Trendsetting Methodologies for Wafer-Level RF Measurements

The vector network analysis techniques have been used for over fifty years for characterization of linear devices at the frequency domain. Starting from simple test sets assembled and manually operated by RF engineers in the late 1950s, it has evolved into highly-sophisticated automated measurement systems that cover an extremely wide frequency range.

This application note discusses unique integrated solutions developed by MPI Corporation and Rohde & Schwarz to satisfy the most challenging wafer-level measurement requirements of modern RF devices and integrated circuits.

DUT courtesy: FBH, Berlin.

The basic measurement concept implemented in modern VNA remains the same for all frequencies: it measures the incident a_i, reflected and transmitted b_i wave quantities at the ith port of the DUT.

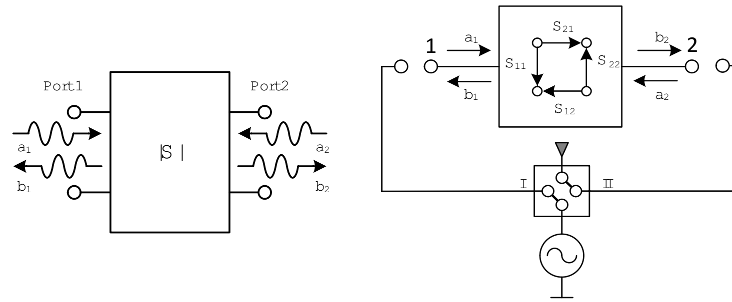

Fig 1: S-parameter definition and measurement concept of a two-port device

In a general way, the VNA allows measurement and computation of S-parameters of the DUT at system reference impedance, typically 50 Ω. The incident signals are generated by the internal source, while the reflected and transmitted signals are measured by receivers. The VNA has an internal switch to redirect the incident signal (Fig. 1). So, the DUT can be automatically measured in both forward and reverse directions without reconnecting. The S-parameter matrix of the DUT is computed as:

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}$$

where

$$S_{11} = \frac{b_1}{a_1}\bigg|_{a_2=0} \quad , \quad S_{21} = \frac{b_2}{a_1}\bigg|_{a_2=0} \quad ,$$

for the forward direction (when a_2=0), and

$$S_{12} = \frac{b_1}{a_2}\bigg|_{a_1=0} \quad , \quad S_{22} = \frac{b_2}{a_2}\bigg|_{a_1=0}$$

for the reverse direction (when a_1=0) (Fig. 2)

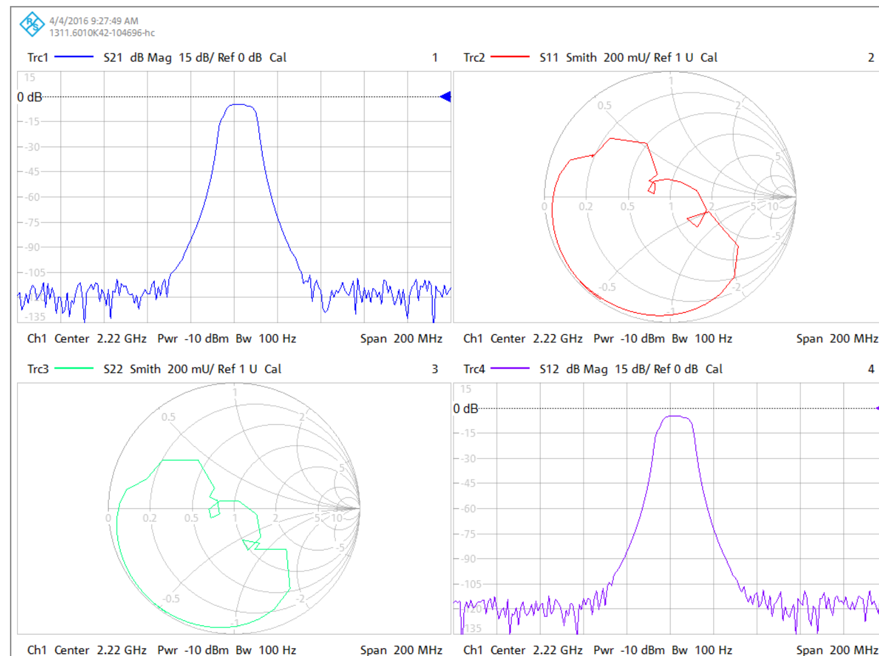

Fig. 2: Example of measured S-Parameters of a two-port device under test

Vector Network Analysis

Modern Measurement Challenges for a Vector Network Analyzer

Accurate characterization of advanced RF and microwave devices and IC's is a complex and challenging task. A wide measurement frequency range, high dynamic range, the need for accurate results obtained in a fast time, - this is just a short list of requirements that have to be accomplished by the vector network analyzer.

