On-Wafer Transistor Characterization to 750 GHz –the approach, results, and pitfalls*

Dylan F. Williams, *Fellow*, *IEEE*, Jerome Cheron, Benjamin Jamroz, Richard Chamberlin

***Abstract*—We review approaches developed at the National Institute of Standards and Technology for on-wafer transistor characterization and model parameter extraction at sub-millimeter wavelengths and compare them to more common approaches developed for use at lower frequencies. We discuss important improvements in accuracy, approaches to estimating the uncertainty of the procedure, and recent research on further improving these methods.**

***Index Terms*—Vector-network-analyzer calibration, on-wafer measurements, scattering parameters, sub-millimeter-wave, transistor, uncertainty.**

I. Introduction

THE National Institute of Standards and Technology (NIST) has been a leader in the development of on-wafer measurement approaches. This work began in the early 1990s, and included the development of methods for extending the bandwidth of on-wafer thru-reflect-line (TRL) vector-network-analyzer (VNA) calibrations [1], measuring the characteristic impedance of the transmission lines used in the calibrations [2, 3], and resetting the reference impedance of the calibration to 50 Ω. This calibration strategy has become the de facto on-wafer calibration of reference to which all other on-wafer calibrations are compared. It has been successfully used in coplanar waveguide (CPW), microstrip, coaxial transmission lines, and rectangular waveguide.

However, excitation of higher-order modes in coplanar waveguide (CPW) makes it difficult to control calibrations at sub-millimeter wavelengths [4, 5]. Figure 1 illustrates this with an example of a measurement of the reverse transmission through a transistor. These measurements were calibrated with commercial impedance-standard substrate (ISS) placed on ceramic and metal chucks, and designed for use with 50 µm-pitch probes at sub-millimeter-wave frequencies. The curves labeled "ISS on ceramic" correspond to measurements performed with the ISS placed on a thick ceramic substrate. The curves labeled "ISS on metal" correspond to measurements calibrated when the ISS was placed directly on the metal chuck. The figure illustrates how difficult it is to accurately measure reverse transmission, which also impacts important figures of merit such as the maximum stable gain and unilateral gain of

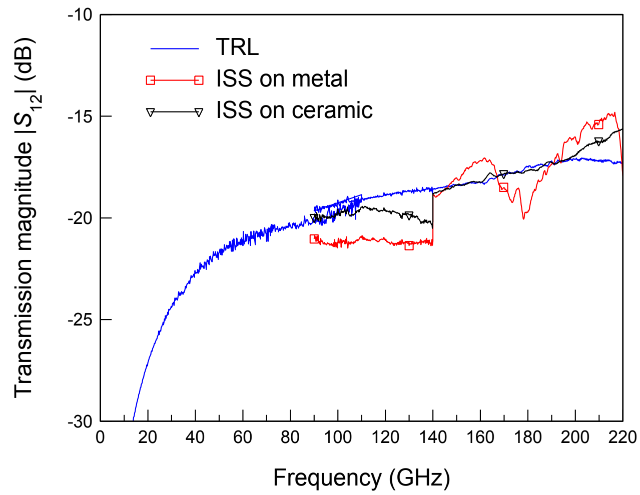

Fig. 1. Comparison of TRL measurements to measurements corrected with an impedance standard substrate (ISS) placed on a metal chuck and on a thick ceramic substrate. The measurements are banded over the frequency ranges 10 MHz – 110 GHz, 90-140 GHz, and 140-220 GHz, resulting in overlaps and discontinuities at the band edges. From [6].

these transistors. We have only been able to do somewhat better with on-wafer CPW calibrations.

In this paper we will show how on-wafer TRL calibration in microstrip lines fabricated on thin BCB layers can be used to make accurate measurements at submillimeter wavelengths. We will also touch on coupling corrections, uncertainty analyses, the importance of Monte-Carlo simulations, and how traceability can be established for transistor measurements at these frequencies.

