$Cu(In,Ga)Se_2$ thin-film micro-concentrator solar cells

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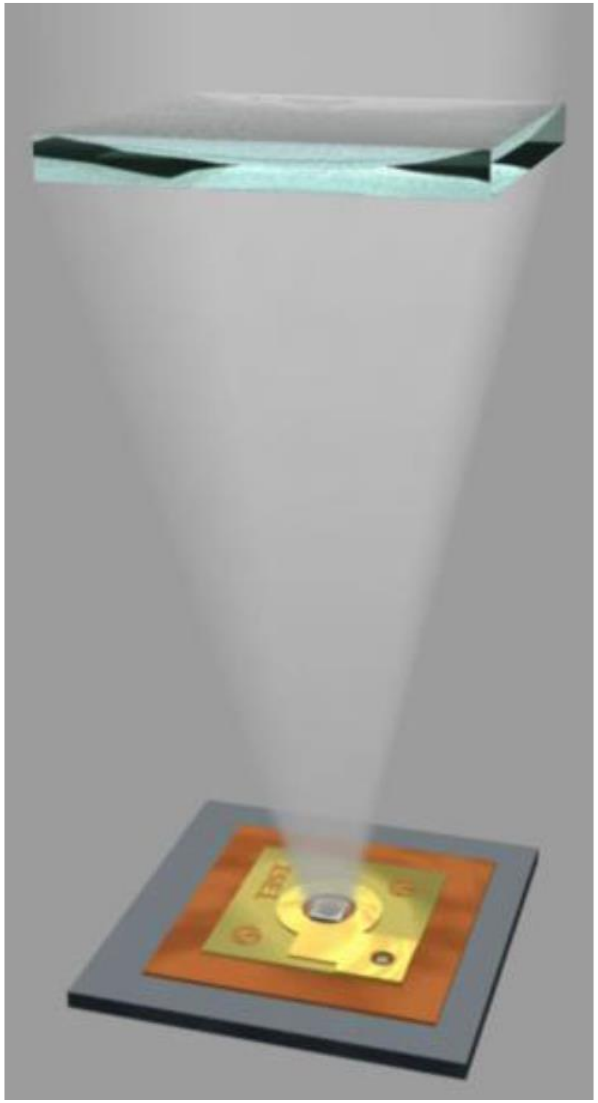
[4] ETS de Ingeniería y Diseño Industrial, Universidad Politécnica de Madrid. 28012 Madrid, Spain

Concentrator photovoltaics (CPV)

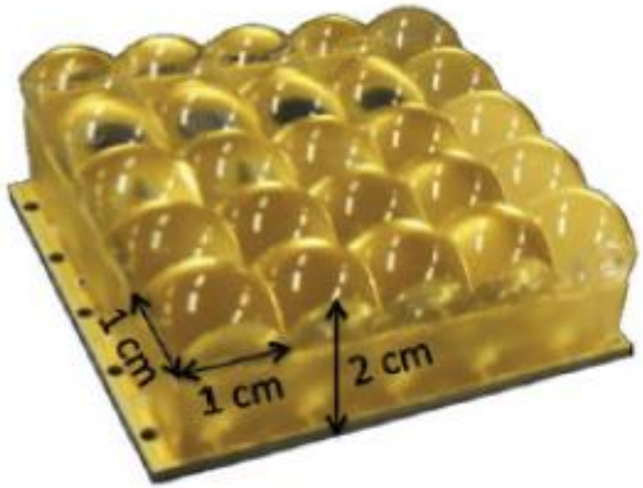


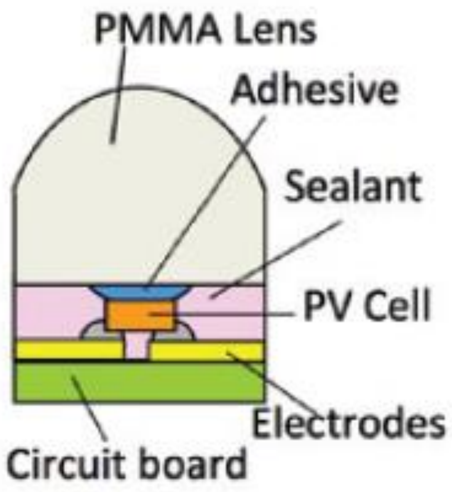
- Idea: Reduce area of solar cell and replace by more cost-efficient optics
- Solar cell area ~ 1 cm^2
- Mostly employs III-V multi-junction solar cells
- Bulky modules
- Sun tracking required → bulky tracker
- Cooling required

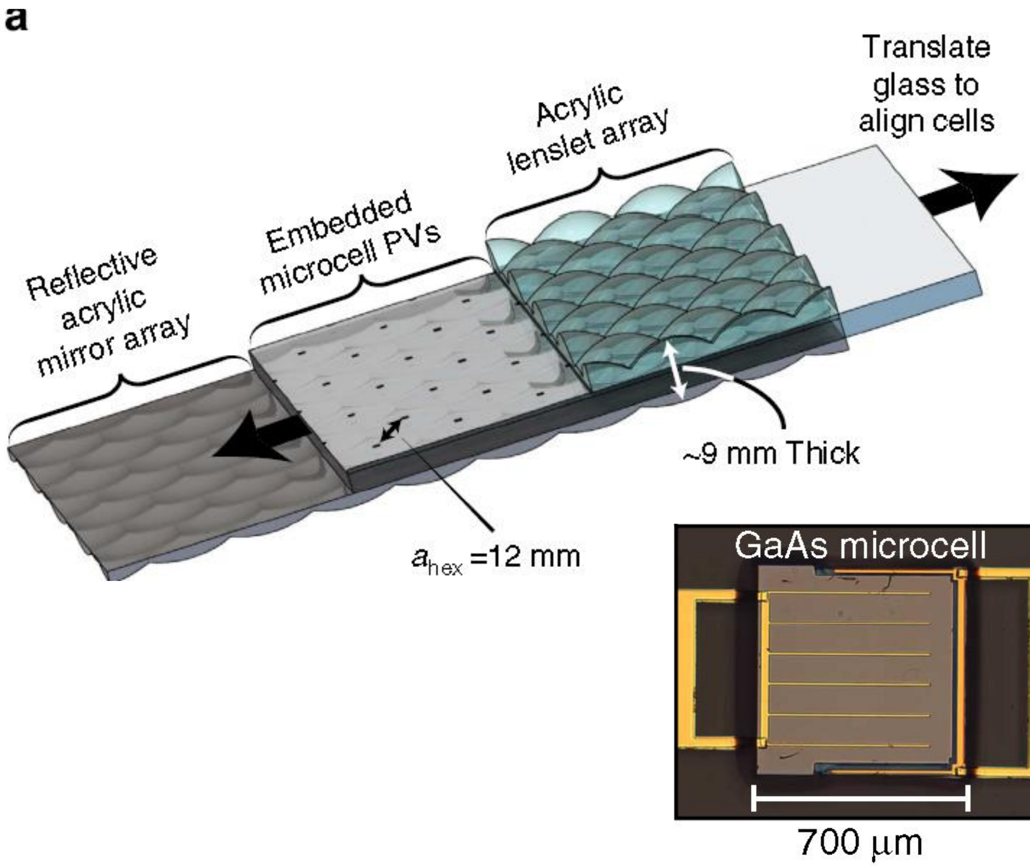
M. Wiesenfarth et al., CPV Report TP-6A20-63916 Natl. Renew. Energy Lab (2017).

Motivation

Micro-scale concentrator photovoltaics (μ-CPV)





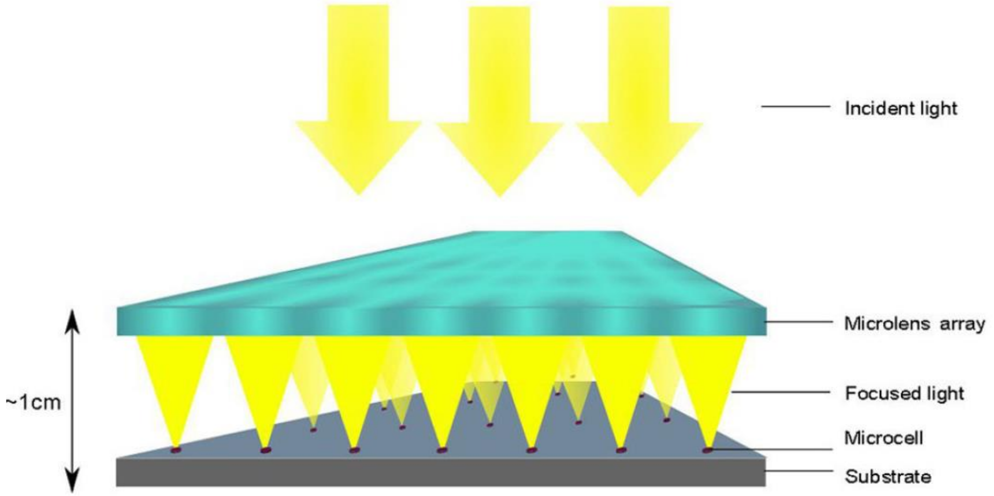


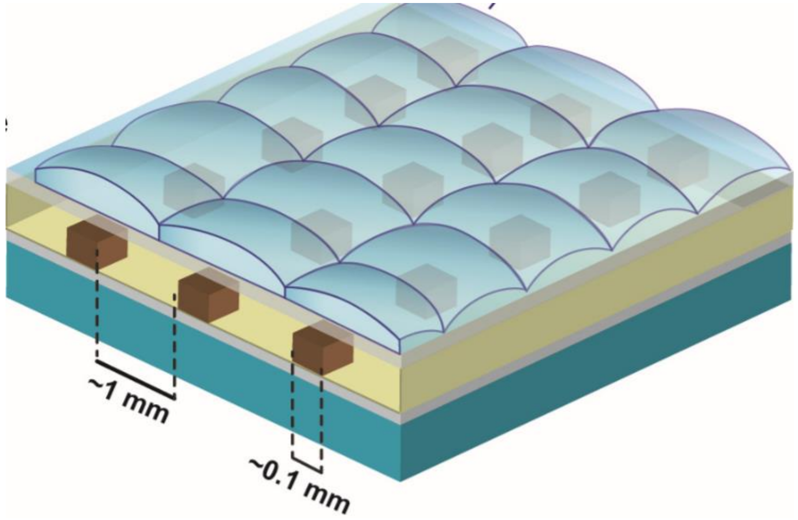
- Idea: Reduce area of solar cell further
- Solar cell area sub-mm^2
- Mostly employs III-V multi-junction solar cells
- Modules get slimmer
- Sun tracking required → option for integrated tracking
- Cooling required

O. Fidaner et al., Appl. Phys. Lett. 104, 103902 (2014).
J.S. Price et al., Nature Comm. 6, 6223 (2015).

$Cu(In,Ga)Se_2$ micro-concentrator thin-film photovoltaics

The Concept





M. Paire et al., SPIE Newsroom 5, 2 (2013)
M. Alves et al., J. Phys.: Energy 2, 012001 (2020).

$Cu(In,Ga)Se_2$ micro-concentrator thin-film photovoltaics

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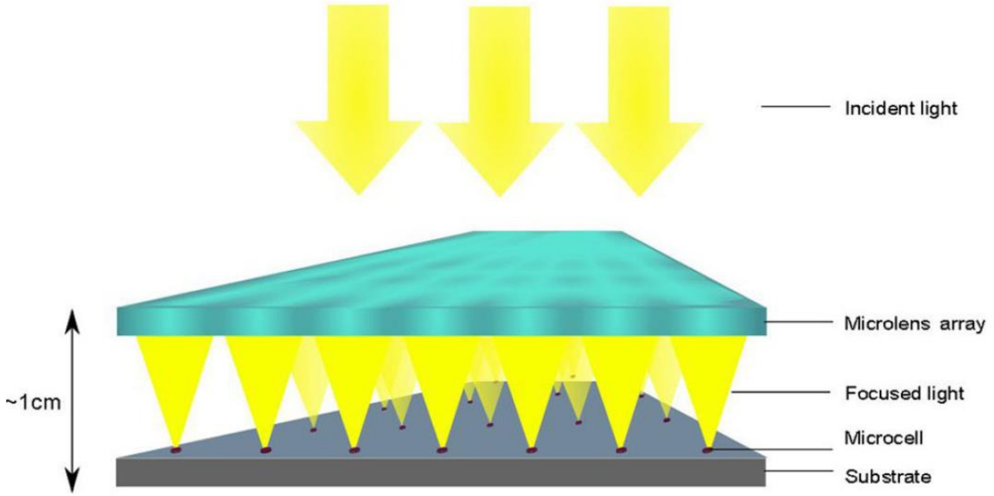
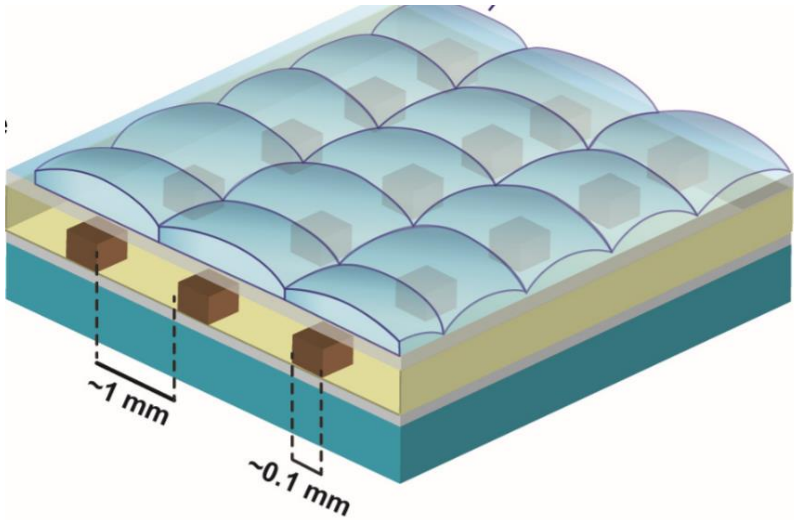




Why ?

