CHEETAH

Europe's Research and Development efforts in support of its PV industry

European Solar Technology Forum
From Research to Industrial Application
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Chalcopyrite Microconcentrator Solar Cells
WP 9

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Objectives

LESS MATERIAL, HIGHER EFFICIENCY

- Save material using micro solar cells
- Enhance efficiency by light concentration

Within CHEETAH:

For Chalcopyrites $CuInSe_2$ (CISe) and $Cu(In,Ga)Se_2$ (CIGSe)

- Top-down proof-of-principle
- Bottom-up approaches for true material saving
- Concentrator optics
- Novel concentrator concepts

Objectives: less material

Supply risk of elements contained in $Cu(In,Ga)Se_2$ may become limiting when aiming at production on the GW scale.

British Geological Survey

Risk list 2015 — Current supply risk for chemical elements or elemer

Element or element group	Symbol	Relative supply risk index
rare earth elements	REE	9.5
antimony	Sb	9.0
bismuth	Bi	8.8
germanium	Ge	8.6
vanadium	V	8.6
gallium	Ga	8.6
strontium	Sr	8.3
tungsten	W	8.1
molybdenum	Mo	8.1
cobalt	Co	8.1
indium	In	8.1
arsenic	As	7.9

http://www.bgs.ac.uk/mineralsuk/statistics/risklist.html

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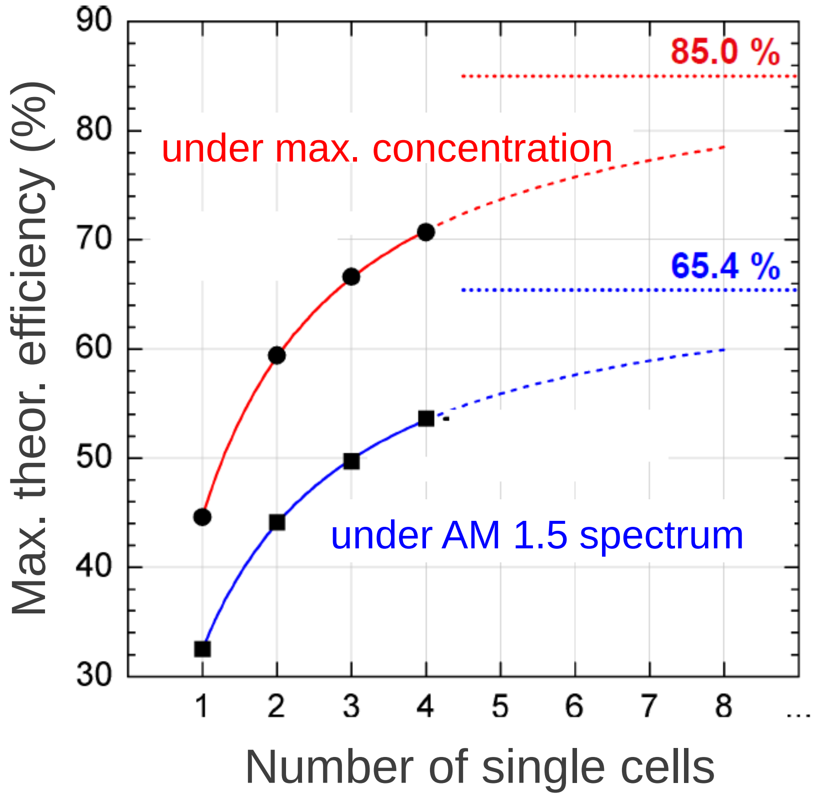
Objectives: higher efficiency

Efficiency enhancement under light concentration



Values according to Marti et al.
SOLMAT **43** 203 (1996)

Increased efficiency resulting from increase in open circuit voltage:

C: concentration factor

$j_{SC}(C) = j_{SC}(C=1)*C$

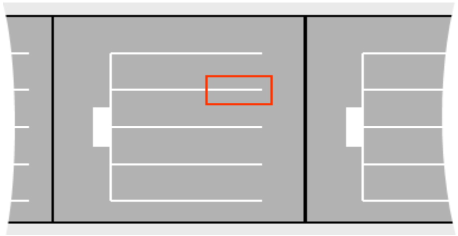
$V_{OC}(C) = V_{OC}(C=1) + nk_BT/e*\ln(C)$

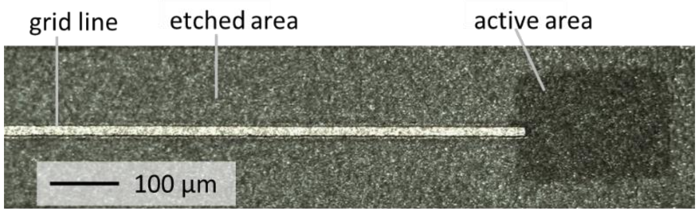
$\eta(C) = \eta(C=1) * (1 + nk_BT/(eV_{OC}(C=1))*\ln(C))$

