Industry Day

PEROVSKITE PRINTING PHOTONICS

Coating and Printing Technologies: From Photovoltaics to LEDs

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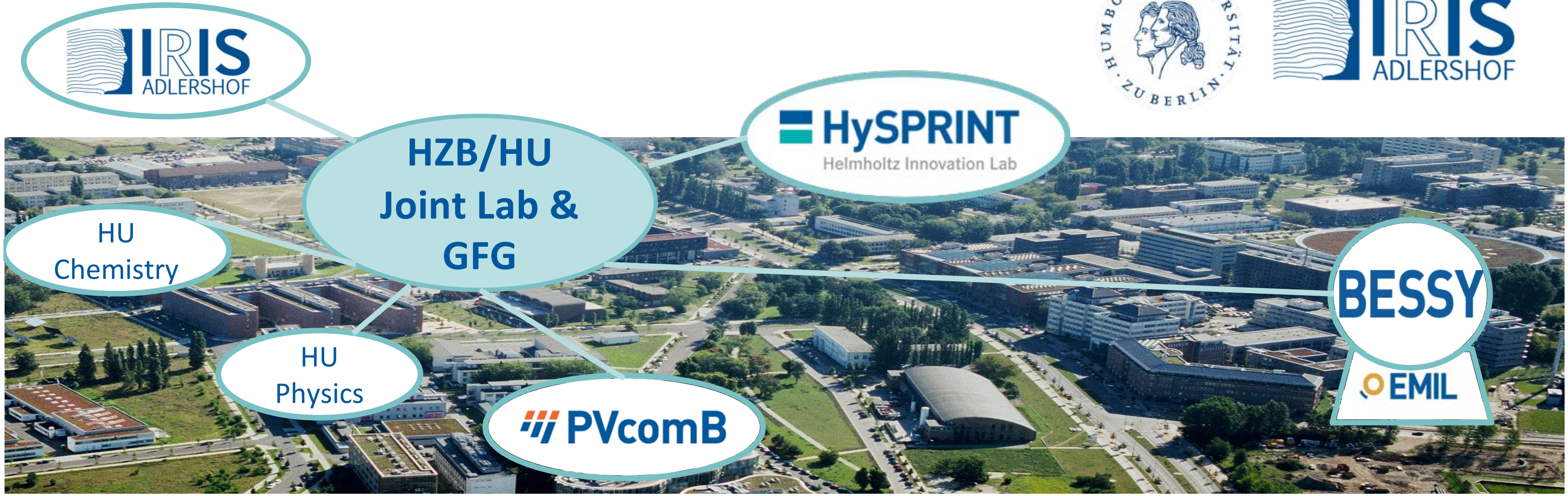
PEROVSKITE PRINTING PHOTONICS

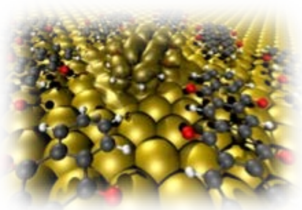
PVcomB
HySPRINT
EMIL

HZB Helmholtz Zentrum Berlin

HUMBOLDT-UNIVERSITÄT ZU BERLIN

IRIS ADLERSHOF





Hybrid Materials | Processing | Function

Basic Research – Validation – Applied Research

Passive: R, C, L
Active: Diode, (O)LED, Sensors, Solar Cells, Memristors

Active: OFET & EGOFET(Sensors)

acknowledgements

Felix Hermerschmidt
Vincent Schröder
Nicolas Zorn Morales
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Oliver Maus

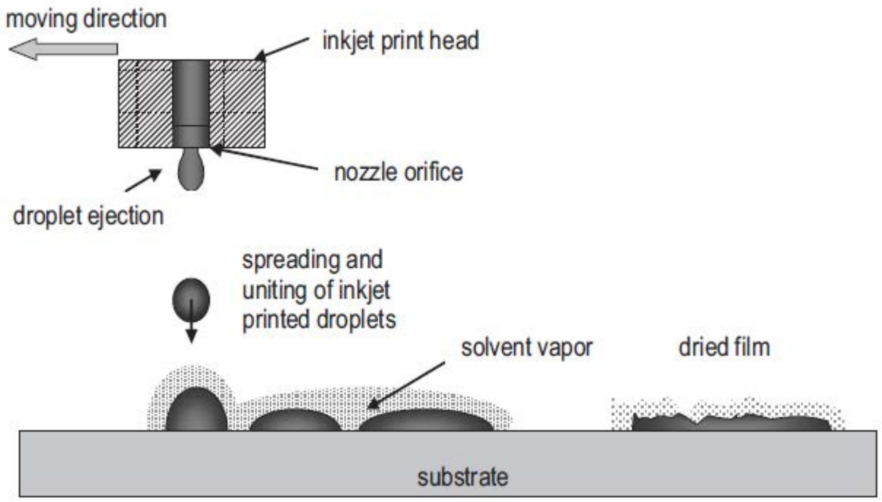
HZB Helmholtz Zentrum Berlin

HySPRINT Helmholtz Innovation Lab

Bundesministerium für Bildung und Forschung

grant no. 03XP0091
PEROSEED (ZT-0024)

Cost effective transparent conductive electrodes (TCEs) fabricated using inkjet-printing



General requirements:

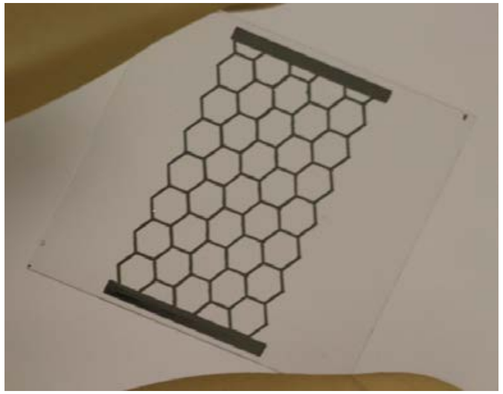
- low cost, flexible, stable,
- low sheet resistance (< 5Ω/sq)

State of the art:

- Indium tin oxide (ITO)
- Aluminium-doped zinc oxide (AZO)

Emerging alternatives:

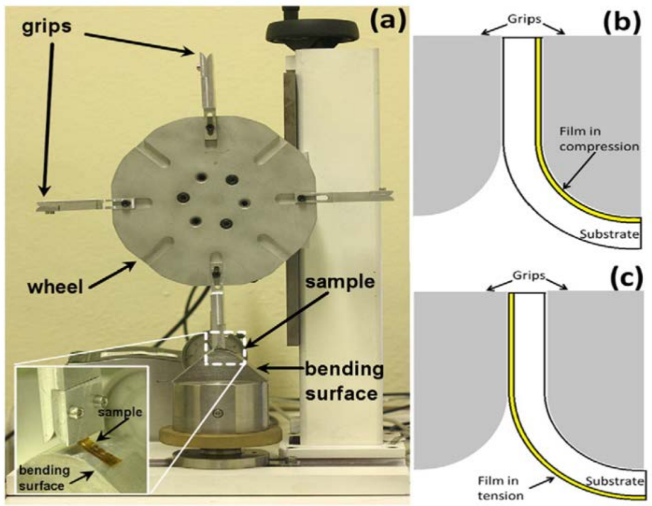
- Carbon nanotubes or graphene
- PEDOT:PSS
- Cu/Ag nanowires (NWs)

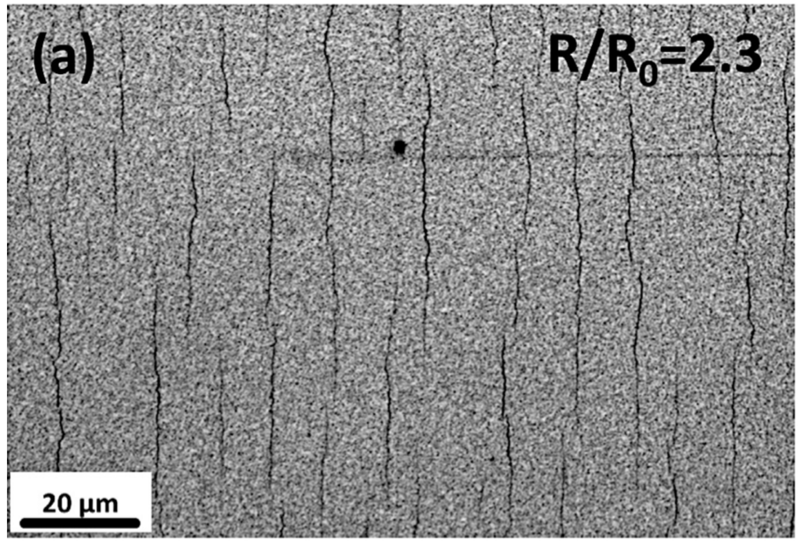


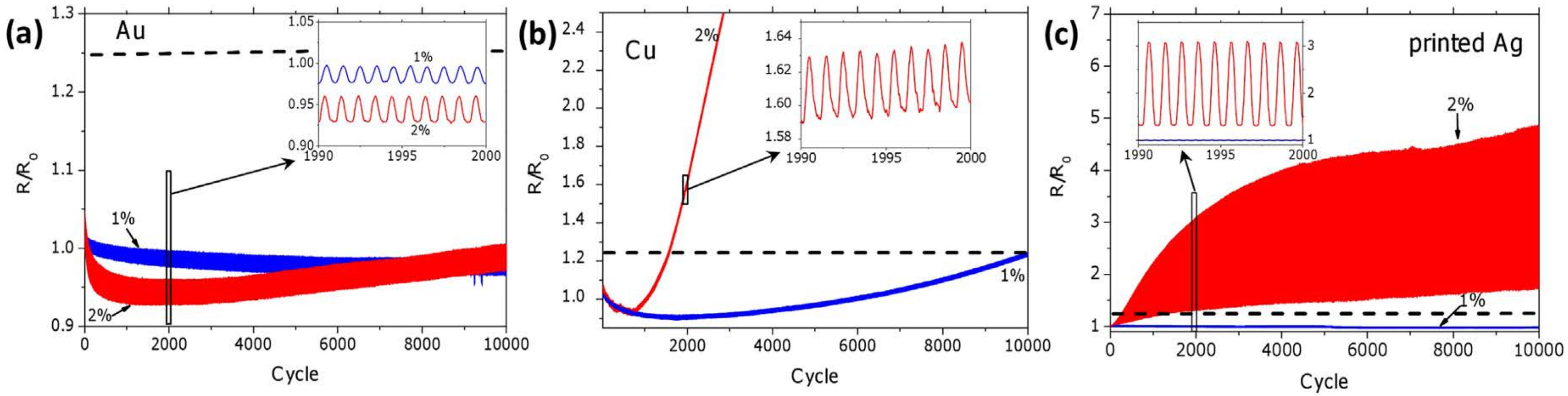
All alternatives need metal-grids for < 5Ω/sq

F. Hermerschmidt, S. A. Choulis, and E. J. W. List-Kratochvil, *Adv. Mater. Technol.* **4** 1800474 (2019).

Bending Tests on Printed Ag Structures

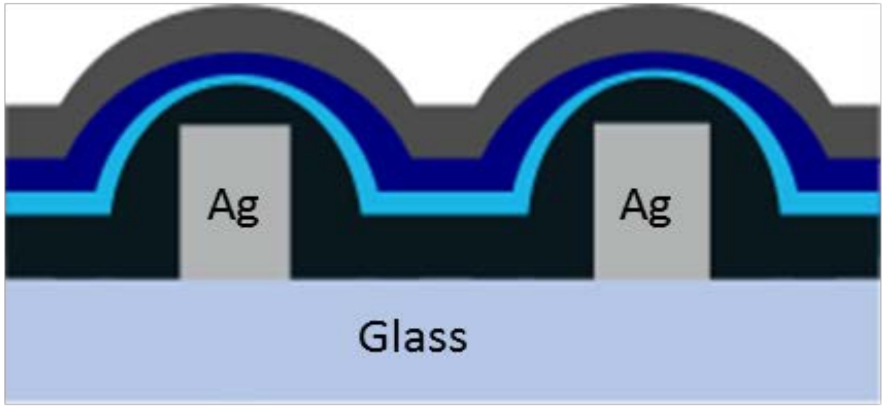




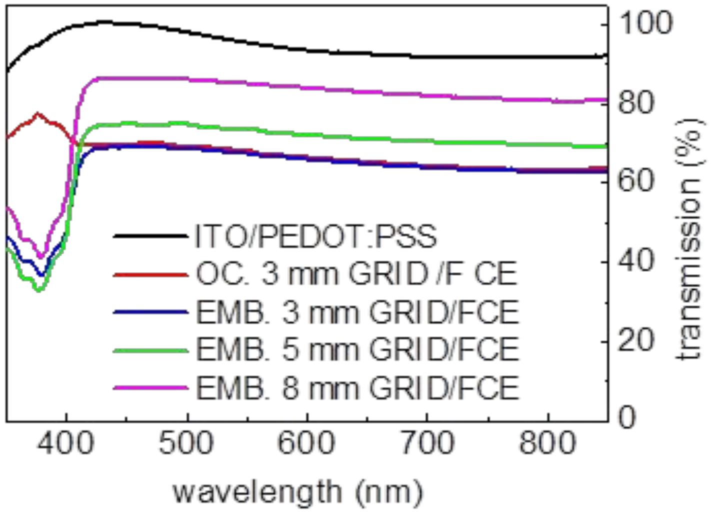


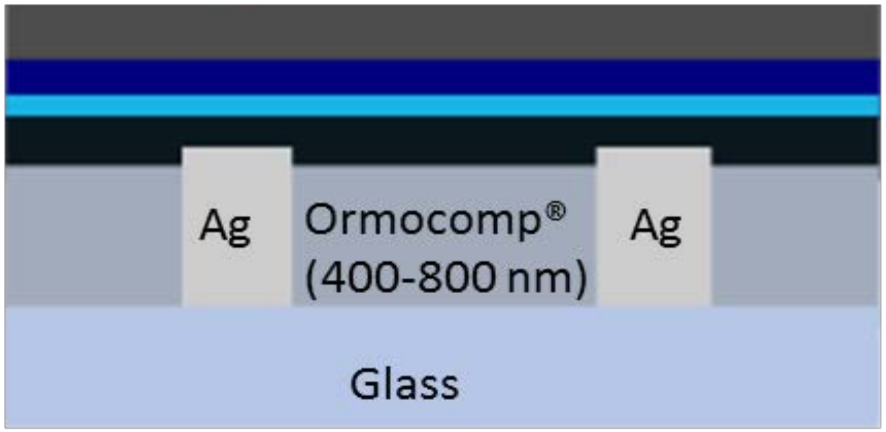
O. Glushko et al. *Mat. Sci. & Eng. A* **662**, 157 (2016) & *Microelectronics Reliability* **56**, 109 (2016) & *J. Mater. Research* **32**, 1760 (2017)

Bilayer PLED with Printed Ag-Metal Grids



Top electrode (10 nm Ca/100 nm Al) LEP (60 nm)
HIL (20 nm) PEDOT:PSS (150 nm)