For instance, a wide dynamic range is important when measuring high rejection filters. A fast frequency sweep, which can also be a combination of several segments with individual settings for each segment, is the key for a high-throughput measurement of passive components in production.

Moreover, the characterization of power amplifiers (PAs), mixers, transmitter-receiver (T/R) modules and complex RF front ends demands for more sophisticated features. Several signal sources in the VNA allow intermodulation distortion (IMD) measurements, frequency conversion and harmonic measurements, True-Differential stimulus, RF measurements under pulsed conditions and Noise Figure measurements.

On-wafer device characterization has the same demands. For active devices, a well defined power level down to the probe tips is required, which can be achieved by performing a power calibration including a compensation for the loss between the coaxial plane and the probe tip.

Rohde & Schwarz Vector Network Analyzers for On-Wafer Measurements

The Rohde & Schwarz®ZVA and ZNB vector network analyzer series are an ideal choice for demanding measurements in the lab - from measurements of passive devices like filters, attenuators, cables and other components to linear and nonlinear measurements on amplifiers, mixers, receivers and transceivers (Fig. 3).

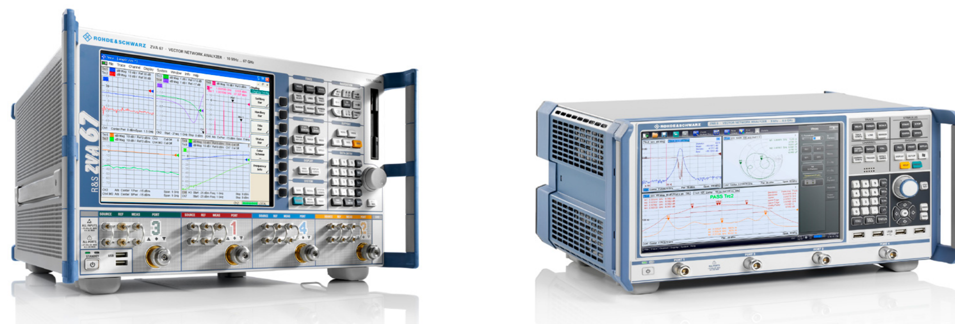

Fig. 3: Rohde & Schwarz®ZVA (left) and Rohde & Schwarz®ZNB (right) Vector Network Analyzers

On-Wafer measurements put additional requirements on the VNA. It has to be very stable over time, especially as the on-wafer calibration takes time and the measurement itself is performed minutes or even hours after the calibration was done. Another requirement, important for active device characterization, is high output power of the VNA in order to compensate for losses in cables or waveguides and in probes. Finally, the network analyzer has to offer calibration techniques which are suitable for on-wafer measurements, like e.g. Thru-Reflect-Line (TRL).

The control from an external calibration software like QAlibria® from MPI Corporation requires that the VNA is integrated in the software package. The Rohde & Schwarz®ZVA and ZNB vector network analyzers fulfill all these requirements for on-wafer testing.

For frequencies above 67 GHz millimeter-wave converters can be used. Rohde & Schwarz offers a wide range of these converters up to 500 GHz. They can be mounted on the TS150-THZ prober from MPI Corporation (Fig. 4).

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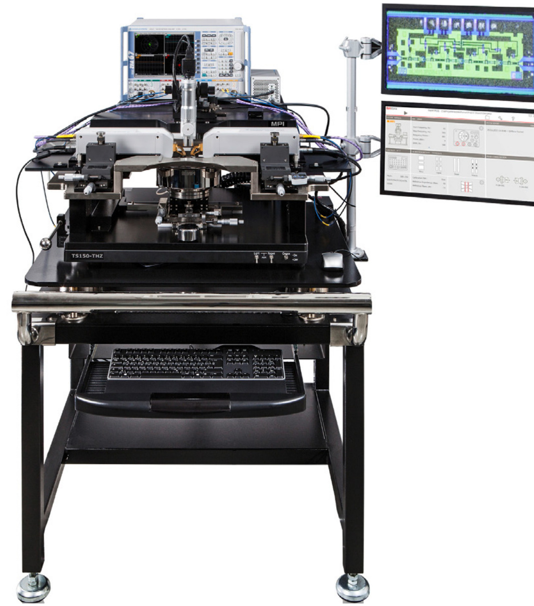

Fig. 4: Rohde & Schwarz ZVA with millimeter wave converters on MPI TS150-THZ Manual Probe System

Rohde & Schwarz offers converters for banded measurements up to 500 GHz and a system for a continuous sweep measurement from 10 MHz to 110 GHz (Rohde & Schwarz®ZVA110).