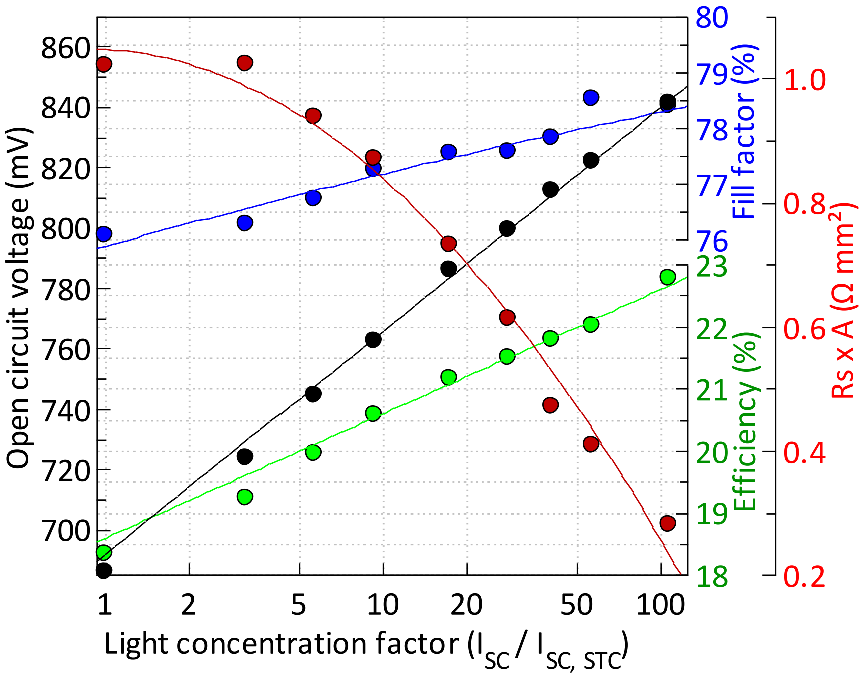
Results: top-down CIGSe micro cells

Proof-of-principle based on high quality absorber material

Selective etching of front-contact for restriction of active absorber area







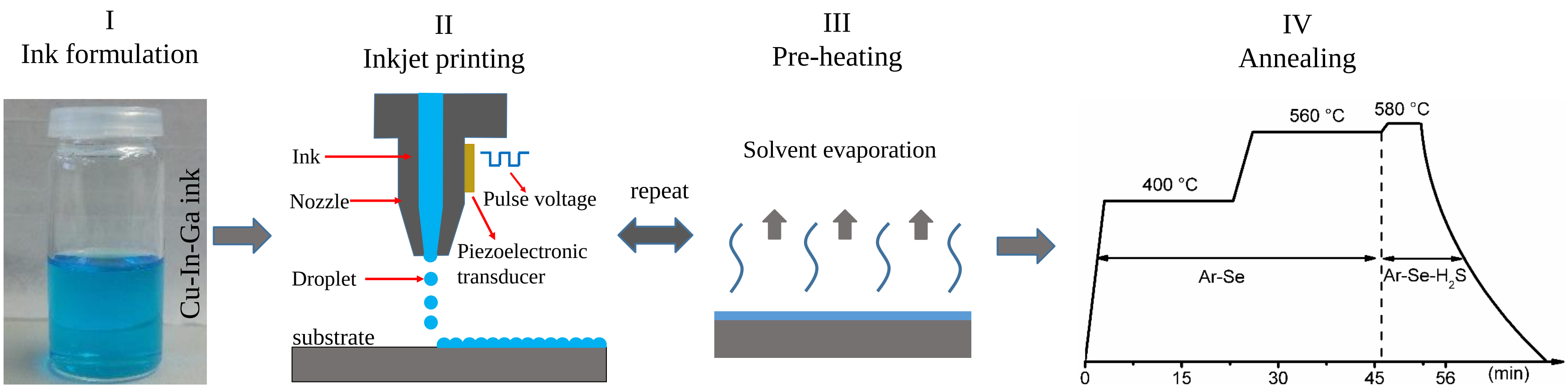
0.06 mm² cell achieved
22.5% @ 100 suns

E. Lotter et al. *32nd Proc. EU-PVSEC* Munich (2016)

ZSW

Results: towards local deposition

Inkjet printing of CIGSe as a technique enabling local deposition

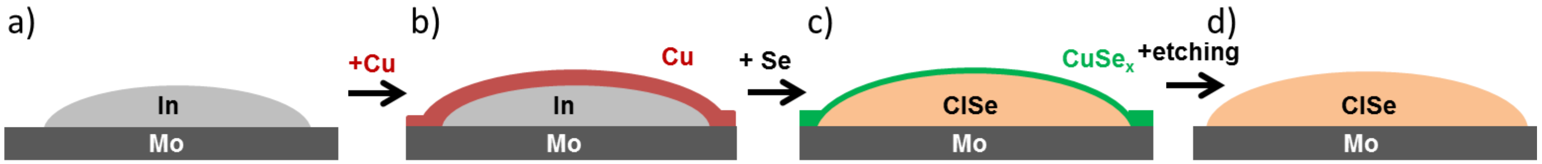


Absorber	Buffer	V_{oc} (mV)	J_{sc} (mA/cm²)	FF (%)	η (%)
Inkjet	Baseline	541	31.1	67.0	11.3
Baseline	Inkjet: In_2S_3	481	38.6	65.0	12.2
Inkjet	Inkjet: In_2S_3	463	33.3	67.5	10.4

