CIRCUIT FOIL

Last update on correlation between copper foil surface conductivity and roughness

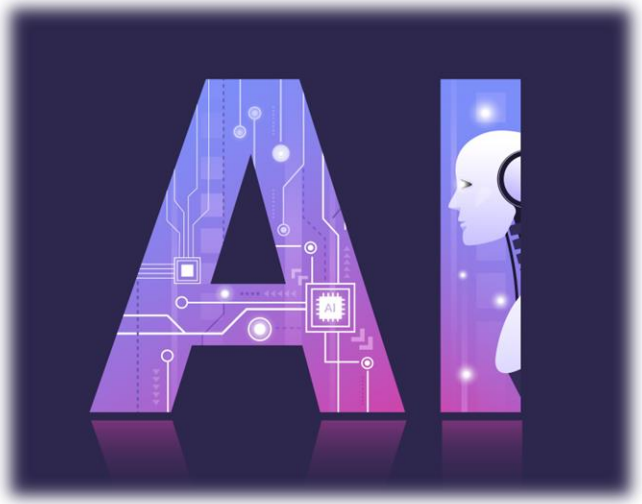
CONFIDENTIAL

Copper foil development Key driver

✓ **Adoption of advanced technologies requiring faster data transfer speeds (5G, AI, automotive sensors, ethernet, etc.)**

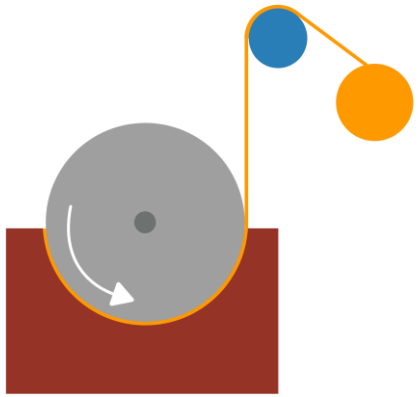
Signal loss reduction

→ Ultra smooth copper foil while maintaining sufficient peel strength and reliability

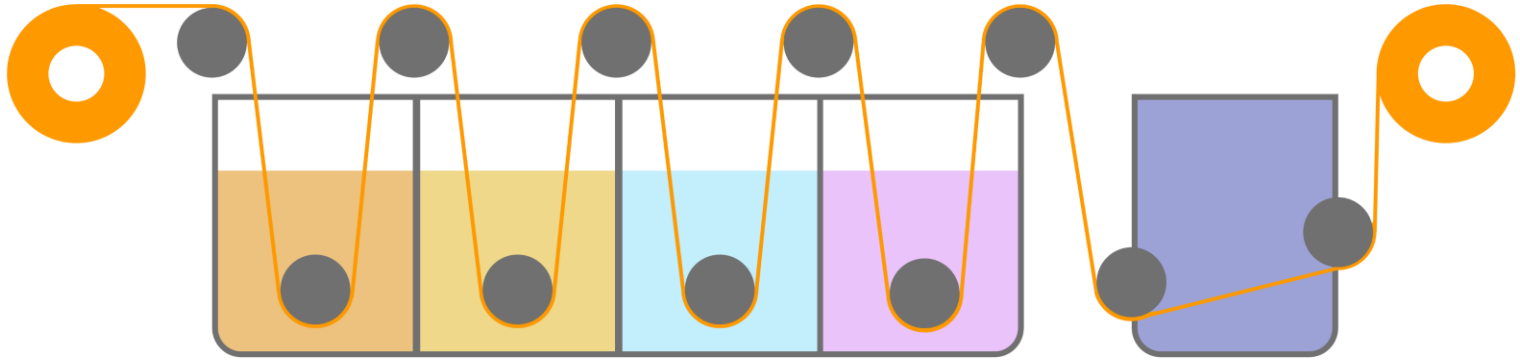


Process Overview

1. Plating

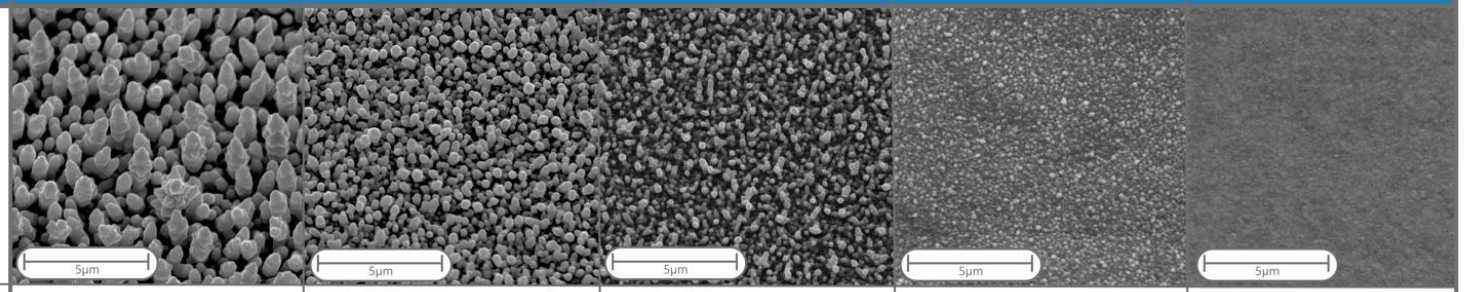


2. Surface Treating



Nodulation, passivation and silane

Products Development

Foil Grade (Thickness 35µm)	HVLP 1 BF-TZA	HVLP 2 BF-ANP	HVLP 3 BF-NN/BFL-NN	HVLP 4 BFL-NX	HVLP 5 BFL-NF
SEM Pictures (x5000)					
Key Improvement	Standard	Nodular Treatment size Reduction by **5** compared to HVLP	Nodular Treatment Reduction by **20** compared to HVLP	Nano nodular treatment	**Nodule Free** Treatment (NF)
Target application	Switch Routers 100 G (28 GBps)	Switch Routers 400 G (56 GBps)	Switch Routers 800 G (112 GBps)	Switch Routers 1600 G (224 GBps)	Switch Routers 3200 G (Next Gen.)
Treated side Rz ISO/JIS (µm)	< 3.1 / 2.5	< 1.5 / 1.2	< 1.3 / 1.0 (BF) < 0.8 / 0.6 (BFL)	< 0.8 / 0.6	< 0.8 / 0.6
Treated side Sdr* (Surface developed Ratio)(%)	~110	~50	~30	~12	~0.02
PS PPE (N/mm)	~0.7	~0.7	~0.7	~0.7	~0.5

*Keyence VK-X1050; 661 nm laser; x50 lens

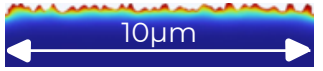
Skin effect: AC has higher current density on the edges of the conductor (the "skin") at high frequency

