



De-Embedding Procedures for On-Wafer Measurements at Millimetre Wave Frequencies

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Abstract

Scattering parameters measured on a wafer include the probe pads and access lines that connect the probes to the device under test. Removing these, the task called de-embedding, is routine at a few gigahertz with a pair of open and short dummy structures. At millimetre wave frequencies the same routine fails quietly: the pads are no longer small compared with the wavelength, the dummies cease to behave as ideal lumped elements, and coupling between the probes and neighbouring structures enters the result. This article brings the established procedures together into a single proposed workflow for measurements above about 30 GHz. It reviews the lumped methods, from open and short subtraction to multi-step variants, and the distributed methods based on through and line standards and on-wafer calibration. It then sets out six steps: defining the reference planes, designing the test structures with the device, choosing the method by frequency and layout, performing and checking the first tier calibration, applying the correction, and verifying the result with independent structures. Each step carries a stated check. The workflow is a proposal built from published methods and has not been validated on measured data in this article. The final sections discuss its limits and the evidence a validation would need.

Keywords: *De-embedding, On-wafer measurement, Millimetre wave, Vector network analyser calibration, Thru-reflect-line, Scattering parameters*

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1. Introduction

Compact models of transistors, and the design of the amplifiers and oscillators that use them, depend on scattering parameters measured directly on the wafer with coplanar probes. The probes cannot touch the device itself. They land on metal pads tens of micrometres across, and the pads are joined to the device by short lengths of interconnect. What the network analyser records is the device embedded in this fixture. As transistor cut-off frequencies have risen past 100 GHz, the parasitic elements of the fixture have become comparable with, or larger than, the intrinsic elements being extracted (Yau et al., 2012).

De-embedding is the mathematical removal of the fixture from the measurement. A family of

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procedures exists, most of them published in the device literature as short papers each improving on the last, and a practitioner choosing among them has to reconstruct their assumptions from scattered sources. The choice matters more as frequency rises, because the assumptions that make the simple methods work are low frequency assumptions.

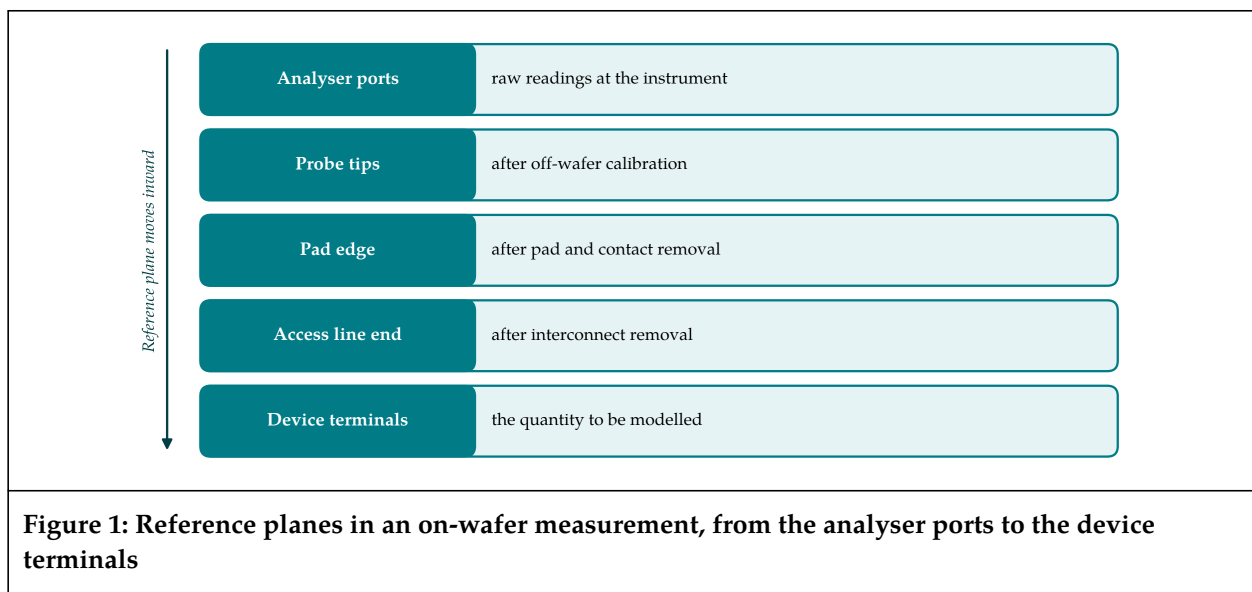
This article proposes a workflow that orders the decisions involved, from the design of the test structures to the verification of the corrected data. It is a synthesis of published procedures. No measurements are reported, and the workflow has not been validated here. The aim is to make explicit which method suits which circumstances and what checks expose a failed correction.