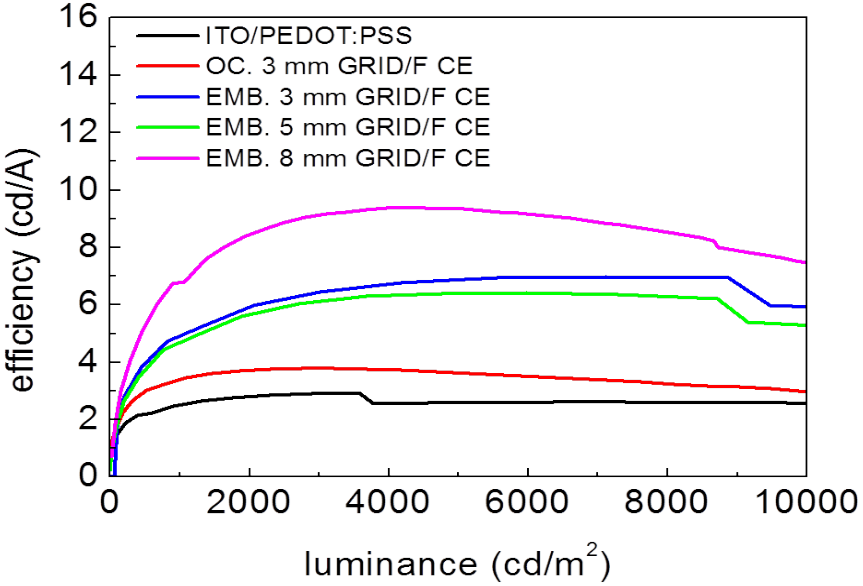


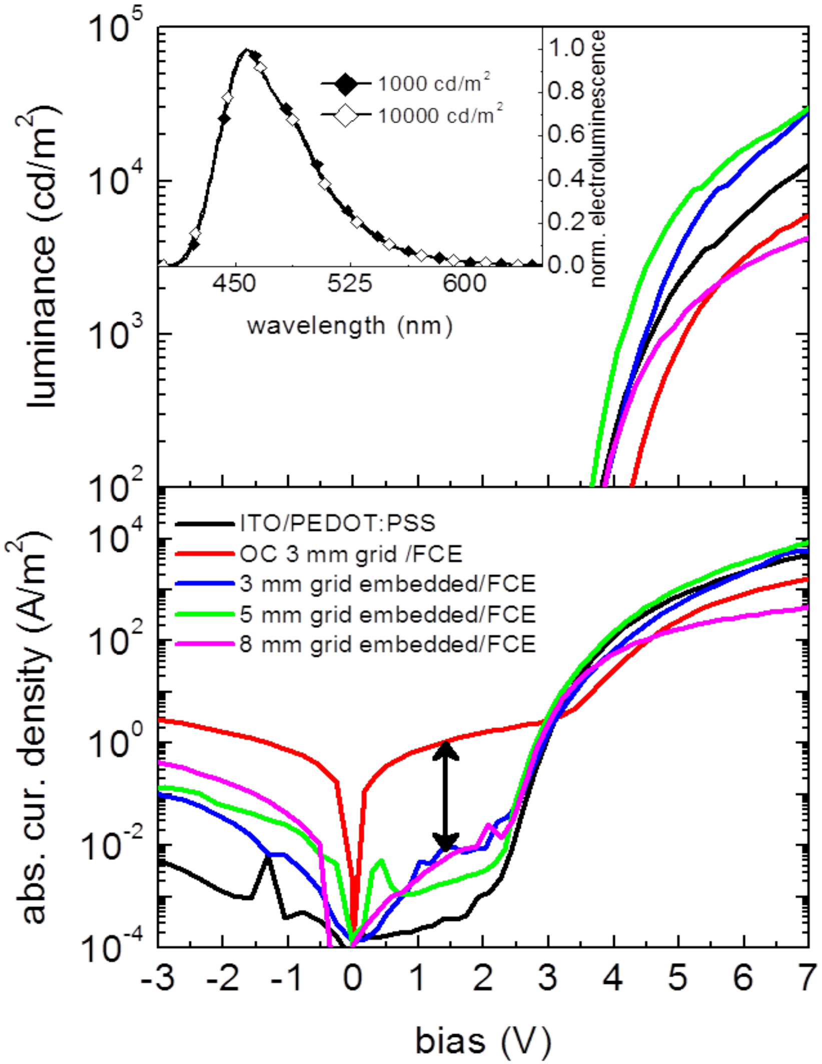
L. Kinner, et al. *Appl. Phys. Lett.* **110**, 101107 (2017)

A bilayer PLED with printed Ag metal grids

Device parameters:

- Ag-grid/PEDOT:PSS/HIL/LEP/Ca/Al
- improved stability due to embedding
- max. lum. 20000 cd/m²
- max. eff. 9.4 cd/A
- reduced shunt current





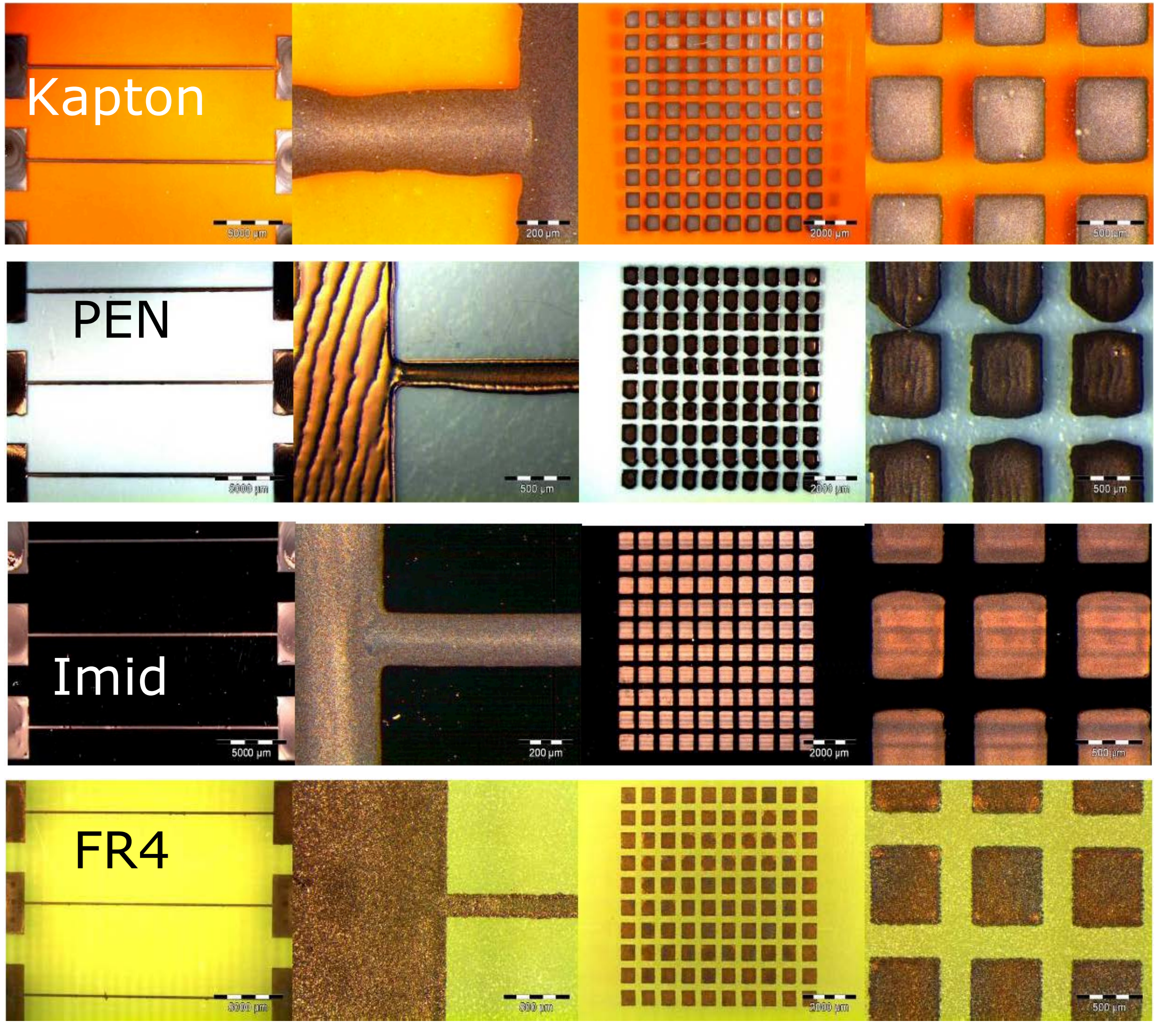
L. Kinner, et al. *Appl. Phys. Lett.* **110**, 101107 (2017)

Inkjet-Printed nano-Cu

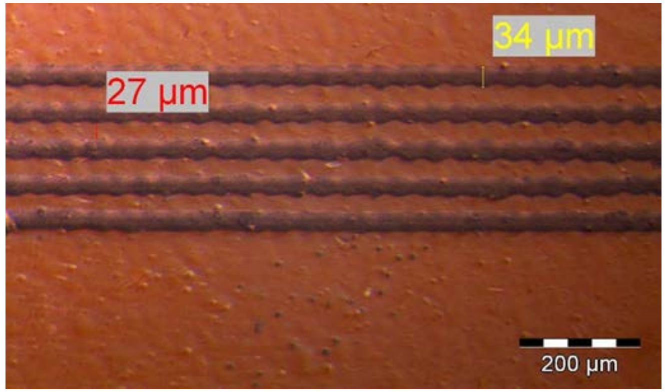
PLASMAS

intrinsiq materials

qualified on various substrates



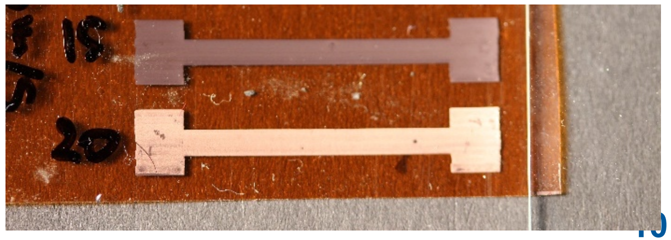
high resolution printing



well defined inks

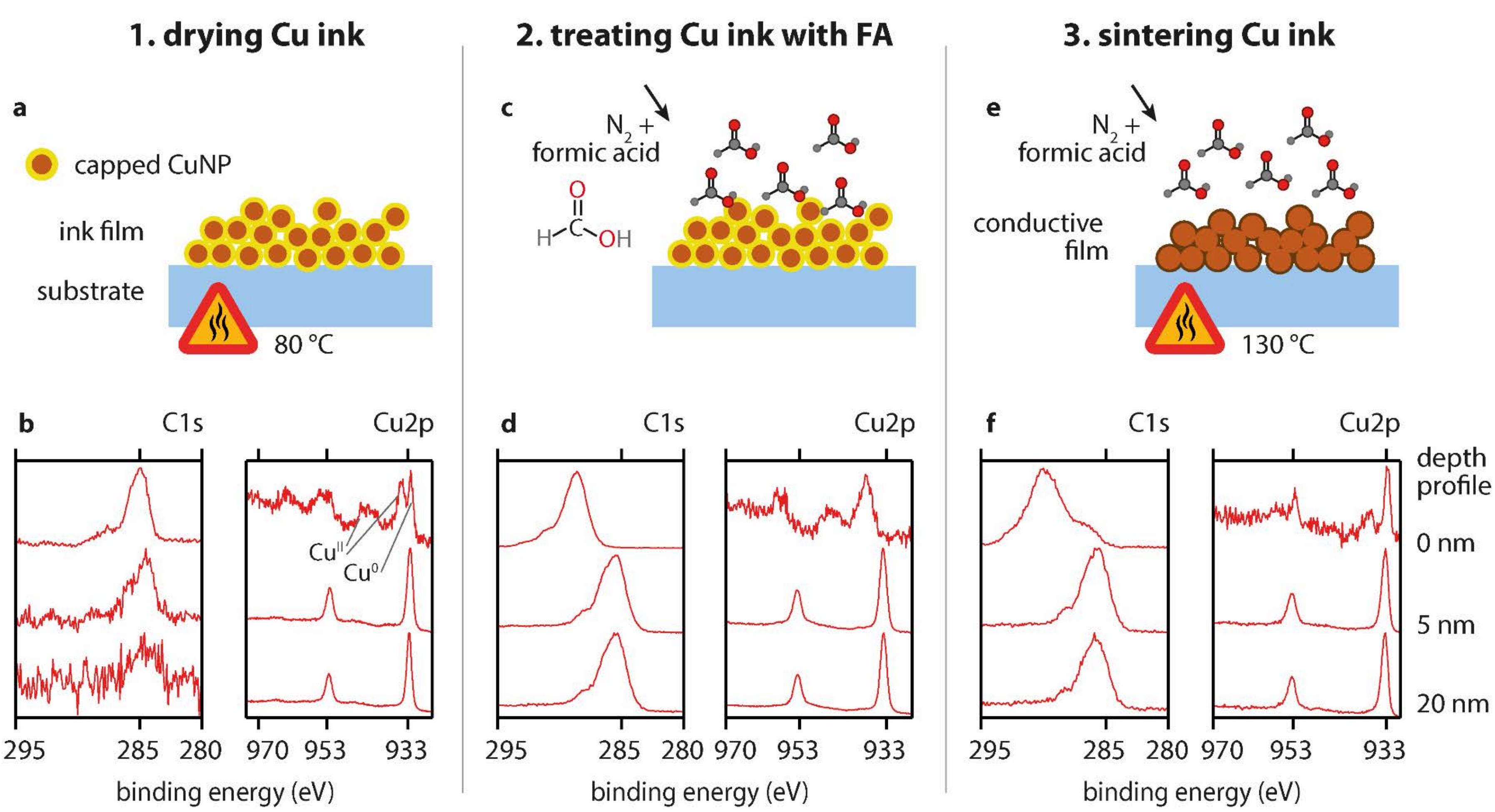
Viscosity @20°C [cP]	~32
Surface Tension @RT [mN/m]	~29
Solid Content [%]	~12
Density [g/ml]	~1,1

