
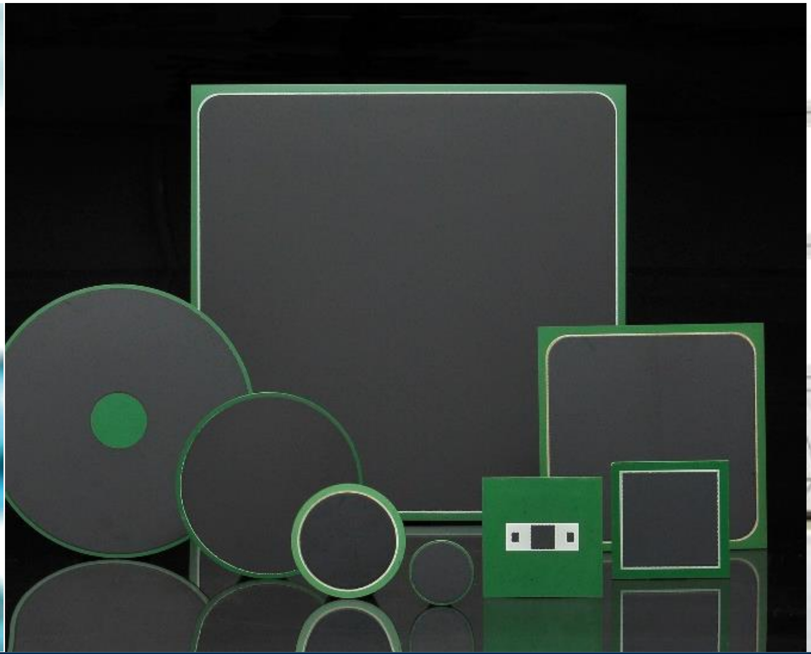


Processing and durability of fuel electrode-supported cells with Ni-GDC electrode

APRIL 16TH, 2026 | CHRISTIAN LENSER, DENISE RAMLER, STEFAN KUCHARSKI, IURII KOGUT, ANDRÉ WEBER, AND NORBERT H. MENZLER

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(2) Institute for Applied Materials (IAM-ET), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

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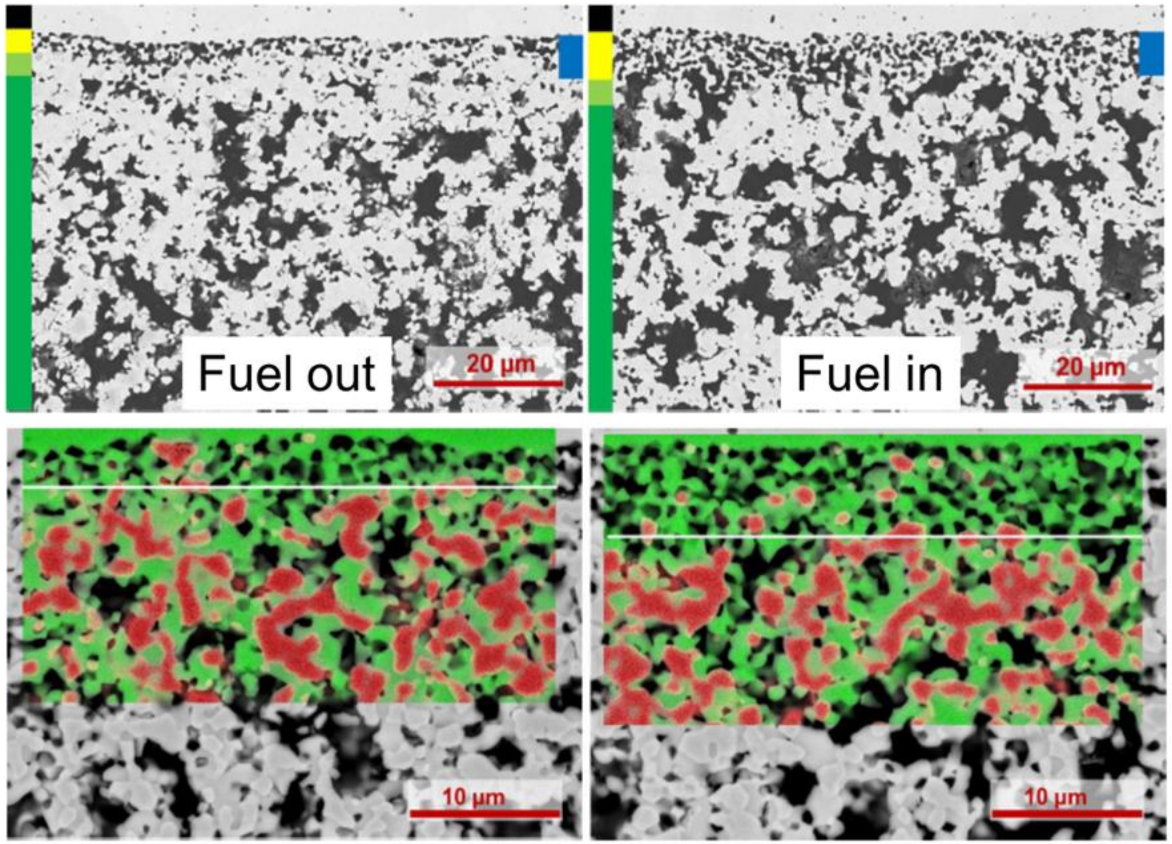
Wandel gestalten

Motivation: Ni migration in Ni-YSZ



Ni depletion in fuel electrode after 20.000 h of electrolysis operation

C. Frey, et al., *J. Electrochem. Soc.* (2018);165:F357-F64.
Q. Fang, et al., *J. Electrochem. Soc.* (2018);165:F38-F45.

- Voltage / ASR degradation of 0.6 / 8.2% / kh
- Ni migration as the primary degradation mechanism
- Can Ni-GDC cathodes solve this problem?

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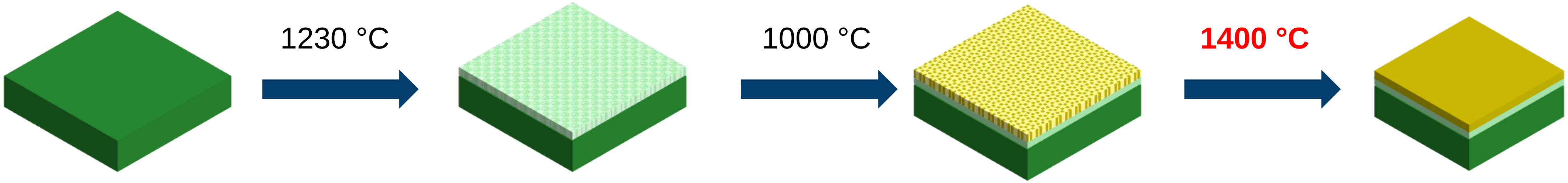
Material challenge - Integration of Ni-GDC into FESCs

- Ni-GDC fuel electrode is common in metal-[1,2] or electrolyte-supported[3,4] cell designs
- Very rarely encountered in fuel electrode-supported cells
- The problem can be located in the manufacturing route:



NiO-YSZ support
Tape casting

NiO-YSZ fuel electrode
Screen printing

YSZ electrolyte
Screen printing

Sintered half cell

[1] D. Udomsilp et al., Cell Reports Physical Science, 1 (2020) 100072.
[2] C. Bischof et al., International Journal of Hydrogen Energy, 44 (2019) 31475-31487.
[3] N. Trofimenko et al., ECS Transactions, 78 (2017) 3025-3037.
[4] M. Kusnezoff et al., Materials, 9 (2016) 906.

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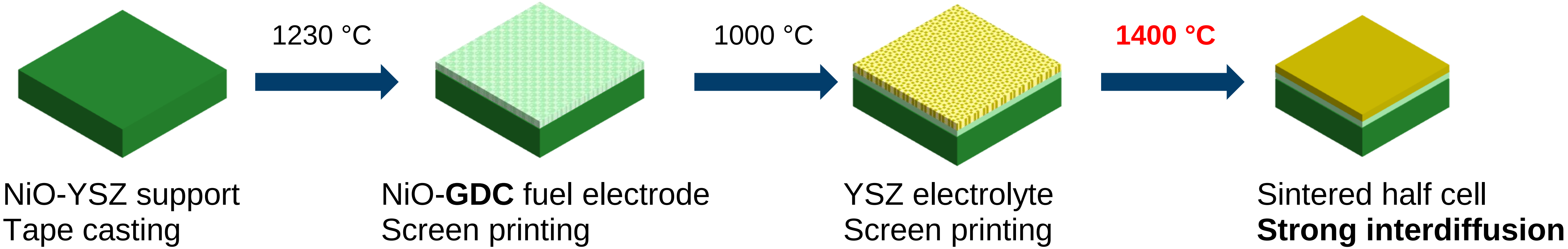

[1] D. Udomsilp et al., Cell Reports Physical Science, 1 (2020) 100072.
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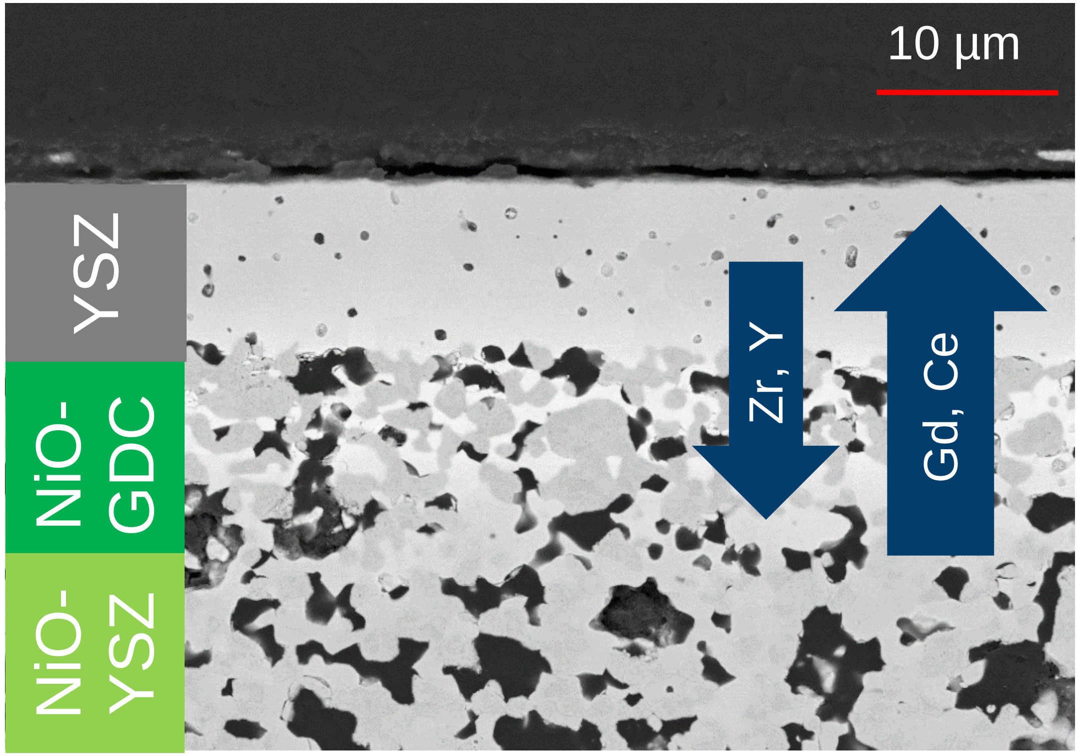
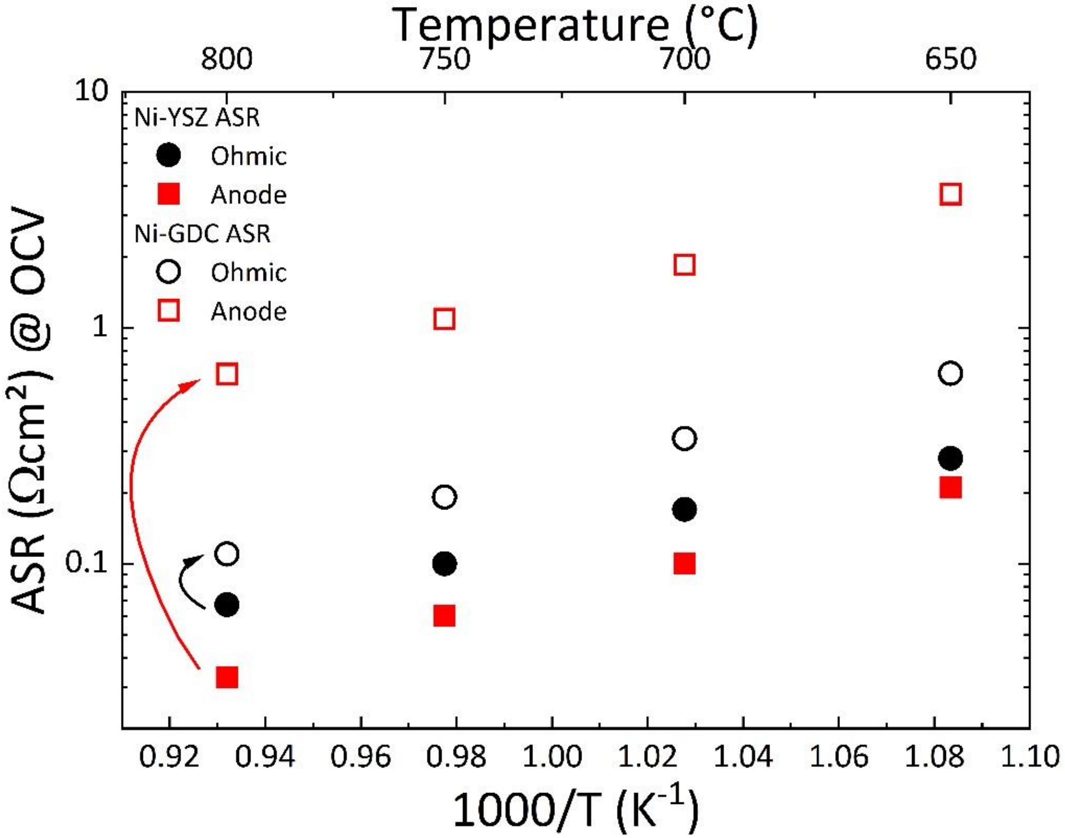
[3] N. Trofimenko et al., ECS Transactions, 78 (2017) 3025-3037.
[4] M. Kusnezoff et al., Materials, 9 (2016) 906.

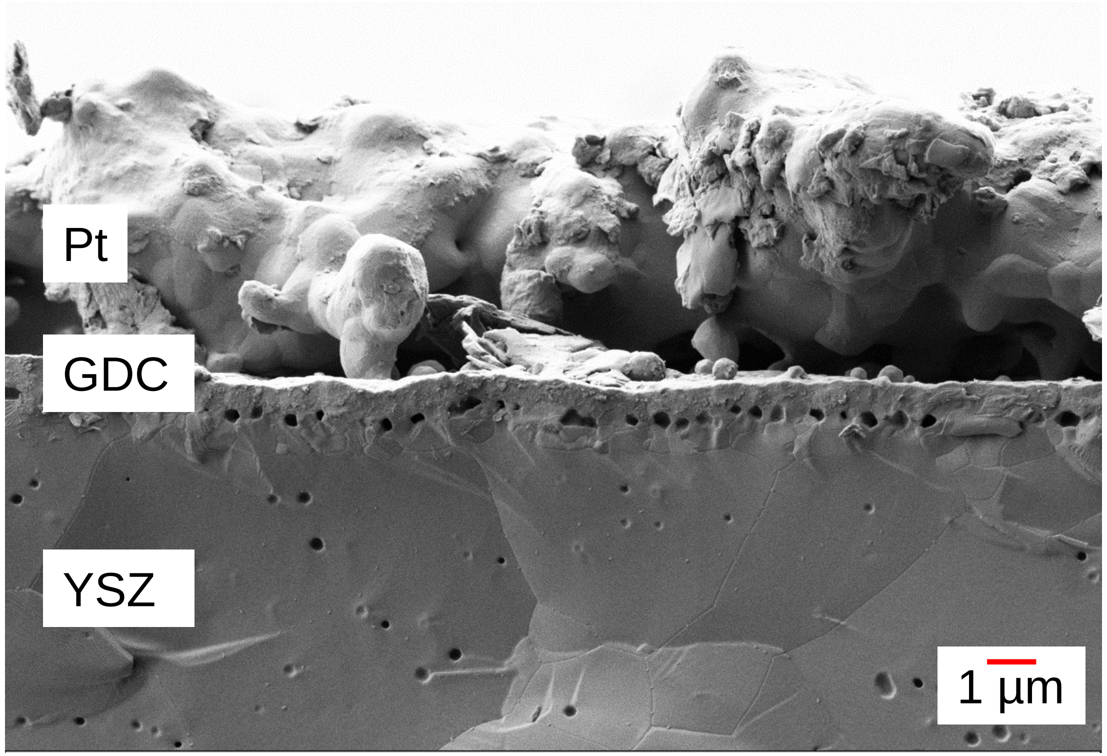
Reduced performance due to interdiffusion

