Advanced Characterization of Copper Foils for High-Frequency Applications Using Ruby Dielectric Resonator Technique

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Outline

1. Motivation
2. Measurements
3. Results
4. Conclusions

Motivation

Why Ultra-Low-Loss Materials Matter

- Need for ultra-low-loss materials in high frequency electromagnetic design and techniques allowing precise determination of such materials.

Beyond PCB Test Circuits: Foil Metrology

- Developing microwave and millimetre-wave resonators for stand-alone coper foils samples measurements as an alternative for time-consuming and cumbersome tests circuit manufactured on a PCB.

Process Impact on Copper Foil Performance

- Better understanding of the impact of individual processes in the production of copper foils.

Measurements

Samples

- We were provided with **24 samples** of copper foils by Circuit Foils Luxembourg sarl.
- Each sample is different combination of base foil and treatment and also delivered in two thickness **35** μm and **75** μm.
- Each sample has measured roughness parameters that will be described later.

Example of two sides of the same sample

Measurements

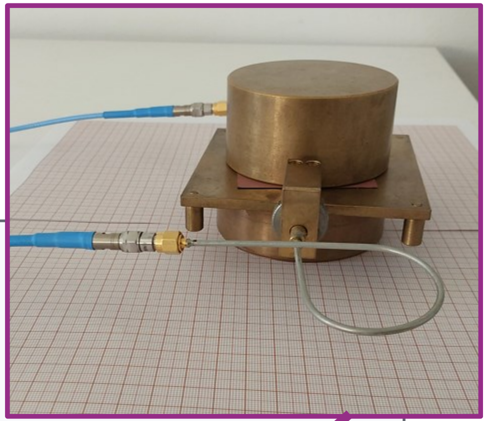
Ruby Dielectric Resonator for Conductors

Key Specifications

- Resonant modes & frequencies: **14 & 20 GHz or 28 & 44 GHz**
- Conductivity range: **$\sigma = 10^5 – 6 \times 10^7$ S/m**
- Sample size: **23 × 23 mm – 60 × 60 mm**
- Sample thickness: **≥ 3 skin depths** (e.g., a few μm for Cu)
- Software-controlled measurement

Measurement parameters

- Foil loss is measured with RuDR operating at 13 GHz & 21 GHz .
- RuDR is connected to VNA (Keysight Streamline P5008B), which extract the 3dB.
- Either the VNA firmware or dedicated application convert this to the Q-factor and then calculates the effective conductivity



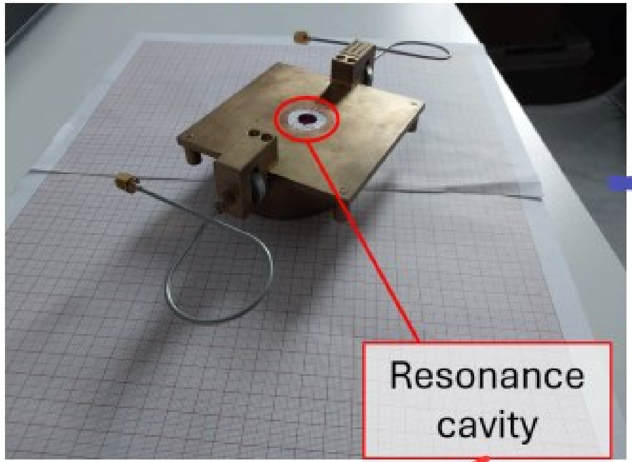
Now new design and approach for measuring conductors

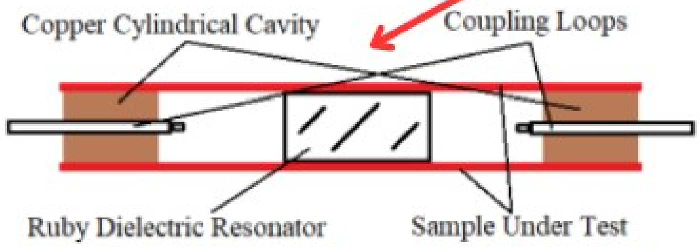
Measurements

Dual mode Ruby Dielectric Resonator measurement setup which also includes VNA and laptop with dedicated software.