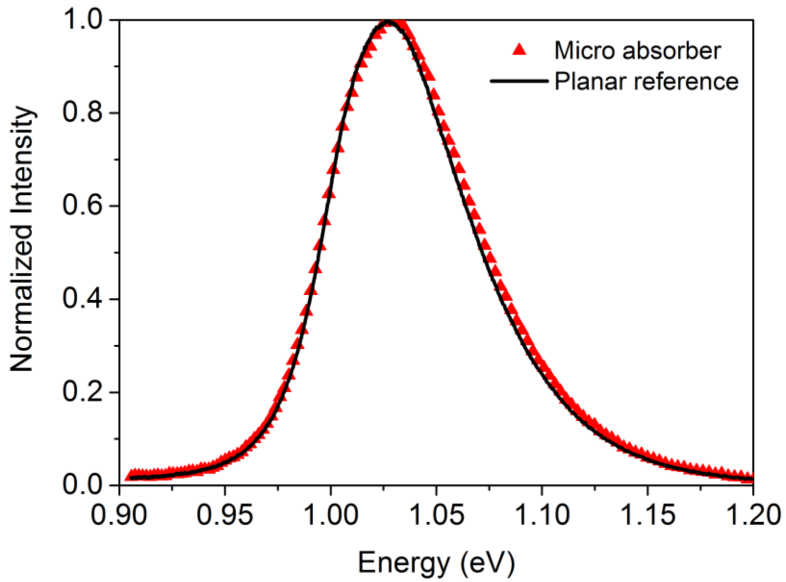
X. Lin et al. *Energy & Environmental Science* **9** 2037 (2016)

Results: bottom-up CISe micro cells

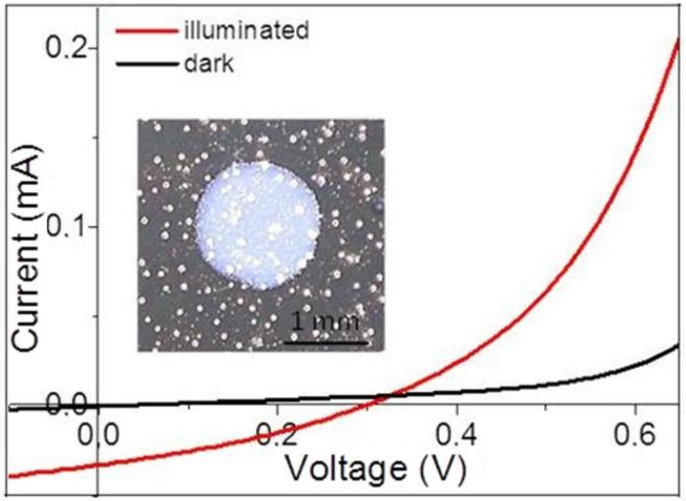
Local growth of CISe from indium droplets



PL signal comparable to planar reference



Working micro solar cells



B. Heidmann et al. *Materials Today Energy* **6** 238 (2017)

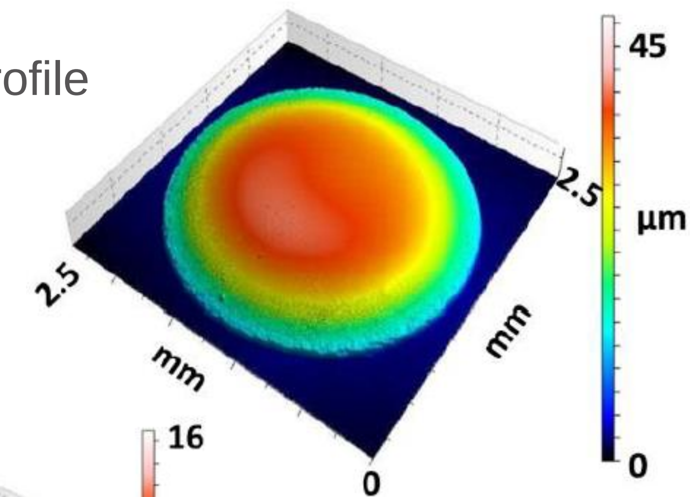
IKZ, HZB

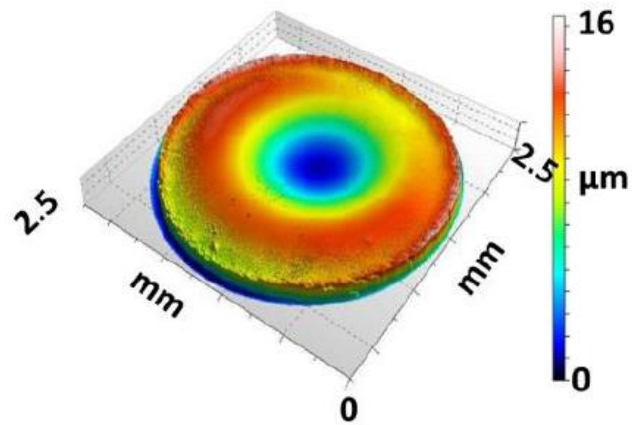
Results: concentrator optics

Concentrator lenses by printing – for all printed device

Deposition of PMMA solution by drop-casting to achieve dimensions in the mm range

