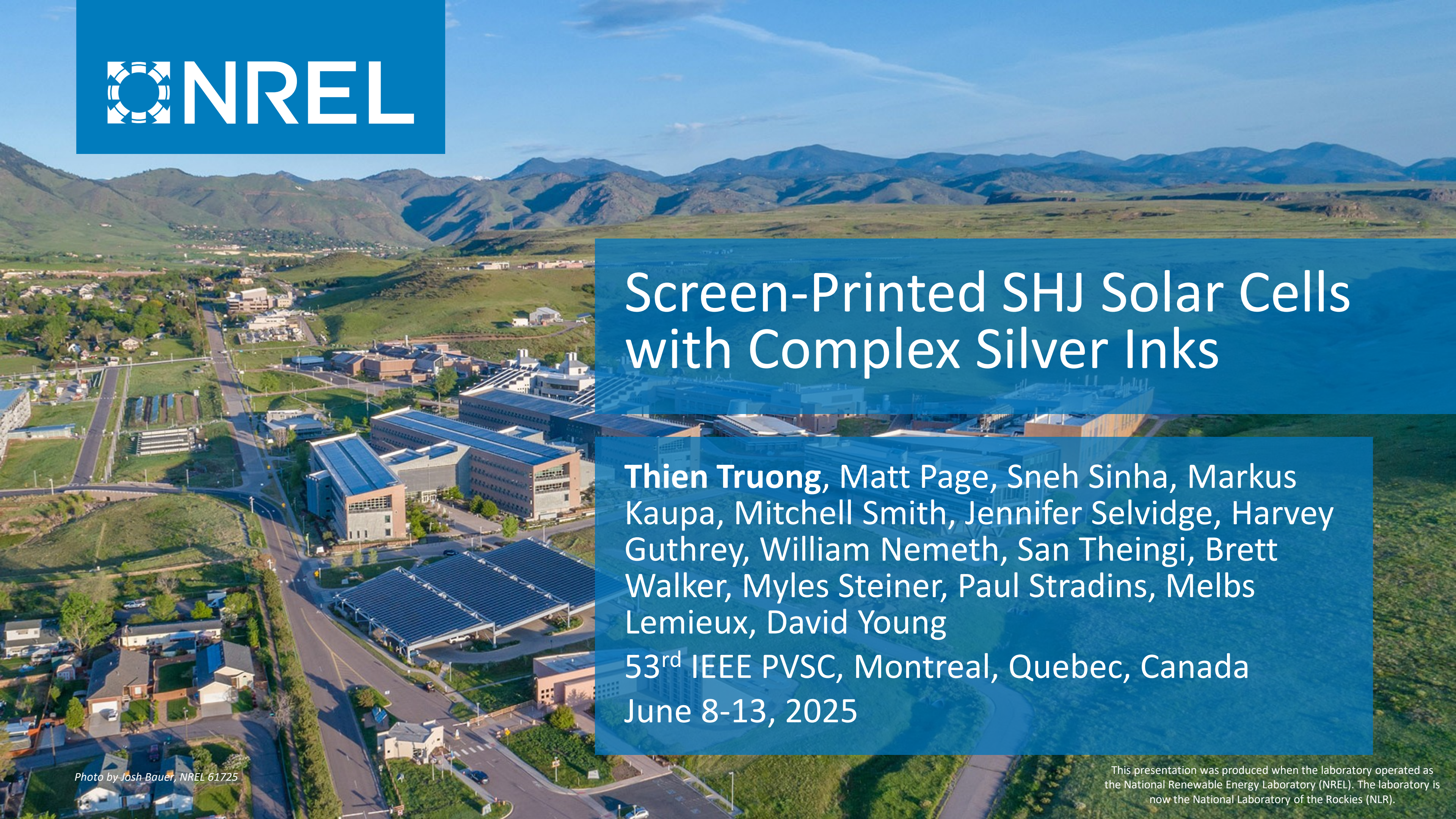
Photo by Josh Bauer, NREL 61725

NREL

Screen-Printed SHJ Solar Cells with Complex Silver Inks

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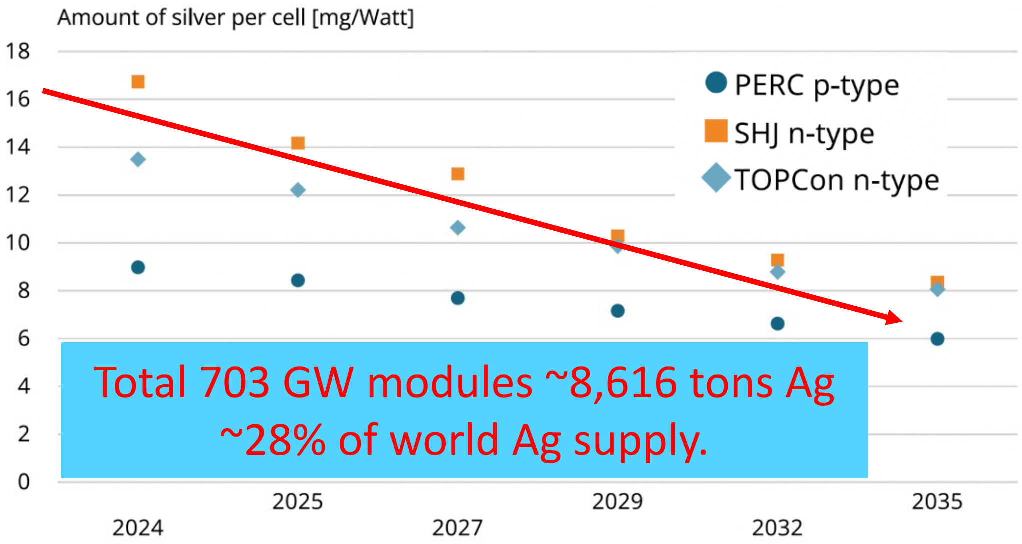
Contents

Motivation

- SHJ cells: >20% world market share in the next decade.
- Record efficiency on SHJ-based cells: 27.81% [2].
- Drawback: high Ag consumption due to:
  - low-temperature processing (200C)
  - high resistivity metal paste.

