Portfolio Department Fuel Cell Systems @ Fraunhofer ISE

Photo: Joscha Feuerstein
Our R&D focus is on PEM fuel cells and systems

0 Some facts and figures

1 Development

2 Modelling and Simulation

3 Characterization
Some facts and figures

PEM fuel cells are our profession.

- Characterization and modeling of PEMFC from cell to system level
- Development of fuel cell components, stacks, and systems
- System technology for membrane fuel cells up to 50 kW_{el}

➢ Back to overview ➢ Back to chapter 0: some facts and figures
Some facts and figures
Our department fuel cell systems

- We are assisting industry regarding fuel cells for over 20 years now regarding automotive, back-up power, and portable markets
- Budget 2.1 Mio. € (2017)
- 8 engineers, 5 scientists, 4 PhD students, 1 Technician, up to 15 students
- 10 fuel cell test stands
Development

- Components
- Cells
- Stacks

- Portable fuel cell systems
- Micro fuel cell systems
- System control

Back to overview
Fuel cell component development according to customers’ needs

- We offer customer related fuel cell components and assistance to customers material developments

- Components:
  - Electrodes
  - Catalyst coated membranes (CCMs)
  - Gas diffusion electrodes (GDE)
  - Membrane electrode assemblies (MEA)

- Own manufacturing facilities enable in-situ characterization of customers components

The SEM of a CCM of Fraunhofer ISE shows a homogenous structure of the electrode layers.

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Fuel cell component development according to customers’ needs

Example: Performance of Fraunhofer ISE CCMs

Polarisation curves of CCMs with varying ionomer content and process technologies

Modelling the CCM
Stack development according to customers’ needs
Example: LT-PEMFC stack for portable applications

- LT-PEMFC stack with 390 $W_{el}$
- Single cell cooling with cooling elements
- Integrated humidifier for anode and cathode gases
- Stack design optimized for assembling (no screws for stack contact pressure and single cell pre assembling)
- Cell design optimized for cost-effective manufacturing by simple punch cutting tool

Photo: Joscha Feuerstein

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1 Stack development according to customers’ needs
Example: Portable LT-PEMFC stack (performance)

$\lambda_{\text{Air}} = 2.5; \rho_{H_2} = 350 \text{ mbar}$

cell voltage / V

current density / mACm$^2$

Load 30 A
Stack development according to customers’ needs

HT-PEMFC stack concept

- HT-PEMFC short stack with 45 $W_{el}$ power (5 cells); full stack with 250 $W_{el}$
- Open, air-cooled cathodes
- Fixing technology of the stack is patented by Fraunhofer ISE

Photo: Joscha Feuerstein
System development according to customers’ needs
Example: 1.5 kW_{el} LT-PEMFC system

Example: PEMFC system with freeze start capability for grid independent telecommunication tower.
1 System development according to customers’ needs
Example: 1.5 kWel LT-PEMFC system (Performance)

System start-up: nominal power after 31 s; max. T difference 4 K between cooling in- and outlet

Test at +40 °C and 10% r.H. shows continuous power over 4 h.

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System development according to customers’ needs
Example: 300 W LT-PEMFC system for outdoor use

- Low temperature PEMFC Stack
- Air cooling
- E-PAC® housing
- Integrated battery for power management and autonomous startup
- Integrated charger for one to four cell lithium ion batteries
- Dimensions: 40 x 40 x 27 cm³
- Weight: 14.5 kg

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Back to chapter 1: Development
1 System development according to customers’ needs
Example: freeze start capability of 300 W LT-PEMFC
1 System development according to customers’ needs
Example: HT-PEMFC module for portable applications

- Compact module with high power density
- Power range 50 to 500 W
- Integrated heating unit
- Simple system handling and control by one fan
- Stack fully enclosed and thermally insulated
- Lightweight polymeric materials with 2.2 kg
- 240 x 120 x 100 mm³
1 System development according to customers’ needs
Example: HT-PEMFC module (Performance)

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1 System development according to customers’ needs
Example: Micro fuel cell systems

- 0.5 W DMFC
- Injection molding
- Passive evaporation of Methanol

Photo: Joscha Feuerstein

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Back to chapter 1: Development
System development according to customers’ needs

Example: Micro fuel cell systems

- DMFC with 0.5 W power
- PEMFC with 2.5 W power
- Injection molding for mass production
- Planar technology for self-breathing operation
- Application for container tracking, industrial sensors, towel supply, etc.

