National Institute of Standards and Technology Programs in Electrical Measurements for Electronic Interconnections

Donald C. DeGroot and Dylan F. Williams

National Institute of Standards and Technology, Radio Frequency Technology Division
Mail Code 813.01, 325 Broadway, Boulder, CO 80303-3328
Phone: 303-497-7212; Fax:303-497-3970; E-mail: degroot@nist.gov

Abstract

The National Institute of Standards and Technology operates a number of research projects to advance measurement science and technology for the microelectronic industries. We report here on one component of the NIST program, the fundamental electrical characterization of electronic interconnections through accurate measurement. We have developed and continue to develop measurement techniques for fully calibrated time-domain network analysis, lossy transmission lines on silicon, coupled transmission lines, fully calibrated multiport network analysis, low dielectric constant thin-film materials, and at-speed test.

Introduction

In this report, we present important research challenges in the fundamental electrical characterization of electronic interconnections and the resulting research at the National Institute of Standards and Technology (NIST).[1] NIST has conducted electronic packaging research as part of its mission to promote U.S. economic growth and competitiveness [1]. Our approach to packaging characterization focuses on guided waves at the microelectronic level, with the goal of extending basic field approaches to the immediate demand for complicated measurements of numerous signals passing through a maze of interconnections. The following sections list the research challenges and describe our responses.

Interconnection Measurements with Time-Domain Network Analysis

***Challenge:** Fully characterize of transmission lines and transitions using time-domain instruments.*
***NIST approach:** Fully calibrate digital sampling oscilloscopes using frequency-domain network analyzer methods to obtain accurate frequency-dependent parameters.*

The key challenge to characterizing high-speed interconnections with time-domain instrumentation is that the propagation constant, characteristic impedance, *and* the equivalent circuit resistance-inductance-conductance-capacitance parameters (*RLGC*) of any transmission line are frequency-dependent whenever the conductor thickness is on the order of the skin depth and less, or the dielectric losses are significant; they are almost always so for high-speed microelectronic circuits. Consequently, CAD and design engineers need to obtain data in the frequency domain to completely characterize their interconnections.

Until recently, the lack of accurate calibration methods for commercial time-domain instruments limited the extraction of complete frequency-dependent interconnection parameters from time-domain reflection/transmission (TDR/T) measurements. To address this need, we cooperated with an industrial partner to apply complete vector network analyzer correction algorithms to Fourier-transformed TDR/T waveforms [2,3]. The result is a fully calibrated time-domain network analyzer (TDNA). It provides frequency-dependent data that agree with commercial frequency-domain network analyzers within 2% to 3% from dc to 12.5 GHz. Figure 1 compares fully calibrated transmission data for a thin film transmission line measured with the NIST TDNA and with a commercial frequency-domain network analyzer.

This research not only produced new methodology, but resulted in publicly available software known as *TDNACal* [4]. This software is continually updated as new techniques extend the accuracy and capabilities of a fully calibrated TDNA. We are currently working to improve time-base error correction in the software, and since oscilloscopes have several measurement channels, we are also now developing a fully calibrated multi-port TDNA system.

Contacts: Don DeGroot (degroot@nist.gov) and Jeff Jargon (jjargon@nist.gov)

0-7803-4965-2/98/$10.00©1998 IEEE

Transmission Line Measurements for CMOS

Challenge: *Characterize transmission lines on lossy silicon substrates.*
NIST approach: *Compare measurement methods and their sensitivity to contact parasitics.*

NIST has a long-standing effort to develop, evaluate, and compare methods for measuring the characteristic impedance and propagation constant of planar transmission lines at microwave frequencies. Recent work has focused on extending our methods to transmission lines on silicon substrates, where the substrates are lossy and the contact pad admittance is large. This has resulted in improved methods for characterizing these essential and difficult to model interconnection components [5,6], and has provided the means to test proposed models for transmission lines in commercial CMOS processes [7,8].

Two measurable parameters, characteristic impedance Z_0 and propagation constant γ, characterize a single-mode transmission line; the frequency-dependent equivalent circuit parameters *RLGC* are easily calculated from Z_0 and γ. The multiline TRL method [9,10] accurately determines the propagation constant from complete two-port measurements of two lines that differ only in length. However, measuring Z_0 is more difficult. The method of [11] most accurately measures Z_0 on low-loss microwave substrates. This method is based on assumptions of small G and constant C. C is measured with the methods of [12], and Z_0 is determined directly from $Z_0 = \gamma / j\omega C$. While this method is extremely useful for the evaluation of many transmission lines on low-loss substrates, it fails on CMOS silicon substrates.

