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Lens-Based Free-Space Characterization of High-Resistivity Silicon Wafers at Microwave Frequencies

Zhonghao Hu[1], Bevan Jones[1], Katja Parkinen[2], Anton Saressalo[2] and Iiro Lehto[2]
[1] Ascan Technologies Pty Ltd
[2] Okmetic Oy, P.O. Box 44, FI-01301 Vantaa, Finland

Introduction

5G and 6G RF front-end systems demand filters and passive components with low insertion loss, high linearity, and strong isolation to support increasingly complex wireless networks. High-resistivity silicon is widely used as a substrate material because it suppresses RF coupling and substrate losses, helping maintain effective resistivity, high Q factor, and improved harmonic/intermodulation distortion (IMD) performance.

Accurate characterization of wafer resistivity at RF frequencies is therefore essential for both device design and manufacturing qualification. Reliable RF resistivity measurement enables better prediction of component performance, tighter process control, and improved consistency for next-generation high-frequency applications.

Test Method Gap

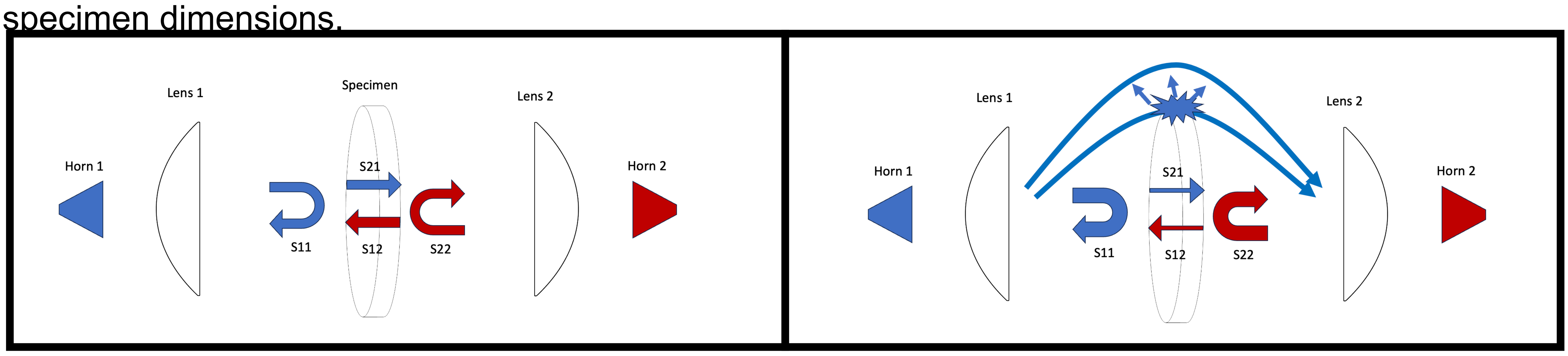
- Four-point probe DC testing measures bulk resistivity, but it is limited to sample-based analysis because it requires destructive contact. Additionally, it does not capture the effective resistivity at RF frequencies or account for dielectric losses under microwave excitation.
- Conventional non-contact techniques based on eddy-current lack sensitivity for high-resistivity silicon wafers because the induced and detected currents are too small for accurate measurement.
- Coplanar Waveguide (CPW) or transmission-line methods require fabricated test structures, increasing processing time, cost, and dependence on fabrication quality.
- Cavity resonance methods offer high accuracy, but typically require fixture-specific sample preparation and are less suitable for rapid wafer-level screening.
- A Free-space measurement lens-based free-space technique enables direct, non-contact broadband extraction of dielectric constant (DK), loss tangent, and effective resistivity. However, achieving high accuracy can be challenging due to strong reflections from thin wafers.

Theory and Challenges

A High-resistivity silicon wafer is characterized in a focused free-space quasi-Plane wave system using horn-and-lens assemblies positioned on both sides of the specimen. The wafer is placed between two mirrored lens structures.