→ Decrease significantly the use of critical raw materials (In, Ga)

→ Decrease solar cell size to ~100 μm

→ Increase efficiency

→ Heat input per cell is reduced. As the ratio of surface area to volume becomes higher, heat dissipation is improved.

→ $Cu(In,Ga)Se_2$ enables direct structured deposition

→ Shorter optical paths lead to lower absorption losses.

→ The short focal length leads to thin modules that employ less material.

→ The current generated at each cell is lower ➔ series resistance losses can be reduced.

→ Lower impact of light spot inhomogeneity

M. Paire et al., SPIE Newsroom 5, 2 (2013)
M. Alves et al., J. Phys.: Energy 2, 012001 (2020).

Benefits

Micro-concentrator thin-film photovoltaics

→ **Significant decrease in use of critical raw materials (In, Ga)**

→ Increase efficiency

→ Improved heat dissipation at micrometer scale

Rough Estimates:

Regular CIGSe thin-film photovoltaics:

- Indium per m^2: ~ 2 g
- If all PV production of 1 year would be CIGSe: 100 GW
- 1 module with 20% efficiency gives 200 W/m^2
- → 500×10^6 m^2 CIGSe production / year
- → 1000 tons indium / year
- Annual In production in 2019: 760 tons

For micro-concentrator with 100X concentration:

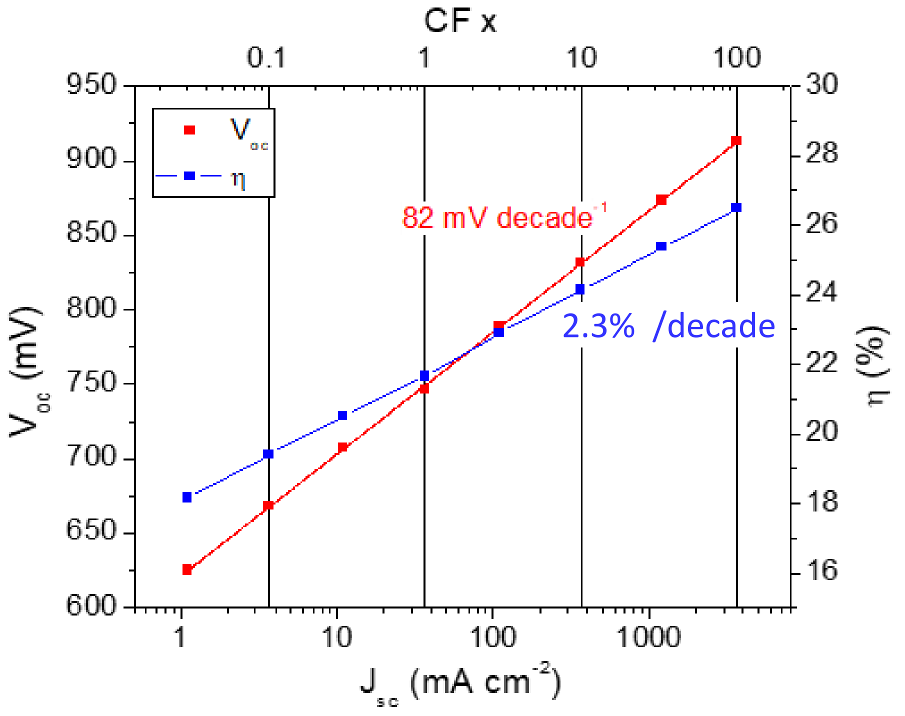
- → Indium need of 10 tons / year

Micro-concentrator thin-film photovoltaics

- → Significant decrease in use of critical raw materials (In, Ga)
- → **Increase efficiency**
- → Improved heat dissipation at micrometer scale

- Concentrated light leads to an increase in V_{oc}

$$V_{oc} = \frac{Ak_BT}{q}\ln\left(\frac{J_{ph}}{J_0}+1\right)$$



- Parameters from P. Jackson 21.7% solar cell
- Assume no change in FF, A, J_0 with concentration

D. Siopa et al., submitted (2020)
P. Jackson et al., *pss RRL 9*, 28 (2015).

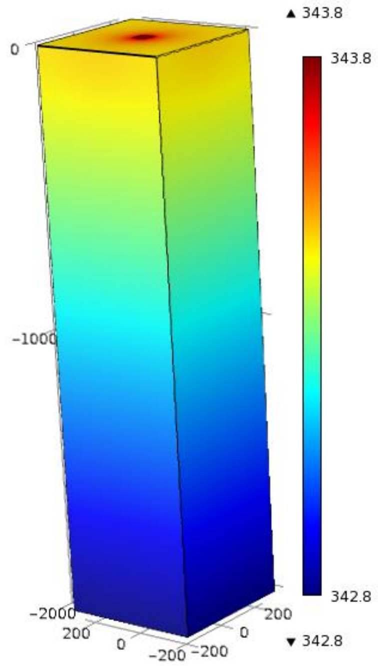
Benefits

Micro-concentrator thin-film photovoltaics

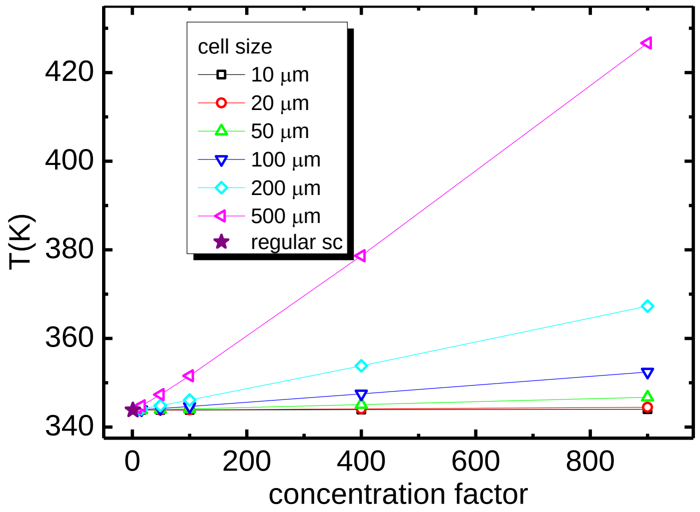
→ Significant decrease in use of critical raw materials (In, Ga)

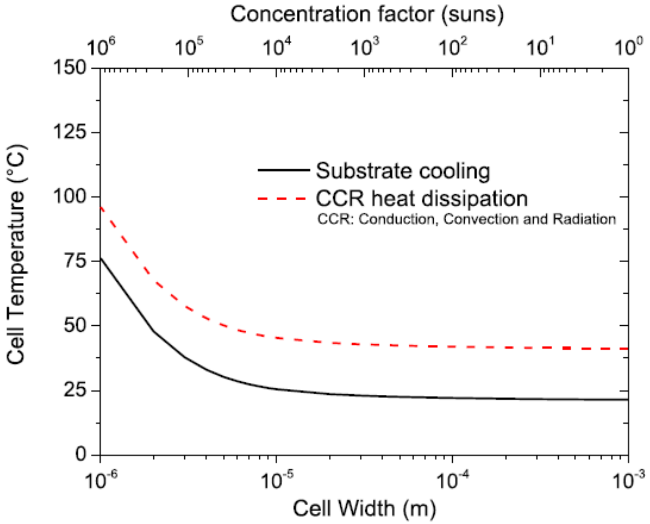
→ Increase efficiency

→ **Improved heat dissipation at micrometer scale**

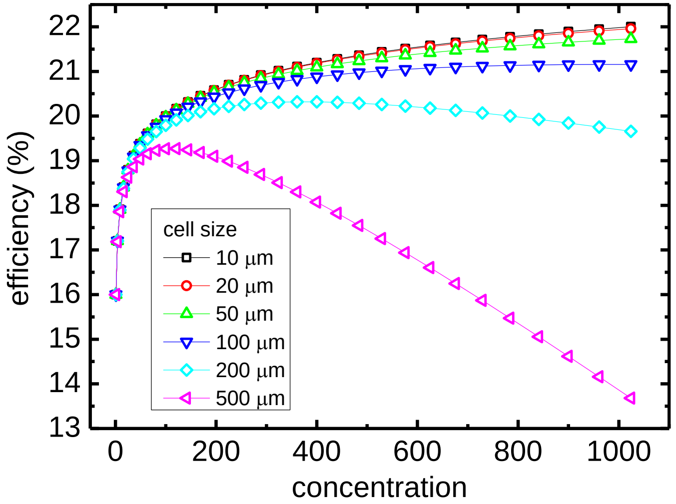


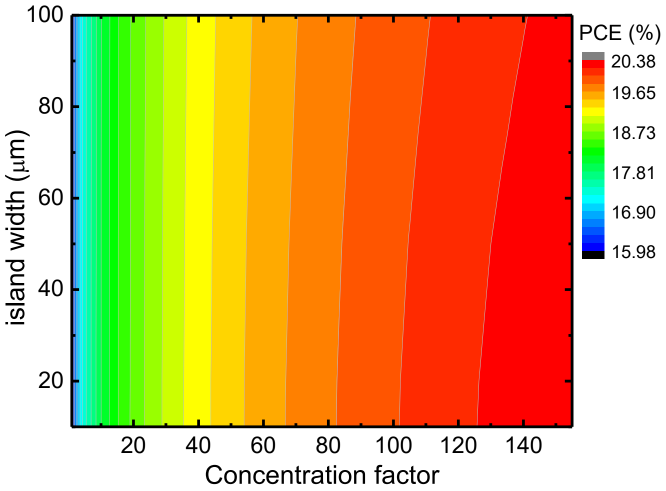
- Heat management through finite element simulations





- Efficiency → positive effect of V_{oc} & negative effect of temperature



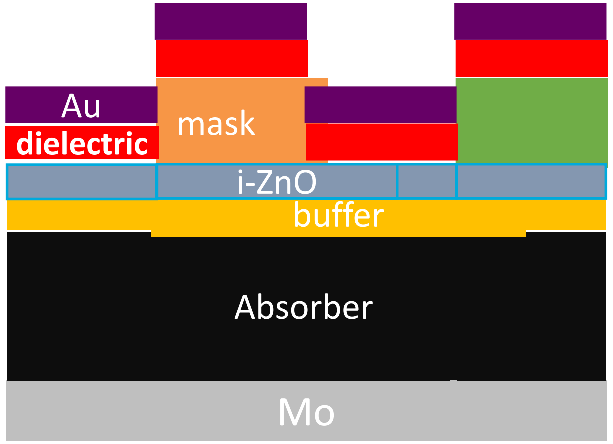


S. Sadewasser et al., Sol. Energy Mat. Sol. Cells 159, 496 (2017).
S. Sadewasser, Solar Energy 158, 186 (2017).
D. Sancho-Martínez et al., *J. Phys. D: Appl. Phys.* 50, 445501 (2017).

