Permittivity Characterization of Low-k Thin Films From Transmission-Line Measurements

Michael D. Janezic, *Senior Member, IEEE*, Dylan F. Williams, *Fellow, IEEE*, Volker Blaschke, Arun Karamcheti,
and Chi Shih Chang

***Abstract*—We have developed a broad-band technique for measuring the relative permittivity of low-k thin films using microstrip transmission-line measurements. From measurements of the complex microstrip propagation constant *and* the characteristic impedance, we determined the relative permittivity of thin films incorporated in microstrip lines. We present measurement results to 40 GHz for both an oxide and a bisbenzocyclobutene low-k thin film and show a variability of permittivity of approximately ±5% over the entire frequency range.**

***Index Terms*—Dielectric constant, low-k, measurement, microstrip, permittivity, thin film, transmission line.**

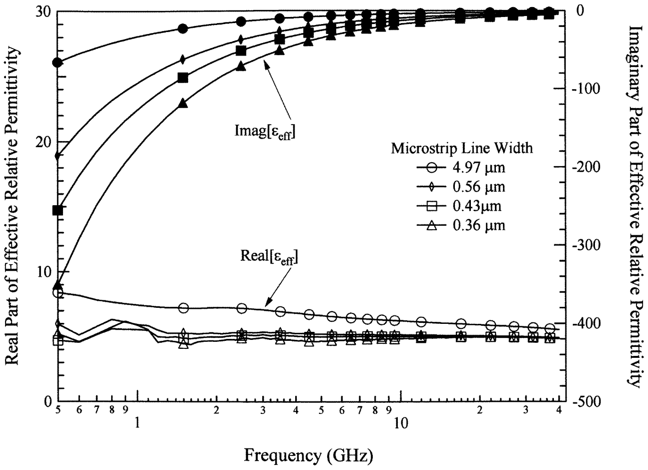

Fig. 1. Real and imaginary parts of the effective relative permittivity ϵ_{eff} determined solely from the propagation constant.

I. Introduction

In this paper, we propose a method of determining thin-film permittivity that uses microstrip transmission lines incorporating the thin film. Unlike conventional methods that are based solely on a measurement of the microstrip propagation constant, we also measure the characteristic impedance of the microstrip. We use this extra information to separate the electrical effects of the conductors and thin film and are, thus, able to more accurately determine the permittivity of the thin film.

When measuring the permittivity of a bulk dielectric material, one might choose one of the many resonator measurement methods available such as the cylindrical cavity resonator, dielectric post resonator, or the split-post resonator [1]. However, because traditional resonator methods have a limited frequency range and are insensitive to thin low-permittivity (low-k) materials, these methods are inappropriate for characterizing the permittivity of low-k thin films.

In an effort to broaden the frequency range and increase measurement sensitivity, researchers have developed measurement methods that make use of planar tranmission lines such as a microstrip and coplanar waveguide, which incorporate the thin film as part of the transmission line. For example, work described in both [2] and [3] determined the permittivity of a thin film incorporated in a microstrip transmission line from measurements of the frequency-dependent propagation constant γ. However, the propagation constant is a function of both the dielectric thin film and metallic conductors that make up the transmission line [4]. Using only the propagation constant, it is difficult to separate the two, and the calculation of the thin film's permittivity is problematic.

Fig. 1 illustrates the difficulty of separating the properties of the dielectric thin film from those of the metallic conductors using only the measured propagation constant. This figure shows the effective relative permittivity $\epsilon \equiv -(c\gamma/\omega)^2$, where c is the speed of light and ω is the angular frequency of the signal of four planar microstrip lines with center conductor widths of 4.97, 0.56, 0.43, and 0.36 μm that we fabricated on a low-loss dielectric thin film. While the thin film itself had low losses, the effective relative permittivity (and, therefore, the propagation constant) of the transmission line is both frequency-dependent and complex, and depends heavily on the width of the microstrip center conductor. This complicated behavior of the effective relative permittivity is due to the losses within the small metallic microstrip lines, not to the dielectric properties of the thin film.

Previously, we developed several measurement methods for determining the permittivity of dielectric substrates using coplanar-waveguide transmission-line measurements [5]. One of these techniques is based on the calibration comparison method [6] and uses measurements of both the propagation constant and characteristic impedance of the transmission line to find the permittivity of the substrate. This enables us to separate the electrical properties of the coplanar-waveguide conductors from those of the substrate.