CW-LASER Sintered



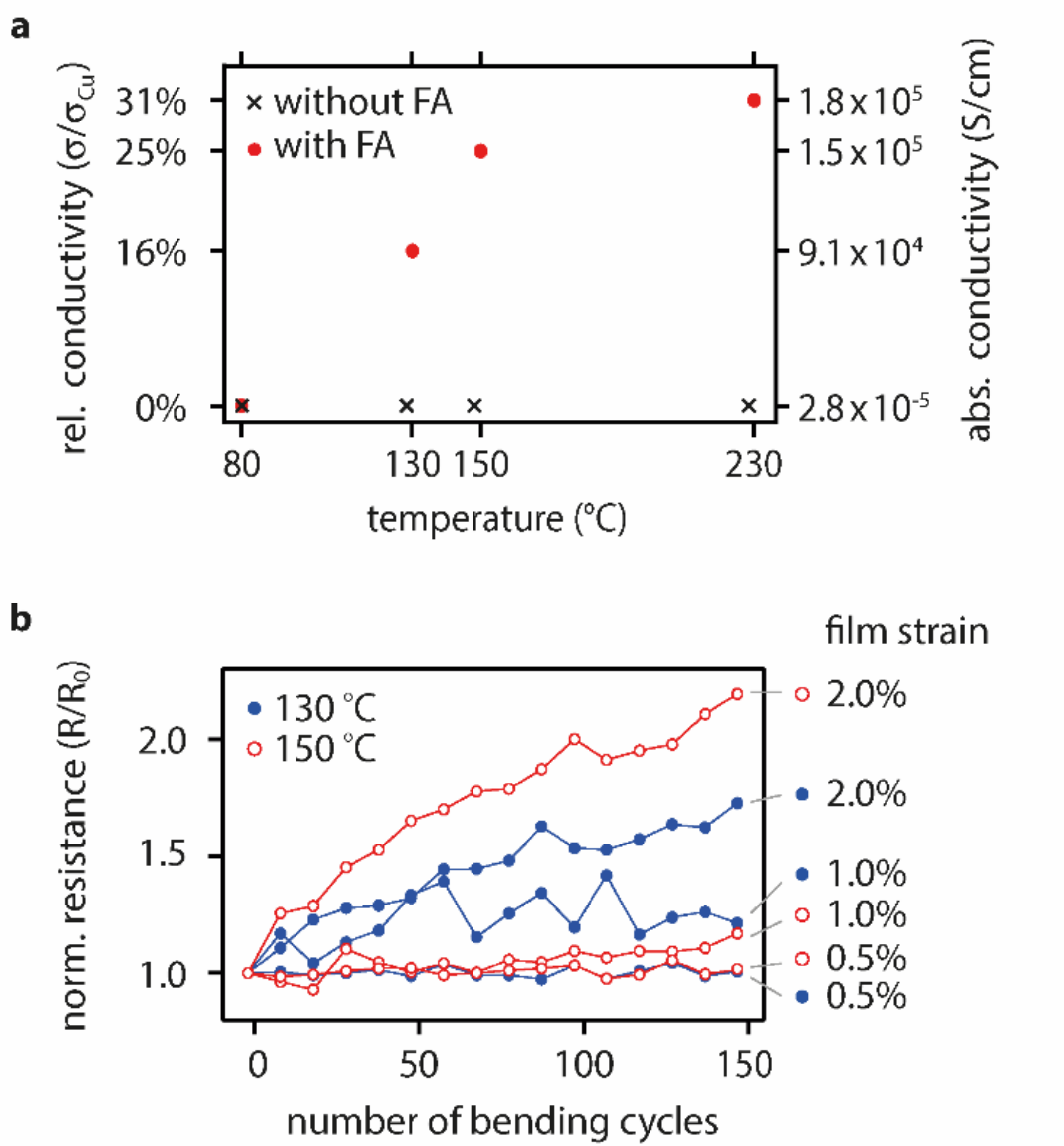
A. Klug et al., Proc. SPIE **9569,** 95690N (2015)

A universal sintering alternative is a process using formic acid



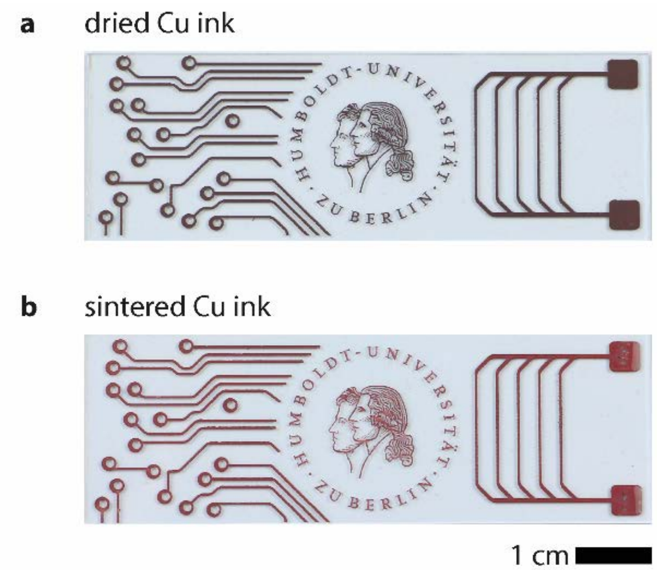
F. Hermerschmidt et al. *Adv. Mat. Techn.* 1800146 (2018) & 1800474 (2019)

High conductivity achieved even at low temperature conditions



Adhesion test: 0 (ISO), 5B (ASTM)

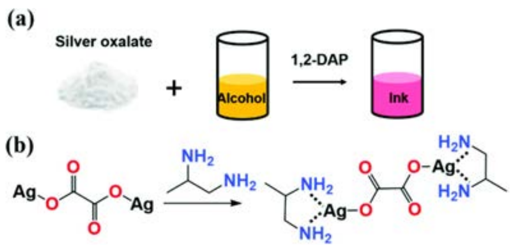
No noticeable increase in resistivity after five days under ambient conditions

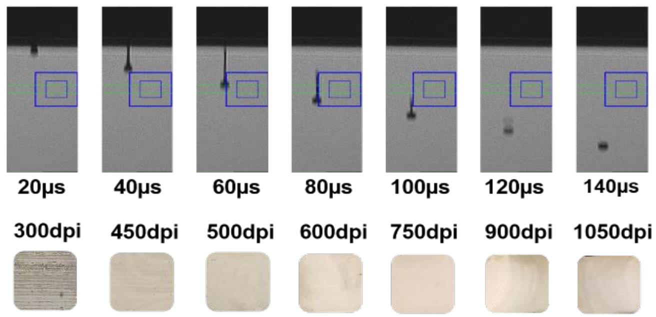


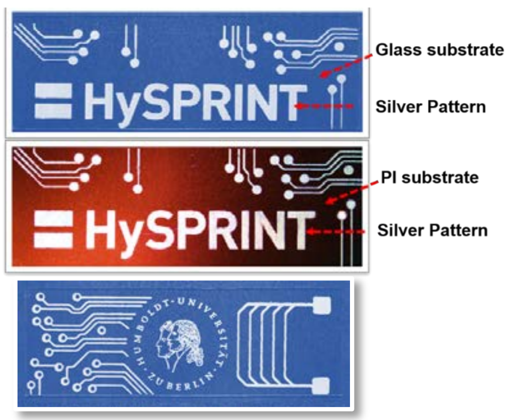
F. Hermerschmidt et al. *Adv. Mat. Techn.* 1800146 (2018) & 1800474 (2019)

one-pot particle-free Ag ink

JointLab



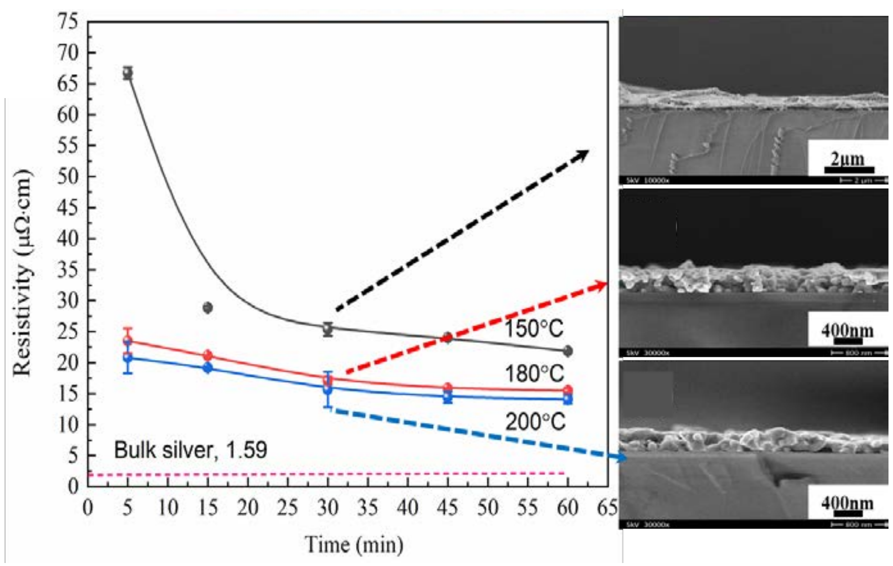




simple one-pot process to fabricate stable, cheap and printable silver particle-free ink

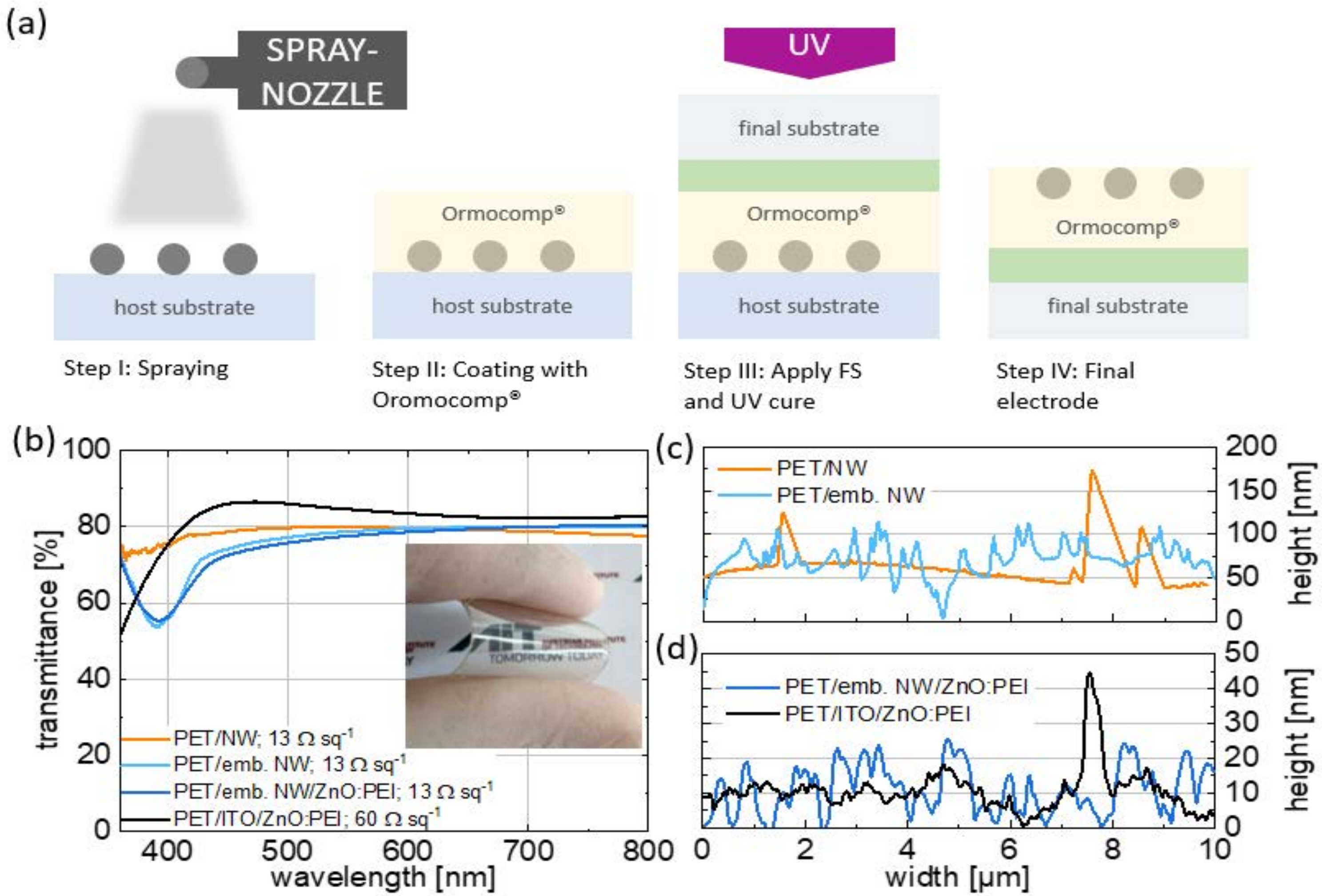
choice of alcohol enables control of morphology and electrical performance of the films

highly conductive silver pattern printed on both glass and flexible polyimide substrates.



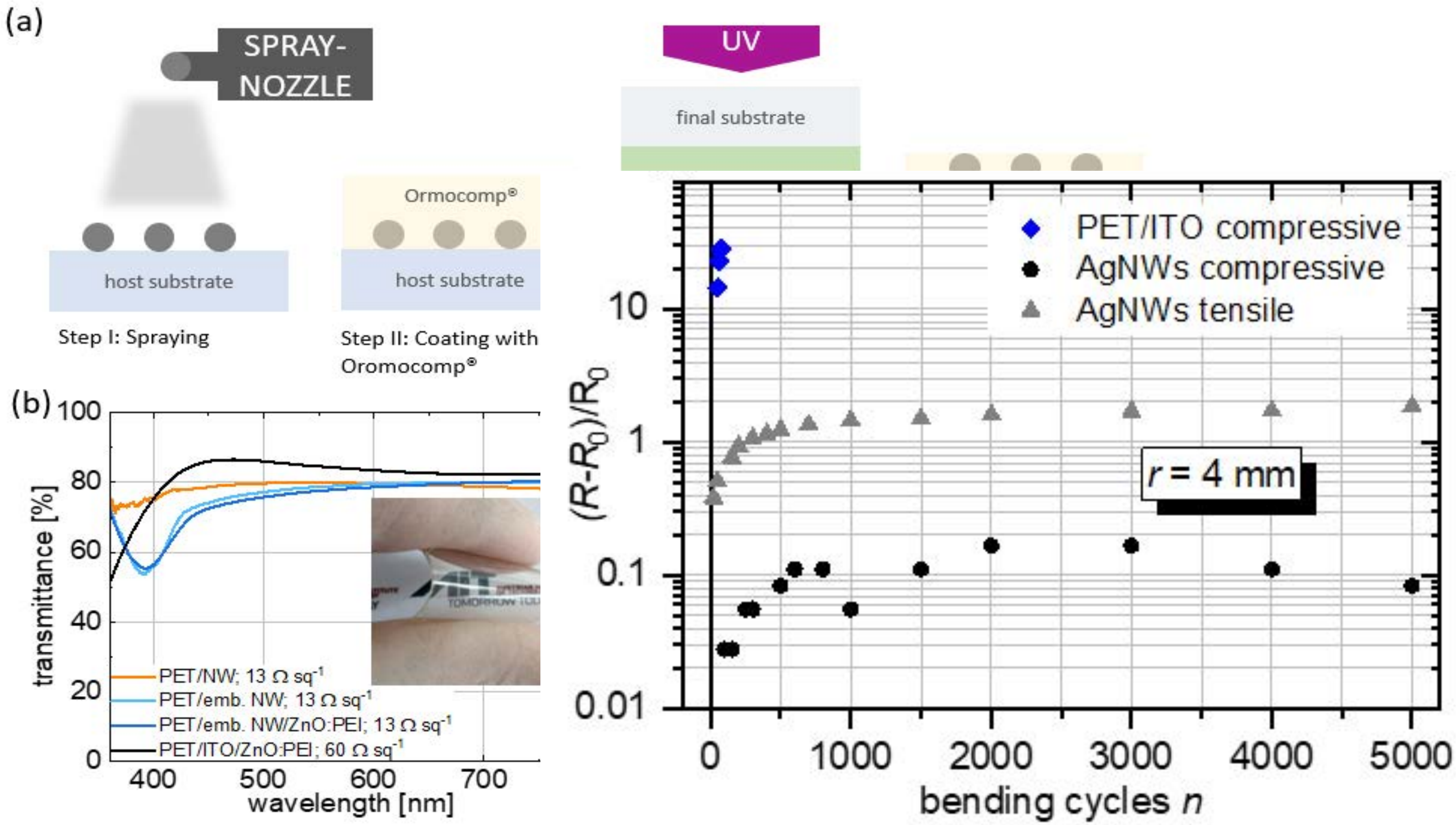
W. Yang et al. J. Mater. Chem. C d0tc03864d (2020).