Measurements

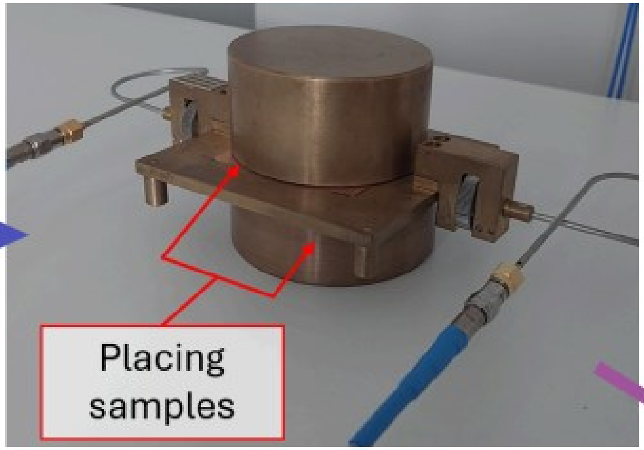
Ruby Dielectric Resonator RuDR

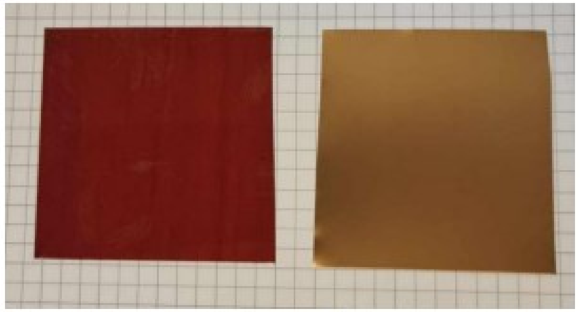




Cross-section of the resonance cavity

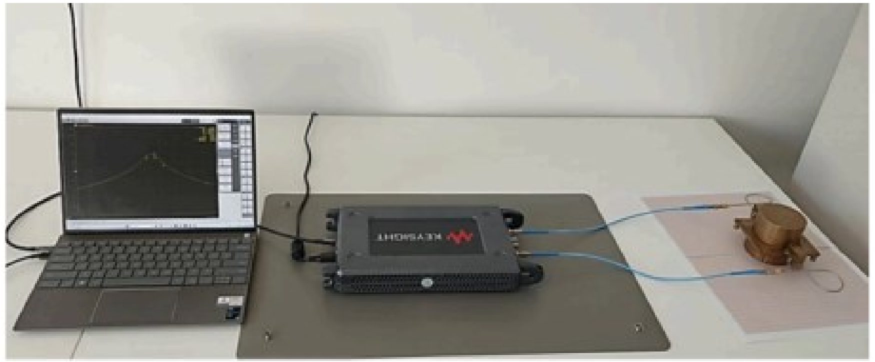
Placement of samples

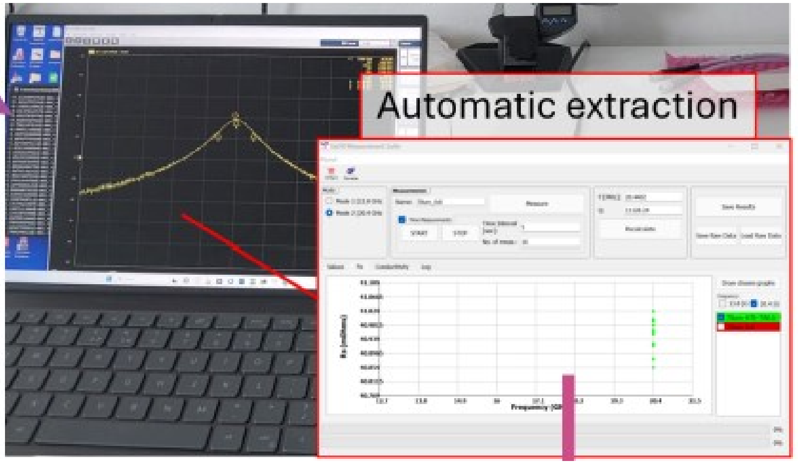




Example of two sides of the same sample

Dual mode RuDR measurement setup which also includes VNA and laptop with dedicated software.

