SOLIBRO RESEARCH | A COMPANY OF Hanergy



From lab research of CIGS solar cells to massproduction of PV modules – historic and futurechallenges

Lars Stolt, CTO Solibro BU and (part-time) Professor at Uppsala University

HOW IT STARTED

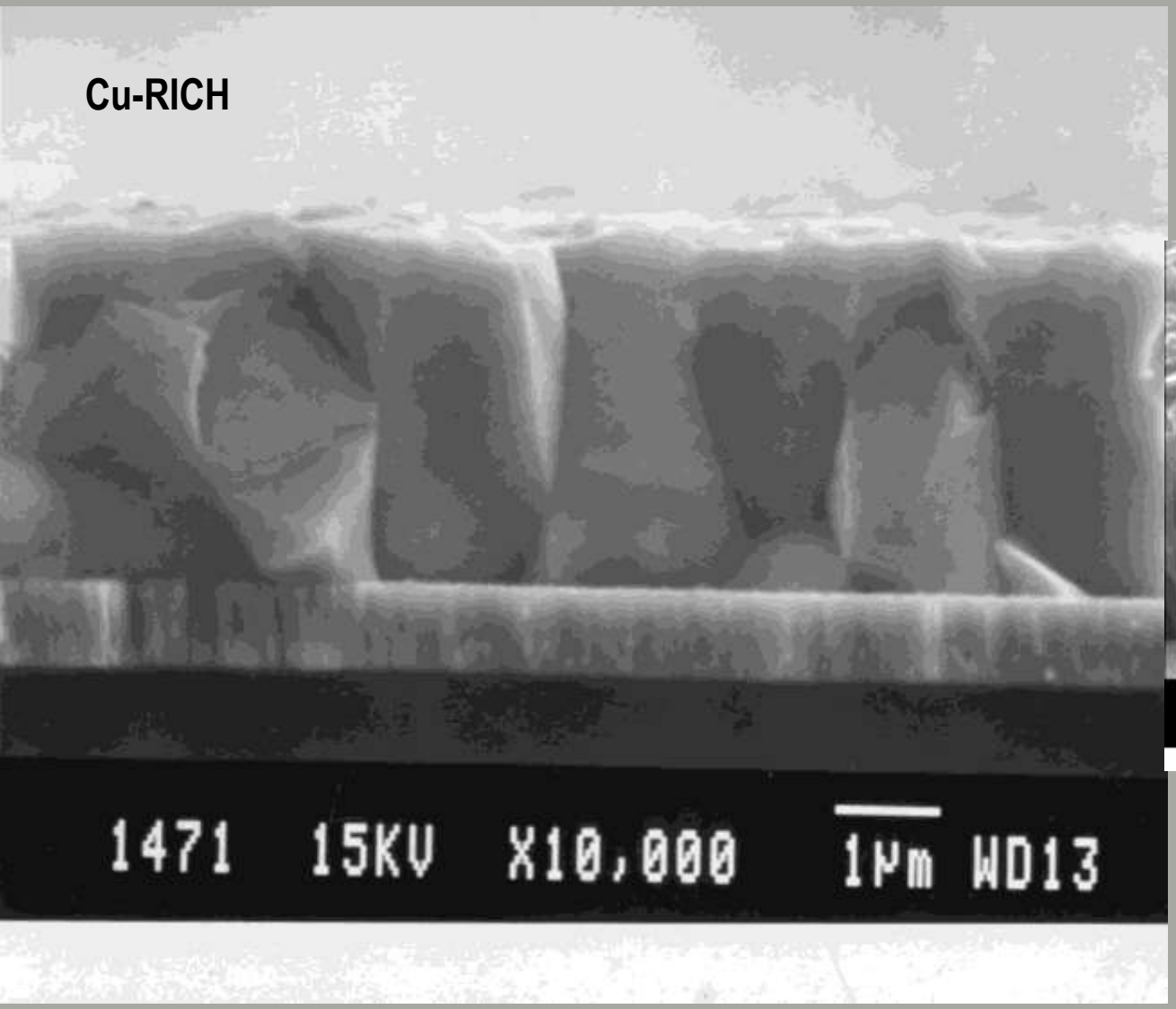
EARLY CI(G)S SOLAR CELL MILESTONES

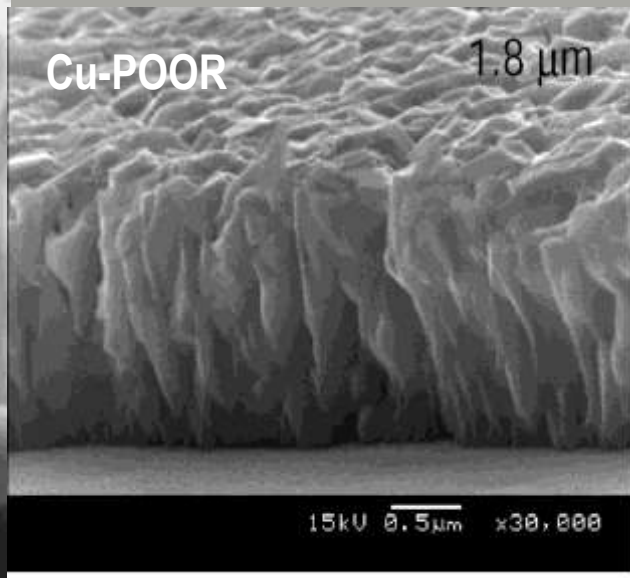
Singlecrystal $CuInSe_2$/CdS heterojunction **12 %**
J.L. Shay et al, Appl. Phys. Lett. 27 (1975) 89

Thin Film $CuInSe_2$/CdS heterojunction **4 %**
L.L. Kazmerskiet al, Appl. Phys. Lett. 29 (1976) 268

Thin Film $CuInSe_2$/CdS heterojunction **10 %**
R. Mickelsen, W. Chen, Proc. 15th IEEE PVSC (1981) 800
The Boeing two-step process recipe
1. Grow a CIS film with Cu-excess (Cu/III > 1) – Cu-RICH
2. Deposit under In-richconditionsuntil Cu/III <I –Cu-POOR

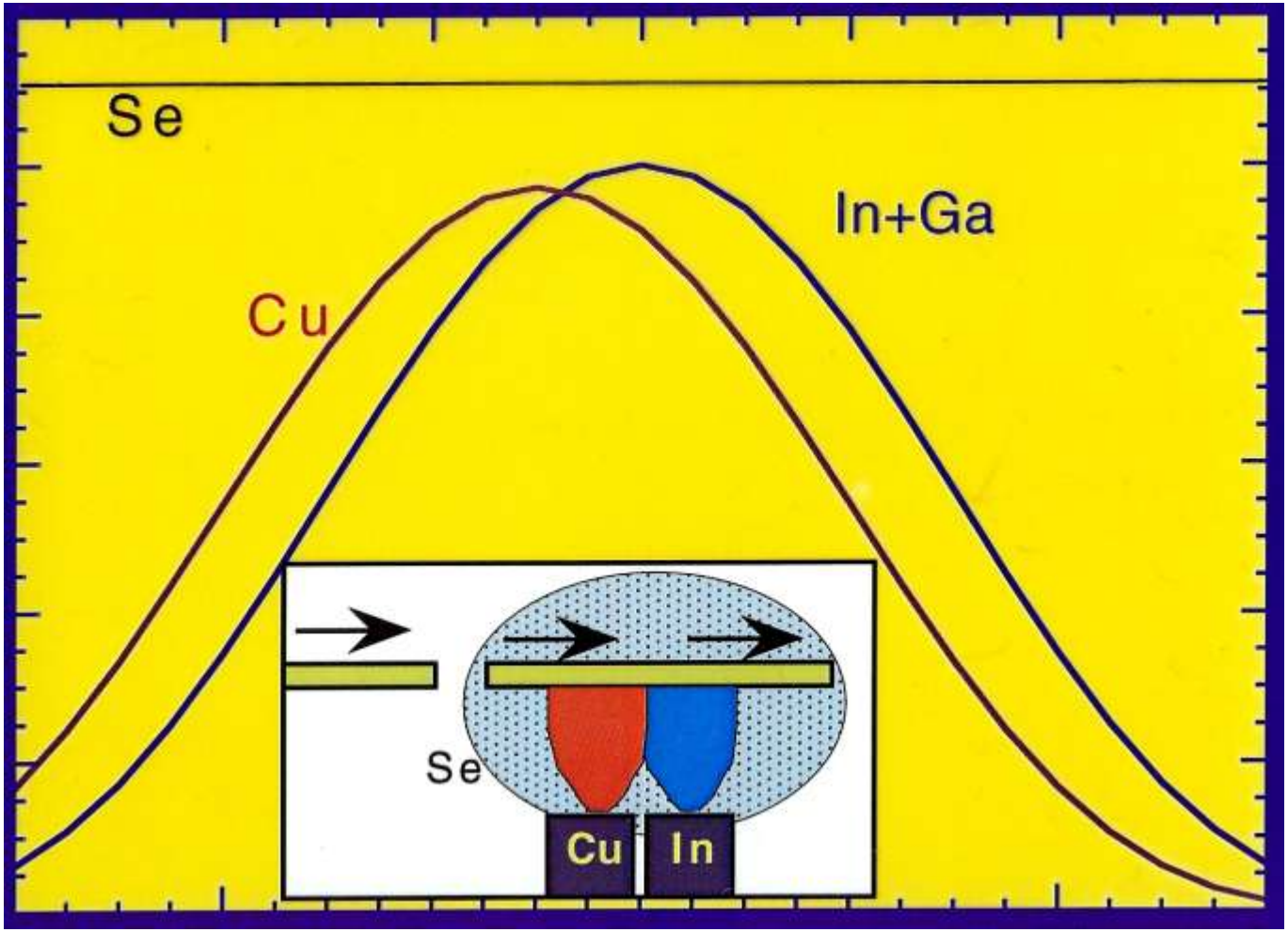
Cu-RICH vs Cu-POOR GROWTH





A RECIPE FOR PRODUCTION

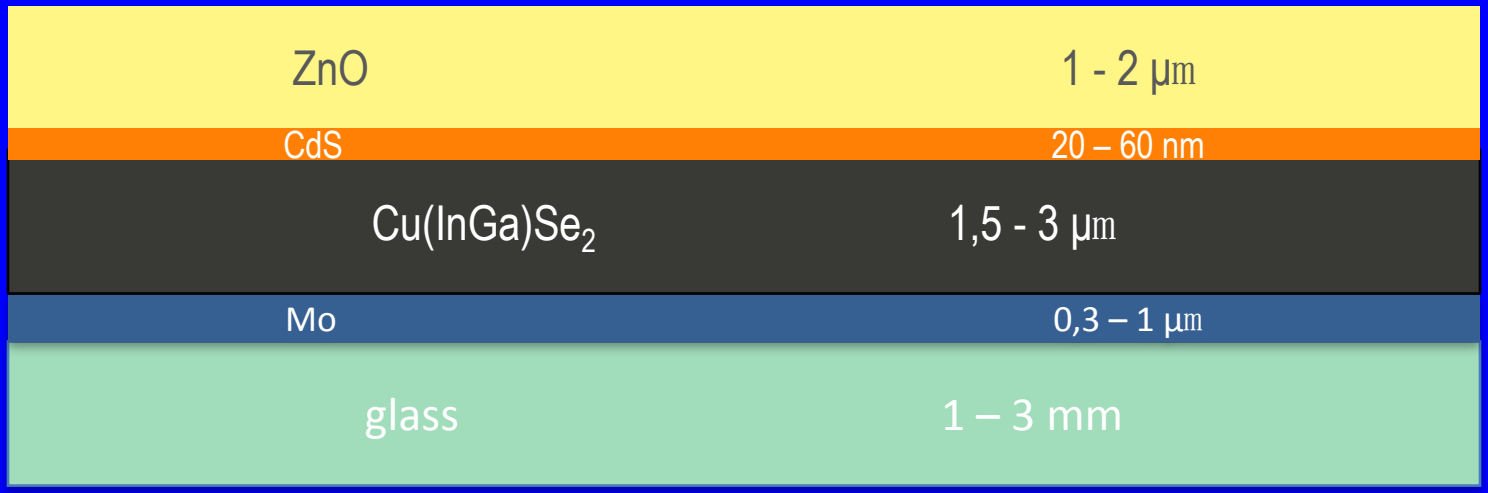
IN-LINE IMPLEMENTATION OF A Cu-RICH + Cu-POOR PROCESS



DEVICE STRUCTURE OF TODAY

FURTHER EARLY CI(G)S SOLAR CELL MILESTONES

Devicestructure with ZnOwindow

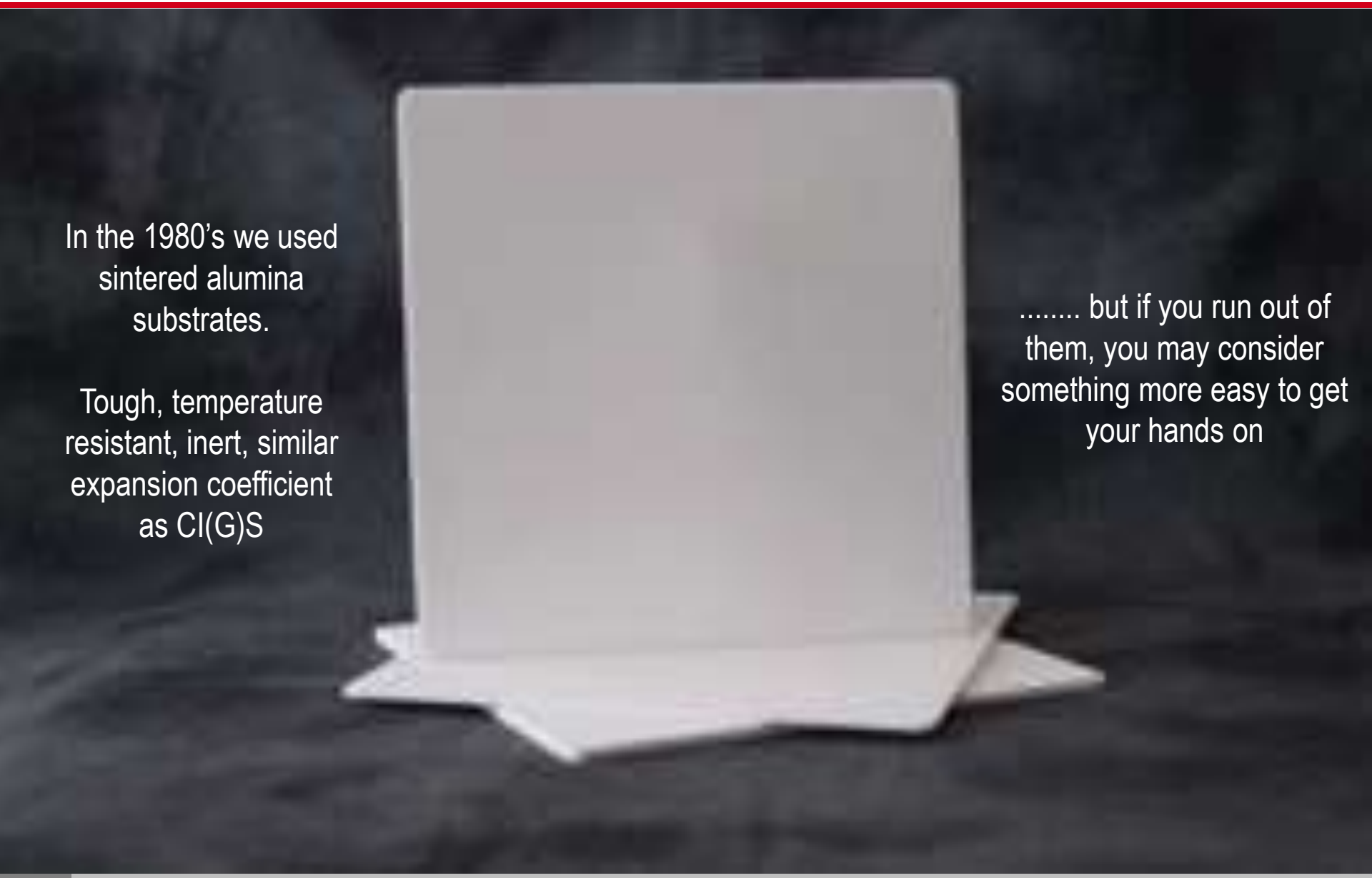


R. Potter et al, Proc. 18th IEEE PVSC (1985) 1659

14,1 % efficiency with soda-lime glass substrates

K. Mitchell et al, Proc. 20th IEEE PVSC (1988) 1384

CHOICE OF SUBSTRATES FOR CIGS



In the 1980's we used sintered alumina substrates.

