ON-WAFER MEASUREMENT OF MILLIMETRE-WAVE CIRCUITS AT THE NATIONAL PHYSICAL LABORATORY

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Abstract:

Reliable S-parameter measurements of on-wafer devices play an important role in the development of planar integrated circuits (ICs) for applications exploiting the millimetre-wave spectrum. However, at these high frequencies, additional complexities are introduced as compared with measurements at RF and microwave frequencies. Factors such as the choice of calibration method, electromagnetic boundary conditions, crosstalk between probes and the design of calibration standards, amongst others, all significantly affect measurement results at millimetre-wave frequencies and above. This paper aims to provide insight into the impact of these factors, giving case studies as evidence. Additionally, some 'good practice' for on-wafer measurement is provided, giving guidance on areas such as achieving good consistency in results between different operators, and how to ensure confidence in measurement results. The UK's National Physical Laboratory (NPL), based in Teddington, actively supports industry and academia through on-wafer S-parameter measurement, and provides test facilities and consultancy in support of a variety of applications. This paper will also briefly describe the current on-wafer measurement capability at NPL and the latest NPL research activities in this area.

1. Introduction

With the ongoing development of planar IC technology, we are seeing more and more advances in both established and emerging applications, such as wireless communications, satellites, security imaging, automotive radar sensors and radio astronomy. The wafer-level measurement domain involves the accurate measurement of such planar circuits, utilising probes to establish contact between the circuit and the measuring instrument. On-wafer measurements enable the characterisation and evaluation of ICs which can yield multiple benefits for both the manufacturer and the end-user. For the manufacturer, these measurements provide essential performance parameters of these circuits which can inform the optimisation of their design or build a specification of performance. This can result in benefits for the end-user such as faster and more powerful consumer electronics for everyday uses and applications.

Scattering parameters, or S-parameters, are used to describe electrical networks and devices operating at RF, microwave, millimetre wave and terahertz frequencies. S-parameters describe the electrical properties of a device in terms of the magnitude and phase of its reflection and transmission coefficients. For example, the magnitude of the transmission coefficient of a device specifies it loss or gain and the phase of the transmission coefficient specifies the phase change experienced by a signal being transmitted through the device. Assessment of these properties is fundamental for the accurate evaluation of the performance of a device. On-wafer S-parameter measurements are particularly challenging at millimetre-wave frequencies and beyond [1], despite the fact that probes suitable for measurement at frequencies up to 1.1 THz are commercially available.

In order to meet the measurement challenges presented by the continual advancements in this area, NPL has established a state-of-the-art Terahertz on-wafer measurement facility [2] and has developed measurement procedures which incorporate the best metrological practices based on decades of experience in the field of electromagnetic measurement.

In Section 2 of this paper, we briefly describe the on-wafer measurement capability at NPL. In section 3, we give an overview of the sources of error affecting on-wafer measurements at millimetre-wave and terahertz frequencies. Two of these sources of error are then discussed in more detail, with experimental evidence: the effect of electromagnetic boundary conditions in Section 4 and the effect of crosstalk in Section 5. Finally in Section 6 we provide some good practice guidance for millimetre-wave on-wafer measurements.

2. Overview of the on-wafer measurement capability at the National Physical Laboratory

The core of NPL's capability lies in the combination of a vector network analyser (VNA) and a probe station. The MPI TS-150 THz probe station is a state-of-the-art system that enables accurate on-wafer measurement up to terahertz frequencies. The station incorporates both ceramic and metallic chucks allowing different electromagnetic boundary conditions to be imposed on the wafer under test as well as a thermal chuck to enable measurement at temperatures up to 150 °C. The micrometer-controlled probe positioning system allows for precision probe landings and high connection repeatability.