The traditional method [13] for finding Z_0 on silicon takes advantage of a one-to-one correspondence between Z_0 and the measured scattering parameters of a single transmission line. However, the resulting values of Z_0 are extremely sensitive to small electrical parasitics at the connection between the measurement instrument and the line being tested, and measuring and subtracting these parasitics from the measurements is not straightforward.

NIST developed the calibration comparison method [14] to reduce the sensitivity of the measurements to contact parasitics. The calibration comparison method determines Z_0 for the lines under test starting with a TRL calibration based on a series of uniform test lines that differ only in length. It then compares the correction factors of the test calibration to a 50 Ω reference calibration. Z_0 can be extracted from the comparison in a way that is insensitive to certain pad parasitics, most notably pad capacitance [5,6]. Figure 2 illustrates the improvement over the traditional method on a lossy silicon substrate. Further, we recently applied this calibration comparison method to determine the *RLGC* parameters of transmission lines on silicon substrates and compared the measured values to proposed models [7,8] (see Figure 3 for the *R* and *L* comparison in [8]).

Contacts: Dylan Williams (dylan@boulder.nist.gov) and Don DeGroot (degroot@boulder.nist.gov)

Lossy Multiconductor Transmission Lines

Challenge: *Characterize multiconductor transmission lines with large conductor and substrate losses.*
NIST approach: *Develop multiport measurement methods that rigorously account for loss.*

NIST has been developing measurement methods to characterize multiconductor transmission lines based on a rigorous equivalent circuit theory relating the modal and conductor descriptions in the presence of significant loss [15]. This approach differs from previous measurement work because it does not rely on the usual lossless assumptions employed in many characterization procedures. Such procedures fail in lossy systems, even when they are quasi-TEM, because they assume that the voltages and currents impressed on the conductor by any given mode are frequency independent. The NIST approach measures these as frequency-dependent quantities and correctly constructs the total voltages and current on the conductors even in the presence of high loss [16,17]. Recent work has focused on evaluating measurement errors of the new method [18]. Figure 4 compares calculated values of the inductance matrix for a lossy coupled line pair to measured values. The measurement uncertainties are also shown and expressed as 95% confidence intervals.

Contacts: Dylan Williams (dylan@boulder.nist.gov) and Janet Rogers (jrogers@boulder.nist.gov)

Multiport Network Analysis

Challenge: *Characterize complex electronic interconnects with many input and output ports.*
NIST approach: *Develop accurate multiport calibration and measurement procedures.*

NIST has been developing multiport measurement systems and calibration algorithms for the frequency-domain characterization of complex multiport electronic interconnects. The associated calibration procedures produce fully corrected multiport data. Our approach is unique in that it allows multiport probe stations to be corrected with standard two-port calibrations [19], including the most accurate procedure known at this time, the multiline TRL calibration [9]. This is possible because only in-line connections are required: this contrasts with existing short-open-load-thru (SOLT) approaches that require all ports to be connected to each other during calibration.

The NIST method also contrasts strongly with the approach embodied in the JEDEC 123 Guideline for Measurement of Electronic Package Inductance and Capacitance Model Parameters. This procedure attempts to construct multiport impedance parameters from a series of two-port measurements performed with the remaining ports either open-circuited or wire-bonded shut. Not only does the JEDEC method offer an incomplete characterization of the interconnection, but it is also sensitive to fringing field capacitance and wirebond inductances of the terminated ports.

The current NIST implementations are based on conventional network analyzers and switching networks. Figure 5 compares the NIST fully calibrated four-port measurements to conventional two-port measurements of a two-port device. While the figure confirms that the bandwidth and accuracy of the system are good, it is restricted at present to four measurement ports. We are working to circumvent this limitation by extending the calibrations to ground-signal-ground-signal-ground probes that simultaneously support several measurement signals and by implementing the methods with time-domain instruments that easily support many measurement channels.

Contacts: Dylan Williams (dylan@boulder.nist.gov), Don DeGroot (degroot@boulder.nist.gov), and David Walker (walker@boulder.nist.gov)

Dielectric Properties of Thin-Film Materials

Challenge: *Develop accurate broadband methods to directly determine the constitutive parameters of new dielectric thin films for high-speed electronic interconnections.*
NIST approach: *Characterize thin film parameters from complete transmission line measurements.*

The NIST program has produced accurate methods for extracting the frequency-dependent permittivity of thin films from measurements of transmission lines that incorporate the thin films of interest. Much of the existing work in this area uses only measurements of the transmission line's propagation constant, which [10] shows is measured accurately only with the Multiline method. However, it is difficult to separate metal and dielectric loss from measurements of the propagation constant alone, since wave propagation is strongly affected by both.