Optical profile and





error profile

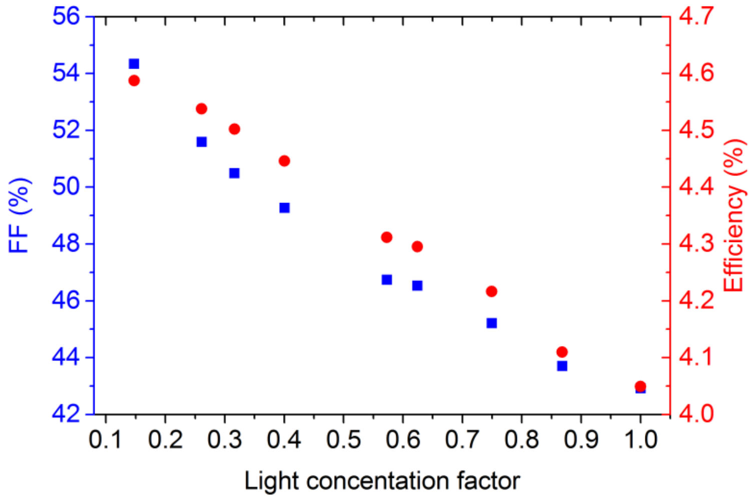
F. Loffredo et al. *33rd Proc. EU-PVSEC* Amsterdam (2017)

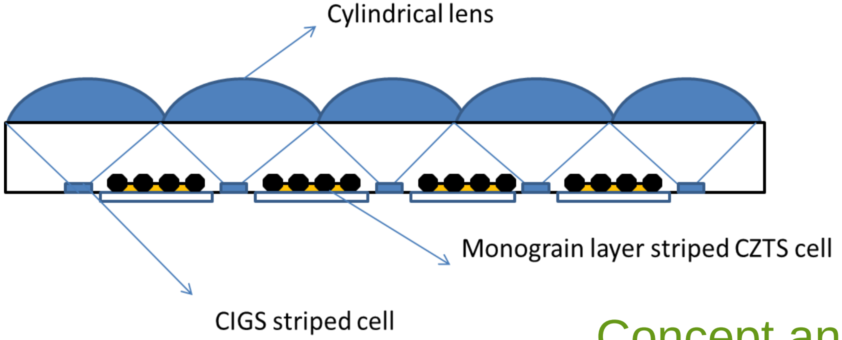
ENEA

Results: novel concentration concepts

Exploitation of direct and diffuse light by combination of CIGSe with CZTS material in areas of light concentration and intermediate spacing, respectively

Improved performance of CZTS Kesterite material under reduced illumination





Concept and proto-type

M. Schmid et al. *33rd Proc. EU-PVSEC* Amsterdam (2017)

TUT, HZB

Significance for the industry

- CIGSe-based micro concentrator solar cells have proven to surpass the record efficiency of planar devices in a top-down approach.
- Methods for bottom-up local absorber growth exist allowing material saving but requiring further development.
- Printing has proven feasible both for absorber as well as for lens fabrication and may therefore be an option for adjusted production processes.
- For maximum exploitation of both direct and diffuse light, combined device designs may be beneficial aiming at efficiency enhancement whilst minimizing additional fabrication costs at the expense of material saving.
  All CIGSe direct-diffuse configurations also appear promising.
- Opportunity for efficiency enhancement at equal or lower cost exists.
- Multiplication of fields of application like BIPV.

Significance for the industry: cost estimation

Savings:

- Material costs: assuming local absorber deposition ~ 2 €/m^2 can be saved on Cu, In, Ga
- Scribing: in case of local deposition a scribe line might be saved, estimated ~ 0.5 €/m^2

Additional costs:

- Isolation: additional process step for passivation of the local absorbers, estimated ~ 1 €/m^2
- Optical system: to be combined with front glass, thus minor additional costs; potentially corresponding to one additional process step like printing / hot embossing ~ 1 €/m^2

Challenges: approaches for local deposition like printing to be equalized in cost and efficiency as compared to PVD or RTP

See also Bachelor thesis J. Dippel *University Duisburg-Essen* (2017)

Interconnected CIGS micro concentrator modules
WP 9/WP 8

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Objective

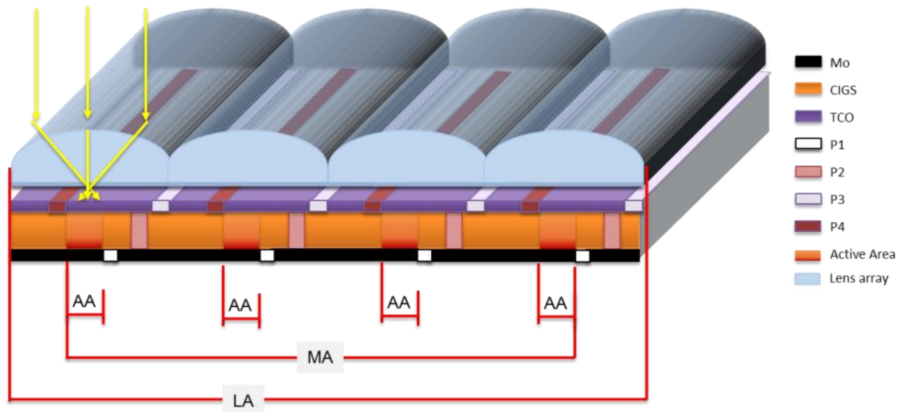
LESS MATERIAL, HIGHER EFFICIENCY

- Save material using micro solar cells
- Enhance efficiency by light concentration