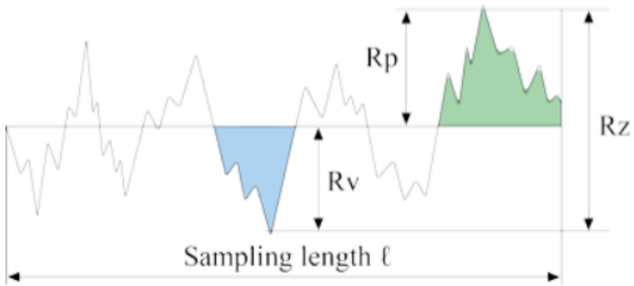




Roughness parameters (contact stylus profilometre)

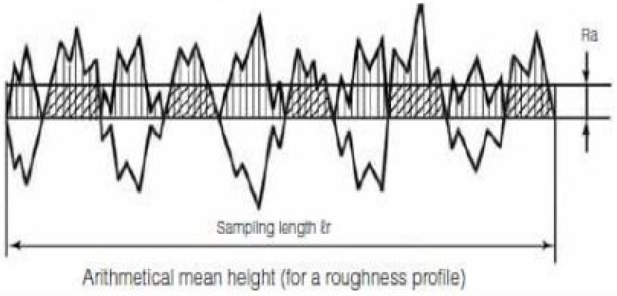
Maximum Height (Rz)

$$Rz = Rp + Rv$$



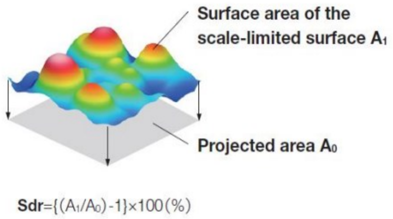
Arithmetical Mean deviation (Ra)

$$Ra, Pa, Wa = \frac{1}{lr}\int_0^{lr} |Z(x)|\, dx$$



Developed interfacial area ratio (Sdr)

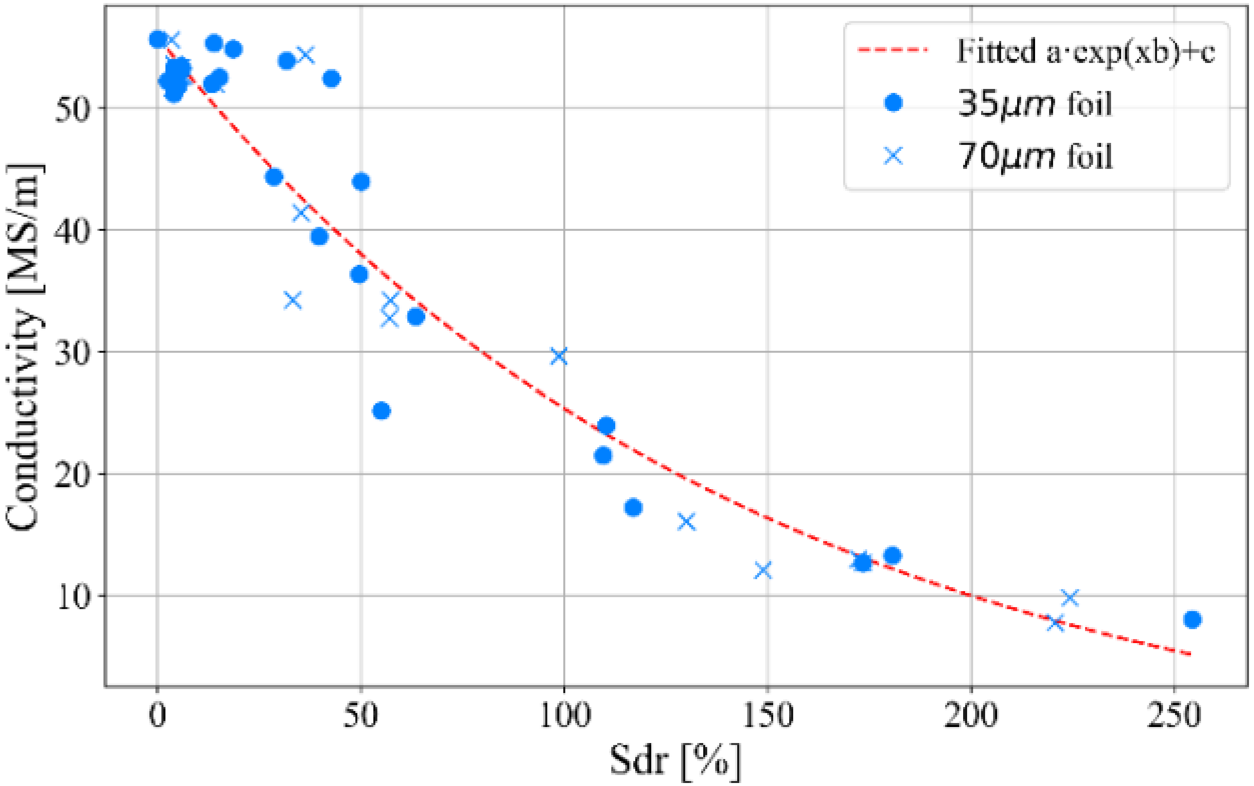
$$Sdr = \frac{1}{A}\left[\iint_A \left(\sqrt{\left[1+\left(\frac{\partial z(x,y)}{\partial x}\right)^2+\left(\frac{\partial z(x,y)}{\partial y}\right)^2\right]}-1\right) dxdy\right]$$