The Need for Calibration

The RF calibration is intended to remove systematic errors from the instrument hardware (and to take into account the presence of any accessories that may have been added to enable specific measurements to be performed) at the required frequencies for the measurements. The calibration of the S-parameter measurement is required already at relatively low frequencies of hundreds of megahertz: the wavelength of the test signal is of several orders of magnitude shorter than the equivalent length of the measurement signal path.

In the case of wafer-level measurements, first, cables need to be connected to the VNA front panel connectors (ports), followed by wafer probes. RF calibration will correct the impact of these added components as well as the systematic measurement errors of the VNA itself. That is why this type of calibration is often referred to as "system error correction".

The error correction procedure can also be imagined as a virtual shifting of the measurement reference plane (i.e. the "zero point" of the magnitude and phase of the measurement signal) to the desired location (Fig. 5).

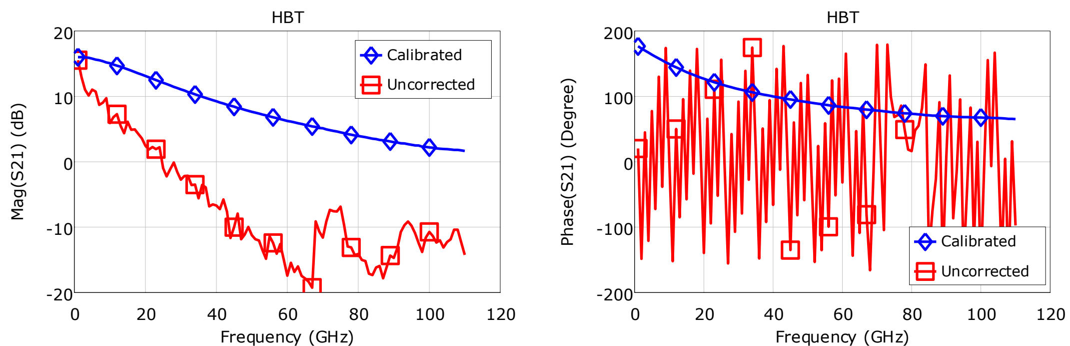

Fig. 5: Example of uncorrected and RF calibrated measurement results of an heterojunction bipolar transistor (HBT) made by an advanced BiCMOS process

Wafer-Level Measurements

The key components of an analytical probe system comprise the wafer chuck, the optical system (microscope), and the probe platen with the MicroPositioners. RF cables and wafer probes as well as calibration substrates and auxiliary (AUX) chucks accomplish the RF wafer-level measurement system.

Chuck and Chuck Stage

Many RF DUTs are realized in a coplanar waveguide (CPW) design. In particular, this refers to the III-V's semiconductors. The large vacuum holes as well as the vacuum rills on the chuck surface (used to hold the wafer on the chuck on a conventional system) may interact with those DUT's breaking consistency of the grounding conditions and thus have an impact on the electrical characteristics, particularly at higher frequencies. To overcome this problem, MPI RF Systems use RF chucks with a special surface and very small vacuum holes (Fig. 6).

The typical operational workflow includes two different tasks: firstly, the loading of the wafer and quick navigation to the desired area. Secondly, a highly precise positioning of the DUT under the probe tips. The MPI unique air-bearing stage design, with simple single-handed puck control, provides unsurpassed convenience of operation for fast XY navigation and quick wafer loading (Fig. 7). Accurate and fine positioning capability is achieved by implementing precise micrometers for 25 mm X 25 mm XY- and Theta-movement. This enables a fine wafer adjustment as well as precise navigation from DUT to DUT.

