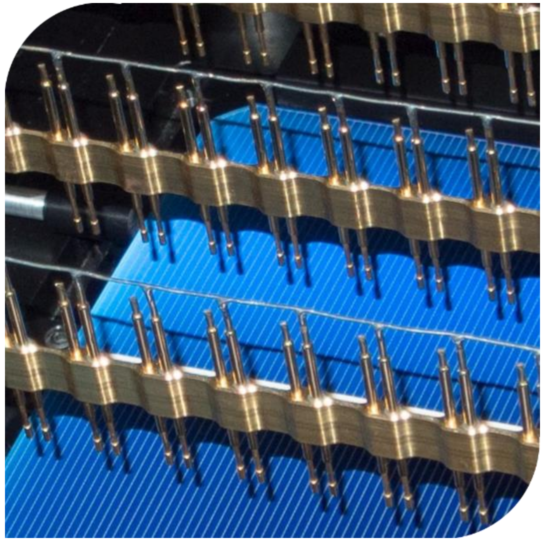


# Validation of methodology to determine the contact resistivity of ECA–based bonds

ISC research for a sunny future

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MIW Metallization & Interconnection WORKSHOP
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# Outline

- Introduction & motivation
- Transmission Line Method (TLM) test structure
- Analytical method to determine contact resistivity of ECA-based joints
- Validation procedure
- Validation results
  - Sample size not optimized
  - Sample size optimized
- Conclusions

# Introduction and motivation

- ECAs → Electrically conductive adhesives.
- Broad formulation:

**Conductive fillers (80-95 wt.%) + Insulating polymer matrix (5-20 wt.%)**

- ECA advantages (✓) and disadvantages (✗) compared to solder:

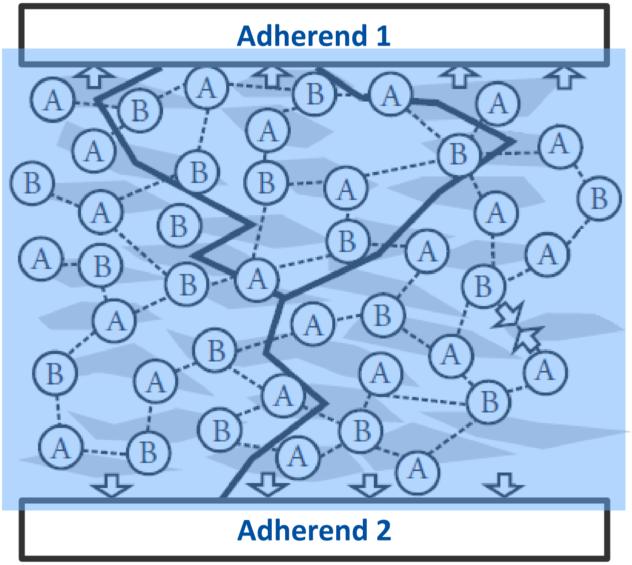
| ✓ Advantages | |
|---|---|
| Free of lead & flux | Low T & Flexible |
| Fine pitch possible | Cured during lamination |
| Excelent long-term stability | |

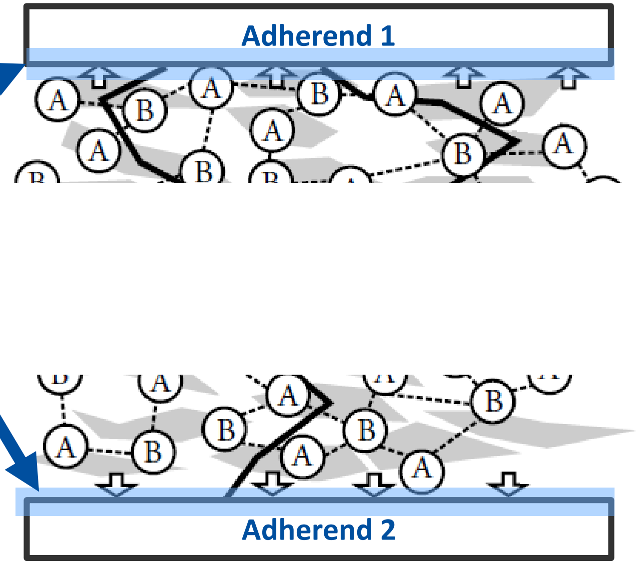
| ✗ Disadvantages | |
|---|---|
| High amount of silver | Lower thermal/electrical conductivity |
| It bleeds | Requires low temperature for storage |

- ECA applications: IBC cells, shingling, VIPV, SHJ interconnection, conductive backsheets, tandem, etc.

# Introduction and motivation

- ECA-based joints requires → long-term performance research
- Long-term research → electrical characterization of the joint
- Figure of merit → **contact resistivity ($\rho_c$)**
- Literature and research groups focus on extrapolation of $\rho_c$ using ECA-based joints with **multiple contact layers**.
- We aim to characterize $\rho_c$ for **„pure“ ECA-based joints**. That is, joints that only posses the adhesive adjacent to one adherend.
- This way we are able to see the contribution of the contact resistance separately.
- This work aims to validate a suitable analytical method to determine $\boldsymbol{\rho_c}$.



# Introduction and motivation

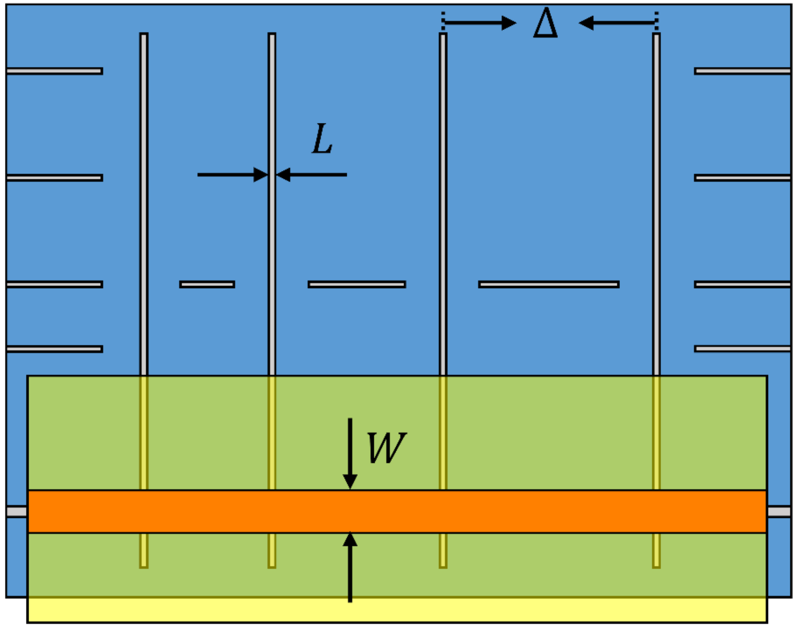
| Adhesive | Adherend 1 | Adherend 2 | $\rho_c$ [mΩ cm²] |
|---|---|---|---|
| Not specified | Ag-coated ribbon | Low-temperature Ag paste | 0.1 |
| Ag-filled acrylate | Ag-coated ribbon | Sintered Ag paste | 0.09 to 0.55 |
| CNT-filled epoxy | Ag-coated ribbon | Sintered Ag paste | 3.9 |
| Ag- reduced silicone | Ag-coated Cu<br>OSP-treated Cu | Not specified | <0.1 |
| Not specified | Not specified | Not specified | 0.07 to 0.6 |
| Four ECAs | Evaporated Ag | Sn(Pb) Ag | 0.1 to 1 |
| Epoxy based | Ag-coated ribbon | Front Ag busbar | 0.003 to 0.012 |
| Epoxy based | Ag-coated ribbon | Rear Ag busbar | 0.05 to 0.1 |

[1] T. Geipel, "Electrically conductive adhesives for photovoltaic modules," 2018.