NIST has been investigating methods that circumvent this problem by directly measuring the characteristic impedance of transmission lines as described above [5,6,14]. This additional information is used to calculate the line's equivalent circuit parameters—its capacitance C, conductance G, resistance R, and inductance L per unit length—directly. The advantage of this approach is that the material parameters are more simply related to equivalent circuit parameters than the propagation constant. This allows dielectric and metal material parameters to be extracted with little modeling effort [20]. Figure 6 illustrates some of the methods being investigated at NIST, including the calibration comparison method [14], that directly determines the characteristic impedance of the transmission line.

NIST is currently working with industrial partners [7] to apply these methods to evaluate mature dielectric film technology, and is also developing standard substrates with coplanar waveguide transmission lines to test the new low-k materials. Our colleagues in the NIST Electricity Division are investigating the characterization of printed wiring board materials using time-domain methods and are also collaborating on related thin-film measurements [21-22].

Contacts: Mike Janezic (janezic@boulder.nist.gov), Dylan Williams (dylan@boulder.nist.gov), and Nick Paulter, NIST Electricity Division (npaulter@nist.gov).

At-Speed Test

Challenge: *Accurately test complex digital integrated circuits at full operating speed.*
NIST approach: *Develop calibration tools for at-speed test systems.*

While at-speed test data are extremely useful for diagnosing failure mechanisms and could prove even more important as tools for understanding speed limitations of complex electrical interconnections, the measurements themselves are essentially uncalibrated. NIST is developing chips with known high-speed voltage and current waveforms on tightly coupled lines in an attempt to explore the accuracy of these measurement systems and to improve calibration algorithms.

The chips will be characterized with accurate and well-understood probe-based measurement methods. On-chip power sensors will allow the exact voltage and current levels during testing at NIST to be reproduced in the at-speed test system.

Contact: Dylan Williams (dylan@boulder.nist.gov)

Summary

In this presentation, we identified a number of research topics that address the fundamental nature of wave propagation on microelectronic interconnections and then briefly described current research at NIST to respond to these opportunities. The work at NIST continues to increase the understanding of wave propagation on lossy and coupled transmission lines and to provide practical measurement methods for industrial applications, while closing the gap between basic electromagnetic analysis and the characterization of many signals on an intricate mesh of interconnections.

References

[1] M. A. Schen, "Electronics Packaging, Interconnection and Assembly at NIST: Guide and Resources," National Institute of Standards and Technology, Natl. Inst. Stand. Technol. Interagency Rept. 5817, April, 1996.

[2] R. B. Marks, D. C. DeGroot, and J. A. Jargon, "High-speed interconnection characterization using time domain network analysis," *Advancing Microelectronics*, vol. 22, no. 6, pp. 35-39, Nov./Dec., 1995.

[3] D. C. DeGroot, and R. B. Marks, "Optimizing time-domain network analysis," *46th ARFTG Conf. Dig.*, pp. 19-28, Nov. 30-Dec. 1, 1995.

[4] D. DeGroot, and J. Jargon, "Taking rf and microwave device measurements with a digital sampling oscilloscope," *Instrumentation Newsletter*, vol. 9, no. 4, pp. T1-T2, Winter, 1997.

[5] D. F. Williams and R. B. Marks, "Accurate transmission line characterization," *IEEE Microwave Guided Wave Lett.*, pp. 247-249, Aug. 1993.

[6] D. F. Williams, U. Arz, and H. Grabinski "Accurate Characteristic Impedance Measurement on Silicon," *1998 IEEE MTT-S IMS Dig.*, pp. 1917-1920, June 9-11, 1998.

[7] D. F. Williams, M. D. Janezic, A. Ralston, and S. List, "Quasi-TEM model for coplanar waveguide on silicon," *6th Topical Meeting Elect. Performance Electron. Packaging*, pp. 225-228, Oct. 27-29, 1997.

[8] V. Milanovic, M. Ozgur, D. C. DeGroot, J. A. Jargon, M. Gaitan, and M. E. Zaghloul, "Characterization of broad-band transmission for coplanar waveguides on CMOS silicon substrates," *IEEE Trans. Microwave Theory Tech.*, vol. 46, no. 5, pp. 632-640, May, 1998.

[9] R. B. Marks, "A multiline method of network analyzer calibration," *IEEE Trans. Microwave Theory Tech.*, vol. 39, no. 7, pp. 1205-1215, July, 1991.