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

δ: skin depth (m)
f: frequency (Hz)
σ: magnetic permeability ($H.m^{-1}$)
π: electrical conductivity ($S.m^{-1}$)

Frequency << 10 GHz

Frequency > 10 GHz



Higher signal losses

Solution: ultra flat foil

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Product description

SILANE

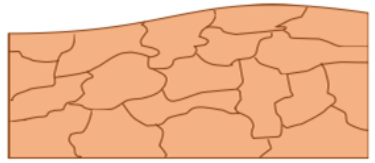
- Type & content: peel strength

PASSIVATION

- Type & content: thermal and chemical reliability

NODULAR TREATMENT

- Size & shape: peel strength and reliability

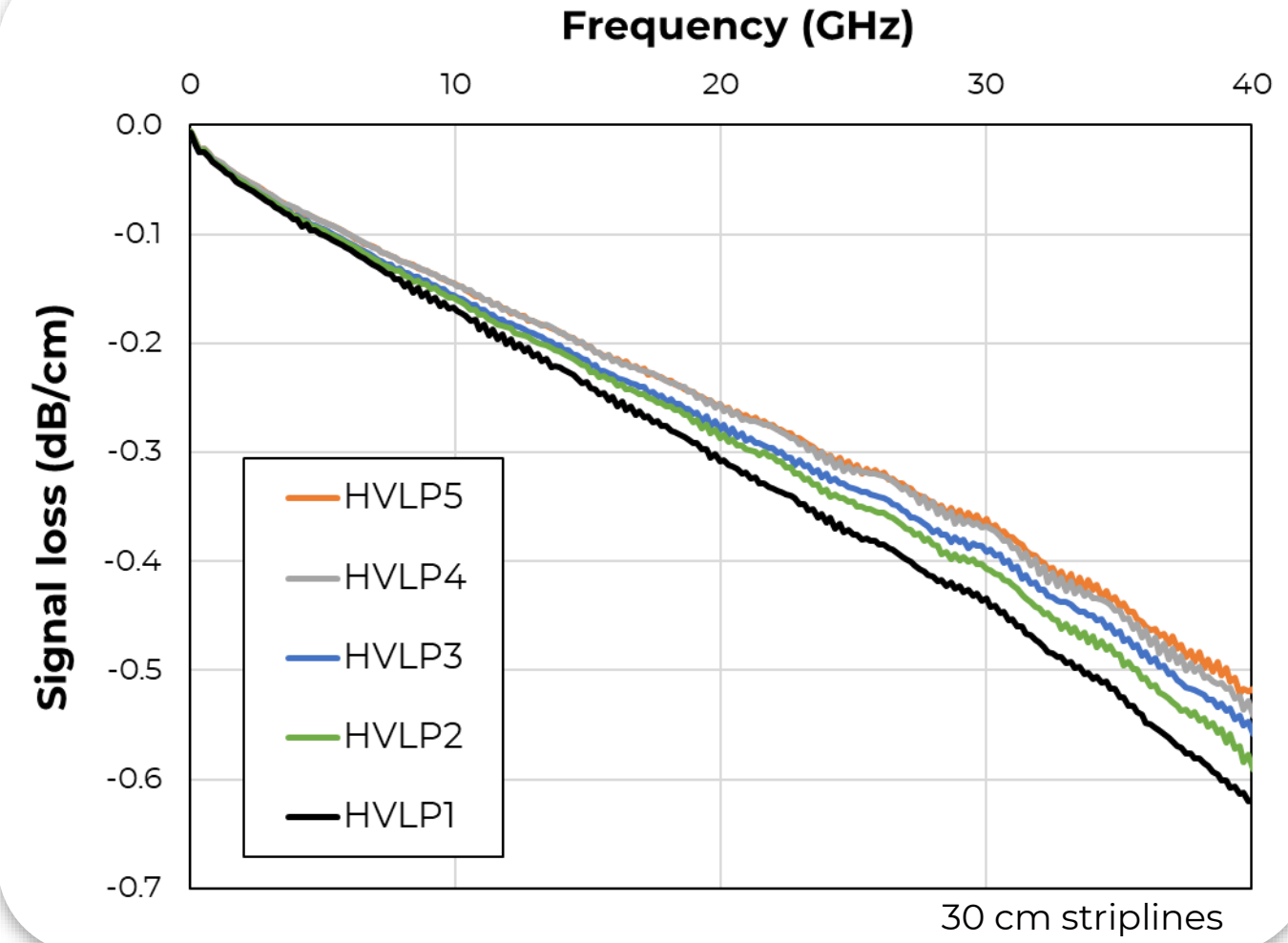


BASE FOIL Profile and microstructure

- Roughness on both sides of the base foil: effect on insertion loss
- Copper microstructure: mechanical properties

Understanding the relative contribution of each parameter to signal loss is the key for the development of next generation products

Insertion loss

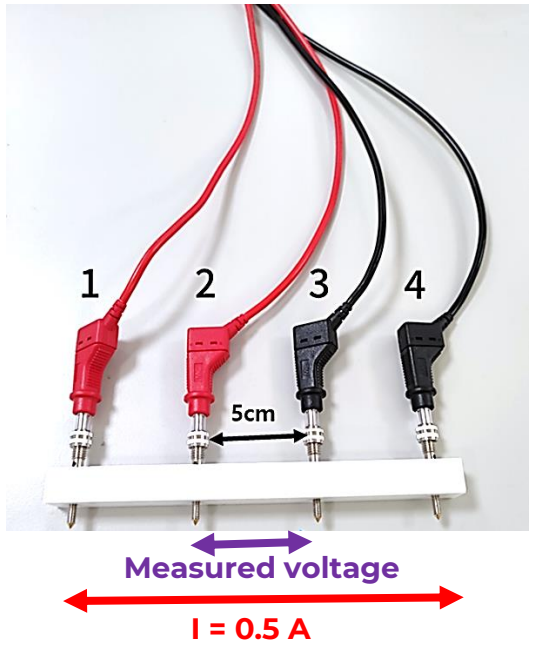


- Gap in performances are decreasing for each HVLP generation
- Better understanding of each copper foil parameter's contribution is required to improve the properties of next generation foils
- Due to the contribution of ppg, board design, etc., and due to their high cost and lead time, insertion loss measurements are not ideal for in-depth characterization of copper foils