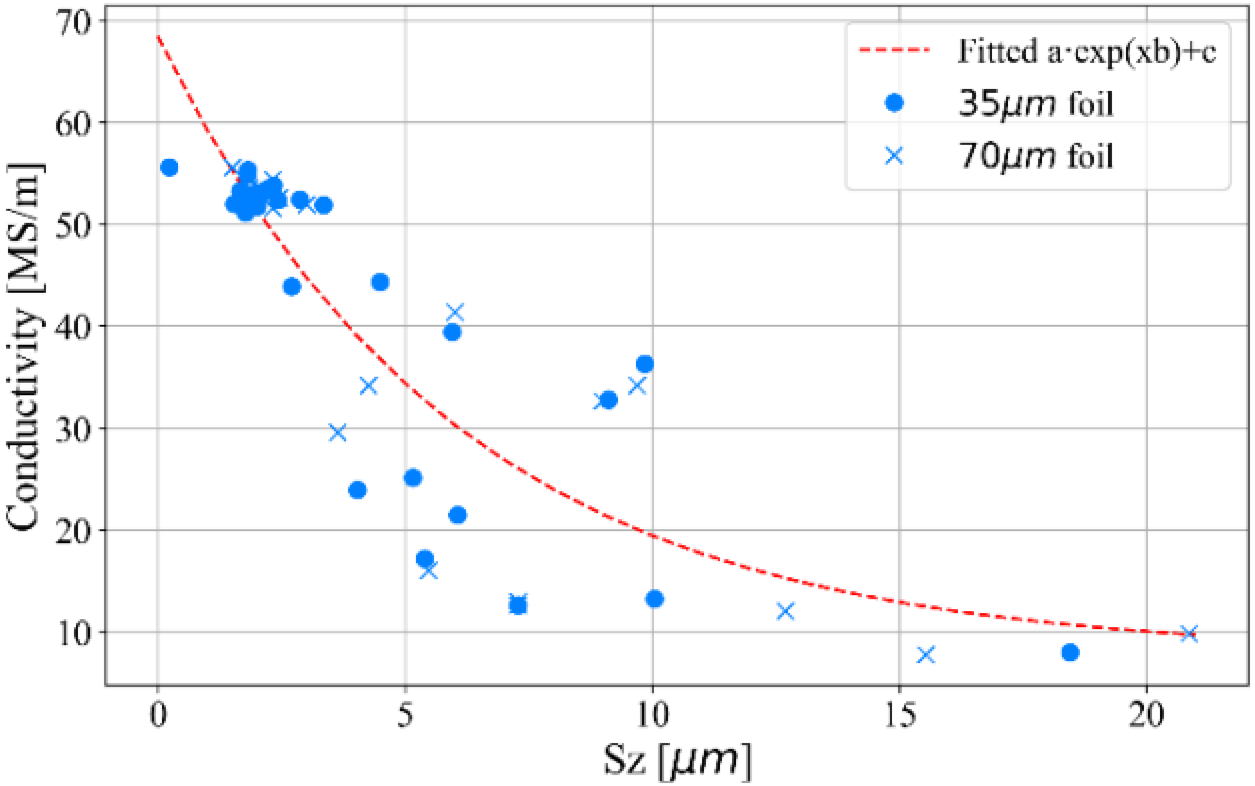


Results

Correlation between effective conductivity σ (measured at **14 GHz** in the RuDR test-fixture and surface roughness parameters