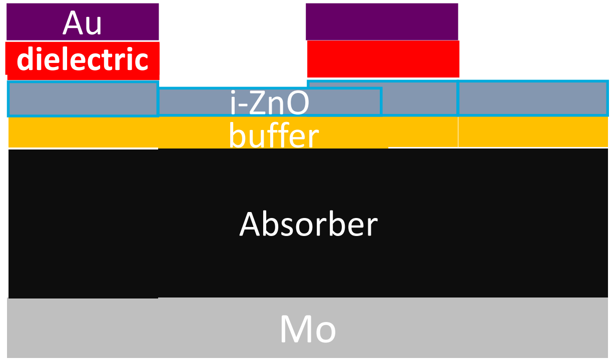
Fabrication Approaches

Top-down fabrication to demonstrate proof-of-concept

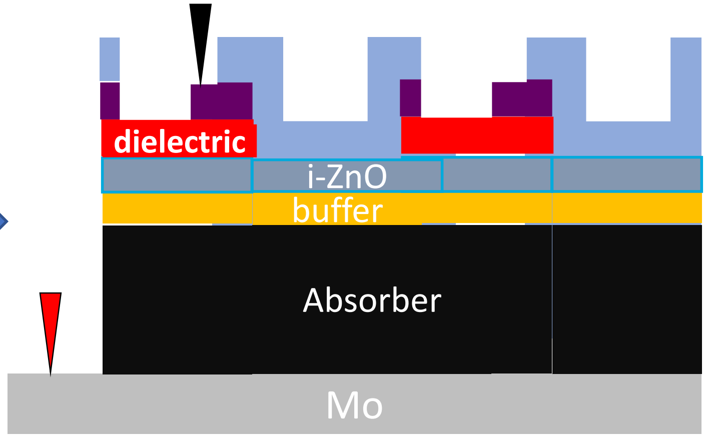
- Insulating top contact by dielectric layer and shadowing by metallic layer



i) Mo/CIGSe/CdS/i-ZnO masked and SiO_2 + Ti/Au layers added



ii) Resist mask removed



iii) ZnO:Al added and cells isolated. Part of the Ti/Au revealed by etching away ZnO:Al

M. Paire et al., Appl. Phys. Lett. 98, 264102 (2011).

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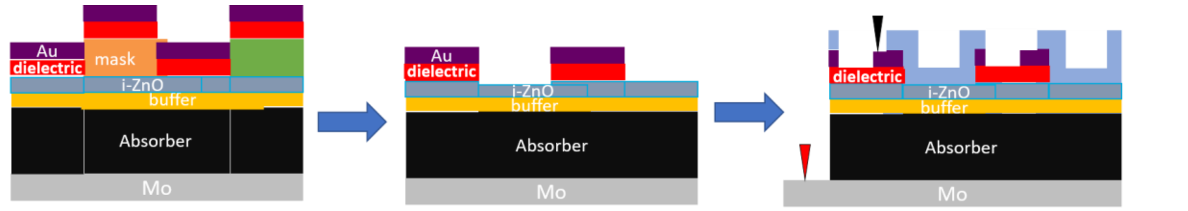

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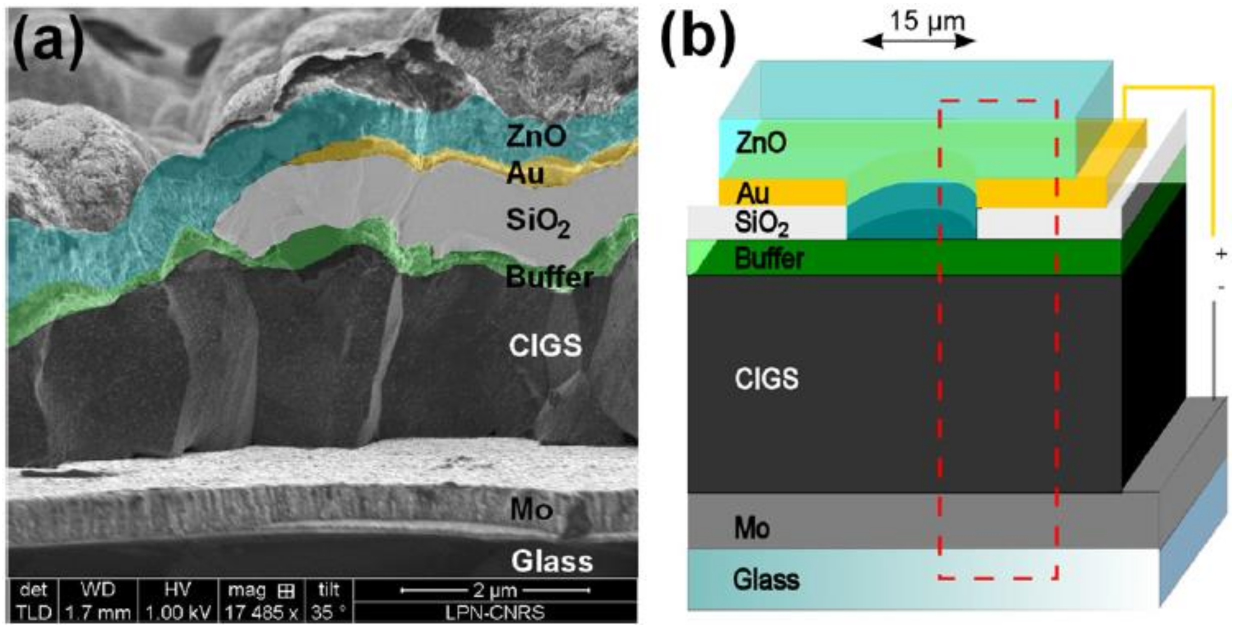

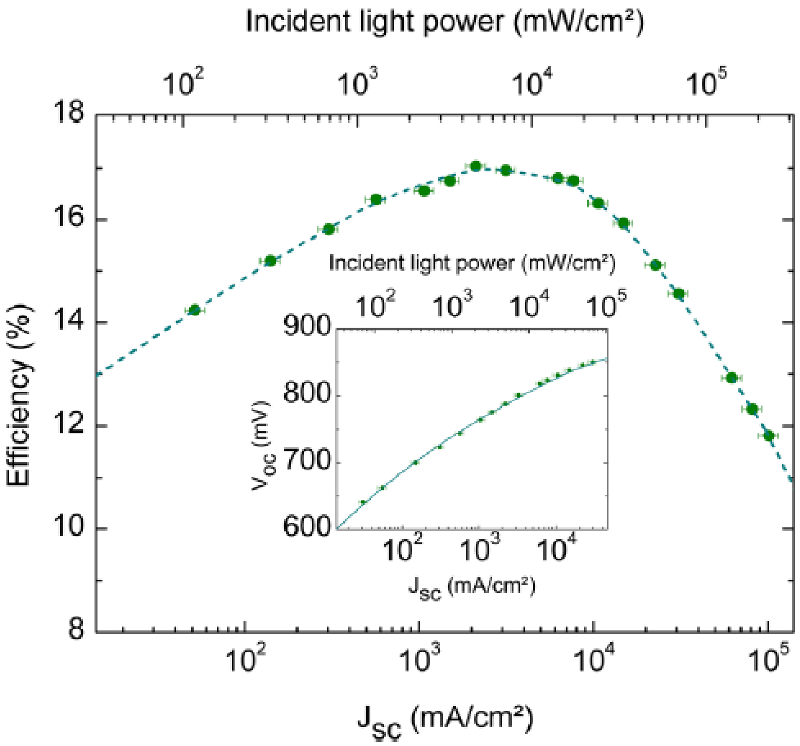

M. Paire et al., Appl. Phys. Lett. 98, 264102 (2011).

- η=17% @ 120X concentration
- Logarithmic V_{oc} increase up to 1000X conc.
- Series resistance from electrical contacts and the absorber layer lead to decrease for higher conc.

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Top-down fabrication to demonstrate proof-of-concept

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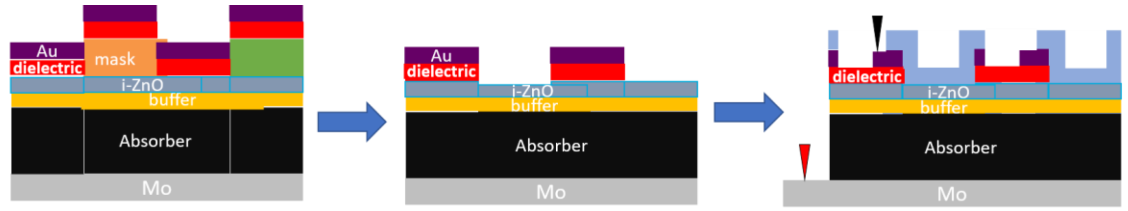

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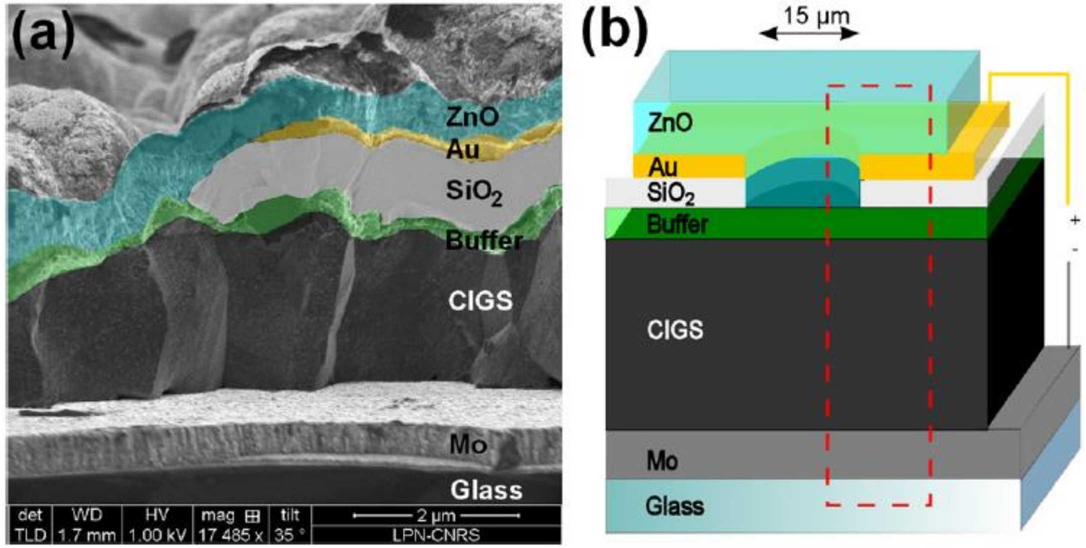
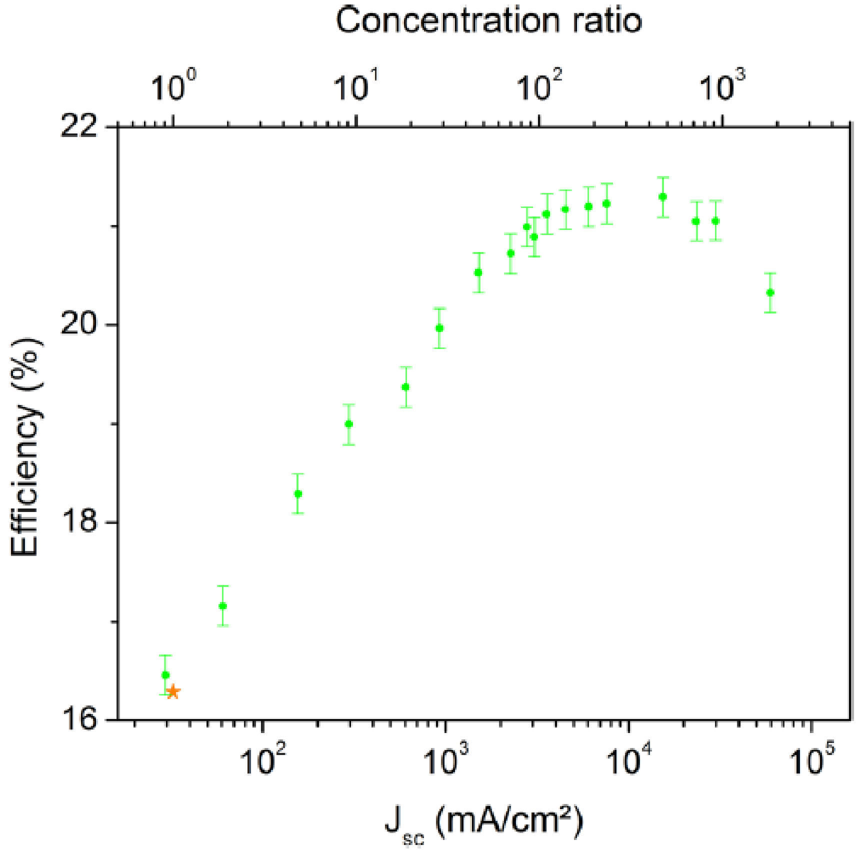




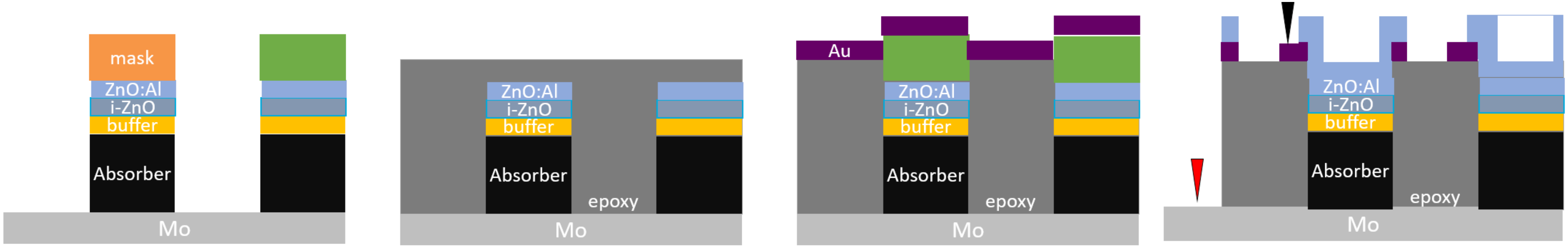
- η=21.3% @ 475X concentration for 50 µm micro solar cell

M. Paire et al., J. Renewable Sustainable Energy 5, 011202 (2013).

Fabrication Approaches

Top-down fabrication to demonstrate proof-of-concept

- Etch top contacts and absorber using photolithography defined mask and protect with epoxy from shunting



i) Mo/CIGSe/CdS/i-ZnO/ZnO:Al masked and etched twice

ii) Resist mask removed and epoxy resin layer added

iii) Micro cells revealed and protected by mask with Ti/Au contact layer added

iv) ZnO:Al added and cells isolated. Part of the Ti/Au revealed by etching away ZnO:Al