Photo: Joscha Feuerstein

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1 System development according to customers’ needs
Example: Micro fuel cell systems

Micro DMFC system of Fraunhofer ISE

Micro PEMFC system to operate a Raspberry Pi micro computer. Fraunhofer ISE

Photo: Joscha Feuerstein
1 System development according to customers’ needs
Example: Micro fuel cell systems

Long-term performance of 2-cell planar fuel cell modules (test cells) at 4 different outdoor sites within the Freiburg city area over 6,000 hours.

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Control strategies including control and power electronics

Current-controlled DC-DC converter for optimized fuel cell operation

Back to overview
Back to chapter 1: Development
2 Modelling and simulation

- Electrode
- Physical modelling of water transport in porous layers
- Modelling of electro-chemical impedance spectra with electrical networks
- Fuel cell system simulation
- Model assisted dimensioning of multi-source power supplies with HOMER

➢ Back to overview
Modelling and simulation

Electrode

- Electrode model takes into account the carbon with catalyst, Nafion distribution and pores, which are (partly) covered with liquid water.

- Simulation enables e.g. the investigation of current production due to proton / current conductivity within the electrode.

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2 Modelling and simulation
Extracting properties by an analytical catalyst layer model

- Analyzing the development of CL properties (degradation) during AST
- Used model developed by A.A. Kulikovsky, JES, 161 (3), F263-F270; 2014
- Assumptions
  - Isothermal, no two-phase flow, no inner cathode structure
  - Inhomogeneous current generation
  - Ohmic Law
  - Fickian Diffusion

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2 Modelling and simulation
Extracting properties by an analytical catalyst layer model

- Curve fitting of model with experimental AST results
- Extracted model parameters show change in electrode structure due to degradation

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2 Modelling and simulation
Water transport in porous media

- Coupling of continuum and discrete model

Discrete model
- \( s_{cond} \)
- \( s_{inj} \cdot p_{intr} \)

Continuum model
- \( T, F_p, c_{O2}, c_{H2O}, l, p \)
- \( s = s_{cond} + s_{inj} \cdot H(p-p_{intr}) \)

\( l_d(i) \)
\( O_d(i) \)
\( D_p \)
\( X \)
\( O_c(i-1) \)
\( O_c(i) \)

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Modelling and simulation
Water transport in porous media: Model validation


Model results

Synchrotron visualization [1]

Toray TGP-H-060 (20 wt% PTFE), T=35°C, I=0.5 Acm-2
2 Modelling and simulation
Water transport in porous media: effect of micro porous layers (MPL)

Without MPL
- Inhomogeneous current density distribution
- Current generation under land due to eruptive water transport

With MPL
- Higher current density despite additional MPL diffusion resistance
- Water only at injection points due to in-plane transport at CCL interface


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Modelling and simulation
Modelling of electro-chemical impedance spectra with electrical networks

- Simplified 2D+1 model
- Tafel law describes charge transfer resistance
- Double layer charging
- Fick’s diffusion of air and water vapor in GDL
- Ohmic loss in membrane as a function of the water content
- Phase change of water in GDL
- Fickian diffusion approach for saturation
- Contact resistance on cathode and anode
- Anode polarization neglected

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Modelling and simulation
Modelling the state-of-health of fuel cells

Performance model
- as simple as possible
- 1D

Degradation model
- Change in GDL, CL, membrane properties

Operating conditions
- Kinetics & structural parameters

Current load
- Cell voltage, overpotentials, actual states

Feedback

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- Back to chapter 3: Characterization
Fuel cell segments are coupled to nearest neighbors (x-y-direction) by:

- Gas convection of air and vapor according to flow field pattern
- Cross current in GDL
- In-plane permeation of liquid water
2 Modelling and simulation
System modelling

- Optimizing system efficiency by studying different operation strategies

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Modelling and simulation
Developing system operation strategies with HOMER

<table>
<thead>
<tr>
<th>Recharging strategy</th>
<th>H2 production kg</th>
<th>Operating time FC (h)</th>
<th>Start / Stop FC</th>
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</thead>
<tbody>
<tr>
<td>30% SOC</td>
<td>11.5</td>
<td>84</td>
<td>16</td>
</tr>
<tr>
<td>90% SOC</td>
<td>22.5</td>
<td>185</td>
<td>8</td>
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</tbody>
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Characterization

- In-situ characterization of PEMFC single cell components
- Fuel cell stack and system characterization
- Testing of balance-of-plant components
3. In-situ characterization of single cell components