Flexible Spray Coated Embedded Ag Nanowire Electrodes



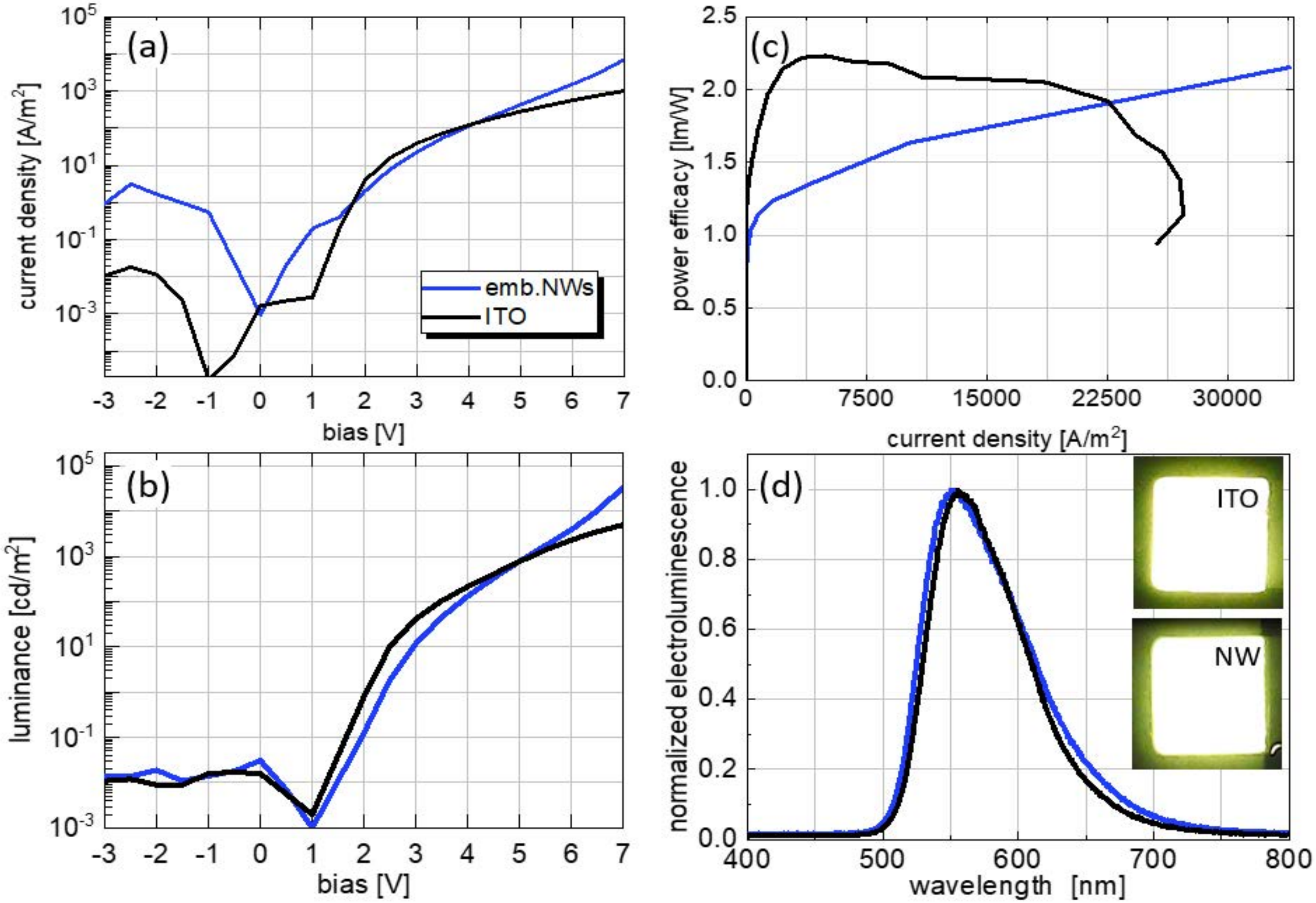
L. Kinner, et al. *Nanotechnology* **31**, 365503 (2020).

Flexible Spray Coated Embedded Ag Nanowire Electrodes



L. Kinner, et al. *Nanotechnology* **31**, 365503 (2020).

Flexible Spray Coated Embedded Ag Nanowire Electrodes - OLEDs



L. Kinner, et al. *Nanotechnology* **31**, 365503 (2020)
L. Kinner et al. *Phys. Status Solidi RRL* 2000305 (2020)

Transparent electrodes using DMDs (dielectric/metal/dielectric)

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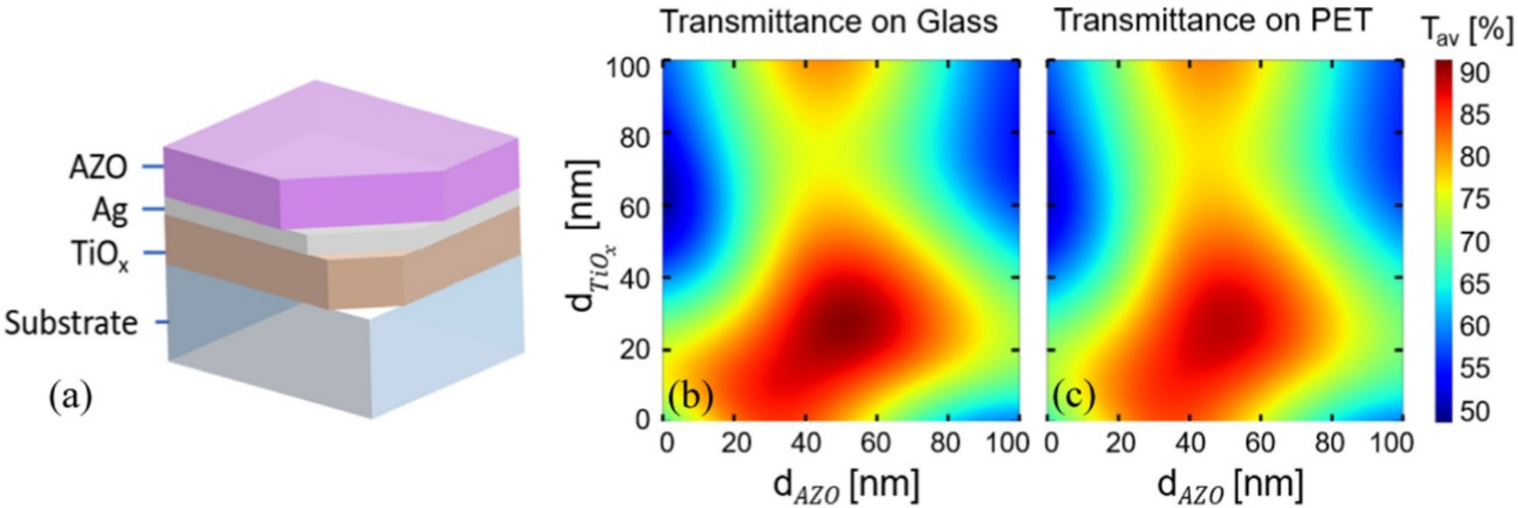

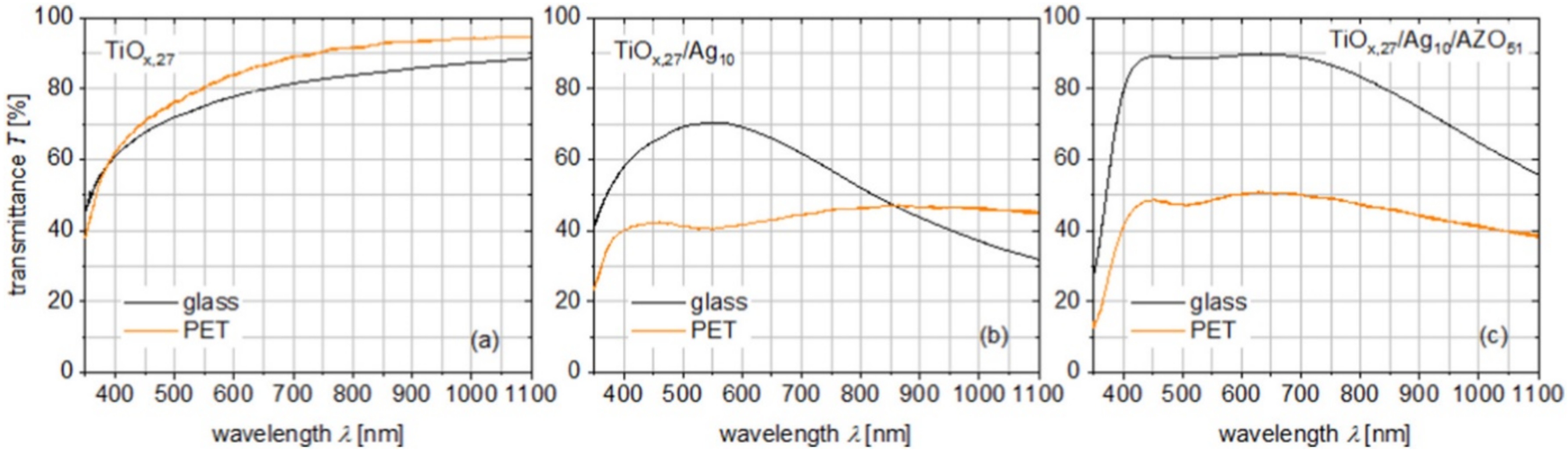

L. Kinner et al., *Mater. and Design* **168**, 107663 (2019).

A polymer interlayer in transparency optimised DMD electrodes

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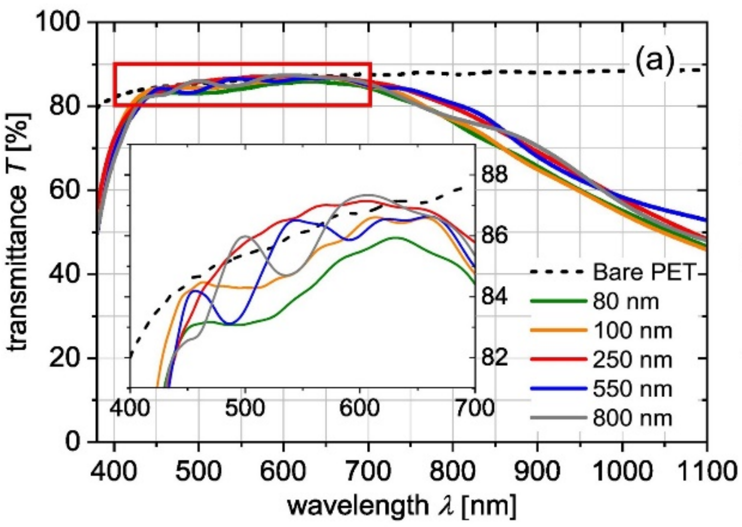
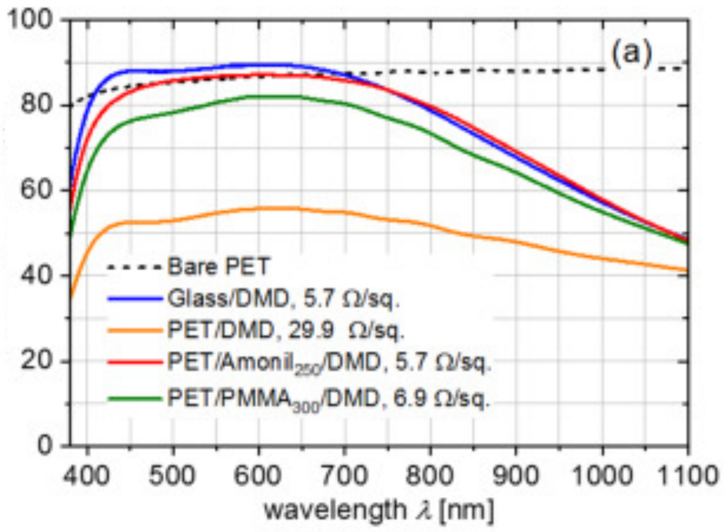
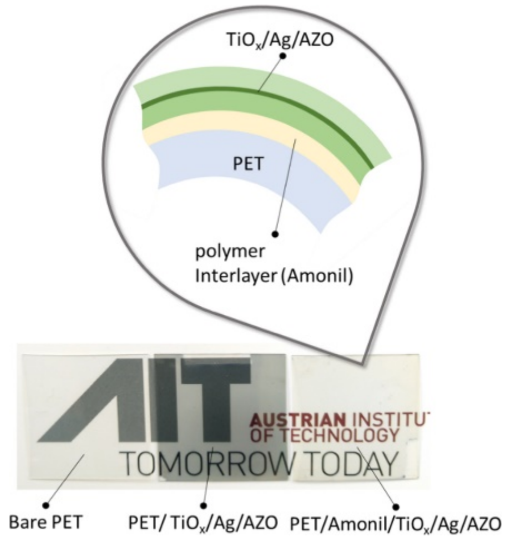