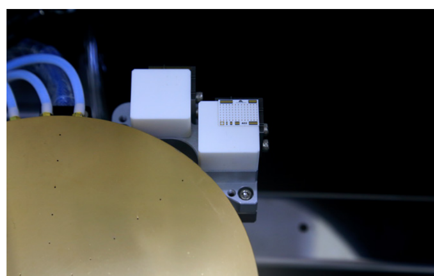

Fig. 6: Dedicated RF chuck with small vacuum holes and two auxiliary sites

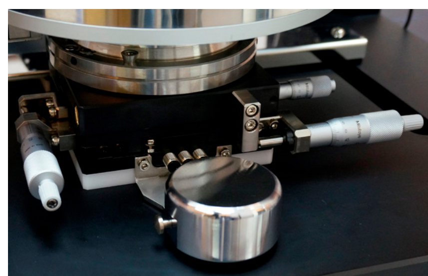

Fig. 7: Air-bearing stage with a single-handed puck control

Optical System

Optical systems for specialized RF measurements should combine the following characteristics: a large field of view (FoV) is necessary for a quick navigation over the wafer and due to the large size of modern high-complexity integrated circuits. On the other hand, a high magnification is needed as the industry trend goes towards further minimization of the device pad size. The higher the magnification, the more precisely RF probes can be placed on the calibration standard. This is a prerequisite for constant and predictable electrical characteristics of the standards and thus ensures accurate and repeatable calibration.

Moreover, several test instrumentation components (such as impedance tuners, frequency extenders, couplers and bias-T's) have to be placed as close as possible to the DUT. This imparts additional mechanical restrictions for the optical system: so, the body of the microscope should be slim and the working distance (spacing between the objective of the microscope and the DUT) should be as large as possible. Finally, the microscope should be easy to remove from the operation area for frequent accessory exchange and system reconfiguration.

A microscope that matches all those requirements is a key success factor of accurate RF measurement results. However, there is currently no such "all-in-one" solution available from microscope vendors. Understanding the need for such a microscope, MPI went into a close cooperation with the leading manufacturers of optical systems. It resulted in the unique, single-tube solutions SuperZoom™ SZ10 (Fig. 8) and MegaZoom™ MZ12 (Fig 9). Small form factors, outstanding combination of the FoV, high magnification and large working distance make these microscopes the ideal choice for all RF measurement applications.

Fig. 8: SuperZoom™ SZ10 microscope with HDMI camera

Fig. 9: MegaZoom™ MZ12 microscope with HDMI camera

All microscopes include TV ports for displaying the live image on the monitor by 1080p HDMI cameras. If necessary, the image settings can easily be changed over the remote control unit. The 5 Mega pixels camera allows capturing and saving pictures to the build-in mini SD memory card. An additional computer is not required.

The MPI proprietary 90-degree microscope tilt is a standard feature of MPI probe systems. It offers quick and sure re-configuration of MicroPositioners and RF probes changeover (Fig. 10).

Fig. 10: The 90-degree microscope tilt for quick and sure changeover of accessories

Cables

A number of special requirements have to be met for RF cables in wafer-level measurement systems. First, optimal cable length has to be found as a trade-off between usability (longer cables) and minimal insertion loss (shorter cables). Next, the weight of the cable itself imposes mechanical stress to the probe arm and thus impacts the probe alignment as well as the quality and stability of the contact. Again, there has to be found an optimal balance between minimal weight and magnitude/phase stability of the cable: double- or triple-armored cables ensure higher stability, but are thicker and significantly heavier.

Thirdly, the design of the RF probe arm requires the male cable connector to be short and slim because of the limited space around the female connector of the RF probe. On the other hand, such cables can easily break at the soldering point between the cable and the connector already after just a few connect-/disconnect-cycles. Therefore, top-bench systems ("connectorized" measurement environment) usually use cables with an extended and strengthened cable-to-connector transmission point. Wafer-level systems, however, require an individual solution.

Fourthly, requirements regarding phase, magnitude and temperature stability remain the same as for top-bench systems. The use of stable cables is indispensable for minimizing the number of re-calibrations and for extending the time of a valid calibration. When using cheap and unstable cables, time-to data rises significantly due to often system re-calibration.

MPI engineers focus on optimal cable solutions taking into account all requirements mentioned above and therefore closely cooperate with the leading cable manufactures. As a result, MPI can offer two series of RF cables — the high-end MMC and the entry-level MRC — covering the entire frequency range starting from 18 GHz. This allows engineers to choose the optimal system configuration in dependence of the required measurement accuracy and budget restrictions (Fig. 11).