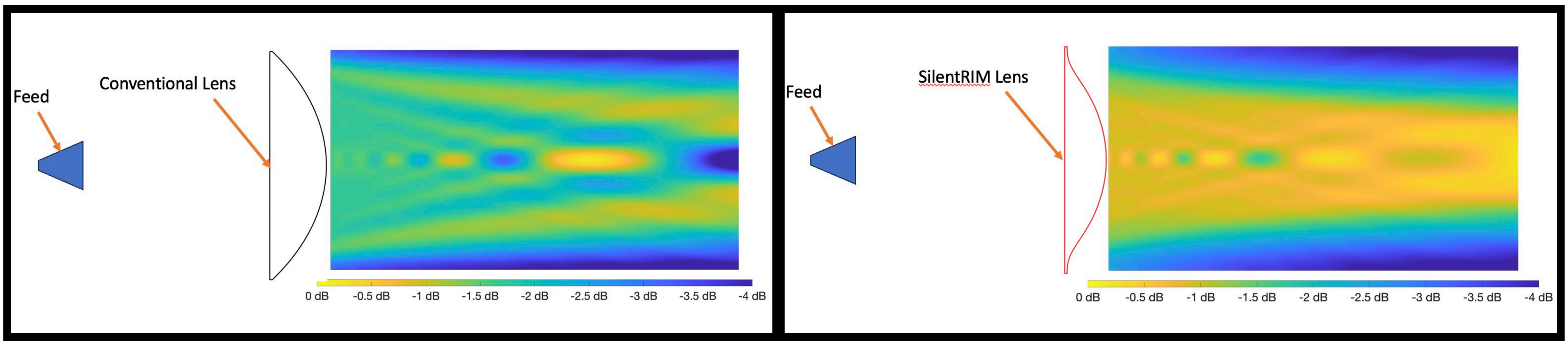
Measured Scattering parameters S21/S12 from a Vector Network Analyzer are fitted to a plane-wave transmission model [3] of a flat dielectric slab. An automated algorithm is then used to extract dielectric constant (DK), loss tangent, and effective resistivity.

For High-resistivity (>1000 Ω·cm) silicon wafer (DK ≈ 11.6 and loss tangent typically < 0.01), strong interface reflections contain a large portion of the incident energy, while the transmitted signals, which carry the material-loss information, are relatively weak. Accurate characterization therefore requires precise calibration, high-quality plane-wave formation, and careful lens-beam design matched to the specimen dimensions.

