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An interlaboratory study of the reproducibility of on-wafer S-parameter measurements from 140 GHz to 220 GHz

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Abstract — The development, modelling and characterization of millimeter-wave semiconductor devices calls for accurate and reproducible on-wafer measurements. We report on an interlaboratory study involving on-wafer S-parameter measurements in the 140 GHz to 220 GHz band, conducted by three well-established measurement laboratories. The measurements can be used to form typical reproducibility limits for these measurements when conducted in different laboratories using different equipment and calibration methods.

Index Terms — On-wafer measurement, co-planar waveguide, measurement repeatability, measurement reproducibility, measurement uncertainty.

I. Introduction

The development cycle for millimeter-wave integrated circuits and semiconductor devices is strongly dependent on the availability of measured S-parameter data from which refined circuit models may be extracted. The extent to which measurement results are known to be reproducible by different laboratories is an important factor in determining the confidence which may be placed in a given set of measurement data. The provision of uncertainty estimates and traceability to SI base units also provides measurement assurance. For on-wafer measurements at millimeter-wave frequencies beyond 110 GHz there is currently no established traceability path. Thus, confidence in measurement data currently arises largely from demonstrating the equivalence of measurements between different methods and different laboratories [1].

There are a number of factors which may affect the measurement results. The choice of probes is significant, both in terms of the ground-signal-ground (GSG) pitch, and also the probe model/design which will contribute to the parasitic circuit elements produced with the probe-pad interface [2]. The measurements are also invasive due to the inevitable physical damage caused by probe contact with fragile contact pads, and subject to random effects which arise due to the need to physically position/re-position the probes on the calibration or device-under-test (DUT) wafer. The choice of calibration method (e.g., those described in [3], [4]) and the associated assumptions, will determine the nature and extent of residual systematic errors which are also influenced by whether, or not, the calibration standards are on the same wafer as the DUT (i.e., 'on-wafer' or 'off-wafer' calibration, respectively).

For on-wafer measurements to be meaningfully compared, the DUT environment must also be properly defined. A co-planar waveguide (CPW) structure may allow the propagation of unwanted modes, especially where the dielectric substrate is backed by a metallic boundary (e.g. the wafer-chuck [5]).

II. Interlaboratory Study

A. Participating Laboratories

The laboratories that participated in this interlaboratory study were asked to provide a single measurement of each DUT, measured at equally-spaced frequency points, using an IF bandwidth of 100 Hz. Calibration on the same substrate as the DUTs was permitted, although not a requirement; however, none of the DUTs were to be used as calibration standards. Three laboratories participated in the interlaboratory study:

- Fraunhofer-Gesellschaft (IAF), Germany
- Physikalisch-Technische Bundesanstalt (PTB), Germany
- National Physical Laboratory (NPL), United Kingdom

The participating laboratories used different equipment and different approaches to calibration, as would be expected of independent measurement facilities. For example, one participant performed an 'on-wafer' calibration (utilizing additional devices as calibration standards on each DUT wafer). The participants also used different probes and different calibration algorithms, as summarized in Table I (where we refer to the laboratories hereafter as 'Participant 1', etc.). Such differences are in keeping with a reproducibility study [6] designed to evaluate the impact on measurement precision due to known differences in the measurement methods.

After completion of the measurements by all participating laboratories, the first laboratory re-measured the DUTs to confirm that no significant deterioration had occurred during the experimental period.

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TABLE I
EQUIPMENT AND CALIBRATION METHODS USED IN THE STUDY

Laboratory	Measurement Platform	Calibration
Participant 1	VNA: Keysight PNA-X with VDI Extenders Probes: 75 µm GSG Cascade Microtech	TRL 'off-wafer'
Participant 2	VNA: Rohde & Schwarz ZVA24 with Rohde & Schwarz Z220 Extenders Probes: 75 µm GSG GGB Industries	Multiline TRL 'on-wafer'
Participant 3	VNA: Keysight PNA-X with VDI Extenders Probes: 75 µm GSG GGB Industries	SOLT 'on-wafer' using DUT Substrate 1

B. Test Devices

Two commercially available Impedance Standard Substrates (ISSs) were used to provide suitable devices for this reproducibility study. The selected ISSs were manufactured by GGB Industries (CS-15) and Cascade Microtech (138-356). The study measured several devices (flush/offset short-circuits and open-circuits, mismatched terminations and CPW lines). A representative selection of the DUTs is summarized in Table II. For all measurements made in this study, a Cascade Microtech absorber (PN 116-344) was used beneath each DUT to ensure consistency of the test environment.