[10] D. C. DeGroot, D. K. Walker, and R. B. Marks, "Impedance mismatch effects on propagation constant measurements," *5th Topical Meeting Elect. Performance Electron. Packaging*, pp. 141-143, Oct. 28-30, 1996.

[11] R. B. Marks and D. F. Williams, "Characteristic Impedance Determination using Propagation Constant Measurement," *IEEE Microwave Guided Wave Lett.*, vol. 1, no. 6, pp. 141-143, June 1991.

[12] D. F. Williams and R. B. Marks, "Transmission Line Capacitance Measurement," *IEEE Microwave Guided Wave Lett.*, vol. 1, no. 9, pp. 243-245, Sept. 1991.

[13] Y. Eo and W.R. Eisenstadt, "High-speed VLSI interconnect modeling based on S-parameter measurements," IEEE Trans. Comp., Hybrids, Manuf. Technol., vol. 16, no. 5, pp. 555-562, Aug. 1993.

[14] D. F. Williams, R. B. Marks, and A. Davidson, "Comparison of on-wafer calibrations," *38th ARFTG Conf. Dig.*, pp. 68-81, Dec. 1991.

[15] D. F. Williams, L. A. Hayden, and R. B. Marks, "A Complete Multimode Equivalent-Circuit Theory for Electrical Design," *J. Res. Natl. Inst. Stand. Technol.*, vol. 102, no. 4, pp. 405-423, July-Aug. 1997.

[16] D. F. Williams, "Multiconductor Transmission Line Characterization," *IEEE Trans. Comp. Packaging Manufact. Technol. B*, vol. 20, no. 2, pp. 129-132, May 1997.

[17] D. F. Williams, "Embedded multiconductor transmission line characterization," *1997 IEEE MTT-S IMS Dig.*, pp. 1773-1776, June 10-12, 1997.

[18] D. F. Williams, J. E. Rogers, and C. L Holloway, "Multiconductor transmission line characterization: representations, approximations, and accuracy," submitted to *IEEE Trans. Microwave Theory Tech.*

[19] D. F. Williams and D. K. Walker, "In-line multiport calibration," *51st ARFTG Conf. Dig.*, pp. 88-90, June 12, 1998.

[20] M. D. Janezic and D. F. Williams, "Permittivity Characterization from Transmission-Line Measurement," *1997 IEEE MTT-S IMS Dig.*, vol. 3, pp. 1343-1345, June 10-12, 1997.

[21] N. G. Paulter, "A fast and accurate method for measuring the dielectric constant of printed wiring board materials," *IEEE Trans. Comp. Packaging Manufact. Technol. C*, pp. 214-225, 1996.

[22] N. G. Paulter, "Long-term repeatability of a TDR-based dielectric constant measurement system," submitted.

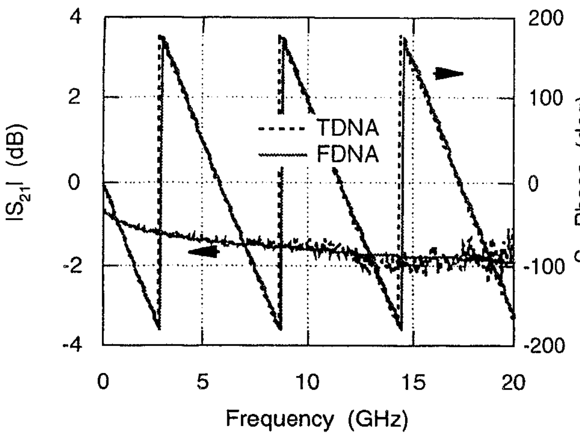

Figure 1. Comparison of TDNA to commercial frequency-domain network analyzer (FDNA) data: Forward scattering parameter for gold coplanar waveguide transmission lines on GaAs substrate (from [3]).

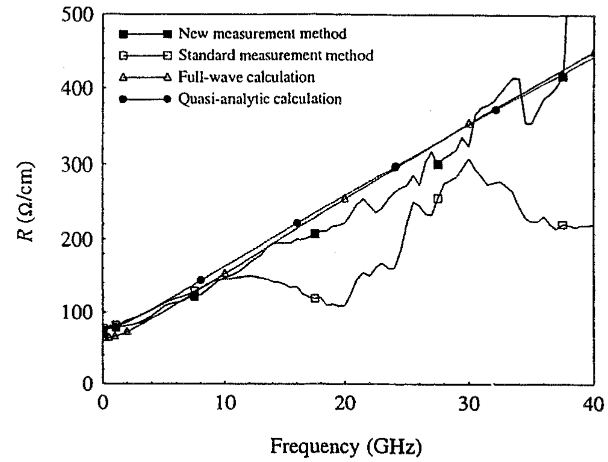

Figure 2. The measured and calculated resistance R per unit length of a transmission line fabricated on a lossy silicon substrate [6].