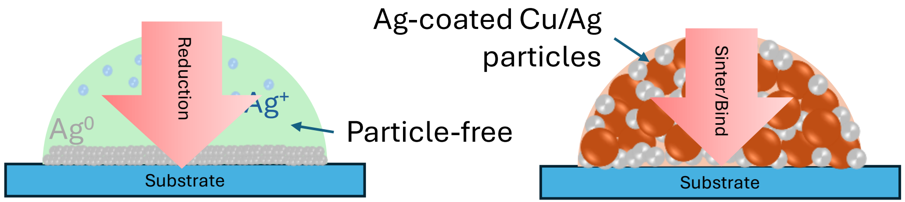


Reduce Ag usage!

[1] ITRPV 2025.
[2] Longi.com.

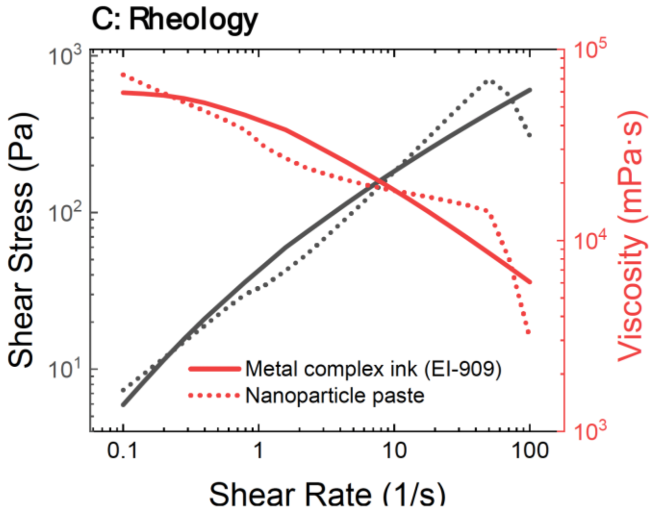
Ag complex ink (reactive Ag ink)?

A: Metal complex ink vs. nanoparticle paste



B: Complex Ag ink reduction

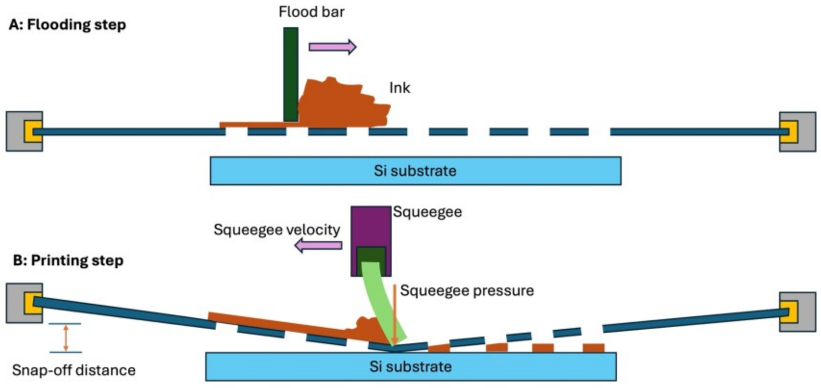
$NH_4OH/H_2O+AgC_2H_3O_2+CH_2O_2$ (Initial solution) → $[Ag(NH_3)_2]^+[C_2H_3O_2]^-$ (Reactive Ag ink) → Ag (Ag feature)

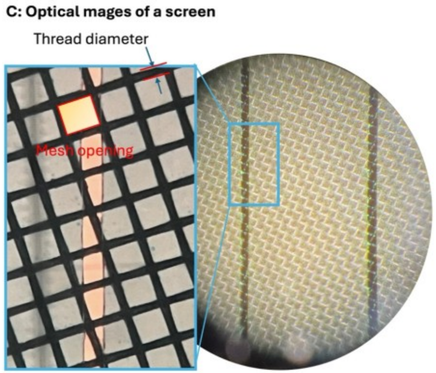


- Metal complex ink (or reactive ink): reduction. Nanoparticle paste: binding/sintering.
- Complex ink reduction: for a denser film, outgassing need to be prioritized.
- Rheology: **commercial product EI-909** has similar viscosity and thixotropy vs. nanoparticle paste.

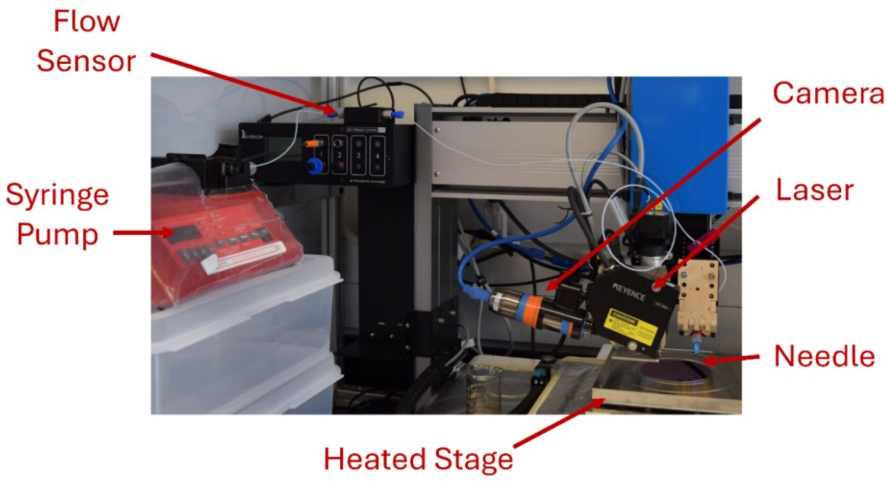
[1] Truong et al., Energy & Environmental Materials (under review).

Printing technology for complex inks





- Screen printing metallization: high throughput, dominant technology (>95% market share).
- This work: reactive ink + screen printing.