# TLM TEST STRUCTURE

# TLM test structure

## Test structure schematic and equivalent circuit diagram



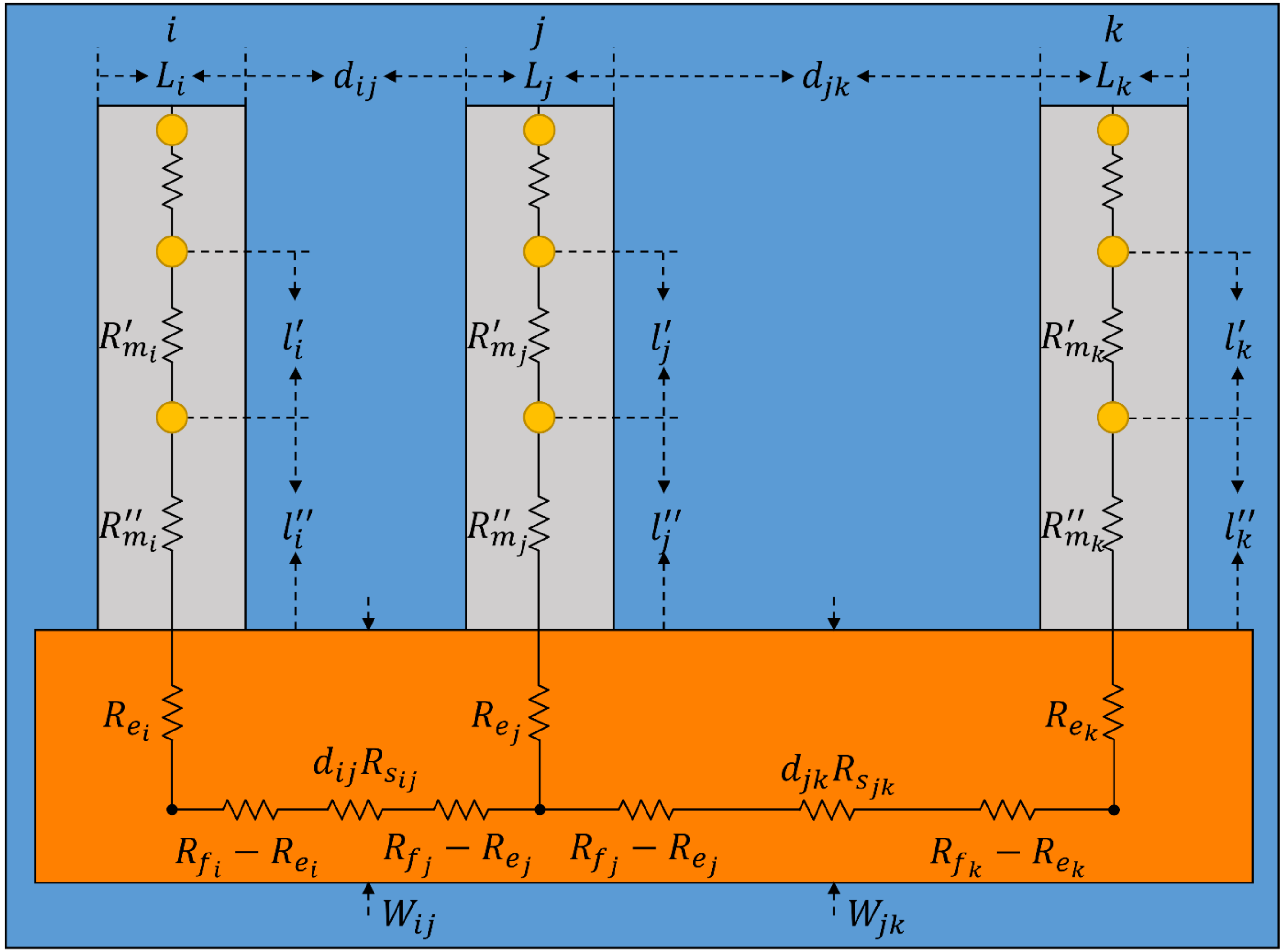

Contacting probes for resistance measurements

Wafer (physical support)

Metal fingers

Needle/jet-dispensing

Microscope cover glass



# ANALYTICAL METHOD

# Analytical method

## Finger and sheet resistance measurements

- Finger line resistance:

$$r_j = \frac{V_j}{I_{jk}} = \frac{R'_{m_j}}{l'_j}$$

- Sheet resistance:

$$R_{s_j} = m_j$$

Contacting probes for resistance measurements

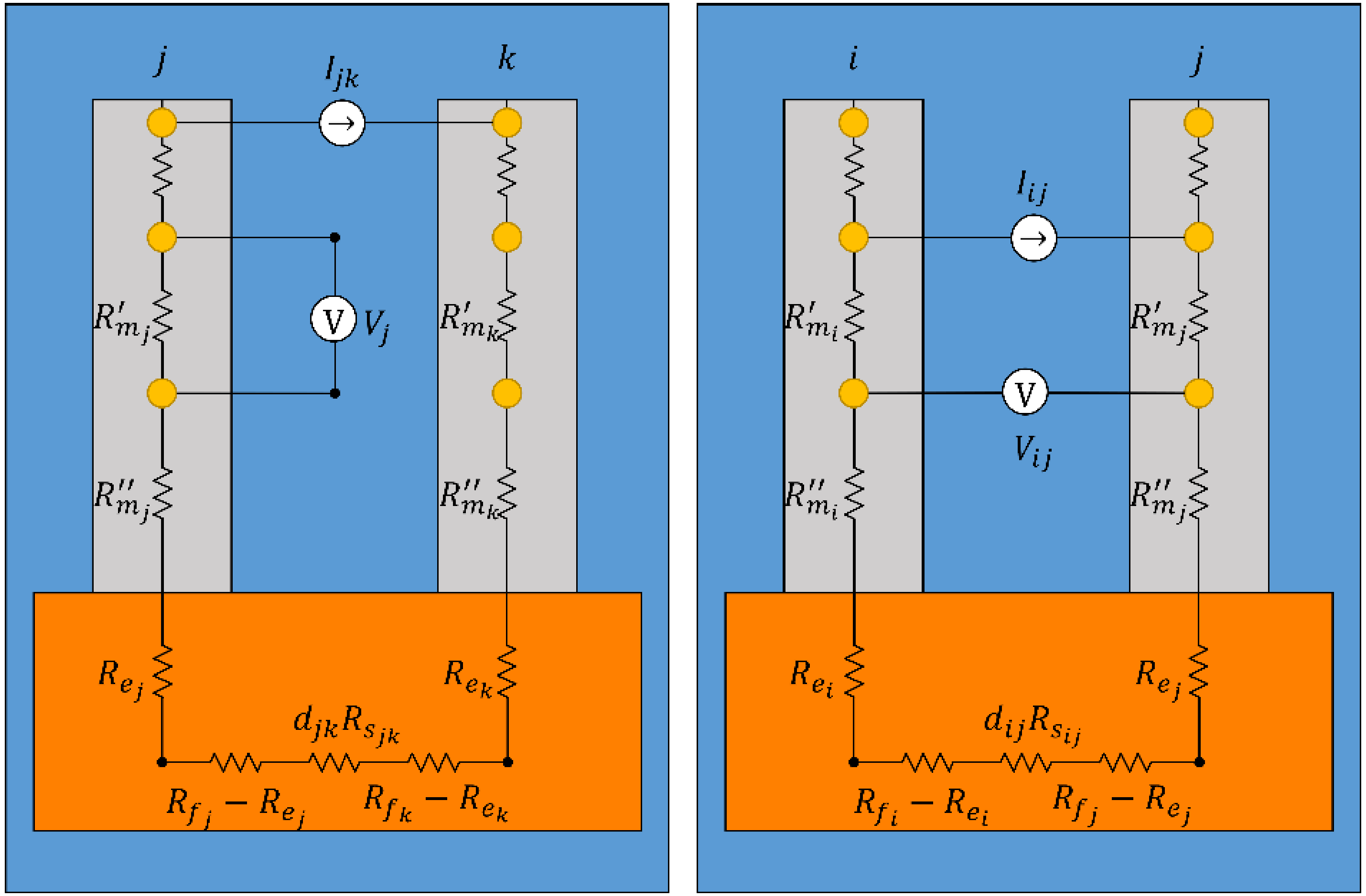
Wafer (physical support)

Metal fingers

Needle/jet-dispensing

DC current source

DC voltmeter

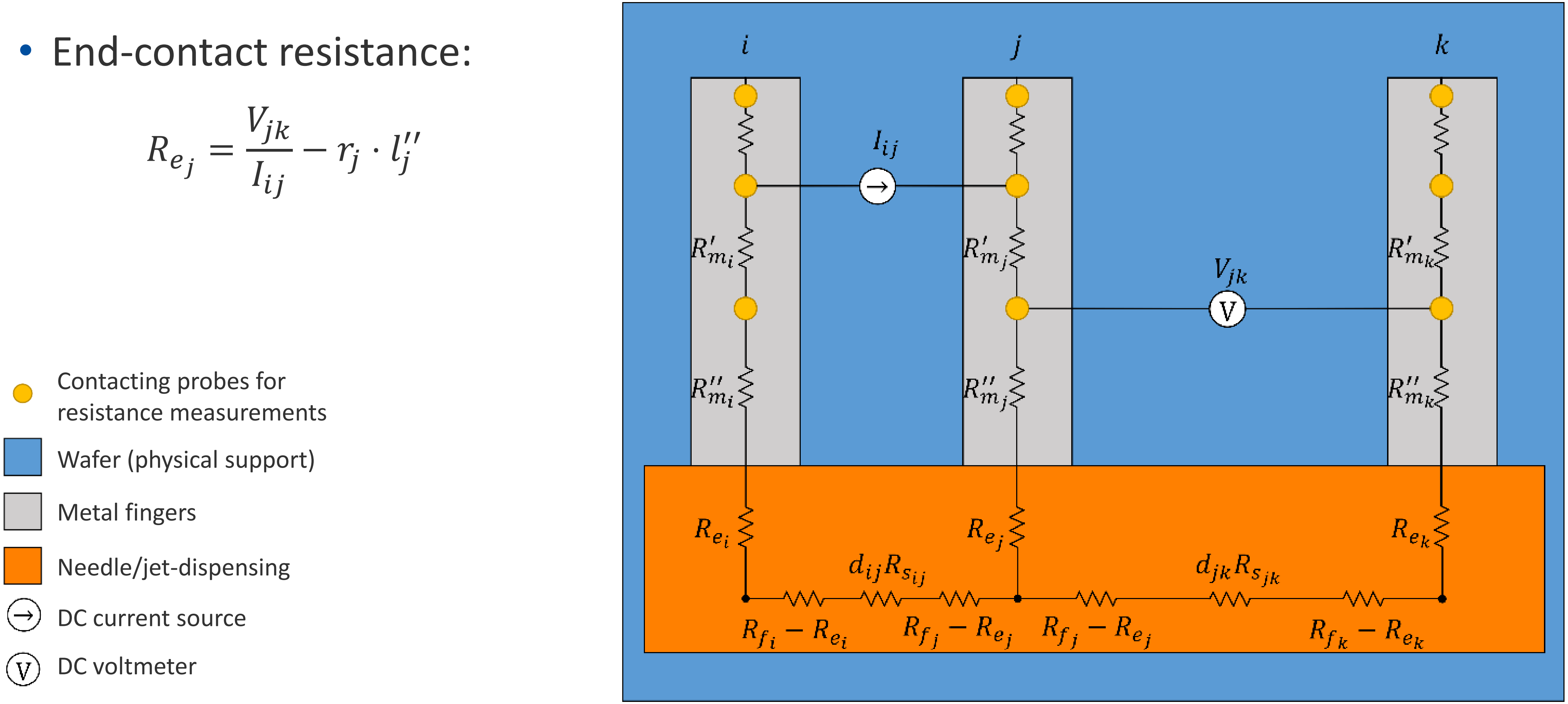


# Analytical method

## End-contact resistance measurement

- End-contact resistance:

$$R_{e_j} = \frac{V_{jk}}{I_{ij}} - r_j \cdot l_j''$$



# Analytical method
## TLM model based on end-resistance

- Local transfer length:

$$R_{e_j} = R_{s_j} \cdot \boldsymbol{L_{t_j}} \cdot sinh^{-1}\left(\frac{L_j}{\boldsymbol{L_{t_j}}}\right)$$