We used the multiline thru-reflect-line (TRL) method [7] to measure the frequency-dependent propagation constant γ. This calibration technique is the most accurate method of

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M. D. Janezic and D. F. Williams are with the National Institute of Standards and Technology, Boulder, CO 80303 USA.

V. Blaschke, A. Karamcheti, and C. S. Chang are with International Sematech, Austin, TX 78741 USA.

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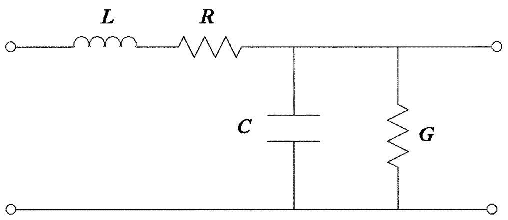

Fig. 2. Transmission-line equivalent-circuit model.

determining the propagation constant, as it is independent of impedance mismatches [8].

Reference [9] shows that the calibration comparison method measures the characteristic impedance Z_0 much more accurately than conventional methods based on S-parameter measurements of a single length of transmission line [10], thus, we adopted this approach. The calibration comparison method compares a calibration performed on a set of reference transmission lines whose characteristic impedance is known to a calibration performed on a set of tranmission lines with unknown characteristic impedance. By modeling the differences as an impedance transformation, the method determines the unknown Z_0 [6].

From the measured frequency-dependent propagation constant γ and the characteristic impedance Z_0, we calculated the distributed capacitance C, conductance G, inductance L, and resistance R per unit length of the microstrip from

$$G + j\omega C = \frac{\gamma}{Z_0} \tag{1}$$

and

$$R + j\omega L = \gamma Z_0. \tag{2}$$

These four distributed circuit parameters correspond to the equivalent-circuit model for an incremental length of microstrip transmission line shown in Fig. 2. These parameters are also related to the dielectric materials and conductors that make up the microstrip transmission line. For a quasi-TEM mode propagating along a microstrip transmission line made up of dielectric material, C and G are related primarily to the permittivity of the material incorporated in the transmission line, while R and L are related to the properties of the transmission-line conductors [4]. Thus, by using both the measured propagation constant and characteristic impedance, we are able to separate the properties of the dielectric from the properties of the metallic conductors. Finally, from the physical dimensions and measured distributed capacitance C of the microstrip lines, we are able to determine the permittivity of the low-k thin film.

II. Test Structures

The test structures were manufactured at International SEMATECH using a 0.25-μm dual-damascene Cu process. We fabricated two sets of microstrip lines, one incorporating bisbenzocyclobutene (BCB) as the low-k thin film, and the other incorporating a conventional oxide (SiO_2) thin film. A cross section of one of the microstrip lines is shown in Fig. 3. The process sequence to build both samples involved a single-damascene metal-1 trench layer, which served as the microstrip line, followed by a dual-damascene metal-2 trench/via layer to form the signal transmission line and via contacts to the ground for the probe pads. The Cu features were lined by a 25-nm Ta barrier and capped with a 100-nm SiN layer to prevent Cu diffusion. We used a 100-nm SiN trench stop layer for the SiO_2 sample and a 100-nm SiO_2 trench stop layer for the BCB lines.

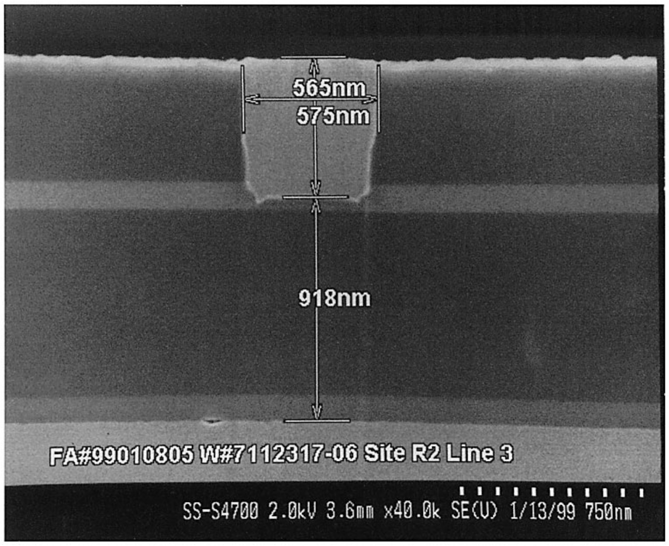

Fig. 3. Typical cross-section of one of the microstrip transmission lines measured with a scanning electron microscope.