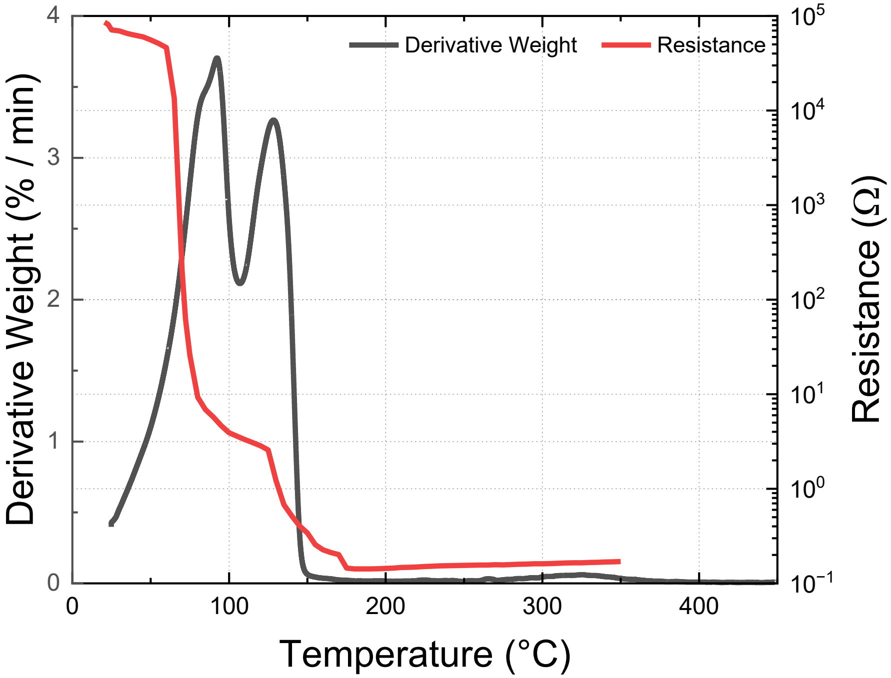
- Previous work on printing reactive inks: nozzle dispensing [2]. Low throughput.

[2] Bertoni et al., Energy & Environmental Science, 2024,**17**, 3218-3227.

[1] Truong et al., Energy & Environmental Materials (under review).

Phase transition of Ag complex ink

- Electroninks EI-909 Ag complex ink.
- TGA: two distinct phase transitions at 90C and 130C.
  - 90C: evaporation of NH_4OH components.
  - 130C: reduction of Ag ions to metallic Ag.
  - >150C: no more mass change.
- Resistance:
  - from 70C: resistance drops.
  - 130C additional decrease.
  - >175C: no further changes are observed. Fully reduced to Ag^0.

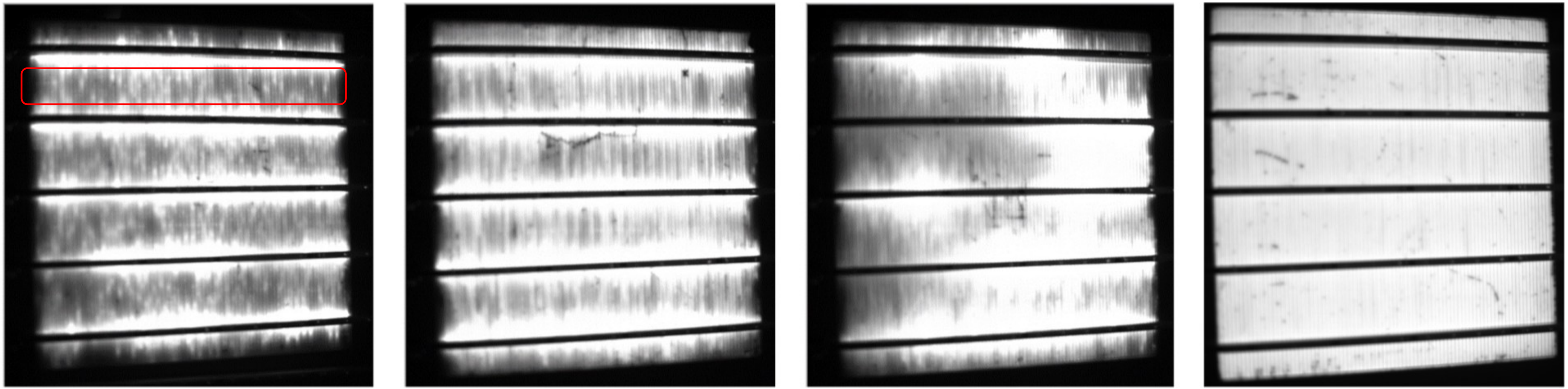


Complex ink printed cells annealed at 180C for 30 min!

[1] Truong et al., Energy & Environmental Materials (under review).

