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Calibration Methods for Microwave Wafer Probing

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Abstract: A new level of accuracy in the measurement of microwave parasitics has been achieved, due to the combined development of microwave wafer probes and on-wafer impedance standards. Repeatable losses and reflections in the probes can be readily removed from measured data, but radiation losses and crosstalk cannot be corrected and must be minimized. Oneport and twoport on-wafer standards for several probe footprints are shown, and their performance verified.

Introduction

Timely development of either monolithic microwave circuits or ultra-high-speed digital circuits requires precise knowledge of monolithic circuit element parameters and their variations and parasitics. The complex nature of some of these elements and their interactions has precluded accurate theoretical prediction or even scale modelling. Microwave wafer probes have been shown to be an accurate and convenient tool for the detailed network analysis of monolithic elements [1,2]. A wafer probe can be viewed as an adapter from coax to bonding pads, and as such will perturb microwave measurements in the same fashion that coaxial adapters affect measurements. Demonstrated microwave wafer probes allow uncorrected measurement accuracies similar to the accuracies achieved with SMA connectors. However, the combination of microwave probes with a corrected network analyzer and on-wafer impedance standards which are much smaller than a wavelength allows on-wafer S-parameter measurements with a new level of accuracy. In this paper we discuss the requirements on the probes to be usable with a corrected network analyzer, some typical oneport, twoport, and balanced calibration techniques and results, and a discussion of probes and calibrations for high-speed digital circuits.

Probe requirements for use with a corrected network analyzer

There are three classes of signal degradations which a wafer probe can cause: losses, reflections, and crosstalk. When using a probe (or any adapter) with a corrected network analyzer, the tolerable level of losses or reflections is relatively high; the only limit is maintaining sufficient signal level for good signal-to-noise ratio.

However, the losses and reflections must be as repeatable as the resolution desired. If significant signal power is radiated from the probe(s), the probe losses are normally not repeatable. This is because the wafer, wafer chuck, or other conductors are moved in relation to the probes, causing changes in the radiation impedance. Radiation from one line to another can also occur, creating crosstalk.

For twoport calibrations, the standard 12-element vector correction model [3] includes a leakage correction element for each direction, but the ability of this element to correct for crosstalk is very limited [1]. In practice, it has been found that limiting crosstalk between probe lines is simpler and more accurate than attempting to correct for it. Crosstalk can be caused either by coupling between transmission lines on the probe(s) or by common-lead inductances. Since the crosstalk is uncorrected, even in a corrected measurement, any crosstalk will appear in low-level transmission measurements. The allowable crosstalk level is approximately equal to the required transmission accuracy. Demonstrated pairs of single-line microwave probes achieve greater than 45 dB isolation through 18 GHz. Two-line probes with a signal-ground-signal contact configuration achieve a worst-case isolation of only about 20 dB through 18 GHz. This is due to the common-lead inductance of the ground contact (about 50 pH), the worst case being when all the contacts are shorted together.

On-wafer calibrations

A "two-tier" deembedding approach [4] is possible, wherein the probe parameters are measured and stored for removal from parameters measured from a coax calibration. However, since the probe contact to the standards on the impedance standard substrate (ISS) is faster and more repeatable than making coax connections, two-tier deembedding is a waste of time and accuracy. Therefore, the preferred approach in calibration is to use the on-wafer standards to calibrate directly at the probe tip(s) ("one-tier" deembedding).

The wafer probe adapts from a coaxial transmission medium to essentially twinstrip or coplanar waveguide or other coplanar lines on the wafer surface. However, since the dimensions of many monolithic structures for ICs and for impedance standards are small with respect to a wavelength, these on-wafer structures are lumped in nature. The impedance standards for both oneport and twoport calibrations are analyzed for accuracy using theoretical predictions of parasitics, measurement at low frequency, comparison to other standards, and scale modelling.

Impedance standards have been built on GaAs, Si, and alumina. The GaAs and alumina calibrations perform very similarly, while the Si calibrations show significantly more capacitance to the substrate, as expected.

The type of calibration standards used must correspond to the contact configuration of the probe(s). For simplicity, the standards for the probes shown in figure 1 [1,2] will be considered first. Generally, narrower contact spacings allow slightly more accurate calibration; bond pads as small as 50 um wide on 100 um centers are readily used.