Within CHEETAH:

- Interconnection schemes and modules for µ-CPV devices
- Module-Lens arrangements for such devices
- Proof of principle with top-down approach.

1D concentration Model



Different areas can be considered:

- AA=Active area
- MA= Module area
- LA=Lenticular or Lens array area

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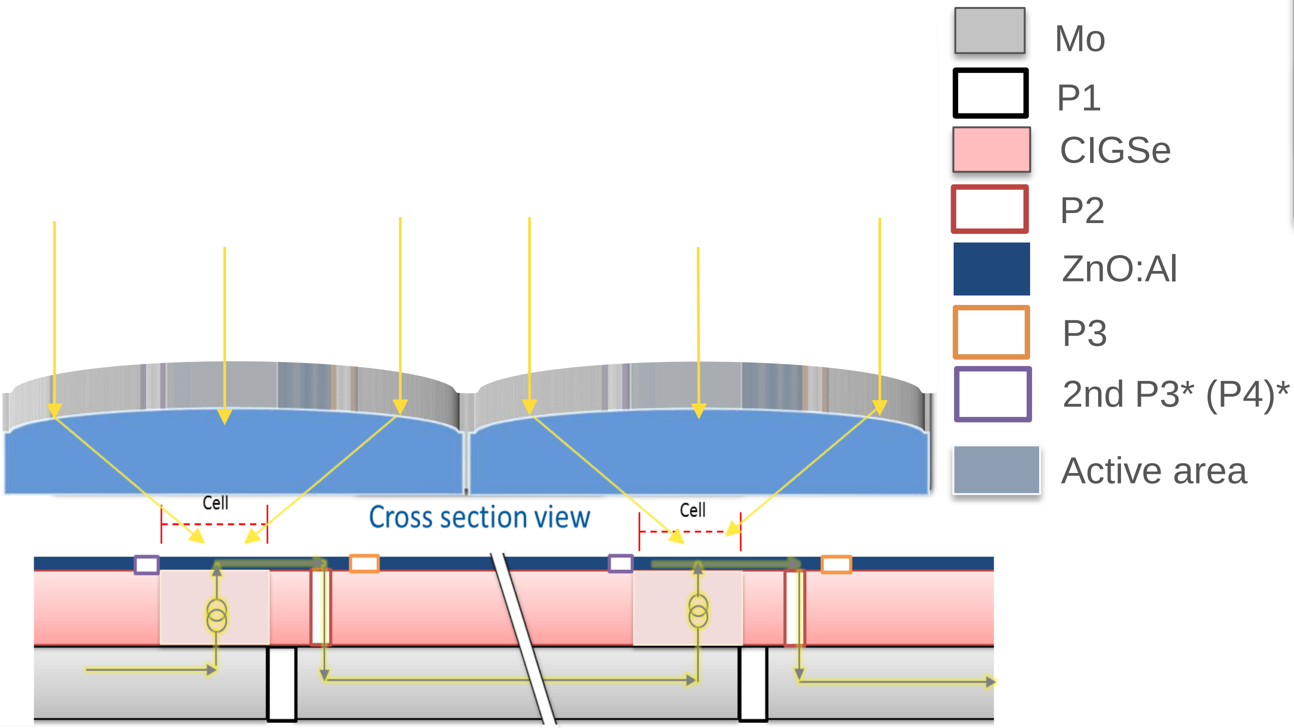
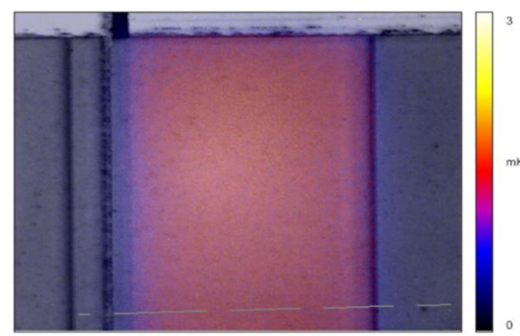
Processing & Scribe Quality (1D)



Scribing quality through:

JV curve measurement

Thermography (DLIT)



Dark lock-in thermograph

- Cell´s width was reduced down to 50µm.
- P3 and P4 were successfully scribed by laser ablation.
- Interconnected CIGSe mini-modules for concentration.