TABLE II
SELECTED DEVICES FOR USE AS DUTS

DUT Substrate (ISS)	DUT
Substrate 1 (GGB)	Offset open-circuit
Substrate 1 (GGB)	100 Ω mismatched termination
Substrate 2 (Cascade)	Flush short-circuit
Substrate 2 (Cascade)	250 µm, 50 Ω CPW line

III. RESULTS AND OBSERVATIONS

A. Reflection and Transmission Measurements

Commercial ISSs usually include one-port devices in pairs, so that S_{11} and S_{22} can be measured together with opposing probes. Figs. 1 to 3 show the reflection coefficient results for pairs of one-port DUTs.

(a)

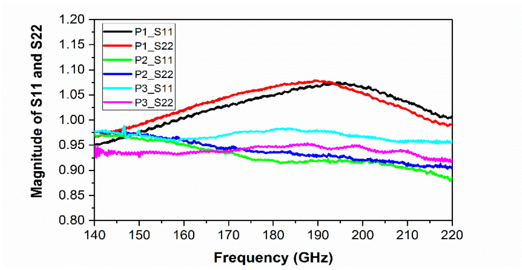


Fig. 1. (a) Linear reflection coefficient magnitude for 50 µm offset open-circuits.

(b)

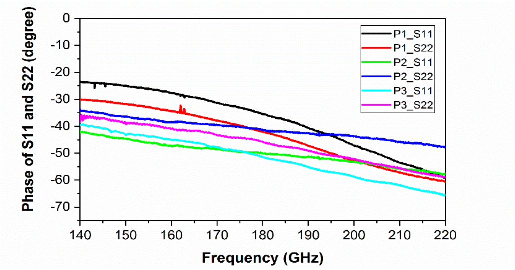


Fig. 1. (b) Reflection coefficient phase for 50 µm offset open-circuits.

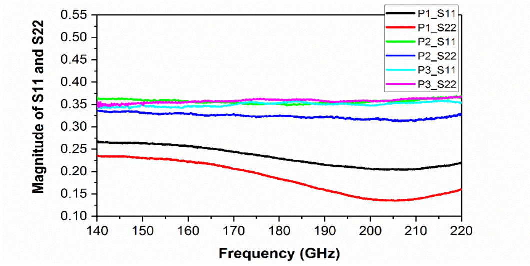


Fig. 2. Linear reflection coefficient magnitude for a 100 Ω mismatched terminations.

(a)

(b)

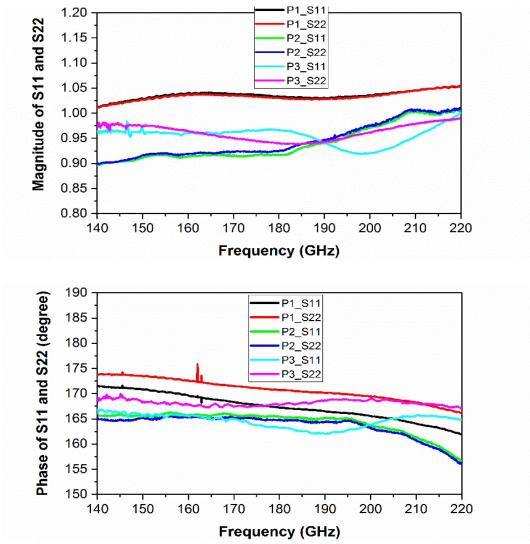


Fig. 3. (a) Linear reflection coefficient magnitude and (b) Reflection coefficient phase for flush short-circuits.

Fig. 4 shows the transmission coefficient results for the two-port DUT.

(a)

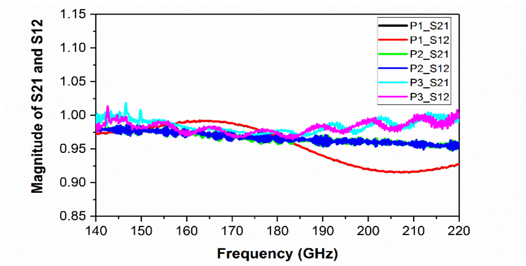


Fig. 4. (a) Linear transmission coefficient magnitude.

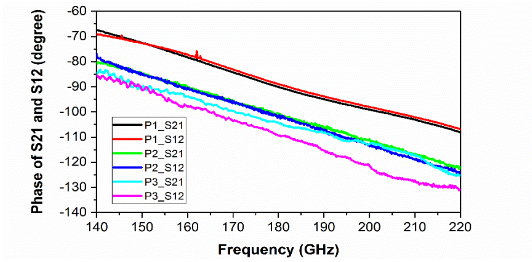
(b) 

Fig. 4. (b) Transmission coefficient phase for a 250 µm CPW line.