M. Paire et al., Thin Solid Films 582, 258 (2015).

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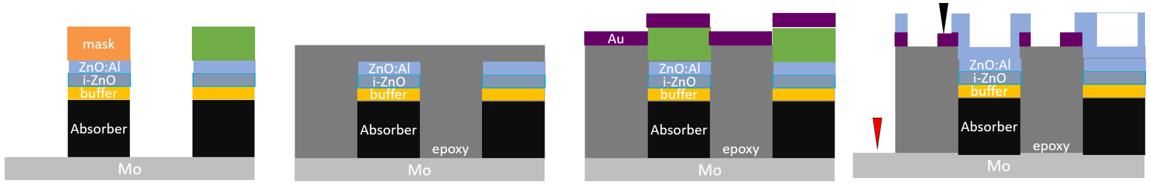

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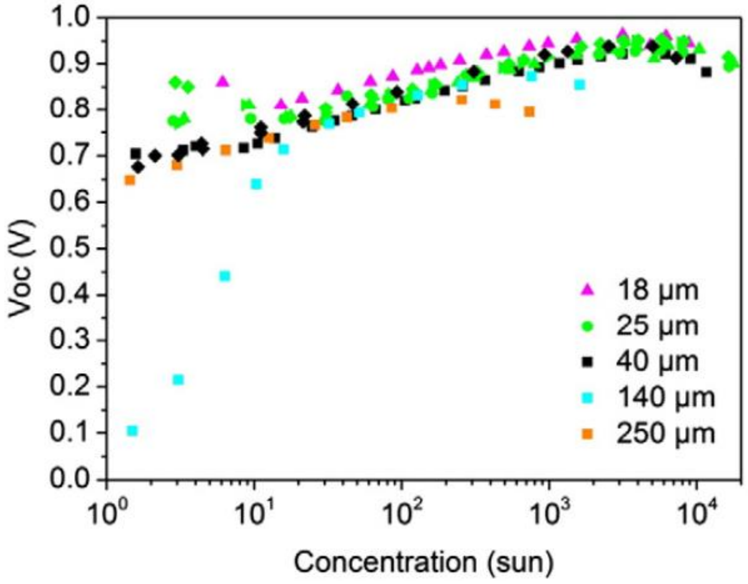
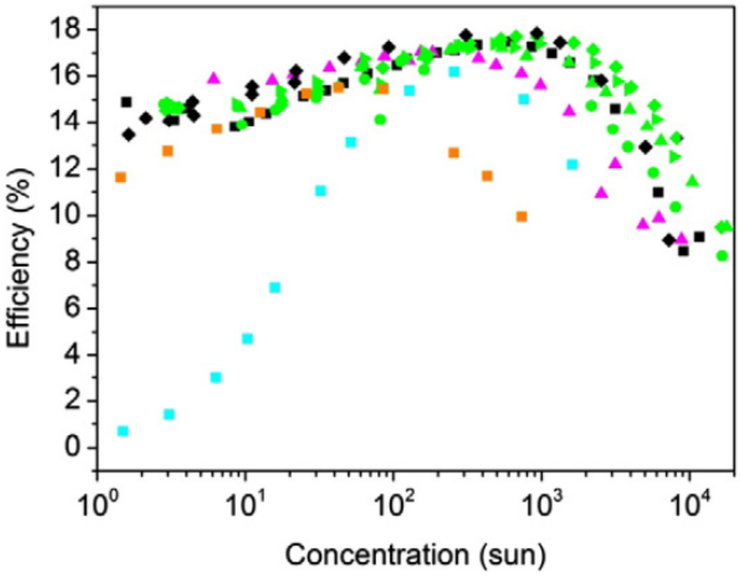
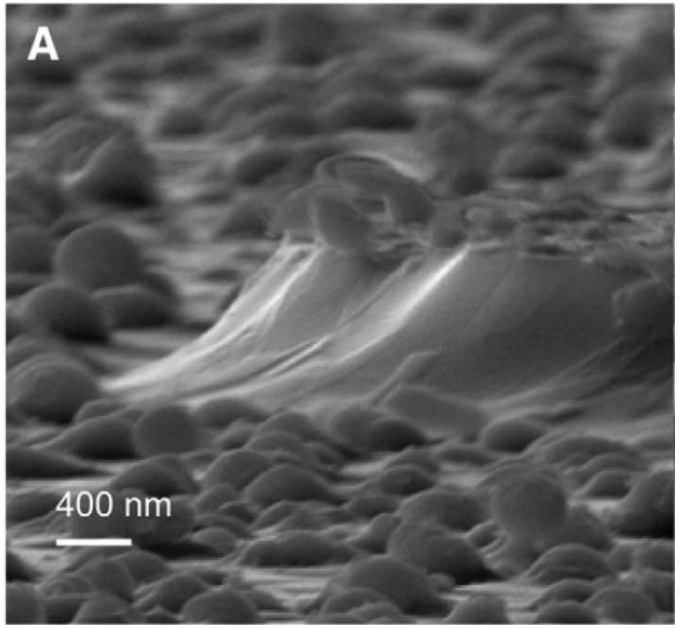
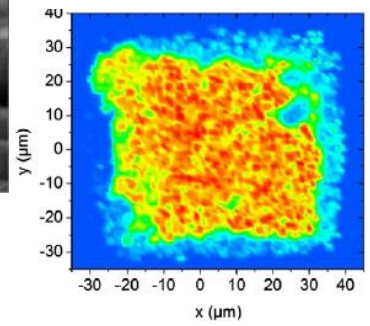








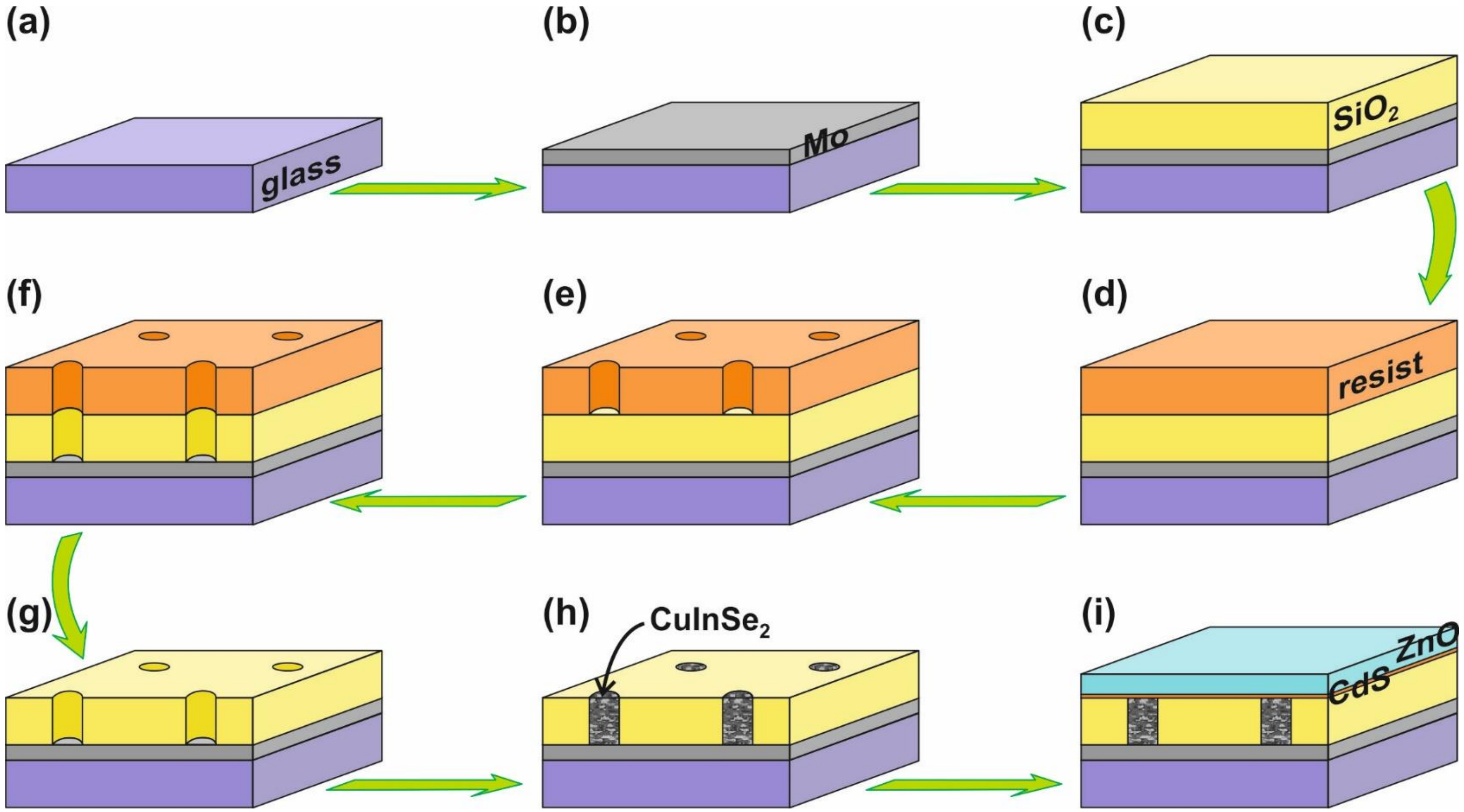
- η=18% @ 900X concentration (40µm cell)
- Well passivated edges confirmed by LBIC and PL measurements

M. Paire et al., Thin Solid Films 582, 258 (2015).

Fabrication Approaches

Bottom-up fabrication to demonstrate materials savings potential

- CIGSe by electrodeposition on micro-electrodes



Fabrication:

- Photolithography and reactive ion etching for etching holes into a SiO_2 layer on Mo back contact
- Electrodeposition of $CuInSe_2$ into holes and selenization
- Finish solar cell device by regular CdS and ZnO deposition

S. Sadewasser et al., Sol. Energy Mater. Sol. Cells 159, 496 (2017).

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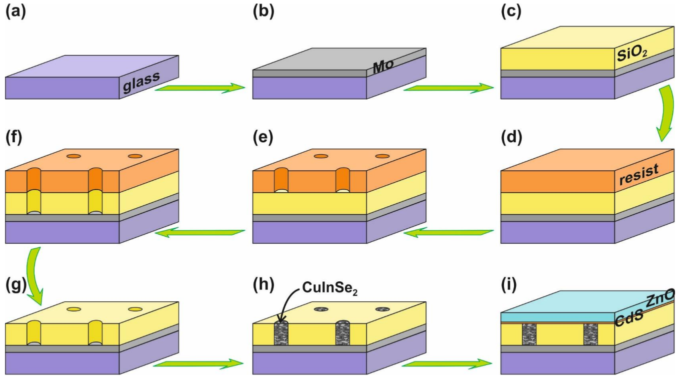