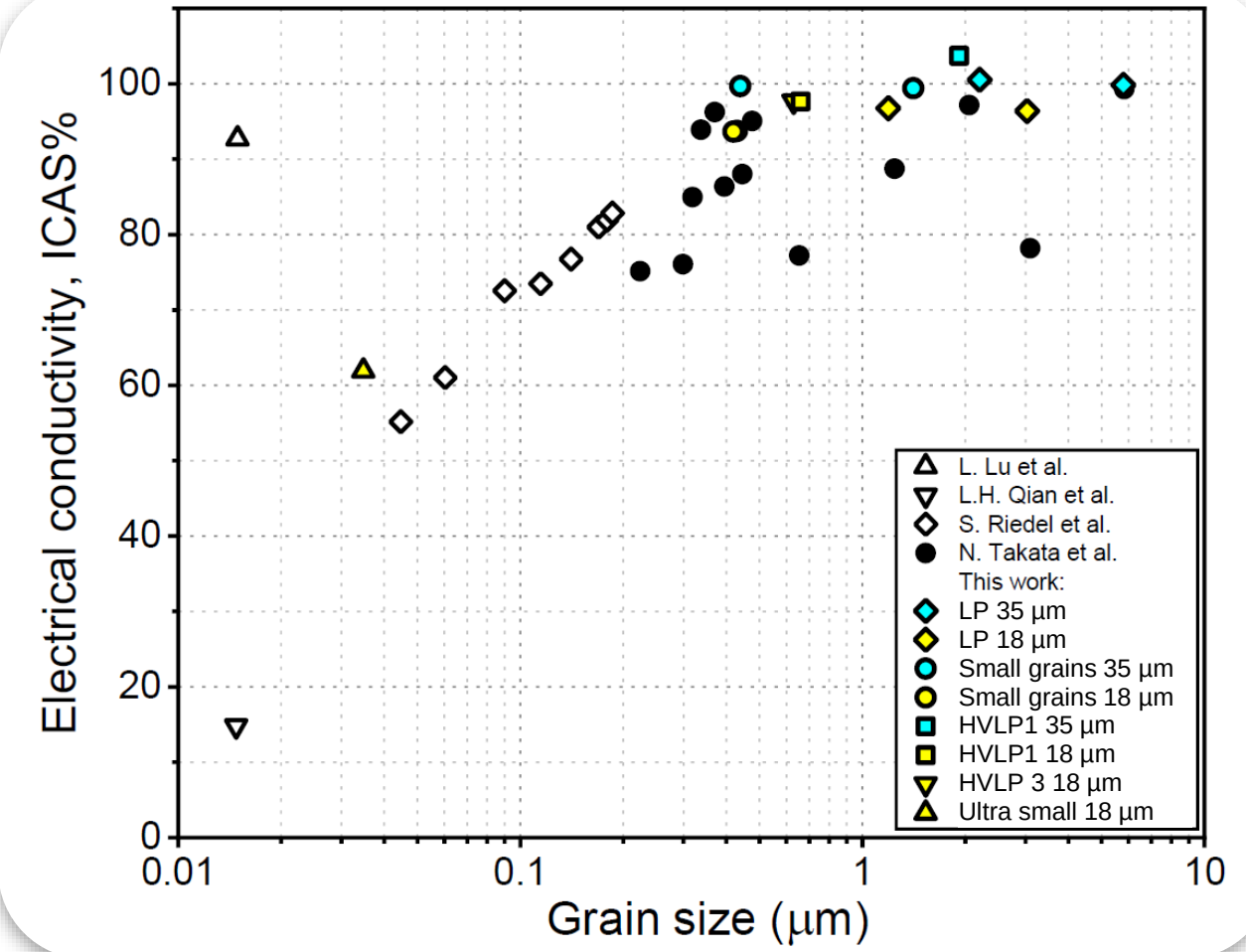
Conductivity measurements

LUXEMBOURG INSTITUTE OF SCIENCE AND TECHNOLOGY | LIST

Bulk conductivity : 4-point probe



Limit*ations:* no information on conductivity at high frequency; can only detect the impact of the bulk



100% ICAS = 5.8001 x10^7 S/m

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Surface conductivity measurement

European project "***5G Foil***" : Measurement and simulation of surface conductivity of copper foils at high frequency

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Sapphire Dielectric Resonator
(up to 21 GHz currently)

Use of resonators to characterize Cu foil conductivity:

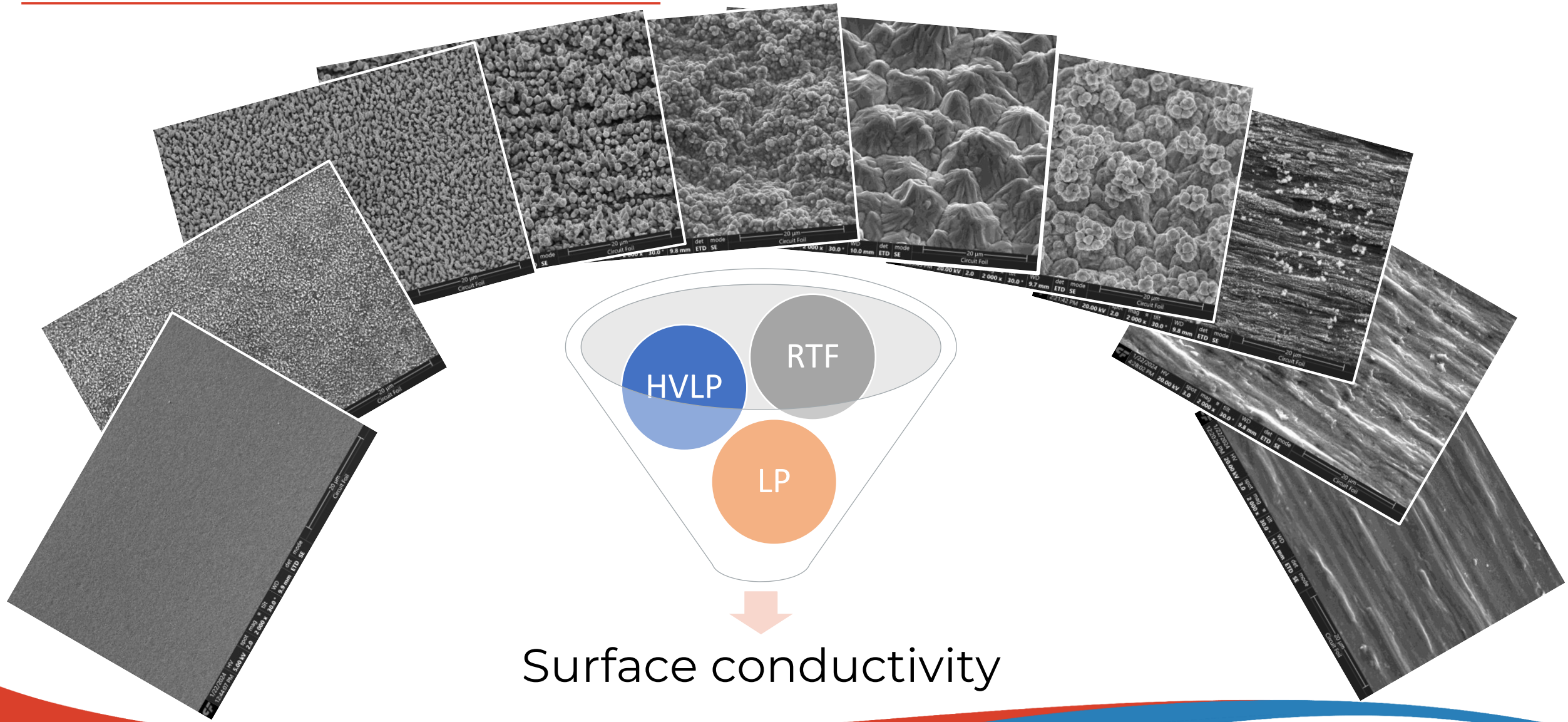
- Alternative current → information on ***surface conductivity at high frequency***
- Direct measurement on copper → **no interferences** related to PCB manufacturing + quicker foil characterisation // development // optimisation