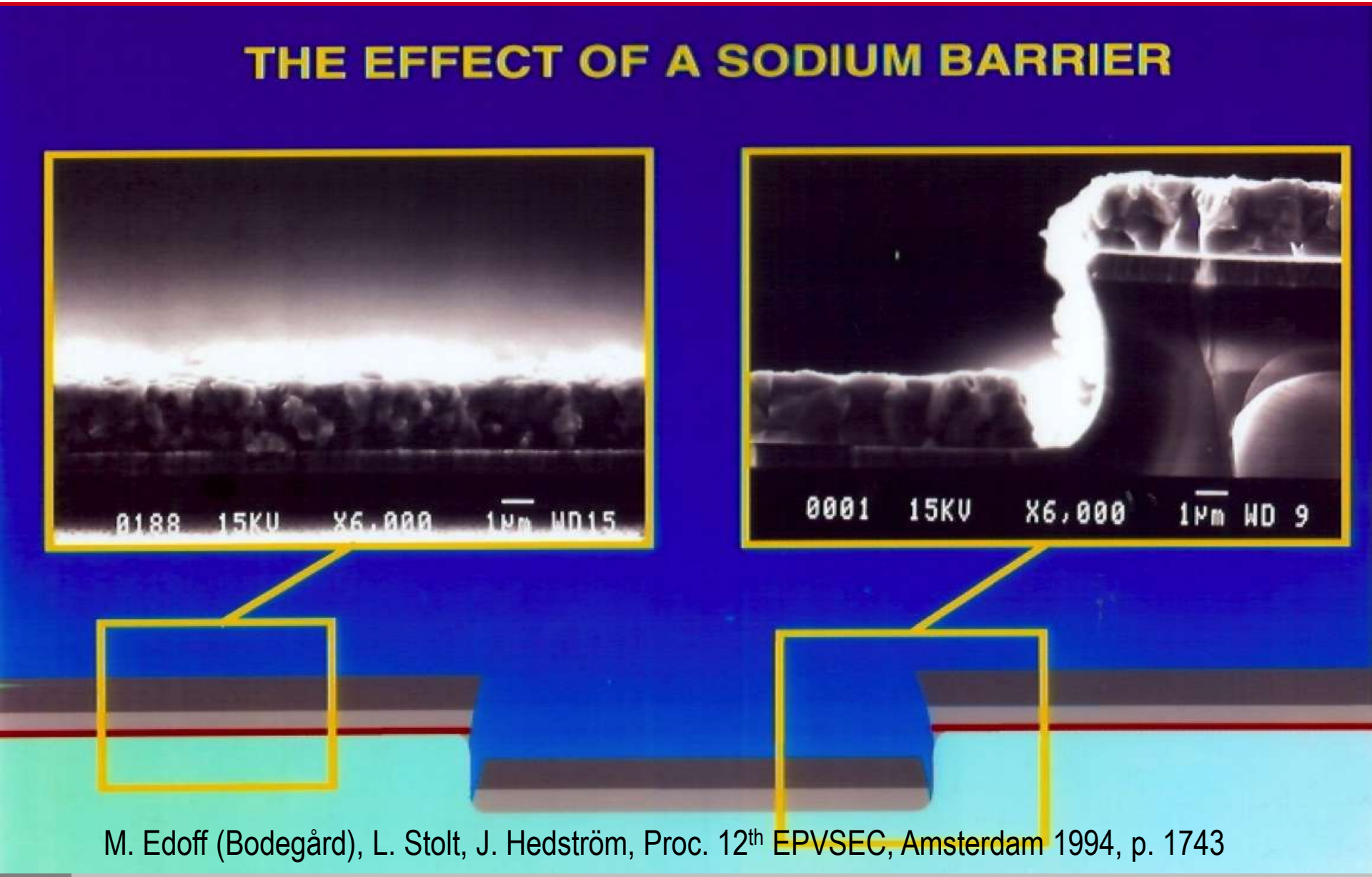
Tough, temperature resistant, inert, similar expansion coefficient as CI(G)S

..... but if you run out of them, you may consider something more easy to get your hands on

SODA-LIME GLASS

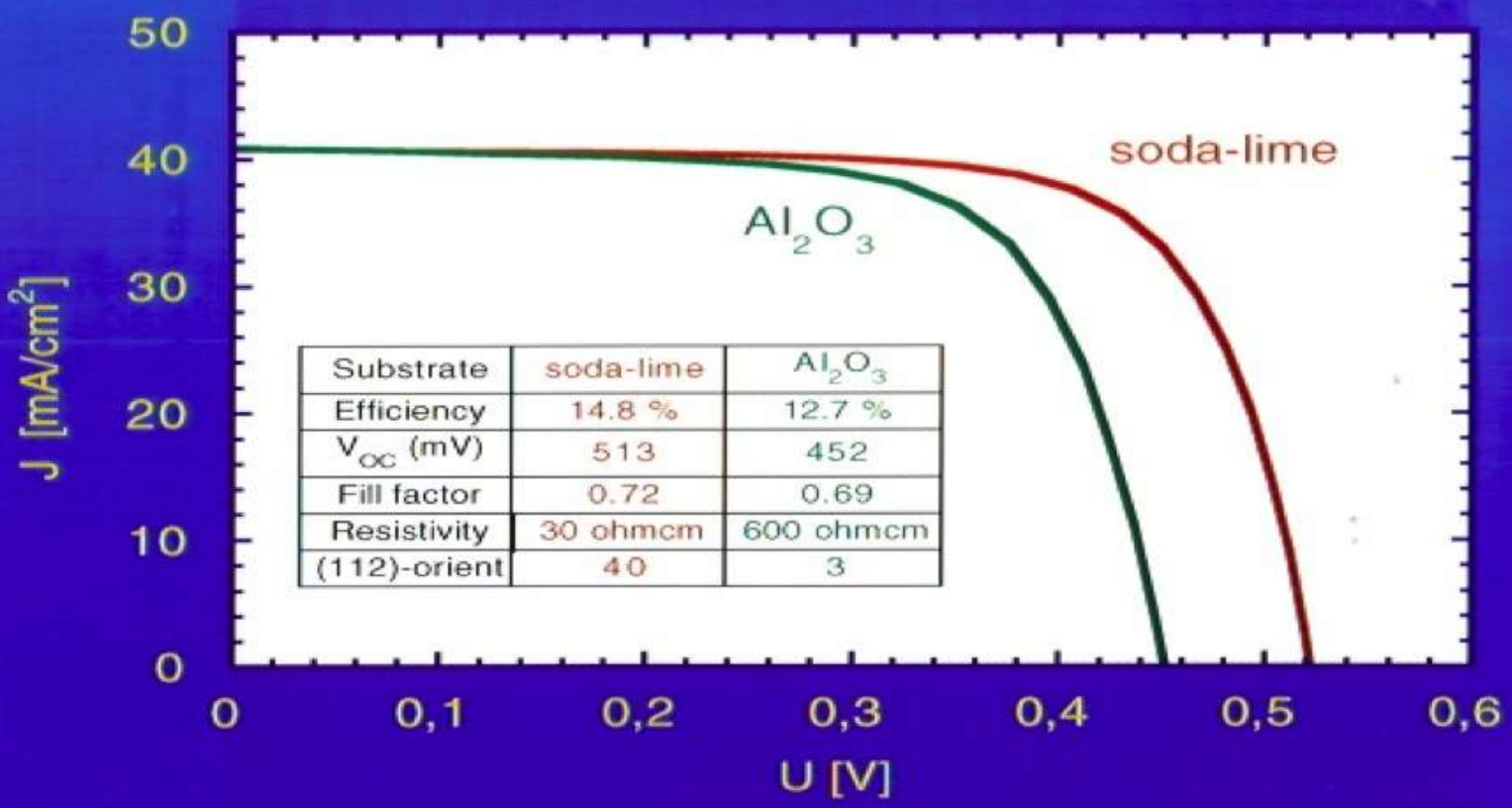


NA IMPROVES THE MICROSTRUCTURE



M. Edoff (Bodegård), L. Stolt, J. Hedström, Proc. 12th EPVSEC, Amsterdam 1994, p. 1743

SODIUM IMPROVES PV PERFORMANCE



Substrate	soda-lime	Al_2O_3
Efficiency	14.8 %	12.7 %
V_{oc} (mV)	513	452
Fill factor	0.72	0.69
Resistivity	30 ohmcm	600 ohmcm
(112)-orient	40	3

L.Stolt, M. Edoff (Bodegård), J. Hedström, J. Kessler, M. Ruckh, K.-O. Velthaus, H.-W. Schock, Proc. 11th EPVSEC, Montreaux, 1992. p.878

THIN FILM PV EFFICIENCY BREAKTHROUGH

Excerpt from US DOE 5 year plan for PV: Target for cost-efficient PV electricity

Table 1. Federal/Industry Long-Term (Year 2000) Technical Goals
(1986 dollars). Based on a levelized electricity cost-target of 6¢/kWh.

	Flat-Plate Systems	Concentrator Systems
Module Efficiency at 25° C	15%-20%	25%-30%
Module Cost	$45-$80/m^2	$60-$100/m^2
Balance-of-System Costs		
— area-related	$50-$100/m^2*	$125/m^2
— power-related	$150/kW	$150/kW
System Life Expectancy	30 yrs	30 yrs

*Balance-of-system costs vary depending upon the type of flat-plate system (fixed, one-axis, or two-axis tracking).

16.9 % cell efficiency reported at IEEE PVSC 1993 – 1st time > 15 %

J. Hedström, H. Ohlsén, M. Edoff (Bodegård), A. Kylner, L. Stolt, D. Hariskos, M. Ruckh, H-W. Schock,
ZnO/CdS/Cu(In,Ga)Se_2 thin film solar cells with improved performance,
Proc. 23rd IEEE PVSC,Louisville 1993, p. 364

SCALE-UP OF THE CO-EVAPORATION PROCESS

Uniformity in the transport direction

•In-line process inherently uniform acrosssubstrate in the transport direction. Process profileverified in stationarylab-scaleco-evaporator

Uniformityperpendicular to the transport direction

- Needs to be solved by evaporation source design and/or evaporation geometry
- Line sources
- Distributedpointsources

Materials yield

- Depends on the solid angleseen from the sources
- Short evaporation distance – drawback: short deposition zone

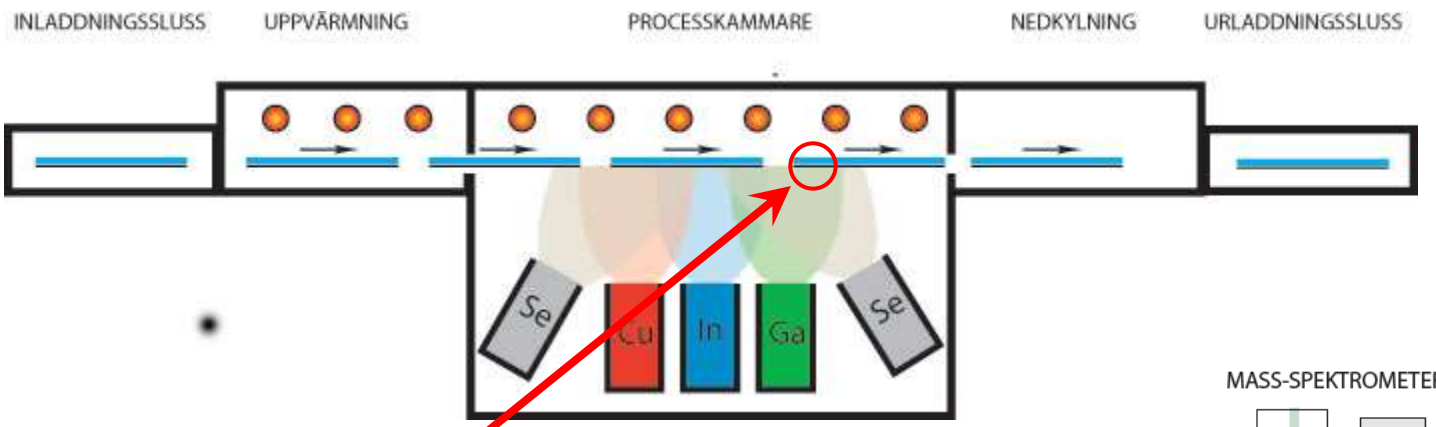
Throughput

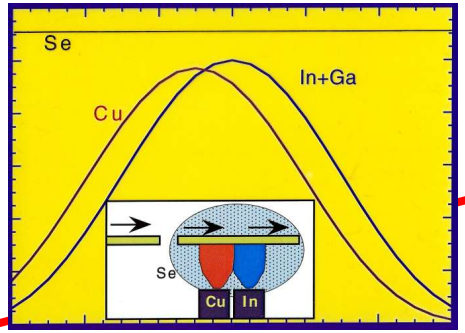
- Long deposition zone to get enoughgrowth time