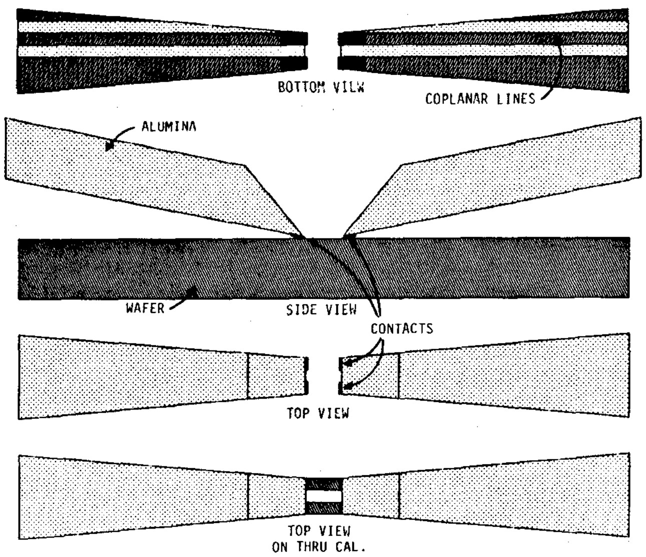

Figure 1. A simple coplanar probe configuration which has achieved accurate microwave results. One probe head has a ground-signal contact configuration and the other probe head has a signal-ground contact configuration. Note that the probe contact areas are visible from the top, since they extend just beyond the end of the probe board.

Oneport calibrations

Figure 2 shows the minimal set of twoport calibrations for the probes in figure 1, and a GaAsFET with the corresponding footprint. In Figure 2, the short standard is simply an area of metallization which creates a low inductance between the contacts. The 50-ohm load is a 50 um

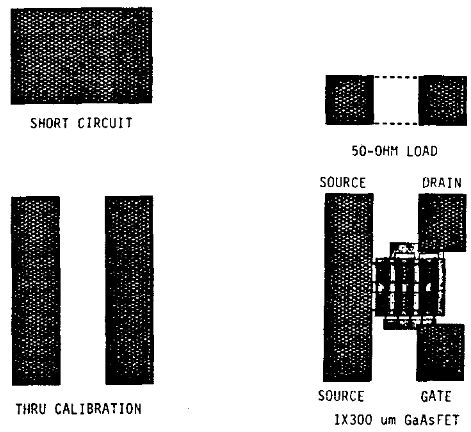

Figure 2. Minimum oneport and twoport standards for the probe footprint illustrated in figure 1, and a GaAsFET with a corresponding footprint.

square resistor deposited on the GaAs. Its resistance can be measured at DC, its series inductance is calculated to be about 30 pH, and the parallel capacitance is calculated to be 4.9 fF on GaAs. The open-circuit standard is just the probe raised from the substrate. The stray capacitance can be empirically determined, as is done for coaxial calibrations. By ensuring that the corrected reflection coefficient magnitudes of high-Q coils and capacitors are less than one, the open-capacitance can be determined to within about 3 fF.

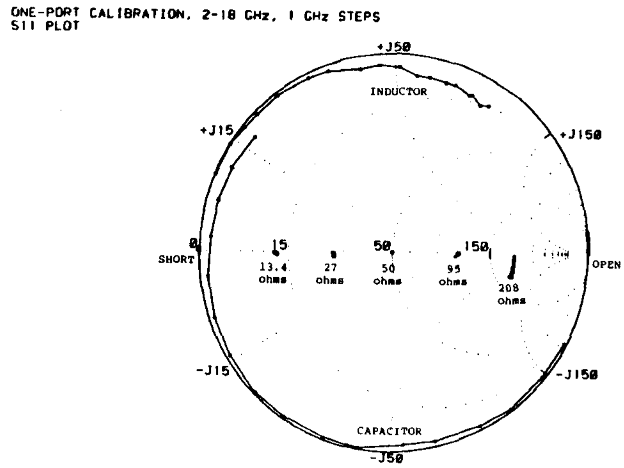

Figure 3. Corrected oneport measurements of various on-wafer impedance standards. The short, the 50-ohm resistor, and the open were used as the three standards for calibration.

Figure 3 shows oneport measurements of the calibration standards and other impedance standards after calibrating the system with a short, a 50-ohm termination, and an open circuit. The other standards are necessary to verify the accuracy of the calibration, since repetition of the calibration standards only proves that the system repeats its measurements. As can be seen in figure 3, the resulting measurements are extremely tightly grouped and demonstrate the lumped nature of these elements.