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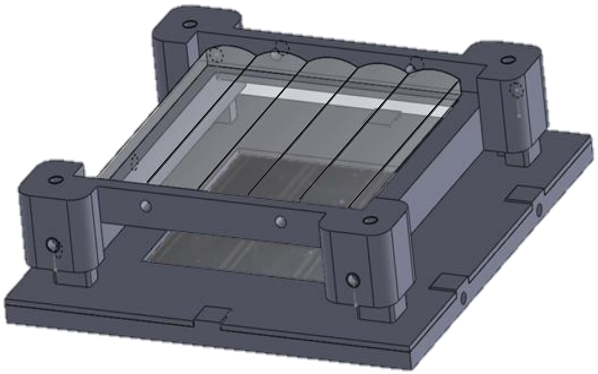
*Similar to [1] Reinhold et al., „Monolithically interconnected lamellar Cu(In,Ga)Se2 micro solar cells under full white light concentration", 2015.

Lens-module array adjustment

- 1-D concentration cylindrical lenses to match cell stripes
- Optical parameters (i.e. Focus length, refraction index, transmission) and pitch (7.52mm)
- Illumination width at lens focus > 500µm → cell´s width >500µm

- 3D printed positioning adjustment + mini-modules
- Lens can be positioned upside down for easier cleaning



Positioner and Lenticular representation.

Thin film sub-module for concentration

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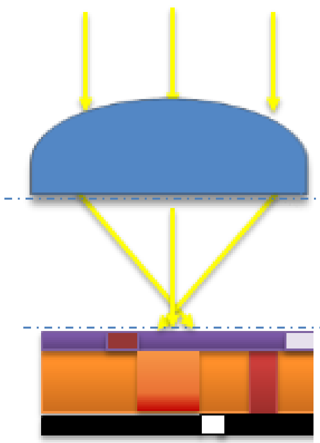
Measurements done with lens array

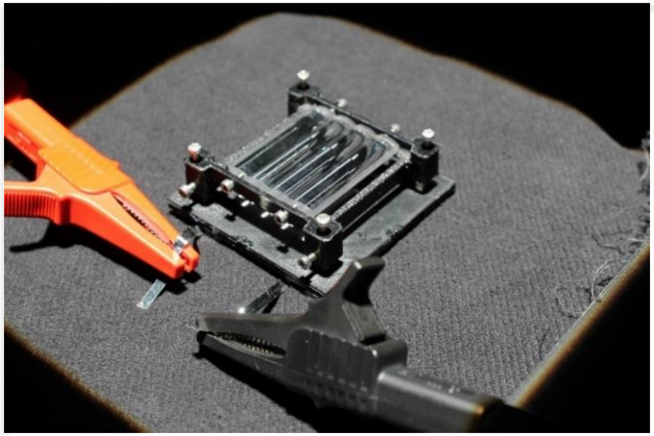
- JV curves with and without lenticular
- Light incident on stripes only
- Stripe widths per module vary from ~500µm to 800µm
- Optical losses included



$$P_{\emptyset} = AM1.5 = 100mW/cm^2$$

$$P_{L,max} = \frac{Lens\ Pitch}{Cell's\ Width} \cdot P_{\emptyset}$$

$$P_{L,meas} = J_{sc}/J_{sc}@AM1.5 \cdot P_{\emptyset}$$



CPV device

Lens pitch	Cell´s width	$P_{L,meas}/P_{\emptyset}$	$P_{max}/P_{\emptyset}$	$P_{L,meas}/P_{max}$
7.52mm	488 µm	**7.62**	15.41	0.49
7.52mm	680 µm	7.34	11.06	**0.66**
7.52mm	**685 µm**	**5.86**	**10.98**	**0.53**

→Highest concentration

→Highest $P_{L,meas}/P_{L,max}$ ratio

→Highest efficiency 1D

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Main results from 1D-concentration

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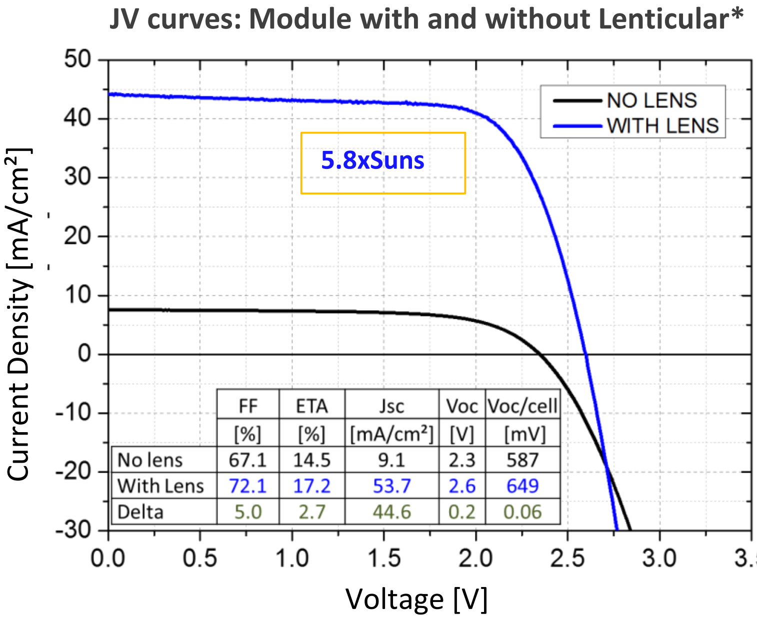
Module JV curves