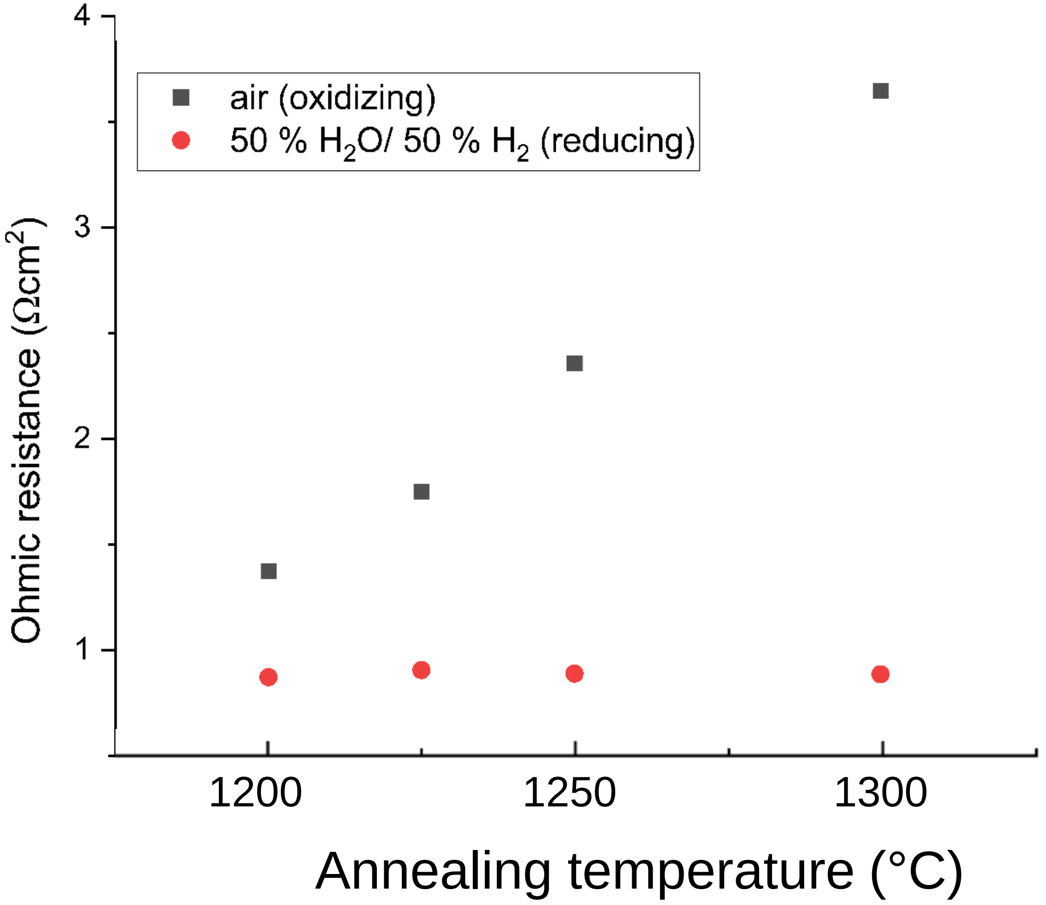
- Substitution of NiO-YSZ by NiO-GDC in FESC manufacturing route → decreased performance
- Well-known: decreasing conductivity, less well-known: Kirkendal porosity





Effect of interdiffusion as a function of pO_2

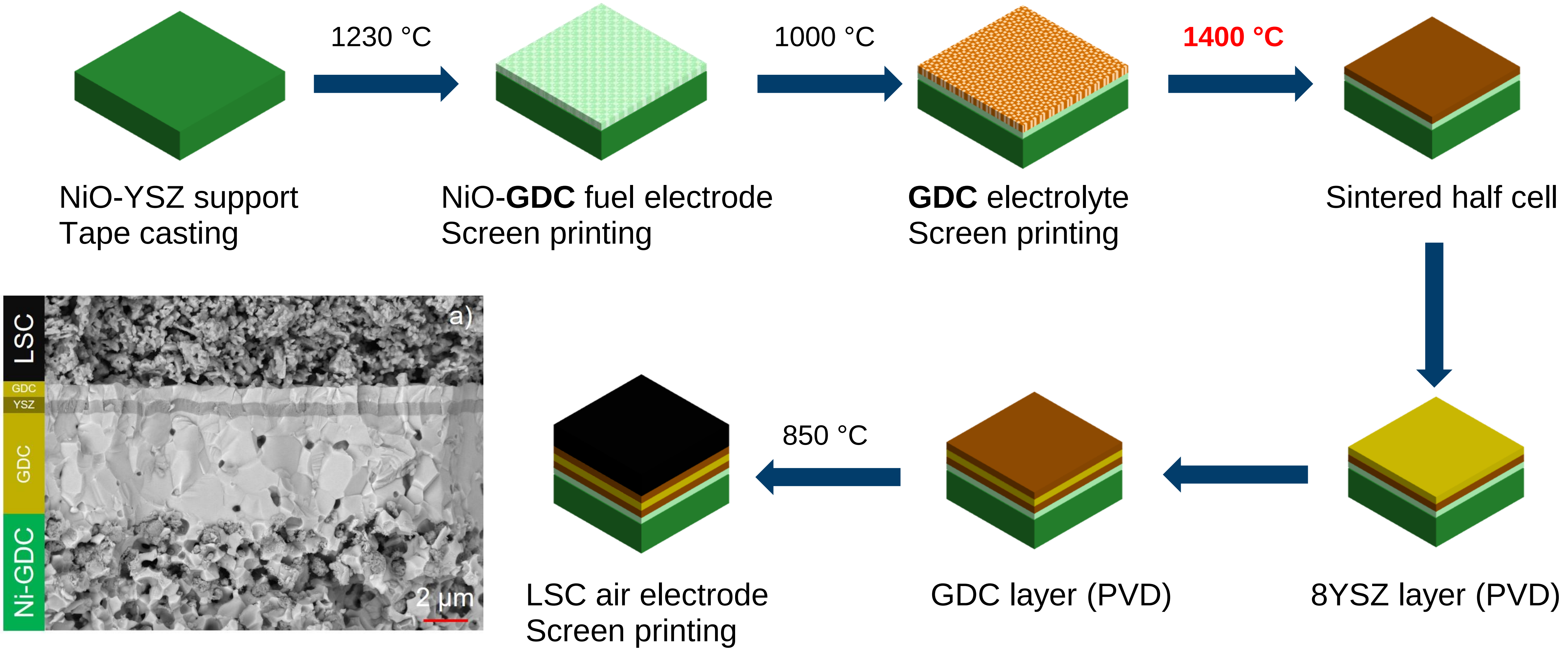




- Interdiffusion at GDC-YSZ model interface
- R_{ohm} in air, R_{pol} in H_2

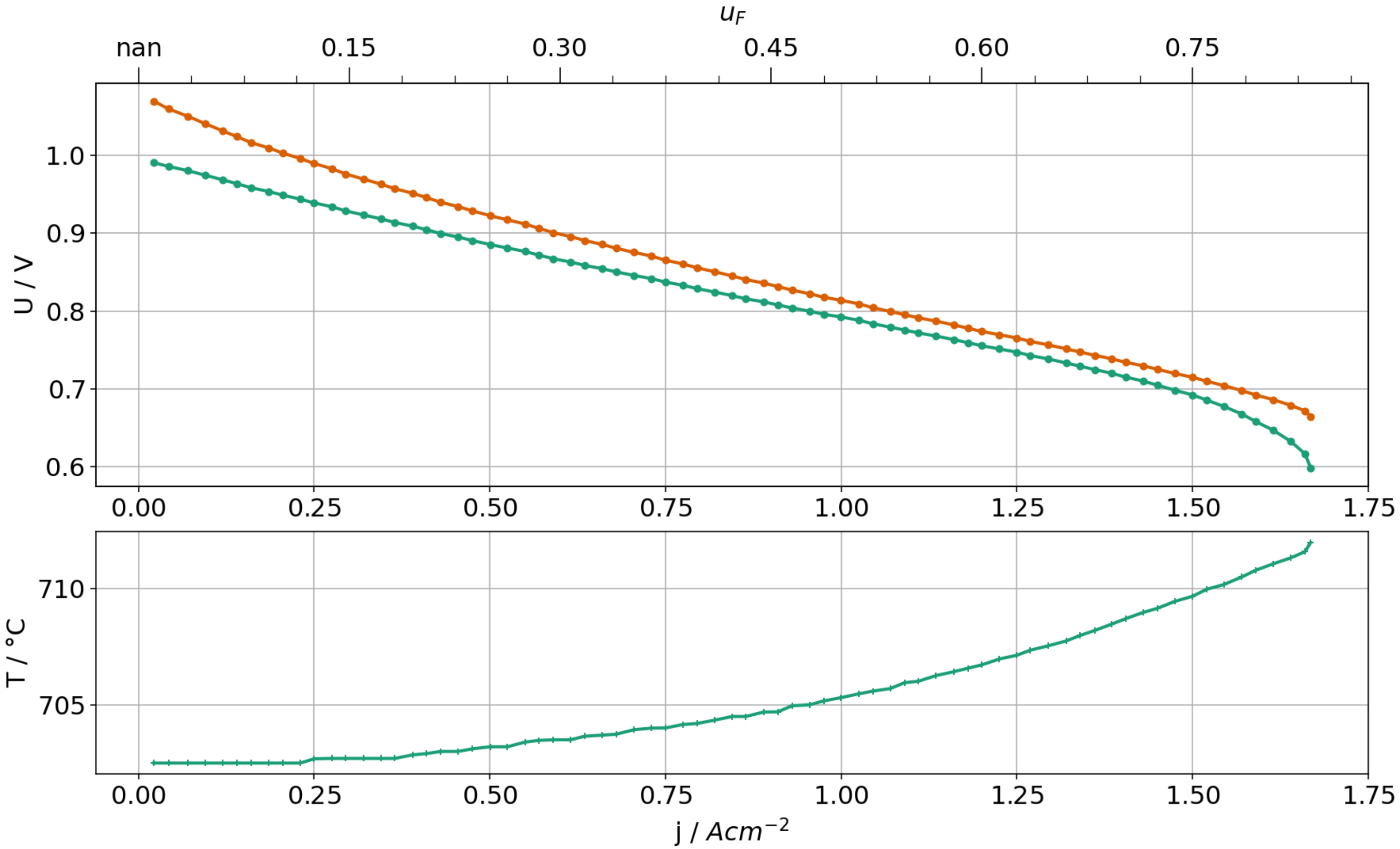
Albert Lopez de Moragas, et al, in preparation

How to avoid interdiffusion



[1] J. Zhang, C. Lenser, N. Russner, A. Weber, N.H. Menzler, O. Guillon, Journal of the American Ceramic Society, 106 (2022) 93-99.

2-layer shortstack with PVD electrolyte

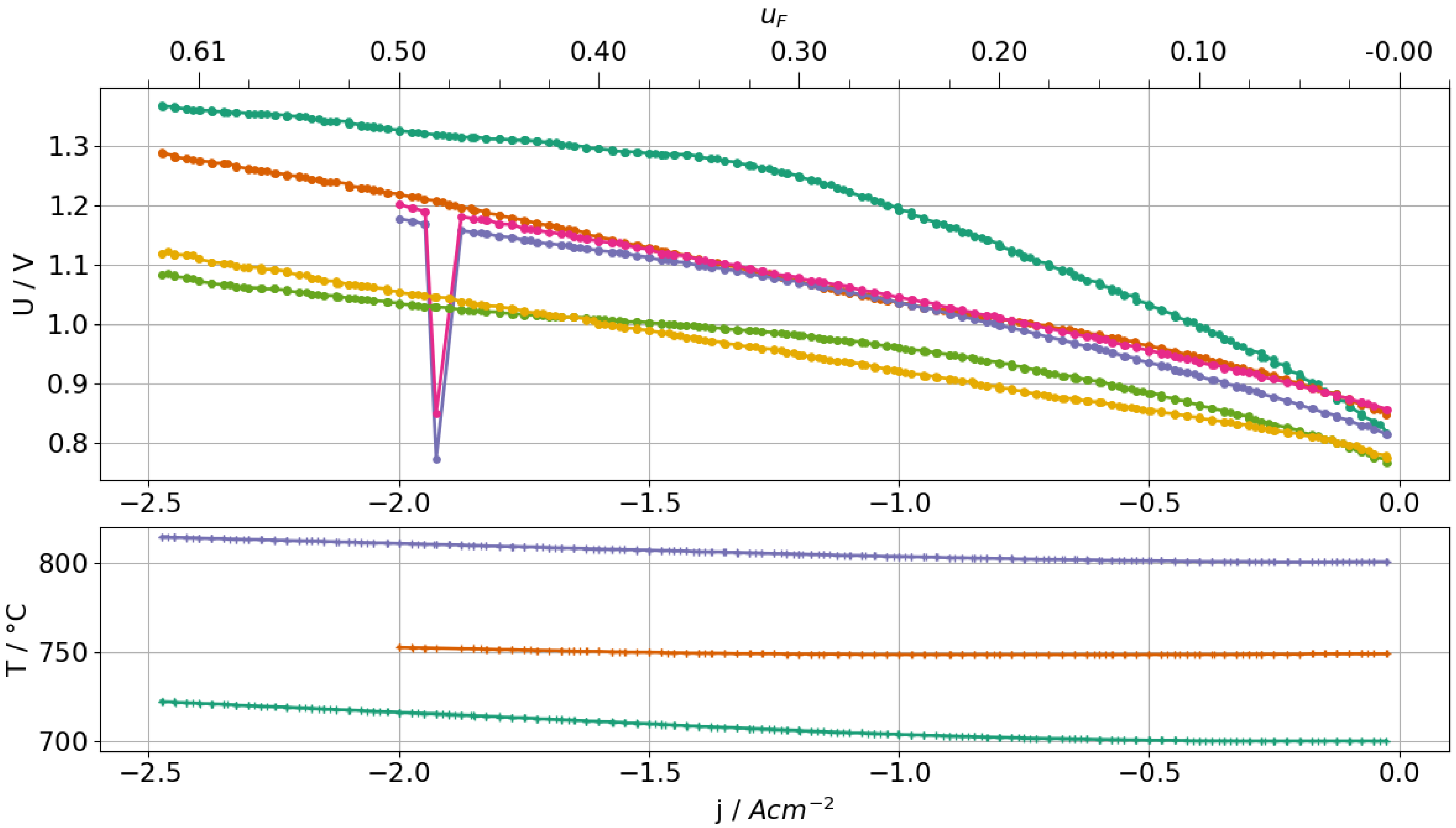


- Dry H_2 vs air
- OCV rather low: 991 mV (layer 1) and 1070 mV (layer 2) at 700°C

- Cell performance is excellent in SOFC mode with ~1.5 A cm^{-2} at 700 mV (Elcogen: ~ 1.4; Type III: ~1)