- Performance characterization of components and designs
- Life-time testing and accelerated stress tests
- Investigation of contamination effects
- Characterization of local effects

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Back to chapter 3: Characterization
3 Performance of components (single cell)

Equipment

- Test cells:
  - Quick Connect (baltic®) or customer cells
  - Differential test cells: Fraunhofer ISE or customers designs
  - Along-the-channel test cell: investigation in real channel-land designs
  - Active area from 4 cm², typically 25 cm², up to 300 cm² (790 A<sub>DC</sub>)

- Test stands:
  - Fully equipped with humidification on cathode and anode, gas pressures up to 3 bar<sub>a</sub>
  - Cathode: air / O<sub>2</sub> / N<sub>2</sub>
  - Anode: H<sub>2</sub> / synthetic reformate

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In-situ characterization of single cell components

Equipment

- Differential cells are used for material / component evaluation independently from concrete designs.
- Our along-the-channel test is especially designed for cost effective investigations regarding material / component performance according to real cell designs and real stoichiometries.

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➢ Back to chapter 3: Characterization
3 In-situ characterization of single cell components
Fraunhofer baltic PEM Fuel Cell Component Evaluation

- Differential test cell
- Easy handling for fast component exchange
- Liquid cooling
- Controllable (pneumatic) clamping pressure directly on the active area

Photo
Joscha Feuerstein

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3 Performance of components (single cell)

Portfolio

- Characterization:
  - i-V-curves
  - Electro-chemical impedance spectroscopy from 0.1 Hz to 10 kHz
  - Cyclovoltammetry
  - Linear sweep voltammetry
  - Limited current measurements

- NEW:
  - Due to own manufacturing facilities we are able to perform in-situ characterization with customer made catalysts, catalyst supports, membranes, GDLs

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Life-time testing & accelerated stress tests (single cell)

Equipment

- Test cells:
  - Differential test cells: Fraunhofer ISE-baltic® or customers designs
  - Along-the-channel test cell: investigation in real channel-land designs
  - Active area from 4 cm² up to 300 cm² (790 A), typically 25 cm²

- Test stands:
  - Fully equipped with humidification on cathode and anode, gas pressures up to 3 barₐ
  - Cathode: air / O₂ / N₂ | anode: H₂ / synthetic reformate
Life-time testing and AST in single cells

Portfolio

- Characterization:
  - i-V curves
  - Electro-chemical impedance spectroscopy from 0.1 Hz to 10 kHz
  - Cyclovoltammetry | Linear sweep voltammetry
  - Limited current measurements

- Test protocols:
  - Fully automated, highly reproducible characterization
  - Typically according to DOE or defined by customer or Fraunhofer ISE
  - AST for catalysts (H₂/N₂), catalyst supports (H₂/N₂), membrane (humidity cycling), in-situ cycling, constant voltage

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3 Life-time testing and AST in single cells
Example: Accelerated stress tests over 80,000 cycles
3 Testing of contamination effects (single cell)

Equipment

- Test cells:
  - Differential test cells: Fraunhofer ISE-baltic® or customers designs
  - Along-the-channel test cell: investigation in real channel-land designs
  - Active area from 4 cm² up to 300 cm² (790 A), typically 25 cm²

- Test stands:
  - Fully equipped with humidification on cathode and anode, gas pressures up to 3 bar$_{a}$
  - Cathode: air / O$_2$ / N$_2$ | anode: H$_2$ / synthetic reformate
  - Contamination on cathode or anode according to customers specification regarding gases and concentrations
3 Testing of contamination effects (single cell)

Portfolio

- Characterization:
  - i-V curves
  - Electro-chemical impedance spectroscopy from 0.1 Hz to 10 kHz
  - Cyclovoltammetry
  - Linear sweep voltammetry
  - Limited current measurements

- Test protocols:
  - Typically defined by customer

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3 Characterization of local effects (single cell)

Equipment: along-the-channel test cell

- Material screening with stoichiometric operation
- Studying effects of real channel-land geometries
- Along-the-channel test cell: 1 x 25 cm², 5 channels, co- & counterflow configuration possible
- Customer specific designs for channel-land geometries possible
Characterization of local effects (single cell)
Example: along-the-channel test cell

Local dynamics of membrane hydration

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Characterization of local effects (single cell)
Equipment: (automotive) segmented cells

- Cell dimensions max. 650 x 300 mm² (L x W), maximum clamping force 120 kN
- Segmented anode- or cathode plate is realized with customer design; unchanged customer design on unsegmented side