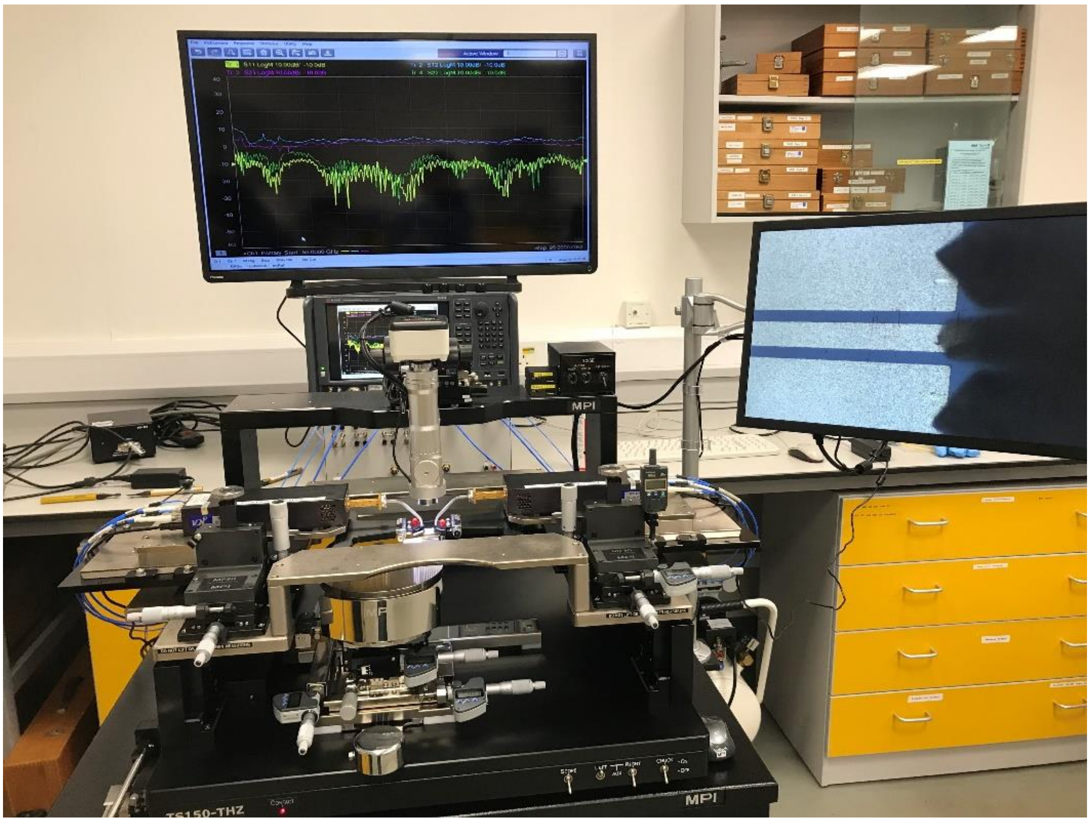

Figure 1 - Probe station setup for on-wafer measurements in the NPL High Frequency Network Analysis Laboratory

The Keysight PNA-X N5247B Vector Network Analyser enables four-port coaxial measurements between 10 MHz and 67 GHz via 1.85 mm coaxial test ports, and combination with a range of VDI waveguide frequency extension modules enables the frequency range for two-port S-parameter measurements to be extended up to THz frequencies. Table 1 provides a summary of the frequency coverage of NPL's millimetre-wave S-parameter measurement capability.

Table 1 – NPL millimetre-wave S-parameter measurement capability by waveguide band

Waveguide Band	Frequency Range
WR-15 / V-Band	50 to 75 GHz
WR-12 / E-Band	60 to 90 GHz
WR-10 / W-Band	75 to 110 GHz
WR-6.5 / D-Band	110 to 170 GHz
WR-5 / G-Band	140 to 220 GHz
WR-1.5 / WM-380	500 to 750 GHz

NPL maintains a range of probes (with integrated bias-tees) and calibration substrates for each of these waveguide bands, as well as for each of the popular coaxial line sizes.

To achieve improved connection quality and better maintain the condition of our probes, NPL has recently installed a side-view camera in the probe station to provide live, magnified monitoring of the probe landings.