Electroluminescence images

Single print | Double print | Triple print | Single NP print

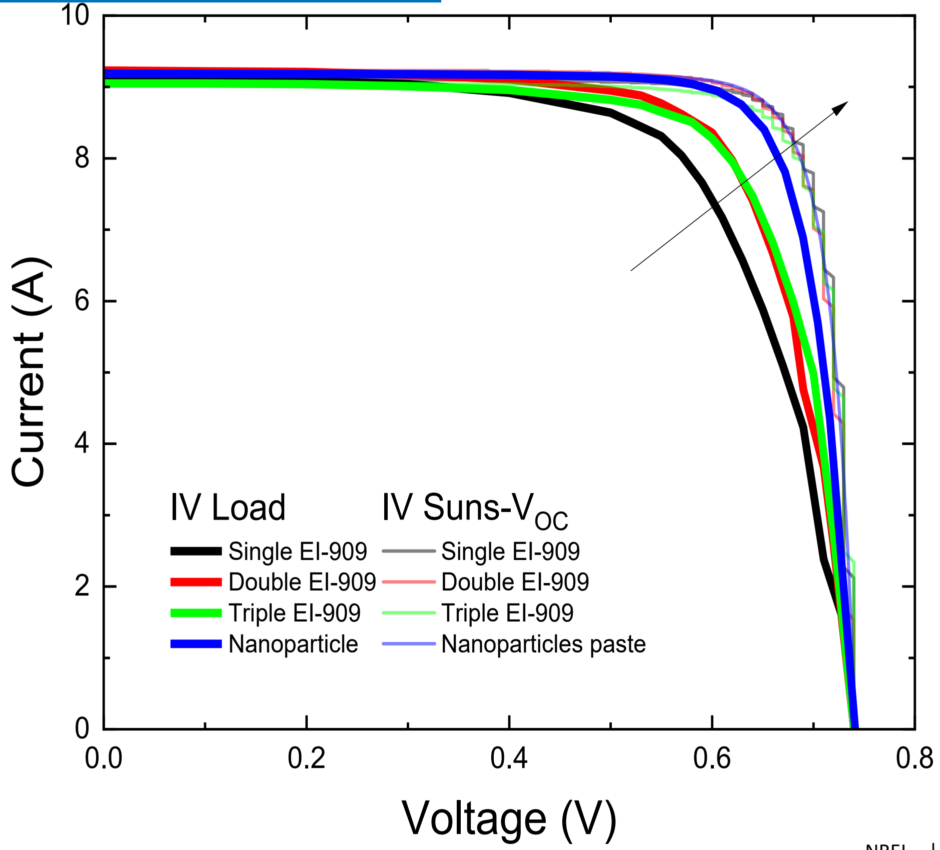


- Single print: often see discontinuity, inhomogeneous fingers, led to high series resistance.
- Multiple print: fingers are more uniform, additional prints fill up broken fingers, improve conductivity.
- Nanoparticle paste: uniform EL, due mainly to the well-printed fingers.

[1] Truong et al., Energy & Environmental Materials (under review).

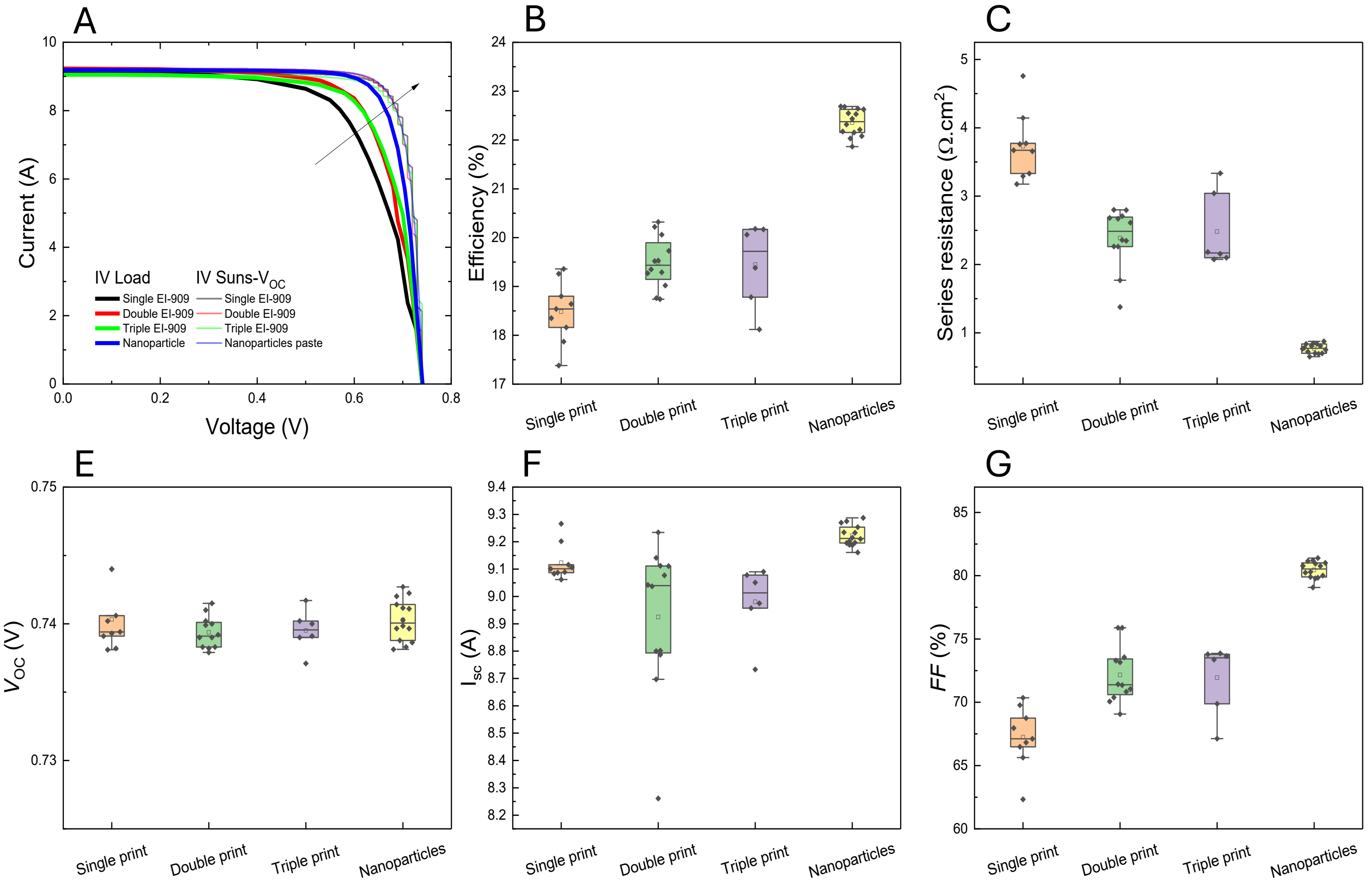
JV curves of printed devices

- Suns-Voc IV curves are all the same.
- Nanoparticle paste printed device has better fill factor, closing to the Suns-Voc curve.
- Double print and triple print show not much difference.



