# On-Wafer Millimeter-Wave Characterization

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## Abstract

This paper overviews the on-wafer characterization of microelectronic components in the millimeter-wave and microwave regions of the spectrum. This method has proven an invaluable tool in design and manufacturing. The paper reviews the literature in the field and notes some specific considerations required at millimeter-wave frequencies.

## INTRODUCTION

On-wafer characterization makes use of microwave probes which contact the surface of a component and inject and receive electrical signals. This process is well suited to the characterization of microelectronic structures while still in the wafer stage, that is, before the wafers have been diced into chips and the chips packaged. On-wafer measurements are advantageous in manufacturing because defective parts can be identified before further effort goes into packaging them. On-wafer measurements are also useful and popular in research and development environments.

On-wafer characterization began with the introduction of commercial microwave probes in the mid-1980s [1,2]. The method grew rapidly in popularity and revolutionized microwave measurements. In 1991, the Microwave Theory and Techniques Society of the Institute of Electrical and Electronics Engineers presented Eric W. Strid and K. Reed Gleason the Microwave Application Award by the "for the development of microprobe technology, its applications to on-wafer test of microwave semiconductor devices, and for innovative microwave measurement techniques." Much of the fundamental literature exploring the details of on-wafer measurements and the required calibration techniques was presented in three consecutive winter conferences of the Automatic RF Techniques Group in 1989, 1990, and 1991, all devoted to on-wafer measurement.

On-wafer measurements are well suited to use at short wavelength. They have long been applied to the longer-wavelength end of the millimeter-wave spectrum, which ranges from 30-300 GHz (1-10 mm in open space). However, at the higher frequencies, additional considerations come into play. In this paper, we will first review some of the basic aspects of on-wafer measurements in general and then deal with applications at higher frequencies. We focus primarily on measurements of scattering parameters.

## TRANSMISSION LINE THEORY

Microwave measurements are grounded in microwave circuit theory, which defines waves, voltages, currents, impedances, and scattering parameters in analogy to low-frequency circuit theory, even though the dimensions of the circuit are not small compared to the wavelength. The measurements are of little meaning without a suitable theoretical foundation. The first problem in dealing with on-wafer measurements is to ensure that such a foundation remains in place for microfabricated planar transmission lines. In fact, traditional microwave circuit theory, as developed in the 1940s, does not apply because the dielectrics are significantly inhomogeneous and the metals significantly lossy; the result is modes of propagation that are neither TE, TM, nor TEM, in contrast to the assumptions of the classical theory. The generalized waveguide circuit theory [3], however, demonstrates that the problem can be formulated to maintain the low-frequency analogy. One significant discovery concerns the characteristic impedance $Z_0$ of a transmission line mode. Specifically, while the magnitude of $Z_0$ is normalization-dependent, the phase of $Z_0$ is a fixed physical property of the line. In the presence of lossy metal, $Z_0$ has a significant nonzero phase that must be carefully accounted for in the measurement of scattering parameters. The problem is pronounced at low frequencies but can also affect millimeter-wave measurements. The solution is to carefully measure the characteristic impedance of the line and correct for it. Many methods for the measurement of $Z_0$ have been published [4, 5, 6, 7, 8].

The generalized waveguide circuit theory models planar transmission lines simply but effectively as uncoupled, single-mode transmission lines that are uniform in the direction of energy propagation and interconnect arbitrary discontinuities. This model leaves out potentially significant effects, including crosstalk and multimode behavior. However, it fully describes the discontinuities and the fundamental electrical properties of the line, including propagation delay, loss, signal distortion, and characteristic impedance. It also thoroughly models the line's fundamental physical properties of capacitance, inductance, conductance, and resistance per unit length while fully accounting for the intricate effects arising due to the complicated physics of current flow in the conductors. Furthermore, the transmission line model forms a foundation for more sophisticated descriptions.

## ON-WAFER MEASUREMENTS

Scattering parameter measurements can be carried out using a vector network analyzer (VNA), typically a swept-frequency instrument. For on-wafer measurements, the VNA test ports are connected to the planar transmission lines by an on-wafer probe connecting a coaxial cable to a coplanar tip that can be brought into contact with three (or two, if the line is unbalanced) contact pads, typically spaced on the order of 100 µm apart, on the wafer surface. If the transmission line is a microstrip configuration, the center pad connects to the microstrip center conductor and the outer pads to the backside ground plane through metallized "via" holes in the dielectric.