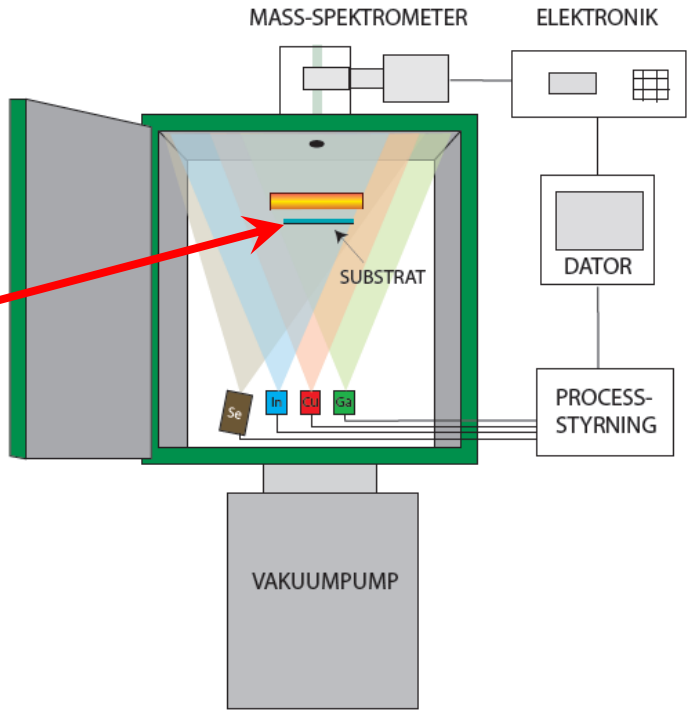
Process stability

- Feedback control

VERIFICATION OF PROCESS PROFILE







SAME SITUATION FOR THE GROWING FILM IN THE LAB TOOL AS IN THE IN-LINE PRODUCTION PROCESS

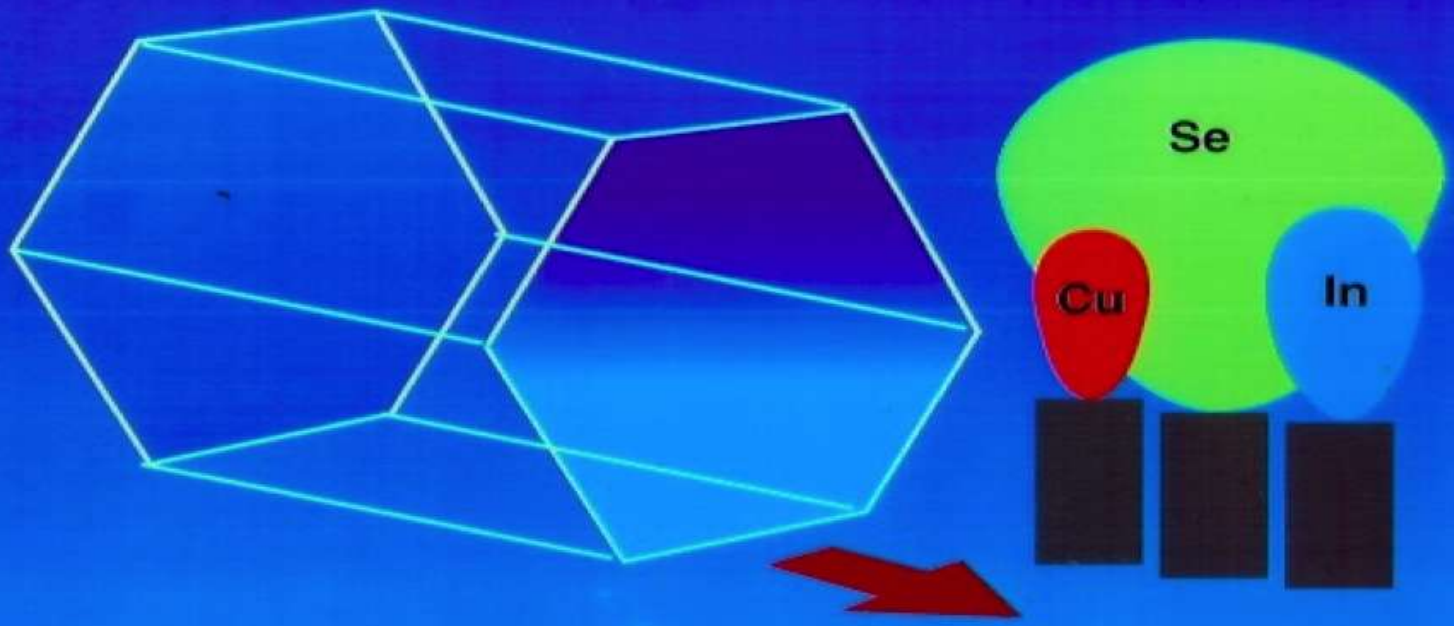
CIGS SCALE-UP KEY TO COMMERCIALIZATION

SOLIBRO A COMPANY OF Hanergy

Large area coevaporation

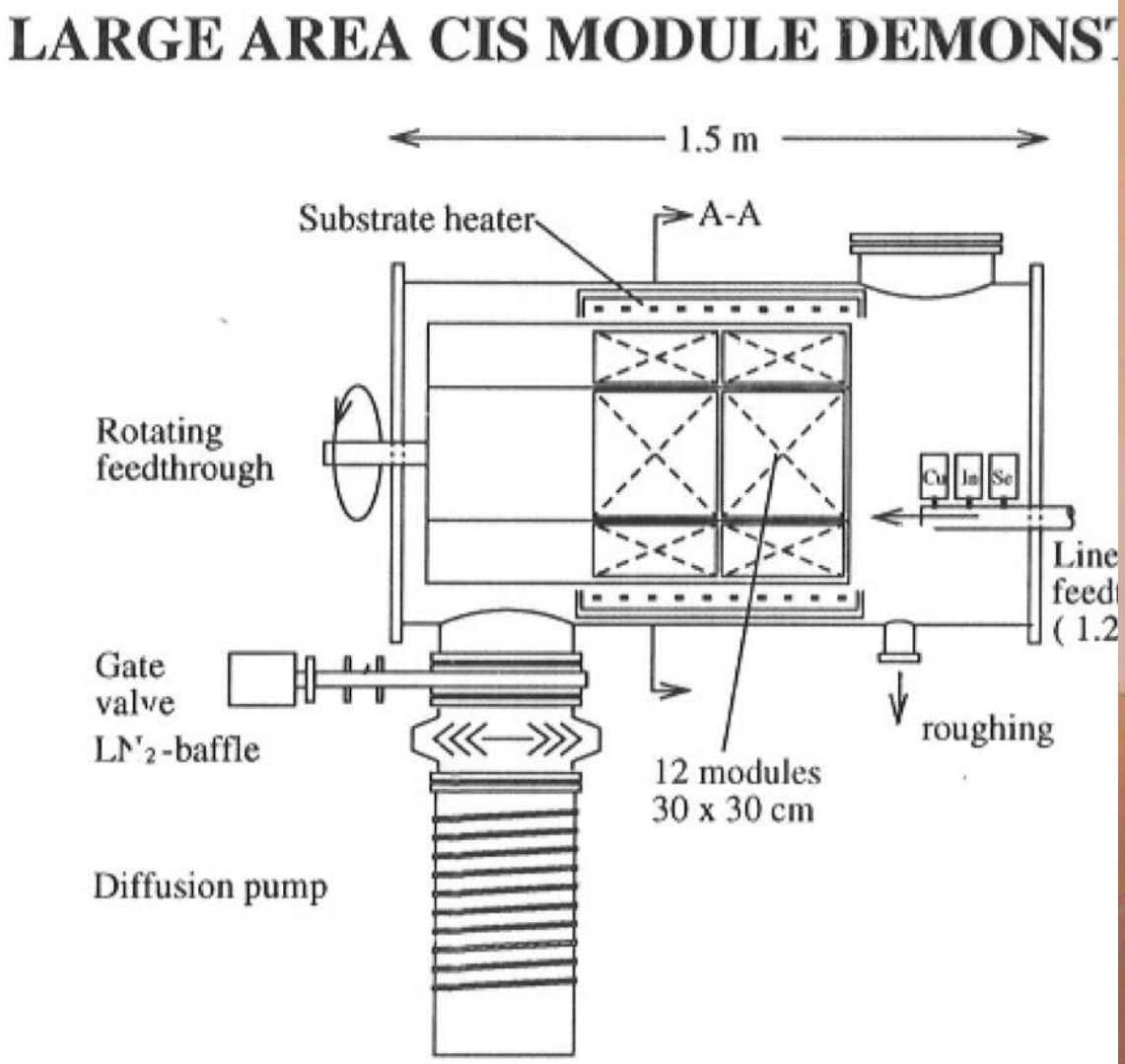
With simple point sources

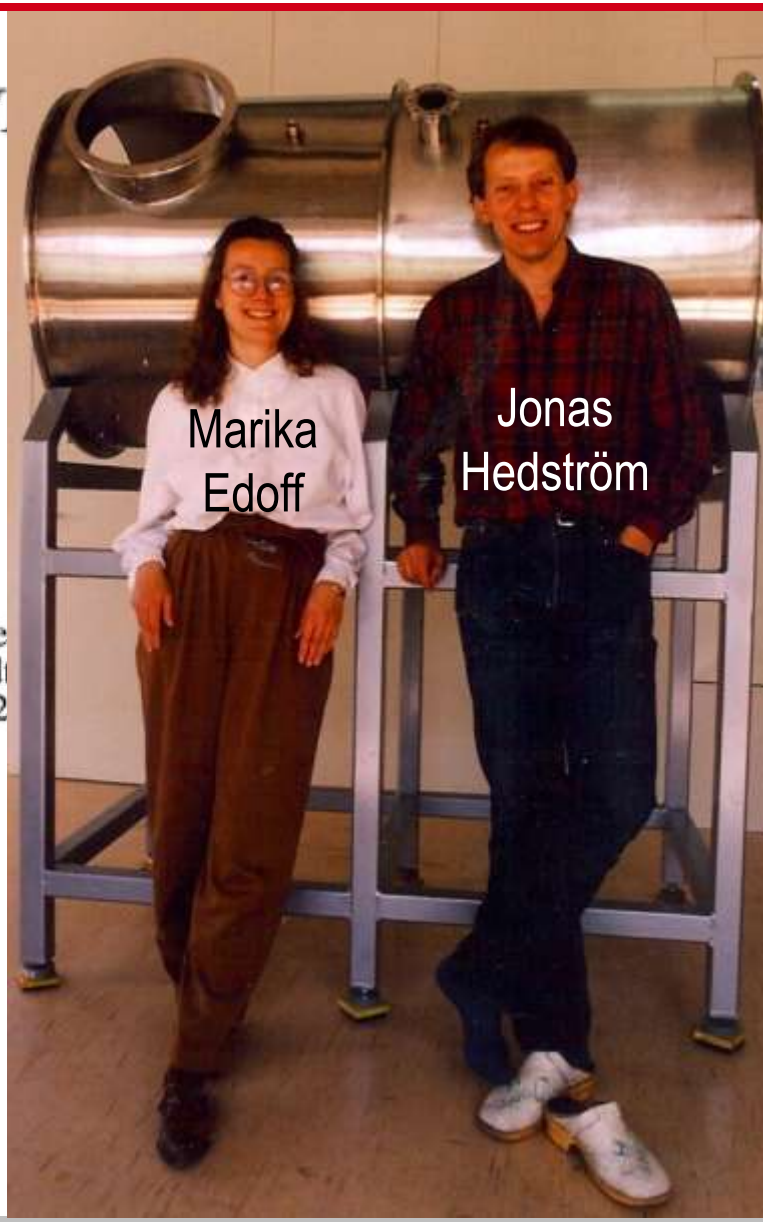
- High uniformity
- High materials utilization



Patented in SWE, DEU, GBR, FRA, ITA, ESP, NLD, USA, JPN (WO 9220103)

REALIZATION OF "THE SPINNING TOP" (SNURRAN)

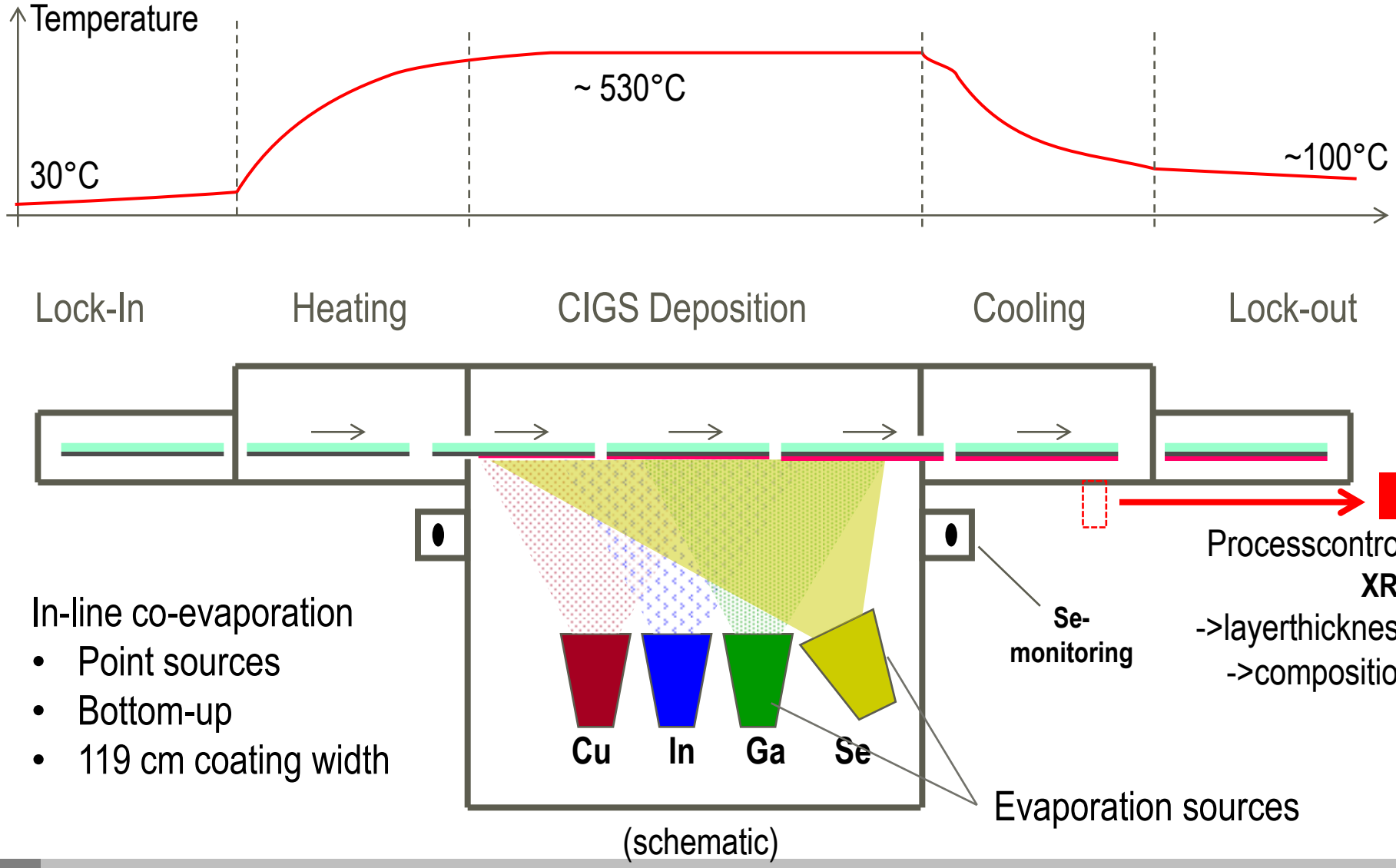




SOLIBRO AB GOT STARTED IN 2003



CIGS COEVAPORATION

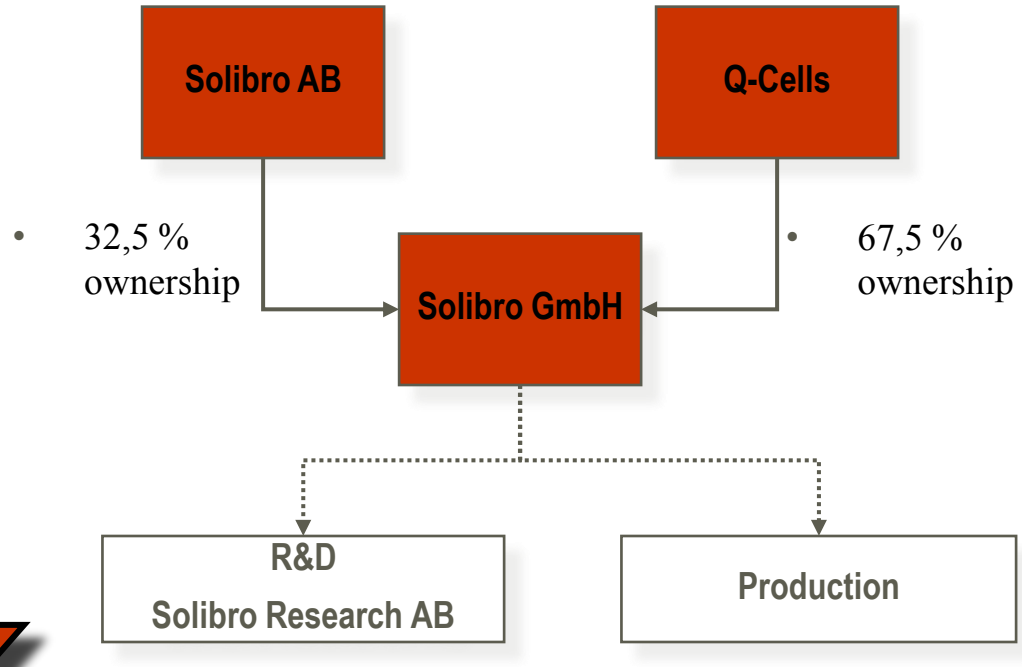


In-line co-evaporation

- Point sources
- Bottom-up
- 119 cm coating width

New Company Structure

- Solibro och Q-form a Joint Venture – ”Solibro GmbH”
- Q-Cells providescapital and industrialexperience> 100 M€
- Solibro AB providestechnology and R&D