2. Background

A corrected on-wafer measurement is usually produced in two tiers. The first tier calibration moves the reference plane from the ports of the analyser to the probe tips. The second tier, the de-embedding proper, moves it from the probe tips to the device terminals. Figure 1 shows the sequence of reference planes. The methods of the second tier divide into lumped and distributed families.

2.1. First tier calibration

Probe tip calibration is normally carried out on an impedance standard substrate supplied by the probe maker, using short, open, load and through standards or one of the self-calibration methods that need less knowledge of the standards (Rumiantsev and Ridler, 2008). The thru-reflect-line method of Engen and Hoer (1979) requires only that the line be uniform and the reflect be the same at both ports. Eul and Schiek (1991) generalised this family, and the line-reflect-reflect-match variant with automatic determination of load inductance (Davidson et al., 1990) became popular for broadband probing because it needs no long lines. The multiline method of Marks (1991) combines several line lengths statistically and yields the propagation constant of the line as a by-product.



2.2. Lumped de-embedding

The lumped methods model the fixture as a few shunt admittances and series impedances and measure them with dummy structures in which the device is omitted. An open dummy alone removes the shunt capacitance of the pads (van Wijnen et al., 1987). Koolen et al. (1991) added a short dummy, so that the series impedance of the interconnect is removed as well, and this open-short method remains the default in most laboratories. The three-step method of Cho and Burk (1991) adds a through, and later variants refine the fixture model further: Kolding (2000) used four steps, Vandamme et al. (2001) improved the treatment of pad parasitics on silicon, and Tiemeijer and Havens (2003) calibrated the lumped elements for high quality inductors and fast transistors.

All of these share one assumption: each dummy is electrically small, so that its parasitic elements can be treated as lumped and as identical to those around the real device. The assumption weakens as the pad and line dimensions approach an appreciable fraction of the guided wavelength.

2.3. Distributed de-embedding and on-wafer calibration

The distributed methods treat the access structure as a transmission line. [Mangan et al. \(2006\)](#) showed how two through lines of different length give the pad parasitics and the line parameters without open or short dummies. The more radical step is to place the calibration standards on the same wafer, in the same metal stack as the device, and to perform a multilayer thru-reflect-line calibration that sets the reference plane inside the access line in one tier. [Williams et al. \(2013a\)](#) set out the design of such calibration kits for silicon circuits, and [Williams et al. \(2013b\)](#) gave a prescription for transistor characterisation at sub-millimetre wavelengths that rests on it. The characteristic impedance of the on-wafer line, needed to renormalise the result, can be obtained from the propagation constant and the line capacitance ([Marks and Williams, 1991](#)).

3. The Proposed Workflow

The workflow has six steps. Table 1 sets out the candidate methods with the structures each requires and the condition under which each is recommended, and the steps below refer to it.

3.1. Step 1: Define the reference planes

Before any structure is drawn, the engineer states where the corrected data should refer to. For model extraction the plane is normally at the edge of the lowest metal contacting the device. For circuit design it may be more useful to leave the lowest wiring levels in the device, since the circuit will use the same wiring. Writing the choice down prevents the common error of comparing a model extracted at one plane with a measurement de-embedded to another.

3.2. Step 2: Design the test structures with the device

The dummies and standards are laid out at the same time as the device, with identical pads, the same ground arrangement and the same distance to neighbouring structures. A solid ground shield under the signal pad keeps the lossy substrate out of the fixture and makes the pad behave as a nearly ideal capacitor. Access lines should be long enough to keep the probes apart, since probe to probe coupling grows with frequency, and should support a single mode. If on-wafer calibration is intended, lines of several lengths, a reflect and a through are required, with line lengths chosen so that no pair differs by a multiple of half a wavelength anywhere in the band ([Williams et al., 2013a](#)).

3.3. Step 3: Choose the method

The proposed rule of choice has three branches. Where the pads and access lines are much shorter than the guided wavelength at the highest frequency, and the device impedance is not extreme, open-short de-embedding is adequate and its simplicity is a virtue. Where the lines are longer, or the wafer area for dummies is limited, a through based distributed method is preferred. Above roughly 110 GHz, or wherever the highest accuracy is needed, on-wafer multilayer calibration is recommended, followed if necessary by a small lumped correction for the remaining length of line ([Williams et al., 2013b](#)). The frequency boundary is indicative only: what governs is the electrical length of the fixture, not the frequency as such.