II. The TRL Approach

The same measurements calibrated with the TRL approach based on microstrip lines printed on the integrated circuit, as developed at the National Institute of Standards and Technology in [6], are shown in blue lines in Fig. 1. This is a true on-wafer calibration, as the calibration and transistor test structures use the same access lines. This ensures that electrical contact-pad and access-line parasitics are removed from the measurements as accurately as possible. This calibration

This work was supported by the Defense Advanced Research Projects Agency's Terahertz Electronics Program. The views, opinions, and/or findings contained in this article are those of the author and should not be interpreted as representing the official views or policies, either expressed or implied, of either the Defense Advanced Research Projects Agency or the Department of Defense.

D. F. Williams, Jerome Cheron, Benjamin Jamroz and Richard Chamberlin are with the National Institute of Standards and Technology, Boulder, CO 80305 USA (phone: 303-497-3138; e-mail: dylan.williams@ nist.gov).

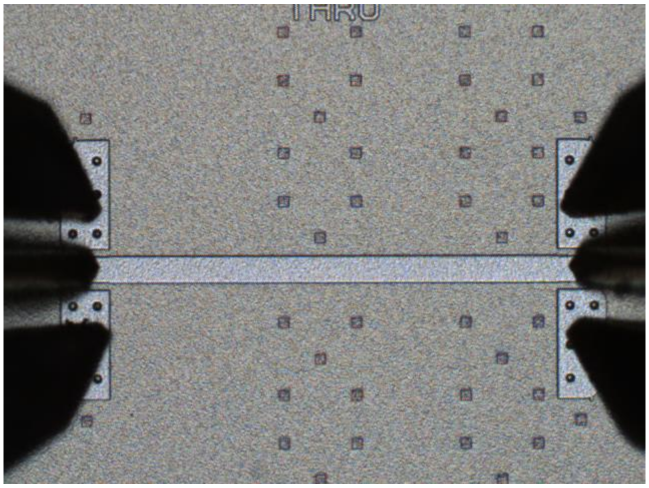

Fig. 2. The thru line used in our calibration kit. The small squares are dielectric fill patterns, and have a negligible impact on the electrical behavior of the microstrip transmission lines. From [6].

exhibits none of the problems of the CPW calibrations.

The TRL calibration locates the measurement reference plane directly in small, single-mode microstrip lines shown in Fig. 2. These are placed adjacent to the transistor, minimizing extrinsic transistor parasitics. In this case, the transmission lines were low-loss 22 µm-wide microstrip lines printed on bisbenzocyclobutene-based (BCB) monomers approximately 8 µm thick, which raises the cutoff frequency of any higher-order modes to well over 1 THz.

The microstrip TRL calibration can be extended to very high frequencies. Fig. 3 compares measurements of the propagation constant of these microstrip lines to calculations performed with the microstrip transmission-line model of [7], and shows excellent agreement to 750 GHz, despite having to acquire these measurements over six different frequency bands,[1] and not always being able to reuse the same calibration kit in each band due to the inevitable damage to probe contacts caused by repeated alignment and testing.

III. Uncertainty and Traceability

Since the introduction of on-wafer TRL calibrations, NIST has continued to work on understanding their uncertainties and developing traceability for these on-wafer measurements. However, because it is difficult to develop standard on-wafer calibration structures with specified metal conductivities, complex permittivities and geometries in different integrated-circuit technologies, the work has not focused on developing standard artifacts as has been done in coaxial transmission lines and rectangular waveguide. Instead, uncertainties and the traceability that follows from them are developed for each specific integrated-circuit technology.

Early work began with a straightforward analytic analysis [8]. This was followed with the automation of frequency-point-by-frequency-point uncertainties in the TRL calibration with the StatistiCAL[2] software package at NIST [9, 10]. This software package was used in [6], and leveraged ODRPACK [11] and its ability to estimate uncertainty from residuals in the measurements.