Efficiencies (η) with and without lens considering different areas

	$\eta = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{in}}$	$\eta = \frac{V_{oc} \cdot J_{sc} \cdot FF \cdot \frac{A_{jsc}}{A_1}}{P_{in}}$
No lens: $P_{in} = P_{\emptyset}$	Active area η=14.5%	
With lens: $P_{in} = P_{L,meas}$	Active area **η=17.2%**	Module area **η=13.2%** Lens area **η=10.1%**

$$P_{\emptyset} = AM1.5 = 100mW/cm^2 = 1 \text{ Sun}$$

$$P_{L,max} = 10.98 - 15.4 \; Suns$$

$$P_{L,meas} = 5.8 - 7.6 \; Suns$$

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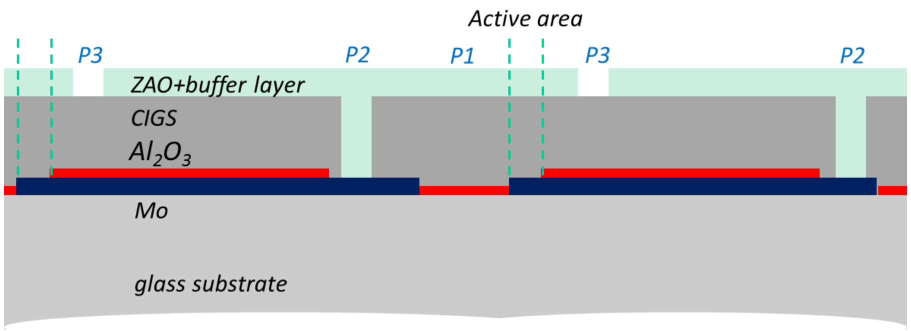
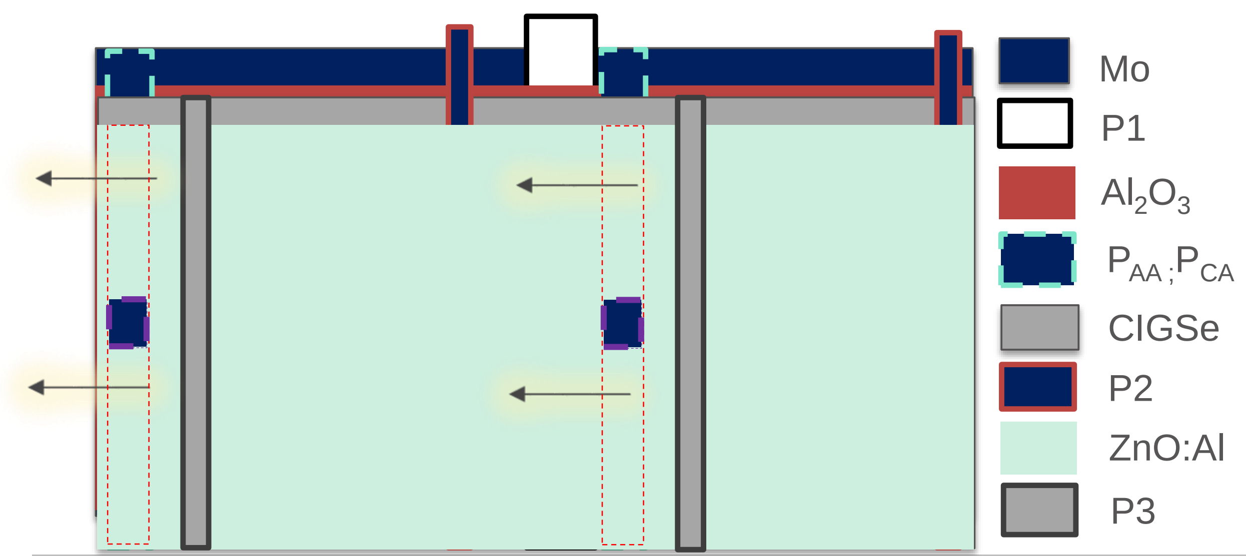
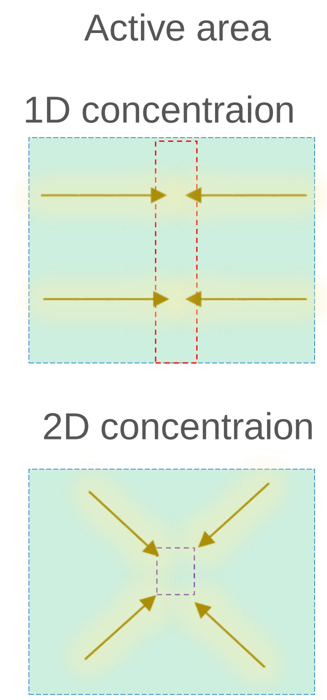
Alternative approach: processing

100 nm thick Al_2O_3 barrier layer to electrically insulate unused parts of the cell area and to limit the Na in-diffusion from the substrate through P1 and the grooves between adjacent cell rows