3.4. Step 4: Perform and check the first tier

Where a probe tip calibration is used, its quality is checked before any device is measured. A standard that took no part in the calibration, such as a long line or an offset open on the impedance substrate, is measured and compared with its expected response. The probes are then lifted and landed again on the same standard to show contact repeatability, which in millimetre wave work is often the largest contribution to uncertainty. The substrate carrying the standards differs from the wafer in permittivity and thickness, so the fields at the probe tip differ too, and that discrepancy is carried into the second tier.

It is one argument for on-wafer calibration at the highest frequencies ([Rumiantsev and Ridler, 2008](#)).

Table 1: Candidate de-embedding methods, the structures each needs and the conditions under which the workflow recommends it			
Method	Structures needed	Key assumption	Recommended when
Open only	Open	Series parasitics negligible	Low frequency, quick screening
Open-short Koolen et al., 1991	Open, short	Fixture lumped; shunt elements outside series ones	Fixture electrically short
Three or four step Kolding, 2000	Open, shorts, through	More detailed lumped fixture model	Silicon pads with notable contact effects
Through based Mangan et al., 2006	Two lines of different length	Uniform access line, symmetric pads	Longer lines, limited wafer area
On-wafer multiline Marks, 1991	Several lines, reflect	Single mode line, repeatable contact	Highest frequencies or accuracy

3.5. Step 5: Apply the correction

The arithmetic of each method is simple once the data are in the right representation: admittance parameters to subtract shunt elements, impedance parameters to subtract series ones, and transmission or chain parameters to remove cascaded sections ([Pozar, 2012](#)). The dummies should be measured in the same session as the device, with the same probe placement, and more than one copy of each should be measured where the wafer allows, so that variation between dummies can be seen. Averaging across copies is acceptable only after outliers caused by poor contact have been removed.

3.6. Step 6: Verify with independent structures

A de-embedding result cannot verify itself, because the dummies were used to produce it. The workflow therefore requires at least one passive structure of known behaviour that shares the fixture but not the correction: a transmission line of a length not used in the calibration, or a metal capacitor whose value is known from low frequency measurement. After correction the line should show the propagation constant found from the multiline analysis, and the capacitor a capacitance that is flat with frequency. For transistors, further signs of trouble are extracted capacitances that change sign or drift with frequency, and a unilateral gain that departs from a smooth slope without physical reason ([Yau et al., 2012](#)).

4. Fitting the Workflow to Practice

Wafer area is the usual constraint. A full multiline kit for every device geometry is rarely affordable, and a workable compromise is one multiline kit per metal stack, with open and short dummies for each device geometry to remove the last few micrometres. Laboratories using frequency extender heads in rectangular waveguide bands must repeat the calibration and its checks in every band, and should overlap the bands where possible so that discontinuities at the band edges reveal errors.

Reporting deserves the same care as measurement. A table of corrected parameters is of limited use unless accompanied by the reference plane, the method, the layout of the dummies and the verification result. Where an uncertainty is quoted it should follow the framework of the Guide to the Expression of Uncertainty in Measurement ([JCGM, 2008](#)) and include contact repeatability, not only instrument noise.

5. Limitations and What Remains to Be Shown

The workflow is a proposal and has not been tested on measured data in this article. Its rule of choice in Step 3 is stated qualitatively, and turning it into numerical thresholds would need a comparison of the methods on common devices across several technologies, with an independent reference such as electromagnetic simulation of the fixture. The verification structures of Step 6 detect many failures but not

all: an error that affects the device and the verification line equally will pass.

Some effects lie outside the scope of any de-embedding method. Coupling between the probe body and adjacent structures, excitation of substrate or parallel plate modes, and changes in the device caused by the removal of its neighbours in the dummy are properties of the measurement environment. They are reduced by layout and by absorbing material beneath the wafer, not by arithmetic. The workflow also assumes two port devices measured with a two port analyser, and does not address differential or multiport structures.

6. Conclusion

De-embedding at millimetre wave frequencies is less a matter of choosing a formula than of controlling assumptions. The lumped methods are reliable while the fixture is electrically short, the distributed methods and on-wafer calibration take over as it lengthens, and no method is trustworthy without verification on structures that did not contribute to the correction. The six steps proposed here place those points in a working order. Their validation against measured data, across technologies and frequency bands, is the natural next task.

Conflict of interest

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