Fabry-Perot Open Resonator
(up to 50 GHz theoretically)

eurostars™

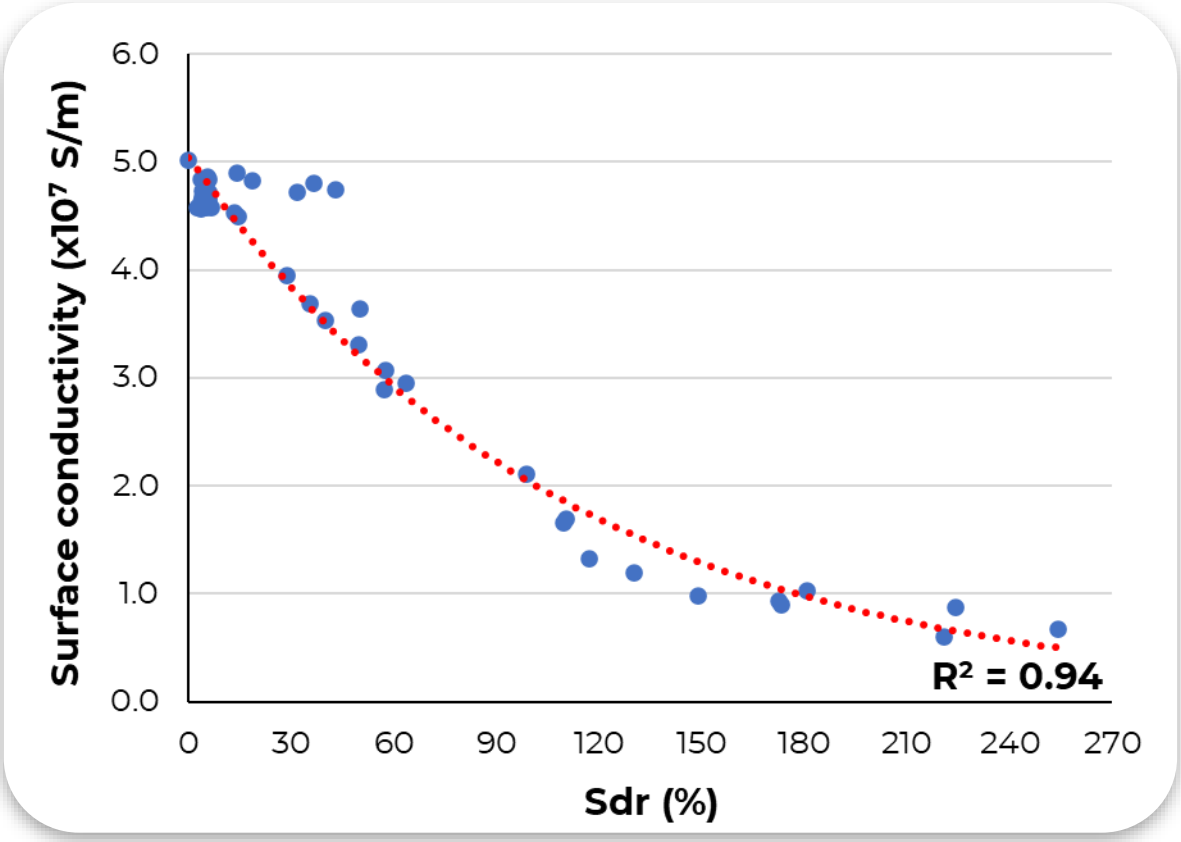
Project co-financed by the Luxembourg National Research Fund under the Eurostars-3 programme
Co-funded by EUREKA member countries and the European Union Horizon2020 Framework Programme