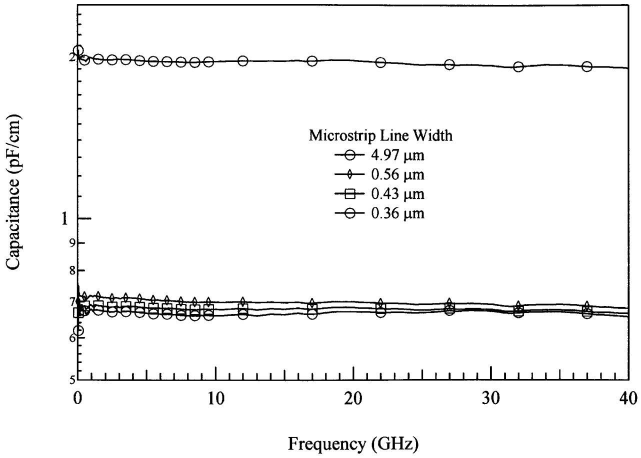

Fig. 4. Measured capacitance per unit length of a transmission line for four microstrip lines that incorporate the BCB thin film. The width of the microstrip lines varied from 0.36 to 4.97 μm.

III. Measurements

We performed a multiline TRL calibration [7] on our microstrip test structures at frequencies from 50 MHz to 40 GHz using an automatic network analyzer connected to a microwave probing station to determine the propagation constant γ of the transmission line. We then determined the characteristic impedance Z_0 using the calibration comparison method [6]. From (1) and (2), we calculated the four circuit parameters C, G, R, and L. Figs. 4–7 show C, G, R, and L for the four microstrip transmission lines with varying linewidths.

We are primarily interested in C and G, as these are related directly to the permittivity of the thin film. However, we make a few observations about the conductor properties from our measurements of R and L. Fig. 6 shows the resistance of the four

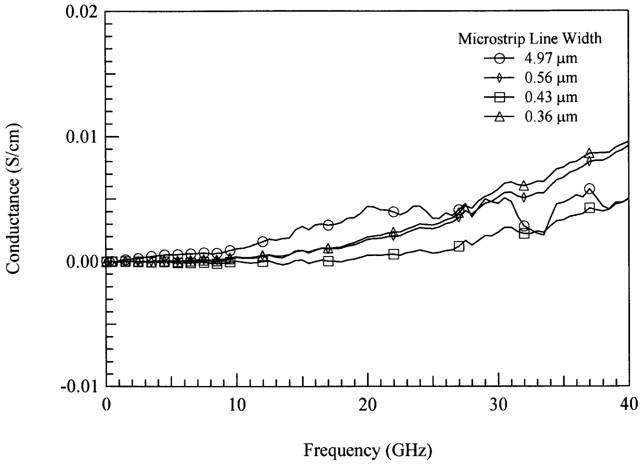

Fig. 5. Measured conductance per unit length of a transmission line for four microstrip lines that incorporate the BCB thin film.

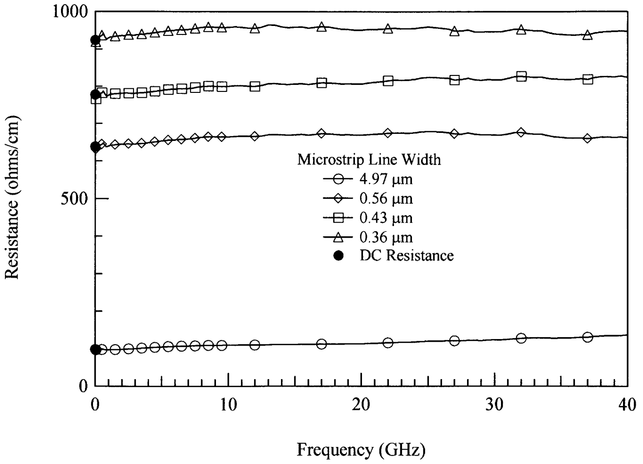

Fig. 6. Measured resistance per unit length of a transmission line for four microstrip lines that incorporate the BCB thin film. Also shown are dc resistance measurements.

microstrip lines. As a check, we measured the dc resistances of the lines, and found good agreement with the resistance per unit length of line at low frequencies, as is shown in Fig. 6. As expected, as the linewidth of the microstrip line decreases, the resistance increases accordingly. Although the resistance increases somewhat with frequency for the smaller lines, the dc resistance is a good approximation to the resistance per unit length of line over the entire frequency range.