Agreementsigned 2006-11-23

SOLIBRO AS AN INDUSTRIAL COMPANY



2007

A new R&D Center in Uppsala



April 2008

Production start in Germany



December 2009

Production start Fab 2



April 2012

Solibro's owner Q-Cells insolvent



September 2012

Hanergy purchases Solibro



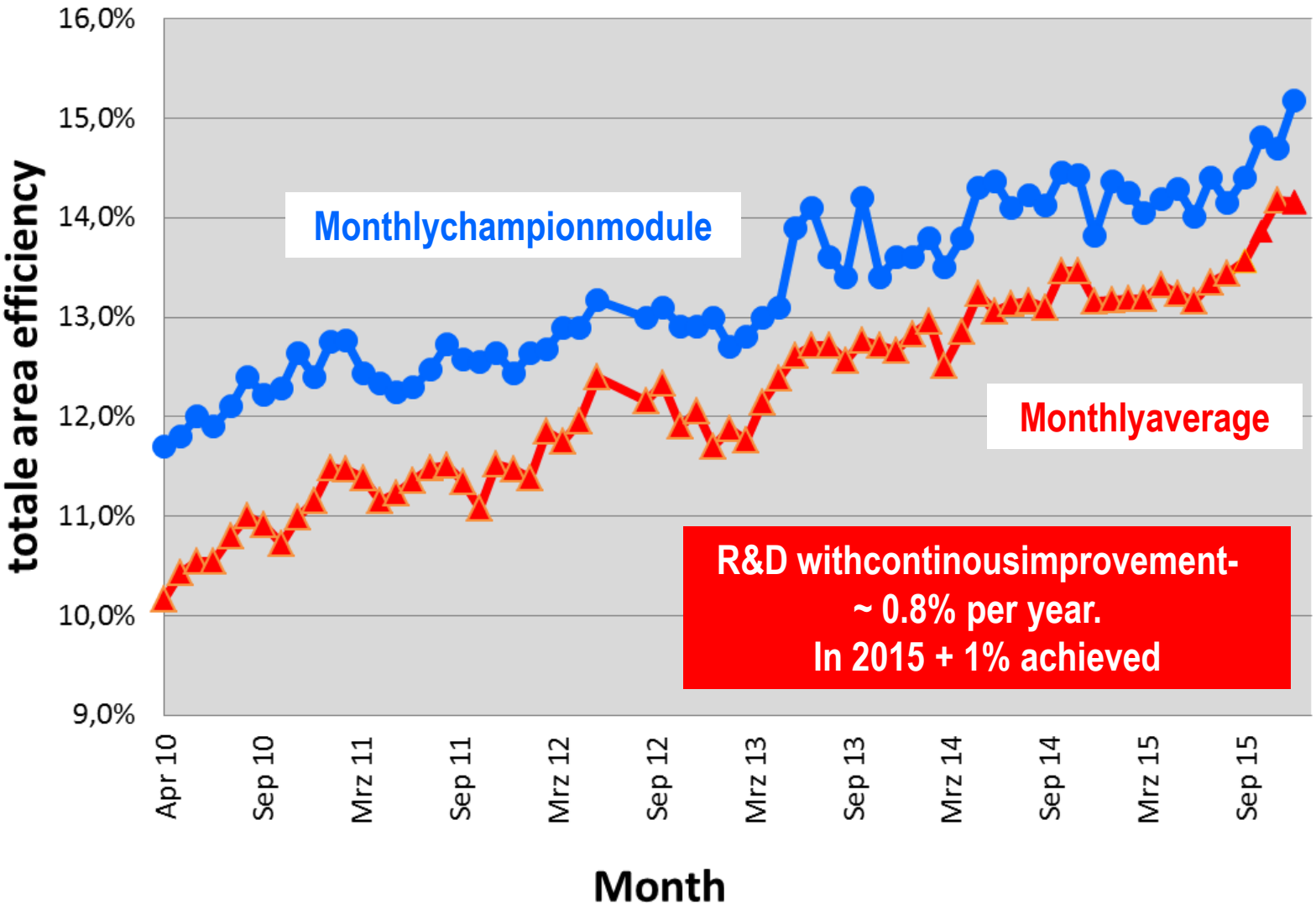
Q3 2013

PV systems at IKEA stores in UK

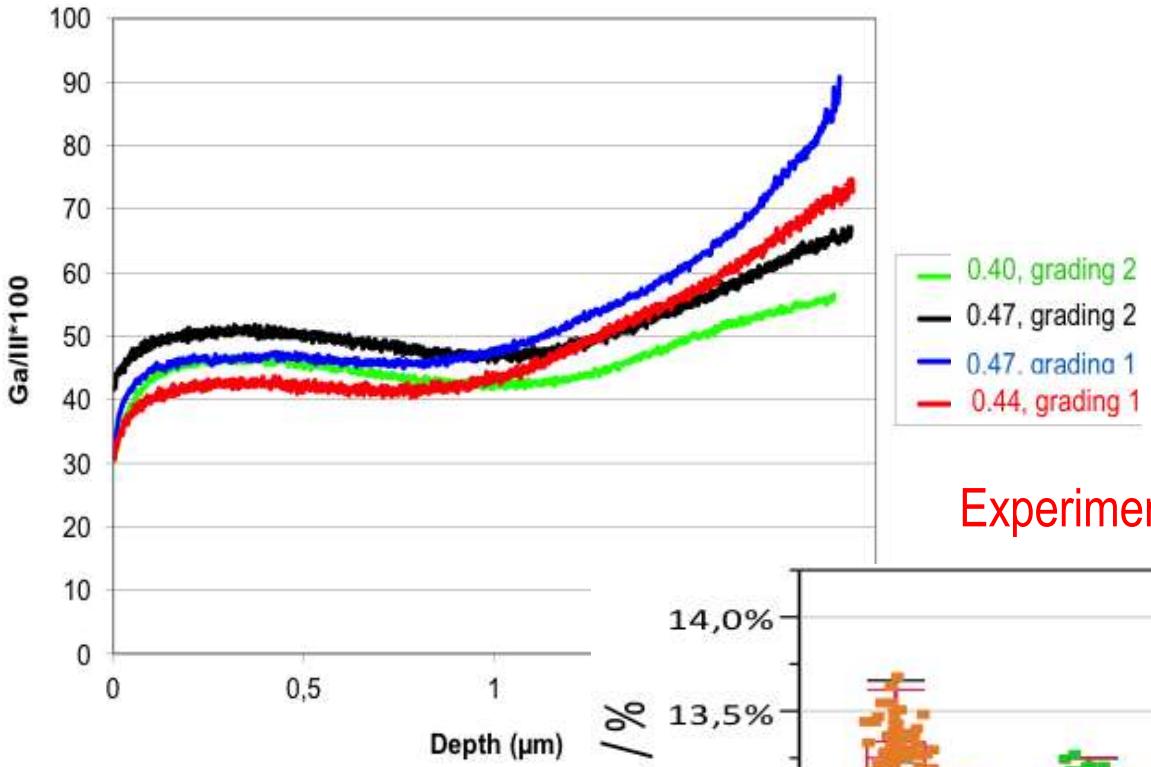
SOLIBRO PRODUCTION



PRODUCTION EFFICIENCY AT SOLIBRO

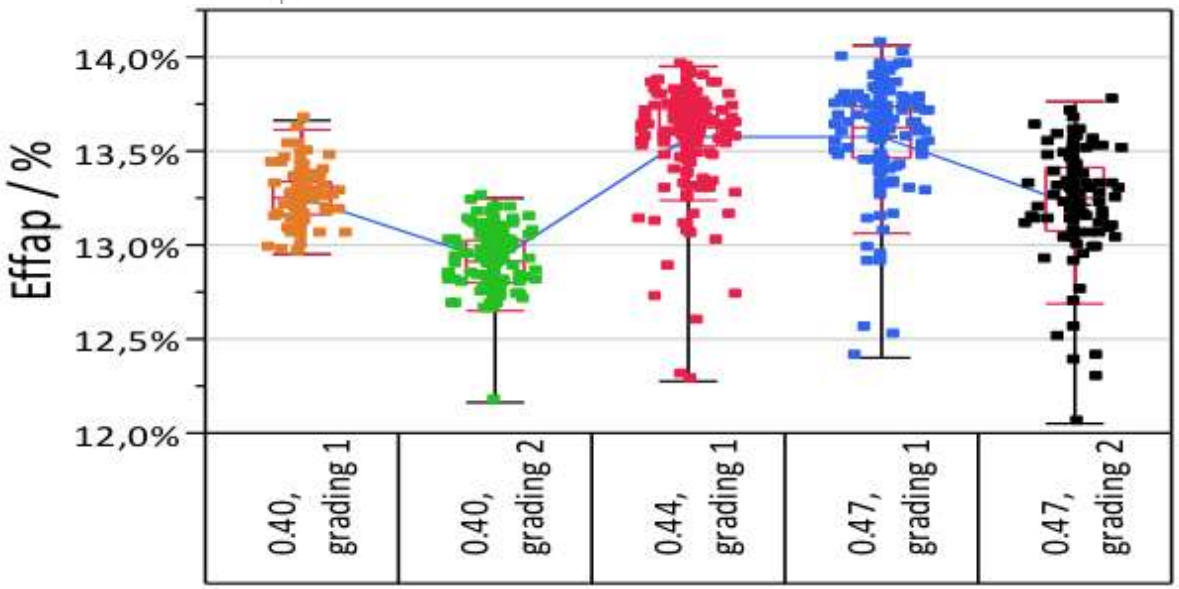


Ga-GRADING FOR IMPROVED EFFICIENCY

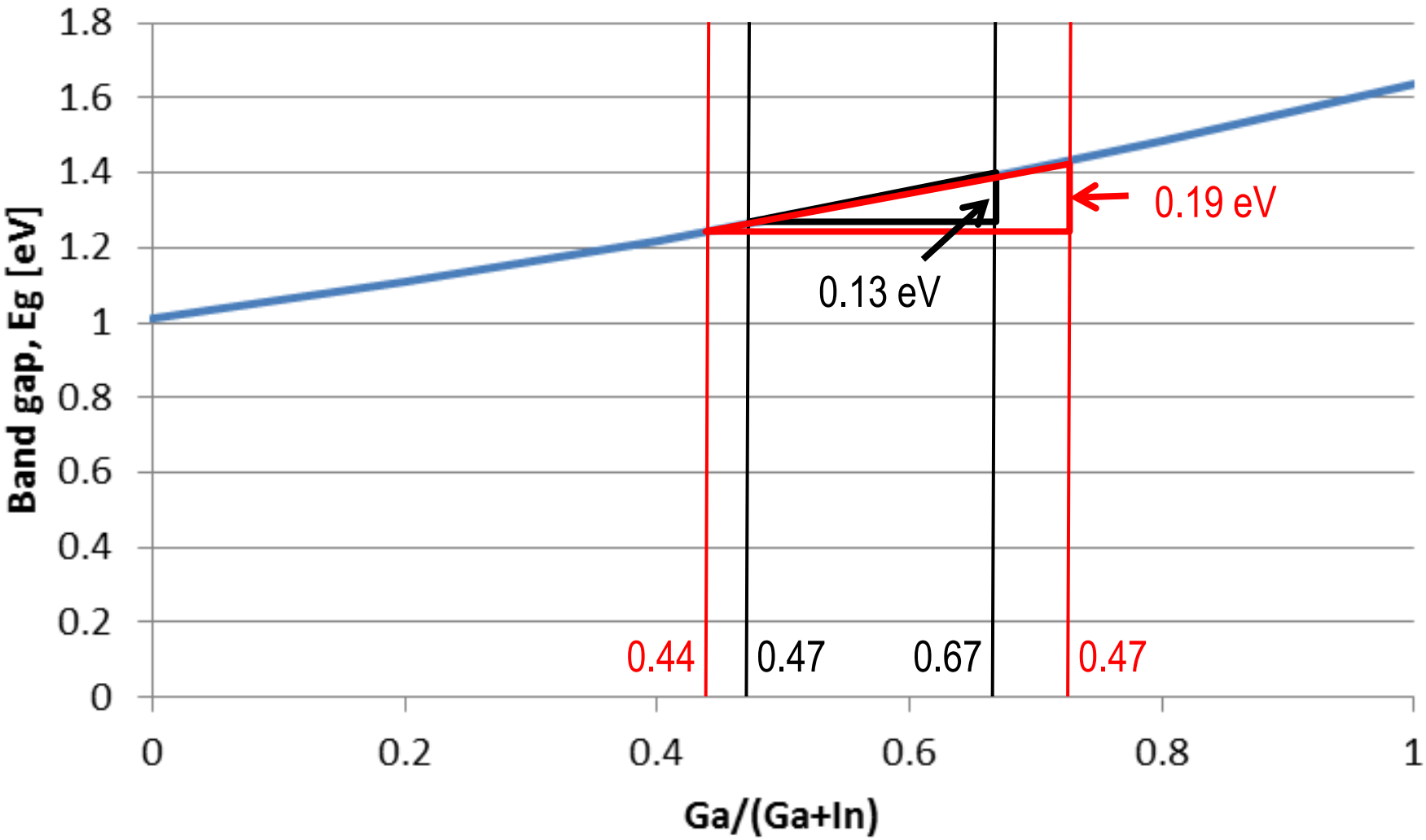


Stronger Ga-grading at the back contact shows potential efficiency gain of 0.5% abs

Experiment in production gives statistics!



OPTIMAL Ga-GRADING



The Ga-grading potential barrier (bandgap widening) should be morethan 0.13 eV, preferablyaround 0.2 eV

THROUGHPUT IS CRITICAL FOR CAPEX

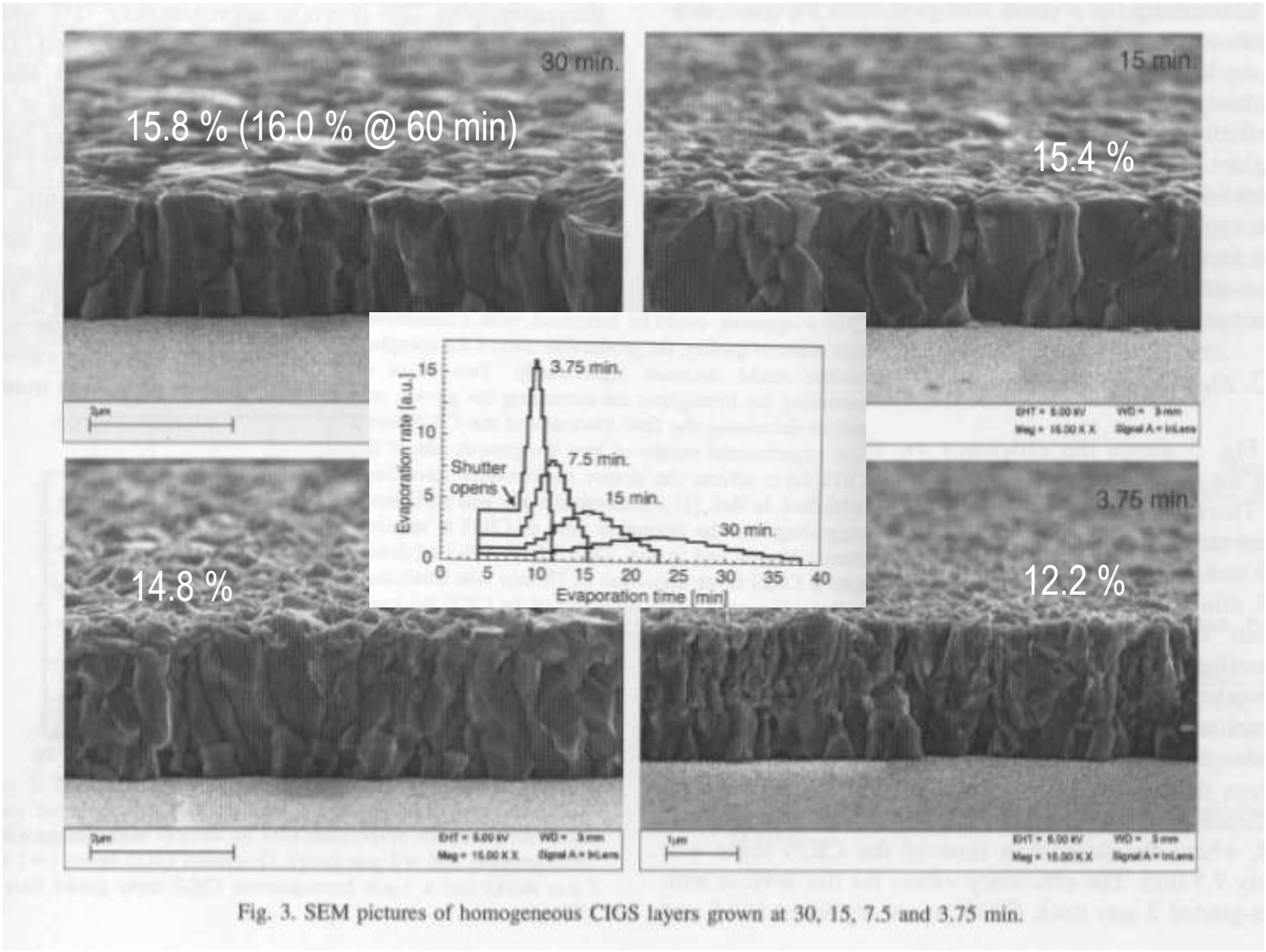
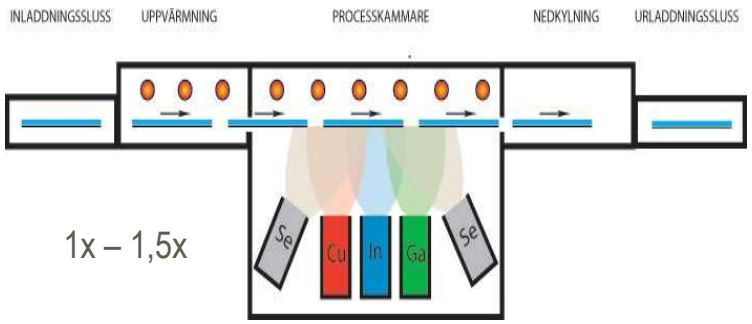


Fig. 3. SEM pictures of homogeneous CIGS layers grown at 30, 15, 7.5 and 3.75 min.