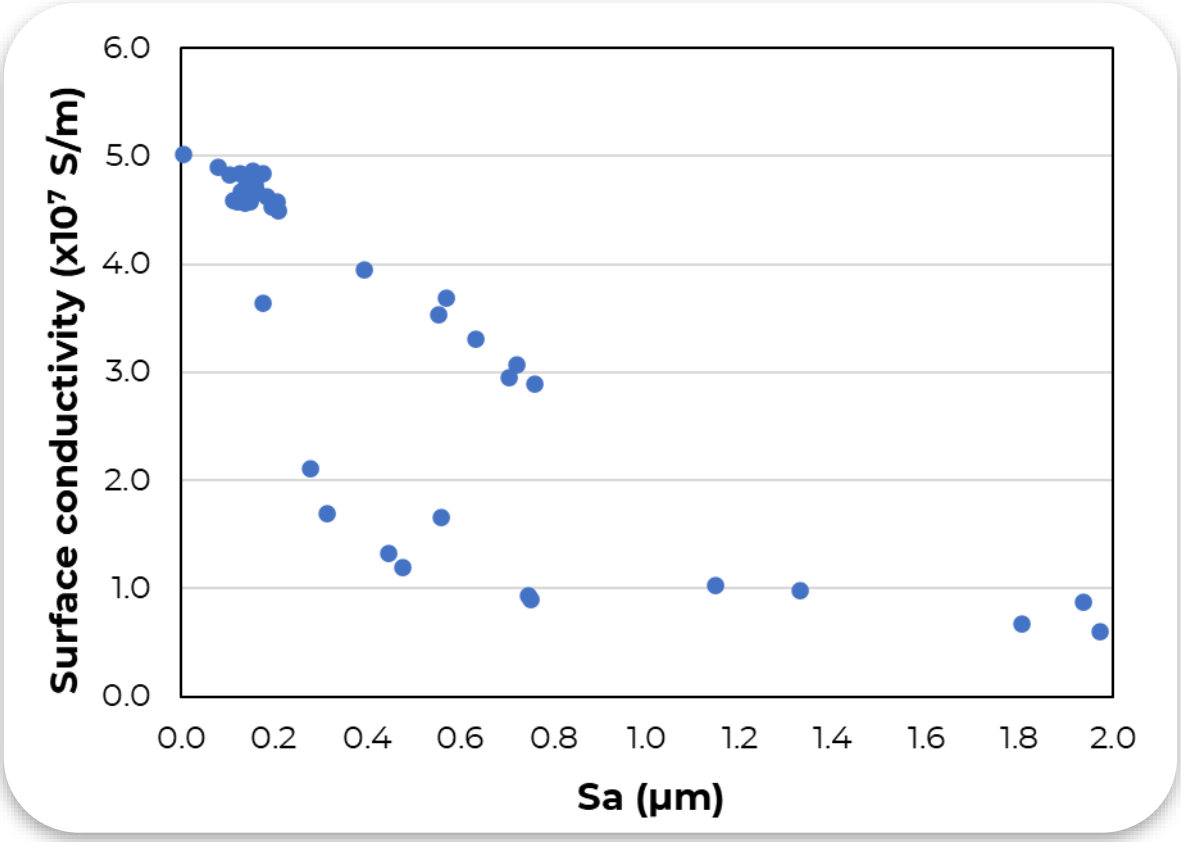
Surface conductivity measurements



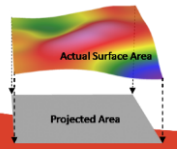
Surface conductivity measurements

Correlation between surface conductivity at **21 GHz** and roughness parameters:





Sa (µm): difference in height of each point with the arithmetical mean of the surface
Sdr (%): difference between the developed (true) and projected surface



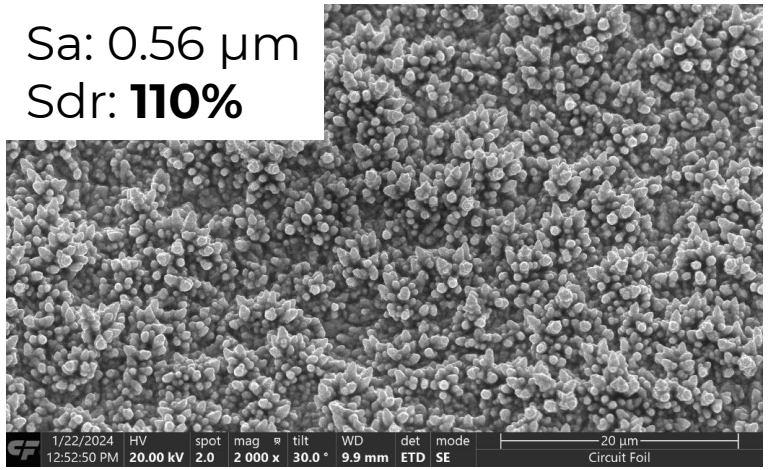
$$sdr = \left[\frac{actual\ surface\ area}{projected\ area} - 1\right] \text{x}100$$

Much better correlation between surface conductivity and sdr than Sa (and other parameters such as Sz, Sq, Rz, Ra)