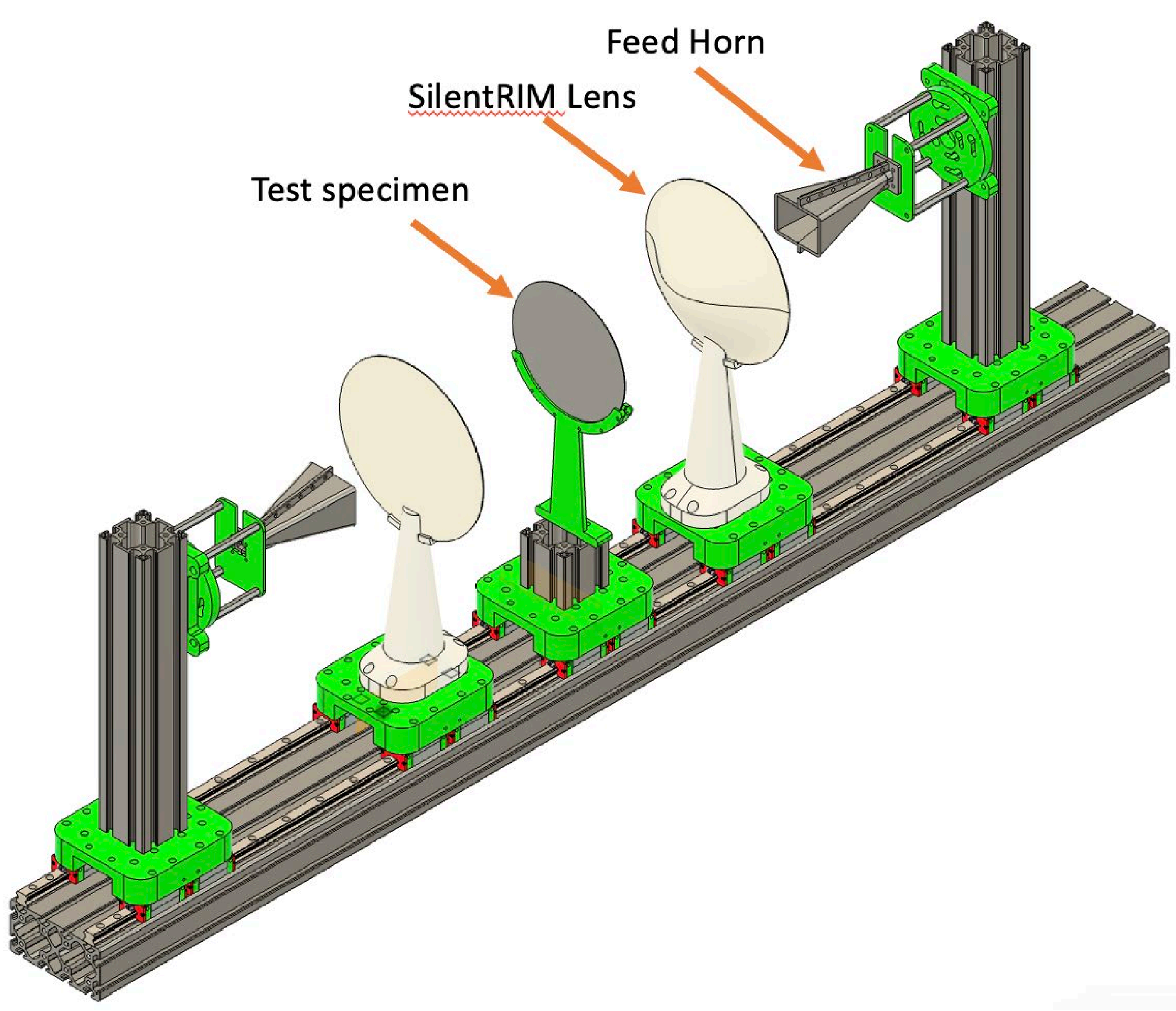


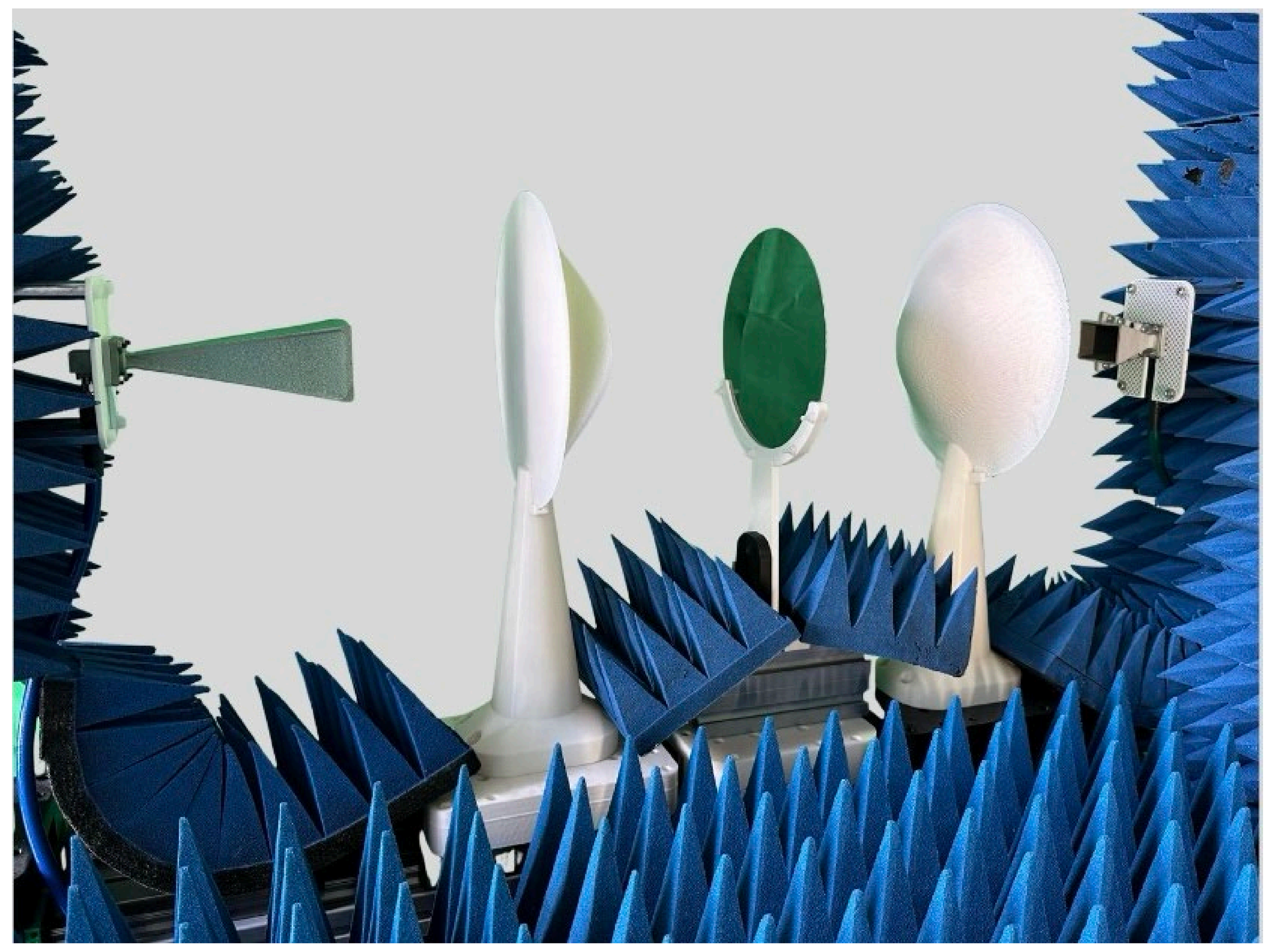
Theoretical model VS Practice model

Solution-Ascan SilentRIM Lens and Test Setup