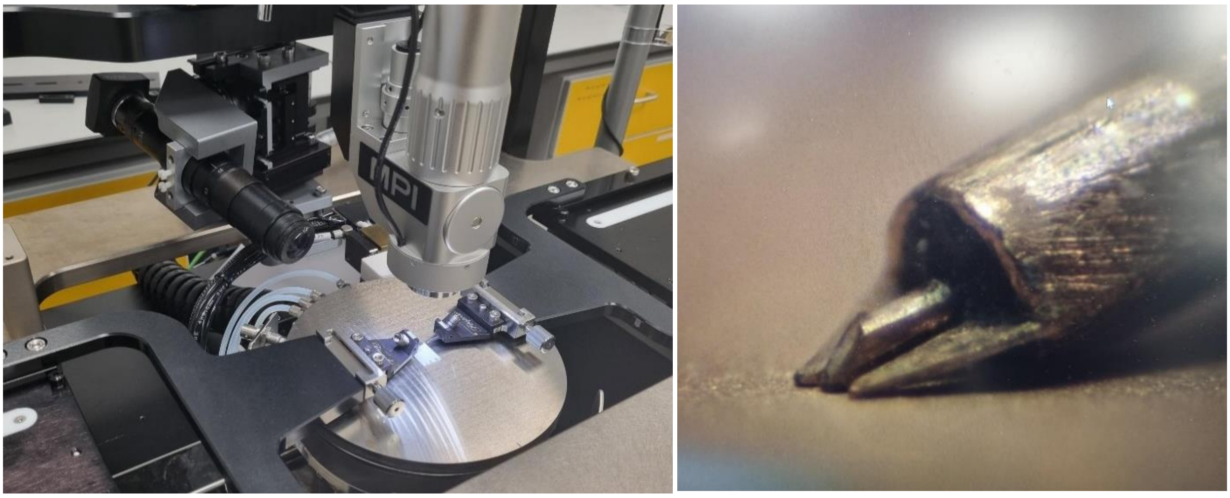

Figure 2 a) Side-view camera installation on the NPL probe station b) magnified image of probe tip landed on gold substrate captured by side-view camera

NPL also has extensive power measurement capability including a VDI Erickson PM5 power sensor, capable of power measurement from 75 GHz to up to 3 THz. This facilitates the measurement of active devices such as amplifiers and transistors up to THz frequencies. In these high frequency waveguide bands, power calibration of the measurement setup ensures that the power output from the frequency extender heads can be accurately controlled and is kept within acceptable limits to avoid damage to any connected equipment or devices under test (DUTs).

With these capabilities, NPL is able to offer high-accuracy on-wafer measurements for the benefit of the RF & Microwave industry and is also able to engage in collaborative development work to further metrological understanding in this domain.

3. Overview of error sources affecting on-wafer measurement accuracy

On-wafer measurements can be susceptible to errors from a wide variety of sources. If these errors are left unaddressed, measurements will not accurately represent the true performance of the DUT. In our work at NPL we have studied these error contributions in detail to identify the cause of each source of error and the physical phenomenon behind them. Some of the main error sources are detailed below.

- **Choice of calibration method** – depending on the method of calibration, different degrees of prior knowledge of the calibration standards are required in order to give accurate measurements. TRL (through-reflect-line) requires relatively little knowledge of the characteristics of the standards whereas SOLT (short-open-load-through) requires accurate knowledge of all of the standards. LRM (line-reflect-match) uses the same standards as SOLT but requires less information about them. This aspect has been covered by previous work [3].
- **Position of reference plane** – this is a very important consideration in the design of the calibration standards. It is essential to ensure the reference planes are positioned correctly with respect to the device under test to ensure results do not contain effects of structures not relevant to the desired measurement. Additionally, the electrical mode requires sufficient length between the probe pads and the reference plane for effective propagation [4].
- **Connection repeatability –** this incorporates probing repeatability, probe repositioning and probe alignment. Each of these factors will bring about differing physical signal paths, and different electrical responses in consequence.
- **Condition of probes & calibration standards** – In the on-wafer domain, the probe and contact pad pair is equivalent to the connector pair in the coaxial domain, or the flange-flange connection in the waveguide domain. As such, the same connection considerations apply. Worn or damaged probes and over-used calibration standards will lead to poor quality connections and errors in the measurements.
- **The test environment/boundary condition** – this mainly refers to the conditions underneath the DUT such as either a metallic or ceramic chuck or the use of absorbing material under the DUT. Different boundary conditions result in different measured S-parameters.
- **Coupling** – electromagnetic coupling occurs between adjacent neighbouring structures on the same wafer; standards are often close together due to space limitations on the substrate.
- **Crosstalk** - otherwise known as signal leakage, this is the name for direct transmission between the probes. This effect increases as the probes are brought closer together.
- **Propagation of unwanted modes** - this can occur, for example, with coplanar-waveguide (CPW) structures measured on a metal chuck where some of the signal can propagate as a microstrip mode with the metal chuck as ground plane.
- **Parasitic circuit elements** associated with the interconnection between the probe and contact pads of the calibration standard or DUT on the substrate.
- **Environmental conditions** – dust can have a significant impact on the quality of a measurement, affecting conductivity of the substrate and, if present in large enough quantities, can prevent the probes from making a planarized landing. Temperature and humidity affect conductivity adversely if outside of ideal laboratory conditions.