CIRCUIT FOIL

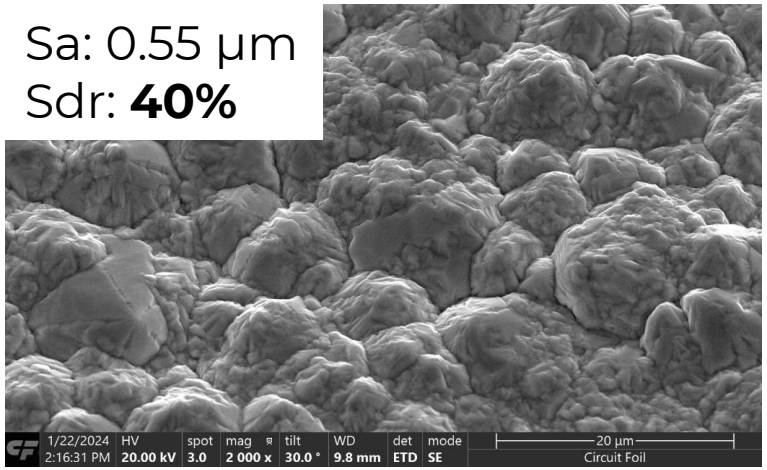
Roughness parameters comparison

Sa: 0.56 µm
Sdr: **110%**

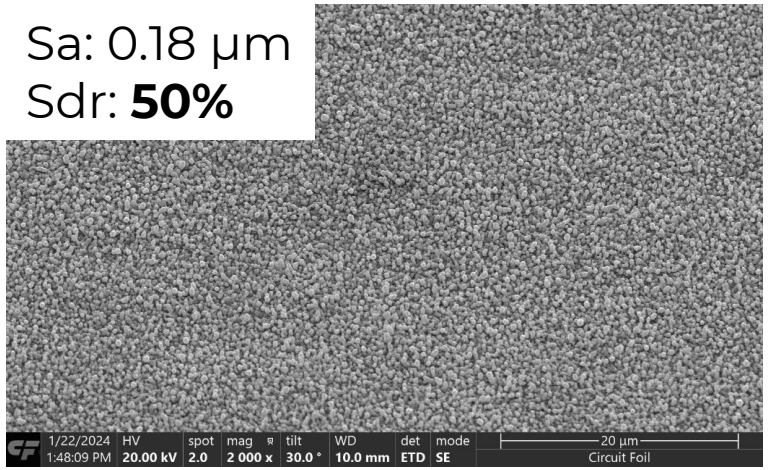


Sa = ≠ Sdr

Sa: 0.55 µm
Sdr: **40%**

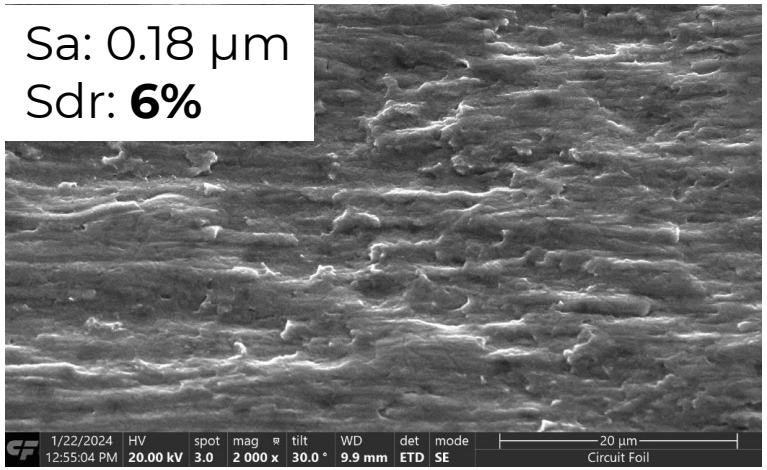


Sa: 0.18 µm
Sdr: **50%**



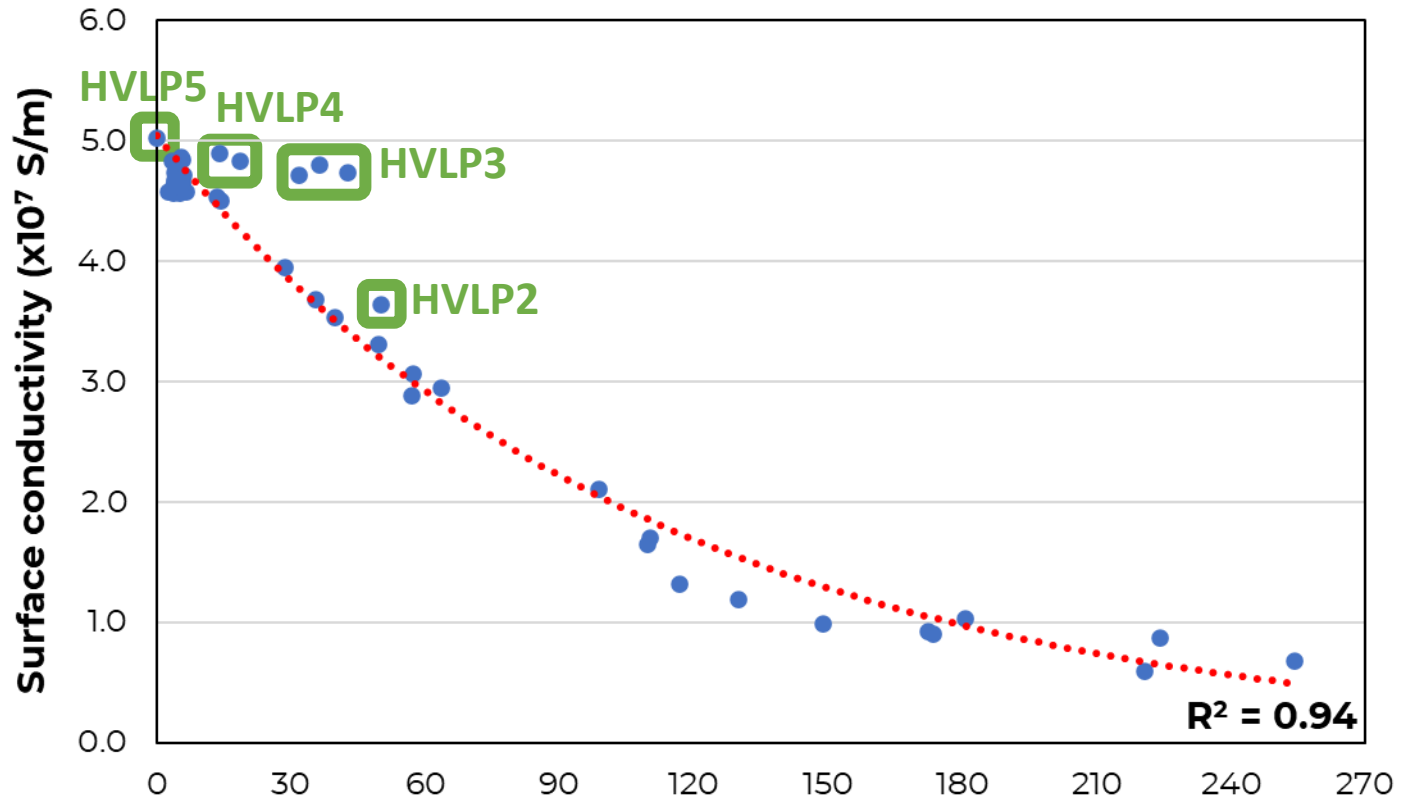
Sa = ≠ Sdr

Sa: 0.18 µm
Sdr: **6%**



Sa does not account well for micro roughness, unlike sdr

Correlation sdr – surface conductivity

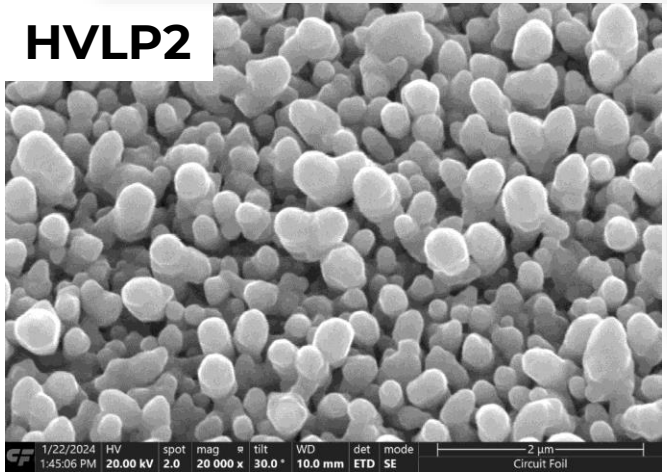


- HVLP+ copper foils deviate from the trend (without them, R^2 is 0.99)
- What is the reason for this deviation?

Skin depth

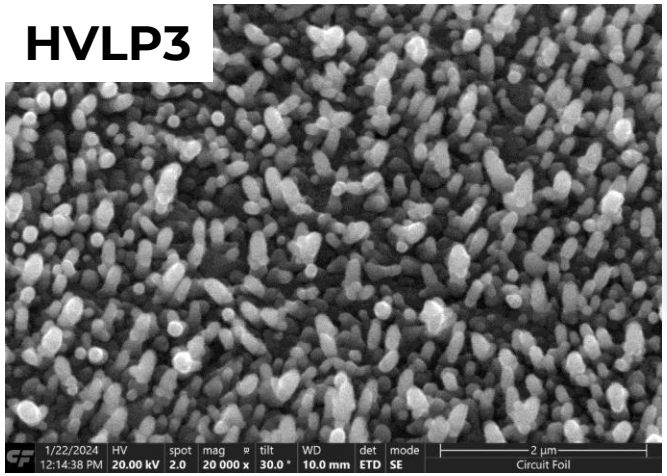
Skin depth at 21 GHz ≈ 0.45 µm

HVLP2

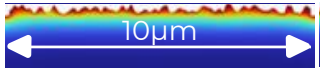
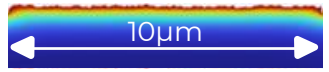
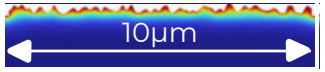
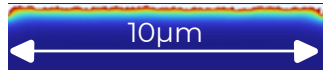


Nodule height: 0.5-1 µm (≈ skin depth)

HVLP3



Nodule height: 0.2-0.5 µm (< skin depth)