The measurement of a 50 X 150 um rectangle of metalization (just large enough to short the signal contact to the ground contact on the probe) is shown in Figure 4. About 30 pH of inductance is measured, comparing well with the expected inductance. Extra conductor under the end of the probe tip causes a small interaction between the conductor and the very end of the probe tip, resulting in an apparent negative inductance as large as -60 pH.

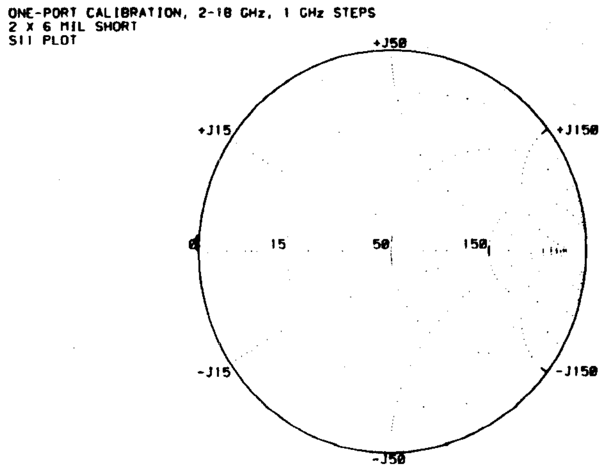

Figure 4. Corrected oneport measurement of a 50 X 150 um metallized rectangle, illustrating the ability to measure inductances below 50 pH.

Twoport calibrations

Twoport corrected S-parameter measurements with the standard 12-element error model use the above calibration for each port, plus a through connection and isolation calibration standards. The through standard connects the two ground contacts together and the two signal contacts together. For the isolation calibration, either the probes are open-circuited in air, minimizing any coupling between them, or the isolation error terms are simply set to zero.

Figure 5 shows the measurement of a 10-dB pad after the twoport calibration, verifying the basic accuracy of the standards. Figure 6 shows the measurement of a typical 1X300 um GaAsFET, along with its lumped equivalent circuit [5].

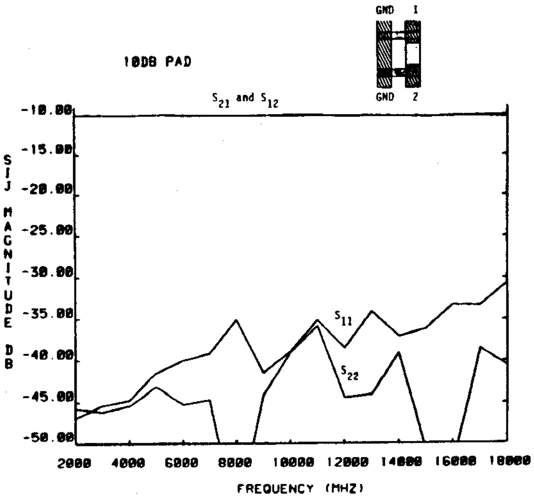

Figure 5. Corrected twoport measurement of a small 10-dB pad. The measured S21 magnitude typically varies ± 0.1 dB over 2 to 18 GHz.

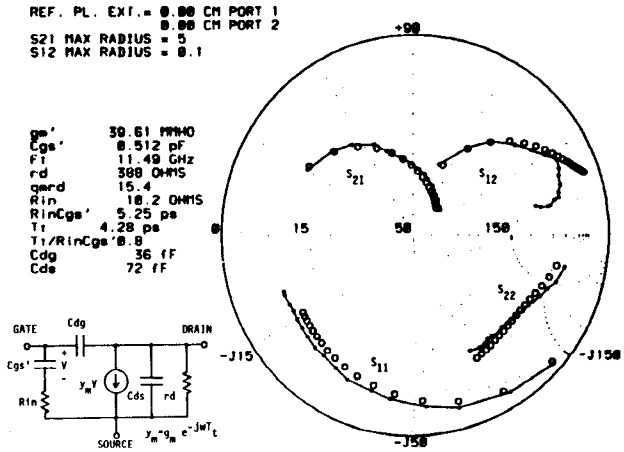

Figure 6. Measured 2-18 GHz S-parameters of a typical 1.0 X 300 um FET, using the microwave wafer probe. The circles are S-parameters of the simplified equivalent circuit calculated from the measured parameters.

The above discussion illustrates the calibrations for a simple probe configuration. Calibrations for other types of probe footprints, including configurations for most commercially-available discrete FETs, are possible. Since most discrete devices have not been designed for RF probing, special ground connections between the gate probe tip and the drain probe tip are often necessary.