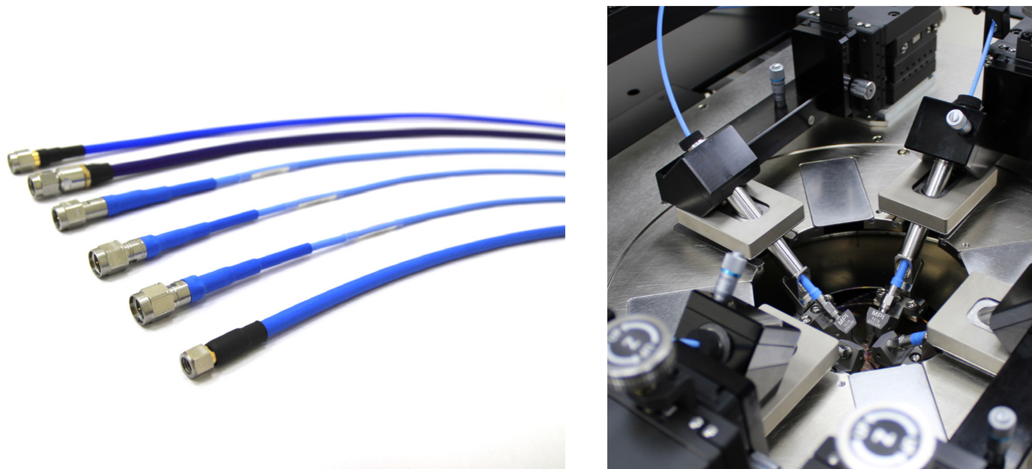

Fig. 11: Dedicated wafer-level RF cables

Platen Lift Mechanism

The accuracy for RF calibration and measurements strongly depends on the quality of the contact and the contact repeatability. To decrease the contact repeatability error of coaxial connectors, a special wrench with a predefined torque is widely used in the "connectorised measurement environment". As far as it concerns wafer-level measurements, it still remains challenging to reduce the contact repeatability and to keep it constant. This usually requires years of experience in operating wafer probe stations.

The uniqueness of the platen lift on MPI manual probe systems is rooted in the combination of "auto-contact" feature and safe operation: the auto-contact mechanism ensures 1 µm contact repeatability independently of the operator experience. Three discrete positions for contact, separation (300 µm), and wafer loading (3 mm) with a safety lock utility prevent unexpected damage of probes or wafers and provide intuitive control of the positioning of the RF probes (Fig. 12, 13).

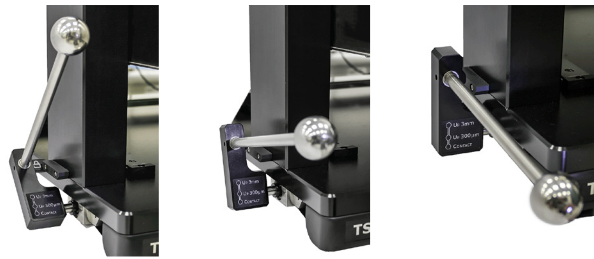

Fig. 12: The platen lift mechanism in three discrete positions: wafer loading (left), separation (middle), and contact (right)

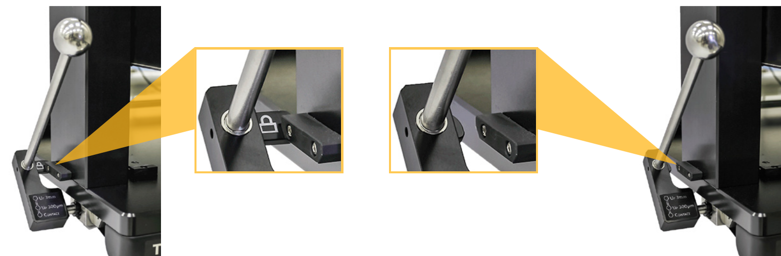

Fig. 13: The safety lock utility of the platen lift in lock (left) and unlocked (right) positions

Probes and Calibration Standards

RF wafer probes are often called the “last inch” of the cable to the device. They convert the electro-magnetic energy travelling along the coaxial cables to the on-wafer DUT and its contact pads. The conversion has to be carried out with minimal distortions and energy loss.

The DUT contact pads can have aluminum, copper or gold metallization, depending upon the semiconductor technology and process used to manufacture the device. The RF probe should provide minimal and consistent contact resistance on any pad material — from aluminum (covered by the Al_2O_3 oxide layer that is highly resistive and is very hard to break though) to the soft and easy to damage gold. Moreover, the industry trend goes to further reduction of the pad size for RF devices and ICs. It is noteworthy that DUTs have to be re-probed several times (e.g. at different temperatures) or have to be bonded after measurements. The risk of DUT failure due to excessive pad damage is higher on smaller pads as each probing cycle reduces the area suitable for further re-contacting or bonding. RF probes should therefore leave small footprint, have short forward skating and provide minimal pad damage.