Fig. 7 shows the measured inductance per unit length of line. At high frequencies, the majority of the total inductance is from the external inductance of the tranmission line and is flat versus frequency. However, as the frequency decreases, the electromagnetic fields penetrate further into the conductors of the microstrip line, and the resulting self-inductance increases the total inductance slightly.

IV. THIN-FILM PERMITTIVITY

Fig. 4 shows that the capacitance of the microstrip is relatively flat over the entire frequency range. As expected, the microstrip lines with smaller linewidths have a capacitance significantly lower than that of the 4.97-μm-wide microstrip line.

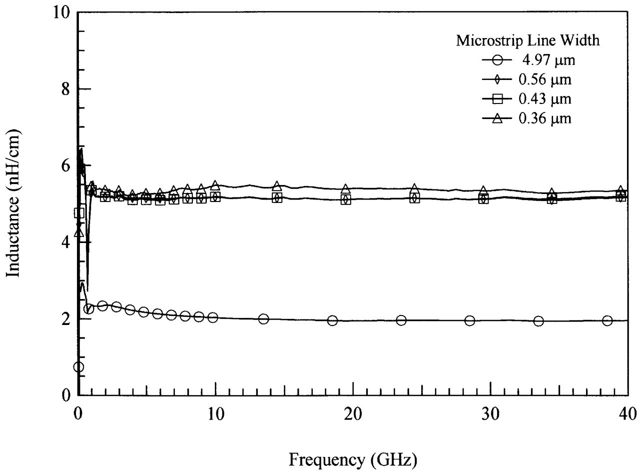

Fig. 7. Measured inductance per unit length of a transmission line for four microstrip lines that incorporate the BCB thin film.

We used RC2,[1] an interconnect analysis module in the RAPHAEL software, to determine the relationship between the measured capacitance and permittivity of the low-k thin film. RC2 is a two-dimensional simulator for solving Poisson's equation, appropriate for the analysis of two-dimensional electrical parameters. It is based on a finite-difference method with an automatically generated rectangular mesh that allows a completely arbitrary configuration of conductors and dielectrics. The required inputs for RC2 are the cross-sectional dimensions of the conductor and dielectric layers, permittivities of the dielectric layers, and the conductor potentials.

Using a scanning electron microscope, we obtained the cross-sectional dimensions of the conductor and dielectric layers. To obtain a better estimate of each dimension, we cross sectioned each microstrip line at multiple sites and averaged the results. Fig. 3 shows an example of a typical cross section of one of the microstrip transmission lines. In our measurement of the BCB thin film, we assumed a relative permittivity ϵ' of 3.9 and 7.9 for the layers of SiO_2 and Si_3N_4, respectively [11]. Thus, the remaining unknown is the permittivity of the low-k thin film.

We used RC2 to compute C as a function of the thin-film permittivity ϵ'_k. We then fitted a second-order polynomial to the simulated data to obtain an equation relating the ϵ'_k to C. Fig. 8 shows results of a typical simulation and polynomial fit. We repeated this process for each microstip linewidth, as the relationship between the thin-film permittivity and the capacitance was different in each case. Finally, we substituted the measured capacitance into the equation obtained by the polynomial fit, and computed ϵ'_k as a function of frequency.

In order to verify the validity of this technique, we first fabricated microstrip tranmission lines that incorporated silicon oxide. Fig. 9 shows the permittivity of the silicon oxide for the four microstrip lines of varying linewidths. The measured permittivity is consistent for silicon dioxide [11] and there is approximately a ±5% variation in permittivity over the entire frequency range.

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[1] RC2, Synipsys Inc., Mountain View, CA.