A CIGS growth time of 7.5 -15 min is feasible for high efficiency

INCREASING AND VERIFYING THROUGHPUT

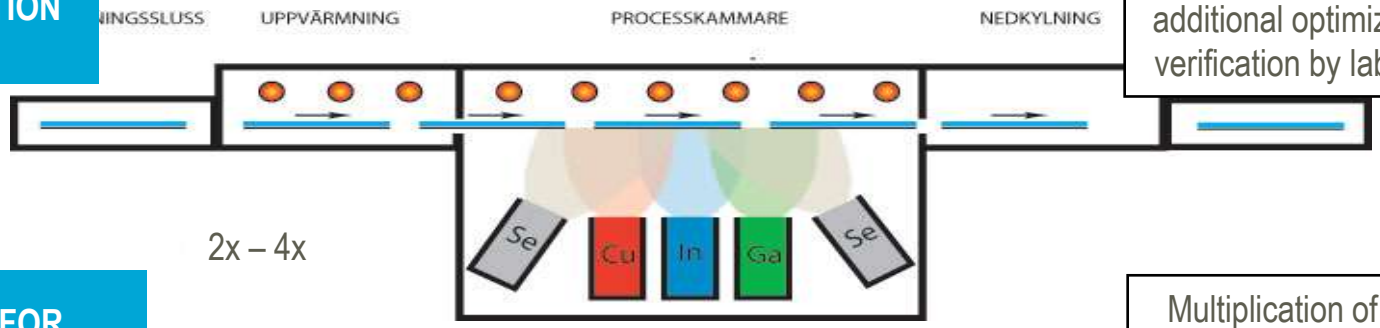
PILOT TOOL IN UPPSALA



1x – 1,5x

Devlopment of basic tool concept – verification by labtool simulation

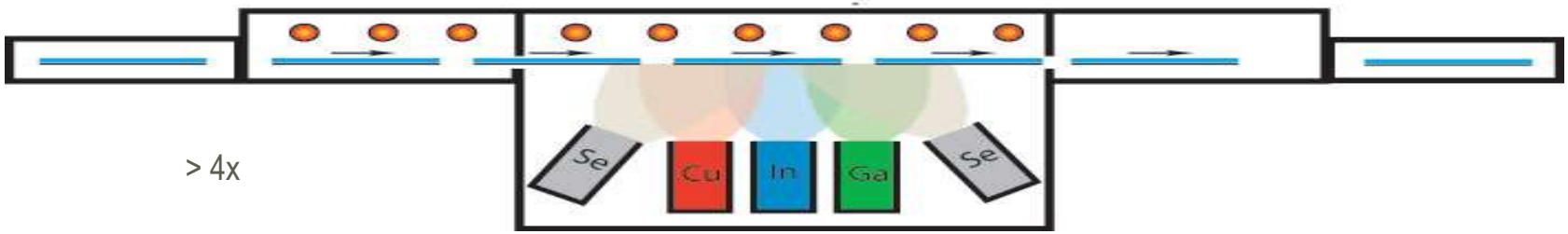
CURRENT PRODUCTION TOOL



2x – 4x

Multiplication of sources gives additional optimization options – verification by labtool simulation

TOOL FOR HIGHER EFFICIENCY

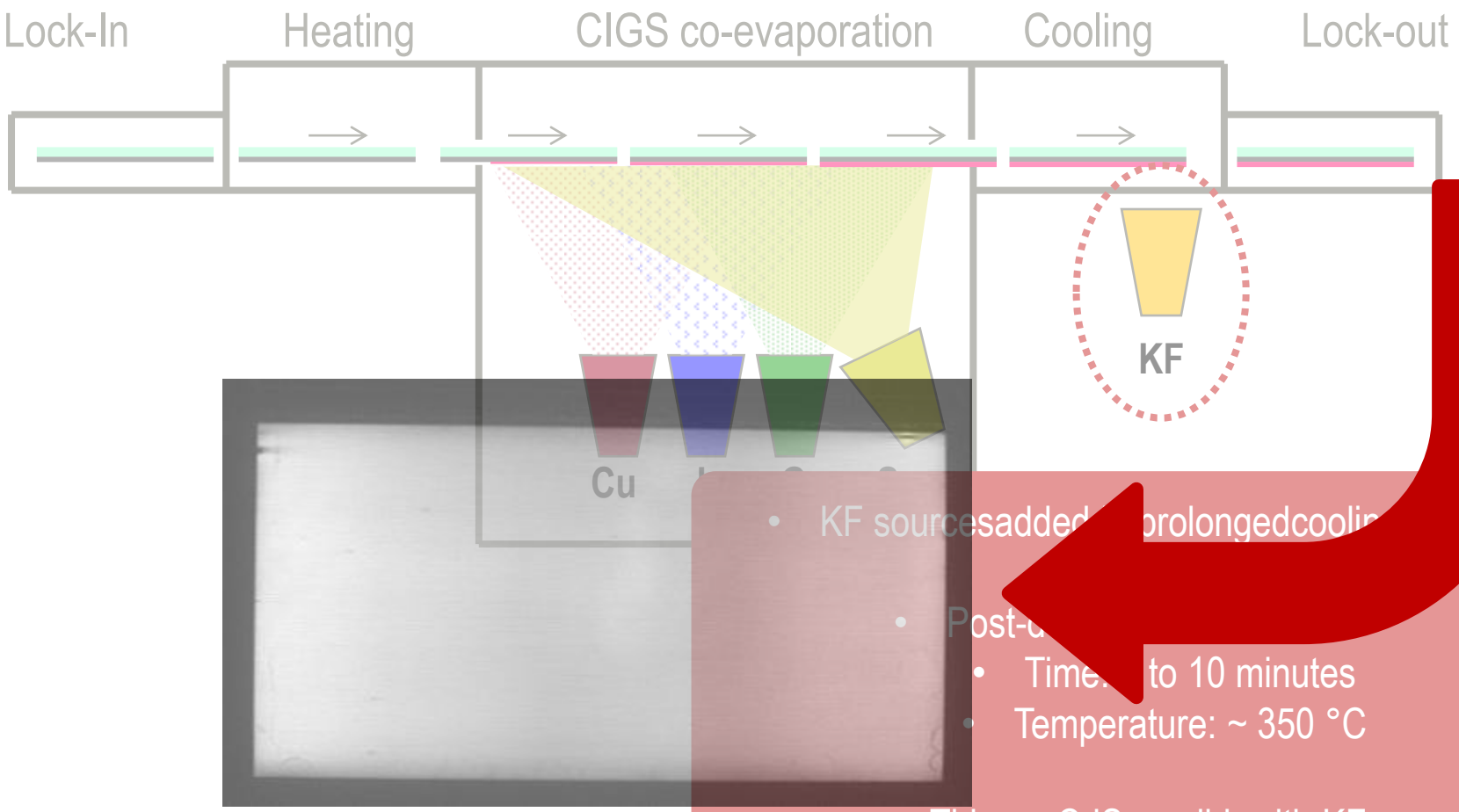


> 4x

Multiplication of sources gives additional optimization options – verification by labtool simulation

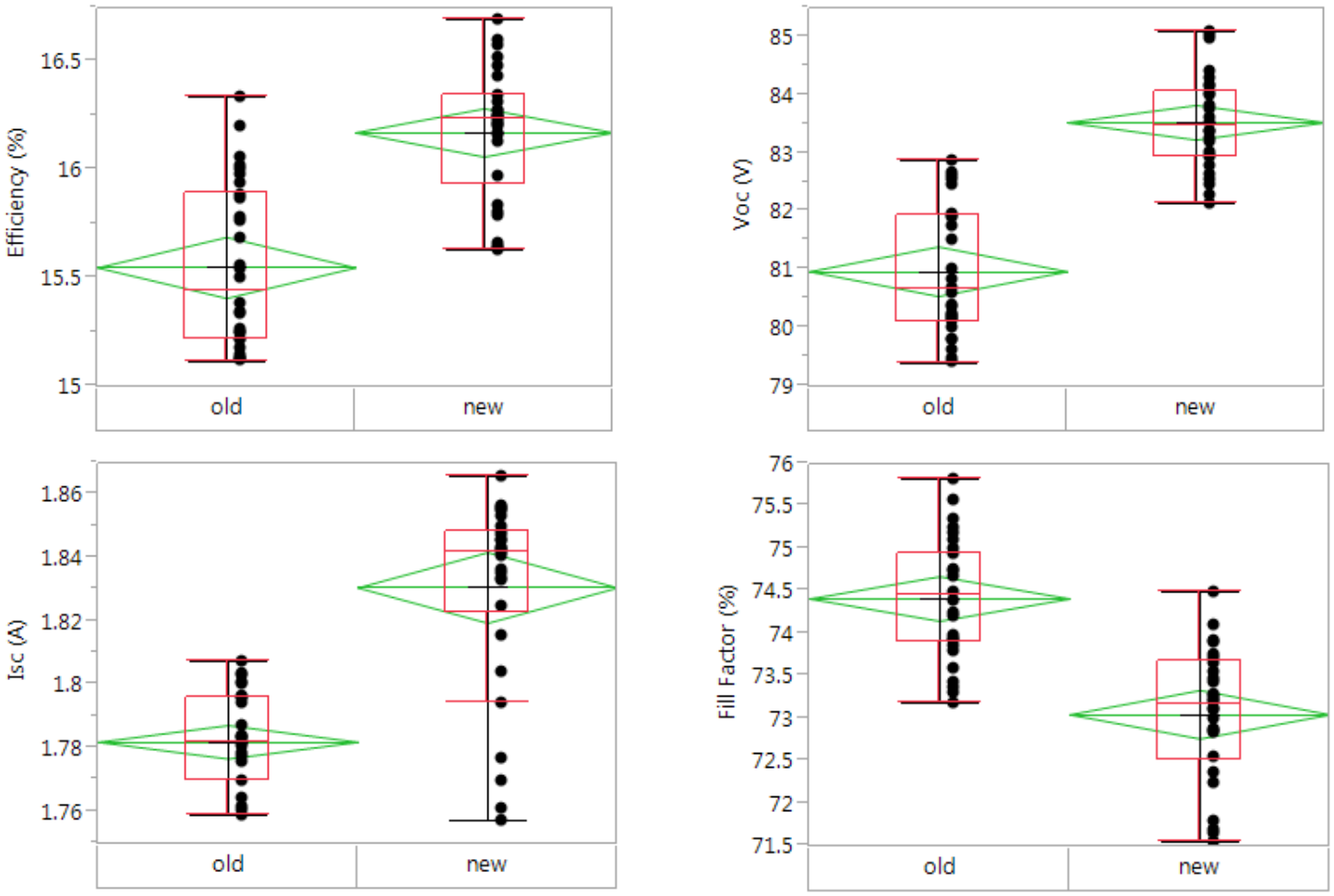
RECENT PROGRESS - KF UPSCALING

Full-size (119×63 cm^2) co-evaporation module pilot line, schematic:



Electroluminescence image

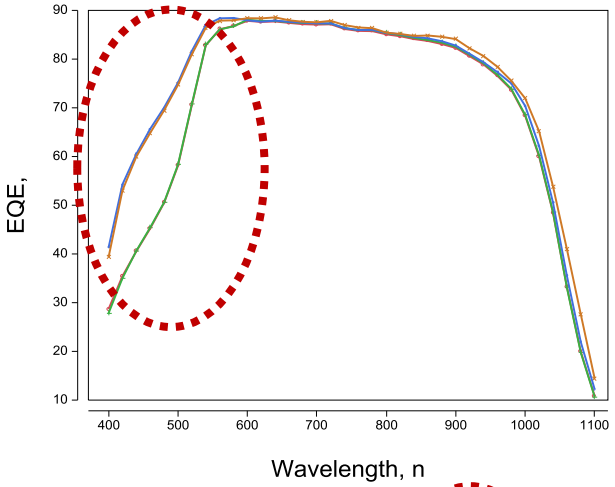
IV PARAMETERS FOR OLD AND NEW PROCESS

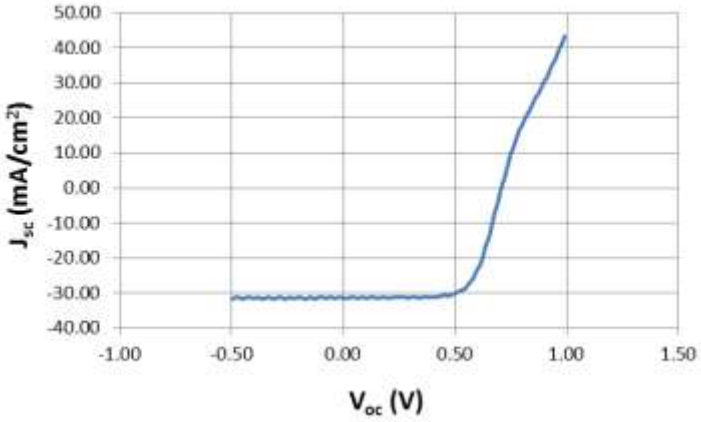


- Gain in efficiency of around 0.7 % absolute driven by increased, V_{oc} and I_{sc}
- Loss in FF for modules with KF post-deposition treatment (PDT)