TABLE III
WORST-CASE STANDARD DEVIATIONS AND REPRODUCIBILITY LIMIT FOR HIGH REFLECTION AND TRANSMISSION COEFFICIENT MEASUREMENTS

Frequency (GHz)	Max SD, s (High Refl.)	R (High Refl.)	Max SD, s (High Trans.)	R (High Trans.)
140-160	0.083	0.233	0.033	0.093
160-180	0.079	0.221	0.024	0.067
180-200	0.082	0.229	0.058	0.163
200-220	0.077	0.215	0.076	0.210

B. Observations

Several results indicate the presence of residual systematic errors, notably when ‘non-physical’ behavior is seen (e.g., by reflection magnitude > 1 for passive terminations). The use of ‘off-wafer’ calibration by Participant 1 may explain some of these ‘non-physical’ results. The SOLT calibration used by Participant 3 shows characteristic ripple for transmission lines (Fig. 1 (a) and Fig. 4 (a)) due to test port mismatches that have not been fully corrected by this type of calibration.

For the 250 µm CPW line, the nominal phase can be determined from knowledge of the velocity factor (≈ 0.432) and the physical line length (which is ≈ 225 µm, assuming a reduced effective length due to probe over-travel). This implies a nominal transmission phase of approximately –113° at 180 GHz. The measured values obtained by the three laboratories are within a range of –89° and –109° at 180 GHz. These results indicate a larger dispersion for the measured transmission phase than might be expected. There is also a notable lack of reciprocity in some of the transmission coefficient results.

For the one-port DUTs, we have obtained comparative measurement data for devices with a relatively high reflection coefficient (≈ 1) including those in Fig. 1 and Fig. 3. Therefore, we can use this data to infer the likely reproducibility limit for measurements of high reflection coefficients, using the method defined in [6] where the reproducibility limit is expressed in terms of a confidence interval between two measurements,

$$R(S_{i,j}) = 1.96\,\sqrt{2} \times s(S_{i,j}). \qquad (1)$$

A similar process may be applied for two-port DUTs where we have comparative measurements for devices with a high transmission coefficient. Table III shows the worst-case from the sample standard deviations, s, and corresponding reproducibility limit, R, in four separate 20 GHz frequency ranges covered by the interlaboratory study.

It is interesting to compare these reproducibility limits with recent efforts to evaluate the uncertainty associated with on-wafer measurements. Fig. 5 shows preliminary uncertainty estimates for the multiline TRL-corrected measurements, based on the work reported in [7]. It is clear from Fig. 5 that, at any given frequency, the between-laboratory variation in results can be considerably larger than the uncertainty interval for a given laboratory. This indicates that there are significant systematic differences inherent in the approaches used by each of the laboratories. Finally, an earlier study [8] has assessed the likely dispersion in results that may be expected due to contact repeatability and found that these effects are typically small. For example, a maximum standard deviation of 0.018 for repeated reflection measurements, compared to the systematic errors we have observed for these types of measurements. We suggest that the reproducibility limits in Table III are unlikely to be affected significantly by the inclusion of repeatability information.

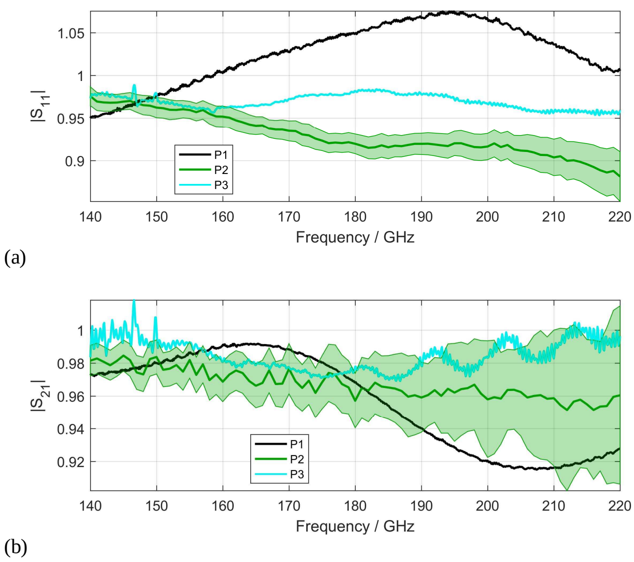


Fig. 5. Uncertainty estimates (shaded area) at 95% confidence level for (a) reflection coefficient magnitude (DUT 1) and (b) transmission coefficient magnitude (DUT 4).

IV. Conclusion

The measurement results from three well-established laboratories show reasonable agreement, although some notable differences are evident. The choice of probe, calibration method and whether an ‘on-wafer’ or ‘off-wafer’ calibration is utilized all have significant effects which contribute to the interlaboratory reproducibility for this type of measurement.

Acknowledgement

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