Effort to assess and control each of these error contributions is part of NPL's ongoing work as the UK's National Measurement Institute (NMI) in collaboration with partners including NMIs from other countries. A recent example of such collaboration is the joint research project TEMMT [5].

In sections 4 and 5, we go into more detail for two of these error contributions (boundary conditions and crosstalk) and the work we have done to assess their effect on measurement accuracy in E-Band (60 to 90 GHz).

4. Assessing the effect of boundary conditions

The boundary conditions involved in the on-wafer measurement scenario relate to the specific properties of the surface that the substrate is mounted on. Probe stations often provide chucks made of different materials such as metal or ceramic for mounting substrates. It is the properties of these materials which are of key interest when assessing the effect of boundary conditions, as each material will interact with the RF signals in different ways. Certain conditions can cause multimode propagation of the RF signals, which will have an impact on results and affect measurement accuracy.

4.1. Methodology

The effect of the electromagnetic boundary condition was assessed using three different chucks, ceramic, absorber and metallic, through the measurement of S-parameters for two structures on a CS5 calibration substrate [6]. This was used to give representative results applicable to the majority of on-wafer users. Two different calibration types were investigated, TRL and LRM, to determine which may be more susceptible to different boundary conditions. As for devices under test, a nominal 25 Ω load and a CPW transmission line were selected to provide a wide range of S-parameter responses for this investigation.

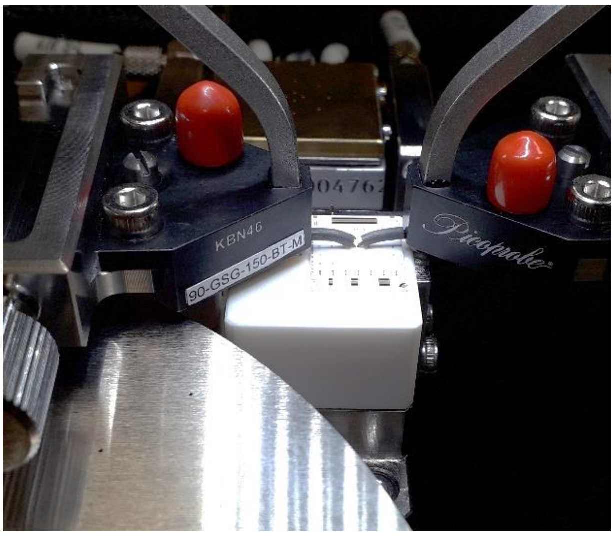

Figure 3 - CS5 substrate mounted on ceramic chuck

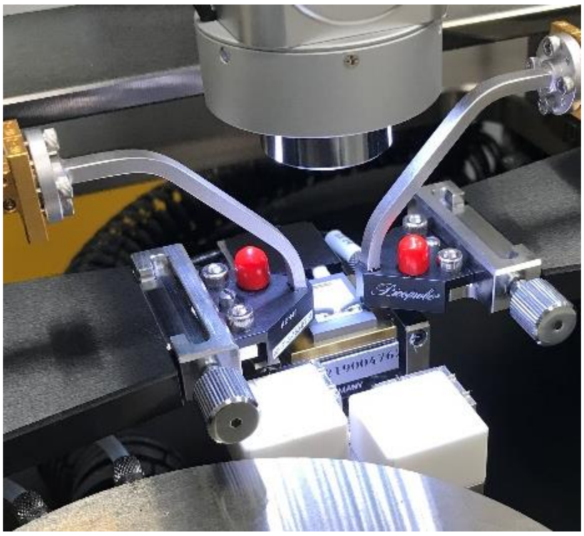

Figure 4 - CS5 substrate mounted on absorber

4.2. Results

The results are given in Figures 5 to 8 for the two calibration schemes with the three different boundary conditions for the S_{11} measurement of the 25 Ω load, and the S_{11} & S_{21} measurements of the CPW transmission line. It is important to note that with the TRL calibration scheme, the results are normalised to the characteristic impedance of the transmission line. Therefore, a direct comparison between the TRL and LRM schemes is not appropriate. However, these results will indicate which calibration scheme is affected more by the boundary condition with respect to the absorber result, which acts as a reference. The TRL results can be re-normalized to 50 Ω by following the approaches described in [7]-[8].