Planewave generated by conventional plano convex lens and SilentRIM Lens





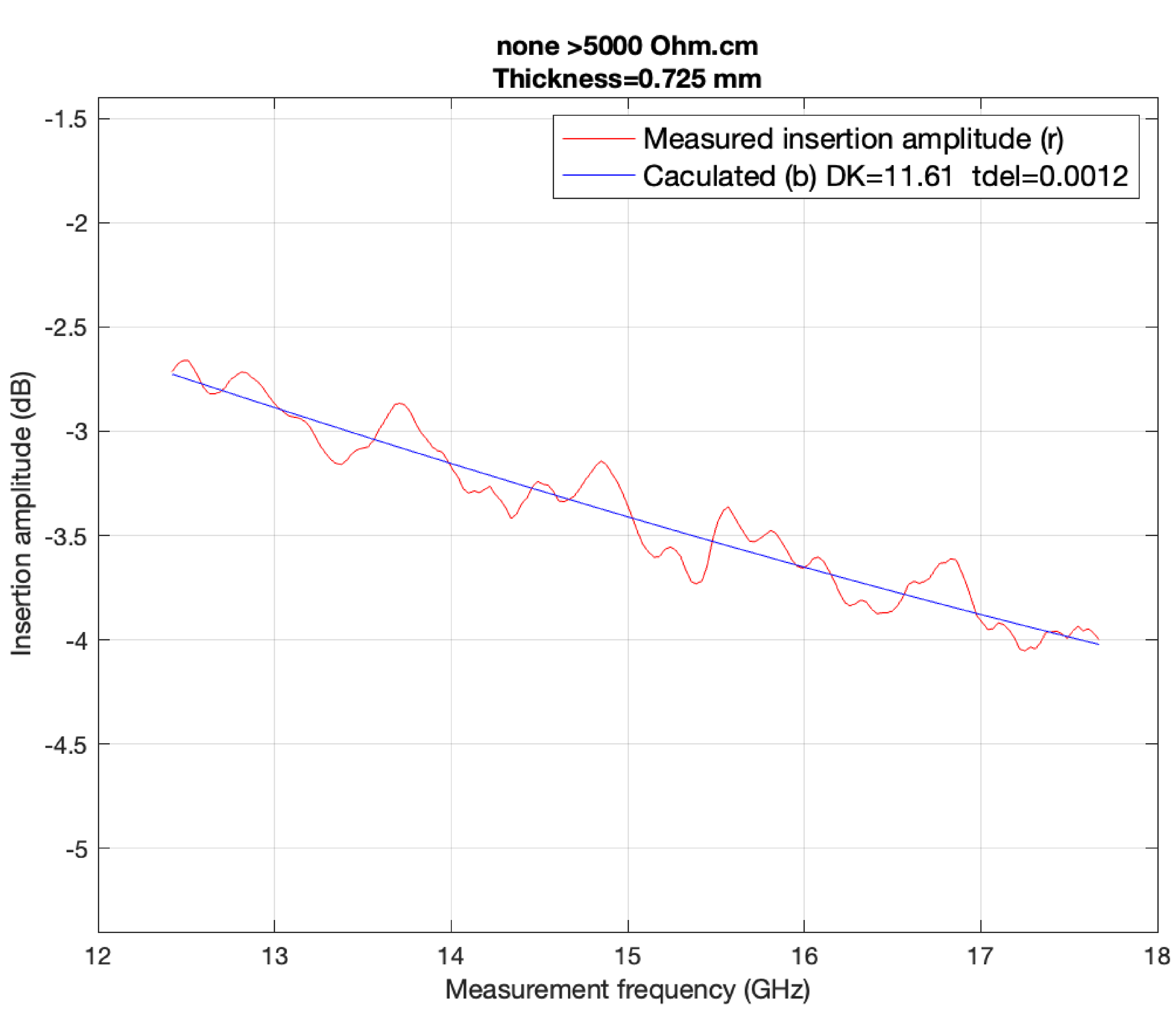
Test Setup: 3D model and physical prototype