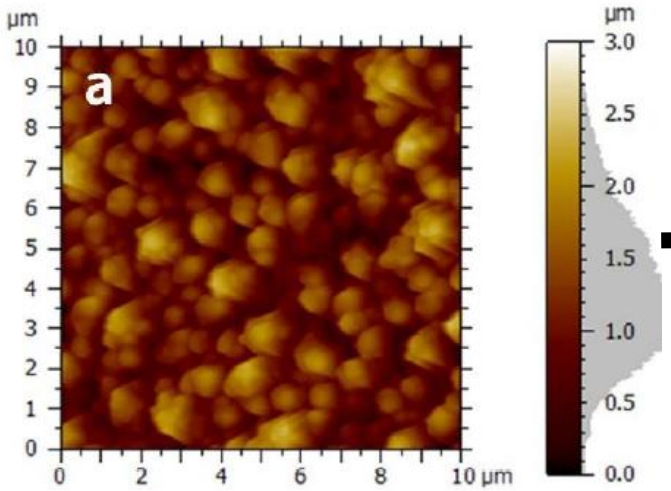
Frequency \ Foil	HVLP3	HVLP4	HVLP5
1GHz			
30 GHz			
100 GHz			

- Nodule size < skin depth has negligible impact on signal losses

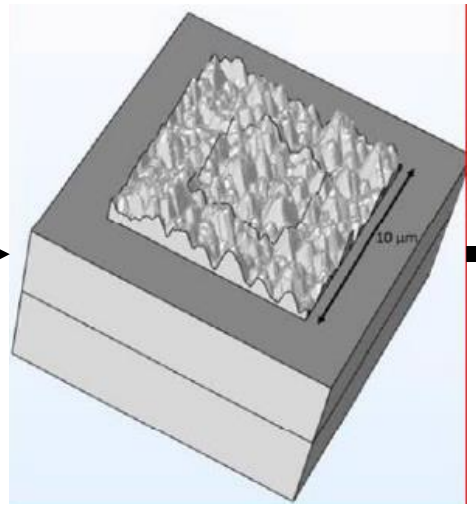
Simulation of Insertion Loss

Finite element modelling :

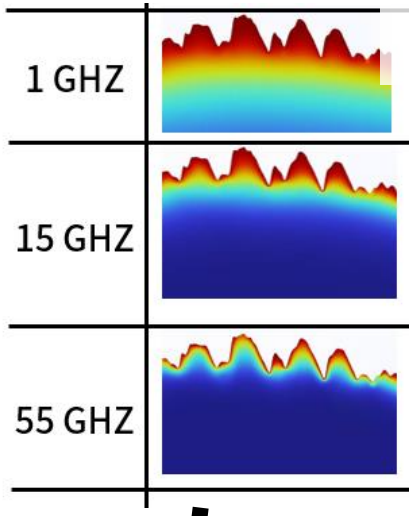
AFM measurements



Numerical model



Magnetic field



Simulation of the influence of roughness and copper conductivity on losses

Power losses:

$$P = \frac{1}{2\sigma}\int_V J.J^* dv = \frac{1}{2\sigma}\int_V (\nabla \times H).(\nabla \times H^*) dv$$

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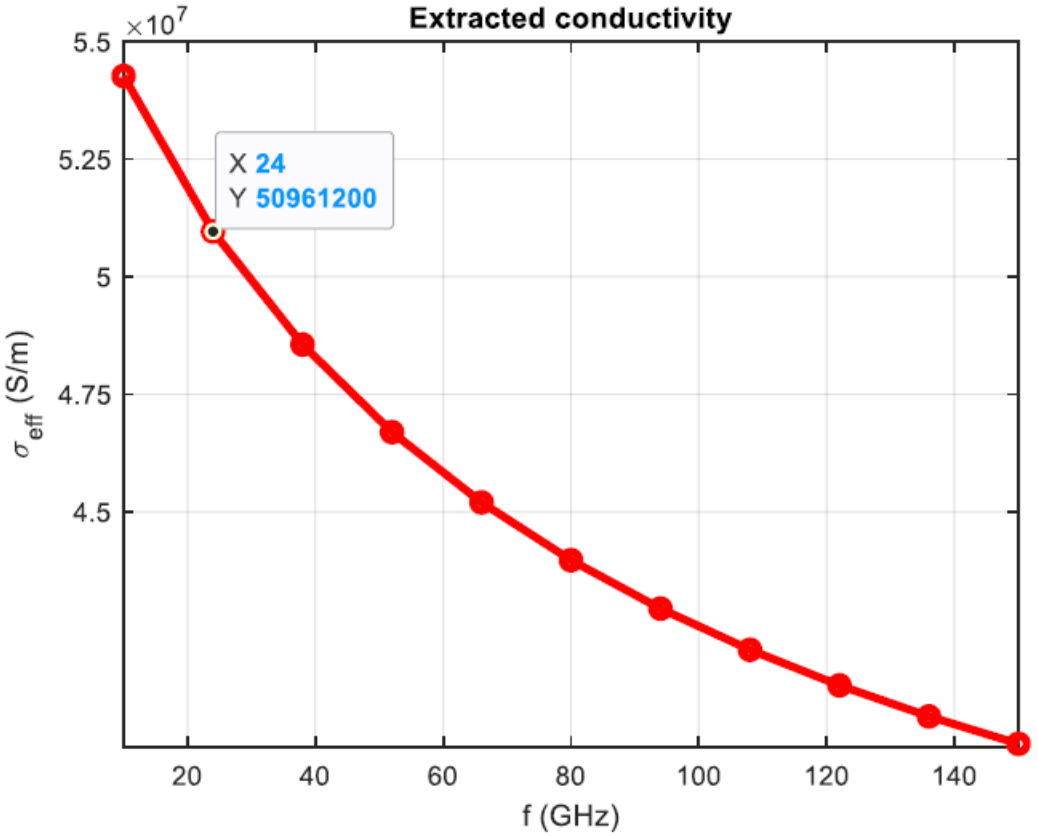
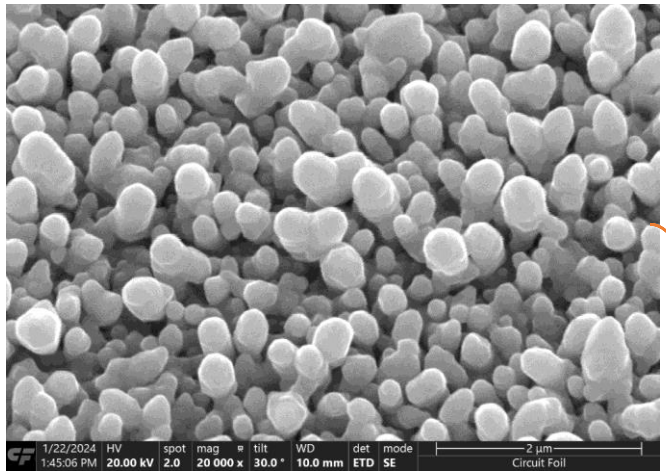
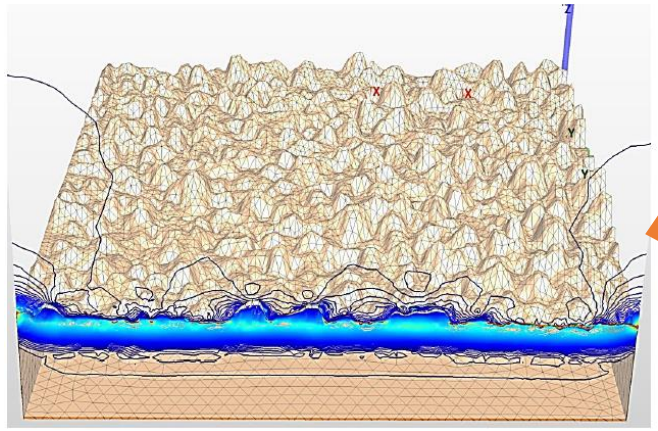
Simulation accuracy