Photo: Joscha Feuerstein
Segmented cell with current collector (PCB with contact pins)

Test cell portal (right), test stand (background), 68 potentiostats and FRAs (left)

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Characterization of local effects (single cell)

Equipment: test stand

- Segments are connected to 50 potentiostats (+/- 5 A; +/- 5 V) & 18 potentiostats (+/- 30 A / +/- 5 V) together with 50 + 18 frequency response analyzers (frequencies: 0.1 Hz to 10 kHz)
- Total cell current up to 790 A
- Gas supply fully humidified; cathode with air, O₂, He, or N₂

Locally distributed high frequency resistance of a fuel cell

Current distribution in a fuel cell

Locally distributed high frequency resistance of a fuel cell

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3 Characterization of local effects (single cell)
Portfolio

- Characterization:
  - Current voltage mapping (up to 790 A in up to 68 segments)
  - Electro-chemical impedance spectroscopy from 0.1 Hz to 10 kHz in each segment simultaneously
  - Dynamic load changes in each segment simultaneously
  - Chronovoltametry, -amperometry in each segment simultaneously
  - Temperature distribution over cell area

- Test protocols:
  - Typically defined by customer
3 Fuel cell stack and system characterization

- Performance testing
- Life-time testing
- Accelerated Stress Tests
- Tests in climate chamber
- Short circuit and isolation tests

Photo: Joscha Feuerstein

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3 Fuel cell stack and system characterization

Equipment: test stands

- Testing of fuel cell stacks up to 20 kW_{el} / 1000 A_{DC}

- Simultaneous analysis of single cell voltage and single cell electro-chemical impedance spectroscopy with 20 or 50 channels, frequency range from 10 kHz to 0.1 Hz

- Fully equipped with humidification on cathode and anode, gas pressures up to 3 bar_{a}, cathode: air / O_{2} | Anode: H_{2} / synthetic reformate

- System oriented stack testing due to possible control of peripherals

- Testing at extreme climate conditions by implementation into walk-in climate chamber

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Fuel cell stack and system characterization
Portfolio: test protocols

- Performance, life-time, and AST testing according to customer defined protocols
- Cold start / freeze start
- Extreme environmental conditions (T, rH)
- Component benchmarking (e.g. differently assembled single cells within one stack)


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Fuel cell stack and system characterization
Portfolio: characterization

- i-V curves
- Simultaneous single cell EIS from 0.1 Hz to 10 kHz and single cell voltage monitoring at inlet and outlet (measurement equipment with 20 and 50 channels)
- Cyclovoltammetry

Electro-chemical impedance spectroscopy of 20 single cells within a stack simultaneously. The diagram shows the average, the minimum, and the maximum spectra at three different current densities.

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The analysis of the simultaneous single cell electro-chemical impedance spectra within a stack allows to analyse the gas distribution within a stack. The diagram shows the gas residence time of the different cells of a 20 cell automotive (short) stack at two stoichiometries.
Fuel cell stack and system characterization

**Equipment: climate chamber**

- Supply of conditioned air up to 2,000 m³/h
- Temperature range from -20 °C to +60 °C
- Temp. tolerance: ± 1 K
- Cooling power: 10 kW<sub>th</sub>
- Humidity range from +5 % r.H. to +95 % r.H. @ temperatures above +10 °C
- Humidity tolerance: ± 3 %

Photo: Joscha Feuerstein

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3 Fuel cell stack and system characterization
Equipment short circuit and isolation testing

- MOSFET used for bounce-free circuit switching
- Direct measured shunt for appreciation of value vs. costs
- Oscilloscope with high sampling rate (100 kHz @ test bench)
- High cable and bar section (5000 A for 20 ms) to avoid losses
- $\text{OCV}_{\text{max}} \leq 20\text{VDC}$
3 Fuel cell stack and system characterization

Example: short circuit testing

MOSFET use (example with sampling rate 50.000 Hz)
Testing of balance-of-plant components

Portfolio: Characterization

- Testing of valves, pumps, fans, coolers, humidifiers, condensers, fittings etc.
- Cycle testing (functionality of the component) under various environmental conditions
- Leakage tests
- (Electro-) chemical stability of fuel cell systems and components
- Electrical conductivity and contact resistance
Testing of balance-of-plant components

( Electro-)chemical stability of fuel cell systems and components

- Analysis of product water with ICP-MS (Inductively Coupled Plasma Mass Spectrometry)
- Analysis of cooling liquid
- Chemical stability of fuel cell components and system components
- Electrochemical stability of bipolar plates
- Investigation of the surface of components before and after aging with SEM/EDX
- Fenton test for membranes
3 Testing of balance-of-plant components

Equipment I

- 2 climate chambers
- Thermal imaging using infrared camera
- Vacuum chamber for simulating high altitudes
- 12 bar hydrogen compressor for pressurized testing of components

Life-time testing of valves with T cycling.