*Contacting IsoCuts not shown

Alternative approach: 1D & 2D concentration

1D-concentration

Array of (7 rows of) 20 interconnected cells.
Each section = 10 mm x 3 mm and an Active area of 10 mm x 100 µm²

$$P_{L,max} = \frac{10\ \text{mm}*3\ \text{mm}}{10\ \text{mm}*100\ \mu\text{m}} \cdot P_{\emptyset} = \text{30x Suns.}$$

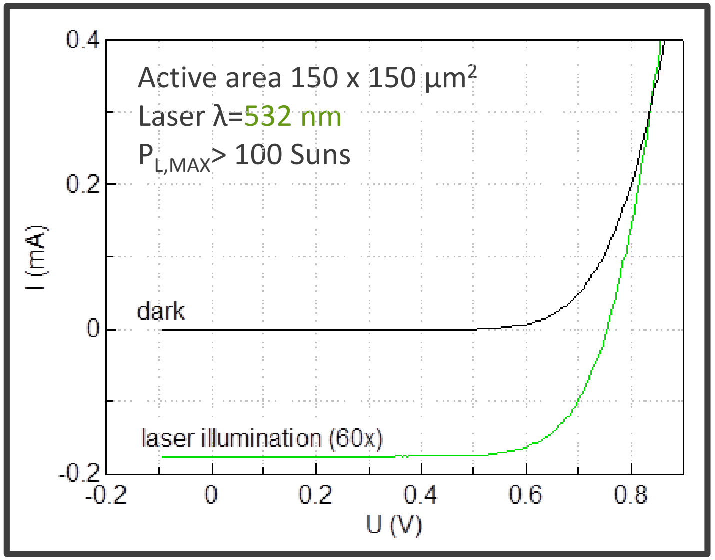
2D-concentration

Array of 67 rows made up of 21 interconnected cells each.
Each section = 1x1 mm² and an Active area of ≈ 100 x 100 µm².

$$P_{L,max} = \frac{1\ \text{mm}*1\ \text{mm}}{100\ \mu\text{m}*100\ \mu\text{m}} \cdot P_{\emptyset} = \text{100x Suns.}$$

Cell performance

I-V measurements replacing Solar simulation with laser power

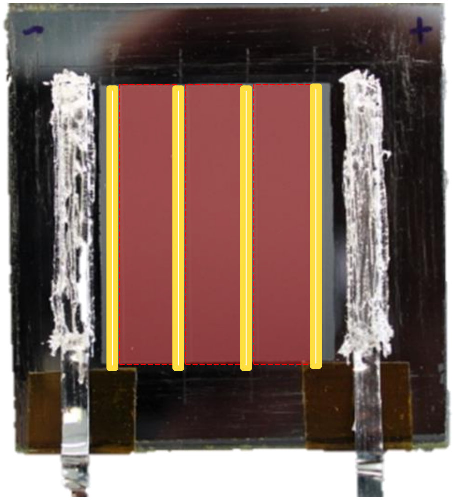


- V_{oc} = 760 mV (agrees with C)
- $P_{L,meas}$ = 60 suns

- FF=74 %
- η>17%

Material saving possibilities

According to the MPP/cm^2 (only 1D), ~11 % of material could be used to produce the same amount of power in comparison to standard modules.



- Bottom-up production
  -Drop-on-demand inkjet printing [2]
  -Local growth of CuInSe2 [3]

- Top-down production.
  -Recycling of inactive material

Over 50% of absorber material with 1D concentration can be saved.

http://theskillsconnection.com

Higher efficiencies → higher production → higher revenue

Lower material usage → lower costs →more benefit
→ Minimizes material supply risk

HZB

[2] X. Lin,11.3% efficiency Cu(In,Ga)(S,Se)2 thin film solar cells via drop-on-demand inkjet printing”,2016.
[3] B.Heidmann et al., “Local growth of CuInSe2 micro solar cells for concentrator application”, 2017.

Conclusions

Functional interconnected CIGSe micro-concentrator modules of 16 % conversion efficiency are feasible

1D concentration

- **Straightforward** interconnection concept
- Relative **efficiency increase** considering the active area
- **No further machinery** needed
- Inactive area can be used separately
- Design structure is **scalable**

- Quality of **lenses** can limit total light concentration
- **Single-Axis tracking** system required
- Lenticular **adjustment** for large modules
- Large **waste** of absorber **material** at current status

2D concentration

- Concentrations > **50 Suns**
- Lower thermal losses
- Even **higher efficiencies**
- Grater material saving (if printed)
- Design structure is scalable

- Quality of lenses can limit total light concentration
- **Dual-Axis tracking** system required
- More complicated lens-cell adjustment
- Larger waste of absorber material at current status

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Thank you!

Any questions for our experts?

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Feedback from the industry

- Do you think these CHEETAH innovations (will) matter?
- What do you think is important for short, medium and long term to further mature these innovations?
- What do you think is important for short, medium and long term for the industry to adopt these innovations?
- How could your company benefit from these innovations?
- What other innovations not investigated in Cheetah are important for the industry on short, medium and/or long term?