For the case of an MMIC, ground contacts should be provided next to the input and output pads to be probed, as well as next to any bias pads which require off-chip bypassing. Low-impedance bypass probes can be used for on-wafer testing, in place of the bypass capacitors to be used in the package. The through calibration standard for probing an MMIC with a fixed probe footprint is a 50-ohm transmission line with ends at positions corresponding to the input and output of the MMIC. However, greater accuracy can be achieved by using an adjustable probe footprint, since a minimum-length through calibration standard can be used.

Balanced calibrations

Oneport and twoport measurements with balanced probes have been performed. A 2-18 GHz 50-ohm balun (Cascade Microwave part no. 010-019) is connected between each port of the network analyzer and its corresponding balanced probe, as in figure 7. Neither probe head has a ground contact, but there is a virtual ground plane vertically through the center of each. In this fashion, most of the imperfections of the baluns are removed, as if they were just other adapters. The corrected oneport measurement results are very similar to those shown in figure 3. A corrected twoport measurement of a 10-dB pad is shown in figure 8.

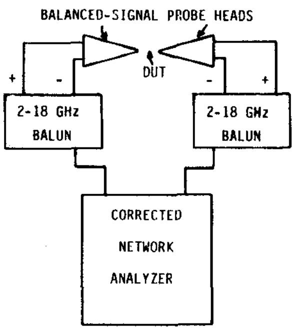

Figure 7. Connection of balanced probe heads with wideband baluns and a corrected network analyzer to achieve balanced on-wafer measurements.

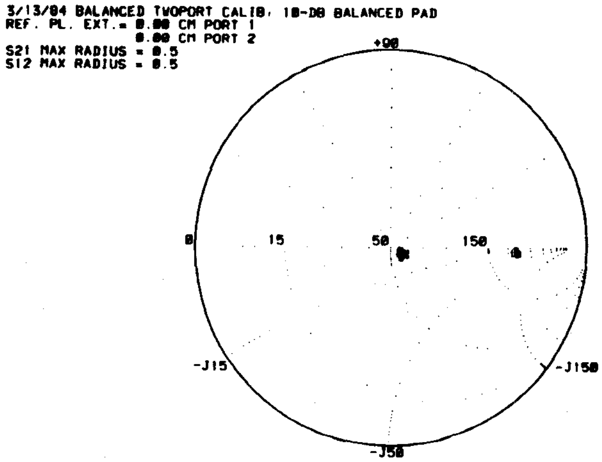

Figure 8. Corrected twoport measurement of a balanced 10-dB pad using the test setup shown in figure 7.

Calibrations for digital measurements

The measurement of a nonlinear circuit will not in general be correctable using linear techniques, such as the error models for a corrected network analyzer. Correction of output signals for frequency response of the output lines (in software) can be useful, and precorrection of input pulses (in hardware) to counteract the response of input lines may be practical in some cases. For the case of digital measurements, crosstalk and radiation again are not removable from the measurements. The main problems with ultrafast digital probing are the same problems with ultra-fast digital packaging: ground inductance and low-impedance power supply requirements. Except for die with balanced low-impedance outputs, wire probe tips are simply far too inductive. In addition to noise from common-lead inductance, crosstalk between transmission lines must also be minimized. For probe crosstalk measurements, a useful pattern is one which connects two signal line contacts and shorts them to a ground or power-supply contact. The transmission between two signal lines is a sensitive measure of the ground or power-supply impedance (usually a small inductance).

Digital circuit risetimes do not yet approach the risetimes of available cables and printable transmission lines, so the need for waveshape correction is relatively minor. More important to the digital designer is the accurate measurement of propagation delays. Through connections for accurate delay calibrations with multi-line probes can be built in the same style as for twoport ANA standards, with lines at enough different angles and positions to make throughs between each pair of signal lines.

Conclusions

The accuracy available with state-of-the-art microwave wafer probes exceeds the best accuracies possible in bonded-chip test fixtures. Wafer-probe measurements are so repeatable that the user can resolve which side of a bonding pad (about 50 pH) is being contacted by the probe tip. In contrast, the bondwires in a chip test fixture (at least 500 pH) often cannot be seperated from the device under test. In addition to accuracy improvements, wafer-probe measurements can be performed non-destructively, and eliminate processing steps to dice and bond up prototype chips. Balanced-signal probes have been demonstrated through 18 GHz, allowing testing of MMIC designs which make use of virtual grounds. During the design stage, MMICs should be laid out with RF on-wafer testing in mind.

References

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