Foil	Surface conductivity @ 21 GHz	
	Measured	Calculated
HVLP2	3.2 x10^7 S/m	5.2 x10^7 S/m

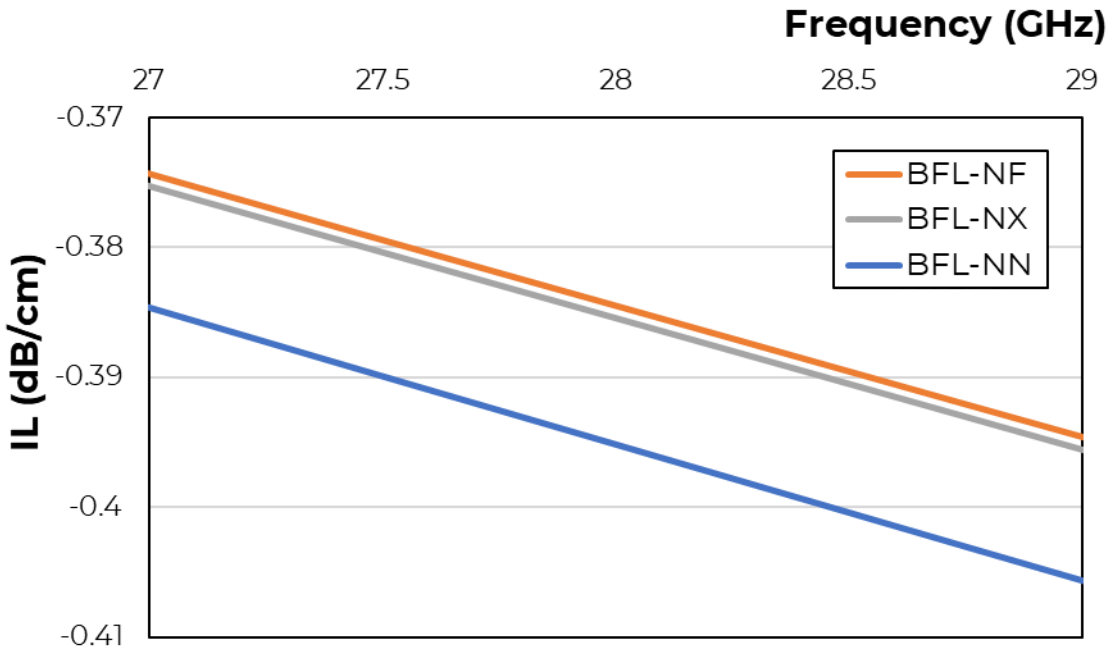




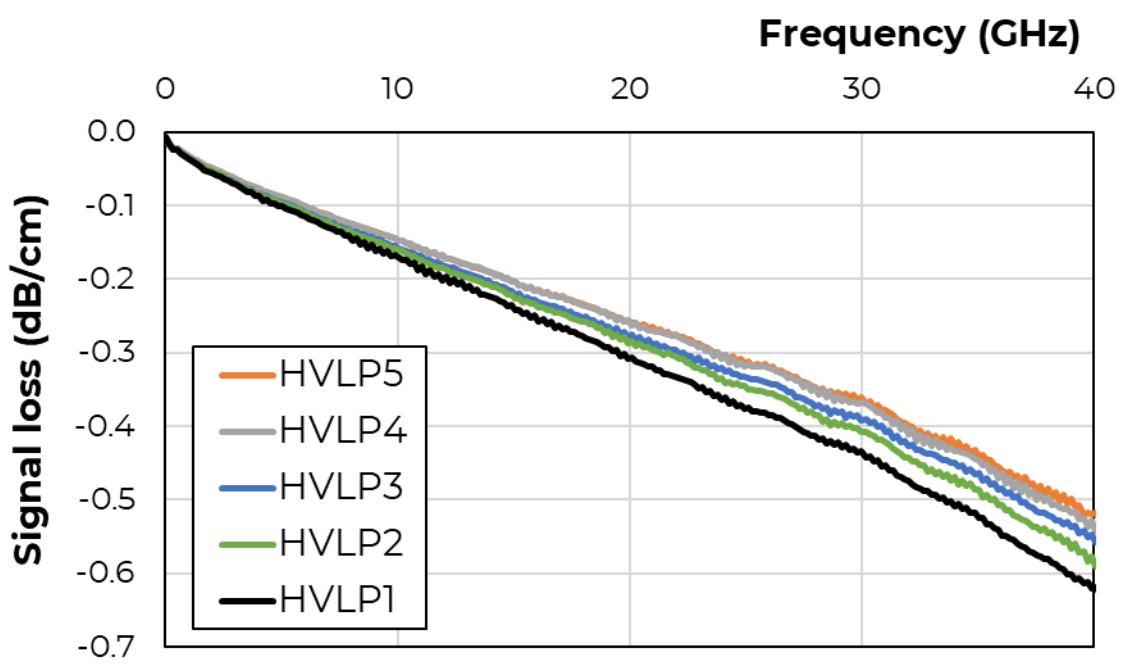
Deviation of the simulation could be due to surface model deviation (much less dendritic surface)

Influence of Nodular treatment

Numerical simulations



Insertion loss measurements (18 µm)



Products (35 µm thickness)	P/S on PPE N/mm
HVLP 3 BFL-NN	~0.7
HVLP 4 BFL-NX	~0.7
HVLP 5 BFL-NF	~0.5

Numerical simulations trends are well aligned with actual measurement results

Conclusion and outlooks

- ✓ Excellent correlation between surface conductivity and sdr
- ✓ Roughness profile lower than skin depth has negligible effect on signal loss

Next steps:

- ➢ Improvement of finite element model accuracy
- ➢ Investigation of copper properties at higher frequency
- ➢ Effect of passivation on surface conductivity
- ➢ Optimization of surface profile to achieve the best compromise between signal loss and adhesion