## PROBES

The first commercial microwave probes were built as coplanar waveguide on the underside of a ceramic plate, with a coaxial connector. At higher frequencies, small coaxial connectors were unavailable, so waveguide-connected probes were developed for millimeter-wave measurements [9]. However, the coplanar probes proved to be delicate and too lossy for some applications, particularly noise measurements.

The early 1990s saw the introduction of coaxial probes that carried the waves in coaxial lines virtually all the way to the probe tip. These proved rugged and low-loss. Both coaxial and waveguide feeds are available, and both are effective at measuring scattering parameters at W-band [10]. Recently, the 1 mm coaxial connector, with single-mode propagation to 110 GHz, has come to market. At least one available commercial VNA uses 1 mm coaxial cables, connectors, and probes to allow on-wafer measurements from 45 MHz to 110 GHz.

In all calibrations, the correct alignment of the probe on the wafer is critical. Automatic probe stations use motors to position the probes accurately. Manual stations using hand-operated manipulators can also provide good alignment, but probe alignment marks on the wafer are critical, particularly at higher frequencies.

## CALIBRATION

The key to accurate on-wafer measurement is the calibration. Calibration must account for the imperfections of the VNA, cables, connectors, and probes. Fortunately, most of these can readily be lumped together into the "twelve-term" error model that is typically used to represent the errors in the VNA error-correction firmware. In some cases, crosstalk between the probes can become problematic. Fifteen- and sixteen- term error models have been applied to this case and even generalized to multiport situations [11]. However, even these are limited in that they assume the crosstalk is constant. In fact, it may depend on the environment below the probe, and it certainly depends on the probe separation, which may vary during the course of the calibration and measurement. Therefore, the value of the crosstalk correction methods remains mostly theoretical.

## ON-WAFER AND OFF-WAFER CALIBRATION

The essence of the calibration problem is to ascertain the unknown errors based on a given error model. This requires the measurement at the test ports of several standard devices, some of whose scattering parameters or impedances are known. The many possibilities can be classified as either "on-wafer" or "off-wafer" calibrations according to how the test port is defined.

In off-wafer calibration, the test port is assumed to lie at the probe tip. The known standards and then the device under test are presented to the probe tip. The calibration standards are generally obtained commercially and are fabricated on a wafer that generally has no special relationship to the device under test except that both must accommodate the probes dimensionally. The accepted values of the standards are typically derived in a measurement that cannot account for the specific probe or contact area experienced in the measurement of the test device. The resulting errors are neglected.

On-wafer calibrations are based on the theoretical foundations of microwave circuit theory, in which parameters are defined only within uniform, single-mode transmission lines. The theory makes no allowance for defining circuit parameters at a discontinuous, nonuniform region like the point at which a probe tip contacts a planar transmission line. Therefore, on-wafer calibration places the test port in a section of uniform transmission line, in a presumed single-mode region, *on the wafer*. This requires that the probe tip region, along with some length of line on the wafer, be considered as part of the unchanging instrument to be calibrated. This leads to the demand that all of the standards be identical to the test device up to the "reference plane" that defines the test port. The only practical way this can be assured is to construct the standards on the same wafer as that of the test device, or possibly on a nearly identical structure.

Off-wafer calibration may postulate the validity of low-frequency, "lumped" circuit theory as a substitute for microwave circuit theory. However, this assumption is likely to become less valid as the frequencies reach high into the millimeter-wave band.

## ON-WAFER CALIBRATION METHODS

On-wafer calibration generally precludes the possibility of using commercial test structures, for commercial products are unlikely to be available in the configuration of the test device. Therefore, users of such methods must typically fabricate standards on the test wafer. The question arises as to how those standards will be characterized. The most direct answer lies in the use of the through-reflect-line (TRL) calibration [12]. This procedure makes use of the fact that the reflection coefficient at a plane in a uniform transmission line is 0. This makes a transmission line an excellent pure standard for the measurement of scattering parameters normalized to the characteristic impedance $Z_0$ of the line. TRL also measures the propagation constant of the transmission lines, so that the reference plane may be accurately located. The primary drawback to TRL is that $Z_0$ must be known in order to renormalize the scattering parameters (to, for example, 50 $\Omega$) or to compute device impedances. However, once $Z_0$ has been measured, these parameters can be readily computed [3]. Another drawback of TRL is the requirement for long transmission lines at low frequency. This is a relatively less significant problem for millimeter waves. TRL also suffers from a bandwidth limitation. The multiline TRL method [13] extends the bandwidth and accuracy of basic TRL by making use of multiple lines of various lengths.