There are significant differences between the various types of RF DUTs: from discrete elements to complex ICs operating at different frequencies. It is of utmost importance, that the configuration of the probe tip (ground-signal-ground GSG, or ground-signal GS and signal-ground SG) as well as the probe pitch (the distance between its individual contacts) complies with the DUT pad layout. RF probe technology therefore must support a wide range of frequencies and pitches as well as the various tip configurations.

Finally, the probe price together with the probe lifetime directly influences the DUT cost of test. The latter, of course, has to be kept as low as possible.

Precisely manufactured, the MPI TITAN™ Probes incorporate perfectly-matched 50 Ω MEMS contact tips. They ensure unmatched calibration and measurement results over a wide frequency range thanks to superior probe electrical characteristics (minimal insertion loss and crosstalk as well as high return loss).

Unlike any other tips on the market, MPI TITAN™ RF probes deliver an excellent and real time visibility of the tip contacts due to the unique protrusion tip design. For the first time, highly accurate positioning of the RF probe on calibration standards or DUT pads became possible even for unexperienced operators and without using probe alignment marks (Fig. 14).

MPI TITAN™ Probes even allow the probing of small passivation window pads because the probe skate was significantly reduced and the attack angle was optimized. Even under extreme measurement conditions, it is possible to achieve consistent and repeatable contact resistance.

The TITAN™ Probe series are available in single-ended and dual tip configurations with pitch range starting from 50 µm and frequencies from 26 GHz. TITAN™ RF Probes are the ideal choice for on-wafer S-parameter measurements of RF, mm-wave devices and ICs as well as for the characterization of RF power devices requiring up to 10 Watts of continuous power (Fig. 15).

Fig. 14: TITAN™ Probe tip design

Fig. 15: The wide range of TITAN™ Probe for various RF applications

One of the strongest features of TITAN™ Probe technology is its uniform wear-out: after hundreds of thousands probe cycles the length of the probe tip naturally shrinks. The electrical characteristics, however, remain unchanged due to the unique probe design. Thus, the life time of TITAN™ Probes outperforms the life time of comparable probe technologies.

Last but not least, TITAN™ Probes stand out thanks to a truly affordable price.

Calibration Substrates

Commercial probe-tip RF calibration standards are made in CPW design: both signal and ground conductors are located on the top of the dielectric (alumina) material – the calibration substrate. Calibration substrates usually include calibration elements of different kinds: open, short, load, and lines. Accordingly, various types of probe tip calibration can be carried out.

MPI AC-series of calibration substrates is specially developed to provide accurate probe tip calibration of TITAN™ Probes. The design of calibration standards is matched with the probe configuration and the pitch size (Table 1). The model parameters for standard equivalent impedances (also known as probe correction coefficients) define the accuracy of calibration and were extracted with highest precision.

Table 1: RF probes and calibration substrate reference table

TITAN™ Probe Configuration	Calibration Substrate Model
GSG, pitch from 100 to 250 um	AC-2
GS/SG, pitch from 50 to 250 um	AC-3
GSG, GS/SG, pitch from 250 to 1250 um	AC-5

All substrates support conventional calibration methods, such as TOSM/SOLT and TRM/LRM. AC-2 includes a set of five CPW lines for accurate broadband multiline TRL calibration. MPI calibration substrates were qualified using NIST methodology (Fig. 16).

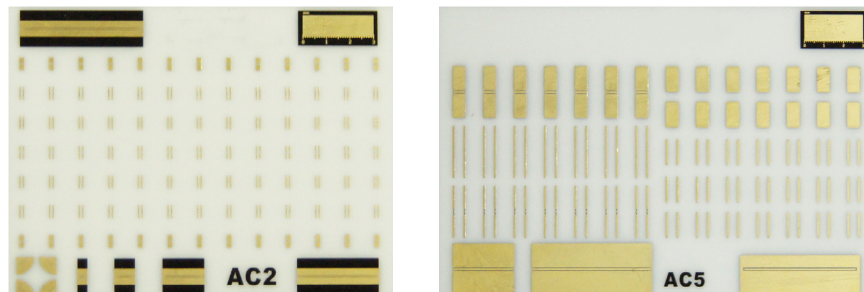

Fig. 16: The AC-2 (left) and AC-5 (right) from the AC-series of alumina calibration substrates

Calibration Auxiliary Chuck

When the measurement frequency approaches the mm-wave range, several parasitic effects occur and have impact on the electrical characteristics of coplanar calibration standards. Among them are: coupling with nearby structures, crosstalk through the substrate, excitation and propagation of the higher order modes. Consequently, calibration accuracy degrades. Moreover, these effects increase with the frequency.