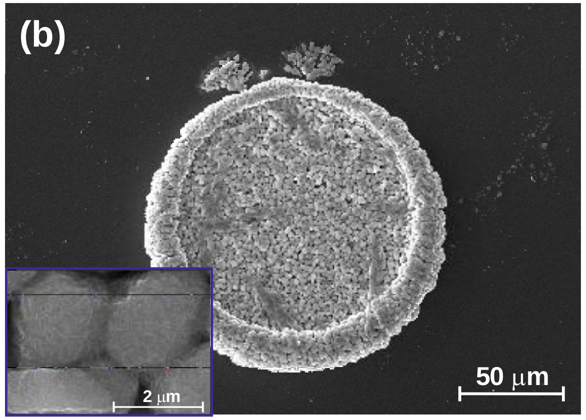

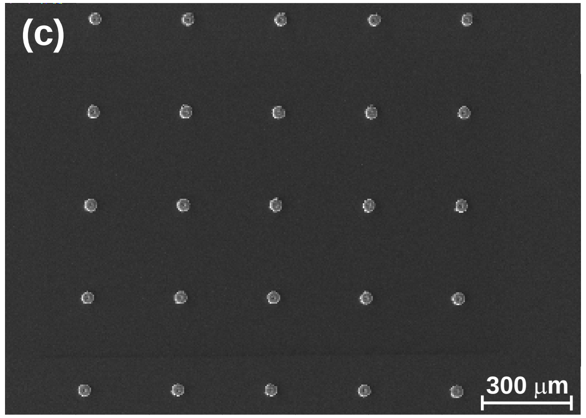

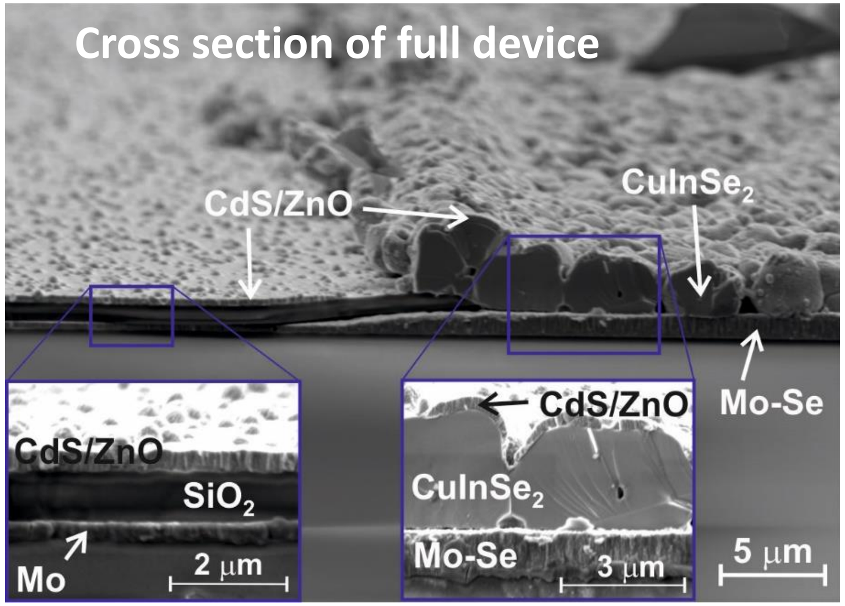

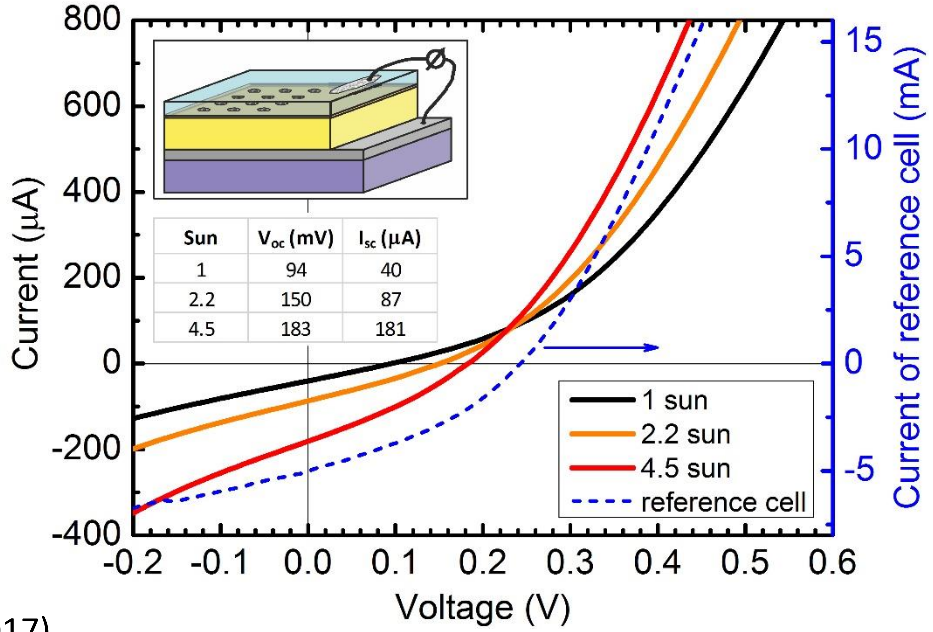

Sun	V_{oc} (mV)	I_{sc} (μA)
1	94	40
2.2	150	87
4.5	183	181

- V_{oc} increase with concentration
- Poor cell performance

S. Sadewasser et al., Sol. Energy Mater. Sol. Cells 159, 496 (2017).

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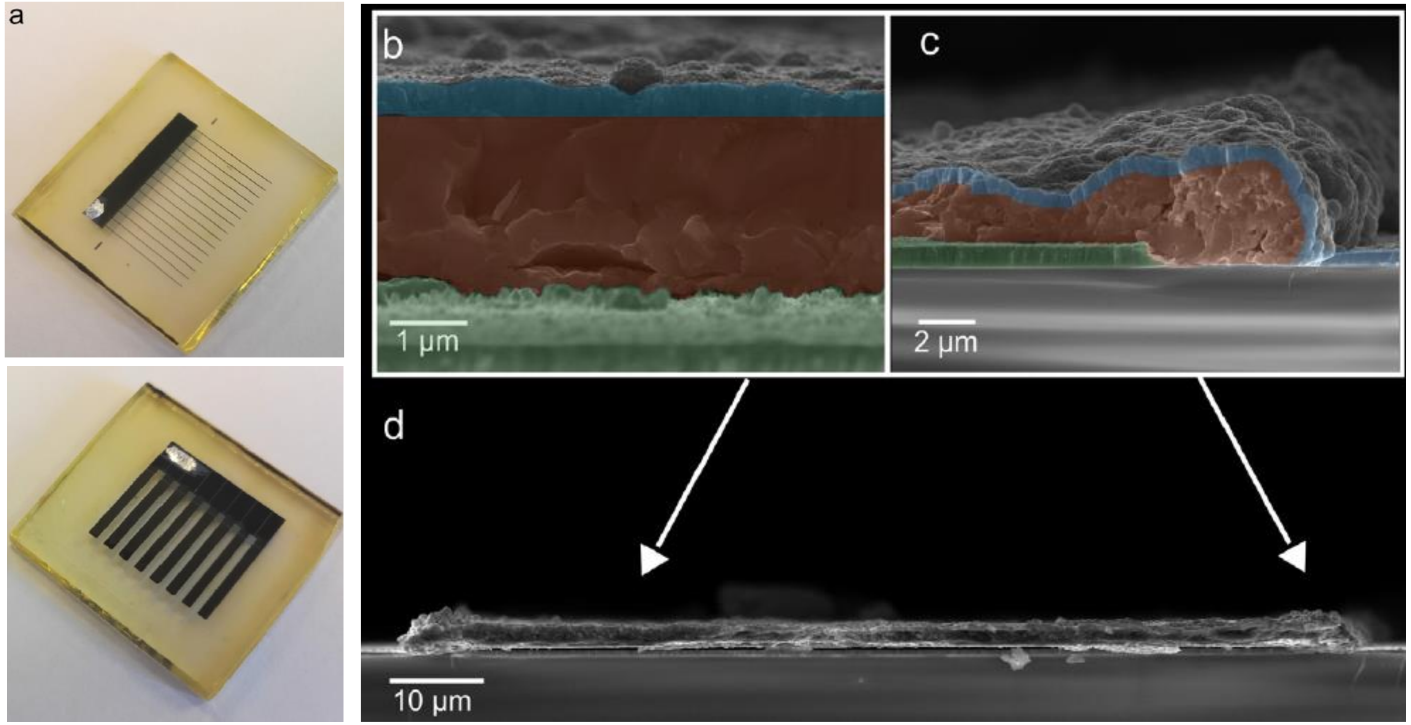

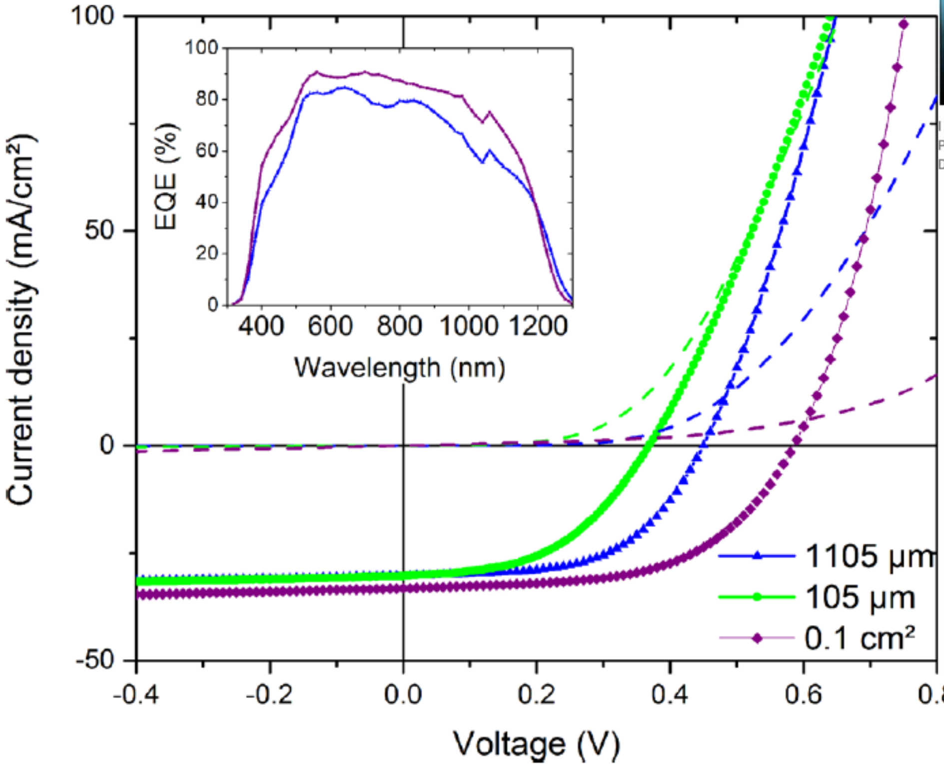

	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF (%)	η (%)	Width (μm)
0.1 cm^2	33.2	587	56.4	11.0	3160
1105 μm	30.3	449	56.1	7.64	1105
105 μm	30.2	368	48.3	5.38	105

A. Duchatelet al., Appl. Phys. Lett. 109, 253901 (2016).

- η = 5.38 % for 105 μm wide line-shaped cell under 1 sun illumination

Fabrication Approaches

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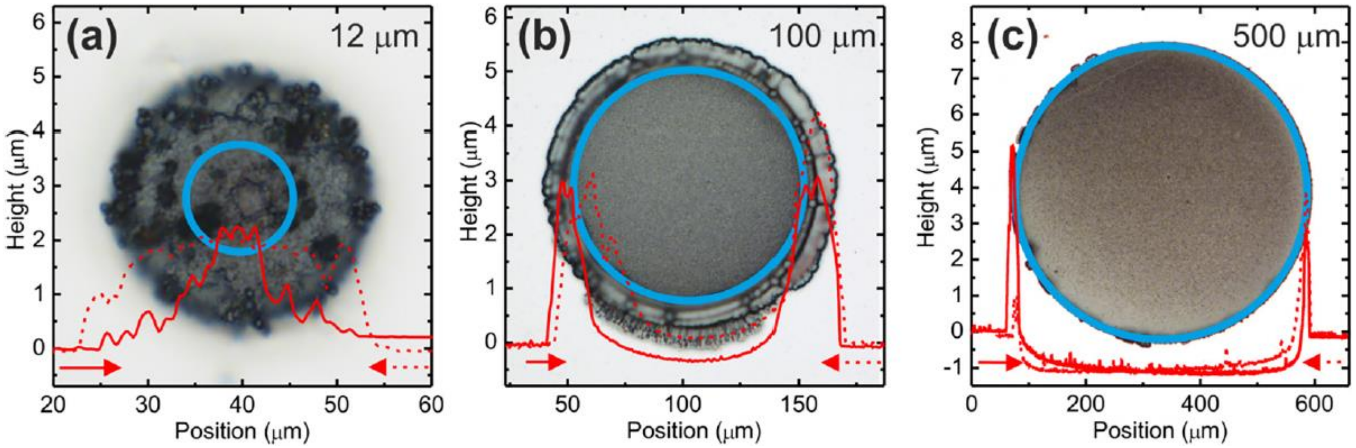
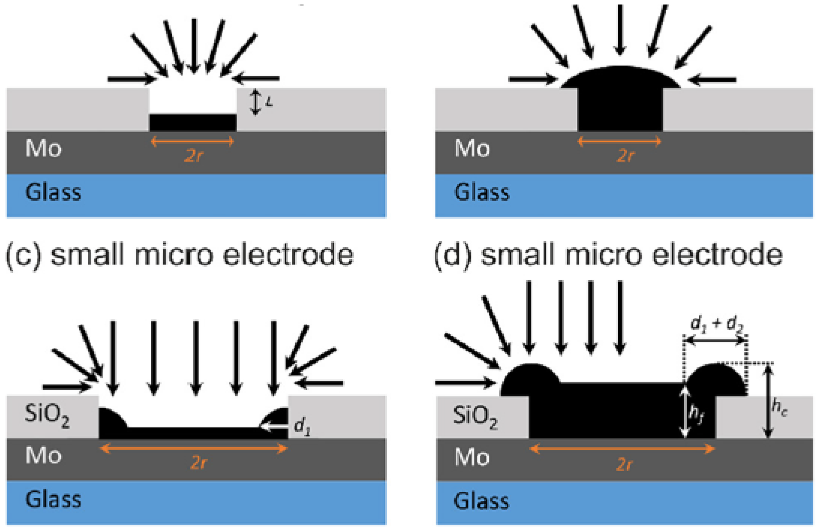
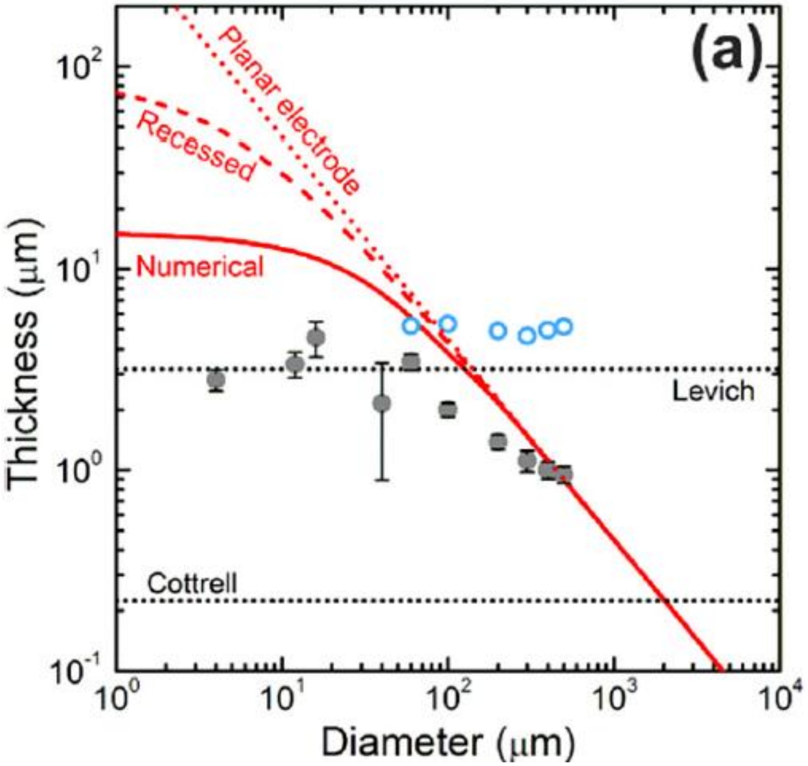




