KEITHLEY

WHITE PAPER

Advanced Membrane Substrate and Interconnects Will Allow Simultaneous RF and DC Measurements During Wafer Probing

Background

Traditionally, probe cards for parametric testers have been designed for either RF signals or low level DC measurements, but not both. This was fine as long as a semiconductor wafer contained only RF test circuits, or those designed for DC operation. However, as digital switching speeds have increased to RF frequencies, and mixed RF and DC test devices are designed into wafers, separate RF and DC probing has become very costly. It requires a changeover from one type of probe card to the other, recalibration of the parametric tester and its interconnects, and then re-probing the wafer for a second set of measurements.

In addition, on-wafer testing of semiconductor devices often utilizes the interfacing between test instruments and the test points and structures located within wafer scribe lanes. As semiconductor dies and scribe lanes decrease in size, it becomes more difficult to connect test instruments to the device under test (DUT). This problem is compounded when both RF and ultra-low current DC measurements are desired. In RF measurements, an important consideration is minimizing RF signal losses through a variety of techniques, such as maintaining the desired characteristic impedance to minimize RF energy reflections along the signal path. In ultra-low current measurements (for

Keithley Instruments, Inc.
28775 Aurora Road
Cleveland, Ohio 44139
(440) 248-0400
Fax: (440) 248-6168
www.keithley.com

example, sub-nanoamp magnitudes), it is important to minimize the effects of extraneous voltage potentials in the vicinity of the test point.

To help alleviate this situation, some probe cards have recently been designed for a few RF connections, with the remaining probes calibrated for DC. This helps to some extent but limits the effectiveness of parametric test systems, most of which could be programmed to conduct either RF or DC measurements on any pin. Still, parametric testers themselves need to be designed so that interconnections on any signal path can handle either type of signal. Up to now, this type of system has not been available.

However, Keithley Instruments and Mesatronic Group (Voiron, France) have formed a technical alliance that is blazing new trails in the quest for small geometry, mixed RF and DC testing. Engineers from the two companies are working together to create probe cards for parametric test systems that take RF and low level DC measurements on any combination of wafer prober pins. Project objectives include easier layout and manufacture of the probe cards, shorter production times, and ultimately lower cost to parametric test users. In addition, users should be able to reduce their probe card inventory by using one card design for many different applications.

Semiconductor Wafer Trends

Because of today's fast switching digital devices and their combination with RF analog devices on the same wafer, wafer level RF testing is needed to predict product performance and reliability. Still, DC parametric testing remains just as important as ever in detecting phenomena that affect device lifetimes and failure modes. As the industry progresses toward the 65nm node and beyond, high-performance/low-cost digital, RF, and analog/mixed-signal devices present a significant challenge to test equipment and probe card manufacturers. The big challenge in parametric tester design is to combine the measurement of GHz frequencies and femtoamp DC signals in a way that helps improve device reliability while lowering test costs.

At the same time, a challenge for probe card manufacturers is the continuous shrinking of wafer scale dimensions to allow more devices per unit area. This includes shrinking scribe lanes on wafers, which are currently trending toward a 30-micron width. That means probe pads must be just as small or smaller. Card designs must incorporate probe needles that can hit these smaller targets without excess scrubbing motion that causes a probe tip to go off the pad. Currently, conventional cantilever probe technology is restricted to pad sizes larger than 50 microns.

Implications For Parametric Testers

For the past few years, manufacturers of parametric testers have been grappling with the technical problems of mixed RF and low level DC measurements. A prerequisite for accurate measurements is the creation of a low-loss broadband signal path and good calibration techniques. The key element in effective calibration is fast, automatic de-embedding of probe pad/interconnect impedance that impairs data integrity. When used with a suitable probe card design and test structures on the wafer, a well designed and calibrated parametric tester should be able to execute independent DC and RF tests in parallel on separate probes, greatly reducing the time and cost of testing.