At higher frequencies, some concern has been expressed about the effect on calibration of surface wave propagation in dielectric slabs and along coplanar waveguide [14]. In that paper, the modes were shown to interact with coplanar probes, and the implications on on-wafer measurements were explored. In contrast, one set of measurements to 110 GHz showed no effects of such coupling and indicated that TRL calibrations were effective even past the critical frequencies at which surface wave effects were predicted [15]. The same paper indicated that on-wafer measurements to 110 GHz can be repeatable and consistent between laboratories.

A variation of TRL known as "LRM" (for line-reflect-match) substitutes a known quasi-matched load for the line. LRM can also be used for on-wafer calibration as long as the load is offset in a transmission line. The load needs to be characterized in advance. This can be done with TRL using a model of the load [16].

Lumped-element calibrations such as SOLT ("short-open-load-thru") are not related to TRL but have also been proposed for on-wafer calibrations. In this case, the standards are normally characterized with TRL. This method has been applied up to 75 GHz [17] but proves ineffective at W-band, where a more complicated variation has been reported [18].

## OFF-WAFER CALIBRATION METHODS

Off-wafer calibration with commercial standard wafers generally makes use of lumped-element standards that are characterized without reference to an on-wafer calibration. Often, this involves DC or low-frequency measurements, particularly of loads. The results are increasingly inaccurate at higher frequencies [19] and may fail drastically at frequencies far into the millimeter range. For instance, V-band measurements differ significantly depending on whether the calibration was on-wafer or off-wafer [20]. Even at much lower frequencies, the accuracy of the off-wafer calibration depends on the similarity between the calibration structures and the devices under test. For example, even a difference in substrate permittivity can significantly affect the calibration, although such differences can be largely corrected [21].

## HIGHER FREQUENCIES AND ACTIVE PROBES

On-wafer probing is suitable for connecting to circuits operating all the way to the 300 GHz limit of the millimeter-wave region. The problems that arise are generally due not to the circuit end of the probe but instead due to unavailability of high-frequency instrumentation and to the connection of the probe to the instruments. The new 110 GHz on-wafer test systems, for instance, mount the test set on the probe station next to the probe to eliminate excess cabling and cable flexing.

At even higher frequencies, the coaxial connection mechanism becomes problematic. One way to address the problem is to integrate the millimeter-wave test components with the probe or package them closely to it, using, for example, wire bonds. This "active probe" technology was discussed in 1989 [22]. A later example [23] operated at only 5-10 GHz but seemed scalable to much higher frequencies since it used dual six-port VNA technology [24] in which only DC data were taken off the probe. The RF source was supplied externally through a coaxial cable.

A later active probe proposal was to connect integrated 300 GHz instrumentation components, including the source, to a GaAs probe tip [25]. The GaAs probe tip was shown to be effective in measurements to 50 GHz, but the mechanical design was painstaking since GaAs is extremely brittle. In later work, a fast pulser and sampler were integrated on the GaAs tip, allowing measurements with an estimated 500 GHz bandwidth [26].

Perhaps the most fully developed active-probing system [27] was documented in a series of papers beginning in 1991 [28]. This system uses time-domain network analysis in which the broadband source is provided by sharp pulses generated in the probe by nonlinear transmission lines, which can produce significant output at frequencies as high as 500 GHz. Scattering parameter measurements to 200 GHz were demonstrated. One limitation to the extension of the method to higher frequencies is the LRM calibration method, since the match was not well characterized at these frequencies. An alternative approach to time-domain network analysis calibration [29], based on the multiline TRL method, may help extend the method.

## OTHER ON-WAFER MILLIMETER-WAVE MEASUREMENTS

Network analysis is a fundamental measurement but not the only measurement of interest for millimeter-wave components. Millimeter-wave on-wafer techniques for noise measurement [30], load-pull [31], and pulsed power [32] have been developed. All of these require accurate network analysis techniques.

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