(c) small micro electrode
(d) small micro electrode
(e) larger micro electrode
(f) larger micro electrode

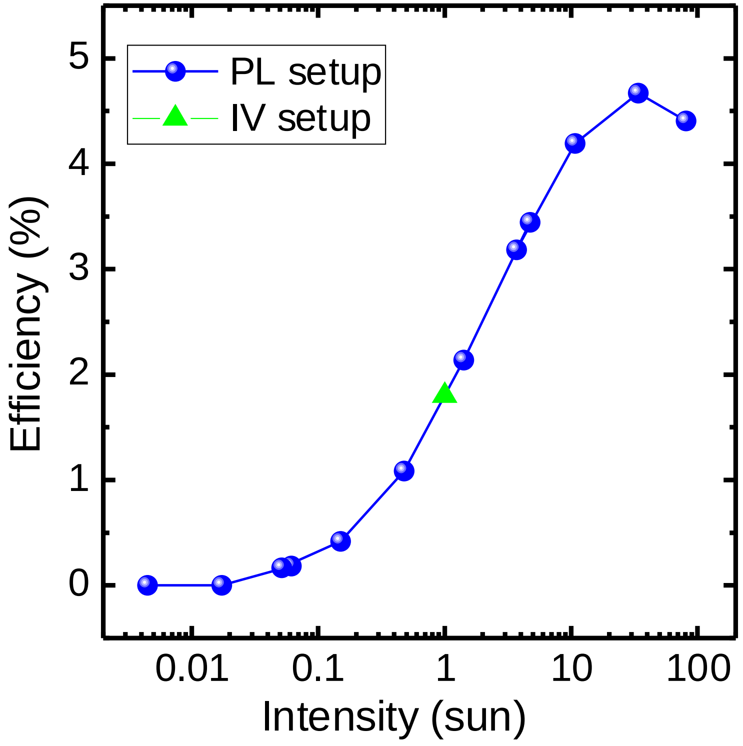


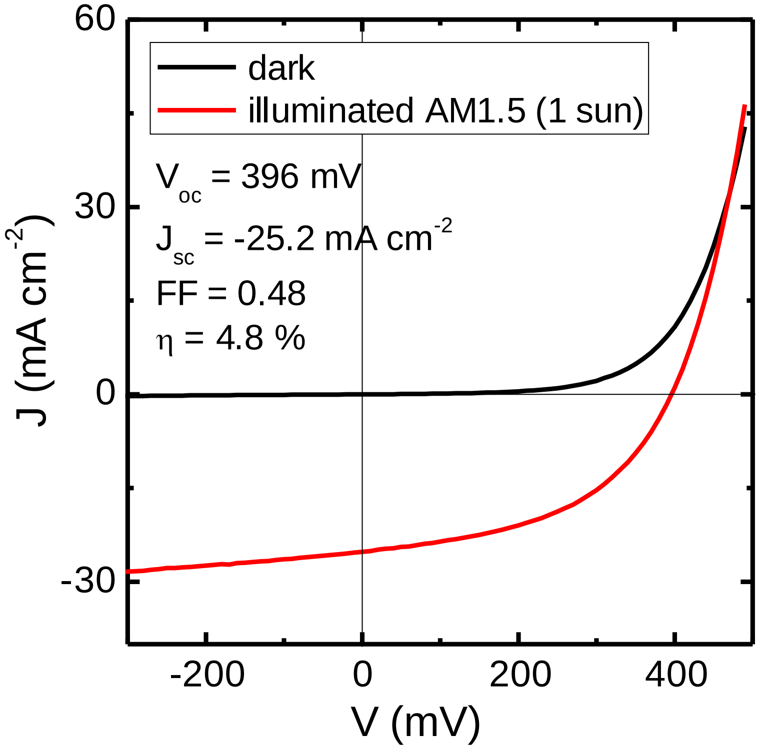
D. Correia et al., Results in Physics 12, 2136 (2019).

- Electrodeposition on micro-electrodes is faster due to species arriving from non-depositing areas
- Balance of electrode size and diffusion length

Bottom-up fabrication to demonstrate materials savings potential

- CIGSe by electrodeposition on micro-electrodes





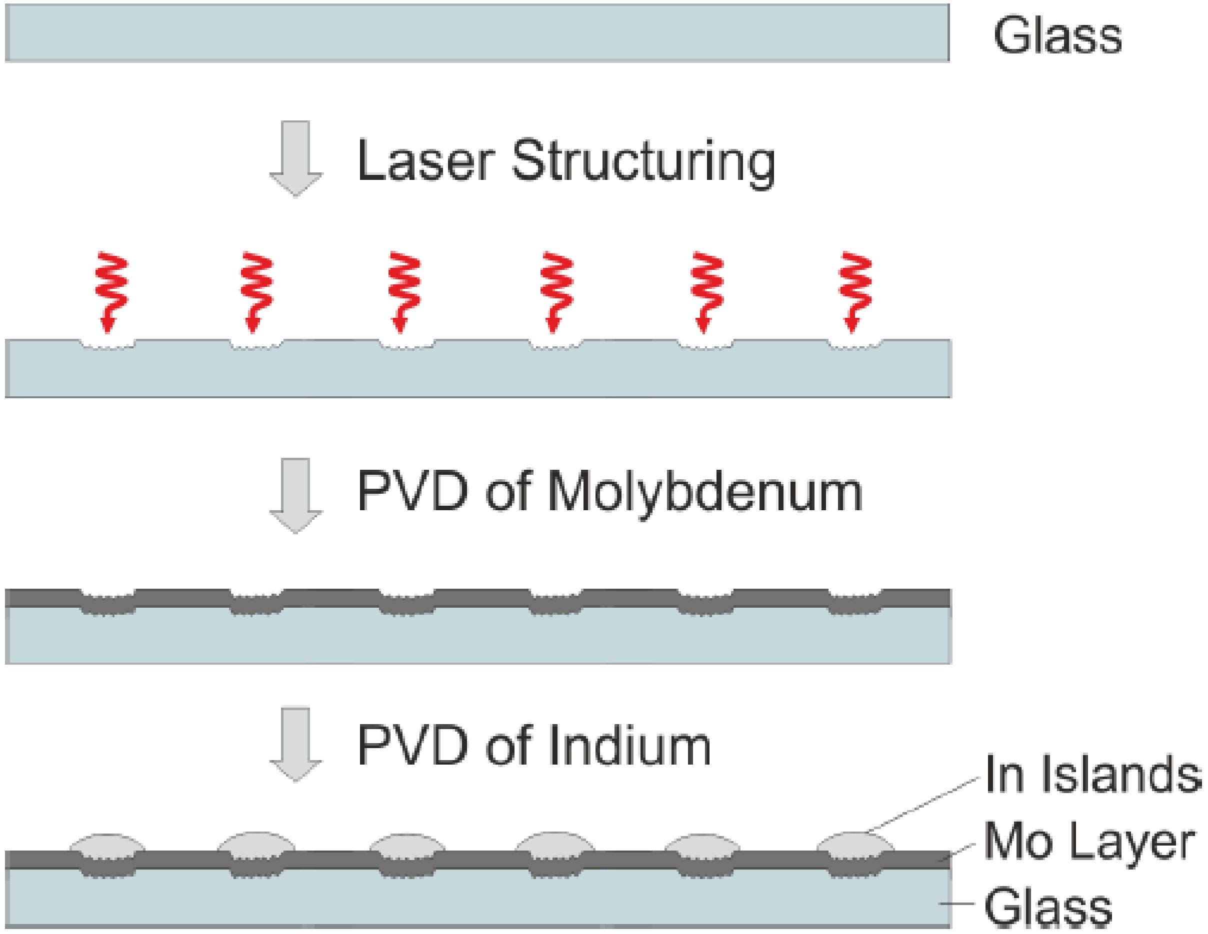
- η = 4.8 % @ 1 sun for 200 μm micro solar cell
- η = 4.6 % @ 35X concentration for 200 μm micro solar cell with 2 % @ 1 sun

D. Correia et al., Results in Physics 12, 2136 (2019).
D. Correia et al., Proc. IEEE PVSC, 794 (2018).
D. Siopa et al., submitted (2020).

Fabrication Approaches

Bottom-up fabrication to demonstrate materials savings potential

- Site-controlled indium deposition and conversion into CIGSe



B. Heidmann et al., Materials Today Energy 6, 238e247 (2017).
F. Ringleb et al., Beilstein J. Nanotechnol. *9,* 3025 (2018).

Fabrication Approaches

Bottom-up fabrication to demonstrate materials savings potential

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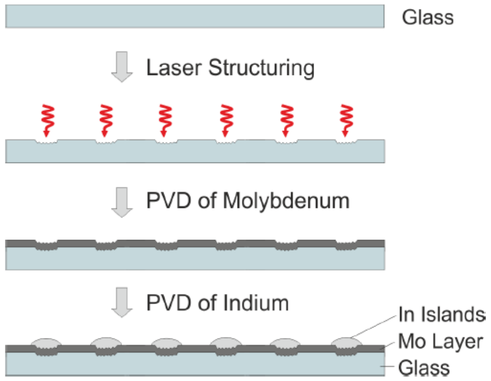