[1] Truong et al., Energy & Environmental Materials (under review).

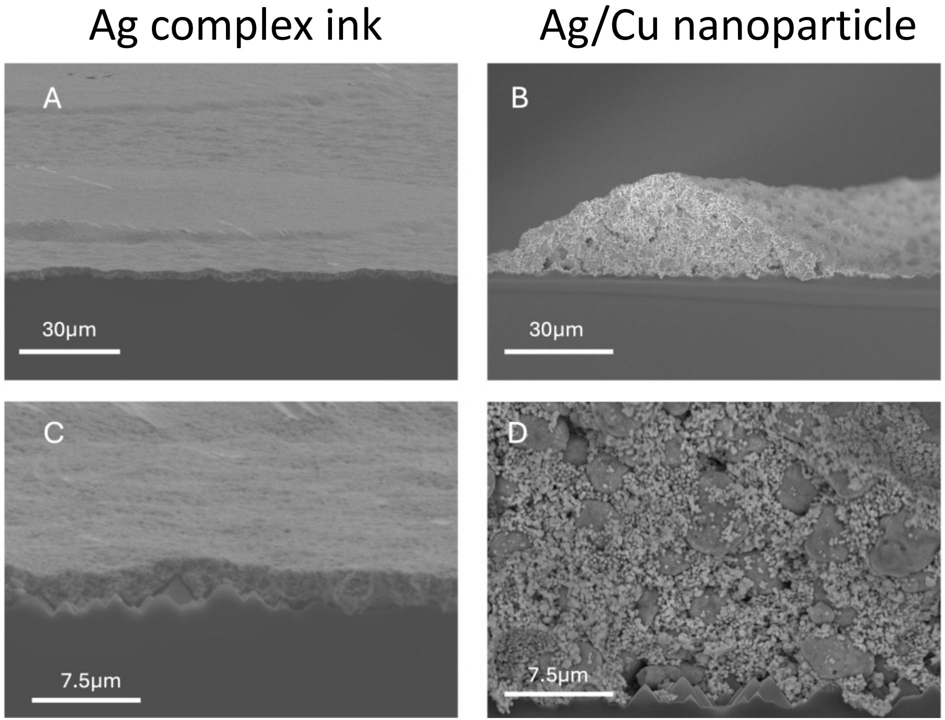
Devices performance



[1] Truong et al., Energy & Environmental Materials (under review).

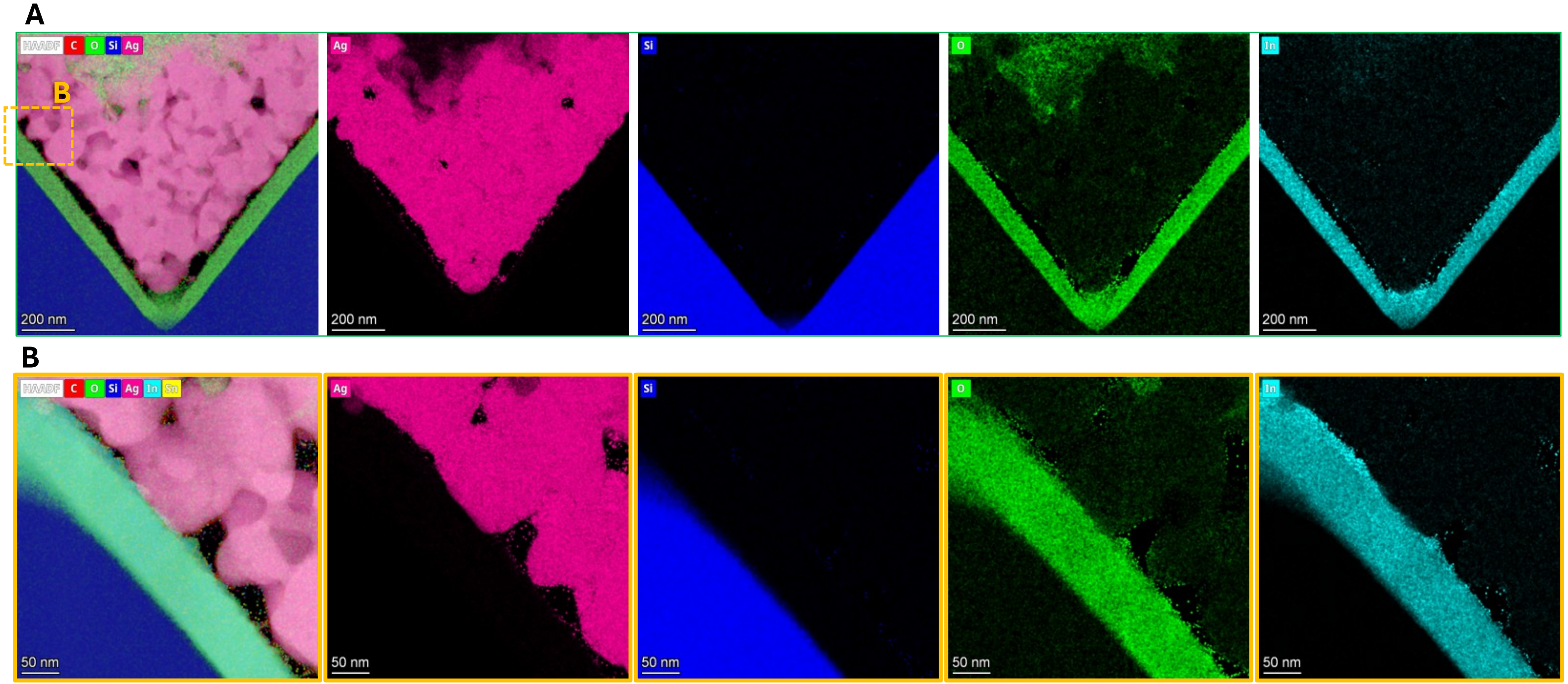
Morphology of printed fingers

- Ag complex ink:
  - Very thin 1-2 μm.
  - Denser, smaller Ag particles.
  - Less Ag.
- Ag/Cu nanoparticle paste:
  - Triangle shaped, thick ~30 μm.
  - Small Ag + large Cu particles.
  - Porous.