However, an "any pin" RF/DC measurement objective faces several technical hurdles. Most of these are associated with interconnections along the signal path and system calibration, which involves wafer test pads, probe pins, the probe card, interconnecting cables, and the parametric tester itself. To successfully probe high frequency and sensitive DC devices, one must master the mechanical and electrical properties of the signal path.

Physically, a probe card is a circuit board. At high frequencies, probe cards become transmission lines, so a major consideration is how they affect signal propagation (for example, RF energy reflections), interaction between signals (crosstalk), and interactions with the outside world (in the form of electromagnetic interference). These and other considerations, such as wave phenomena, are related to the characteristic impedance of the signal path and any mismatch that occurs at the signal source or measurement end.

Keithley/Mesatronic Spatial Transformer Development

Keithley Instruments has partnered with Mesatronic to develop advanced probe cards for parametric test and production applications. When the project is completed, the new cards can be used to measure RF signals and very low level DC currents on any combination of probe pins that contact a semiconductor wafer. Moreover, the probes for these cards will be suitable for 30-micron test pads.

These cards should be of particular interest to manufacturers of RFICs (RF integrated circuits), RFIDs (radio frequency identification devices), and devices for mobile and wireless handsets and infrastructure. Currently, there are very few probe card technologies available that allow single insertion RF and low current DC measurements, and RF measurements are limited to only a few dedicated probe pins that cannot be used for accurate low current DC measurements.

The Keithley/Mesatronic collaboration is concentrating on development of the spatial transformer that is used as an interconnection between test instruments and probe needles or membranes that make actual contact with the DUT on the wafer. Thus, the spatial transformer serves as an intermediate structure that concentrates the test instrument connections into a form more suited to the high density inputs of the needles or membrane.

When both RF and precision DC measurements need to be made, the practice in the past has been to use a specially designed spatial transformer for each desired combination of RF and DC test terminals. Each RF connection uses RF terminals having a desired characteristic impedance and each precision DC connection uses a "guarded" terminal to minimize leakage currents. This greatly complicates and increases the cost of obtaining a suitable spatial transformer.

A key feature of the Keithley/Mesatronic spatial transformer design is the creation of "broadband guarding." As with other types of guarding, the appropriate points along the signal path are effectively surrounded with elements at the same voltage as the points of interest. This prevents them from "seeing" any other potentials that would cause DC leakage currents and measurement inaccuracies. However, the Keithley/Mesatronic development goes a step further. The guard traces on the spatial transformer, in combination with the center conductor traces, also provide the desired characteristic impedance for an RF signal traveling along the same signal path.

Keithley's expertise in sensitive DC and RF measurement guard circuitry and other interconnect technology is being used to create the low-loss broadband signal path design of the spatial transformer. Mesatronic's D.O.D ("Die-On-Die") Technology®, a unique combination of membrane (substrate) technology and semiconductor production techniques, will be used to implement the design. All connection geometries in the design can be the same, thereby reducing layout and manufacturing costs. Ultimately, this should drive down the end price and create a more favorable cost of ownership model for parametric testers.

In the resulting probe card, Mesatronic's vertical probe technology will allow very limited probe pin scrub lengths and minimum pad damage and contamination on the wafer. Reduced contamination may translate immediately to process yield improvements. The shape of the probes can be varied to match up with various probe materials, and they can be used with aluminum, gold, or copper pads, as well as tin/lead bumps. The wafer test pads can be as small as 30 microns, the current trend in scribe lane dimensions, and the probes can consistently hit these smaller targets without excess scrubbing motion that causes probe tips to go off the smaller pads.

Mesatronic's DOD Technology exhibits DC contact resistances as low as 0.2 to 0.5 ohms, while achieving leakages currents of less than 10fA/V at a typical overdrive of 2 mils. DOD Technology has been successfully tested at frequencies of up to 6GHz with a total insertion loss less than –3dB. Probe cards using this technology are being used at various customer sites and are routinely produced at Mesatronic's Voiron facility.