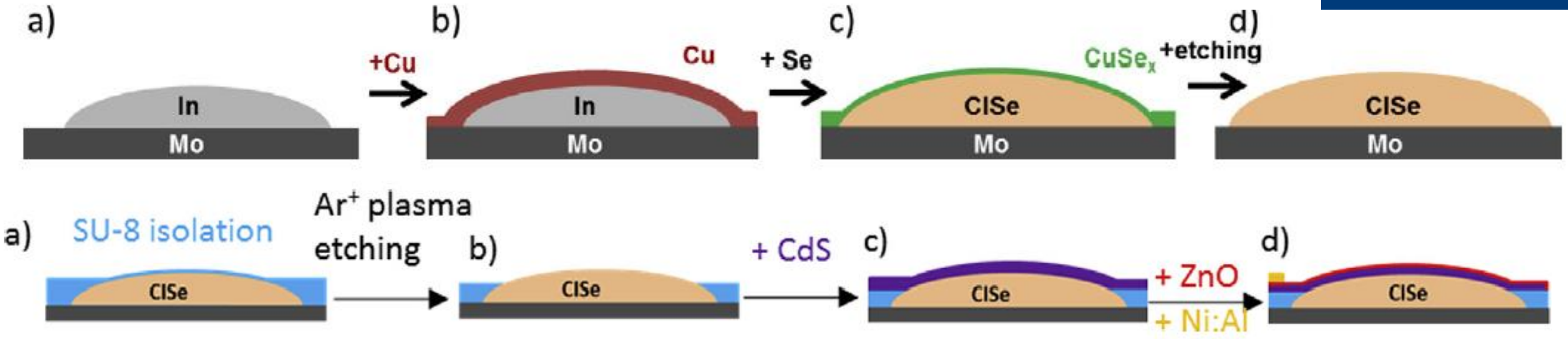

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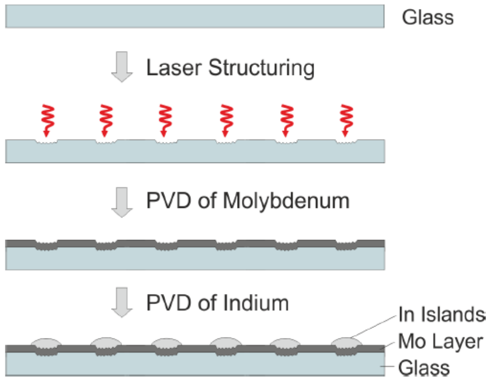
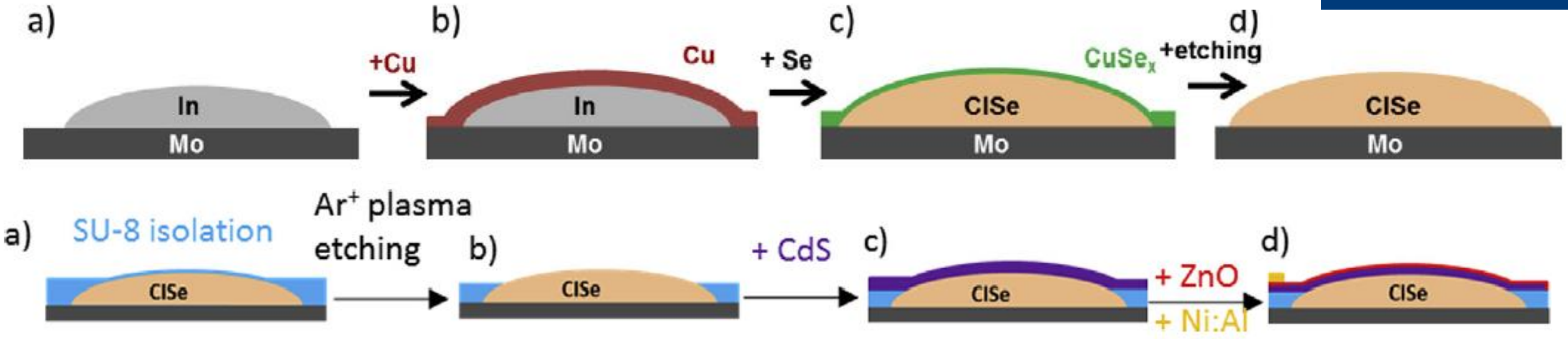
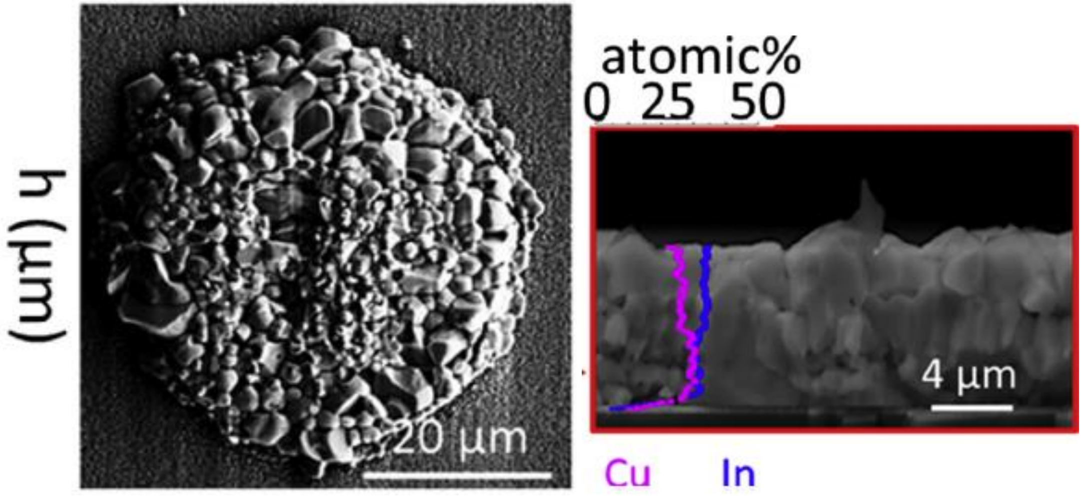
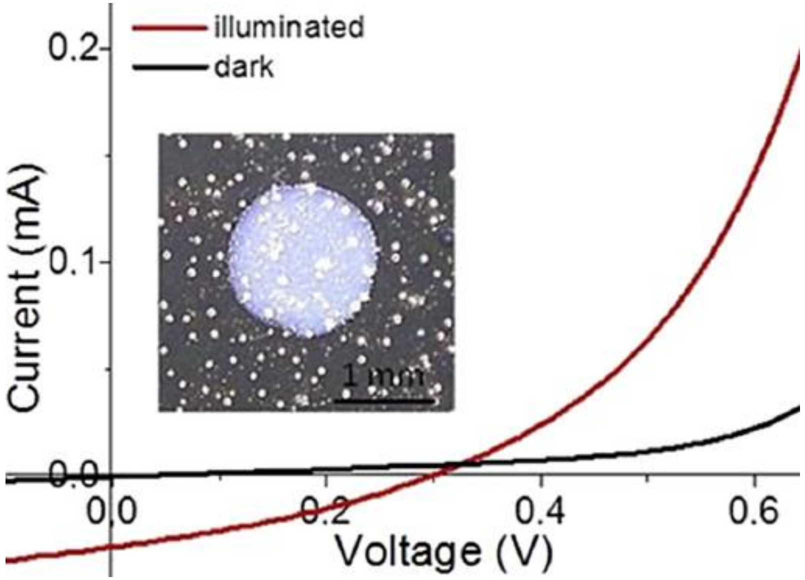








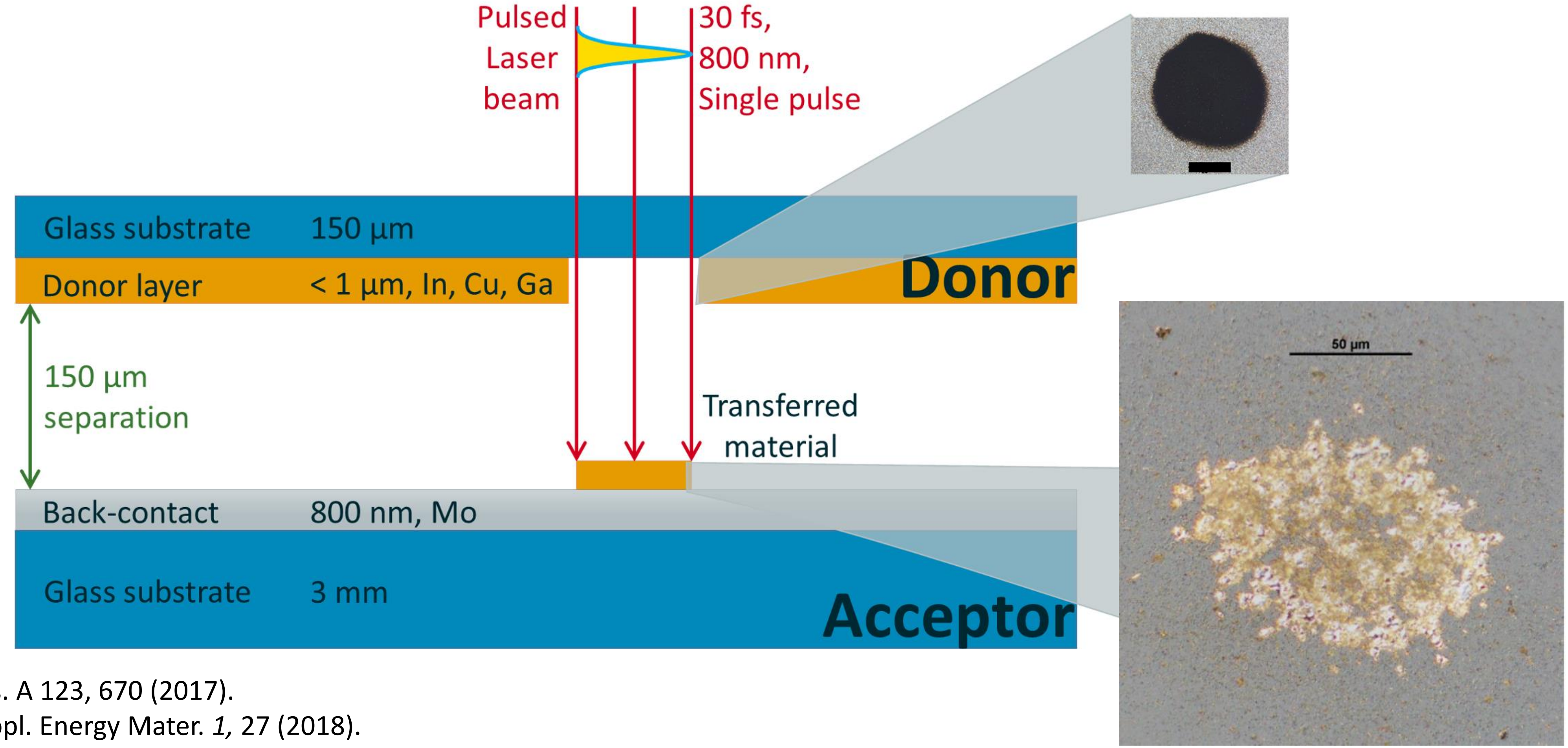
- η = 2.9 % @ 1 sun for 100 micro solar cells of 40 µm
- η = 3.1 % @ 3X concentration

B. Heidmann et al., Materials Today Energy 6, 238e247 (2017).
F. Ringleb et al., Beilstein J. Nanotechnol. *9,* 3025 (2018).

Fabrication Approaches

Bottom-up fabrication to demonstrate materials savings potential

- Site-controlled indium deposition and conversion into CIGSe
  - LIFT – Laser-induced forward transfer

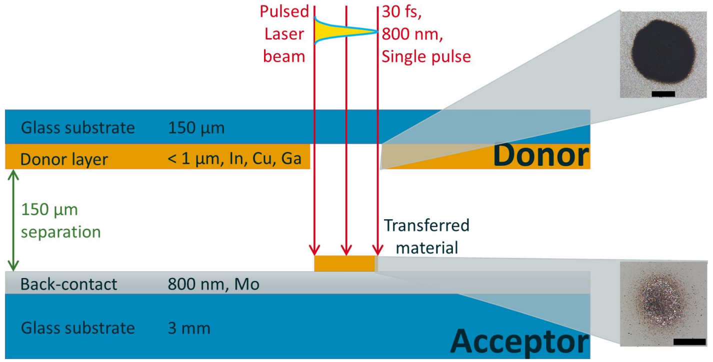


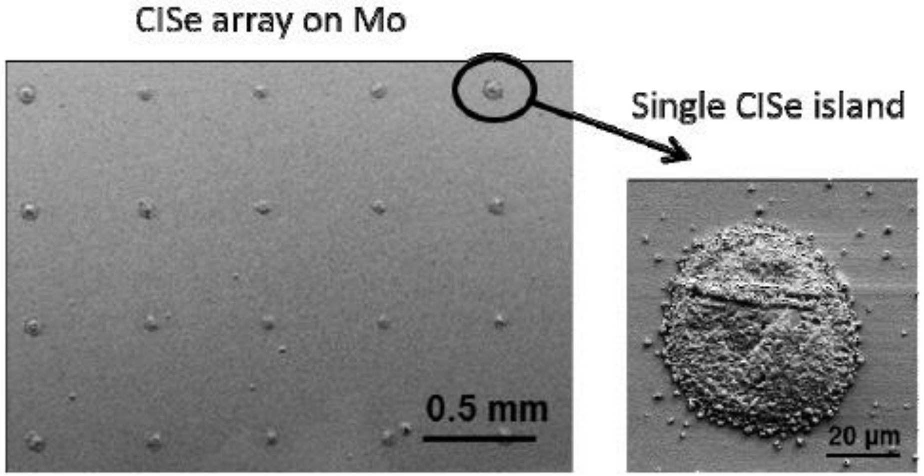
S. Andree et al., Appl. Phys. A 123, 670 (2017).
B. Heidmann et al., ACS Appl. Energy Mater. *1,* 27 (2018).
F. Ringleb et al., Beilstein J. Nanotechnol. *9,* 3025 (2018).

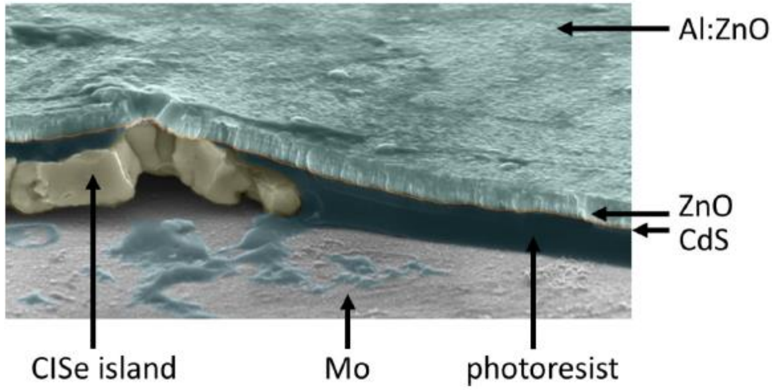
Fabrication Approaches

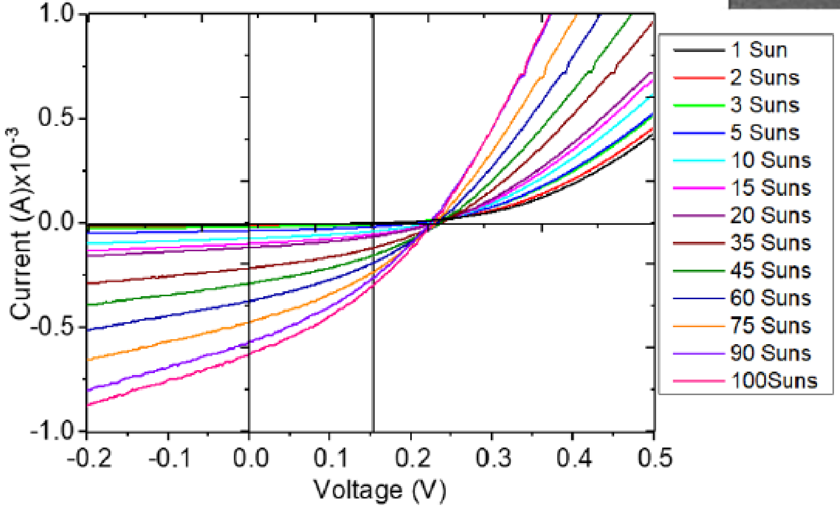
Bottom-up fabrication to demonstrate materials savings potential