- Early diffusion limitation and low OCV point to gas and/or current leakage

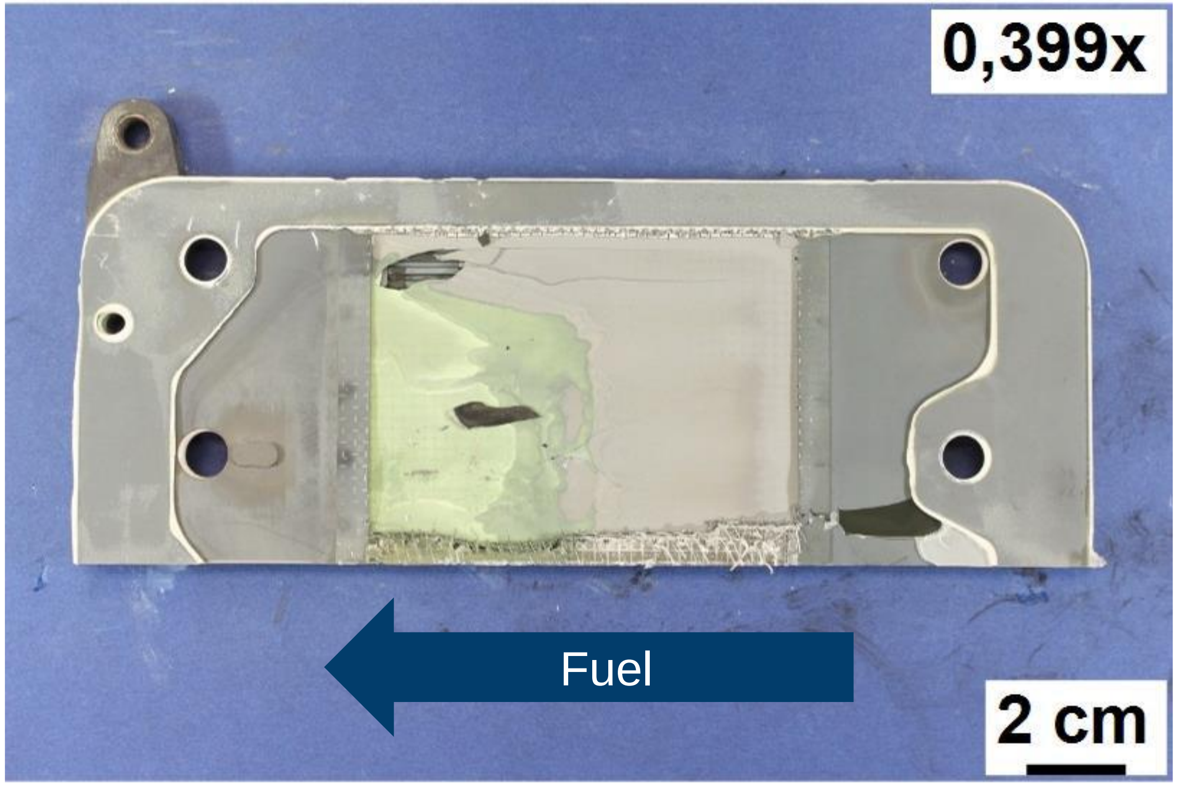
2-layer shortstack with PVD electrolyte



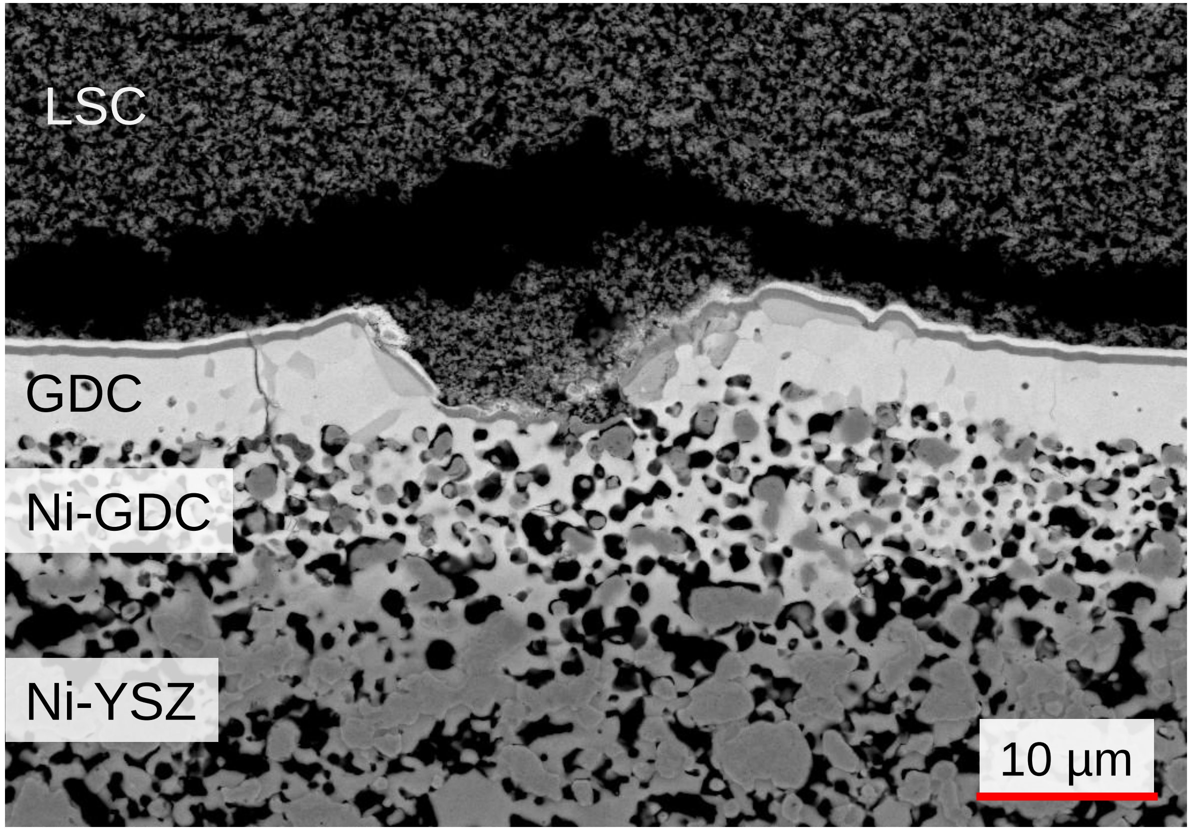
- 90% H_2O / 10% H_2 at inlet
- Excellent apparent performance
- Temperature increase below V_{TN}
- Negative differential resistance

2-layer shortstack with PVD electrolyte

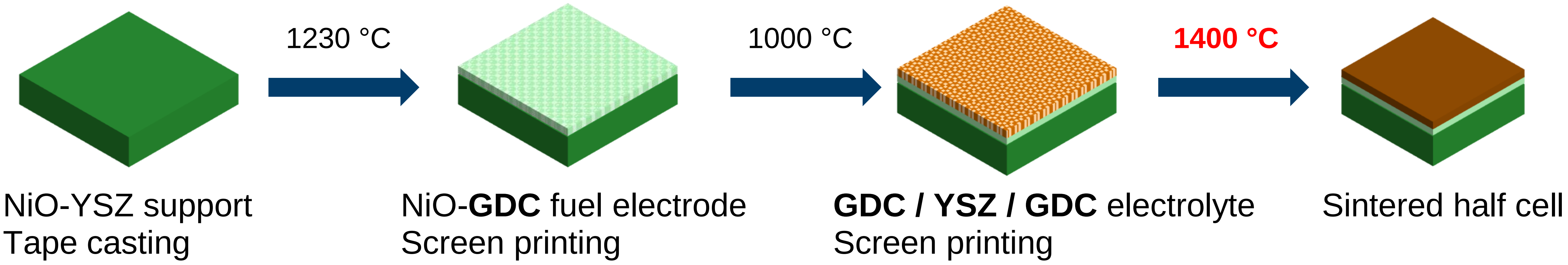
Image from stack opening – massive reoxidation



Air electrode touches GDC



Screen-printing a three-layer electrolyte

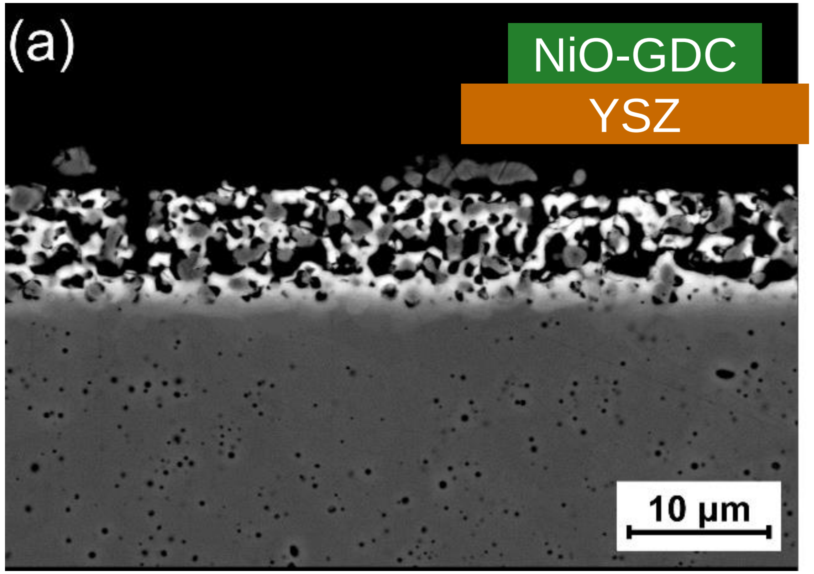


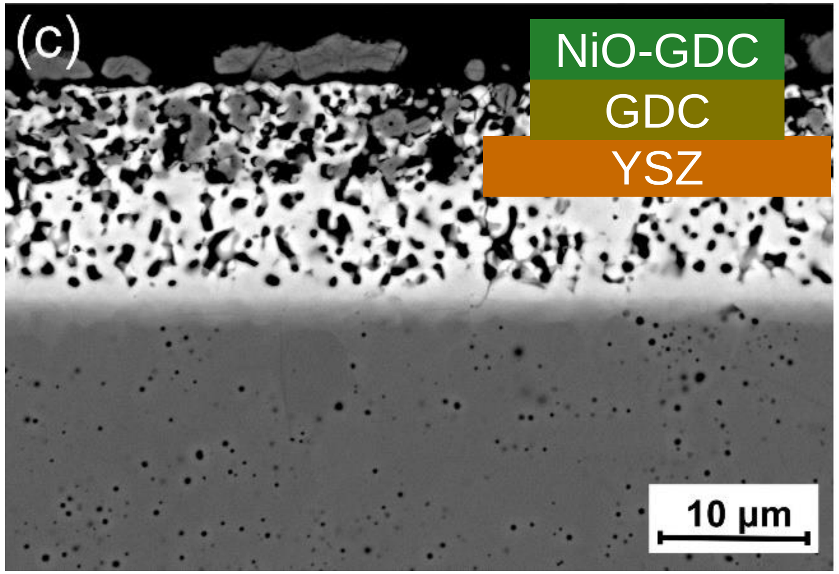
- Fabrication of a three-layer electrolyte by co-sintering
- Layers must be matched in shrinkage during sintering and adapted to support
- Paste rheology must be controlled to achieve uniform and defect-free layers

- But we know what we are doing – right?

Interdiffusion – sintering sequence

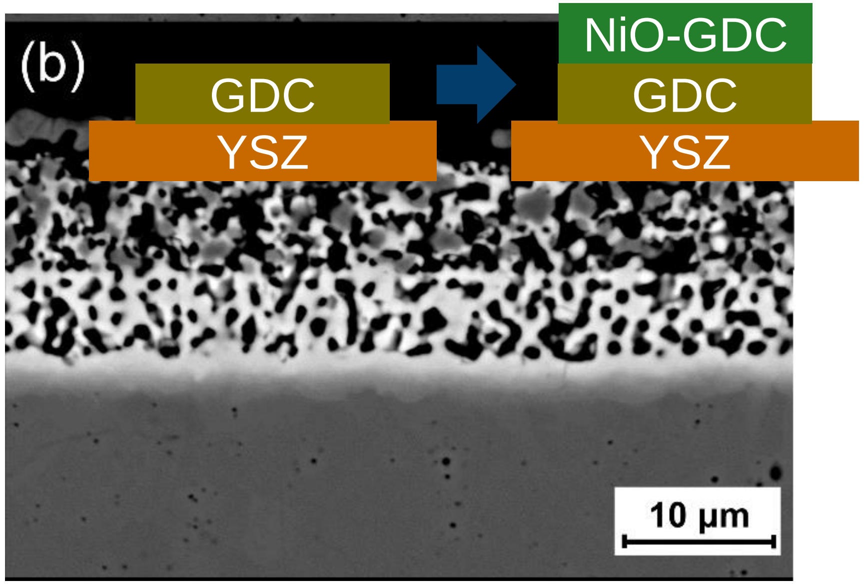
1.8 µm





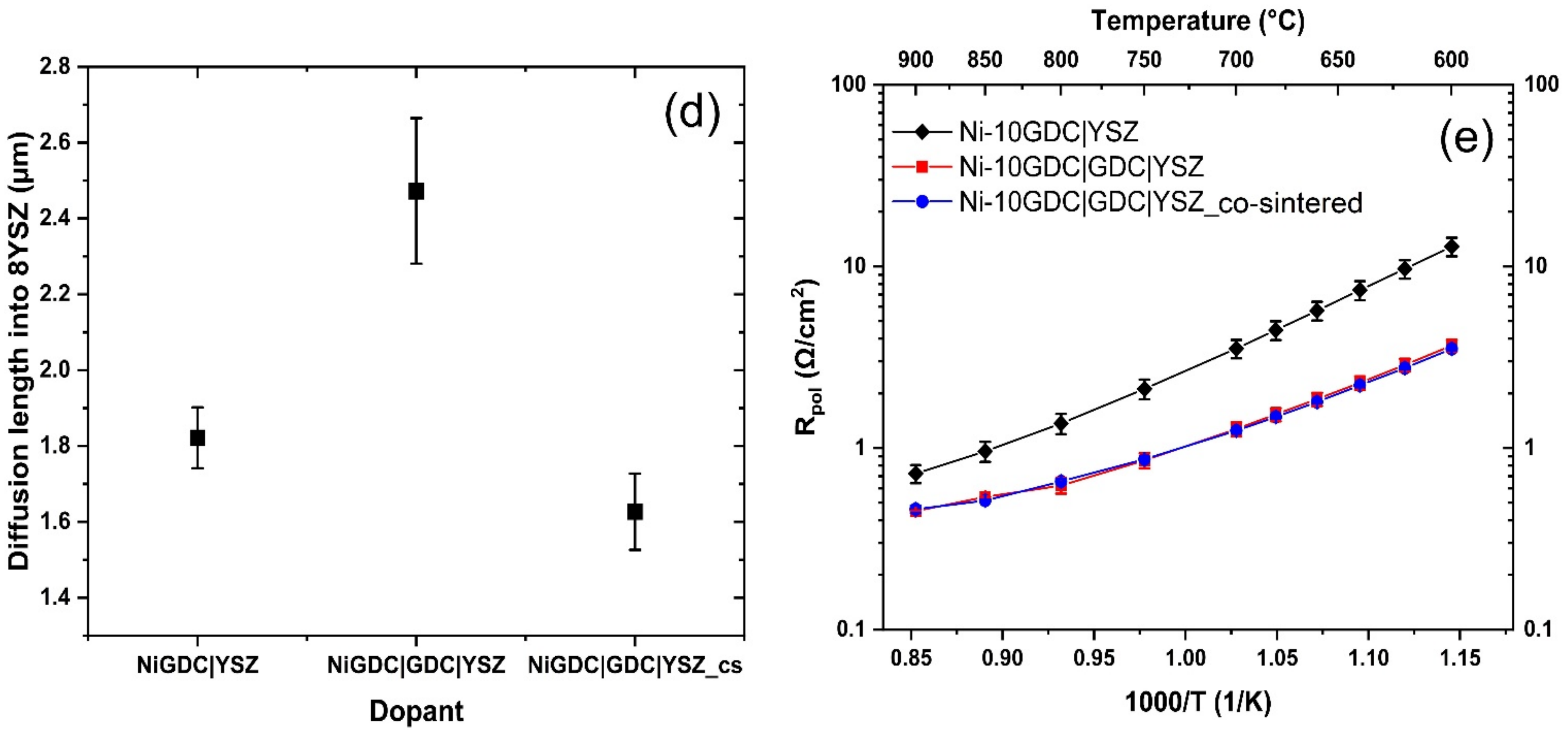
1.6 µm

2.5 µm



- Printed layers on dense YSZ ceramic
- Interdiffusion length scales with sintering T and duration
- Porosity at NiO-GDC; <u>not</u> at GDC-YSZ interfaces

Interdiffusion – electrochemical impedance spectroscopy



- Increased R_{pol} for NiO-GDC sintered on YSZ
- Lower R_{pol} when GDC interlayer is used
- Not correlated to interdiffusion length, but to formation of porosity!

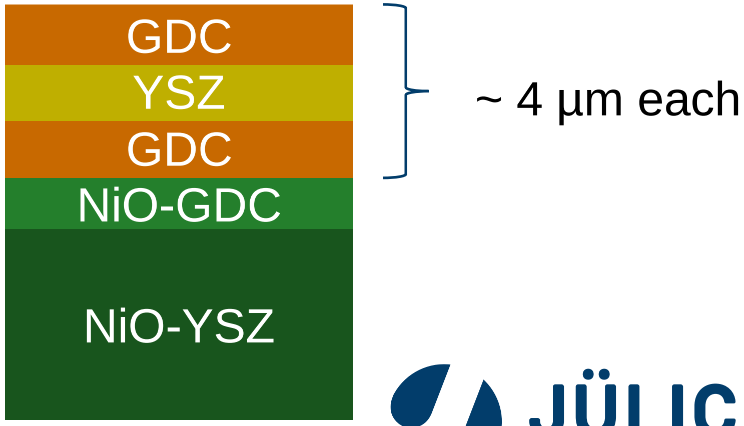
Co-firing strategy

- Previous work shows:
  - Interdiffusion at NiO-GDC / YSZ leads to strongly increased cell resistance
  - Interdiffusion at GDC / YSZ interfaces only leads to small ohmic increases
  - Interdiffusion length during 1400 °C, 5h is smaller than 2 µm

⇒ Hypothesis:

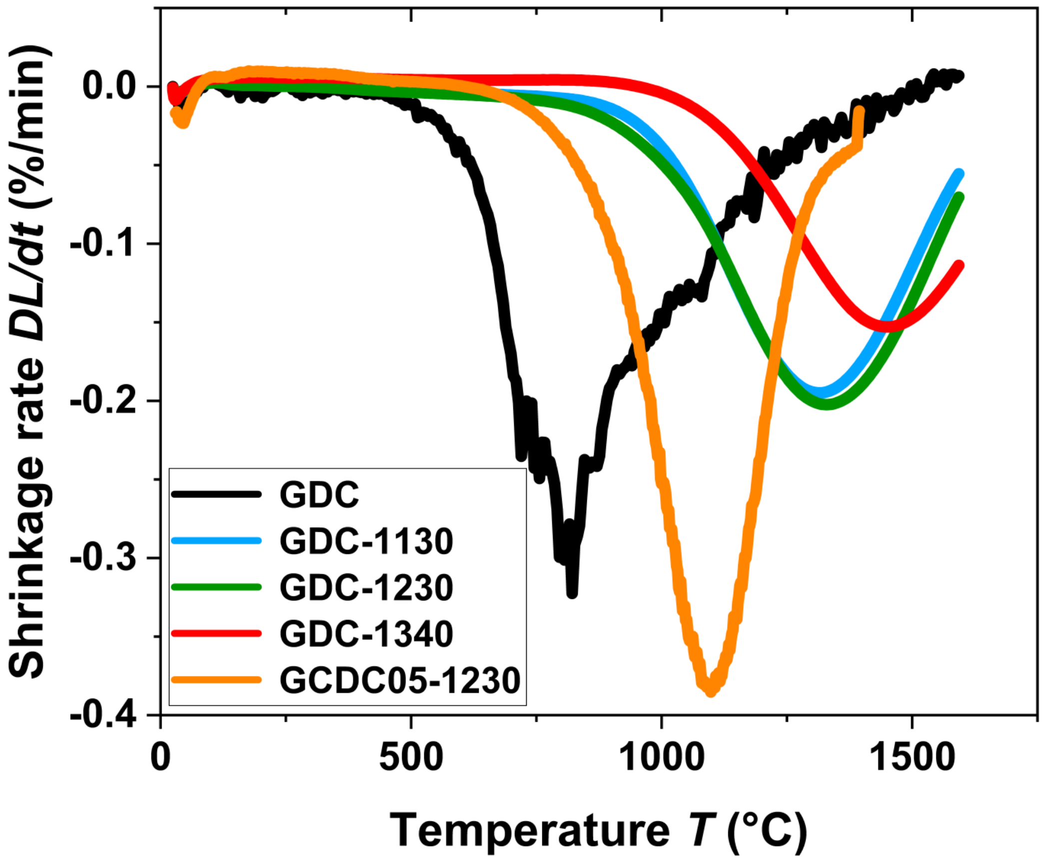
1) interdiffusion located inside the electrolyte should lead to acceptable performance losses!