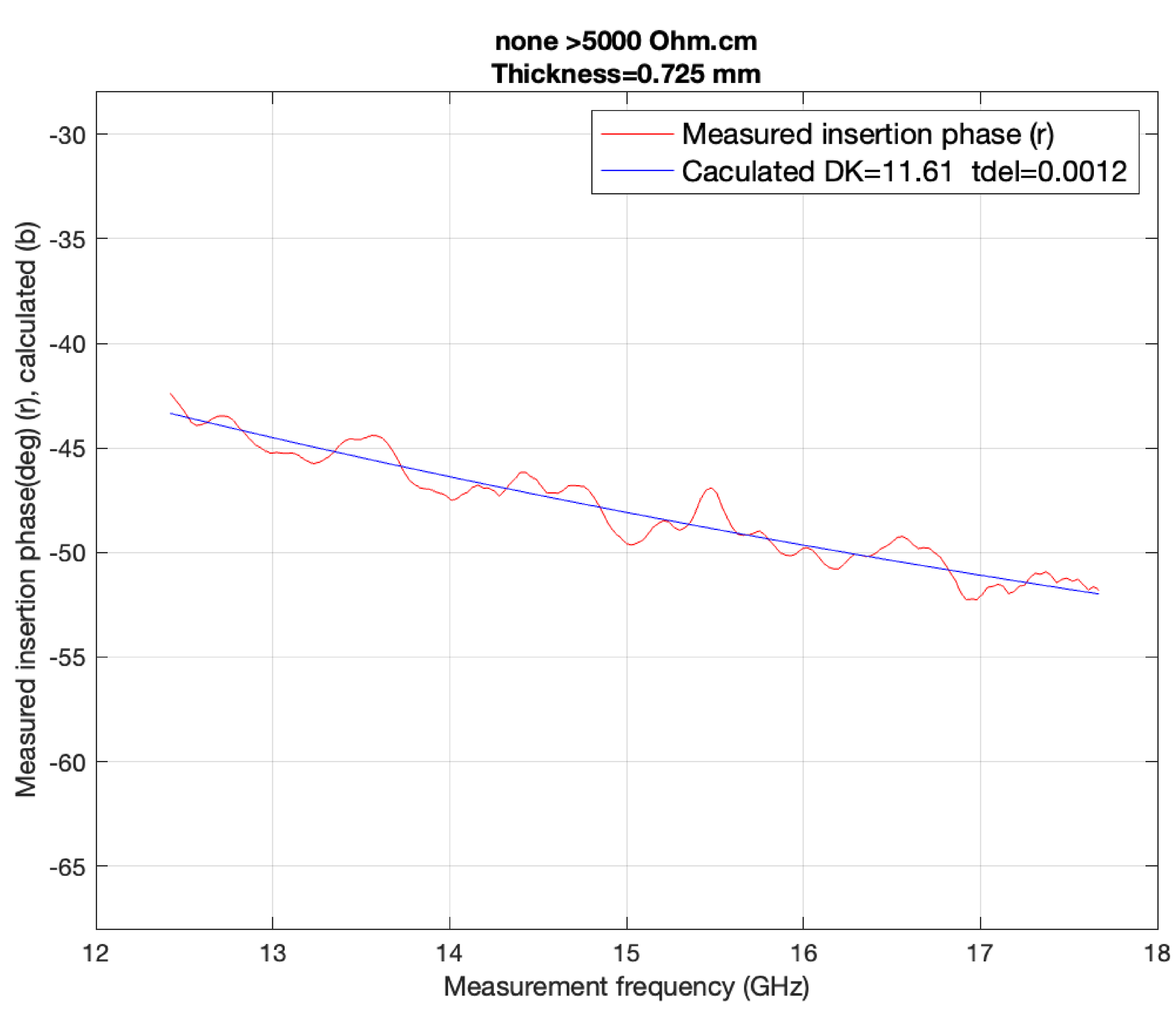
Reference Results

According to reference [2], one high-resistivity (5000 Ω·cm) silicon wafer measured by National Institute of Standards and Technology (NIST) with cavity resonance method, as shown below

$$\varepsilon_r = 11.6, tan\delta = 0.0041\ at\ 9.5GHz$$
$$\varepsilon_r = 11.62, tan\delta = 0.0015\ at\ 22.6GHz$$