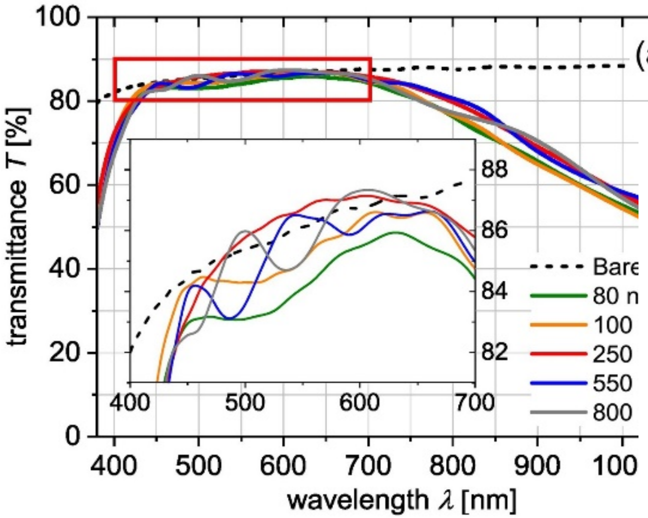


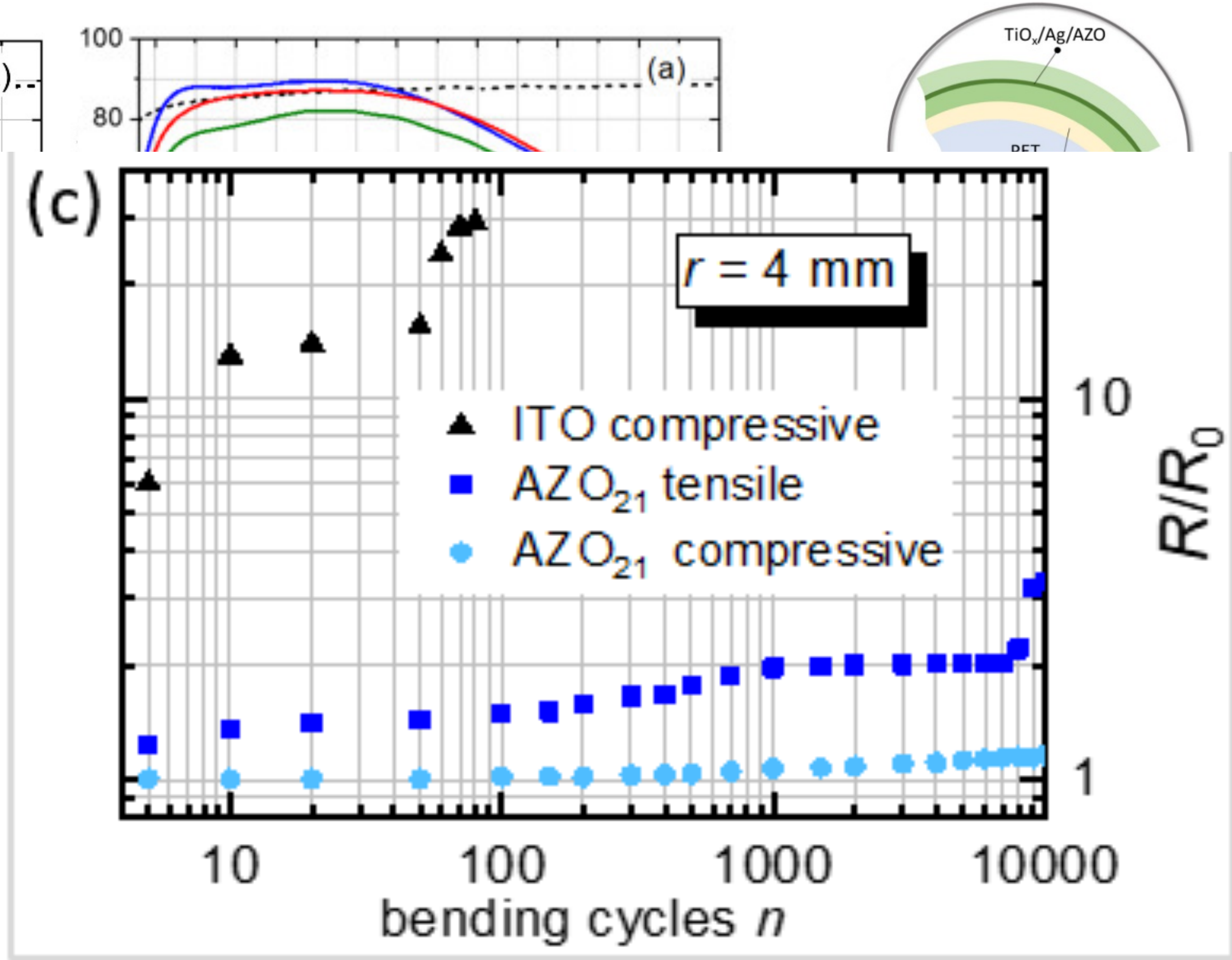


Substrate	RMS [nm]	T_{av} [%]	T_{550} [%]	R_s [Ω/sq.]	Φ_{av} [10^{-3}/Ω]	Φ_{550} [10^{-3}/Ω]
Glass	1.1 ± 0.1	88.1	90	5.7	49	61
PET	8.4 ± 1.5	44.8	47	29.9	0.011	0.018
PET/Amonil®$_{250}$	1.7 ± 0.1	85.1	87	5.7	35	44
PET/PMMA$_{300}$	3.7 ± 2.3	79.0	81	6.9	14	18

L. Kinner et al., *Mater. and Design* **168**, 107663 (2019).

A polymer interlayer in transparency optimised DMD electrodes





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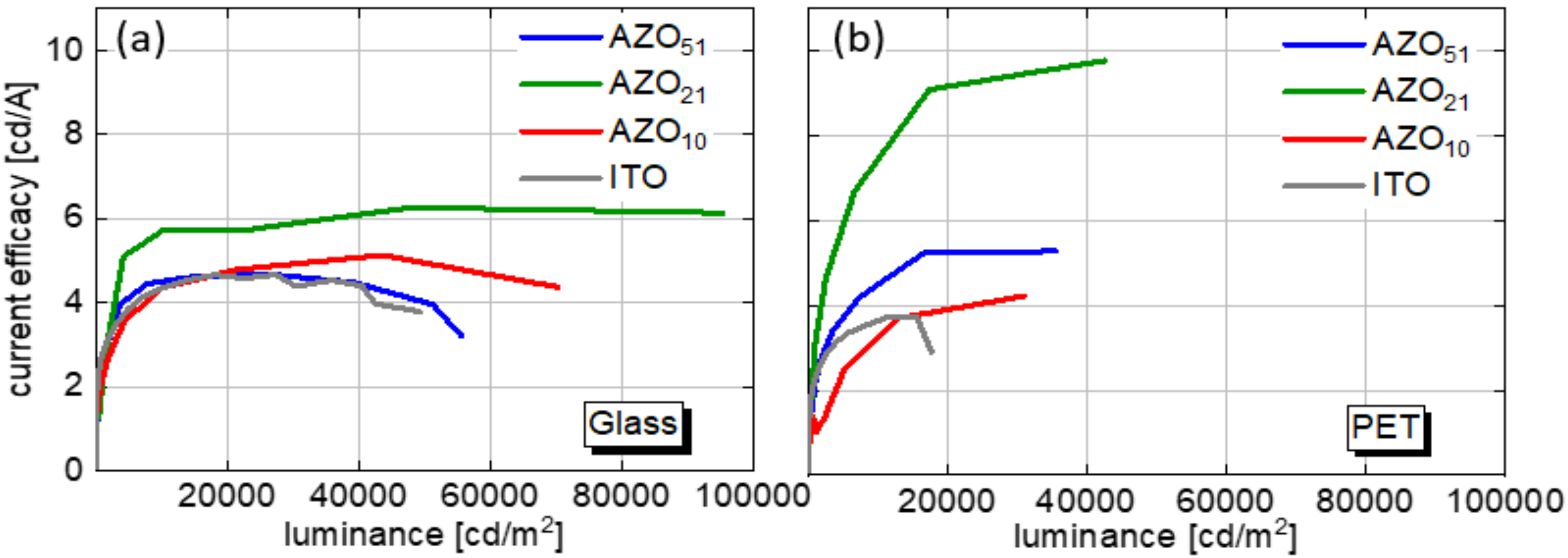
L. Kinner et al., *Mater. and Design* **168**, 107663 (2019). & L. Kinner et al. (submitted for publication)

OLEDs on PET with DMD electrodes

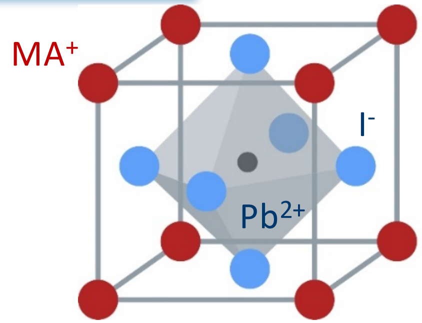
	GLASS					PET				
	V_T [V]	L_{max} [cd/m²]	L_{6V} [cd/m²]	η_{max} [cd/A]	η_{10000} [cd/m²]	V_T [V]	L_{max} [cd/m²]	L_{6V} [cd/m²]	η_{max} [cd/A]	η_{10000} [cd/m²]
AZO_{51}	1.7	75729	8000	5.23	4.52	2.0	43410	7300	5.48	4.54
AZO_{21}	1.9	99910	23000	6.27	5.74	2.1	42629	17400	9.78	7.60
AZO_{10}	1.6	70294	21000	5.14	4.36	1.9	31025	13100	4.22	3.37
ITO	1.7	49314	5000	4.67	4.36	2.4	17650	1300	3.75	3.64

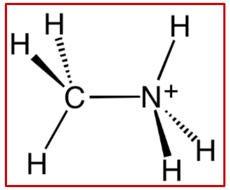


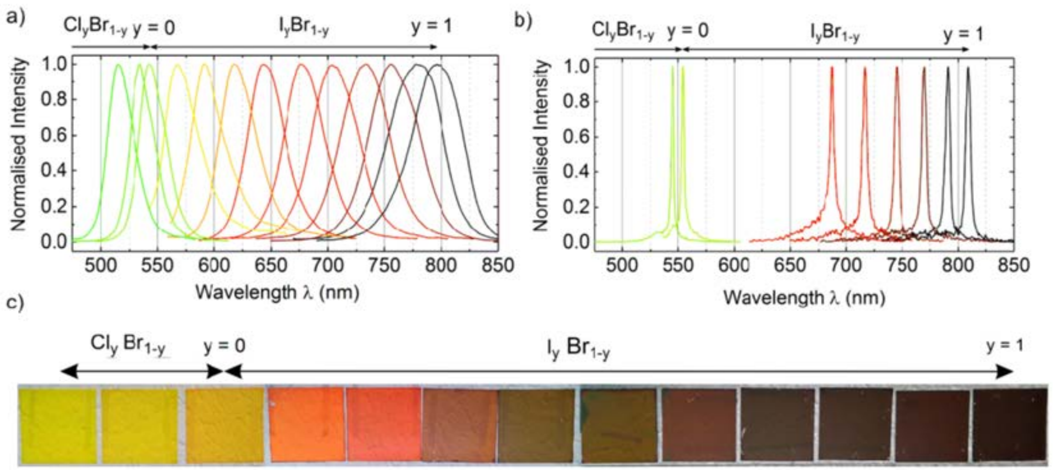
L. Kinner et al., *Mater. and Design* **168**, 107663 (2019). & L. Kinner et al. (submitted for publication)

Exceptional PV properties of OMHP

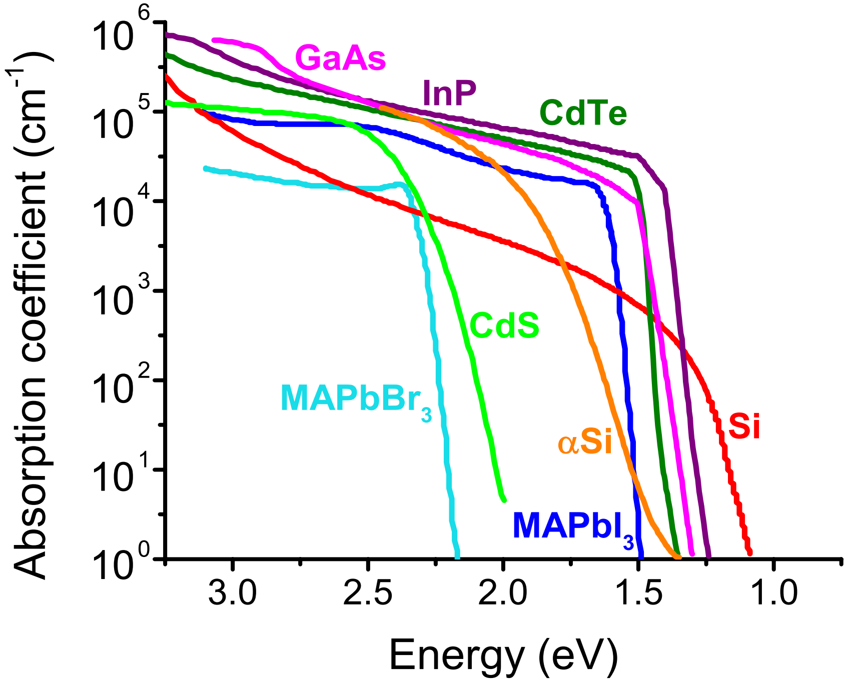
- ABX_3 structure (Methylammoniumleadtriiodide)
- High absorption coefficient
- Charge carrier diffusion length
- Bandgap tunability
- Low temperature process (T < 100°C)
- High defect tolerance
- High PCE (23.7%)







Brenner et al., *Opt. Mater. Express* 7, 4082-4094 (**2017**)

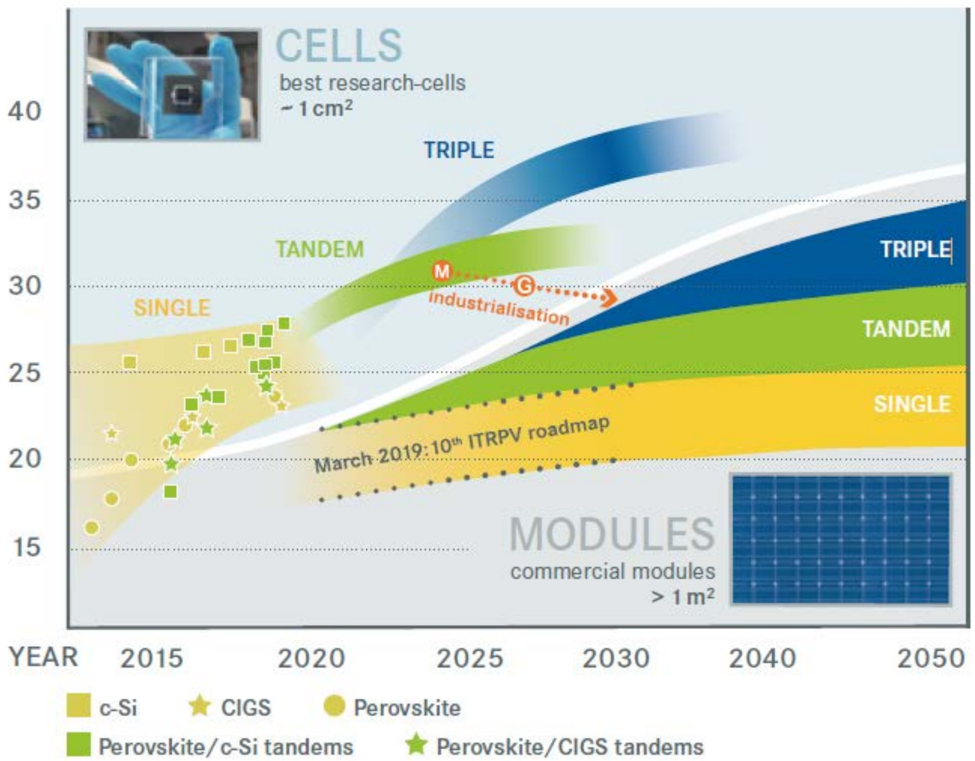


data adapted from pveducation.org, Hoke, Stanford University
Stranks et al. Nat. Nanotech. 10, 391 (2015) and Yin et al. J. Phys. Chem. C 2015, 119, 5253