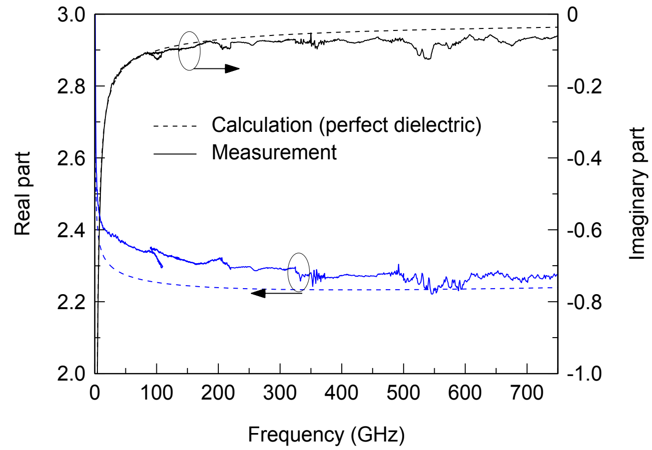

Fig. 3. Real and imaginary parts of the measured effective dielectric constant, as determined by our TRL calibration, compared to calculation. The measurements are banded over the frequency ranges 10 MHz – 110 GHz, 90-140 GHz, and 140-220 GHz, resulting in overlaps and discontinuities at the band edges. From [6].

However, the level of automation was low, and the uncertainties developed with these early approaches were not in a form that could be propagated through more complex processes and analyses. For example, the measurement errors could not be easily propagated through Fourier Transforms used to support complex traceability chains and propagated through other complex analyses such as model parameter extraction.

IV. The Microwave Uncertainty Framework

These limitations led to the development of the Microwave Uncertainty Framework [12] at NIST and VNATools [13] at the Swiss Federal Institute for Metrology (METAS). The Microwave Uncertainty Framework supports both conventional sensitivity analyses, which is useful for linear problems, and Monte-Carlo analysis, which is required for nonlinear problems. The Microwave Uncertainty Framework was developed specifically to support a broad range of measurement applications, including coaxial, rectangular waveguide, and on-wafer VNA calibrations, complex traceability chains including waveform, power, and oscilloscope calibrations, and system level measurements and applications, such as error-vector-magnitude determination, transistor model parameter extraction, and circuit simulations.

In the context of prior work, the Microwave Uncertainty Framework captures correlated uncertainties not available from

[1]The band edges occur at 90 GHz, 110 GHz, 140 GHz, 220 GHz, 325 GHz and 500 GHz.

[2]Registered trademark of the National Institute of Standards and Technology. NIST does not endorse commercial products. Trade names are included only to better define experiments. Other products may work as well or better.

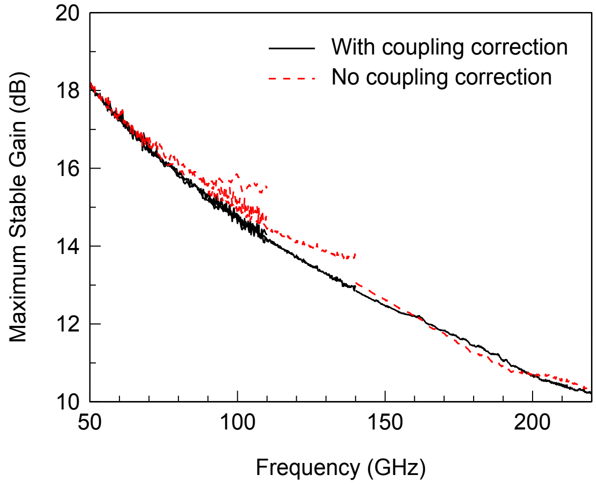

Fig. 4. The maximum-stable gain of a transistor corrected with standard TRL and with TRL augmented with coupling corrections. From [6].

StatisitiCAL. Correlated uncertainties are key to propagating uncertainty though Fourier Transforms, complex traceability chains, and other complex analyses, including the transistor-model-parameter-extraction process.

NIST has now applied the Microwave Uncertainty Framework to many of these problems [14-22], including transistor model parameter extraction and circuit design [23-25]. One of the key conclusions of our work is that correlated uncertainties are *not* enough to solve many of these problems accurately. Monte-Carlo approaches *must* be used in nonlinear problems such as transistor model parameter extraction and error-vector-magnitude calculations at millimeter-wave frequencies [23-25].

V. Coupling

Despite the use of small single-mode microstrip transmission lines in our measurements, correcting for probe-to-probe coupling remains one of the key difficulties in performing accurate on-wafer measurements. Coupling behavior is complex, involves many tradeoffs, and can greatly impact the accuracy of on-wafer transistor measurements.