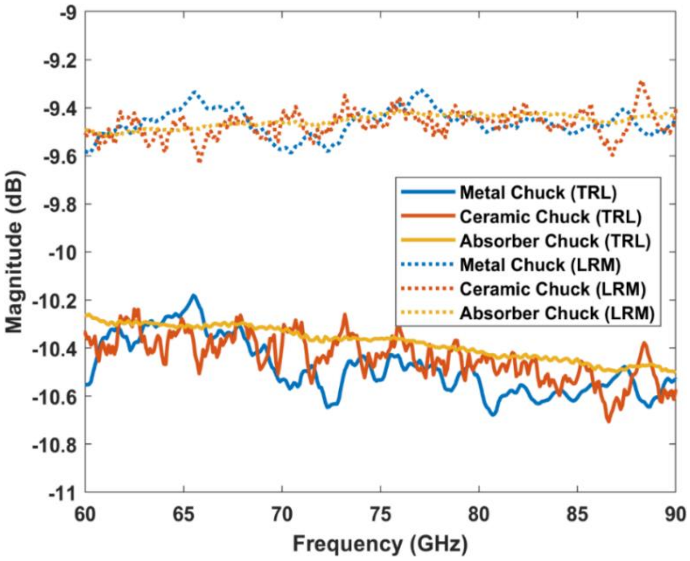

Figure 5 - S_{11} results for the 25 Ω Load

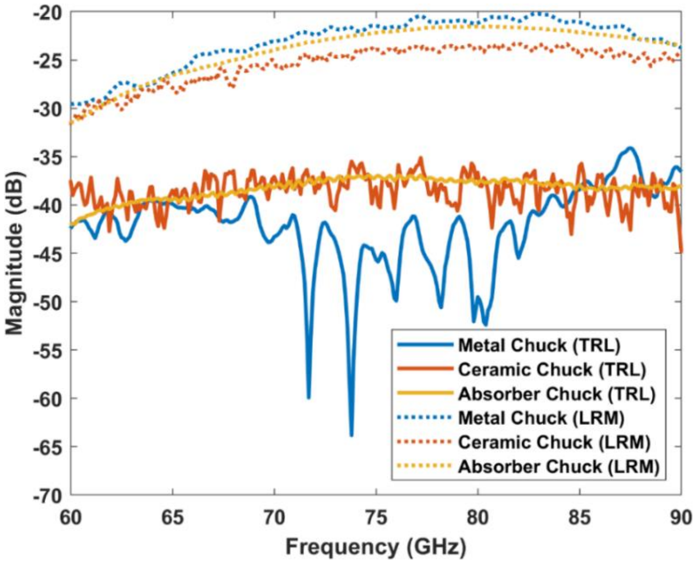

Figure 6 - S_{11} results for the CPW transmission line

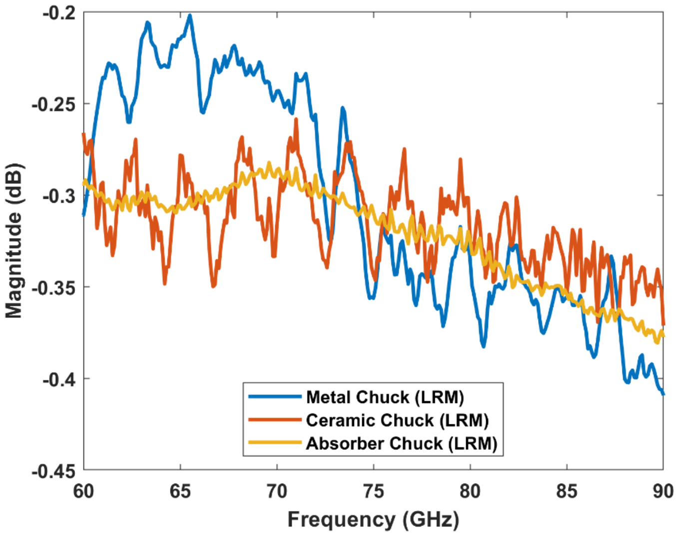

Figure 7 - S_{21} results for the CPW transmission line using the LRM calibration scheme