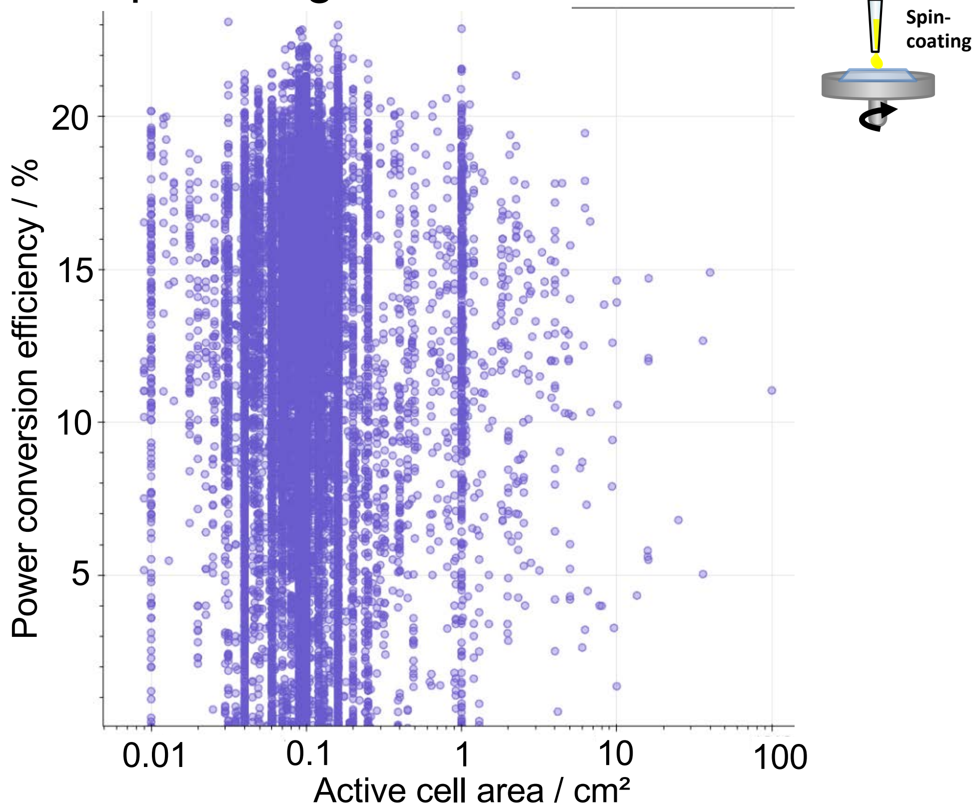
Metal Halide Perovskite Solar cells

HELMHOLTZ STRATEGY

POF IV - roadmap



Up-scaling of PV

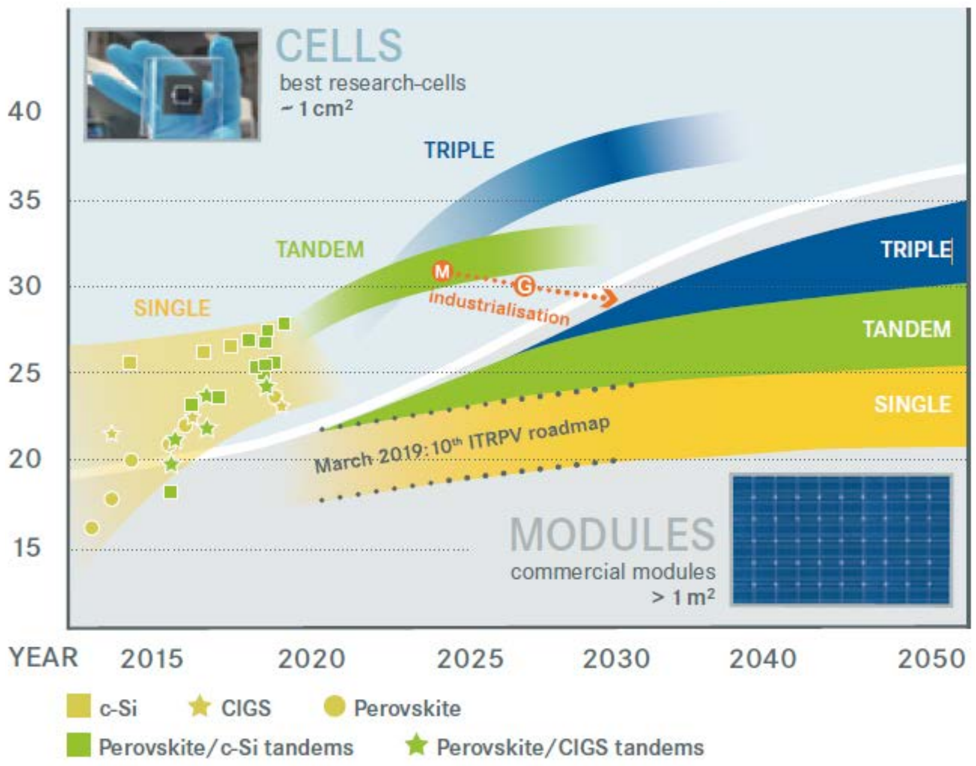


Database Jesper Jacobsson HZB, 2020

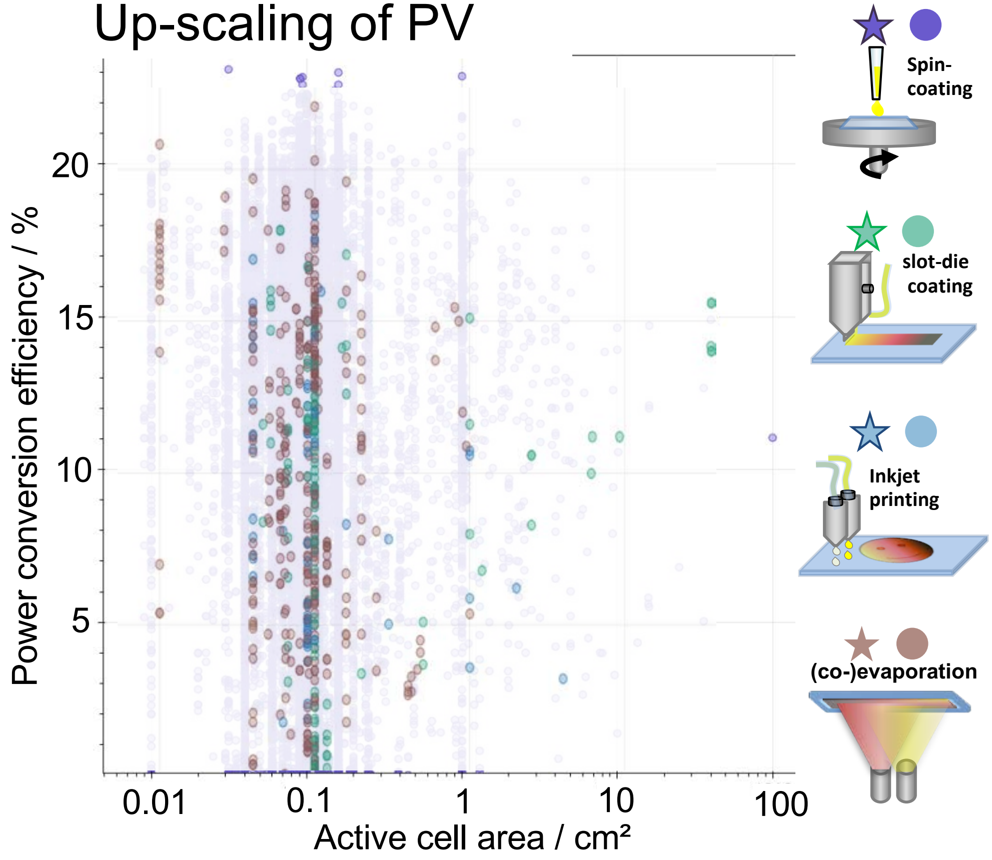
Metal Halide Perovskite Solar cells

HELMHOLTZ STRATEGY

POF IV - roadmap



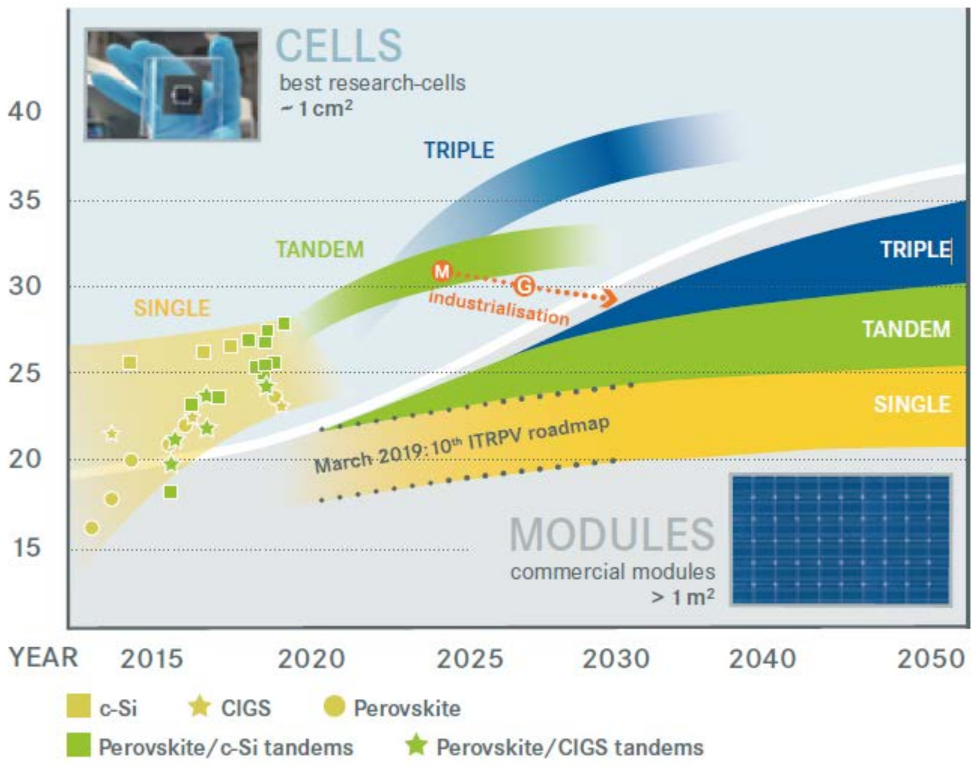
Up-scaling of PV



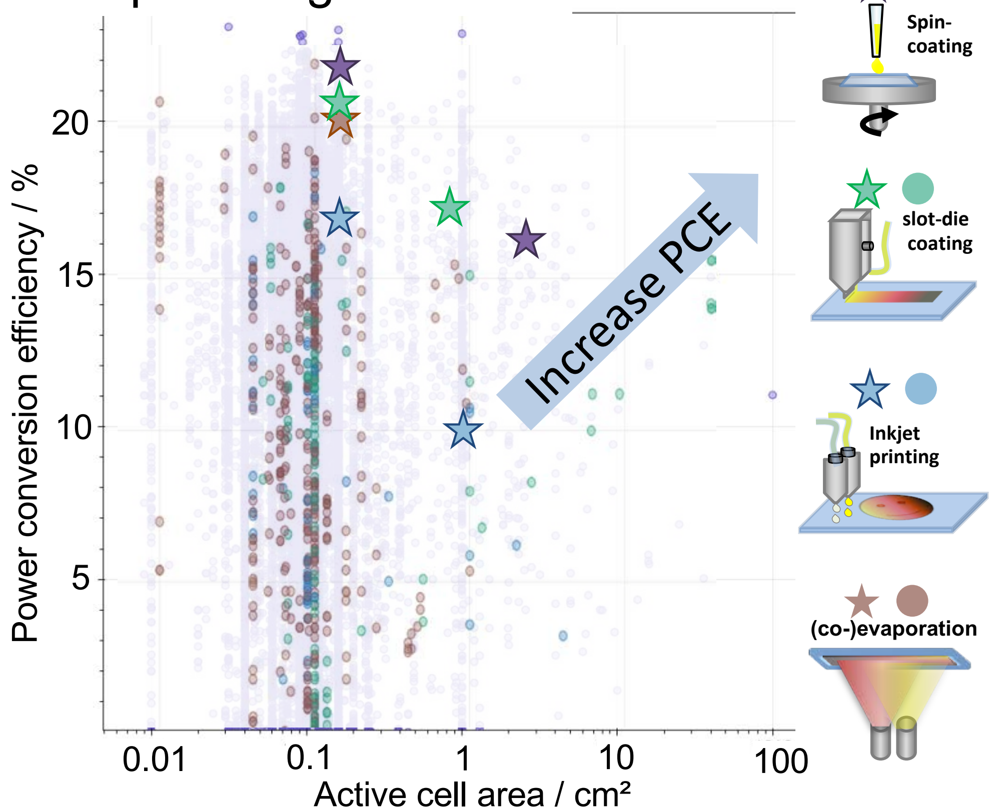
Metal Halide Perovskite Solar cells

INKJET PRINTING: UP-SCALING FROM LAB TO FAB

POF IV - roadmap

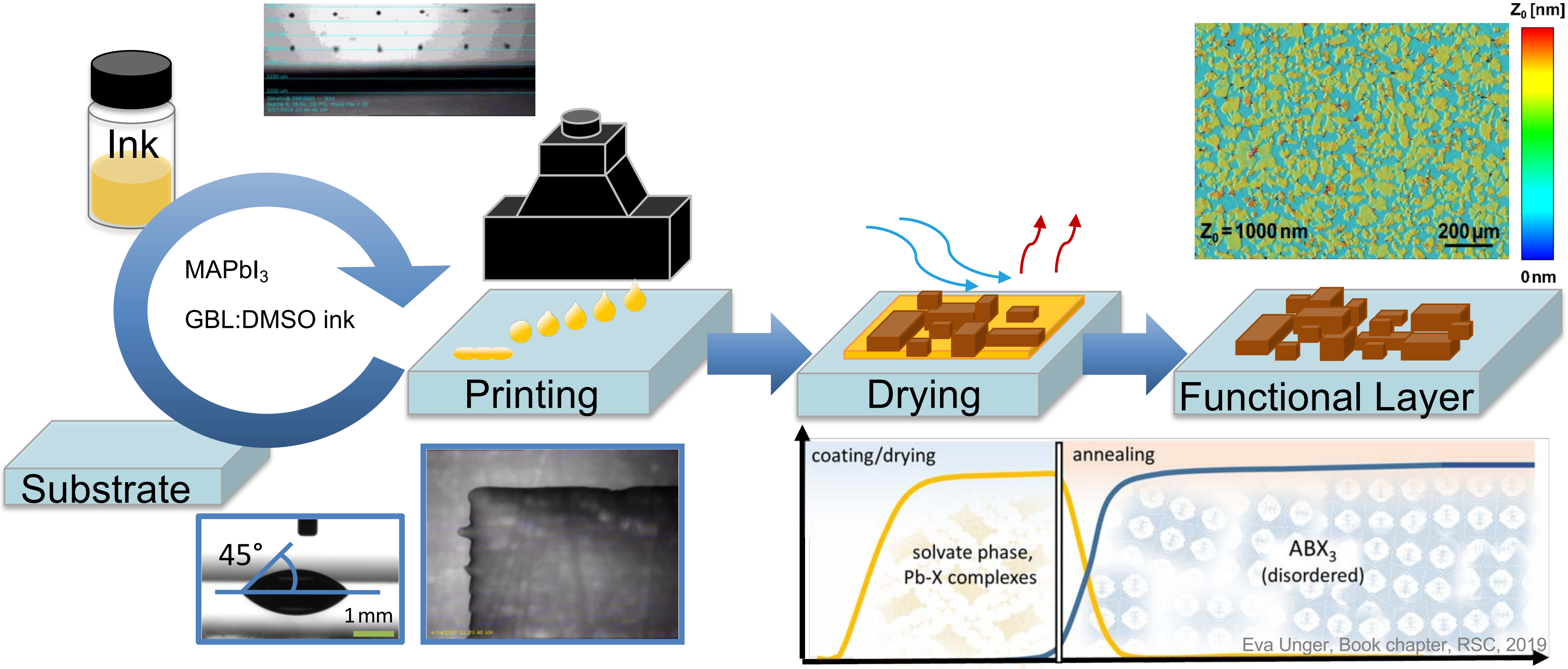


Up-scaling at HZB

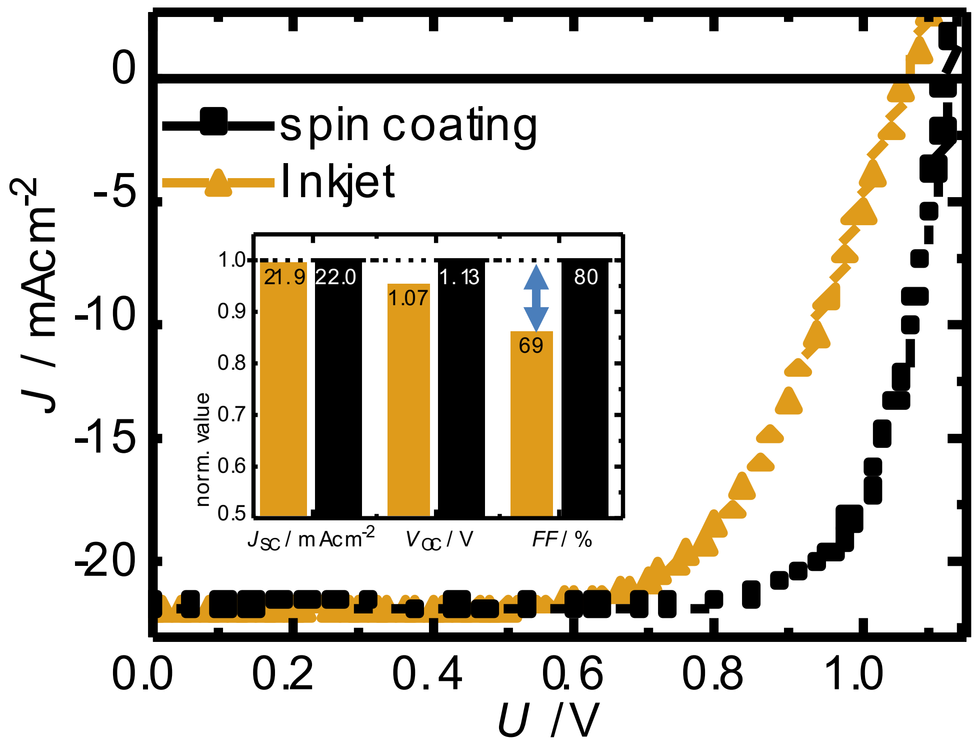


Database Jesper Jacobsson HZB, 2020

Inkjet printing perovskites - from precursor inks to functional layers



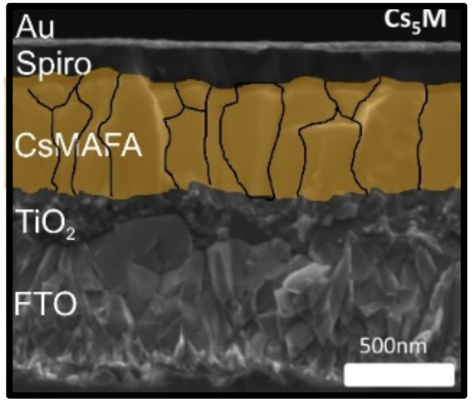