Test Results





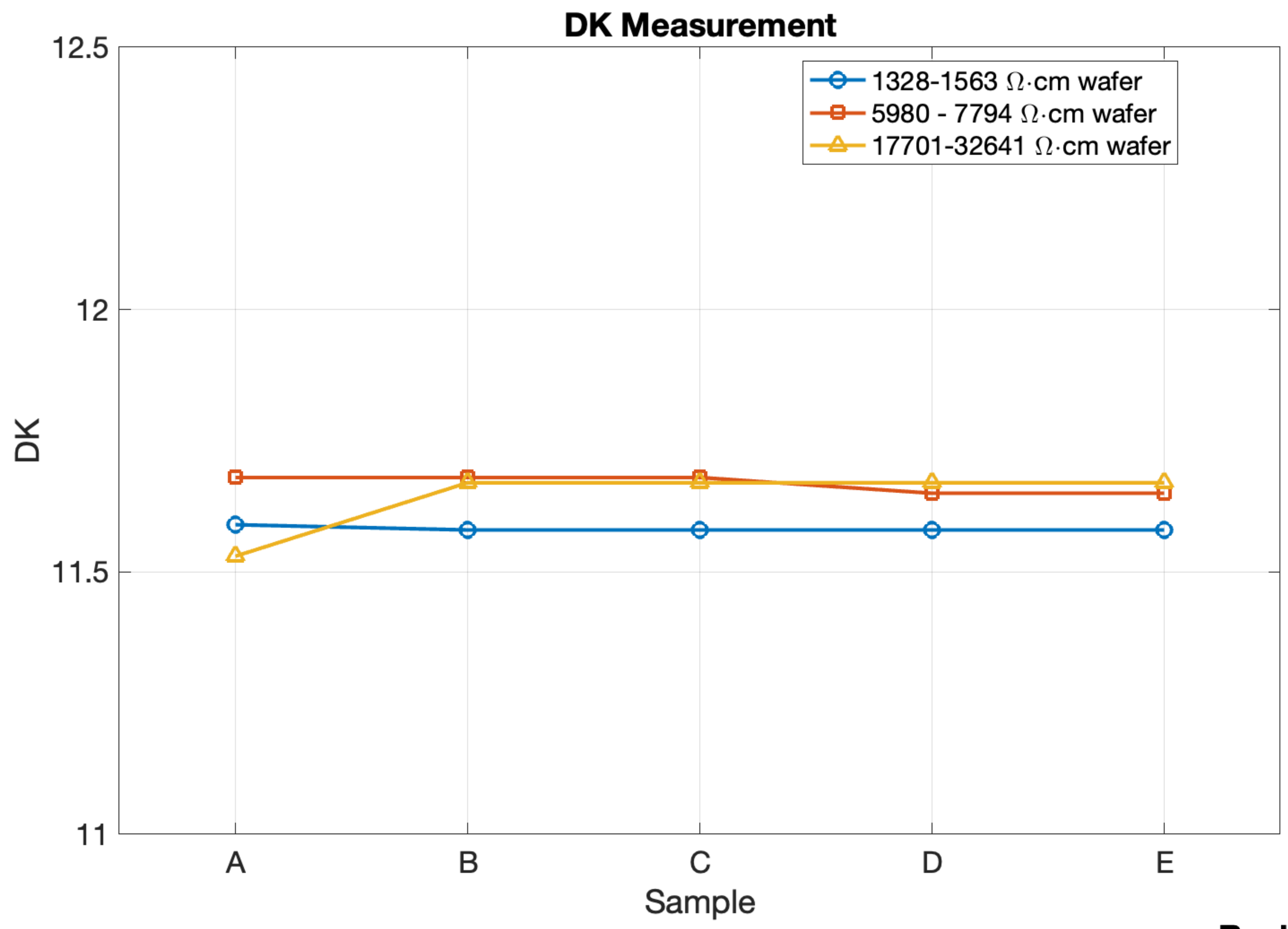
Example test results of silicon wafer larger than 5000**Ω·cm** fitting with calculated sample