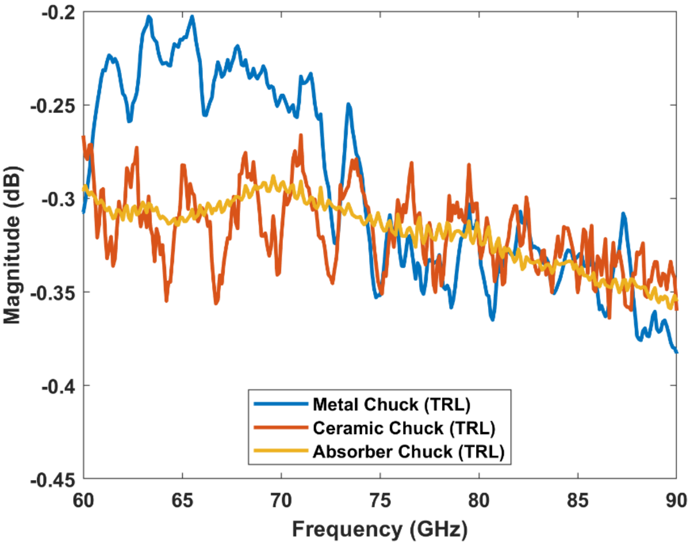

Figure 8 - S_{21} results for the CPW transmission line using the TRL calibration scheme

4.3. Observations & conclusions

- The choice of boundary condition has a noticeable effect on each S-parameter result. In all cases, the results for the measurements on the ceramic and metal chucks show more oscillations compared with the absorber traces.
- Figures 5 -8 clearly show that using an absorber chuck produces the least number of ripples in all the cases. This is expected as the absorber chuck can suppress adverse effects such as surface wave modes [9].
- It is worth noting that with LRM calibration applied for reflection responses, there is no noticeable advantage of using the ceramic chuck over the metallic chuck. However, with TRL

calibration applied, significant improvements were observed when the ceramic chuck was used.
- The results show that for good measurement practice, it is essential to recognise the effect of different boundary conditions. For example, when using non-conductor backed CPW devices a metallic chuck should be avoided.

5. Assessing the effect of crosstalk

Crosstalk is an interesting and elusive phenomenon that affects the accuracy of on-wafer measurements [10]. It is a term for signal leakage which indicates the presence of a leakage path from a source to a receiver in addition to the intended path. In the on-wafer domain, this effect has greater prominence due to the RF probes not having a wholly shielded structure. The effect of crosstalk is a function of distance between the probes, as the closer the two probes are in proximity, the greater is the magnitude of the crosstalk effect.

5.1. Methodology

For our study, the transmission response (S_{21}) between the two E-Band probes was measured in three different circumstances: in-air (known as an air open measurement), in air with an absorber positioned in-between the probes, and on-wafer with probes landed on short-circuit standards.