Inkjet-printed perovskite Solar Cells



Saliba et al. *Energy Environ. Sci.*, *9* (6), 1989–1997, (**2016**)

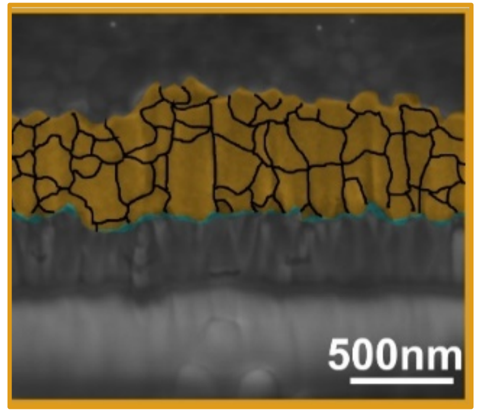
Spincoating CsMAFA

PCE = 19.1 %



Inkjet-printed CsMAFA

PCE = 15.3 %



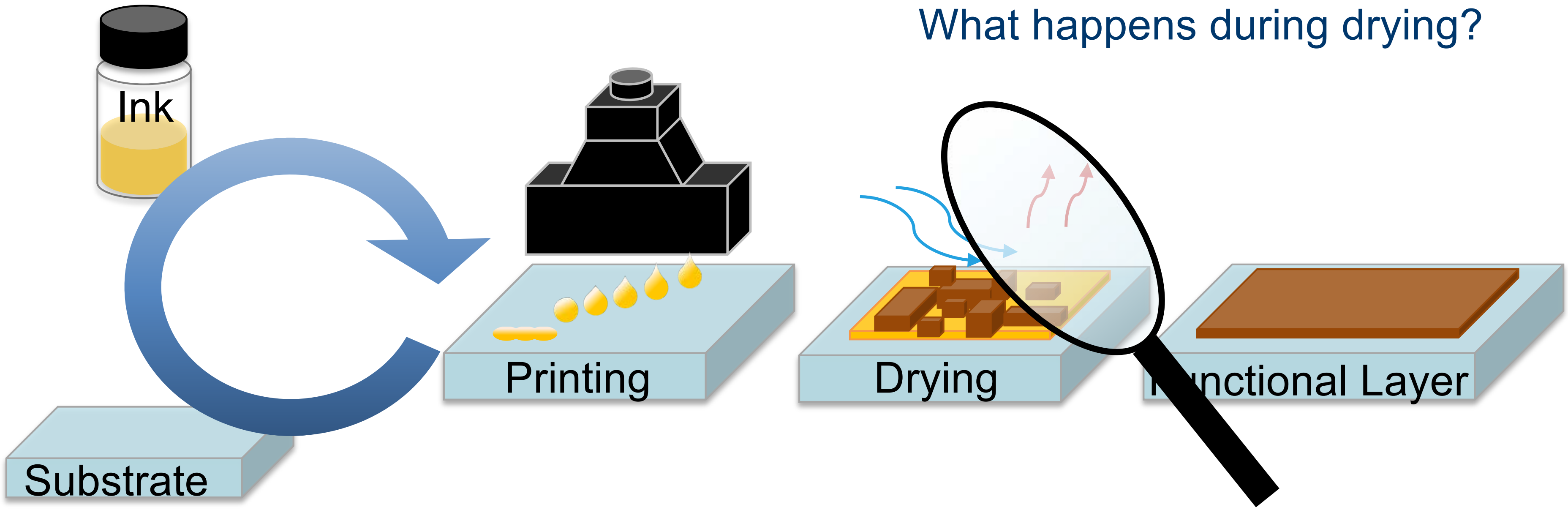
FF limiting *PCE* → grain boundaries, contact resistance

Lower V_{OC} indicates more recombination losses

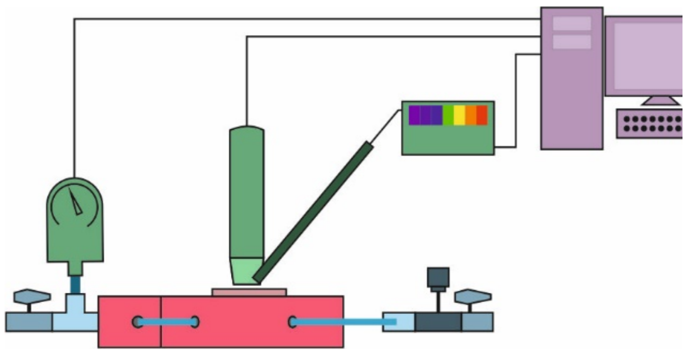
Mathies et al., ACS Appl. Energy Mater. 1, 5, 1834-1839 (**2018)**

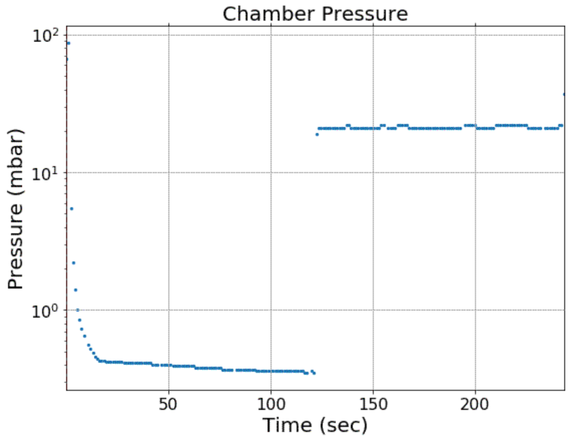
From Precursor inks to Functional layers

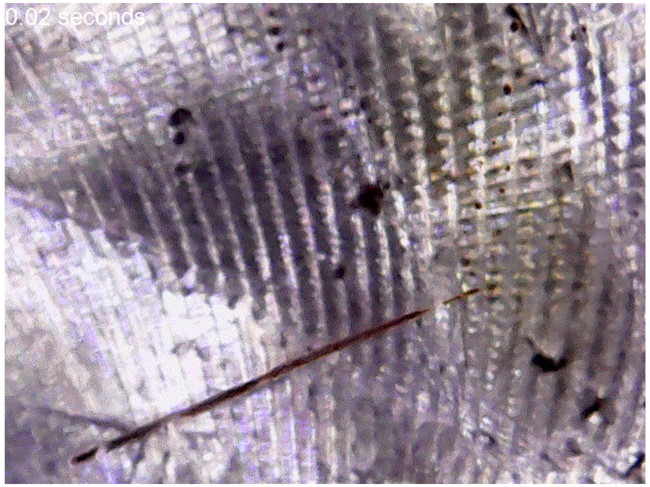
What happens during drying?



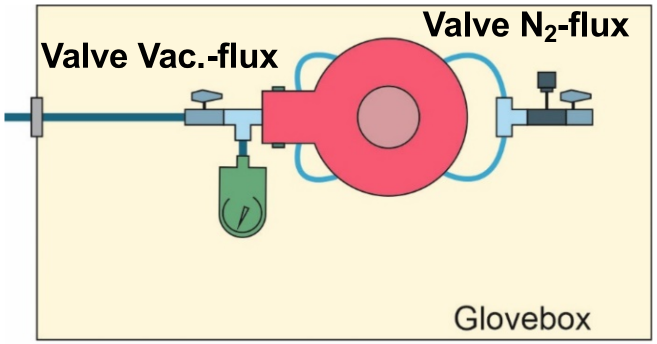
In-situ monitoringg of drying process

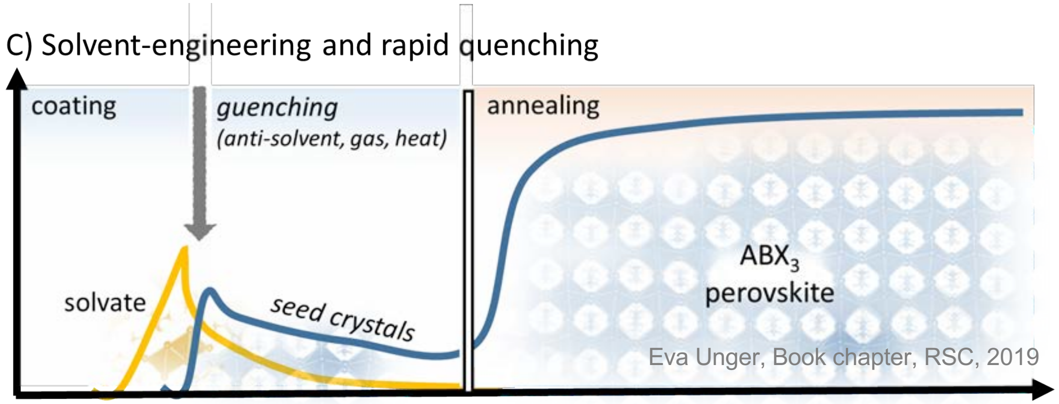






Crystallization starts with N_2-gas flow, not vacuum!