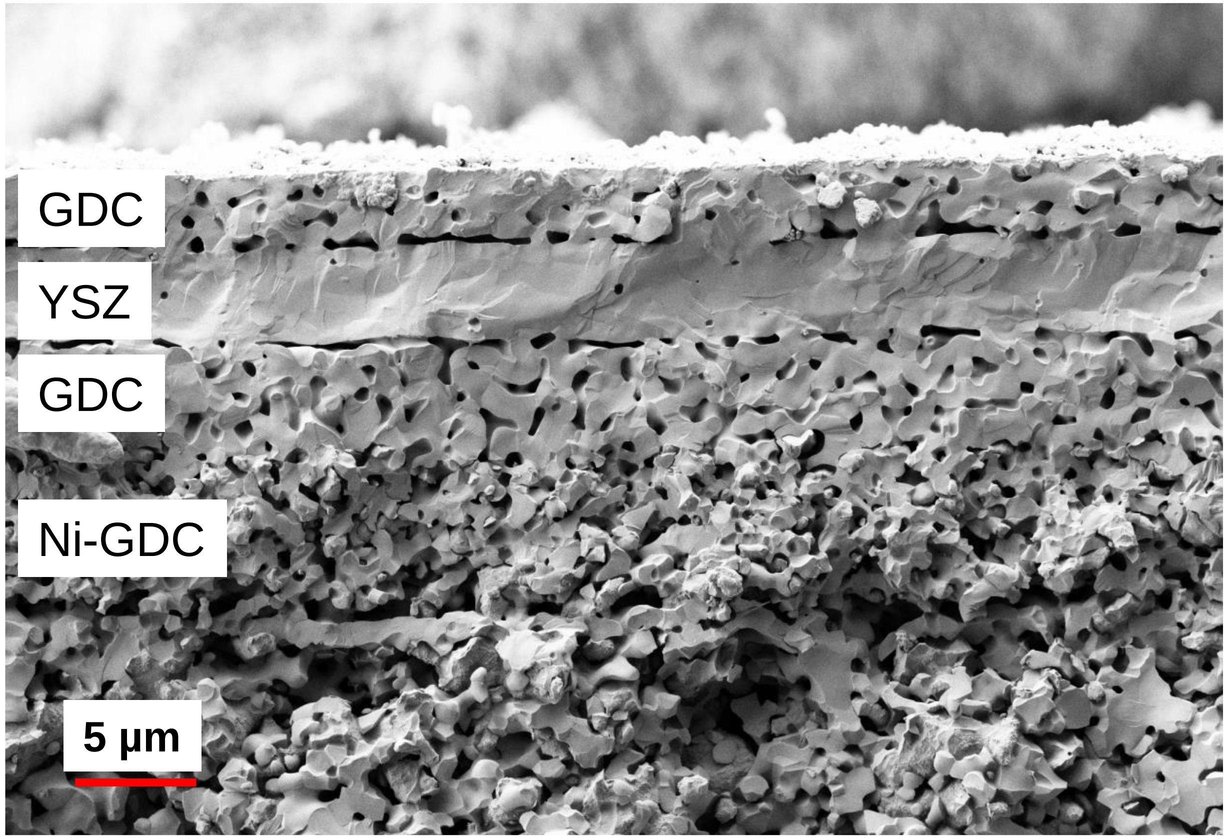
2) a YSZ thickness of 4 µm should be sufficient.



Screen-printing a three-layer electrolyte

- Adjusting shrinkage rate by powder calcination
- First results show complex sintering behavior – very dense YSZ, porous GDC





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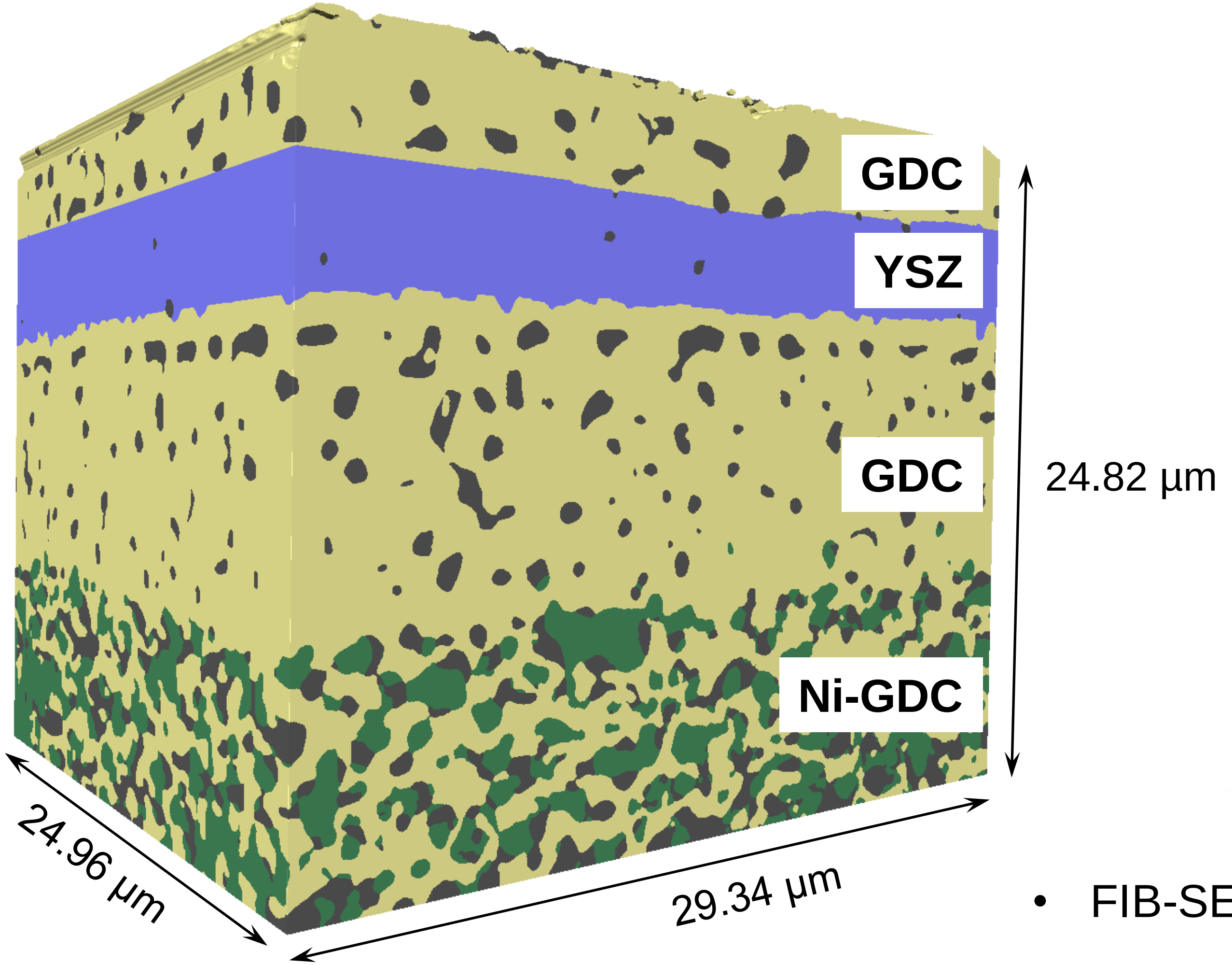
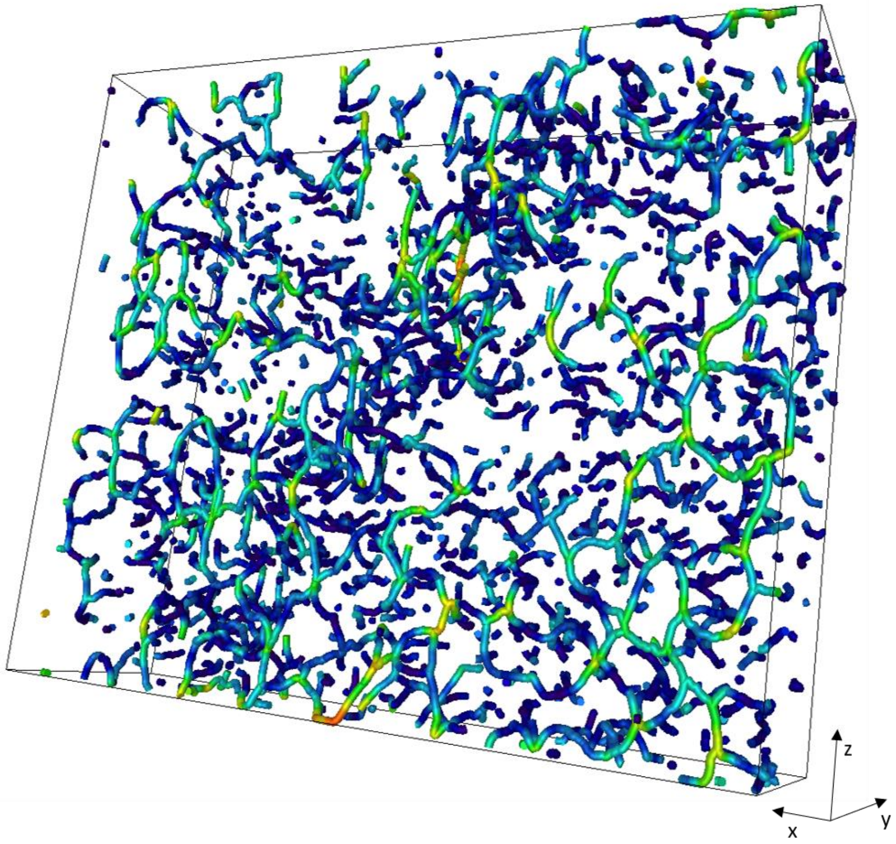
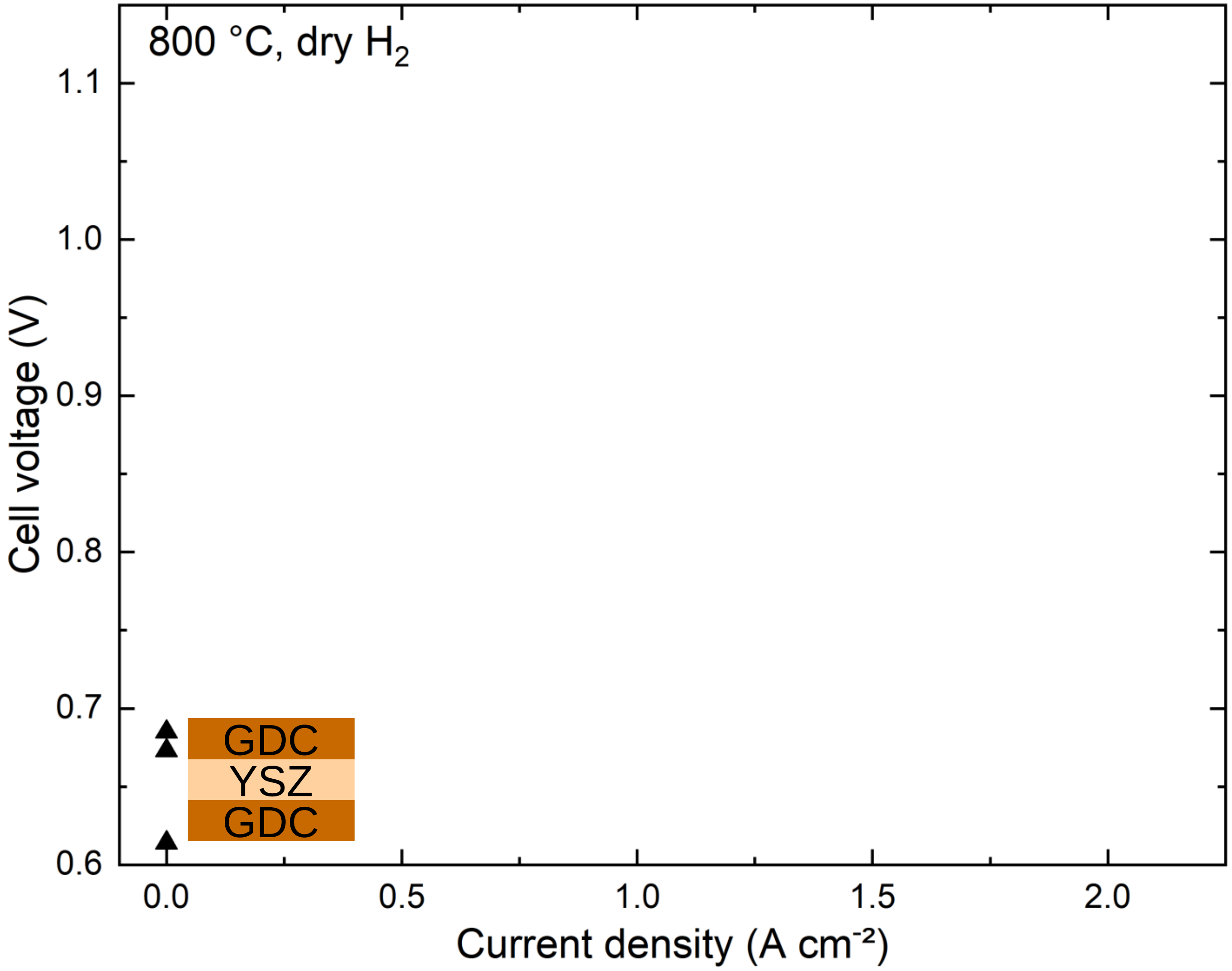
Ordered porosity after sintering





- FIB-SEM tomography confirms 2D connected pore network

Cell performance



- Tested approx. 10 cells
- OCV values @ 800 °C, dry H_2 are between 0.6 and 0.7 V
- TEM investigations confirm that Ce diffuses through YSZ from both sides

➢ Current leakage

- Best result for SP-cells when top GDC layer is sintered separately

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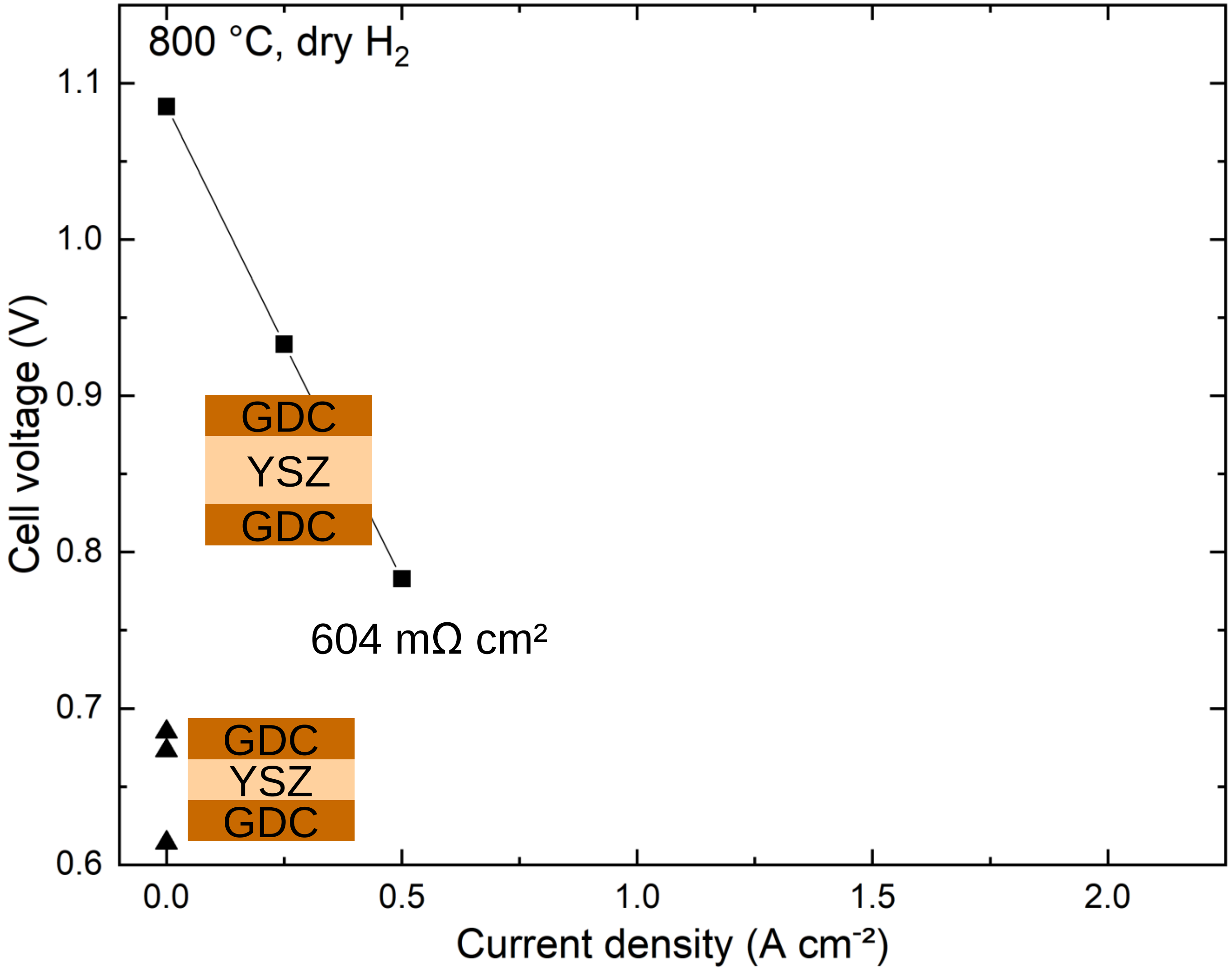
Cell performance