- Local contact length

$$\boldsymbol{L_j} = \frac{L_i + L_j + L_k}{3}$$

- Local contact width:

$$\boldsymbol{W_j} = \frac{W_{ij} + W_{jk}}{2}$$

- Local contact resistivitiy:

$$\boldsymbol{\rho_{c_j}} = R_{s_j} \cdot W_j \cdot L_{t_j}^2$$

- Contact resistivity of sample:

$$\boldsymbol{\rho_c} = \sum_{j=2}^{N-1} \rho_{c_j}$$


[2] W. Shockley et al., "RESEARCH AND INVESTIGATION OF INVERSE EPITAXIAL UHF POWER TRANSISTORS," Sep. 1964.
[3] H. Berger, "Contact resistance on diffused resistors," in 1969 IEEE International Solid-State Circuits Conference. Digest of Technical Papers, 1969, pp. 160–161.
[4] H. H. Berger, "Contact Resistance and Contact Resistivity," J. Electrochem. Soc., vol. 119, no. 4, p. 507, 1972.
[5] H. H. Berger, "Models for contacts to planar devices," Solid. State. Electron., vol. 15, no. 2, pp. 145–158, Feb. 1972.
[6] G. K. Reeves and H. B. Harrison, "Obtaining the specific contact resistance from transmission line model measurements," IEEE Electron Device Lett., vol. 3, no. 5, pp. 111–113, May 1982.
[7] L. Gutai, "Statistical modeling of transmission line model test structures. I. The effect of inhomogeneities on the extracted contact parameters," IEEE Trans. Electron Devices, vol. 37, no. 11, pp. 2350–2360, 1990.
[8] L. Gutai, "Statistical modeling of transmission line model test structures. II. TLM test structure with four or more terminals: a novel method to characterize non-ideal planar contacts in presence of inhomogeneities," IEEE Trans. Electron Devices, vol. 37, no. 11, pp. 2361–2380, 1990.

# VALIDATION PROCEDURE

# Validation of analytical method
## Validation procedure (1)

- ECAs under study:

| ECA | Polymer matrix | Filler | ρ (Ω cm) |
|---|---|---|---|
| ECA 1 | Acryl | Ag | $3.7\ 10^{-3}$ |
| ECA 2 | Epoxy | Cu(Ag) | $3.0\ 10^{-4}$ |

- Groups under study:

| | G01 | G02 | G03 | G04 | G05 | G06 |
|---|---|---|---|---|---|---|
| Adhesive/ECA | ECA 1 | | | | | |
| Wafer batch | Batch 1 | | | Batch 2 | | |
| Jet–dispensing | Day1 | Day2 | Day3 | Day1 | Day2 | Day3 |

| | G07 | G08 | G09 | G10 | G11 | G12 |
|---|---|---|---|---|---|---|
| Adhesive/ECA | ECA 2 | | | | | |
| Wafer batch | Batch 1 | | | Batch 2 | | |
| Jet–dispensing | Day1 | Day2 | Day3 | Day1 | Day2 | Day3 |

- Validation procedure:

1. Determination of proper sample size depending on ECA.

$$n_i = \frac{z_i^2 \cdot \sigma^2}{\varepsilon_i^2}$$

2. Random re-arrangement of samples into new groups of with proper sample size.
3. Determination of how representative each group is when compared to ist respective population.
4. The analytical method is fit for the intended purpose, if all groups are representative of their respective population.

**Definitions:**

σ: population standard deviation

$z_i$: z-score of $i^{th}$ group (according to positive z-score tables)

$n_i$: sample size of $i^{th}$ group

$\varepsilon_i$: error margin of $i^{th}$ group.

# Validation of analytical method
## Validation procedure (2)

- A **group $G_i$** is representative the population from which it was sampled if:
  1. The **sampling distribution** of the group can be approximated to a **normal distribution**.
  2. The **population mean, μ,** is within the **confidence range** determined by the group.

$$\bar{X}_i - \frac{z_i\sigma}{\sqrt{n_i}} \leq \mu \leq \bar{X}_i + \boxed{\frac{z\sigma}{\sqrt{n_i}}}$$

→ error margin

  3. The **mean square error (MSE)** of all observations within the group is comparable to the **population MSE**.

$$\mathrm{MSE}_i = \frac{1}{m}\sum_{j=1}^{m}\left(X_{i_j} - \mu\right)^2$$

Definitions:

μ: population mean

σ: population standard deviation

$\bar{X}_i$: sample mean for $i^{th}$ group

z: z-score according to positive z-score tables

$n_i$: sample size of the group

$X_{i_j}$: $j^{th}$ observation from $i^{th}$ group

# RESULTS ON THE VALIDATION

# Validation of analytical method

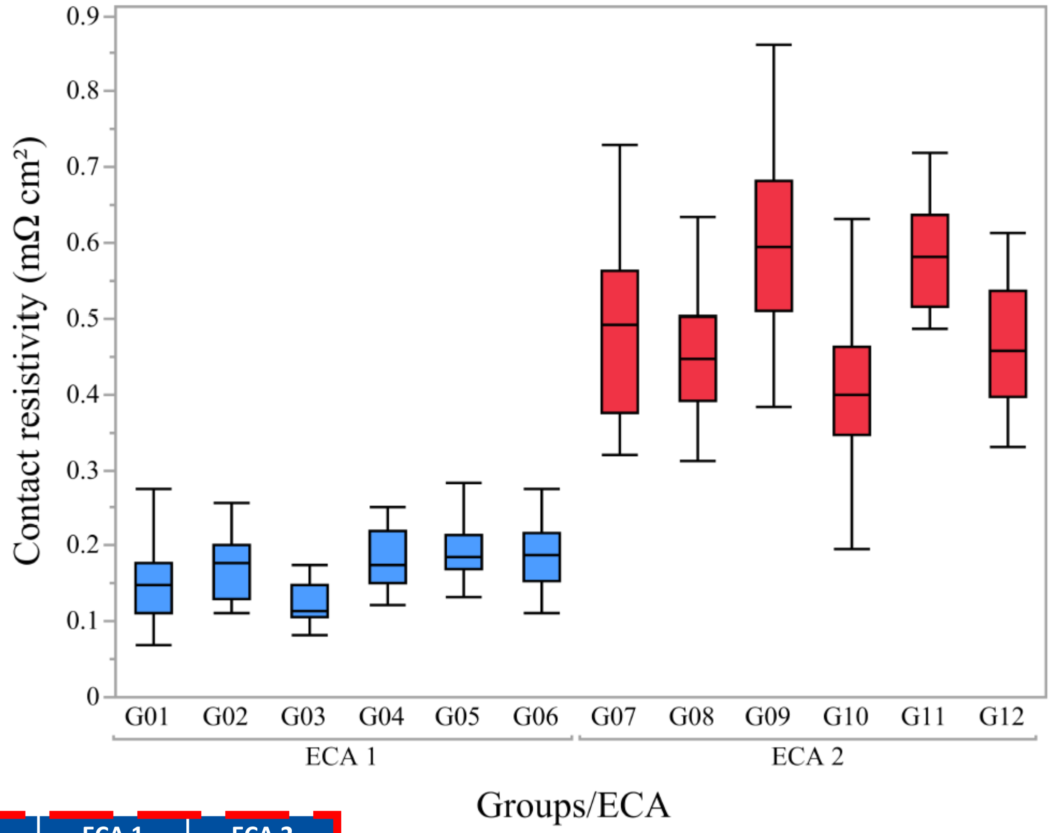
## Groups statistics (proper sample size **not defined**)