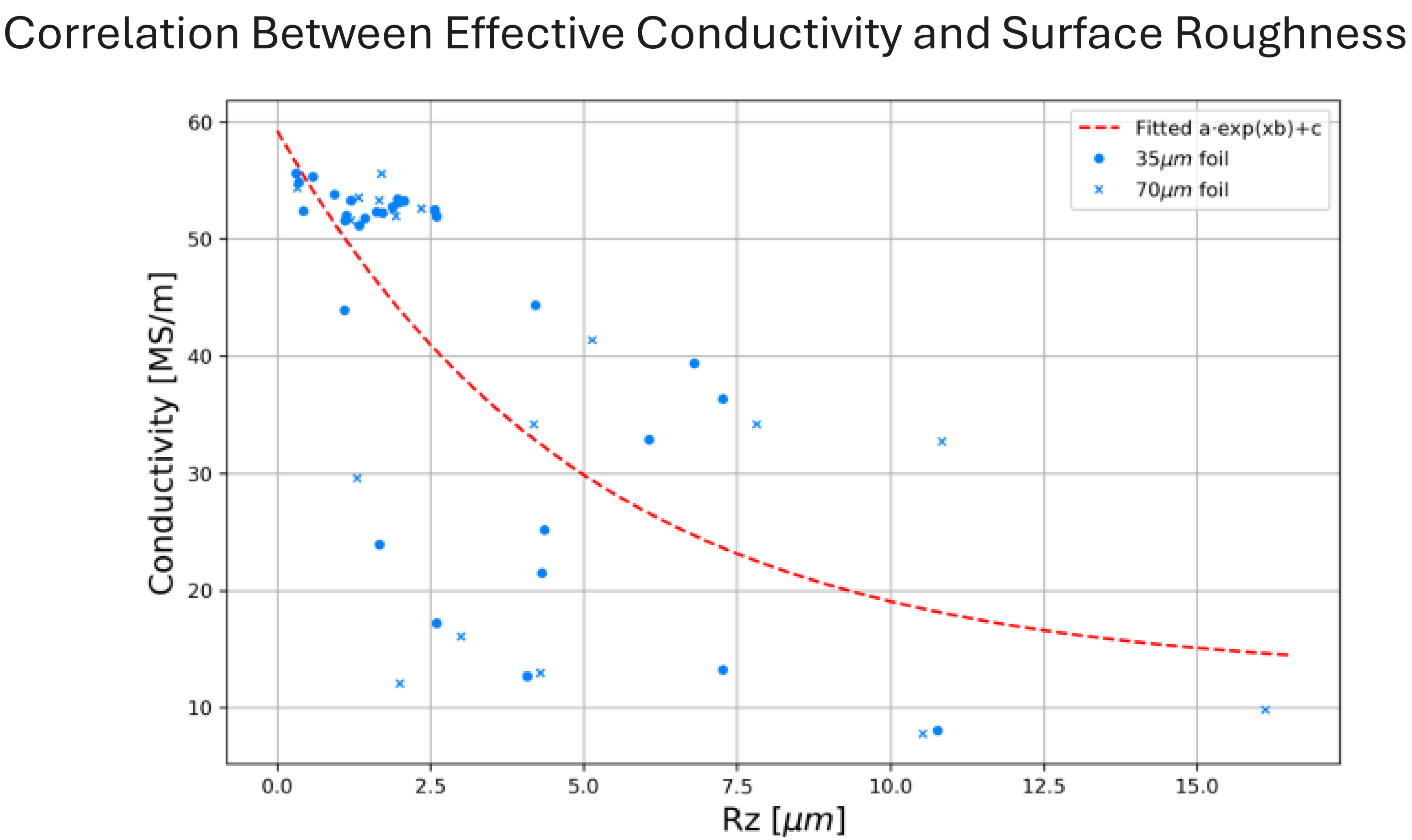
Correlation Between Effective Conductivity and Surface Roughness