[1] Truong et al., Energy & Environmental Materials (under review).

STEM images

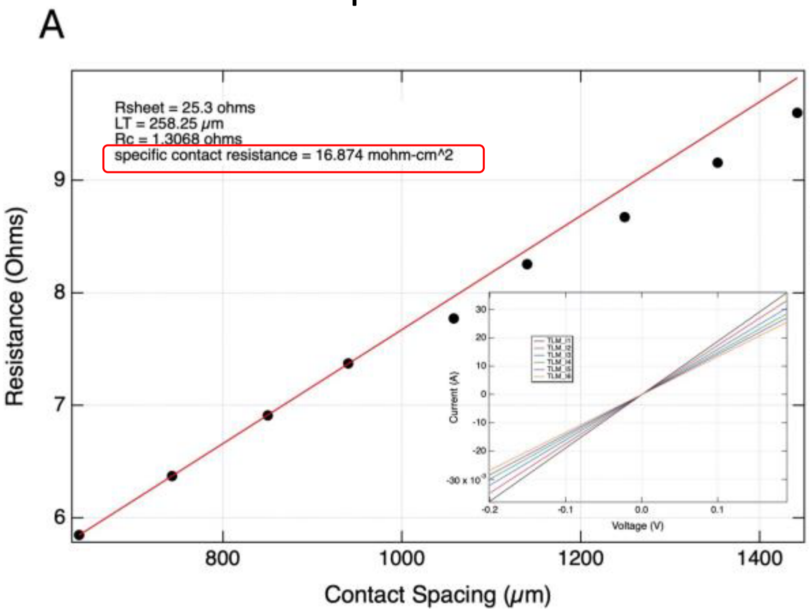


- Gaps between Ag and ITO. Contact resistivity might not be good?
- Clear elemental maps showing interfaces between metal/ITO/aSi.

[1] Truong et al., Energy & Environmental Materials (under review).

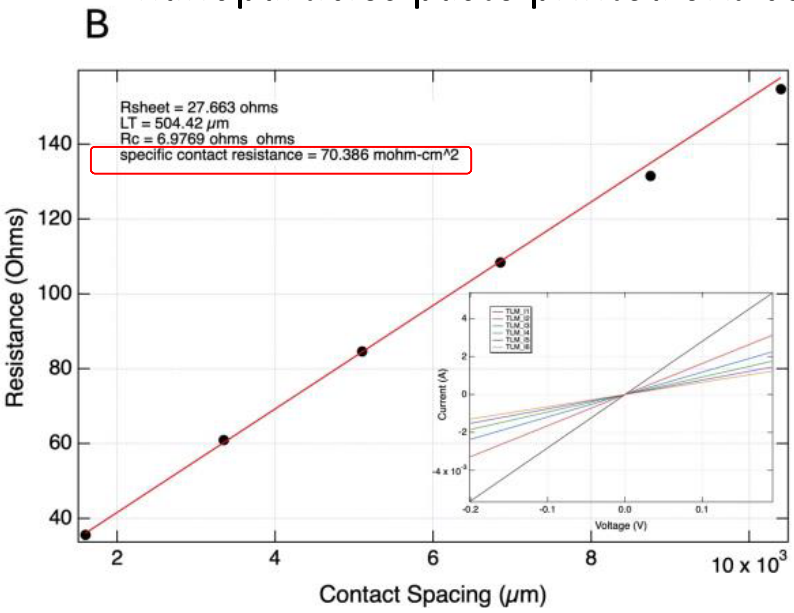
TLM of printed SHJ cells

EI-909 printed SHJ cells



ρ_c ~17 mΩ.cm^2

nanoparticles paste printed SHJ cells

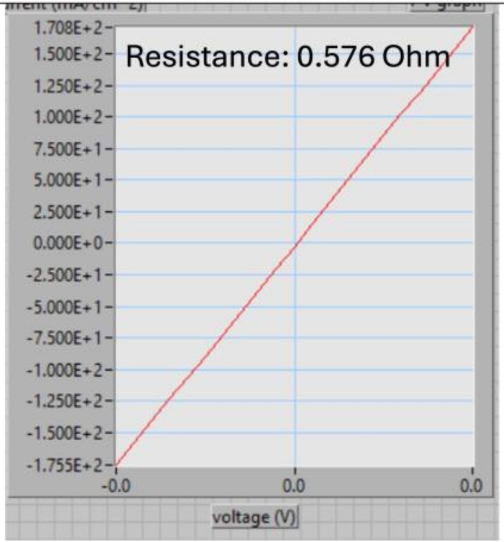


ρ_c ~70 mΩ.cm^2

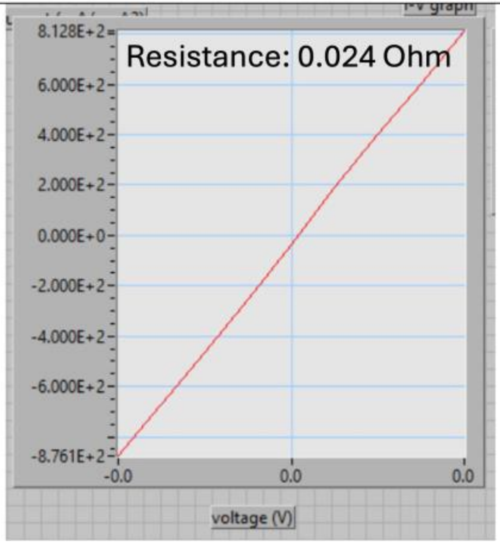
Contact resistivity is better than nanoparticle paste printed devices!