- Population mean for ECA 1 clearly differentiated from that of ECA 2.
- Neither the median nor the interquartile ranges from one ECA overlap with those of the other ECA.

| ECA | Group | n | $\overline{X}_i$ (mΩ cm²) | ε (%) | LCI limit | UCI limit | Is μ included? |
|---|---|---|---|---|---|---|---|
| ECA 1 | G01 | 23 | 0.1518 | 2.02 | 0.1315 | 0.1720 | yes |
| | G02 | 23 | 0.1739 | 2.02 | 0.1537 | 0.1941 | yes |
| | G03 | 18 | 0.1231 | 2.28 | 0.1003 | 0.1460 | **no** |
| | G04 | 20 | 0.1814 | 2.17 | 0.1597 | 0.2031 | yes |
| | G05 | 21 | 0.1943 | 2.12 | 0.1732 | 0.2155 | **no** |
| | G06 | 19 | 0.1886 | 2.22 | 0.1663 | 0.2108 | yes |
| ECA 2 | G07 | 25 | 0.4888 | 4.79 | 0.4409 | 0.5368 | yes |
| | G08 | 23 | 0.4598 | 5.00 | 0.4098 | 0.5098 | yes |
| | G09 | 20 | 0.5956 | 5.36 | 0.5420 | 0.6492 | **no** |
| | G10 | 23 | 0.4065 | 5.00 | 0.3565 | 0.4564 | **no** |
| | G11 | 24 | 0.5811 | 4.89 | 0.5322 | 0.6300 | **no** |
| | G12 | 20 | 0.4629 | 5.36 | 0.4093 | 0.5165 | yes |

**95% confidence level**

| Population | ECA 1 | ECA 2 |
|---|---|---|
| $\mu$ (mΩ cm²) | 0.1707 | 0.5025 |