Life-time testing of a cooler at high T.

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Ex-situ testing of components

Equipment II

- Inductively coupled plasma – mass spectrometry (ICP-MS): Measurement of element concentrations in liquids up to ng/l
- Scanning electron microscopy (SEM): imaging of sample surface
- Energy dispersive X-ray (EDX): element composition of surface

Ex-situ analysis of components by ESEM and EDX.
Ex-situ analysis of liquids ICP-MS.

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### Ex-situ testing of components

**Equipment: ESEM / EDX**

- Above: phase change of water in porous materials.
- Middle: SEM / EDX of catalyst coated membranes
- Right: investigation of hydrophobicity of electrodes.

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Ex-situ testing of components

Equipment: ICP-MS

- Element analysis of liquids: only elements, no molecules
- Sample is nebulized and evaporised
- In Ar-plasma the molecules are destroyed and ionised
- In the mass spectrometer the ions of every mass are counted
Ex-situ testing of components

Equipment: ICP-MS

Insertion of balance-of-plant elements in aggressive solutions

Element concentration in the product water of a LT-PEMFC
Testing of balance-of-plant components
Analysis of product water with ICP-MS

Product water analysis of a fuel cell stack with metallic bipolar plates

Product water analysis of a fuel cell stack with graphitic bipolar plates

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Testing of balance-of-plant components
Chemical stability of fuel cell and system components

Wetted valve components after 8 weeks in deionized water

ICP-MS Analysis of this water after 8 weeks

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Ex-situ testing of components

Corrosion testing

Electro-chemical characterization e.g. to determine corrosion current with working electrode (WE) (sample), reference electrode (RE), and counter electrode (CE).

Test set up with chemical stable material and integrated heating for temperature controlled measurements.

Measurements can be combined with SEM analyses (see figure above), element analyses of the electrolyte with ICP-MS, and contact resistance measurement.

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Ex-situ testing of components

Corrosion testing

Electrochemical Test Cell „FlexCell“ from Gaskatel
Made of PTFE: chemically inert, no contamination of the electrolyte, suitable for element analysis of the electrolyte
Pressing device for plane working electrodes: no contact of edges and back side to the electrolyte
Simulation of fuel cell condition: Bubbling with N₂ (anodic conditions) or O₂ (cathodic conditions)

Gas tube
Temperature sensor
Reference Electrode (Luggin capillary to WE)
Working Electrode
Counter Electrode
Electrical heating

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Ex-situ testing of components
Corrosion testing

Polarization curves of uncoated and coated stainless steel bipolar plate (316L)
Counter electrode: Pt
Reference electrode: RHE (Reversible Hydrogen Electrode)
- anode potential in fuel cell
- no inner electrolyte
- no contamination of electrolyte
- wide temperature range
Potential: 800 mV vs. RHE
Temperature: 80°C
Electrolyte: 1 mM H₂SO₄
Gas: O₂ (cathodic conditions)
3 Ex-situ testing of components

Fenton test for membranes

- Fenton test: adding cations (typically Fe$^{2+}$) to a 30% H$_2$O$_2$ solution and inserting a membrane
- Measurement of F$^-$ release over time
  - Prevent complexes of F$^-$ with cations
  - Remove H$_2$O$_2$ as it disturbs measuring of F$^-$
- Use of chemical inert polymer bottles
- Different temperatures possible
- Testing with different cations and/or membranes; variation of cation concentration
  - Fenton tests with different cations: I: Al, II: Si, III: Fe, IV: Cu, V: Mn
Ex-situ testing of components

Equipment: in-plane conductivity

Measurement of conductivity in dependence of orientation, thickness, pressure, and temperature of the sample

Resistivity of a sample is measured as a ratio of the product of (the resistance, width and thickness) and the length between measurement contacts

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Ex-situ testing of components

Equipment: through-plane conductivity

4 point measurement of through-plane conductivity in dependence of coating, pressure, and temperature of the sample

Measurement principle