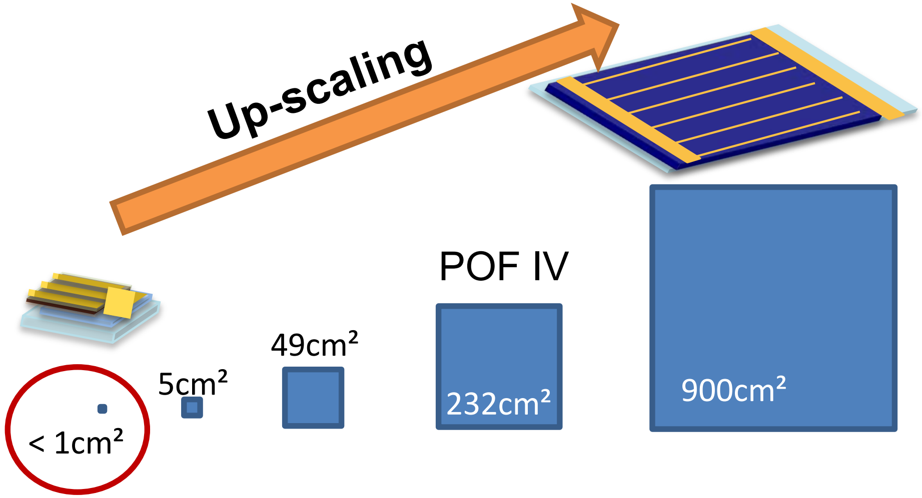


Mathies, **Nandayapa** et al. *manuscript in preparation* (**2020)**

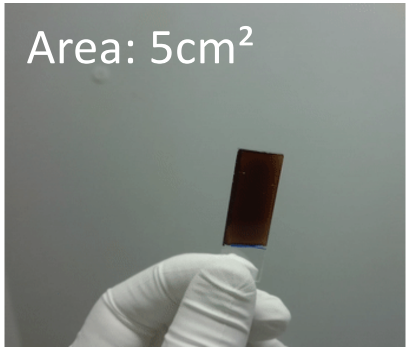
Up-Scaling of Perovskite solar cells

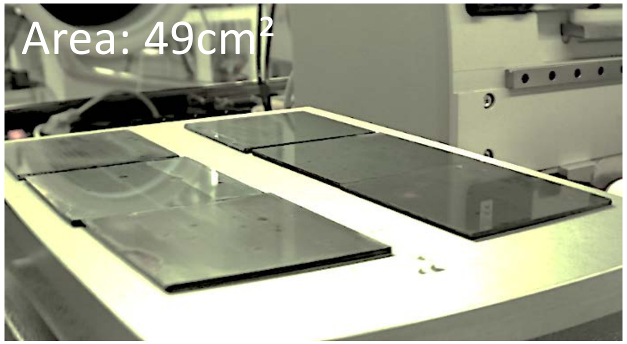
JointLab

PixDro LP50
R&D inkjet printer

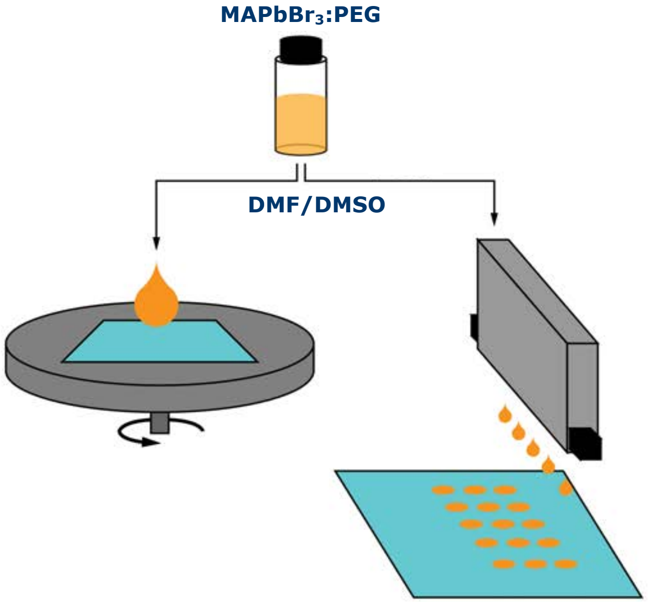


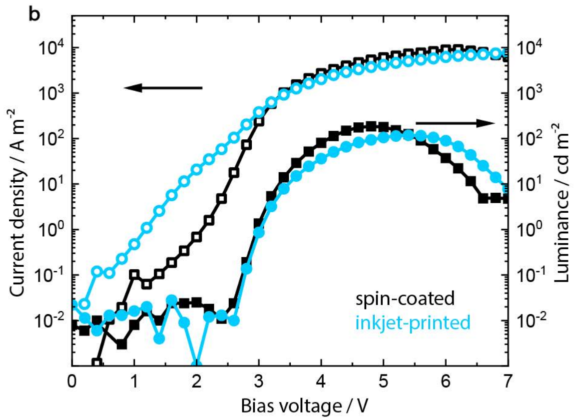
New in 2020:
Industrial Inkjet Printer

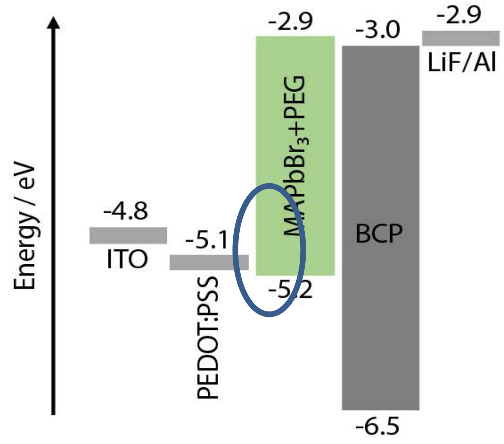




transferring spin coating to inkjet printing is not easy







KCl modification

FULL PAPER Solar RRL www.solar-rrl.com

Alkali Salts as Interface Modifiers in n-i-p Hybrid Perovskite Solar Cells

*Janardan Dagar, Katrin Hirselandt, Aboma Merdasa, Aniela Czudek, Rahim Munir, Fengshuo Zu, Norbert Koch, Thomas Dittrich, and Eva L. Unger**

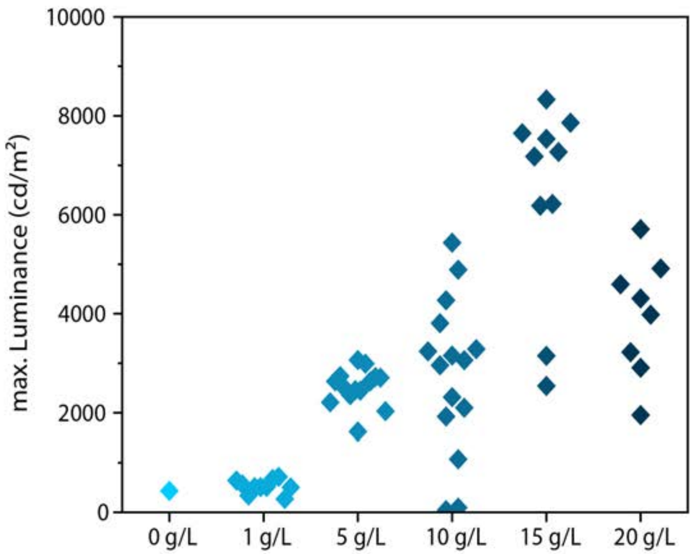
Dagar et al., Sol. RRL **3**, 1900088 (2019).

no antisolvent required

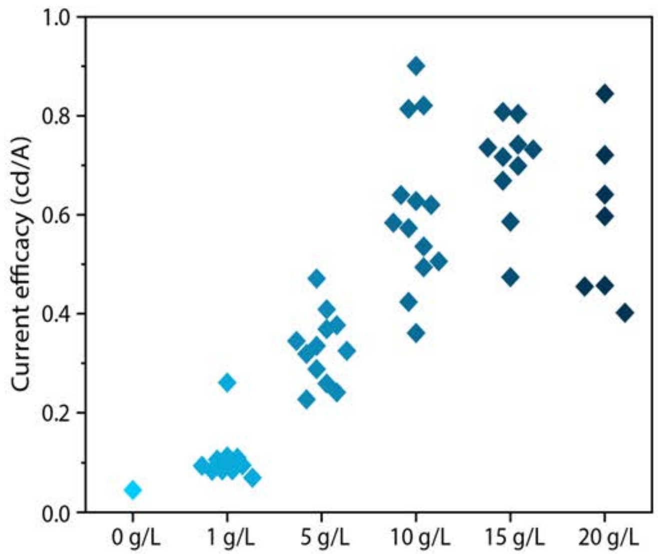
control of crystallization by: perovskite ink (PEG additive)
vacuum drying process
templating (PEDOT:PSS/KCl)

Mathies et al., J. Mater. Chem. A 4, 19207 (2016), Mathies et al., Opt. Express 26, A144 (2018).

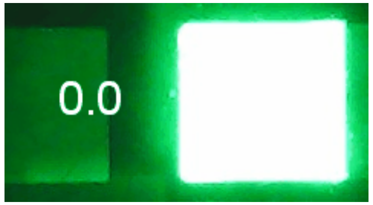
“salty” PEDOT – including KCl leads to significant improvement in LED performance



increase of maximum luminance



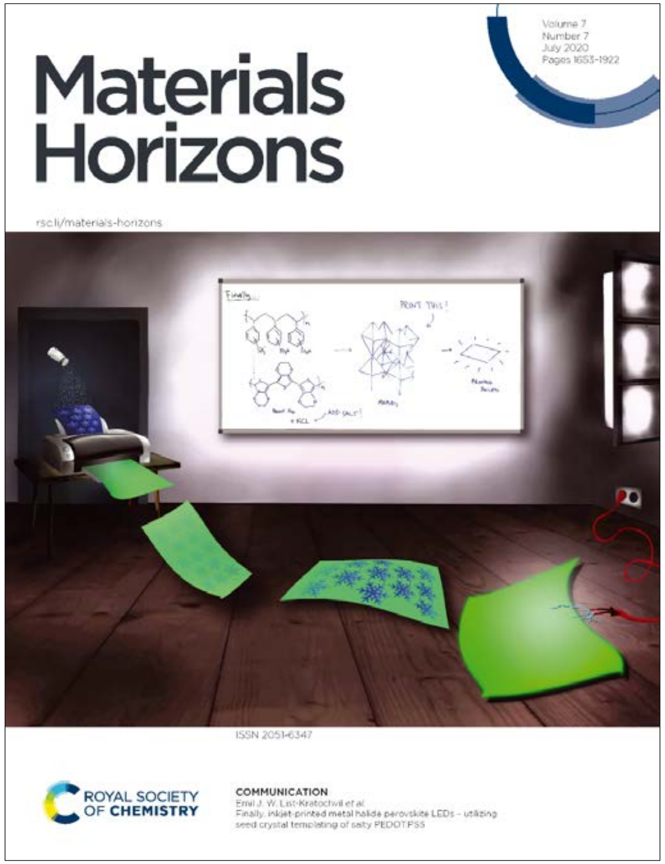
increase of current efficacy

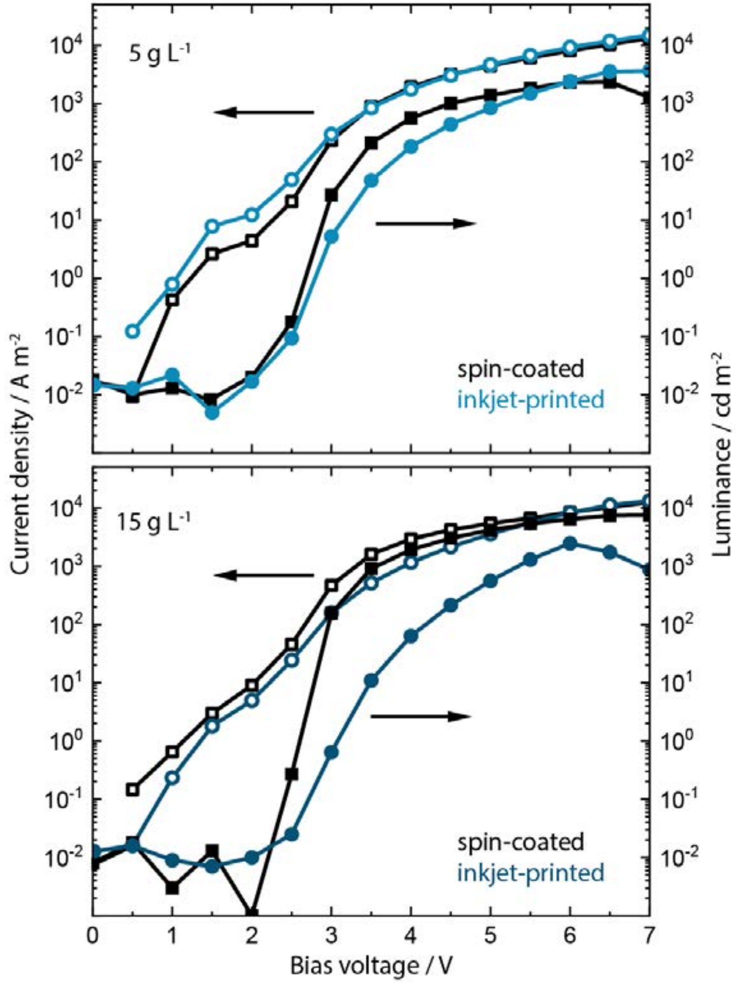


1 g/L

15 g/L

Finally – Printed HyLEDs





F. Hermerschmidt, et al., Mater. Horiz. 7, 1773 (2020).

Transfer: Printed OLEDs for Smart Packaging


Marcin Ratajczak
CEO & FOUNDER

Product & Business Development

10 YEARS EXPERIENCE AS ENTREPRENEUR

Patrick Barkowski
CTO & FOUNDER

Light & Technology

6 YEARS EXPERIENCE IN OLEDS

inuru

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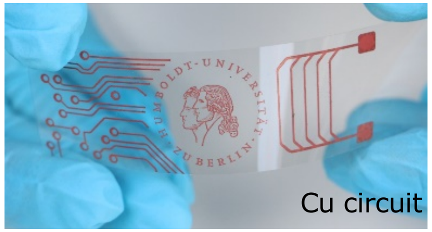
WORLDSTAR WINNER 2019
WPO WORLD PACKAGING ORGANISATION

GERMAN DESIGN AWARD WINNER 2018

GERMAN PACKAGING AWARD 2017

Conclusions

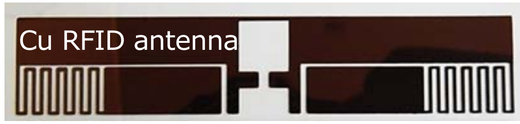


solution processable digital printing technique

scalable with high throughput (R2R compatible)

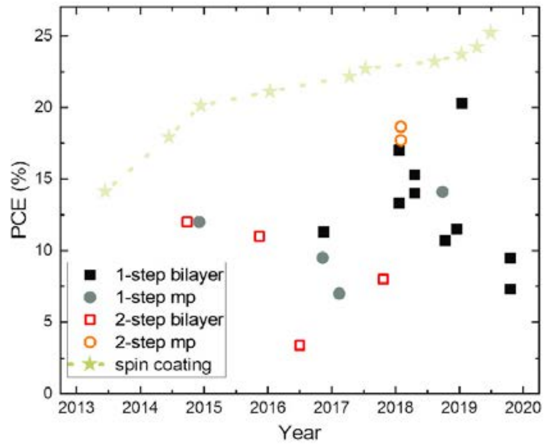
little waste through drop-on-demand

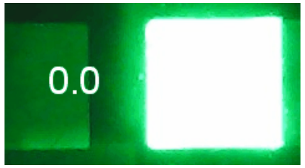
non-contact method



(nanoparticle) inks for circuits and electrodes

perovskite solar cells





ADVANCED MATERIALS TECHNOLOGIES

Progress Report

Implementing Inkjet-Printed Transparent Conductive Electrodes in Solution-Processed Organic Electronics

Felix Hermerschmidt, Stelios A. Choulis, Emil J. W. List-Kratochvil

Adv. Mater. Technol. **4**, 1800474 (2019).

Energy Technology
Generation, Conversion, Storage, Distribution

Review | Open Access

Advances in Inkjet-Printed Metal Halide Perovskite Photovoltaic and Optoelectronic Devices

Florian Mathies, Emil J. W. List-Kratochvil, Eva L. Unger

Energy Technol. **8**, 1900991 (2020).

Industry Day

PEROVSKITE PRINTING PHOTONICS

PVcomB
HySPRINT
EMIL

HZB Helmholtz Zentrum Berlin

HUMBOLDT-UNIVERSITÄT ZU BERLIN

IRIS ADLERSHOF

Thank you for your kind attention !

SEVENTH FRAMEWORK PROGRAMME

HORIZON 2020

HIOS

DFG Deutsche Forschungsgemeinschaft