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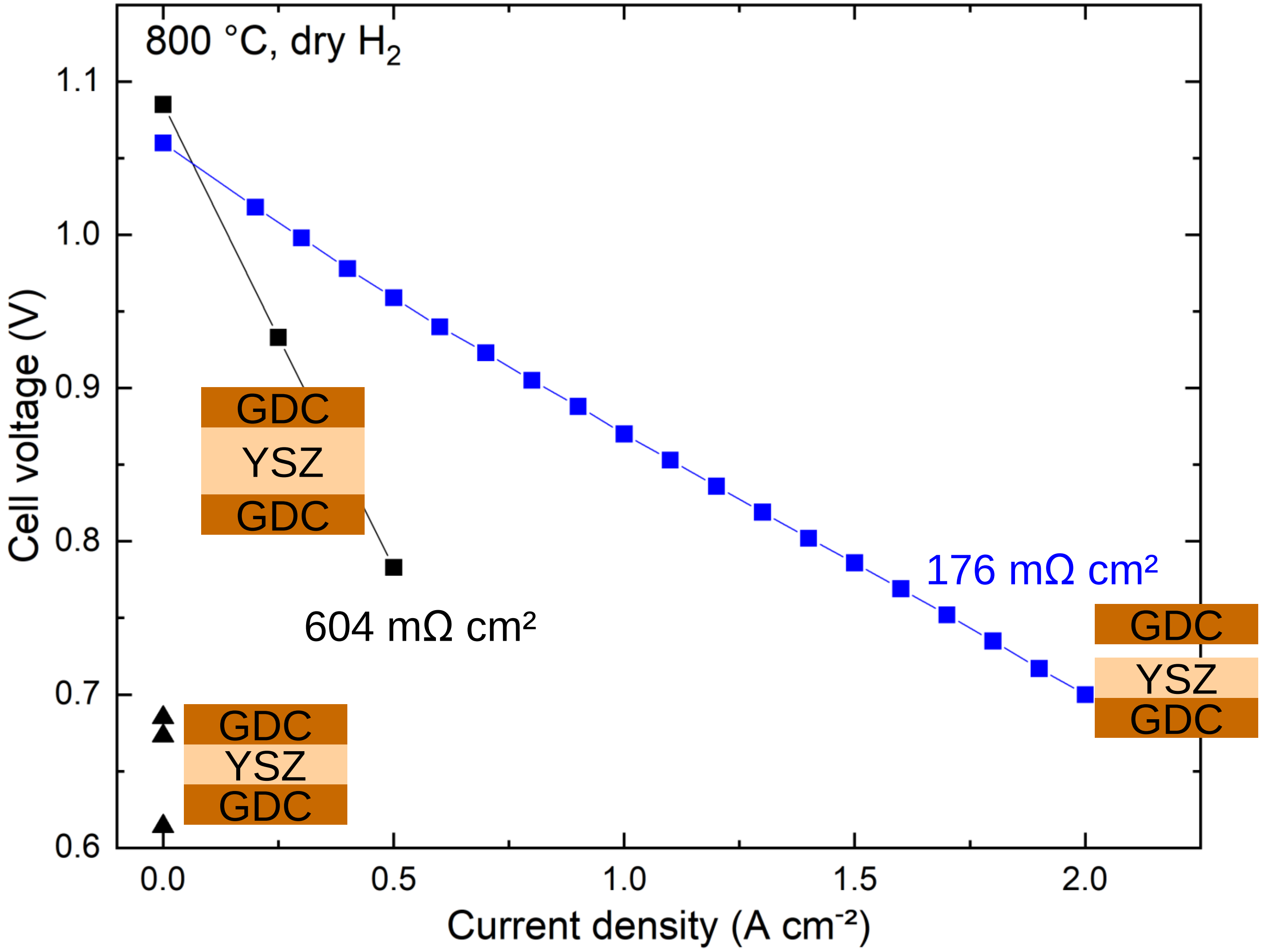

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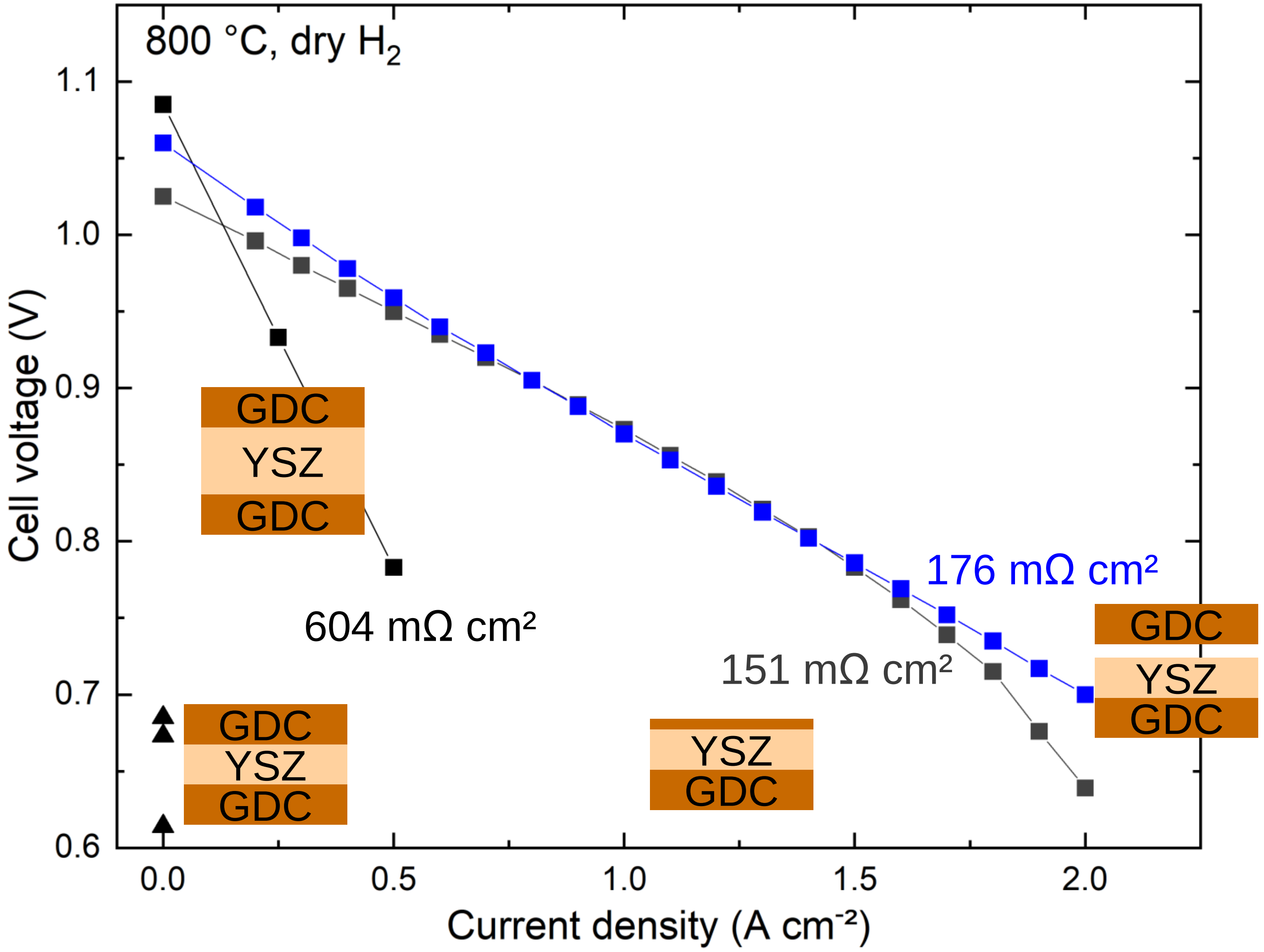

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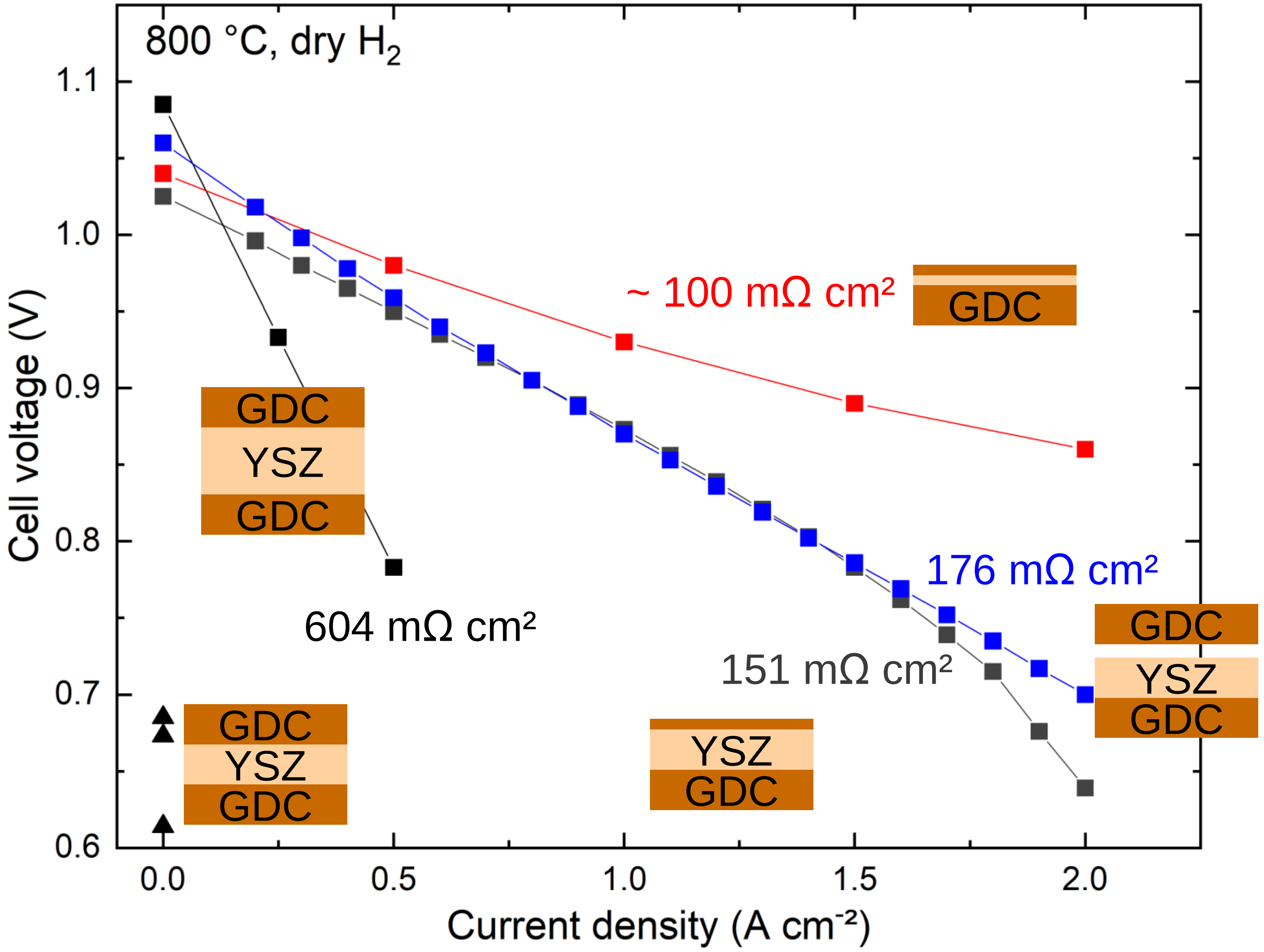

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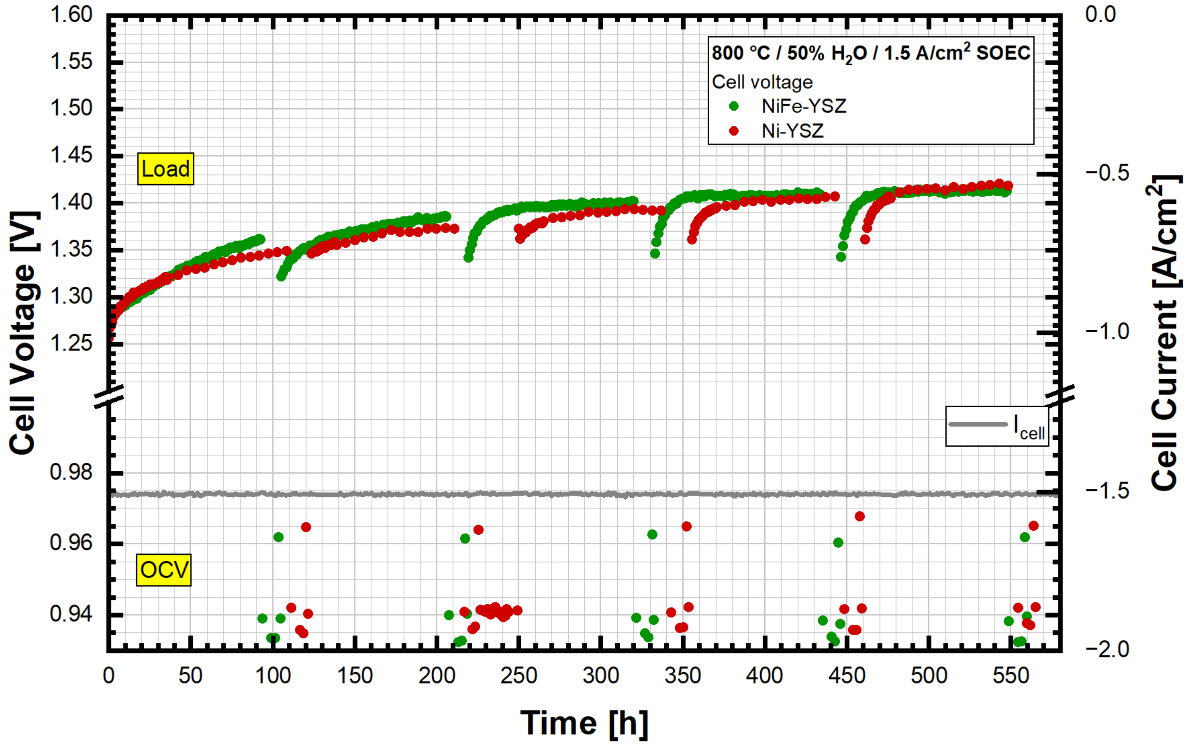
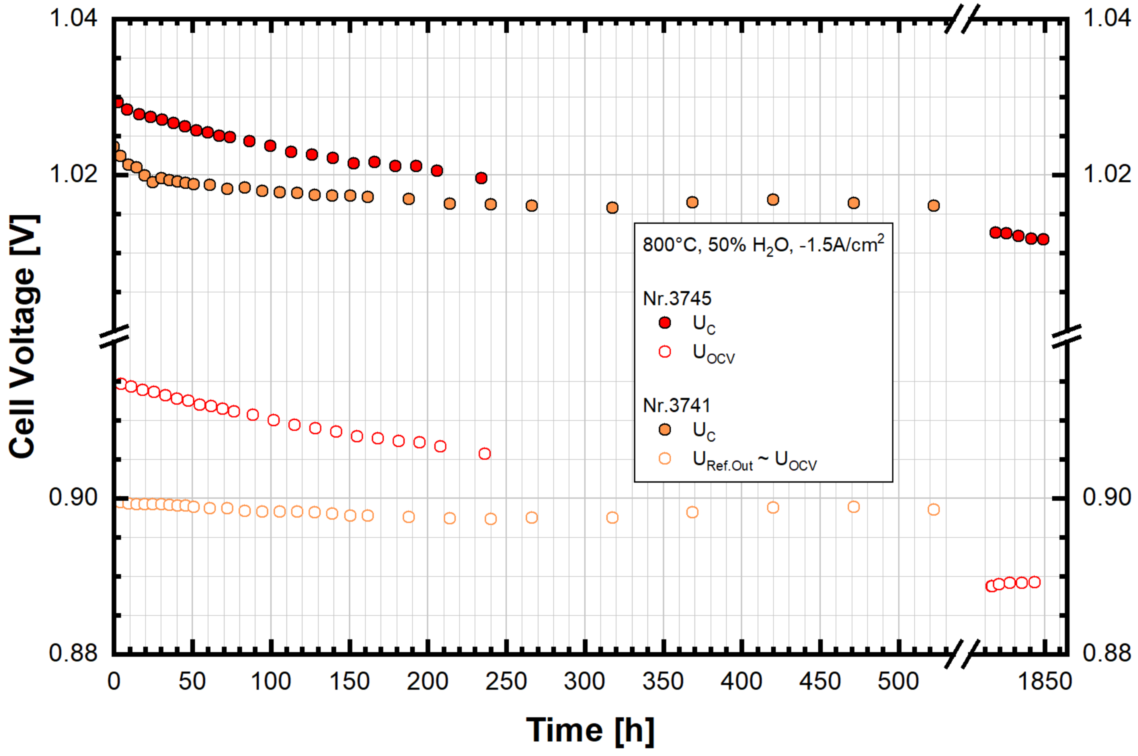
Durability test – PVD cells