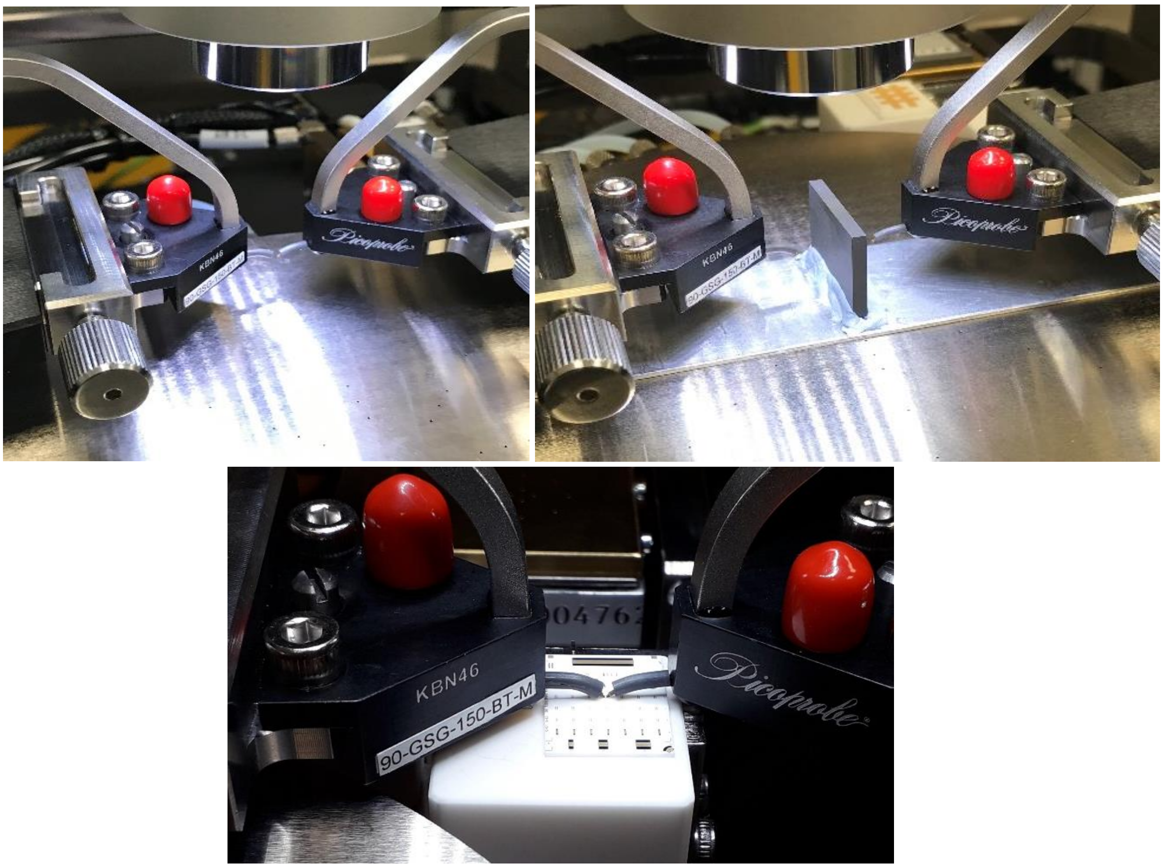

Figure 9 Probe arrangements for a) Air open measurement with probes in close proximity (top left); b) Air open measurement with significant separation between probes plus absorber placed in-between (top right); c) probes landed on short-circuit standards.

5.2. Results

Figure 10 displays the results for the S_{21} transmission measurement with the probes in-air, positioned close together (within 50 microns) compared to far apart (within 1 cm) with an absorber placed in-between. The absorber between two probes ensures that there is minimum free-space coupling between the probe tips. Figure 11 displays the results for the S_{21} transmission measurement with the probes landed on short-circuits positioned close together on the substrate compared with short-circuits at a significant distance apart on the substrate. Note that the results shown in Figures 10 and 11 are uncalibrated (raw data), therefore only qualitative observations can be made.

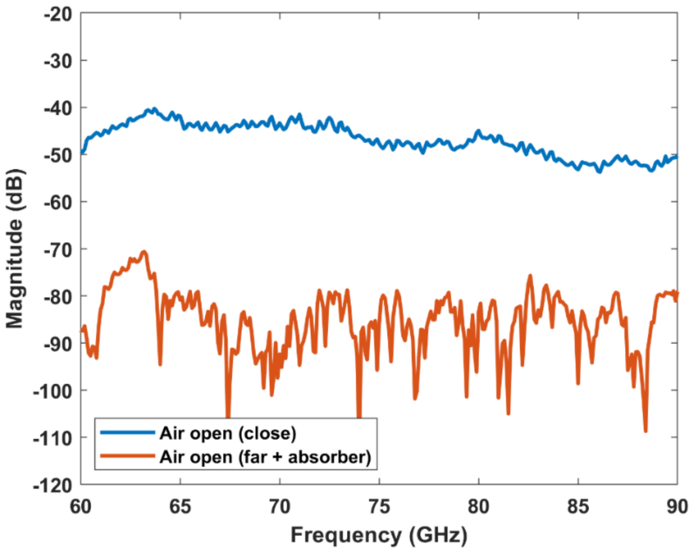

Figure 10 – Crosstalk results for the measurement of the probes in-air at two different distances