Nevertheless, probe-to-probe and other coupling in on-wafer measurement scenarios can be modeled and corrected for to first order [26, 27]. We illustrate this in Fig. 4 with a comparison of the maximum stable gain measured with TRL calibrations using different probes both before and after applying coupling corrections. Clearly, applying coupling corrections improves the consistency and accuracy of the measurements.

However, a key remaining problem is determining the uncertainty in coupling-corrected, on-wafer measurements. This is difficult because coupling models are not easy to develop, and assessing how much of the coupling is left uncorrected by the coupling-correction algorithm is challenging.

Current research at NIST is focusing on how to use measurement residuals to capture correlated uncertainty in coupling-corrected-transistor and other measurements where models of the corrections are suspect.

VI. Conclusion

NIST algorithms allow for on-wafer calibrations traceable to dimensional and other measurements performed on the same integrated circuits on which the transistors are fabricated. These calibrations can now correct for most errors in the measurements, including probe-to-probe coupling, and then used to extract transistor models with measurement uncertainty and process variations [23, 24]. These models can then be used in conventional circuit simulators to estimate the expected range of circuit performance based on the uncertainty and process variations in the transistor models [25].

VII. References

[1] R. B. Marks, "A multi-line method of network analyzer calibration," *IEEE Trans.Microw.Theory Techn.*, vol. 39, pp. 1205-1215, 1/1991 1991.

[2] D. F. Williams and R. B. Marks, "Transmission Line Capacitance Measurement," *IEEE Microwave and Guided Wave Letters,* vol. 1, pp. 243-245, 9/1991 1991.

[3] R. B. Marks and D. F. Williams, "Characteristic Impedance Determination using Propagation Constant Measurement," *IEEE Microw.and Guided Wave Letters,* vol. 1, pp. 141-143, 6/1991 1991.

[4] E. M. Godshalk, "Surface wave phenomenon in wafer probing environments," *Automatic RF Techniques Group Microwave Measurement Conference Digest,* vol. 40, pp. 10-19, 1992 1992.

[5] A. Rumiantsev, R. Doerner, and E. M. Godshalk, "The Influence of Calibration Substrate Boundary Conditions on CPW Characteristics and Calibration Accuracy at mm-Wave Frequencies," *Automatic RF Techniques Group Conference Digest,* vol. 72, pp. 168-173, 2008 2008.

[6] D. F. Williams, A. C. Young, and M. Urteaga, "A Prescription for Sub-Millimeter-Wave Transistor Characterization," *IEEE Trans.THz Sci.Technol.*, pp. 433-439, 7/1/2013 2013.

[7] H. M. Heiliger, M. Nagel, H. G. Roskos, H. Kurz, F. Schnieder, and W. Heinrich, "Thin-film microstrip lines for MM and sub-MM/wave on-chip interconnects," *IEEE MTT-S Int.Microwave Symp.*, vol. 2, pp. 421-424, 6/8/1997 1997.

[8] R. F. Kaiser and D. F. Williams, "Sources of Error in Coplanar-Waveguide TRL Calibrations," in *54th ARFTG Conference Digest*, 1999, pp. 1-6.

[9] D. F. Williams, C. M. Wang, and U. Arz, "An optimal vector-network-analyzer calibration algorithm," *IEEE Trans.Microw.Theory Techn.*, vol. 51, pp. 2391-2401, 12/2003 2003.

[10] D. F. Williams, C. M. Wang, and U. Arz, "An optimal multiline TRL calibration algorithm," *IEEE MTT-S Int.Microwave Symp.Dig.*, vol. 3, pp. 1819-1822, 6/2003 2003.

[11] P. T. Boggs, R. H. Byrd, J. E. Rogers, and R. B. Schnabel, "User's reference guide for ODRPACK

version 2.01 software for weighted orthogonal distance regression," Boulder, CO NISTIR 92-4834, 6/1992 1992.

[12] D. F. Williams and A. Lewandowski, "NIST Microwave Uncertainty Framework," ed: National Institute of Standards and Technology, http://www.nist.gov/ctl/rf-technology/related-software.cfm, 2011.