AA efficiency, 30 best modulesofeachtypeduringautumn 2015

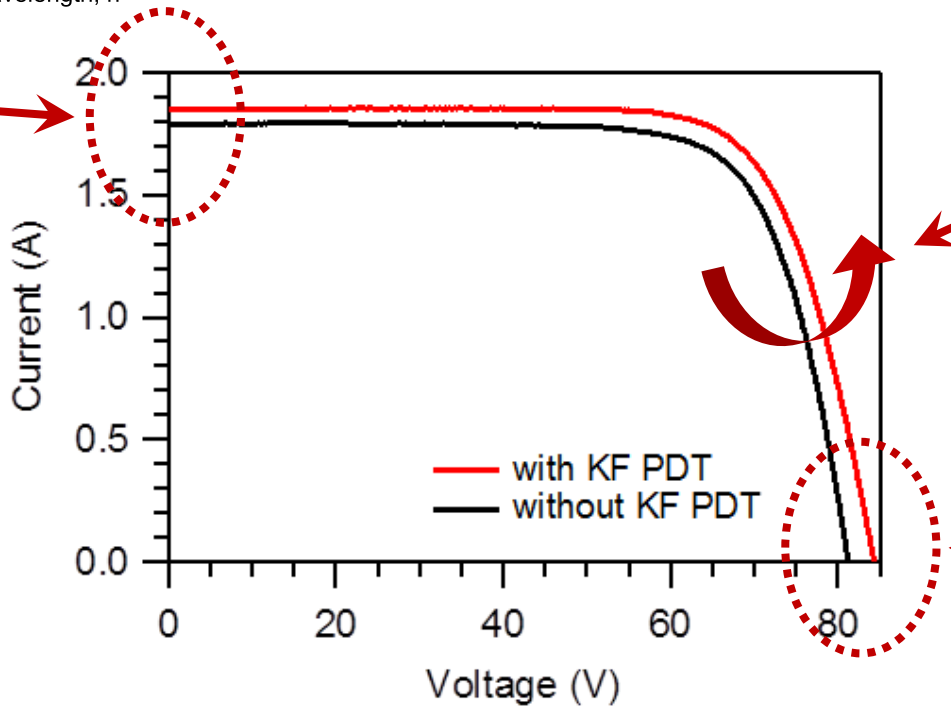
TYPICAL MODULE I-V CURVES





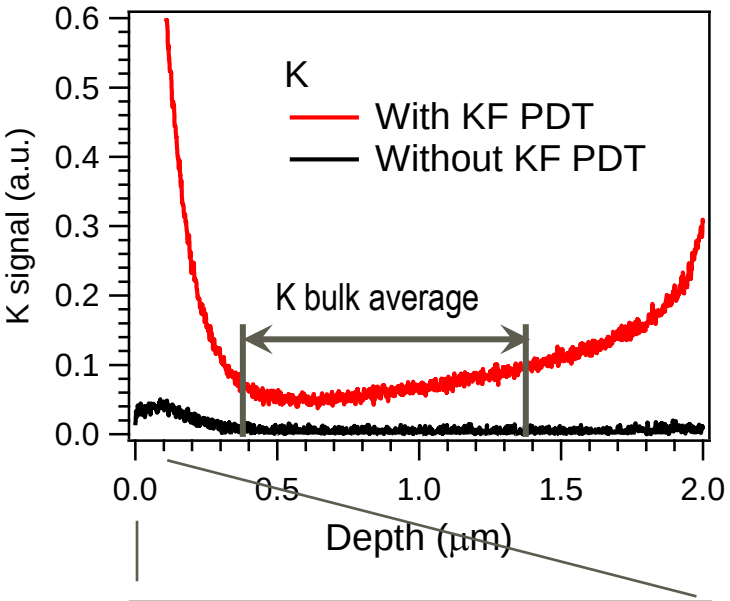
Thinner CdS→
I_{sc}increase

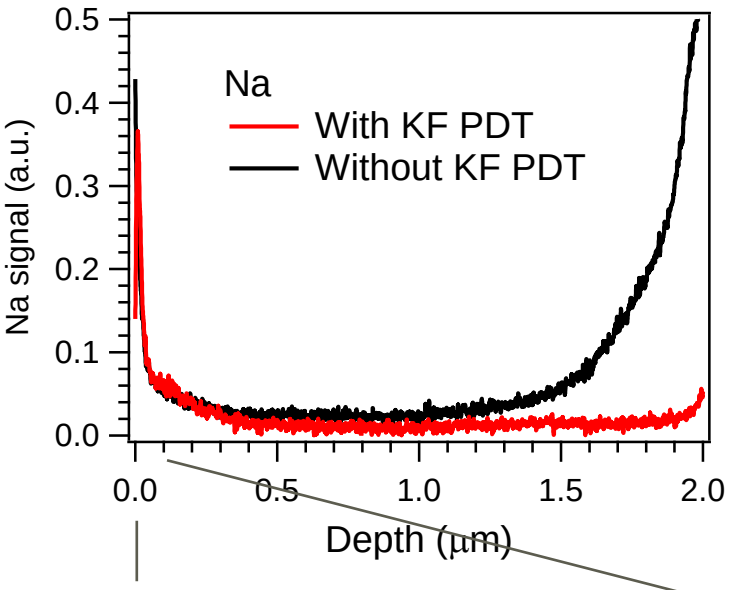
Blocking ("roll-over") tendency→ FF loss

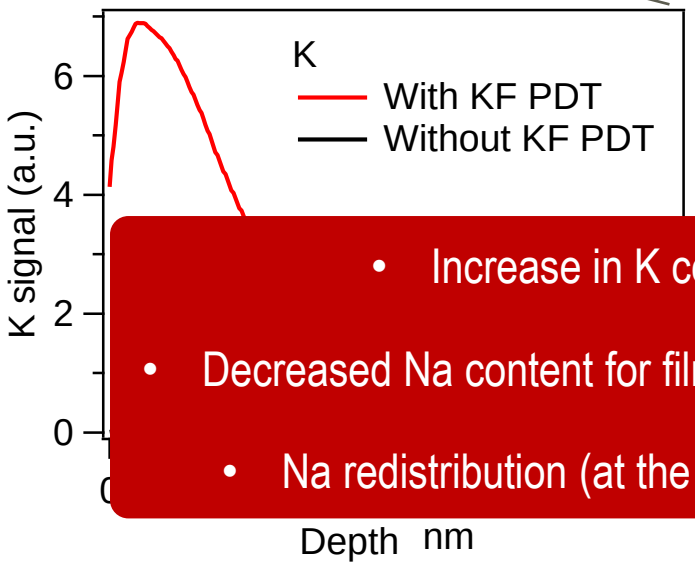


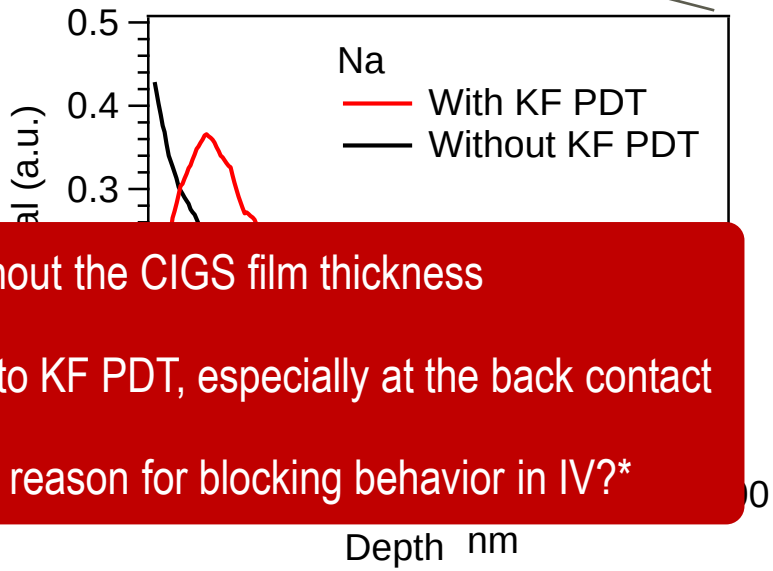
KF PDT →
V_{oc}increase

GDOES DEPTH PROFILES – Na AND K



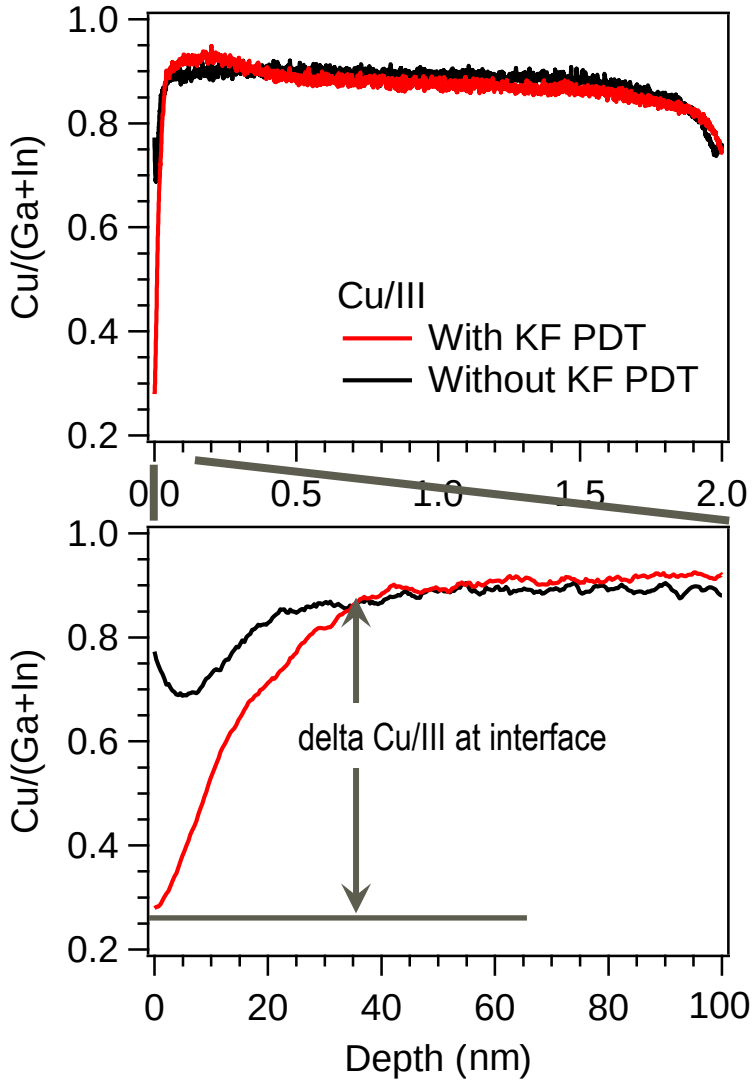


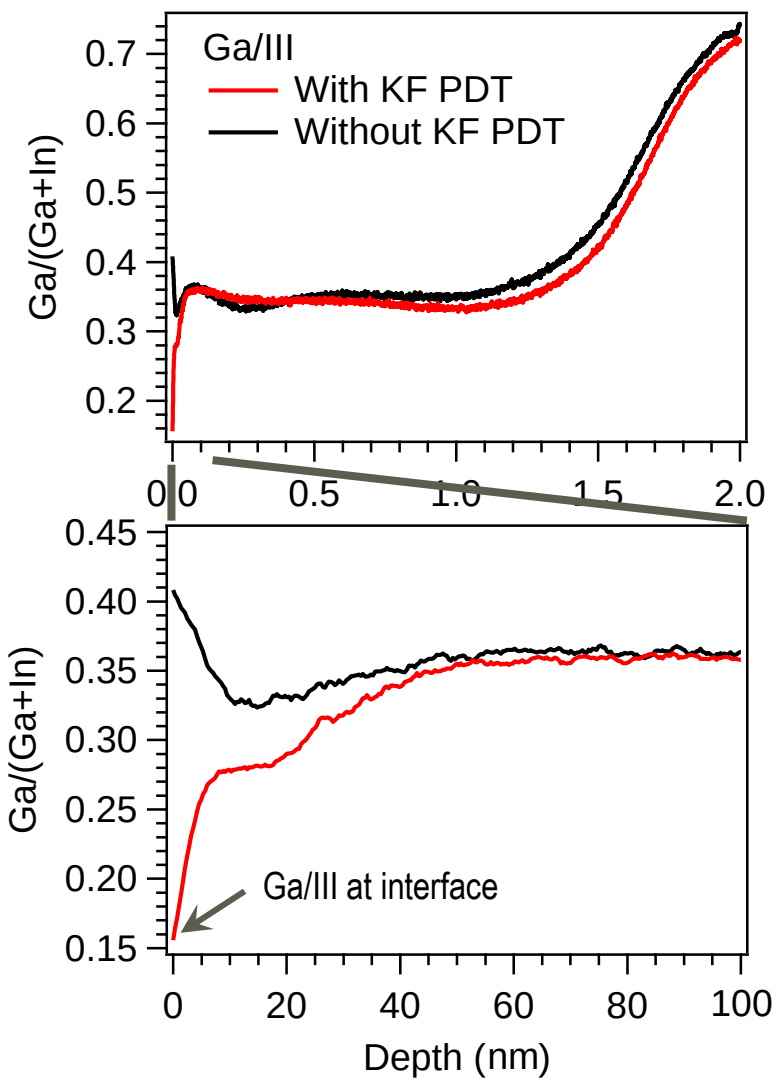




- Increase in K content throughout the CIGS film thickness
- Decreased Na content for films subjected to KF PDT, especially at the back contact
- Na redistribution (at the back contact) reason for blocking behavior in IV?*