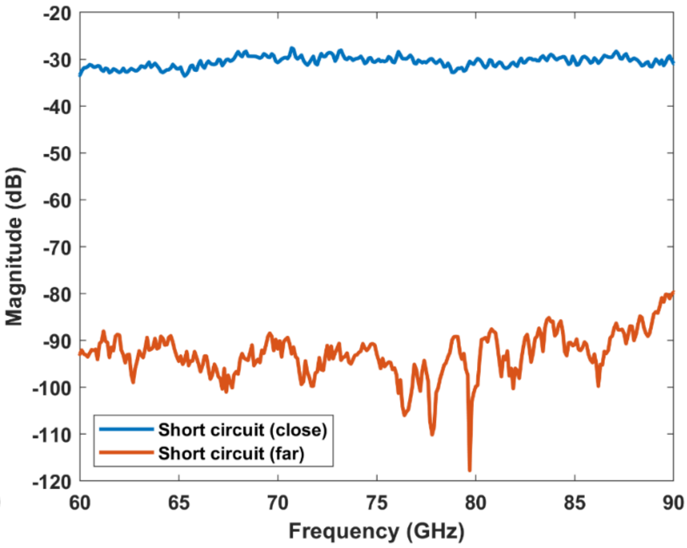

Figure 11 – Crosstalk results for the measurement of a pair of short-circuits at two different distances

5.3. Observations & conclusions

- For an ideal measurement of short or open-circuits, no transmission between port 1 and 2 should be observed. The results in Figures 10 and 11 show that for our measurements of both the open and short-circuits there is a non-zero transmission response. This indicates the presence of signal leakage, or crosstalk.
- This transmission between the probes increases significantly when the probe separation distances are reduced. The blue traces in Figures 10 and 11 indicate a significant amount of crosstalk between the probes when the separation distance is relatively small.
- Comparing the results from Figures 10 and 11 we can conclude that, with sufficient probe separation distance, the crosstalk effect can be suppressed.
- The transmission result with the absorber in place is representative of the isolation performance of the measurement setup; that is, how well the two probes are isolated from each other in terms of signal leakage. Any difference in transmission response between this trace and the trace for the probes positioned closely together is indicative of crosstalk error.
- Crosstalk is an active research topic and has been discussed in many papers (e.g. [10]-[12]). Due to the complicated nature of this problem, no straightforward approach requiring a small number of calibration standard measurements has yet been developed.

6. Good Practice Guidance

Based on the experience we have gained of conducting accurate on-wafer measurements with its many facets, we offer this good practice guidance for the benefit of other operators interested in achieving accurate on-wafer measurements.

- Ensure a dust-free environment – ideally, operate within a cleanroom.
- Limit access to and movement within the measurement environment to limit movement of dust, vibration, and disturbance to the probe station position.
- Consider VNA measurement parameters – averaging and IF bandwidth. The choice of these parameters is a trade-off between accuracy and sweep time.
- Prepare the chuck surface and the substrate. Clean with IPA and compressed air if needed to remove dust or other small debris.
- Assess and ensure good condition of the probe. Inspect under a microscope or strong lens. Look for probe tip damage, compare with a brand-new probe if necessary. Repair if any damage is observed. Replace if good contact is no longer possible.
- Re-planarize if changing to a different chuck/boundary condition. This is to account for the varying horizontal level of the different chucks.
- For manual probing, establish a rigorous practice regime between operators to reduce the impact of operator ability. This can be aided by a detailed measurement procedure.

More suggested good practices can be found in [13]-[14]. Generally, consistent results with good agreement between different operators can be achieved when following good practice guidance [15]-[16].

7. Conclusion

This article covers the on-wafer measurement capability at NPL and some of our recent research activities. The challenges associated with high-frequency on-wafer measurements have been discussed. Some good practice guidance has been provided, with the aim to help users in industry undertake measurements with more confidence. Much of the work presented here was undertaken in collaboration with the UK industry or European research institutes. We welcome such collaborations and are open to supporting further research and development work through on-wafer measurement.

8. Acknowledgements

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9. References

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