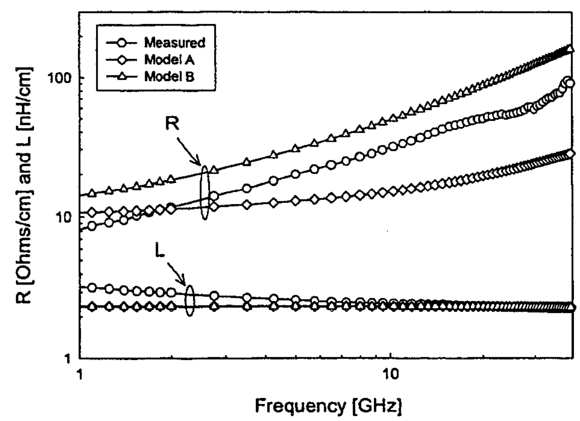

Figure 3. Comparison of measured R & L parameters to prediction of a CMOS transmission line model (from [8]).

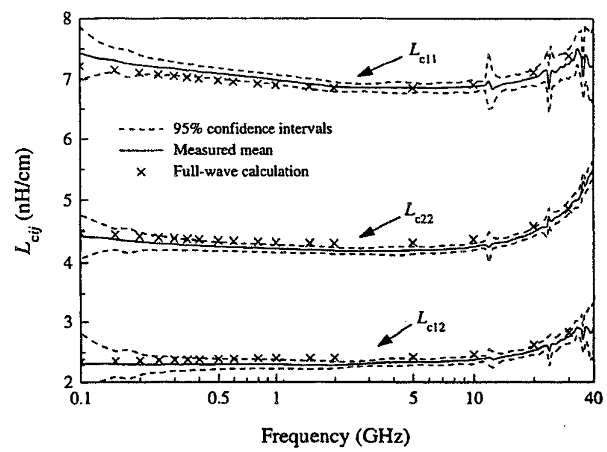

Figure 4. The measured and calculated values of the inductance matrix L per unit length of a lossy pair of microstrip transmission lines (from [18]).

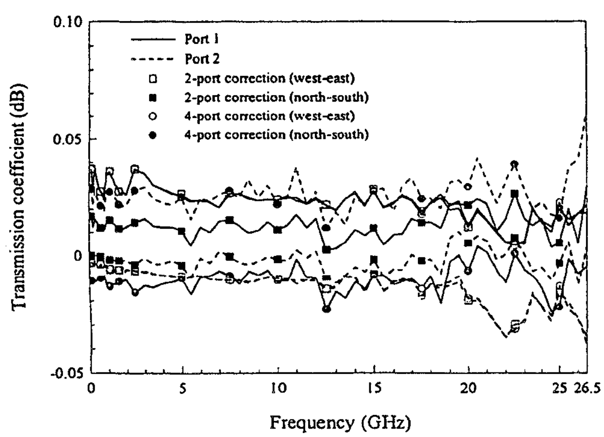

Figure 5. The transmission parameters of a thru line corrected with a conventional two-port algorithm is compared to those corrected with NIST's four-port calibration algorithm (from [19]).

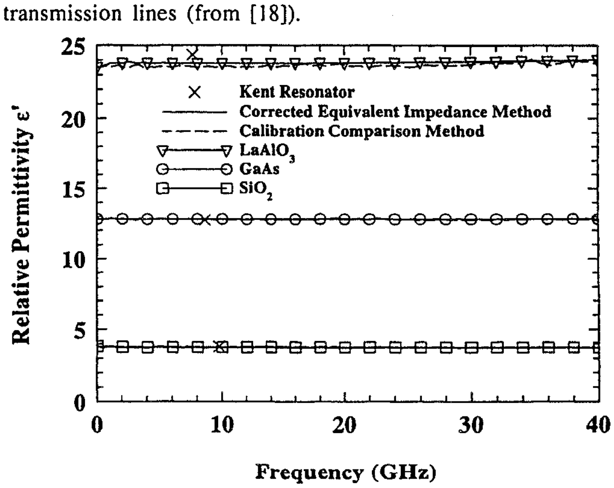

Figure 6. The corrected equivalent impedance method and the calibration comparison method of determining permittivity are compared to precision single-frequency Kent cavity measurements (from [20]).