the Sx00DC/RF's use practical in process monitoring. However, single insertion DC/RF testing requires compatible test structures. Therefore, Keithley offers test structure design support (test programs included) to facilitate this new capability.

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