GDOES DEPTH PROFILES – Cu/III AND Ga/III

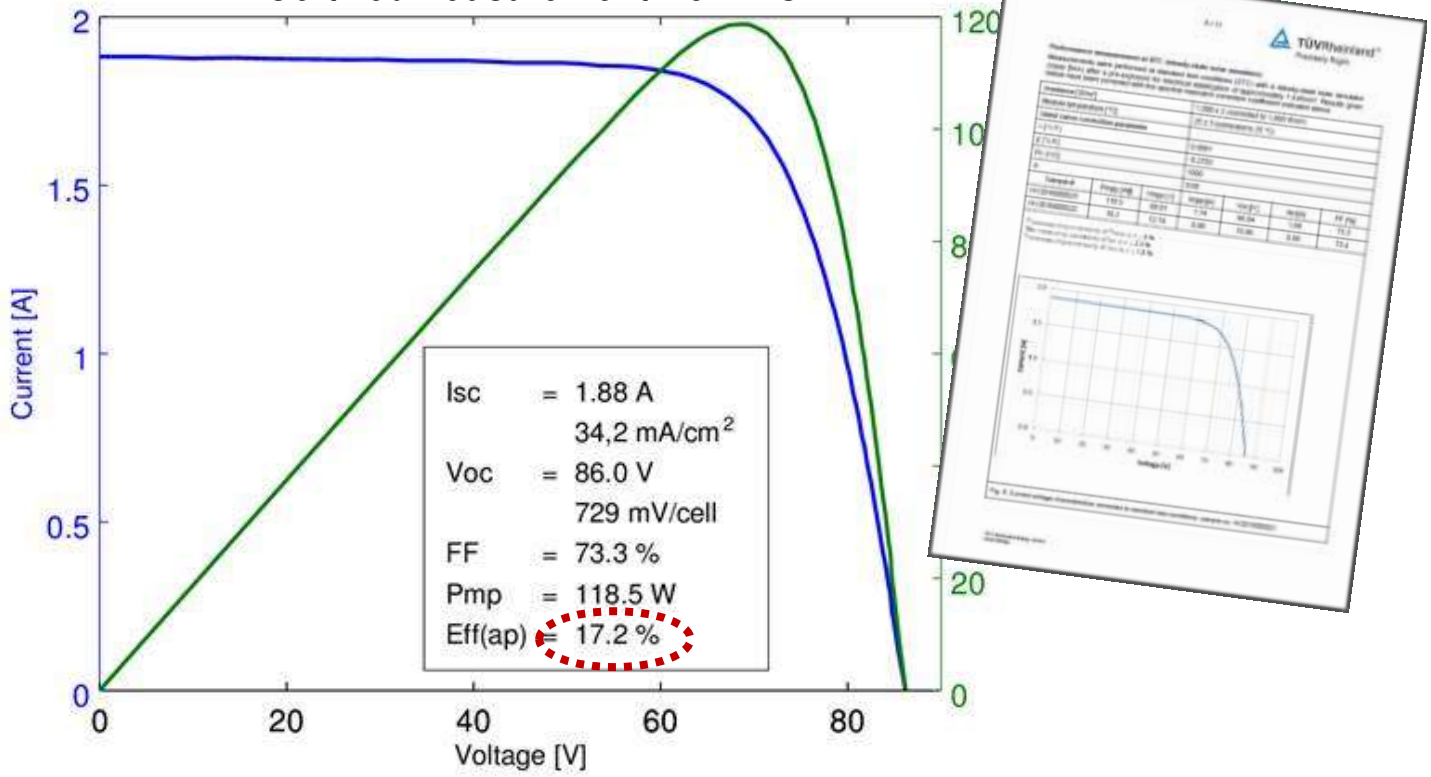




- Formation of K-In-Se rich surface layer upon KF PDT

CERTIFIED MEASUREMENTS: CHAMPION MODULES

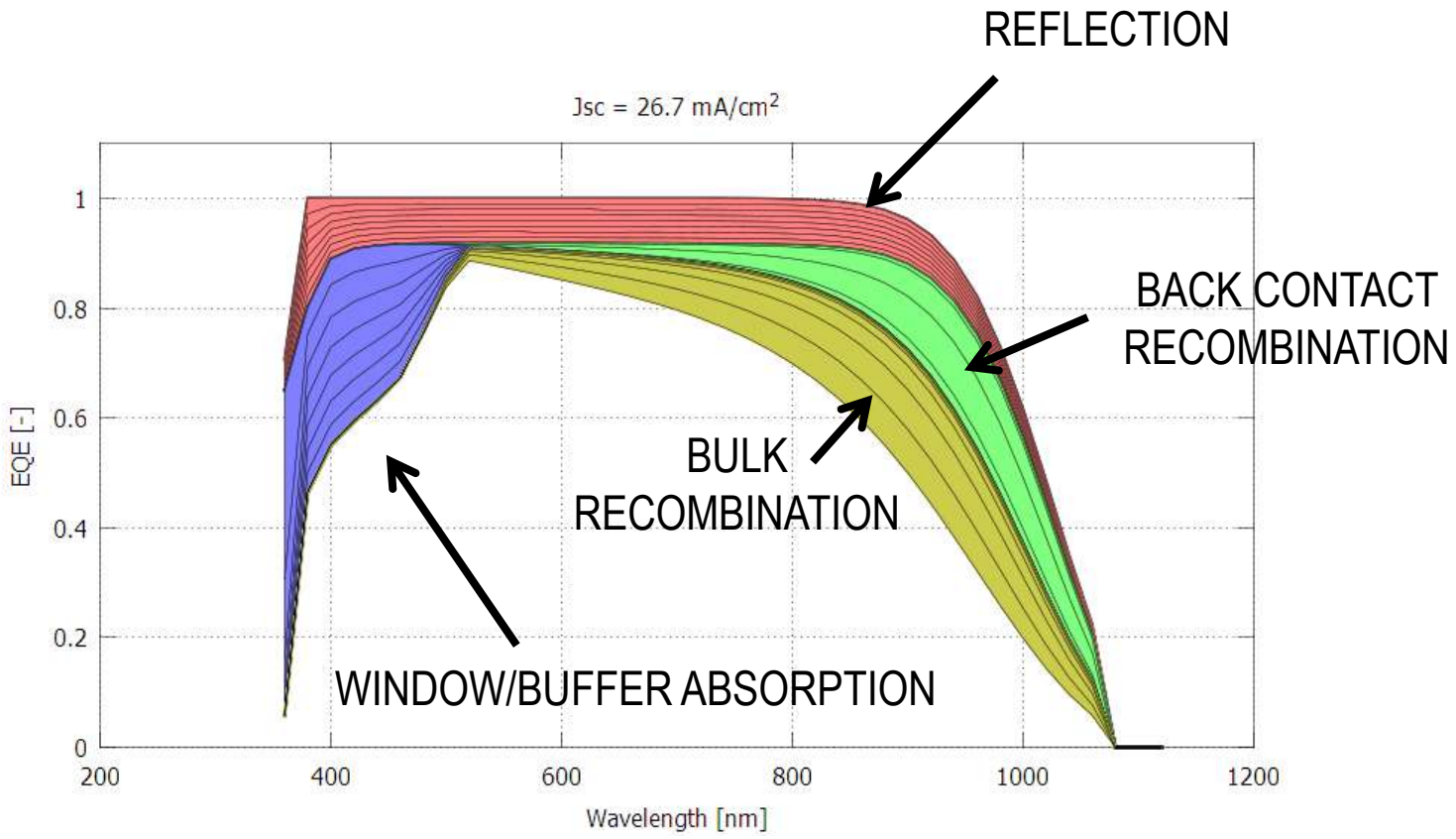
Certifiedmeasurement from TÜV



*Late news: 16.2 % **total area** efficiencyverified by TÛV for improvedSolibro technology on SL2 size (0.94 m²)*

OPPORTUNITIES AND CHALLENGES

EQE LOSSES



Simulation: Ulf Malm

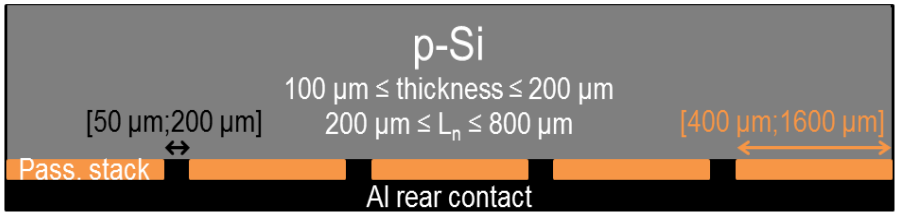
The recombinationlossesdoalsodetermineVoc and limit FF

BACK CONTACT PASSIVATION

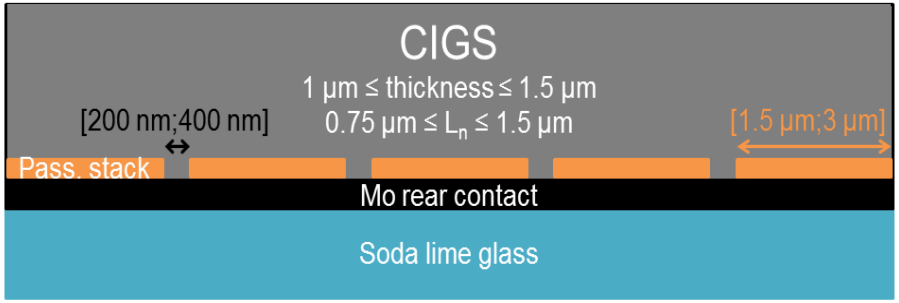
Rear contactpassivationwith nano-sizedopenings, mimicking the Si PERC cell

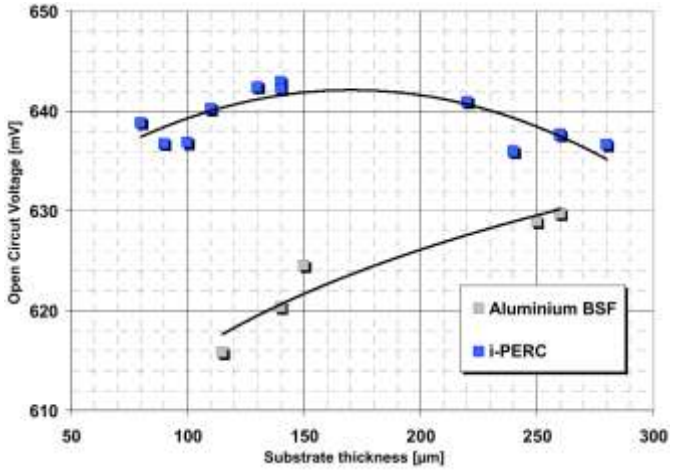
High recombination region at back contactreduced from 100% coverage to < 5%

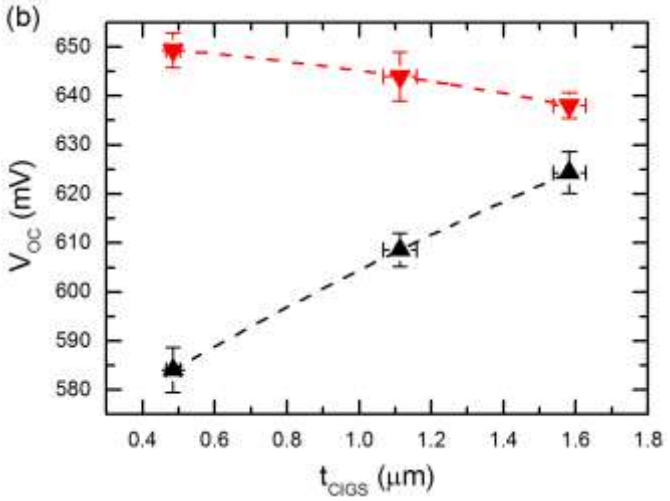
(a)



(b)

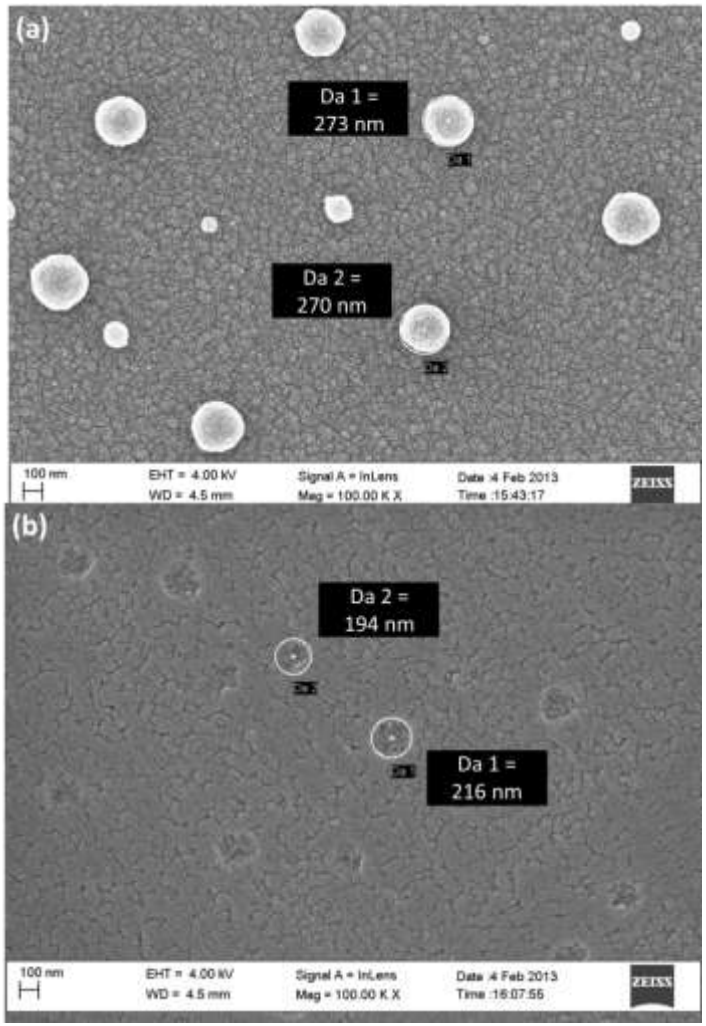






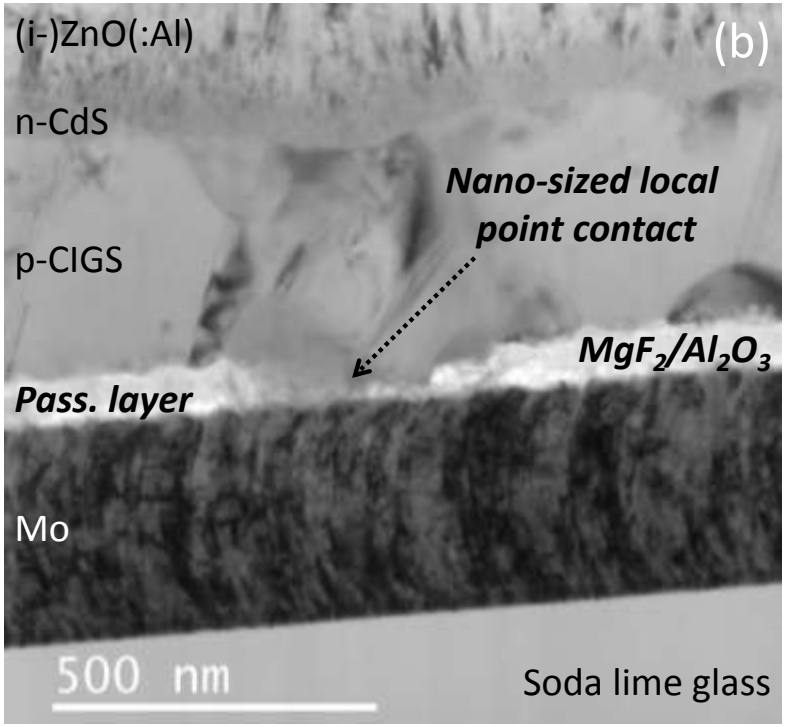
Vermang, Edoff, et al. IEEE Journal of Photovoltaics,, 4 (2014)

A LOW COST POINT CONTACT PROCESS

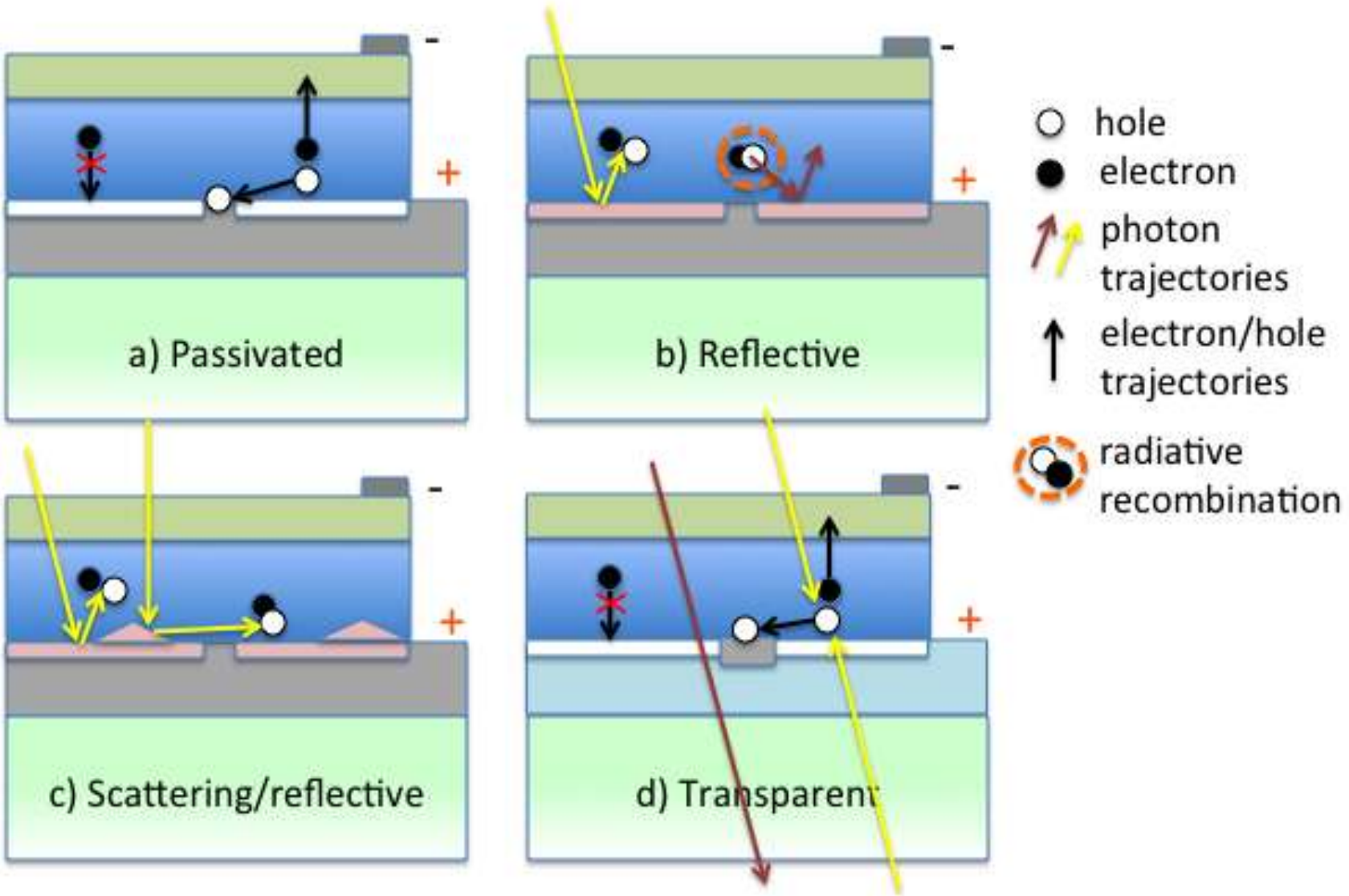


Vermang, Edoff, et al. IEEE Journal of Photovoltaics,, 4 (2014)

1. Deposit nano-particles on topof back contact
2. Depositpassivationlayer on surface and nano-particles
3. Removecoatednano-particles