Conductivity of printed metal traces

A: EI-909
Line resistivity = R.A/L =
0.567*1*623/10000*100 = 3.5 μΩ.cm
Bulk Ag: 1.58 μΩ.cm



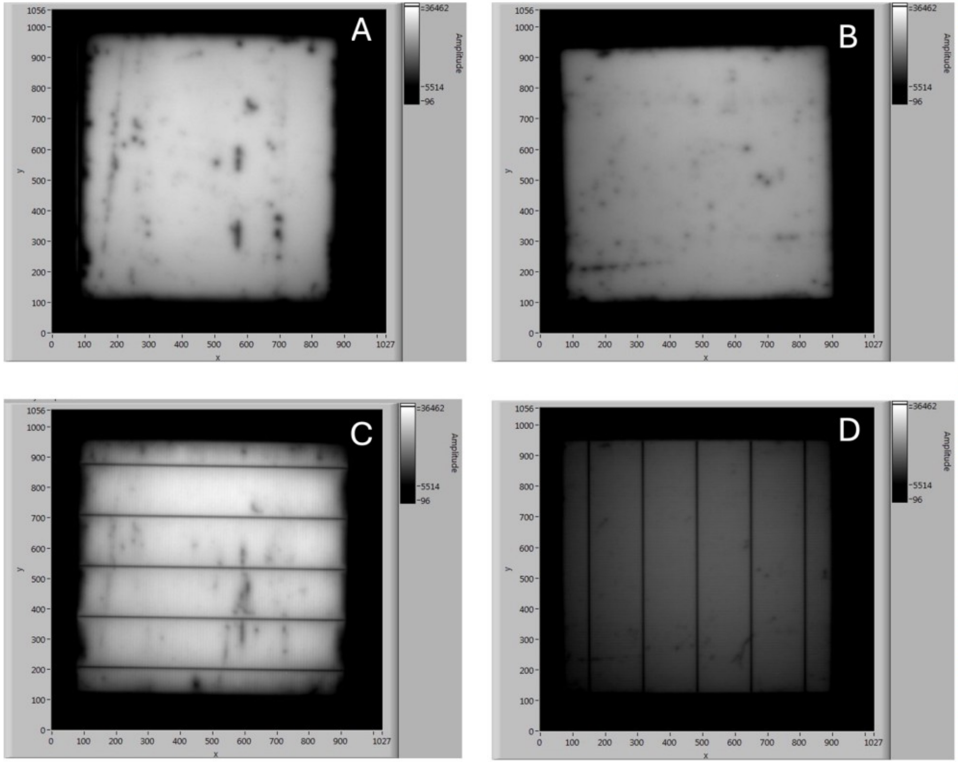
B: Nanoparticles paste
Line resistivity = R.A/L =
0.024*30*1000/15000 = 4.8 μΩ.cm
Bulk Ag: 1.58 μΩ.cm

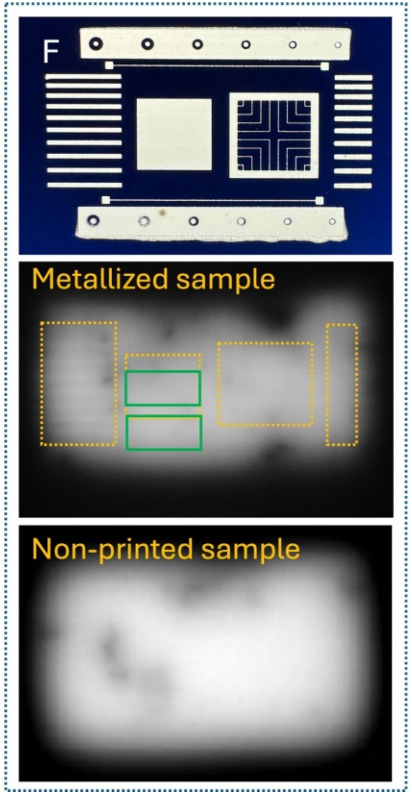


EI-909 printed fingers have better conductivity!

Photoluminescence

- Ag complex ink: PL intensity is similar before and after metallization.
- Nanoparticle paste: PL of device after annealing is darker, due to higher annealing temperature.
- ΔiV_{oc}<3.5 mV.





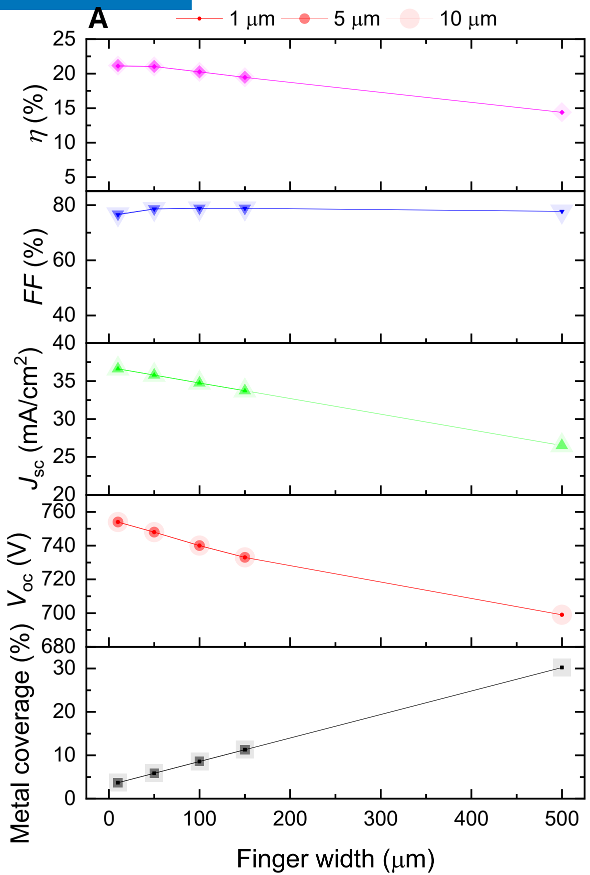
[1] Truong et al., Energy & Environmental Materials (under review).