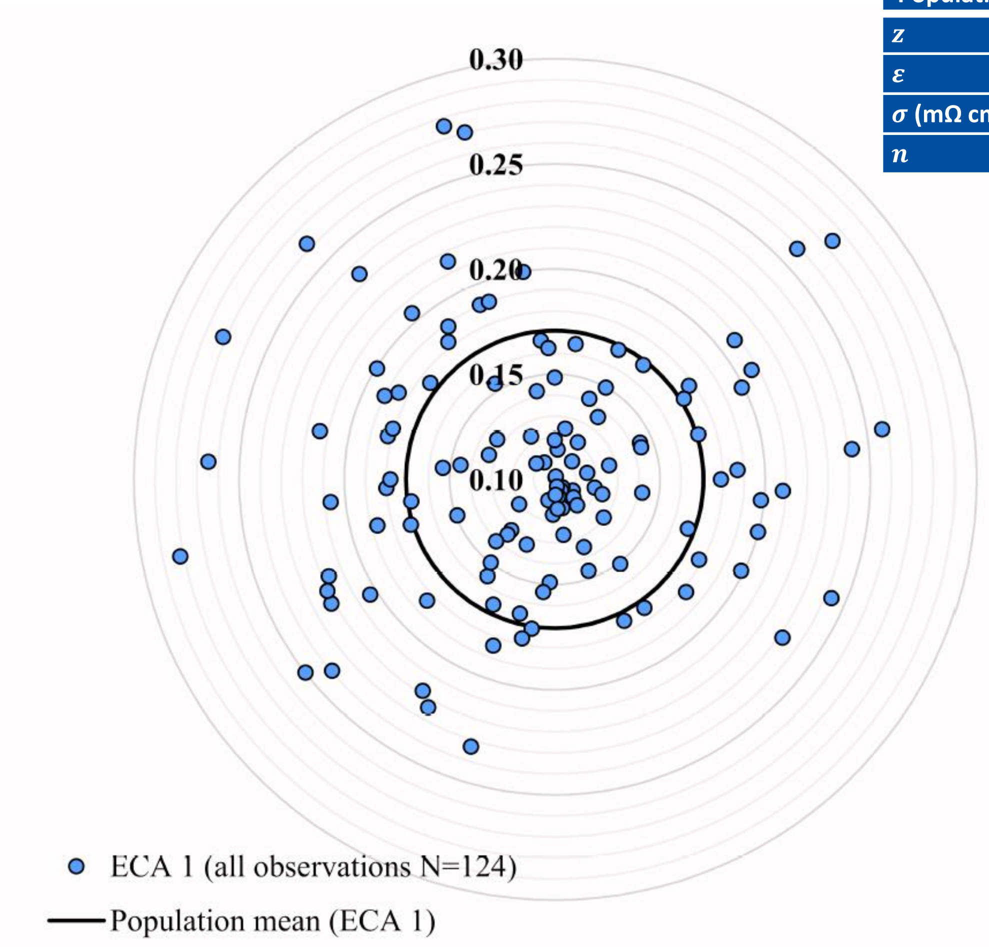


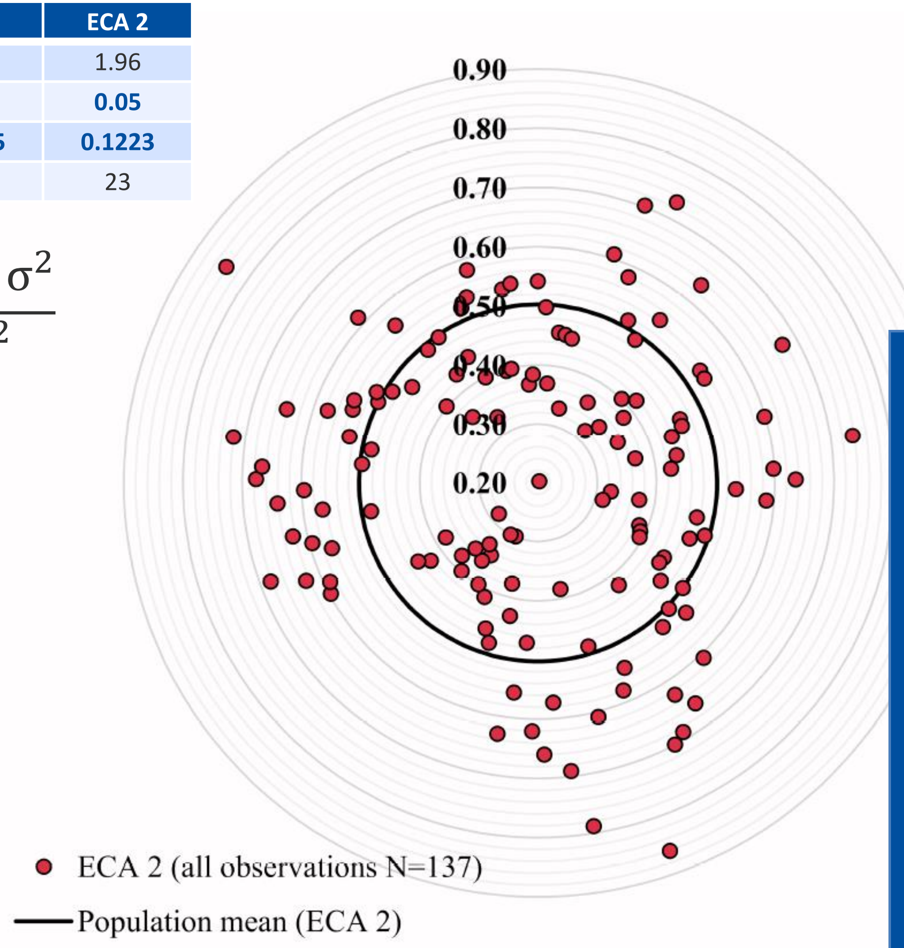
# Validation of analytical method

## Determination of proper sample size

| Population | ECA 1 | ECA 2 |
|---|---|---|
| $z$ | 1.96 | 1.96 |
| $\varepsilon$ | **0.02** | **0.05** |
| $\sigma$ (mΩ cm²) | **0.0495** | **0.1223** |
| $n$ | 23 | 23 |

$$n_i = \frac{z_i^2 \cdot \sigma^2}{\varepsilon_i^2}$$




**Definitions:**

σ: population standard deviation

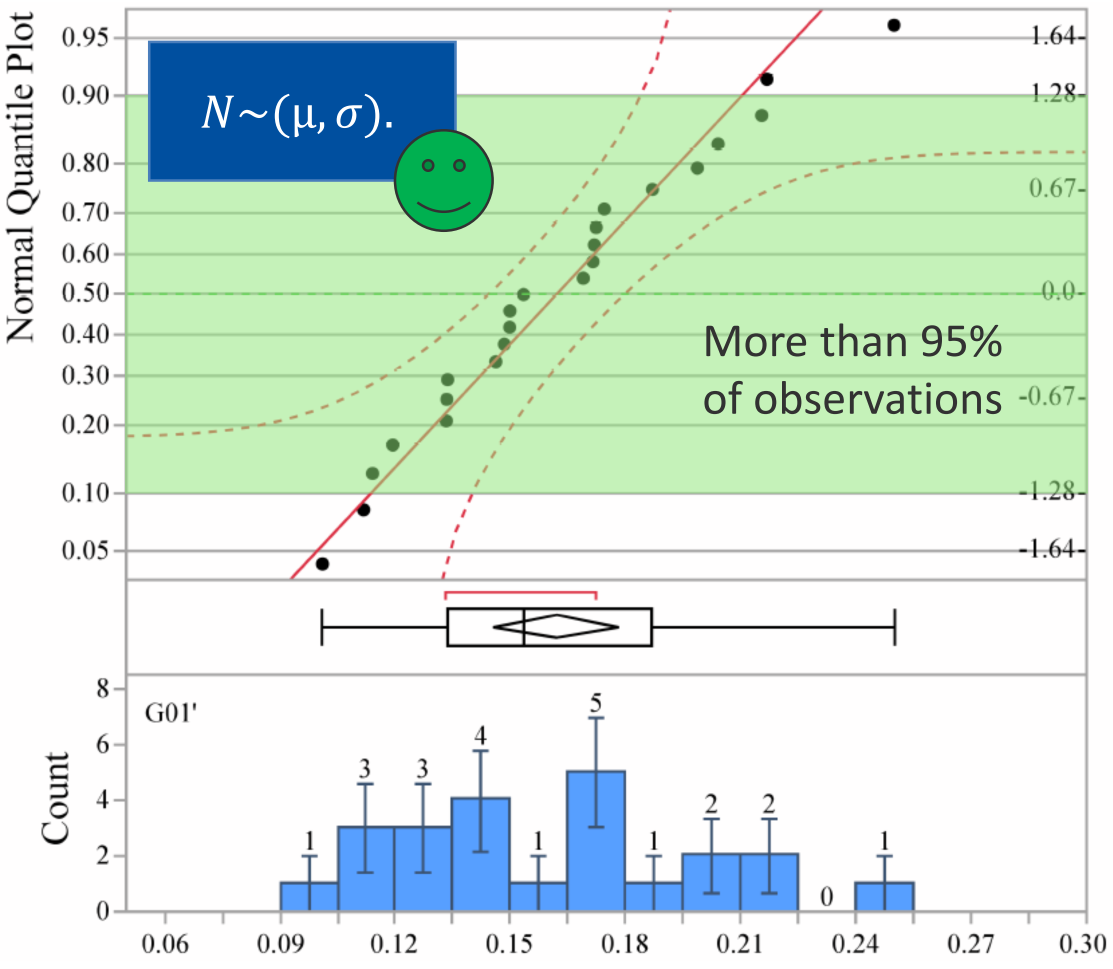
$z_i$: z-score of $i^{th}$ group (according to positive z-score tables)