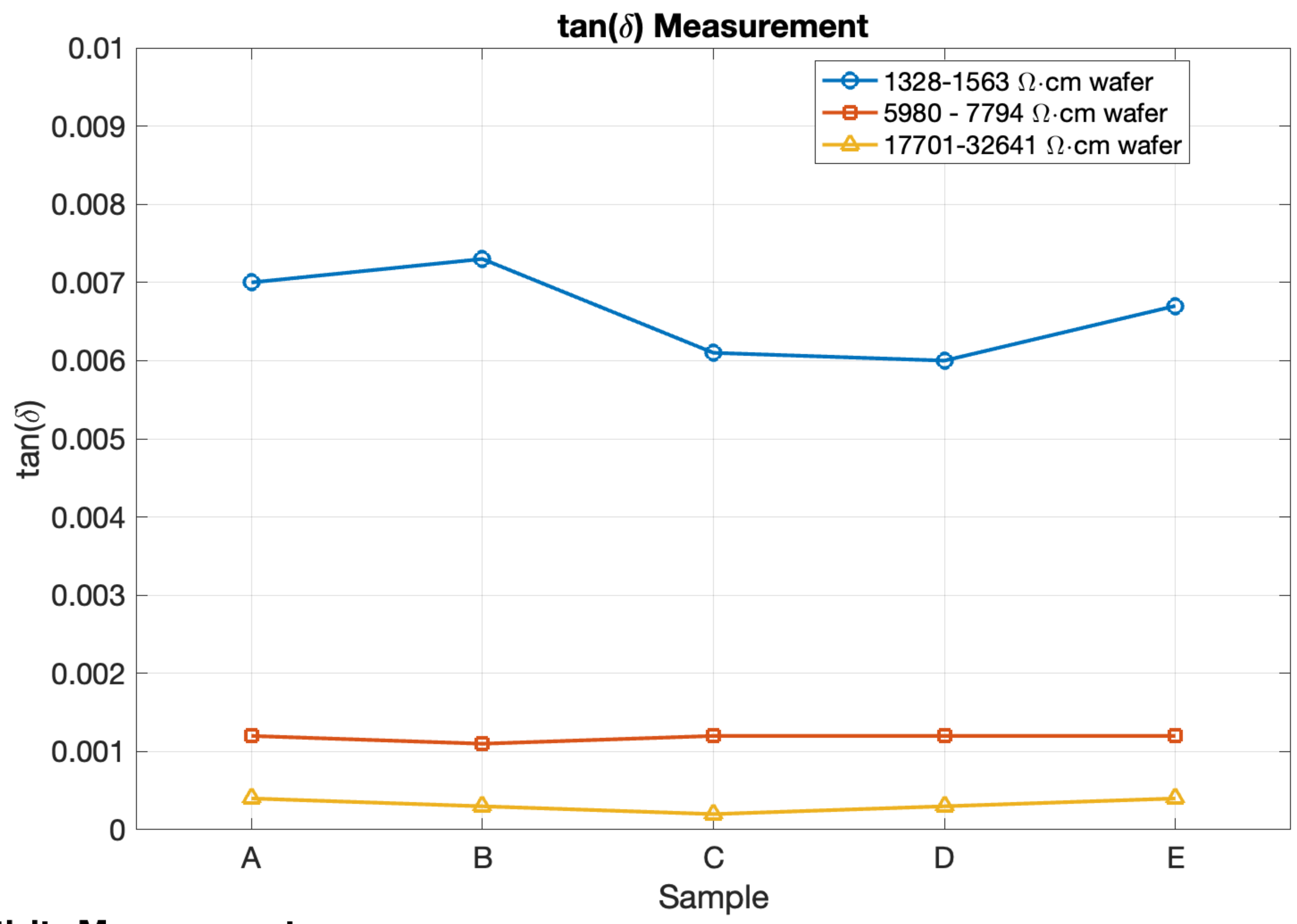
$$\varepsilon_r = 11.61, tan\delta = 0.0012\ 12GHz - 18GHz$$