Griddler Simulation

- Arbitrary device parameters for a 21% device, varying front metal grid parameters/metal coverage.
- Varying finger width with different finger thickness show minimal changes in performance.
- Devices with multipass printing show improved performance. Why?
- This is because: multipass printing can fill in metal ink into breakups, cracks, or disruption.

Key issues with the current complex inks:

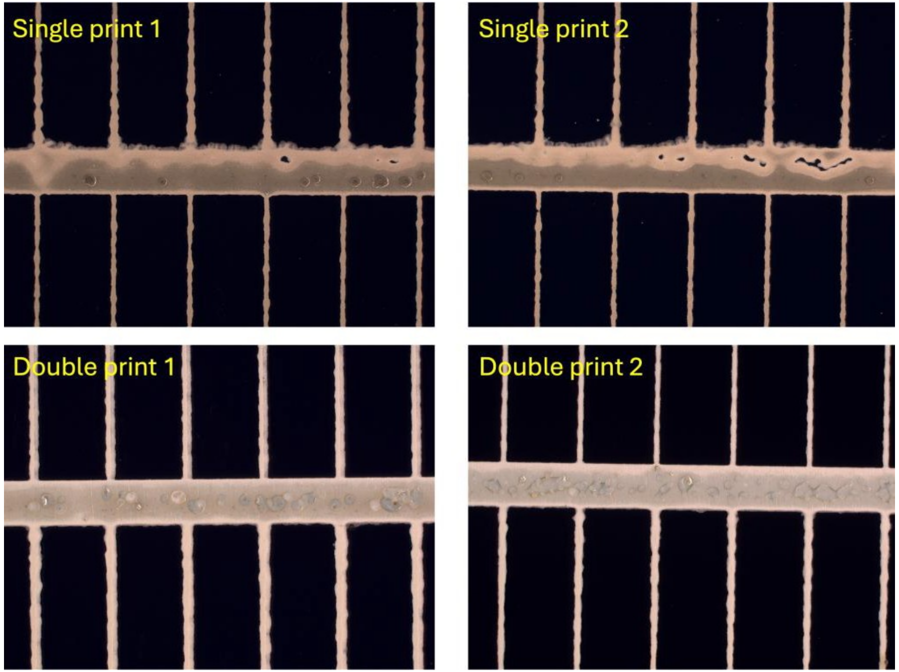
- Printability with screen printing.
- Stability studies.



[1] Truong et al., Energy & Environmental Materials (under review).

Optical images

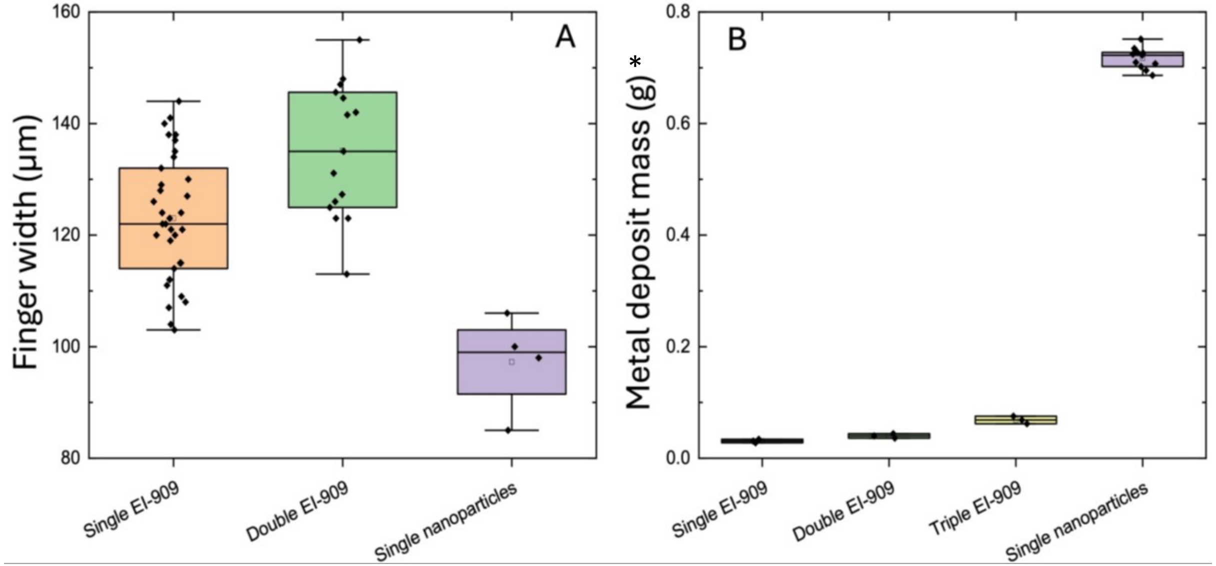
Optical images of screen-printed EI-909 ink on SHJ cells with single and double printing strategy.



Printability:

- Fingers often show necking, nonuniformities, breaks.
- Double print can fill metal ink in those defects but cause spreading, wider fingers.

Width and mass of printed features



- Multi-passes produces wider fingers, likely due to misalignment.
- For Ag complex ink: Screen: 80 μm. Printed: 100-140 μm(10-20 μm spreading).
- Metal deposit: ~0.03 g vs 0.73 g (including 50%wt Ag-coated Cu nanoparticle).

*On G1 wafer 158x158 mm^2.

[1] Truong et al., Energy & Environmental Materials (under review).

Summary

- First demonstration of commercial Ag complex ink EI-909 on SHJ cells using screen printing.
- 20% SHJ solar cells with routes to improve performance.
- Needs improvement in printability with proper viscosity and thixotropy for industrial fine-line screen printing.
- Significant reduction in Ag usage from ~0.4 g to ~0.03g.
- Demonstrated Ag complex inks as a viable alternative to current nanoparticle paste.

Thank you!

Q&A?

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Photo from Getty-181828180

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Appendix

Email Thien.Truong@nlr.gov for more details.