Baseline: Ni-YSZ & NiFe-YSZ

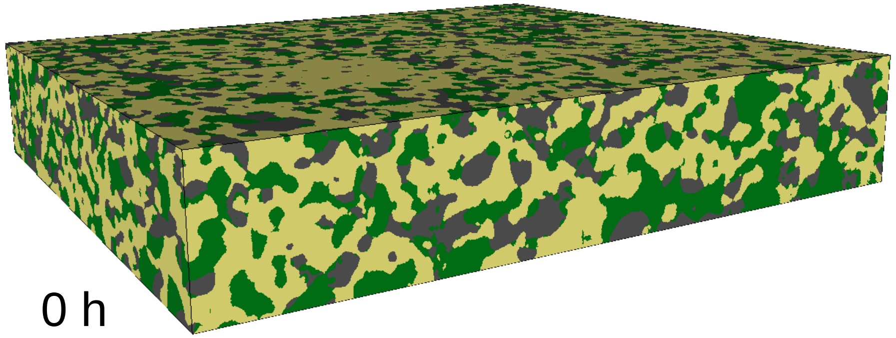


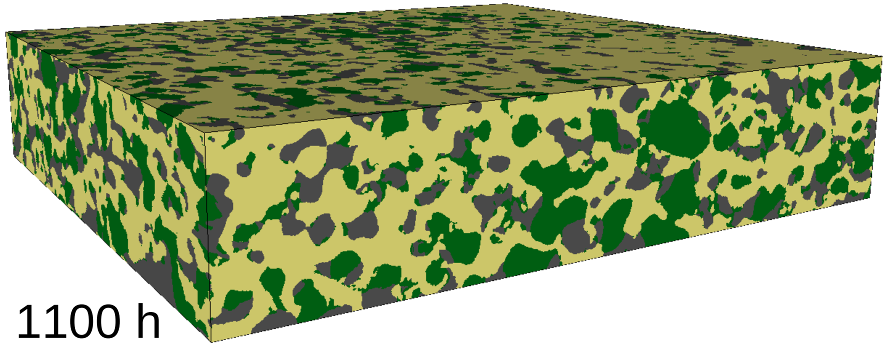
Ni-GDC with PVD electrolyte

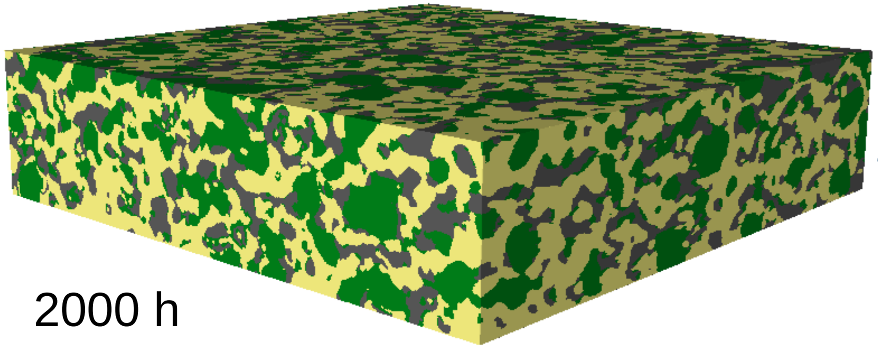


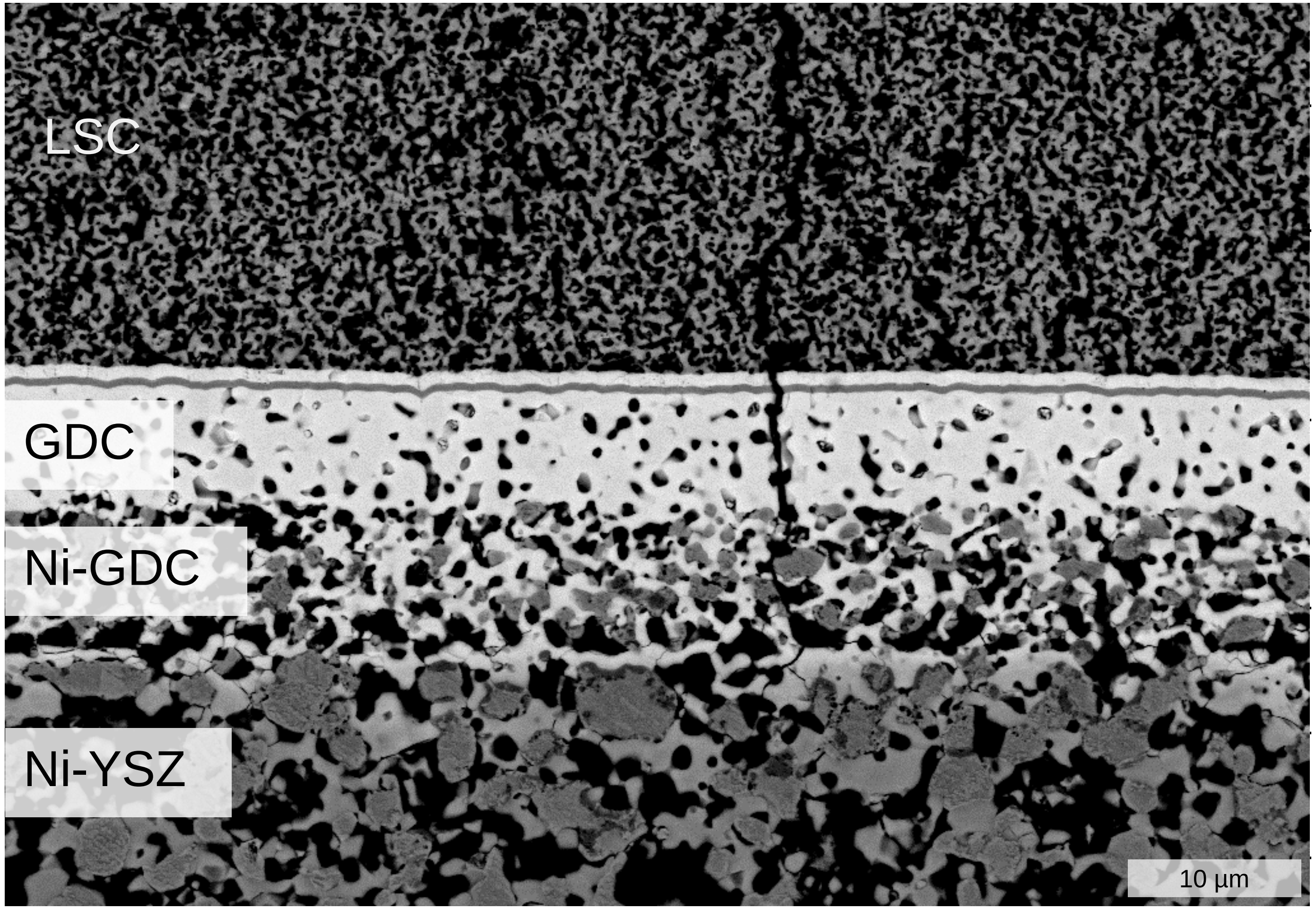
- 800 °C, 50:50 H_2/H_2O, 1.5 Acm^{-2}: Ni(Fe)-YSZ shows strong degradation
- Ni-GDC very stable over 2000 h, slight decreasing in (open circuit) voltage
- But: Faradaic efficiency unknown!

Post-test PVD cells: FIB-SEM reconstructions

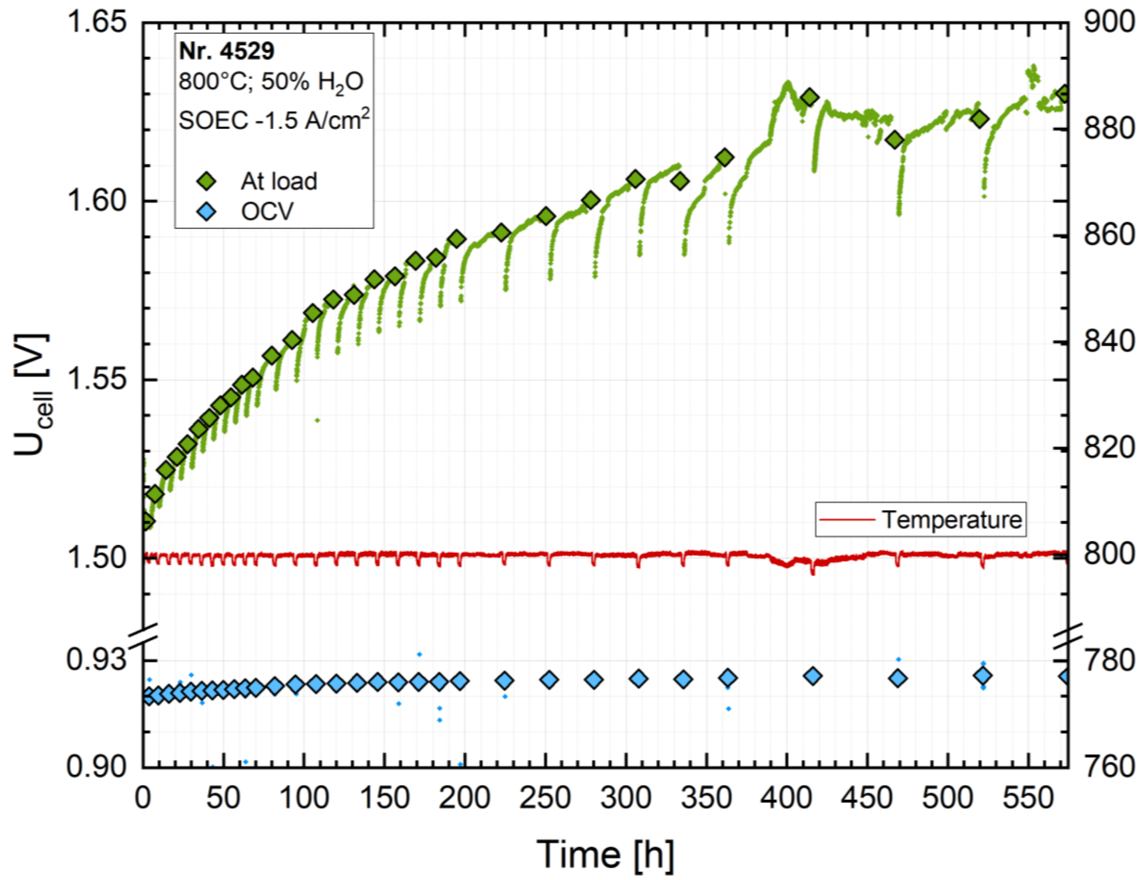

0 h

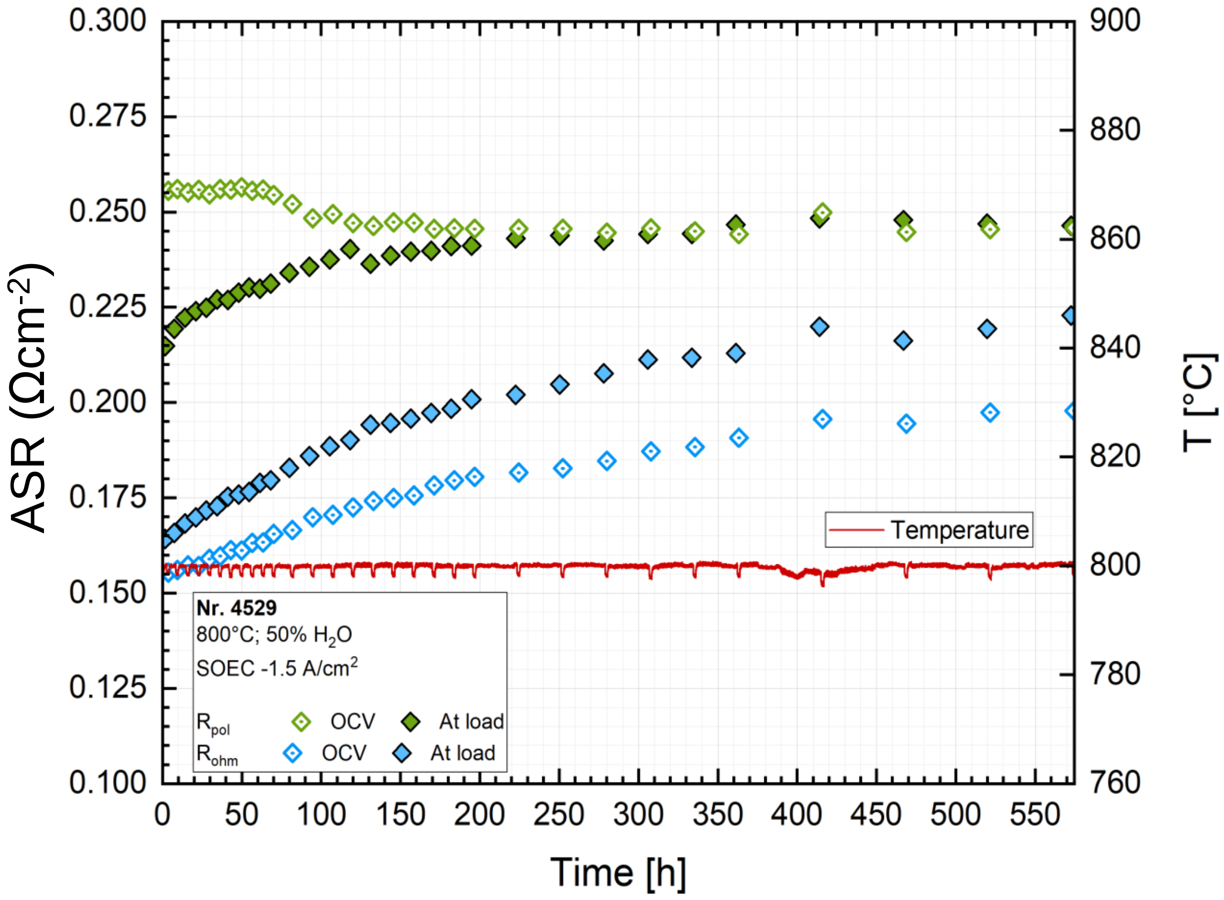

1100 h


2000 h



Durability test – SP cell





- 800 °C, 50:50 H_2/H_2O, 1.5 Acm^{-2}: Substantial degradation; mostly ohmic ASR