All MPI RF probe systems use AUX chucks made of special ceramic (Fig. 6). This solution changes boundary conditions for CPW elements such that parasitic effects are drastically reduced. As a result, commercial calibration substrates can successfully be used for the probe-tip calibration at significantly higher frequencies, up to sub-mm waves range (Fig. 17).

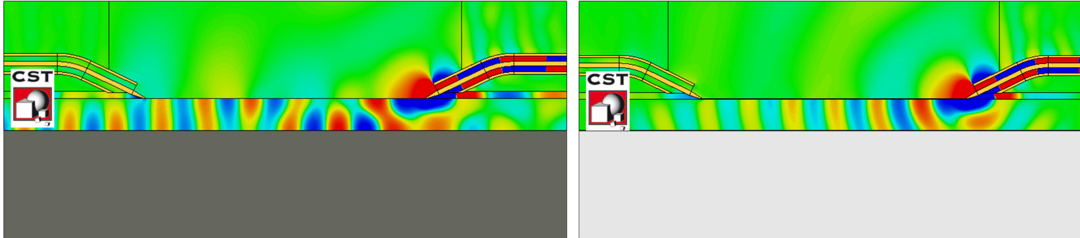

Fig. 17: The electro-magnetic field pattern of a CPW line from a commercial calibration substrate at mm-wave frequencies placed on a metal (left) and on a special ceramic (right) AUX chuck (courtesy of FBH, Germany)

MicroPositioners

The main purpose of RF MicroPositioners is to hold the wafer probes and to accurately position its tips against the DUT contact pads. The specifics of the DUT and system raise several additional requirements to MicroPositioners: stable, consistent and repeatable contact resistance, frequent system re-configuration, the need to multiport measurements and handling of multi-contact DC and RF wedges.

Fig. 18: MPI MicroPostioner series (from left to right): MP25, MP40, MP50, and MP60

A broad variety of carbon-steel-body, backlash-free MPI MicroPositioners address any type of requirements regarding operation, configuration, and measurements (Fig. 18, Table 2). They realize the intuitive Z-axis operation, have fully-integrated magnet bases and provide the whole range of positioner platforms — from small footprint to micrometer driven high resolution units dedicated to RF and mm-wave applications (Fig. 19). The superior positioning accuracy, unobstructed force transmission to the probe tip along the Z-axis and the long-time stability of the contact are the remarkable features of MPI MicroPositioners. All those features guaranty unsurpassed RF calibration and measurement results.

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Fig. 19: MPI MP80-DX MicroPostioner with the digital X gauge option for accurate multiline TRL calibration

Table 2: MicroPositioner and Probe System Matrix

Platform / MicroPositioners	TS50	TS150	TS150-THZ	TS200 TS2000/D/DP	TS200-SE/HP TS2000-SE/HP	TS300
MP25	●	●	●	●	○	●
MP40	●	●	●	●	●	●
MP50 MP50-HR	●	●	○	●	●	●
MP60 MP60-HR	○	●	●	●	●	●
MP60-MR	○	●	●	●	●	●
MP80 MP80-DX		○	●	●	●	●

● recommended ○ available

QAlibria®

Making the complex and tedious task of RF system calibration as simple as possible — this is the key objective of MPI's calibration software QAlibria®. MPI's long-time experience in wafer-level RF calibration and a detailed understanding of the microwave measurement specifics are at the bottom of QAlibria® (Fig. 20). Its multi-touch graphical user interface and optimized logical operation workflow provide intuitive, crisp and clear guidance to the calibration process and monitors its progress. Thus, configuration mistakes are minimized and accurate calibration results can be reached in fastest time even by inexperienced users.

QAlibria® offers industry-standard calibration methods for conventional RF measurements. Its unique feature, however, is the integration with NIST StatistiCal calibration package. For the first time, the NIST multiline TRL metrology-level VNA calibration becomes easily accessible for daily use.

QAlibria® database includes electrical models of MPI TITAN™ Probes and AC-series calibration substrates. The convenient and open database interface allows operator to add probe and calibration standards of any other types in less than a minute, if required.

MPI QAlibria® breaks the language barrier as well: its user-friendly multi-language graphical user interface minimizes operational risk and inconvenience for non-English speaking operators (Fig. 21).

QAlibra® fully supports ZVA and ZNB series of Rohde & Schwarz network analyzers.