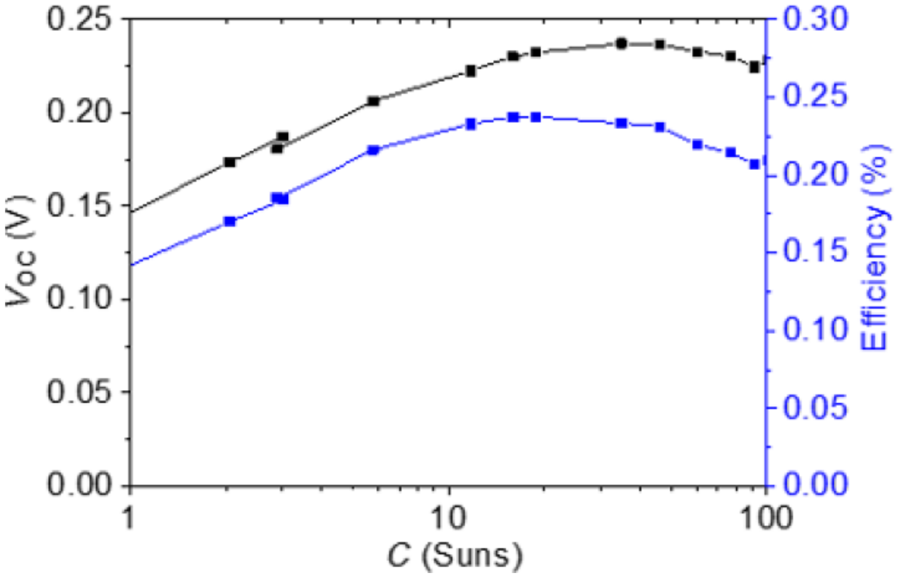
- Site-controlled indium deposition and conversion into CIGSe









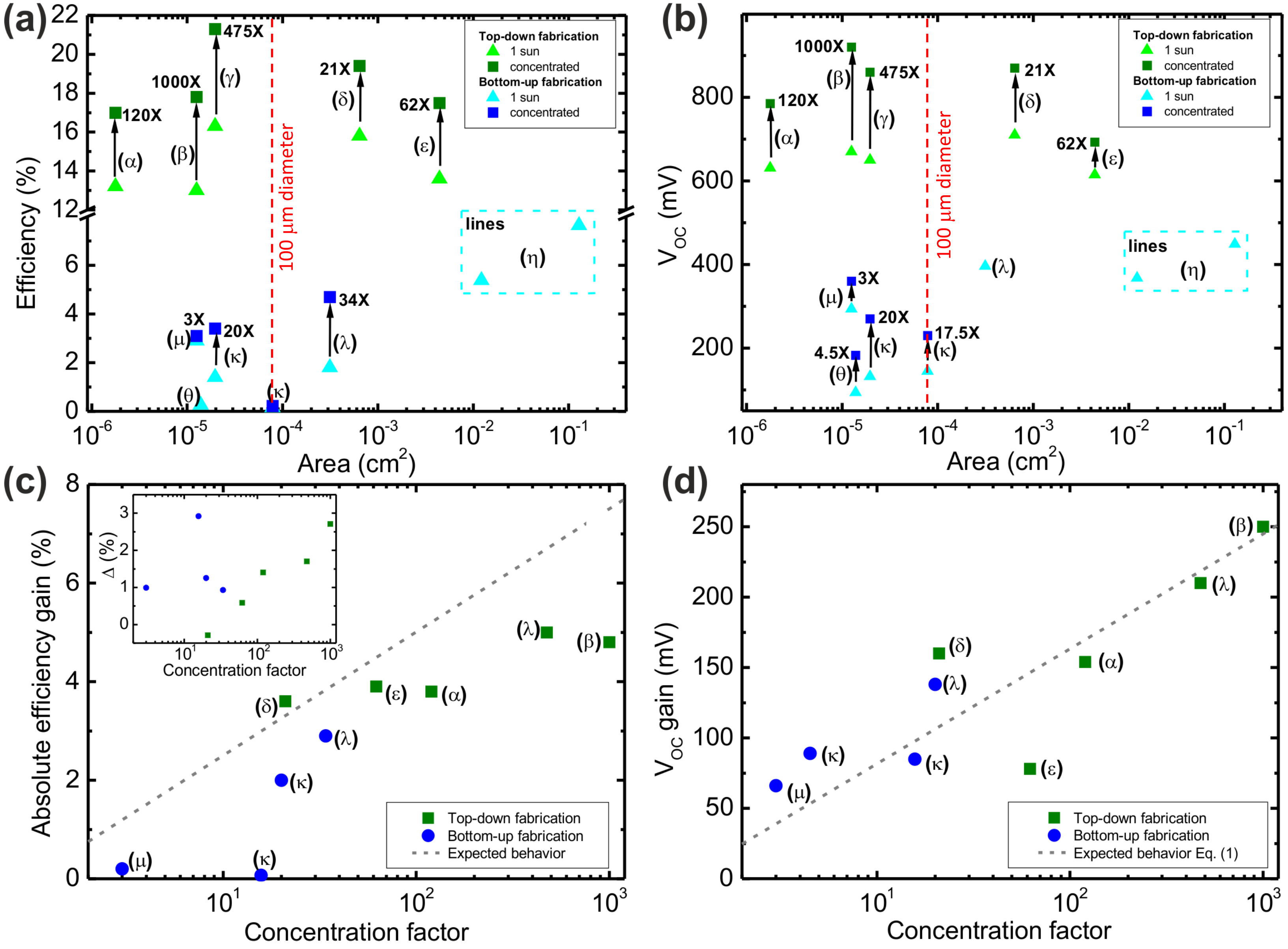


- η = 0.24 % @ 20 suns for 25 micro solar cells of 100 µm

S. Andree et al., Appl. Phys. A 123, 670 (2017).
B. Heidmann et al., ACS Appl. Energy Mater. *1,* 27 (2018).
F. Ringleb et al., Beilstein J. Nanotechnol. *9,* 3025 (2018).

Summary overview

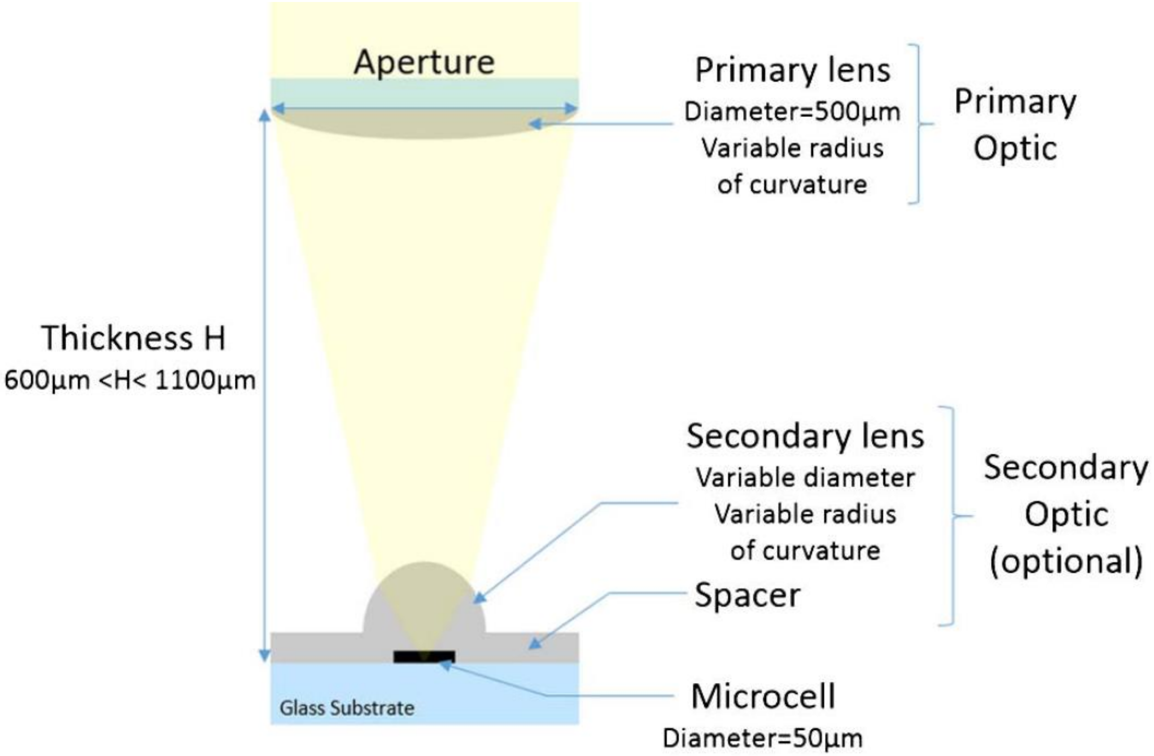
CIGSe micro-concentrator thin-film solar cells

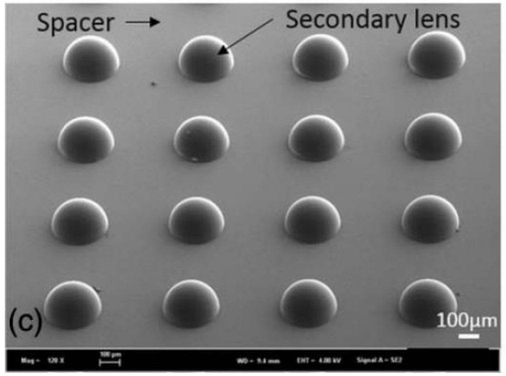


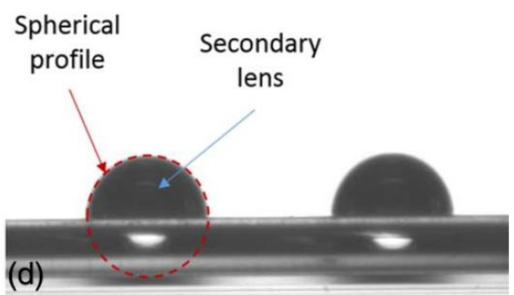
- Top-down fabrication leads to higher efficiencies and V_{oc}s
- Relative efficiency and V_{oc} gains are close to expected behavior
- Relative efficiency and Voc gains are similar for top-down and bottom-up approaches

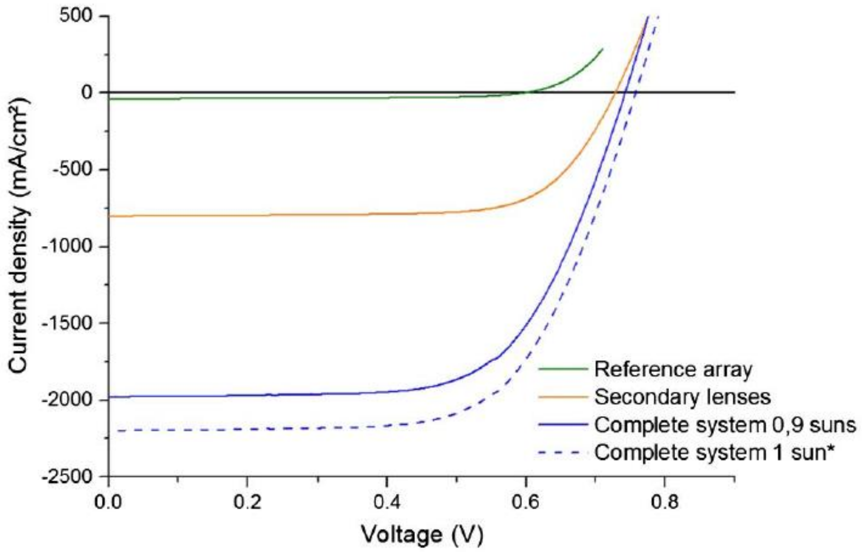
M. Alves et al., J. Phys.: Energy 2, 012001 (2020).

Combination with Concentration Optics
Micro-concentrator thin-film photovoltaics









	Jsc (mA/cm^2)	Voc (V)	FF (%)	C Factor (exp.)	C Factor (th.)	Efficiency (%)
Reference array	30.6	594	59.6	1×	1×	10.8
Reference secondary lenses	799	727	71.9	26.1×	24.7×	13.5
Complete system (0.9 suns)	1978	742	65.5	64.6×	65.7×	12.4
Complete system (1 sun)*	2198	757	65.2	71.8×	73.1×	12.6

S. Jutteau et al., Applied Optics 55, 6656 (2016).

Conclusion

- CIGSe micro-concentrator photovoltaics is a promising approach to reduce the requirement for critical raw materials
- Top-down fabrication of CIGSe micro solar cells has demonstrated up to 21.3 % efficiency at 475X concentration
- Various bottom-up fabrication routes have been demonstrated, currently still lower efficiencies
- Combination with micro optics has been demonstrated

"Thin-film micro-concentrator solar cells"

M. Alves, A. Pérez-Rodríguez, P.J. Dale, C. Domínguez, S. Sadewasser, J. Phys.: Energy 2, 012001 (2020).

Acknowledgments

We acknowledge support by the Micro-concentrator thin-film solar cells project (028922), co-funded by FCT and the ERDF through COMPETE2020. The work of C. Domínguez is supported by the Spanish Ministerio de Economía y Competitividad (MINECO) and Fondo Europeo de Desarrollo Regional (FEDER) under the Project MICRO-PV reference ENE2017-87825-C2-1-R.

Cofinanciado por:

COMPETE 2020 PROGRAMA OPERACIONAL COMPETITIVIDADE E INTERNACIONALIZAÇÃO

PORTUGAL 2020

UNIÃO EUROPEIA Fundo Europeu de Desenvolvimento Regional

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