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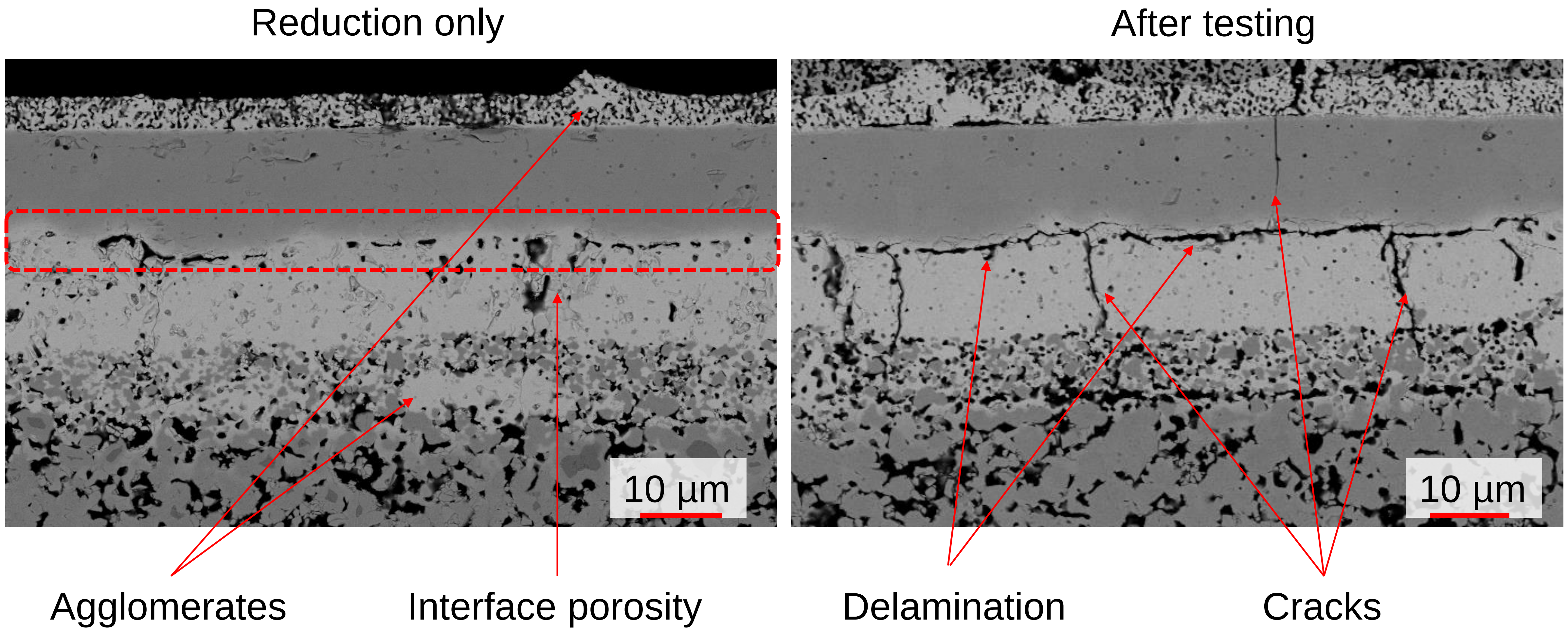
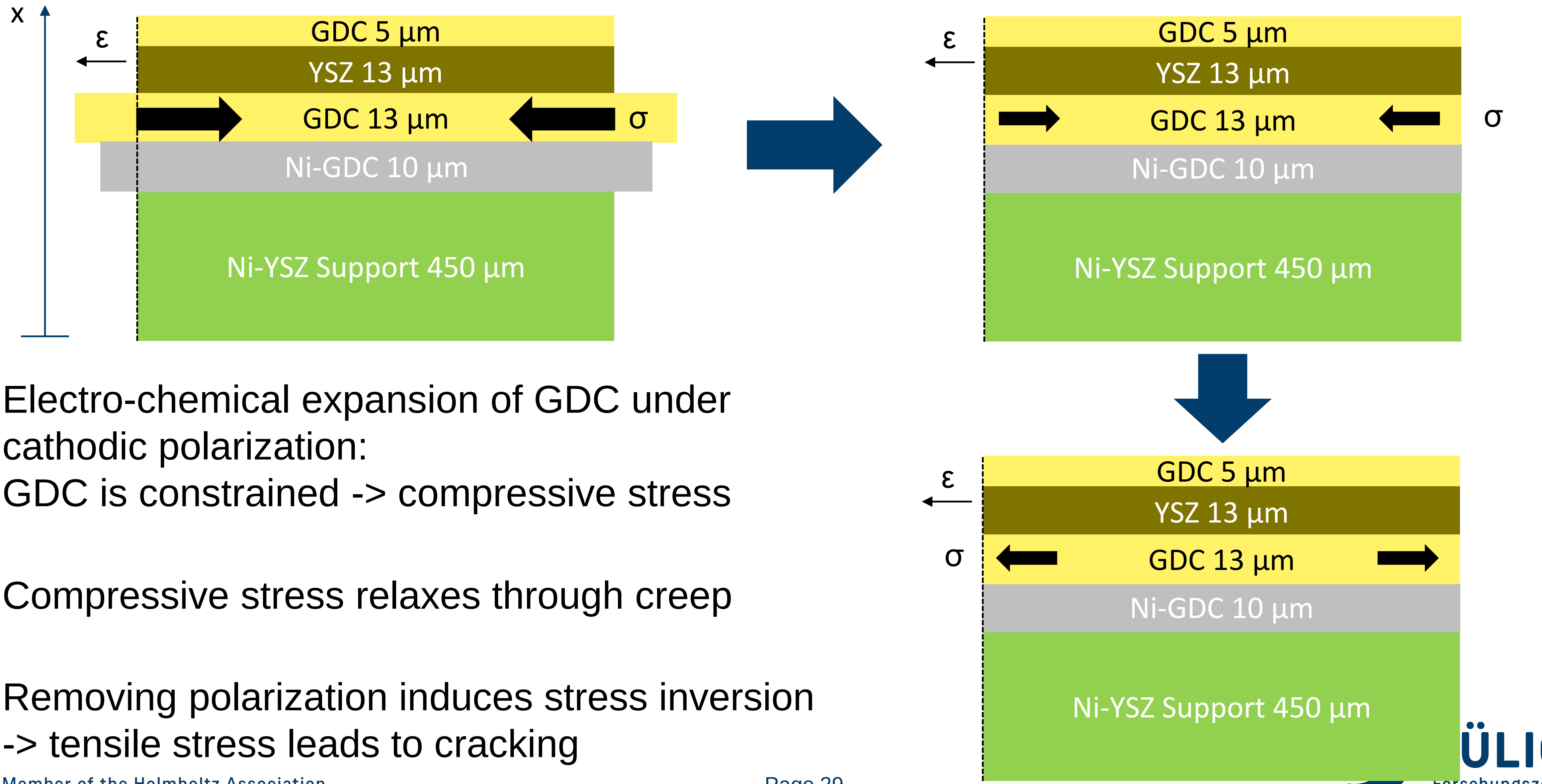
SP- cell: Microstructure



Microstructure degradation: hypothesis



Electro-chemical expansion of GDC under cathodic polarization:
GDC is constrained -> compressive stress

Compressive stress relaxes through creep

Removing polarization induces stress inversion
-> tensile stress leads to cracking

Summary

- Ni-GDC was successfully integrated into an ASC with YSZ blocking layer

- PVD-YSZ requires near-perfect GDC microstructure
  - Pores in GDC result in high leakage currents & gas leakage
  - Performance & durability with improved GDC is exceptional, BUT Faradaic efficiency not known

- Co-firing on GDC-YSZ-GDC requires ~ 15 µm YSZ to prevent current leakage
  - High resistance & degradation due to very limited contact between GDC + YSZ
  - Much lower sintering temperature required to solve this problem

Acknowledgements

Alex Schwiers

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Luzie Wehner

Iurii Kogut

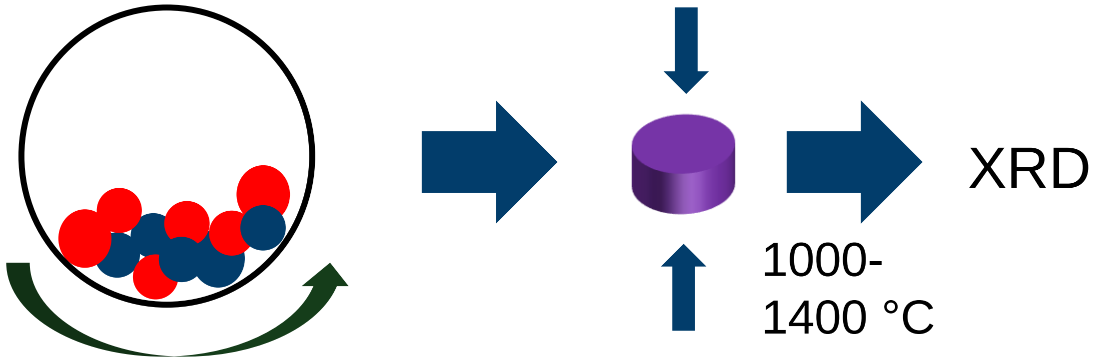
Grant no: 03SF0641A

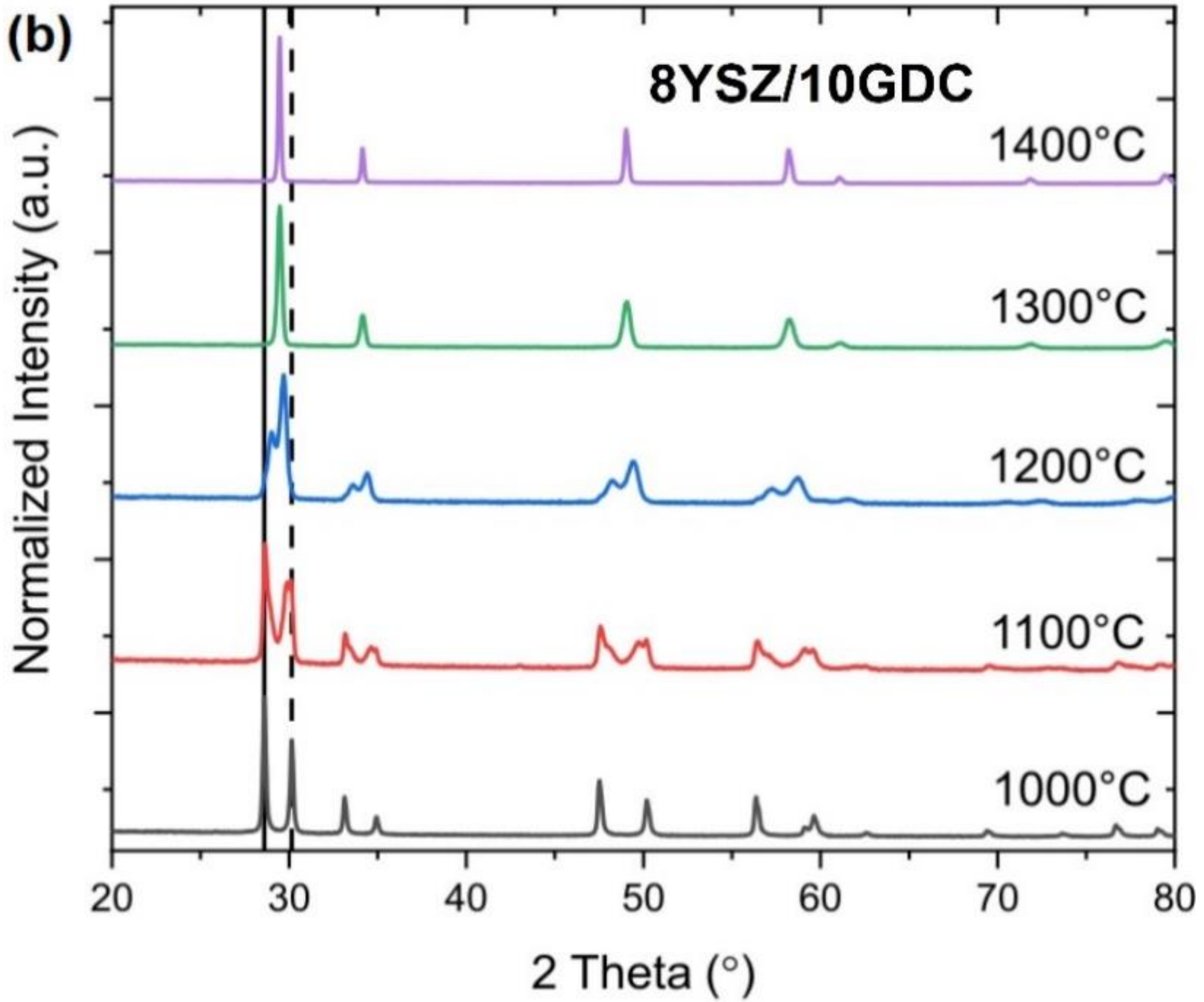
Grant no: 275388933

Thank you for your attention!

Interdiffusion experiments

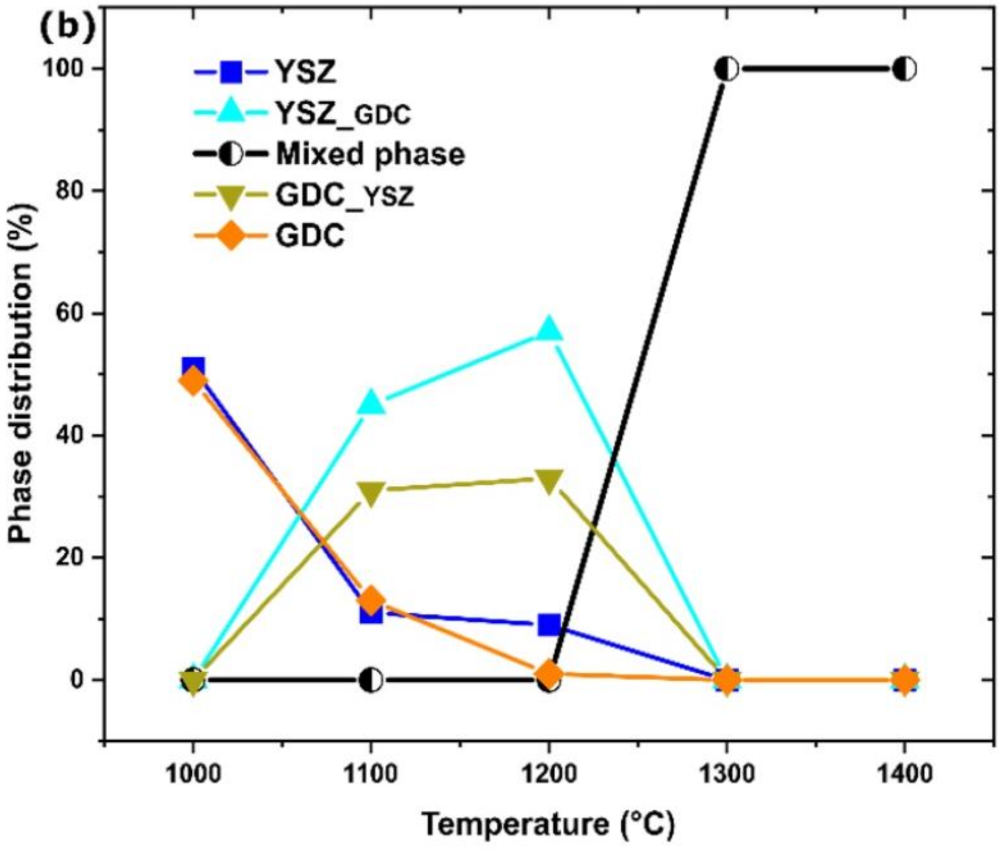
- Started these experiments in 2018
- Sinter well mixed powders
  - GDC: d_{50} = 0.1 µm
  - YSZ: d_{50} = 0.48 µm
- Crush pellets + phase analysis via XRD

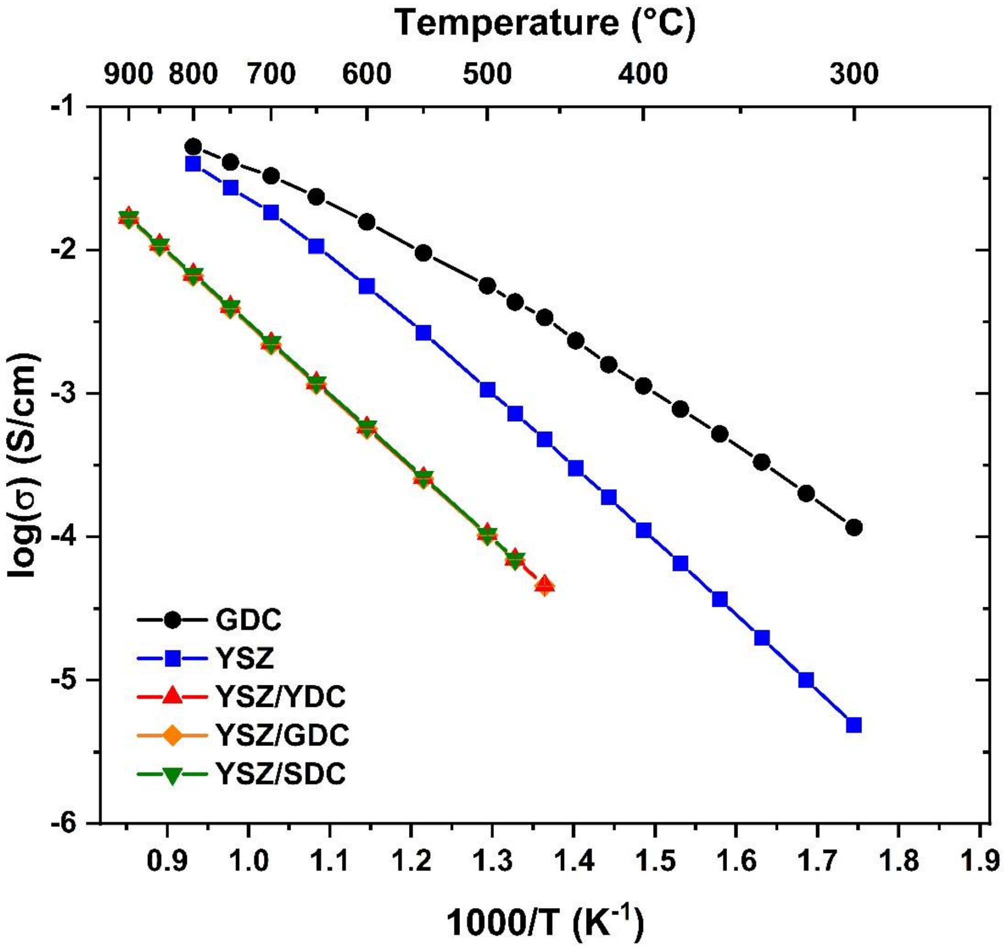




A. Schwiers, C. Lenser, O. Guillon and N. H. Menzler J. Eur. Ceram. 2023, 43, **14**, Pages 6189-6199
DOI: https://doi.org/10.1016/j.jeurceramsoc.2023.06.015