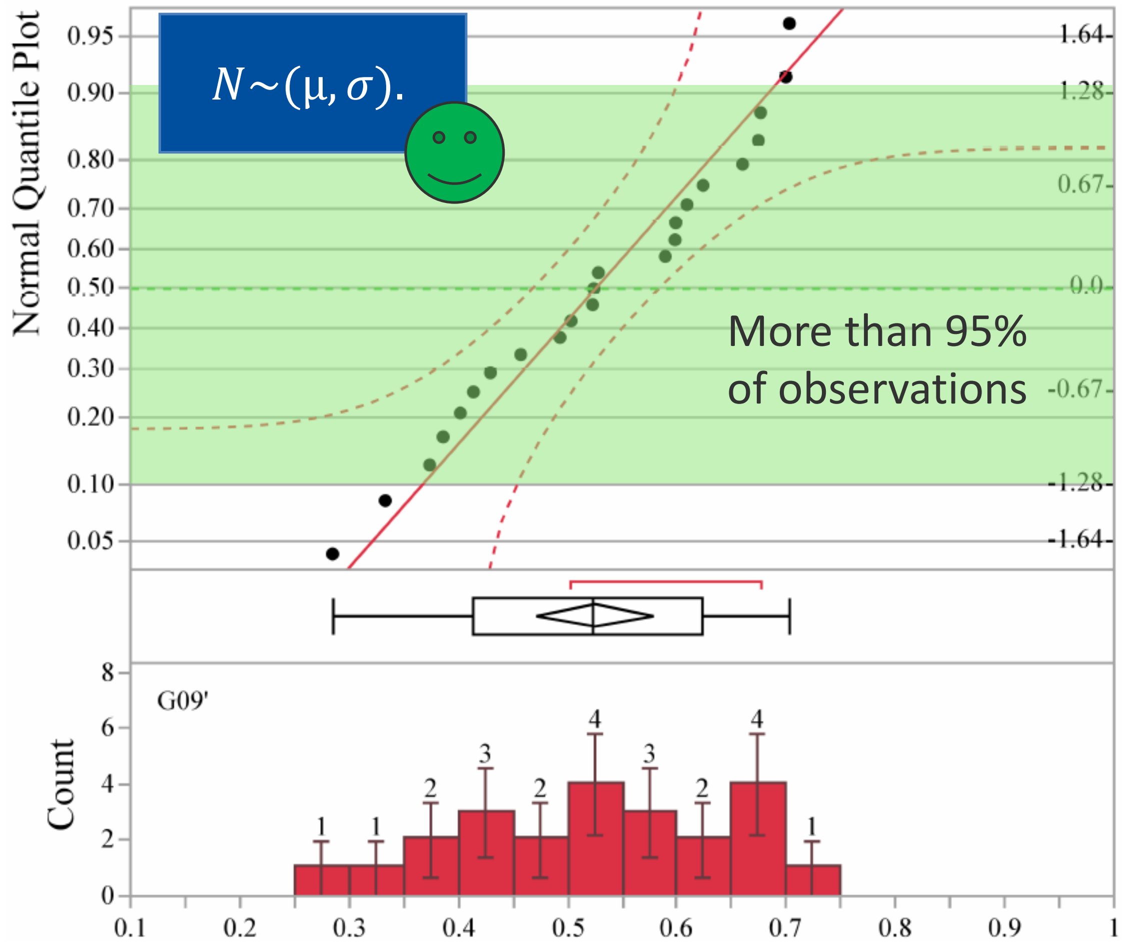
$n_i$: sample size of $i^{th}$ group

$\varepsilon_i$: error margin of $i^{th}$ group.

# Validation of analytical method

## Sampling frequency distribution (e.g.,G01’ & G09’)



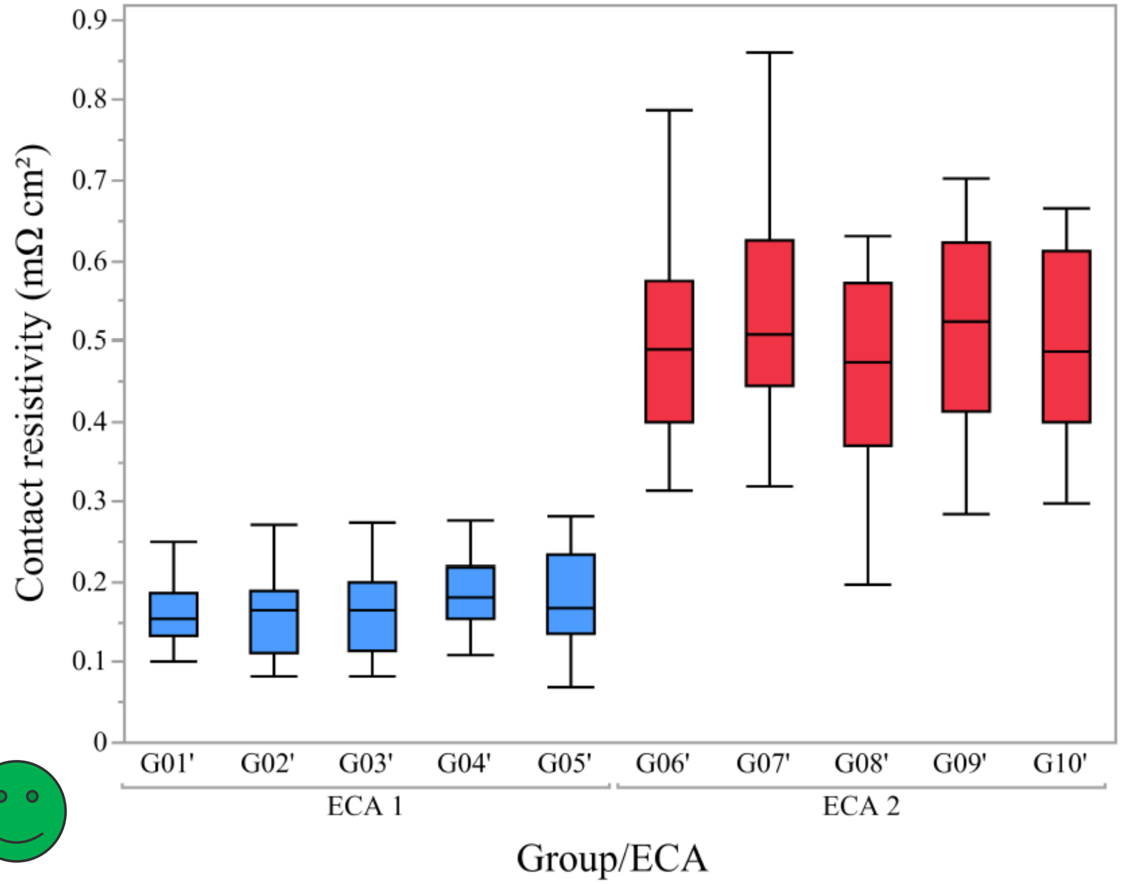
# Validation of analytical method
## Trueness evaluation via confidence interval

- Population mean for ECA 1 clearly differentiated from that of ECA 2.

- Neither the median nor the interquartile ranges from one ECA overlap with those of the other ECA.

| ECA | Group | $\overline{X}_i$ (mΩ cm²) | LCI limit | UCI limit | Is μ included? |
|---|---|---|---|---|---|
| ECA 1 | G01' | 0.1620 | 0.1418 | 0.1822 | yes |
| | G02' | 0.1590 | 0.1388 | 0.1792 | yes |
| | G03' | 0.1590 | 0.1388 | 0.1792 | yes |
| | G04' | 0.1860 | 0.1658 | 0.2062 | yes |
| | G05' | 0.1790 | 0.1588 | 0.1992 | yes |
| ECA 2 | G06' | 0.5021 | 0.4521 | 0.5521 | yes |
| | G07' | 0.5343 | 0.4844 | 0.5843 | yes |
| | G08' | 0.4643 | 0.4143 | 0.5143 | yes |
| | G09' | 0.5253 | 0.4754 | 0.5753 | yes |
| | G10' | 0.4955 | 0.4455 | 0.5455 | yes |