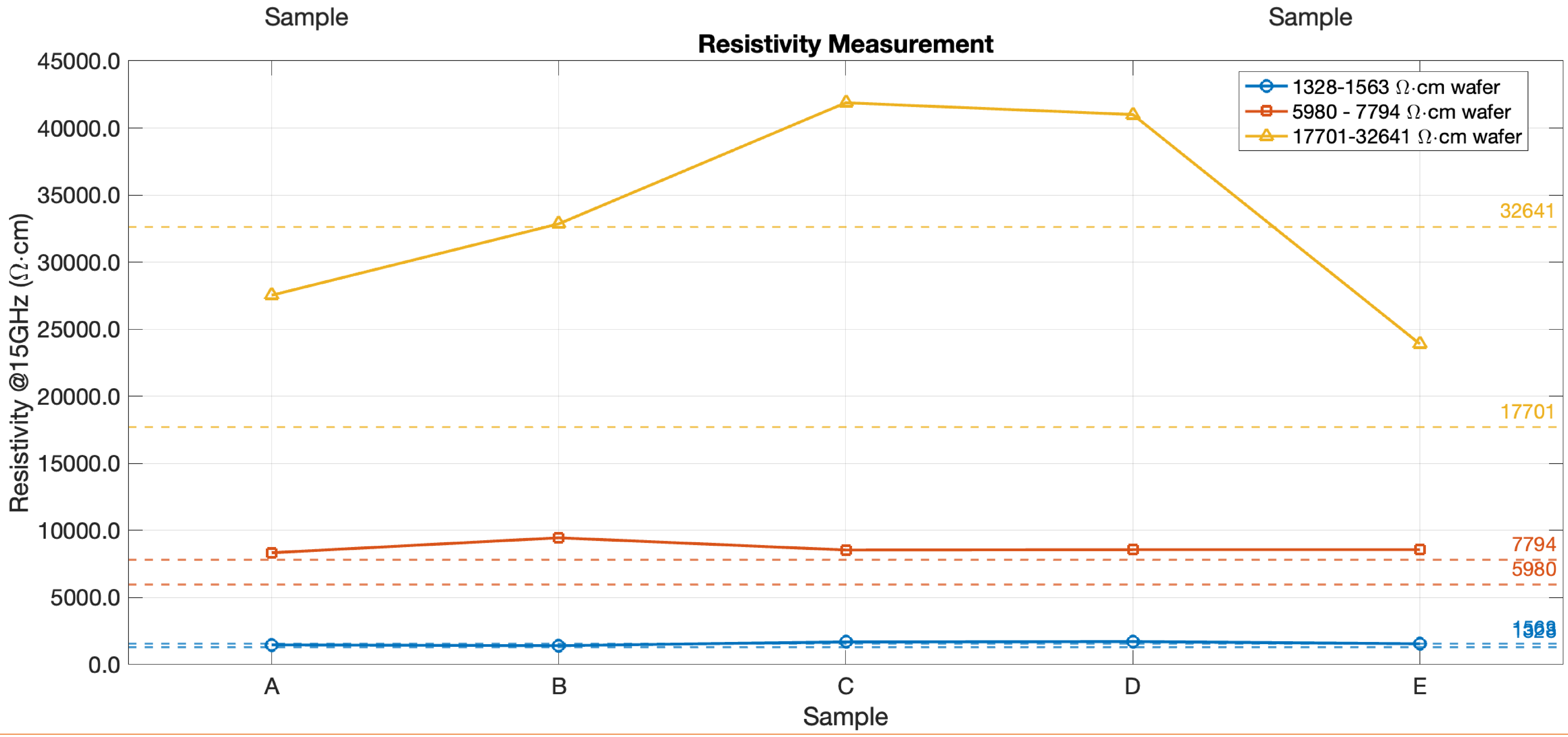
Repeatability and Resistivity Study

Fifteen Okmetic wafers from three groups were measured using the lens-based setup. The groups were defined by DC resistivity measured with the four-probe method which is a range to represent the same batch of the samples. RF resistivity was calculated at middle frequency the measured band (15 GHz) from the measured DK and tan(δ): $\rho = 1/2f.\varepsilon.\tan\delta$.

As shown below, DK remained stable across all samples, while tan(δ) decreased with increasing resistivity. This repeatable trend supports the reliability of the lens-based measurement system and indicates good wafer consistency. The calculated RF resistivity also followed the DC resistivity grouping, showing a clear correlation between higher resistivity and lower dielectric loss.







Conclusions

This study demonstrates a lens-based Free-space measurement method for characterizing High-resistivity silicon wafers. The technique successfully measures dielectric constant and very low loss tangent values (<0.001) or equivalently wafer resistivity close to or larger than 10000ohm.cm, with validation against reference materials and NIST data. Measured loss tangent also shows clear correlation with the manufacturer-specified resistivity, where higher resistivity corresponds to lower loss. In addition, the samples exhibited excellent measurement repeatability.

This method provides a RF broadband, non-destructive alternative to four-point probe DC techniques for wafer characterization, with strong potential for high-throughput production quality control and supplier wafer acceptance testing.

References

[1] N. Binti Md Kamal, “Measurement of dielectric constant of silicon wafer using microwave non-destructive testing and direct current technique,” B. Eng. (Hons.) thesis, Faculty of Electrical Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia, 2023. Available: Ir. UiTM eRepository.

[2] N. Gagnon, “Design and study of a free-space quasi-optical measurement system,” M.Sc. thesis, School of Information Technology and Engineering, University of Ottawa, Ottawa, Canada, May 2002. CRC Rep. No. CRC-RP-2002-002.

[3]C. A. Balanis, Advanced Engineering Electromagnetics, 2nd ed. Hoboken, NJ: John Wiley & Sons, 2012.