Results

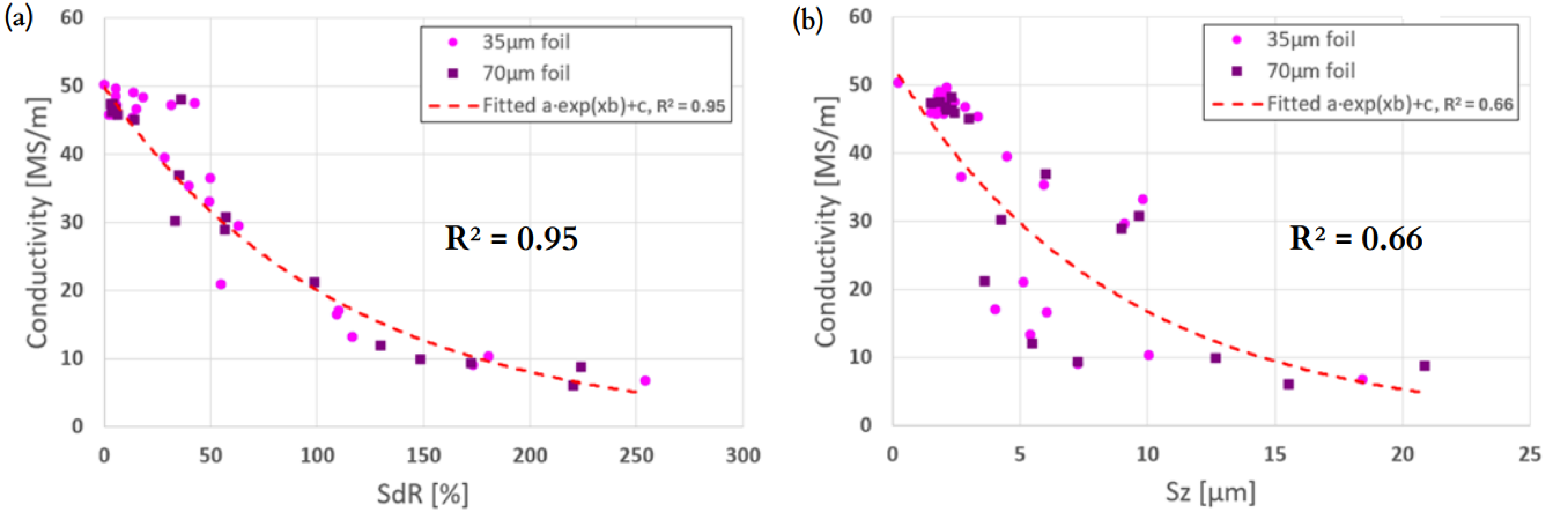
Correlation between effective conductivity σ (measured at **14 GHz** in the RuDR test-fixture and surface roughness parameters



Results

Correlation between effective conductivity σ (measured at **21 GHz** in the RuDR test-fixture and surface roughness parameters:
(a) SdR - Developed Interfacial Area Ratio, (b) Sz - Maximum Height

Correlation Between Effective Conductivity and Surface Roughness



Research Overview

1. Study Overview:
- **72 samples**: 24 foil types
- 3 sheets per type, cut to **60 x 60 mm**.
- Foils measured for conductivity σ using a RuDR at 14 & 21 GHz.

2. **Industrial Copper Foils:**
- Manufactured by Circuit Foil Luxembourg.
- Two thicknesses: **35 μm** and **70 μm**.
- Characterized by roughness parameters Sz, Sa, Sdr using laser interferometry.

3. Measurement Process:
- Two identical samples from each foil sheet.
- Samples mounted in a cylindrical ruby resonator and tested with a VNA.
- Conductivity values derived from Q-factor and resonance frequency via full-wave modeling.
- 16 repeated measurements, every 5 seconds (averaged values shown in the graphs).

4. Key Findings:
- Exponential relationship: Conductivity σ decreases as surface roughness Rs increases.
- Thickness does not affect conductivity.
- Factors like grain size may also influence conductivity (investigated in the **5GFoil project**).

Conclusions

- The RuDR method effectively characterizes copper foils for microwave and mmWave PCBs, offering precise conductivity σ and surface resistance Rs measurements without substrate interference.
- Operating at 13.8 GHz and 20.4 GHz, it highlights an exponential correlation between conductivity and surface roughness, with SdR being the most representative parameter (R^2 = 0.97 at 13 GHz and R^2 = 0.95 at 20.4 GHz). While surface roughness strongly influences conductivity, additional factors like grain size also play a role.
- The method is scalable and practical, supporting advancements in 5G and mmWave PCB materials. Further research will explore additional manufacturing parameters influencing conductivity.

Acknowledgment

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5G Foil

https://qwed.eu/projects/5g-foil

Thank you

Questions?

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