[13] *VNA Tools II*. Available: https://www.metas.ch/metas/en/home/fabe/hochfrequenz/vna-tools.html

[14] G. Avolio, A. Raffo, J. Jargon, P. D. Hale, D. M. M. Schreurs, and D. F. Williams, "Evaluation of Uncertainty in Temporal Waveforms of Microwave Transistors," *IEEE Trans.Microw.Theory Techn.,* vol. 63, pp. 2353-2363, 7/2015 2015.

[15] J. A. Jargon, U. Arz, and D. F. Williams, "Characterizing WR-8 waveguide-to-CPW probes using two methods implemented within the NIST Uncertainty Framework," in *80th ARFTG Microwave Measurement Conference*, 2012, pp. 1-5.

[16] J. A. Jargon, D. F. Williams, T. M. Wallis, D. X. LeGolvan, and P. D. Hale, "Establishing traceability of an electronic calibration unit using the NIST Microwave Uncertainty Framework," in *79th ARFTG Microwave Measurement Conference*, 2012, pp. 1-5.

[17] J. A. Jargon, D. F. Williams, P. D. Hale, and M. D. Janezic, "Characterizing a noninsertable directional device using the NIST uncertainty framework," in *83rd ARFTG Microwave Measurement Conference*, 2014, pp. 1-3.

[18] K. A. Remley, D. F. Williams, P. D. Hale, C. M. Wang, J. Jargon, and Y. Park, "Millimeter-Wave Modulated-Signal and Error-Vector-Magnitude Measurement With Uncertainty," *IEEE Transactions on Microwave Theory and Techniques,* vol. 63, pp. 1710-1720, 2015.

[19] J. A. Jargon, C. Cho, D. F. Williams, and P. D. Hale, "Physical models for 2.4 mm and 3.5 mm coaxial VNA calibration kits developed within the NIST microwave uncertainty framework," in *2015 85th Microwave Measurement Conference (ARFTG)*, 2015, pp. 1-7.

[20] J. A. Jargon, D. F. Williams, and P. D. Hale, "Developing models for Type-N coaxial VNA calibration kits within the NIST Microwave Uncertainty Framework," in *2016 87th ARFTG Microwave Measurement Conference (ARFTG)*, 2016, pp. 1-4.

[21] B. F. W. Jamroz, D.F.;Remley,K.A.;Horansky,R.D., "Importance of Preserving Correlations in Error-Vector-Magnitude Uncertainty," presented at the ARFTG Conference Digest, Philadelphia, PA, 2018.

[22] J. W. Jargon, D.F., "A New Calibration Method for Achieving High Insertion-Loss Measurements with a Vector Network Analyzer," presented at the ARFTG Microwave Measurements Conference, Philadelphia, PA, 2018.

[23] D. F. Williams, W. Zhao, R. Chamberlin, J. Cheron, and M. Urteaga, "Verification of a foundry-developed transistor model with measurement uncertainty," *ARFTG Microwave Measurement Conference Digest,* vol. 87, 5/27/2016 2016.

[24] D. F. Williams, R. Chamberlin, W. Zhao, J. Cheron, and M. Urteaga, "Transistor Model Verification Including Measurement Uncertainty," *IEEE Trans.Microw.Theory Techn.,* vol. 64, pp. 3927-3933, 11/2016 2016.

[25] D. F. Williams, R. A. Chamberlin, W. Zhao, J. Cheron, and M. E. Urteaga, "The Role of Measurement Uncertainty in Achieving First-Pass Design Success," in *2016 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*, 2016, pp. 1-4.

[26] F. J. Schmuckle, R. Doerner, G. N. Phung, W. Heinrich, D. F. Williams, and U. Arz, "Radiation, multimode propagation, and substrate modes in W-band CPW calibrations," *European Microwave Conf.,* vol. 41, pp. 297-300, 10/2011 2011.

[27] D. F. Williams, F. J. Schmuckle, R. Doerner, U. Arz, and W. Heinrich, "Crosstalk Corrections for Coplanar-Waveguide Scattering-Parameter Calibrations," *IEEE Transactions on Microwave Theory and Techniques,* vol. 62, pp. 1748-1761, 2014 2012.