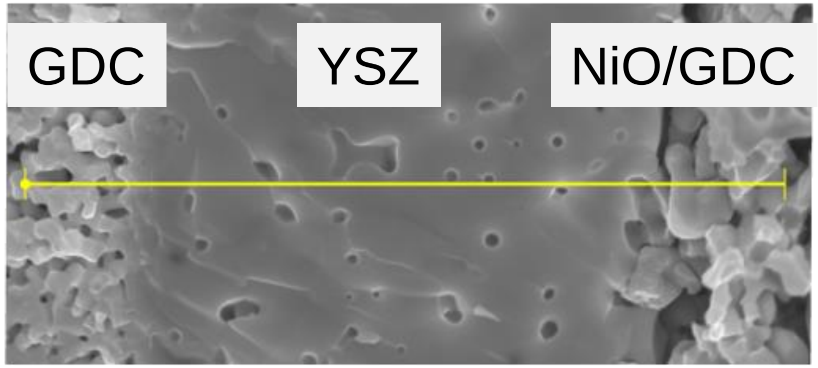
Interdiffusion – phase composition

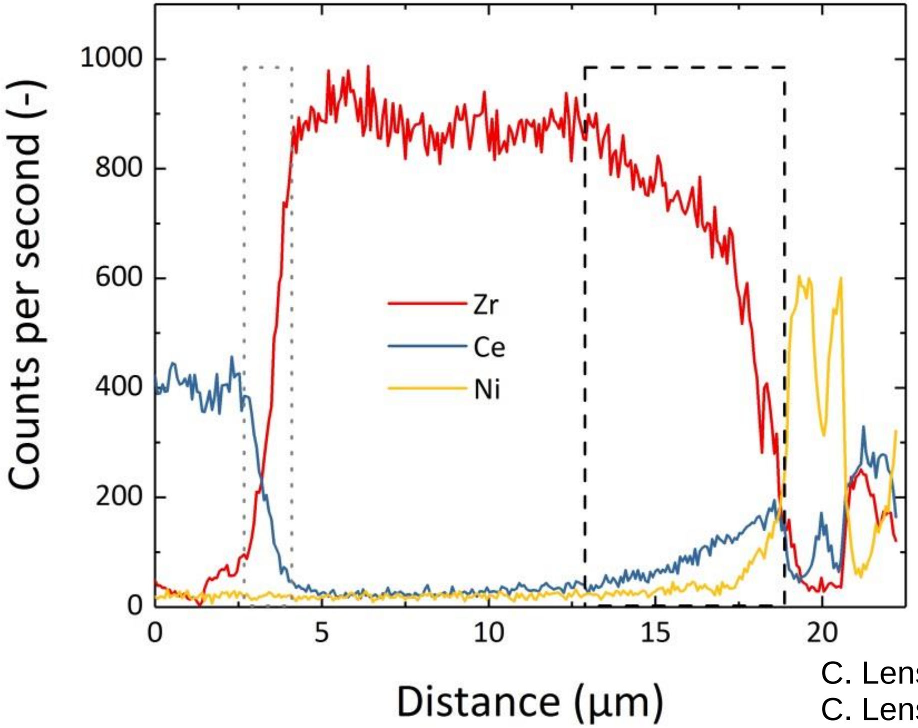


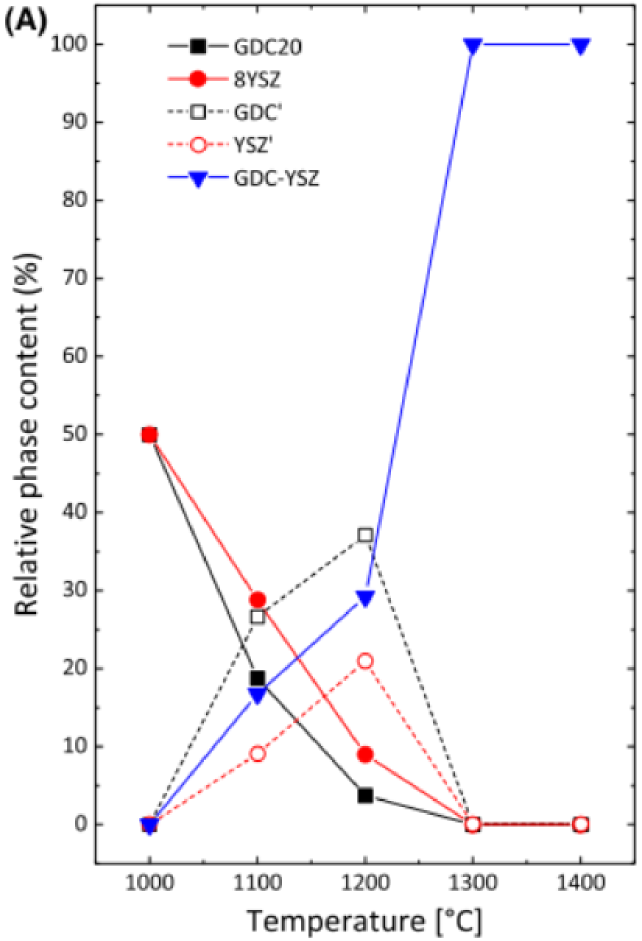


- Complete mixing after 1400 °C, 5h
- Decreased conductivity as reported in literature

Interdiffusion - the role of NiO

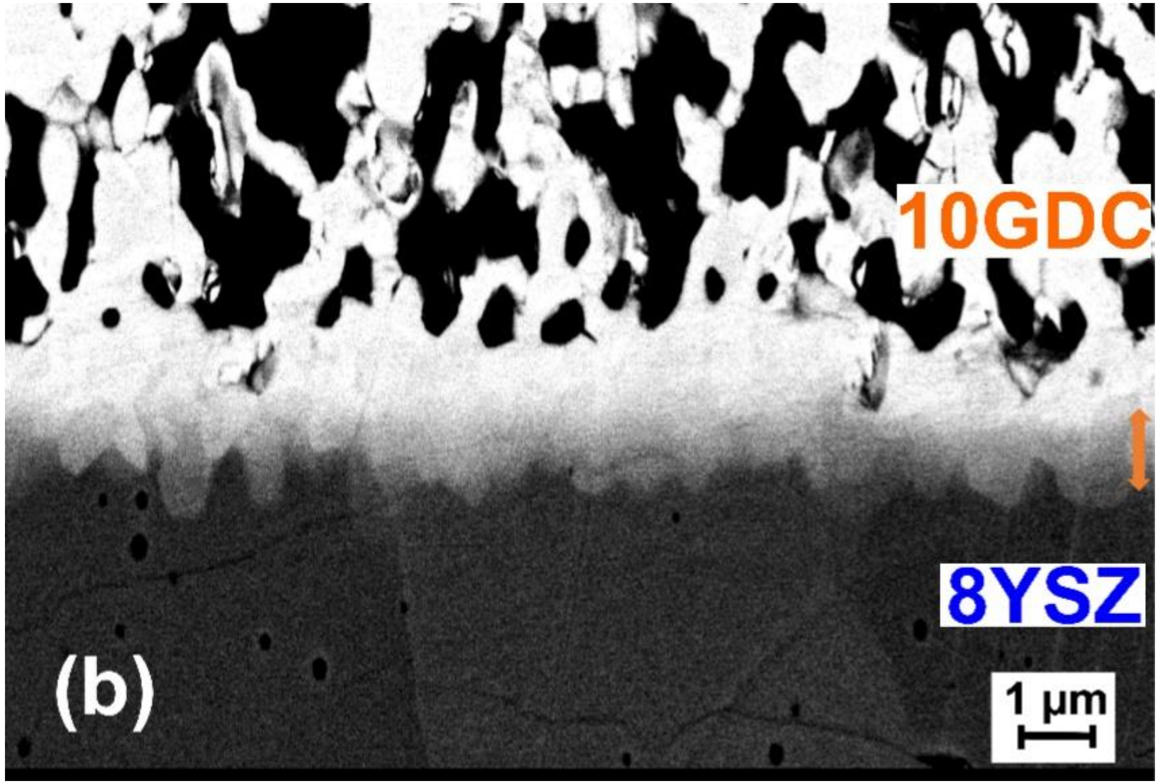


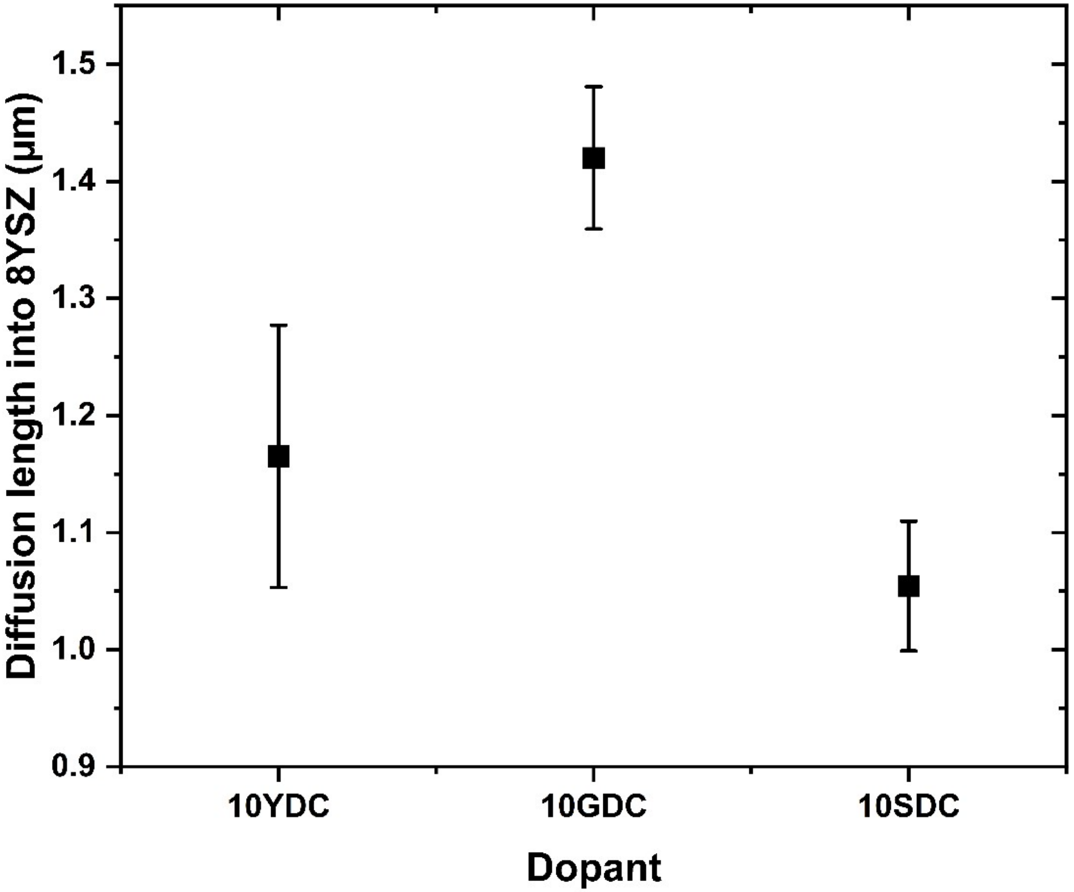




C. Lenser et al., Journal of the American Ceramic Society, 101 (2017) 739-748.
C. Lenser, N.H. Menzler, Solid State Ionics, 334 (2019) 70-81.

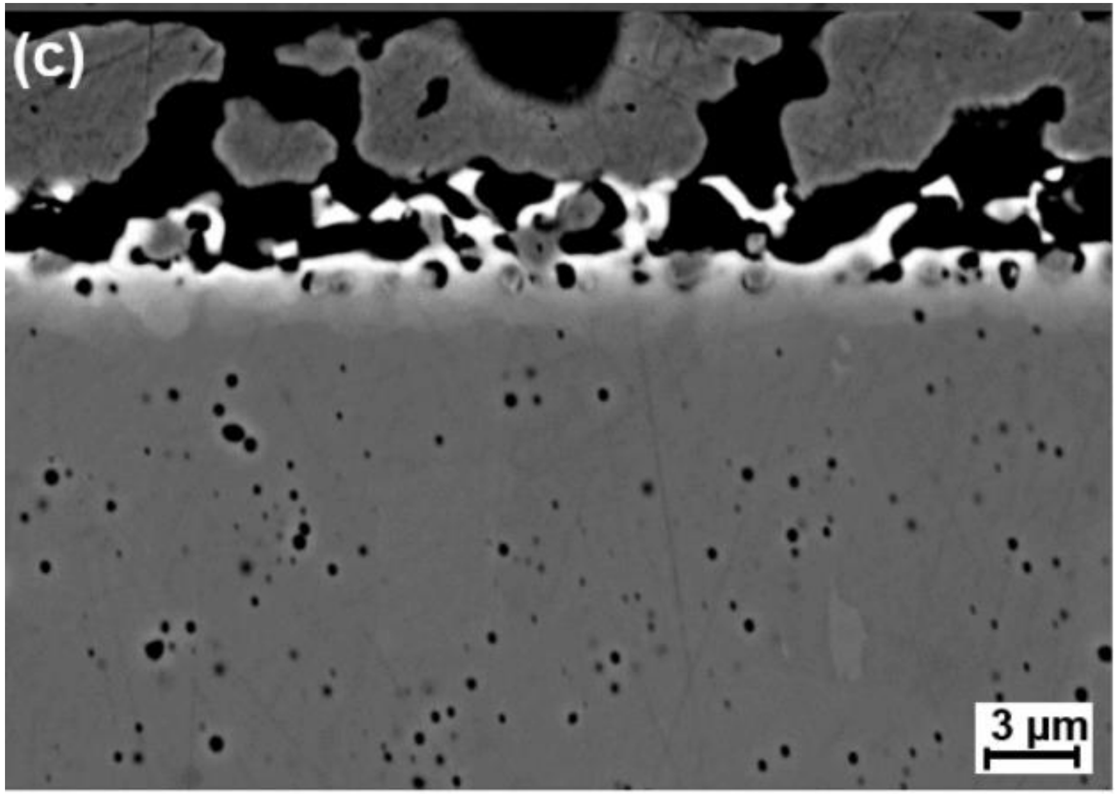
Interdiffusion length – GDC on YSZ

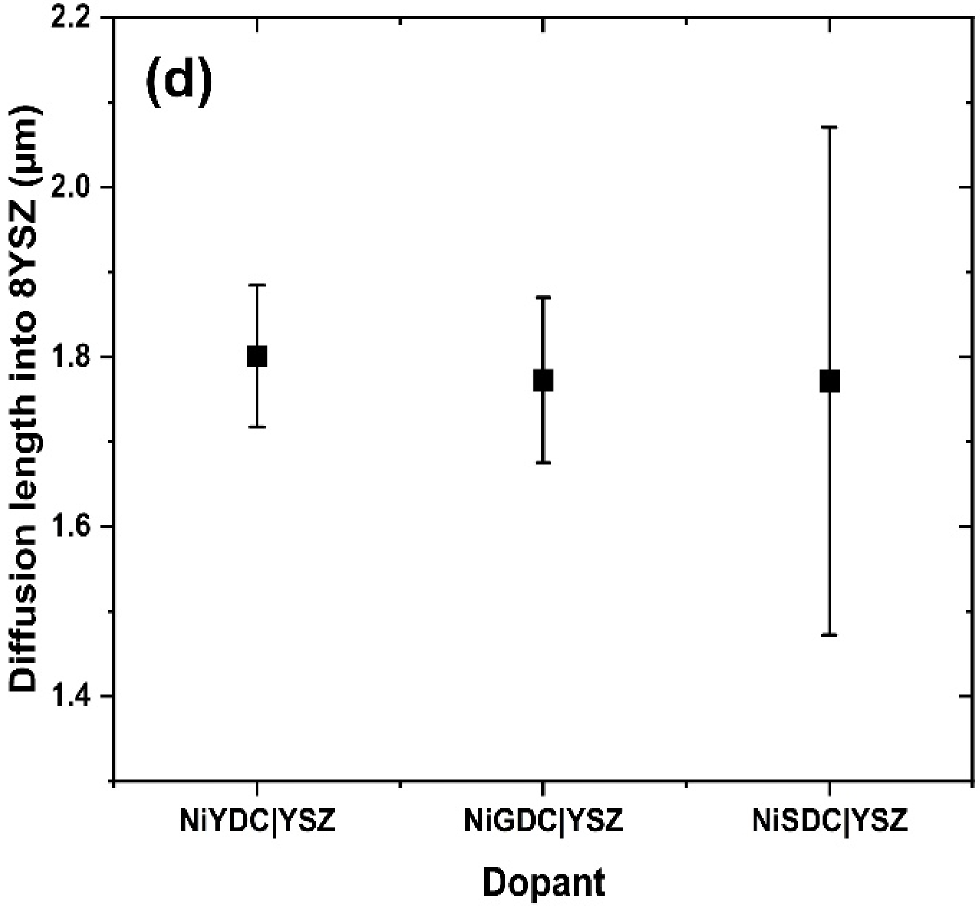




- Printed layers on densified ceramic
- SEM analysis using Z-contrast show interdiffusion length 1 – 1.5 µm

Interdiffusion length – NiO-GDC on YSZ





- Printed layers on densified ceramic
- SEM analysis using Z-contrast show higher interdiffusion length ~ 1.8 µm
- Notable porosity is formed at interface