**95% confidence level**

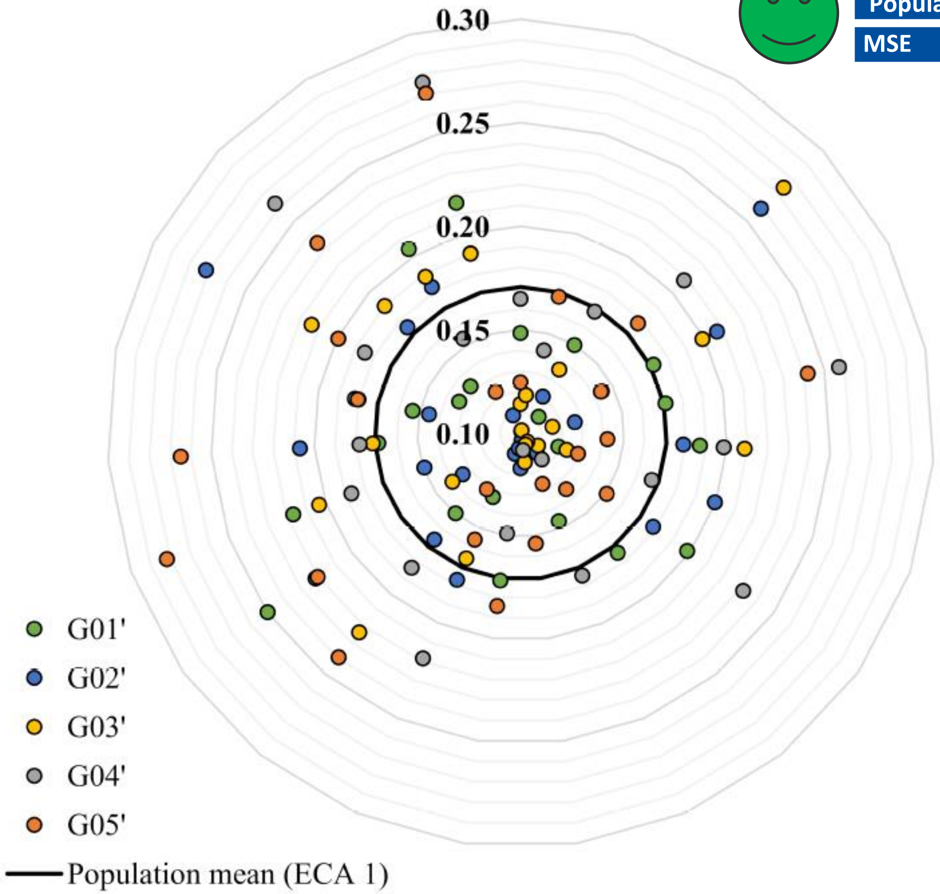


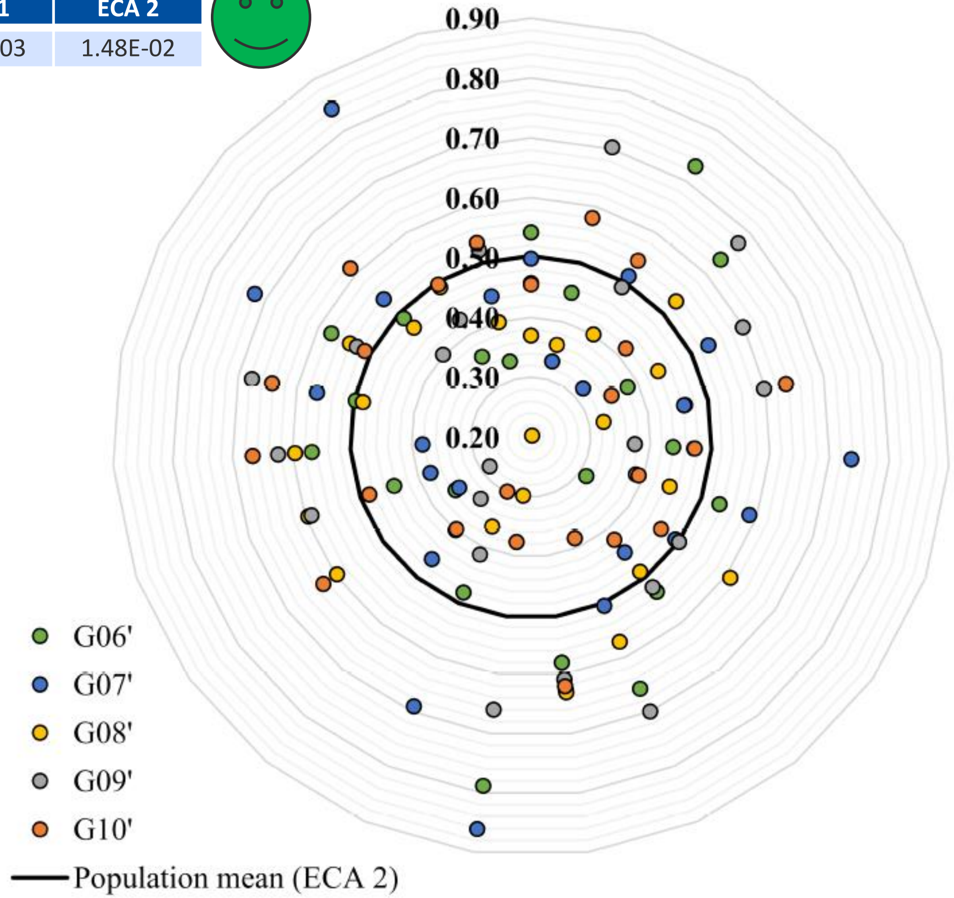

| Population | ECA 1 | ECA 2 |
|---|---|---|
| $\mu$ (mΩ cm²) | 0.1707 | 0.5025 |

# Validation of analytical method
## Precision evaluation via mean square error

| Group | G01' | G02' | G03' | G04' | G05' | G06' | G07' | G08' | G09' | G10' |
|---|---|---|---|---|---|---|---|---|---|---|
| MSE | 1.4E-03 | 2.7E-03 | 2.7E-03 | 2.5E-03 | 2.1E-03 | 1.5E-02 | 2.3E-02 | 2.3E-02 | 1.4E-02 | 1.5E-02 |

| Population | ECA 1 | ECA 2 |
|---|---|---|
| MSE | 2.33E-03 | 1.48E-02 |



# CONCLUSIONS

# Conclusions

- It was demonstrated that **realistic sample size** can be determined with a minimum **confidence level of 95%** and a maximum **error margin of 5%**.
- It was shown that the **sample size is highly dependent on the adhesive composition**. Thus, the margin of error may be required to be relaxed for ECAs displaying high degrees of scattering/standard deviation.
- The sampling distribution was demonstrated to follow the central limit theorem and the law of large numbers.

# Conclusions

- Accuracy of proper representative groups was evaluated via trueness and precision.
  - [**trueness**] The population mean was always found within the confidence interval in all groups.
  - [**precision**] The mean square error for the groups was comparable to the population.
- All groups with proper sample size were found to be representative of the population from where they were sampled.
- This work provided evidence that the **analytical method is fit for the intended purpose**.

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- For further questions, please refer to Ignacia Devoto via **ignacia.devoto@isc-konstanz.de**


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