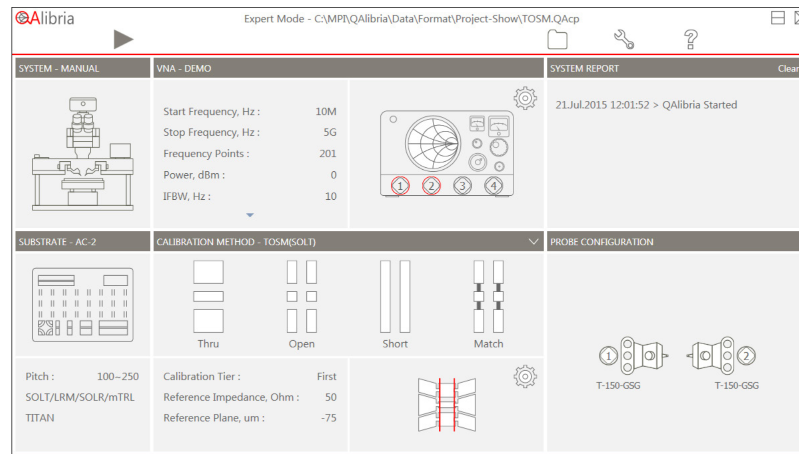

Fig. 20: The dashboard of the multi-touch RF calibration software QAlibria®

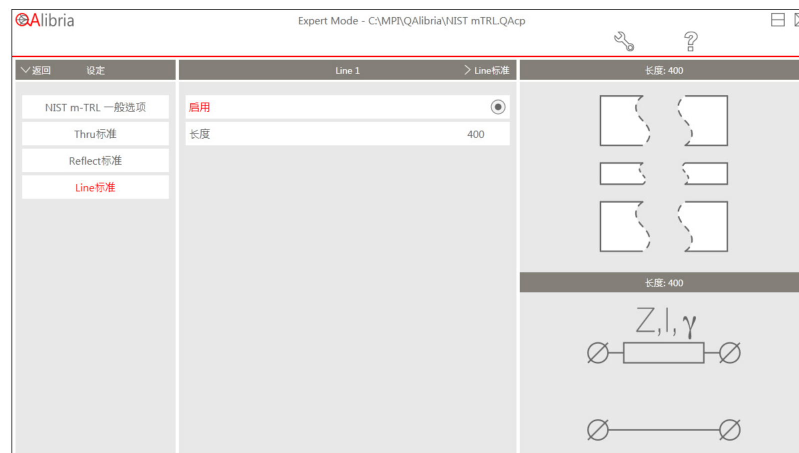

Fig. 21: Multi-language interface of QAlibria®

Wafer-Level Power Calibration

Powerful calibration software features, available on both Rohde & Schwarz®ZVA and ZNB models, allow for shifting the measurement reference plane for the calibrated power down to the wafer-level and set it accurately directly at the probe tips. It is especially important for characterizing advanced high-frequency semiconductor devices. The Rohde & Schwarz®NRP-Z58 thermal power sensor has the unique capability to cover the widest frequency range: from DC to 110 GHz. It allows to calibrate e.g. the broadband measurement system ZVA110 in different frequency bands or, if required, in the whole range using just one power sensor and in a single calibration step. The Rohde & Schwarz®NRP-Z58 significantly simplifies the calibration procedure, as it eliminates the need for different frequency-limited power sensors, waveguide to coaxial connector adapters, multiple connect-disconnect cycles and calibration runs. Hence, the highest accuracy and reproducibility of the power calibration can be achieved.

Conclusion

Continuously increasing complexity of modern RF ICs and the need for accurate and reliable data impose challenging requirements when characterizing ICs at the wafer-level. Modern Vector Network Analyzers and wafer probe systems should deliver highly-accurate measurement results, realize novel, efficient operation workflow and be integrated into an optimized complete measurement solution.

Based on decades of experience in RF and microwave measurements and wafer probing, MPI Corporation and Rohde & Schwarz provide unique features, set across the wide product offering to satisfy the most challenging measurement requirements. Tight integration of Rohde & Schwarz VNAs with MPI probe systems, calibration and control software as well as optimized system configuration and accessories deliver unique measurement solutions even to the most challenging measurement needs. Together with outstanding accuracy of the RF system calibration, consistent and highly-repeatable measurement data, the fully integrated measurement solutions from MPI and Rohde & Schwarz realize simple and intuitive operation workflow, minimize the risk of possible mistakes and drastically shorten the learning curve for users inexperienced in area of RF measurements.

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