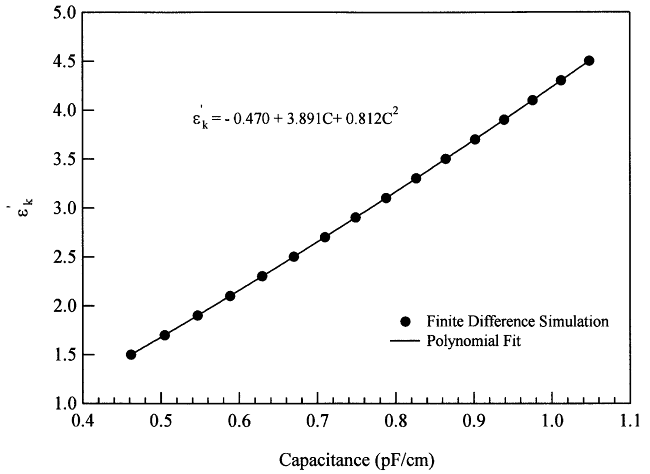

Fig. 8. Permittivity of BCB thin film as a function of capacitance as calculated with a finite-difference simulator. The fitted line is a second-order polynomial fit to the simulated data.

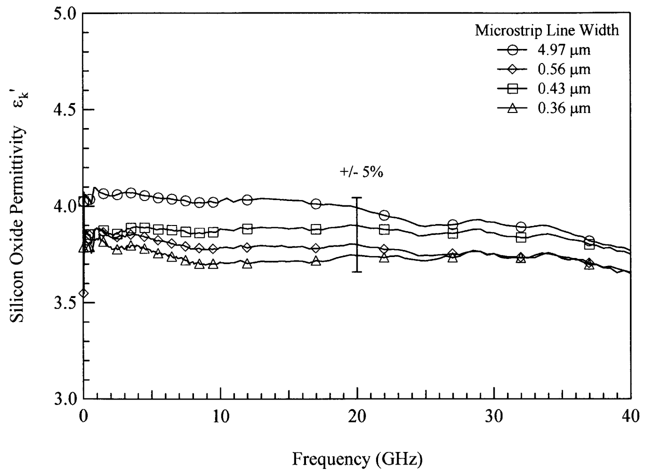

Fig. 9. Relative permittivity of oxide thin film as a function of frequency.

We then used the method to characterize the permittivity of the BCB thin film. Fig. 10 shows the permittivity of the BCB thin film for the four microstrip lines of varying linewidths. As in the case of the silicon dioxide, there is less than ±5% variation in the permittivity over the entire frequency range.

V. CONDUCTANCE

Fig. 5 shows the measured conductance of the microstrip lines. Unfortunately, determining the loss tangent of the low-k thin film from the conductance proved to be problematic. First, the conductance is a measure of all the dielectric losses in transmission line. This includes not only the low-k thin film, but also thin layers of SiO_2 and SiN, whose loss tangents we do not know. Therefore, at best, only the loss tangent due to all the dielectric layers might be determined. Secondly, the resistive losses due to the metal conductors are much greater than the dielectric losses due to the low-k thin film, greatly reducing the measurement sensitivity necessary to measure dielectric losses. Fig. 11 compares $R/\omega L$, a unitless measure of the metallic losses, to $G/\omega C$, a unitless measure of the thin-film dielectric losses. This figure shows that the conductive loss of the microstrip is much greater than the dielectric loss for the entire frequency range. Although this plot shows why a measurement of the low-k thin film is infeasible, it also shows that the designer can neglect the dielectric loss of the low-k thin film since metallic conductors are the primary source of losses in the transmission line.

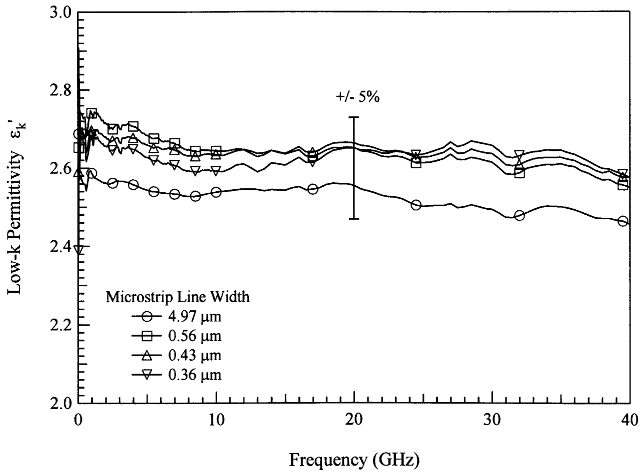

Fig. 10. Relative permittivity of BCB thin film as a function of frequency.