Conclusions

When this new probe card technology is combined with Keithley's S600 Series parametric testers, users will be able to make single insertion RF/DC wafer measurements for automated process monitoring. This will include fully automated single-pass calibration that is quickly executed during testing without the need for human verification. This calibration includes automatic de-embedding of probe pad/interconnect impedance that would impair data integrity, and can be completed in minutes. With the new probe cards, users will have the ability to measure RF and low current DC signals on any combination of prober pins by simply changing the type of cabling and termination used for the RF and DC pins. This system will provide an unrivaled combination of high-performance, speed, flexibility, ease of use, and compact size – saving users time, effort, and money. ■

Innovative Designs for Sensitive RF and DC Testing

For many years, RF parametric testing at the wafer level was the province of "big iron" ATE systems or lab systems that were not practical 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 RF/DC 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 and other test equipment manufacturers. The results include innovations in probe card and interconnect technology, as well as VNA integration. Since the first introduction of these systems there has been continuous improvement in all aspects of their design.

Recently, Keithley introduced the third generation of these RF/DC 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 vendors' 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 RF/DC 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 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 several 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 existed previously. 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. Soft-Touch control also provides drastically improved probe life. 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 from 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, with a change required 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. Inaccurate calibration occurs also 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 will be avoided entirely with the "any pin" RF/DC probe cards. The test head stays docked for independent RF and DC measurements without the need for recalibration.

With the flexibility to upgrade Keithley legacy systems going back almost 20 years and utilize most production probers up to 40GHz, Keithley's RF/DC 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 RF/DC 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 broadband RF measurements.

KEITHLEY

A GREATER MEASURE OF CONFIDENCE

KEITHLEY INSTRUMENTS, INC. ■ 28775 AURORA ROAD ■ CLEVELAND, OHIO 44139-1891 ■ 440-248-0400 ■ Fax: 440-248-6168 ■ 1-888-KEITHLEY ■ www.keithley.com

BELGIUM
Sint-Pieters-Leeuw
Ph: 32-2363-0040
Fax: 32-2363-0064
www.keithley.nl

CHINA
Beijing
Ph: 8610-82255010
Fax: 8610-82255018
www.keithley.com.cn

FINLAND
Espoo
Ph: 358 9 88171661
Fax: 358 9 88171662
www.keithley.com

FRANCE
Saint-Aubin
Ph: 33-1-6453-2020
Fax: 33-1-60-1-77-26
www.keithley.fr

GERMANY
Germering
Ph: 49-89-84-93-070
Fax: 49-89-84-93-0734
www.keithley.de

UNITED KINGDOM
Theale
Ph: 44-118-929-7500
Fax: 44-118-929-7519
www.keithley.co.uk

INDIA
Bangalore
Ph: 91-80-2212-8027
Fax: 91-80-2212-8005
www.keithley.com

ITALY
Milano
Ph: 39-02-553-8421
Fax: 39-02-55 38 42 28
www.keithley.it

JAPAN
Tokyo
Ph: 81-3-5733-7555
Fax: 81-3-5733-7556
www.keithley.jp

KOREA
Seoul
Ph: 82-2-574-7778
Fax: 82-2-574-7838
www.keithley.co.kr

MALAYSIA
Kuala Lumpur
Ph: 60-3-4041-0899
Fax: 60-3-4042-0899
www.keithley.com

NETHERLANDS
Gorinchem
Ph: 31-1-836-35333
Fax: 31-1-836-30821
www.keithley.nl

SINGAPORE
Singapore
Ph: 65-6747-9077
Fax: 65-6747-2991
www.keithley.com.sg

SWEDEN
Solna
Ph: 46-8-509-04-600
Fax: 46-8-655-26-10
www.keithley.com

TAIWAN
Hsinchu
Ph: 886-3-572-9077
Fax: 886-3-572-9031
www.keithley.com.tw

Printed in the U.S.A. No. 2801 1106