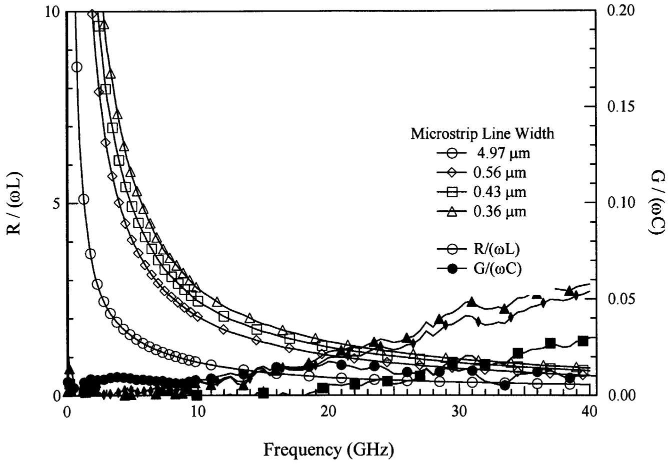

Fig. 11. Comparison between metal conductor losses and thin-film dielectric losses as a function of frequency.

VI. CONCLUSIONS

This paper has presented a new measurement method for determining the permittivity of low-k thin films by incorporating them in microstrip transmission lines. The advantage of this technique is the ability to separate the electrical properties of the metal conductors from the electrical properties of the thin film by separate measurements of the propagation constant *and* the characteristic impedance of the microstrip line. From the propagation constant and characteristic impedance, we determined the measured distributed capacitance and conductance of the microstrip line. Knowing the physical dimensions of the microstrip lines, we were able to relate the thin-film permittivity to the measured capacitance by using a finite-difference solver. We demonstrated the technique for both an oxide and BCB low-k thin film and found approximately a ±5% variation in the thin-film permittivity over the frequency range from 50 MHz to 40 GHz for microstrip lines of various linewidths.

Although we were unable to calculate the loss tangent of the thin films from the measured conductance, we did show that the conductor losses of these particular microstrip lines were significantly higher than the dielectric losses in the thin film, and the dielectric losses could, therefore, be neglected in determining the performance of the transmission line.

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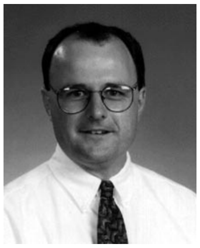
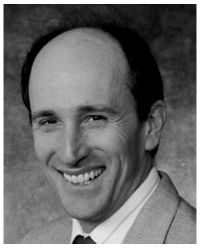


Michael D. Janezic (M'91–SM'02) received the B.S. and M.S. degrees in electrical engineering from the University of Colorado at Boulder, in 1991 and 1996, respectively, and is currently working toward the Ph.D. degree in electrical engineering in the area of electromagnetic theory at the University of Colorado at Boulder.

In 1988, he joined the Radio Frequency Technology Division, National Institute of Standards and Technology (NIST), Boulder, CO, where he has primarily focused on the development of techniques for measuring the broad-band electrical properties of dielectric substrates and thin films.



Dylan F. Williams (M'80–SM'90–F'02) received the Ph.D. degree in electrical engineering from the University of California at Berkeley, in 1986.

In 1989, he joined the Electromagnetic Fields Division, National Institute of Standards and Technology (NIST), Boulder, CO, where he develops metrology for the characterization of monolithic microwave integrated circuits and electronic interconnects. He has authored or coauthored over 80 technical papers.

Dr. Williams was the recipient of the Department of Commerce Bronze and Silver Medals, the Electrical Engineering Laboratory's Outstanding Paper Award, two ARFTG Best Paper Awards, the ARFTG Automated Measurements Technology Award, and the IEEE Morris E. Leeds Award.

Volker Blaschke received the Dipl.Ing. (FH) degree in micromechanics from the University of Applied Sciences, Munich, Germany, in 1988, and the M.S. degree in electrical and computer engineering from University of Texas at Austin, in 2000.

He is a Principal Engineer with Conexant Systems Inc., Newport Beach, CA, where he is involved with RF modeling of passive components. Prior this, he was the Senior Assignee for Conexant Systems Inc. at International Sematech, Austin, TX, where he collaborated with the National Institute of Standards and Technology (NIST), Boulder, CO, on high-frequency transmission-line characterization. He was the Team Leader for the interconnect reliability activities and Chair of the Reliability Working Group, whose charter is to mentor and align reliability activities between International Sematech and its member companies. He possesses over ten years experience in the semiconductor industry in process development, integration, reliability, and modeling.

Arun Karamcheti, photograph and biography not available at time of publication.

Chi Shih Chang, photograph and biography not available at time of publication.