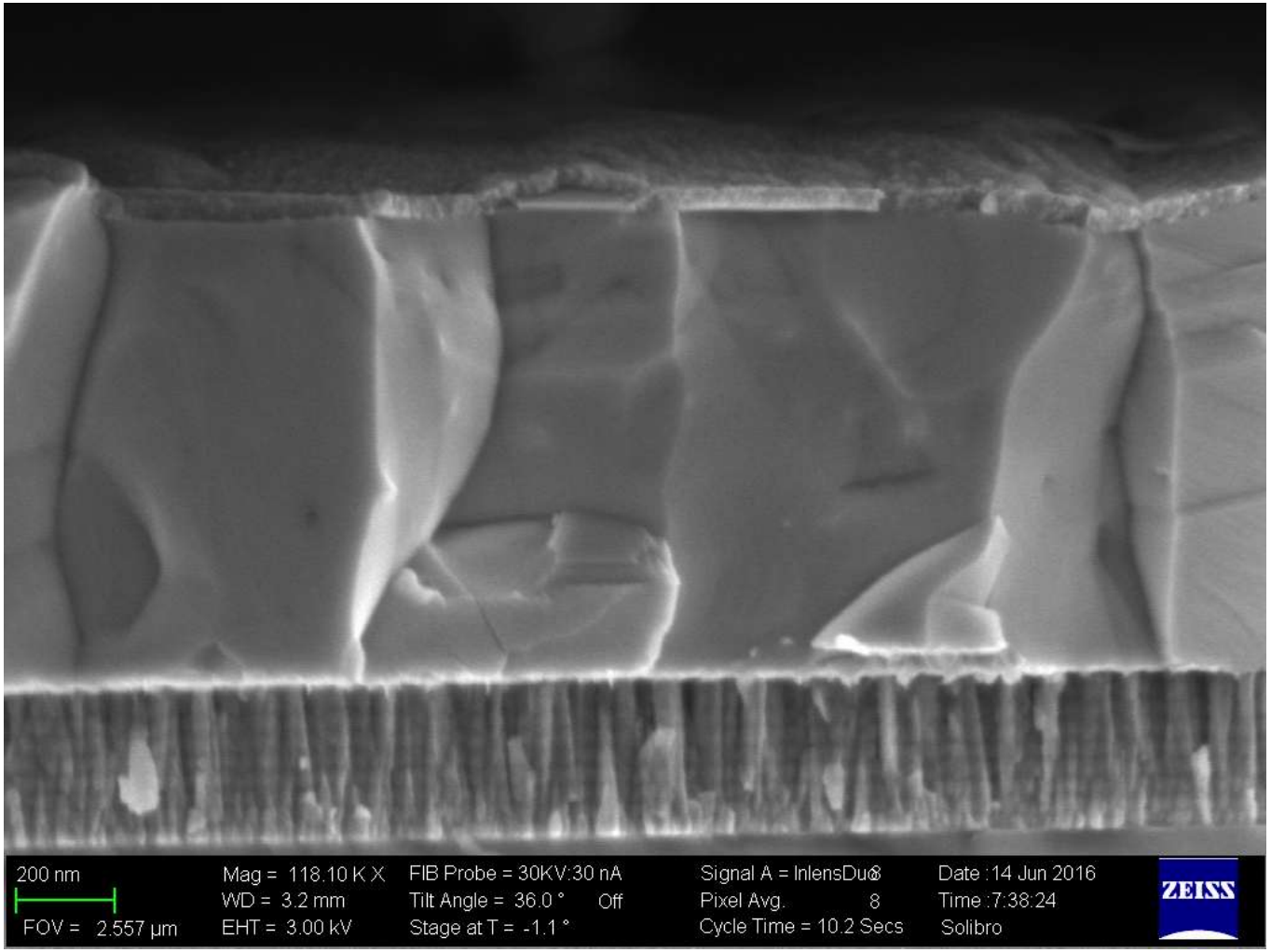


BACK CONTACTS FOR CIGS SOLAR CELLS



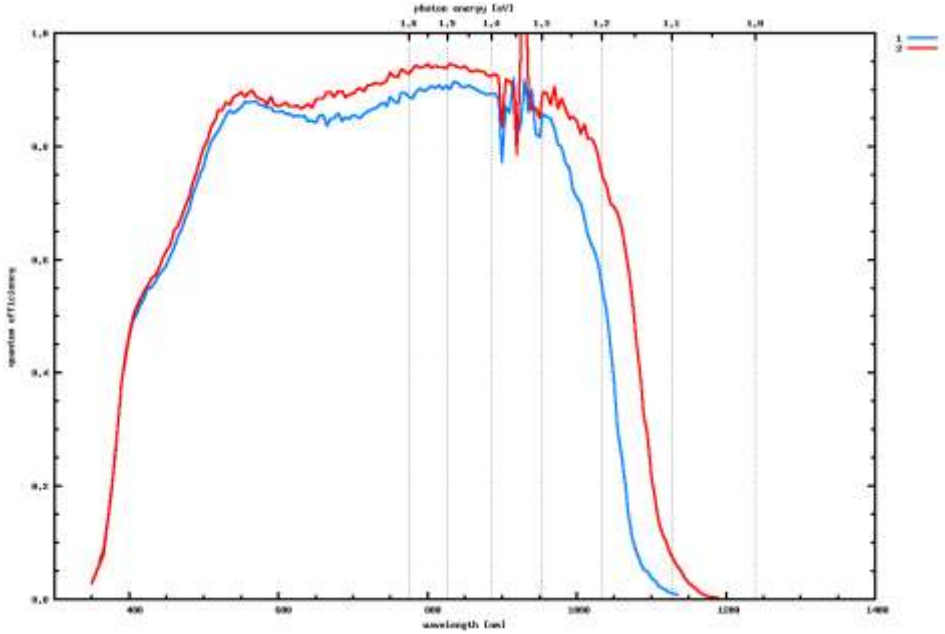
HIGH QUALITY CIGS LAYER

K, Ru, Cs,……., new ideas? Manythingshavebeentried over the years.

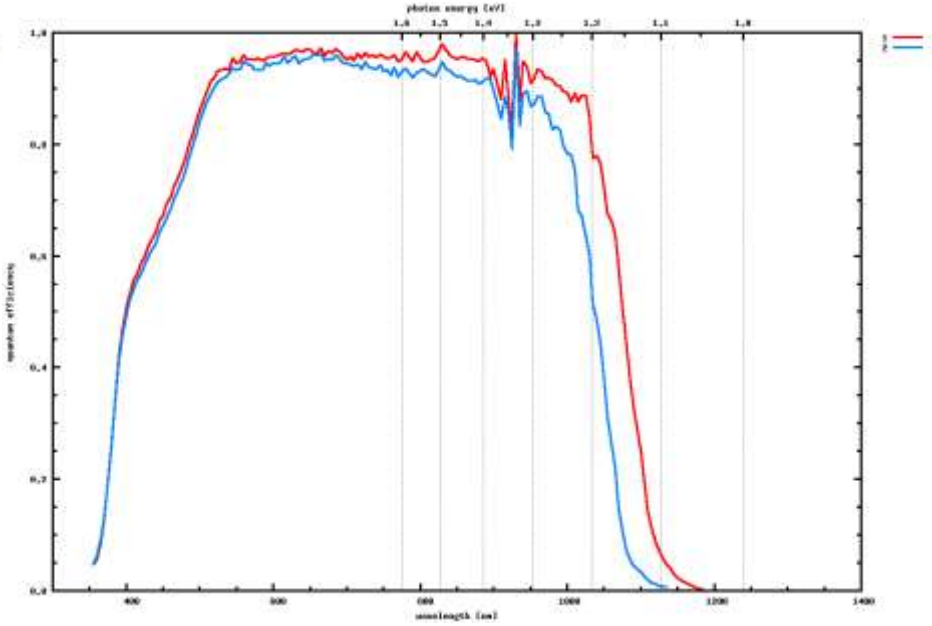


OPTICAL LOSSES - REFLECTION

Without AR



With AR

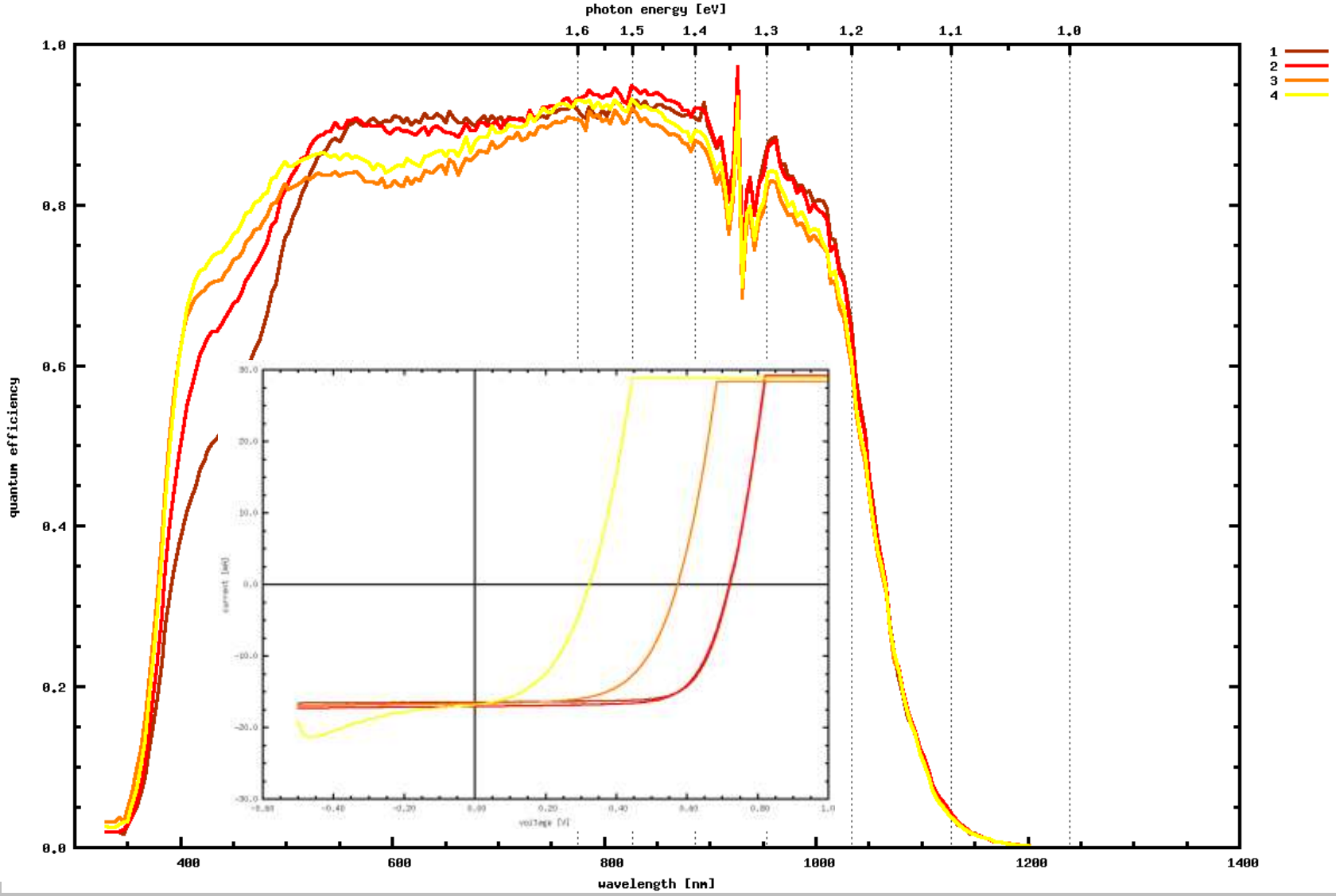


160309-2A-Cell2 (A30_9s267) AM1.5G: JQE: 35.56mA/cm2 IV JSC: 33.81mA/cm2
160310-3A-Cell2 (MS008) AM1.5G: JQE: 32.71mA/cm2 IV JSC: 31.75mA/cm2

160309-2A-Cell2 (A30_9s267) AM1.5G: JQE: 37.53mA/cm2 IV JSC: 35.46mA/cm2
160310-3A-Cell2 (MS008) AM1.5G: JQE: 34.96mA/cm2 IV JSC: 34.11mA/cm2

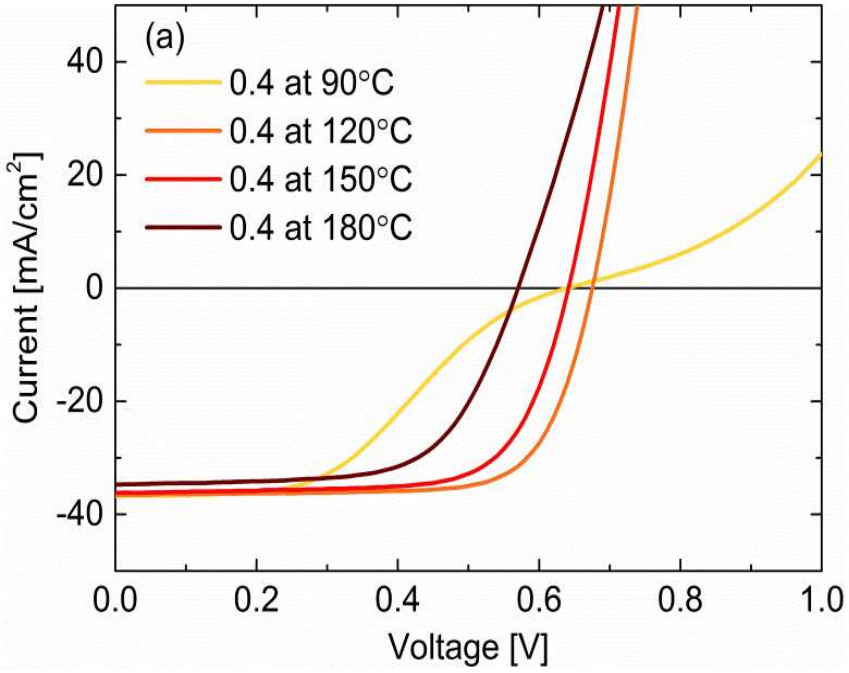
OPTICAL LOSSES - BUFFER

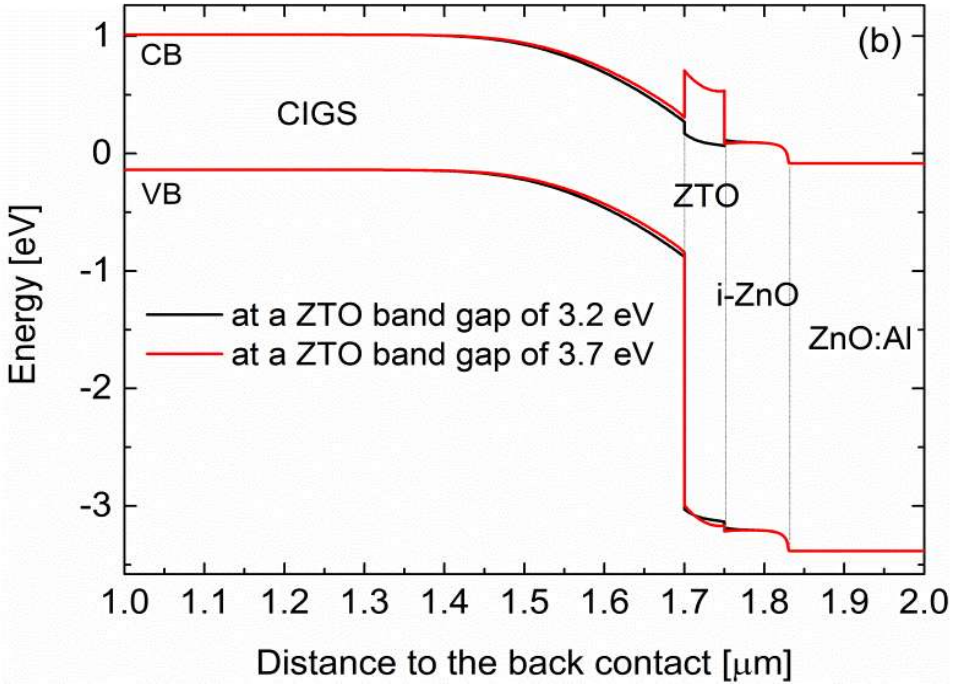
REDUCE CdS THICKNESS



BUFFER WITH WIDER BANDGAP THAN CdS

ALD-ZTO



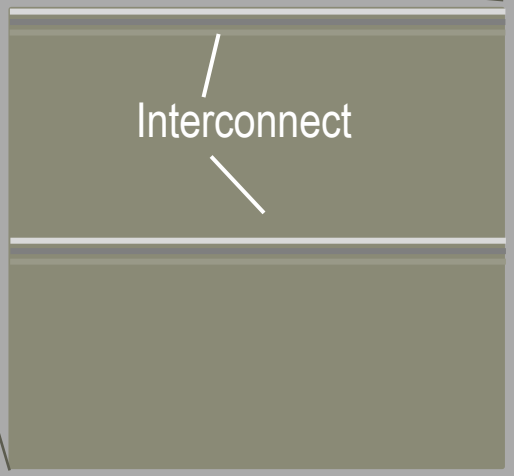


CELL TO MODULE LOSSES

CELL TO MODULE LOSSES



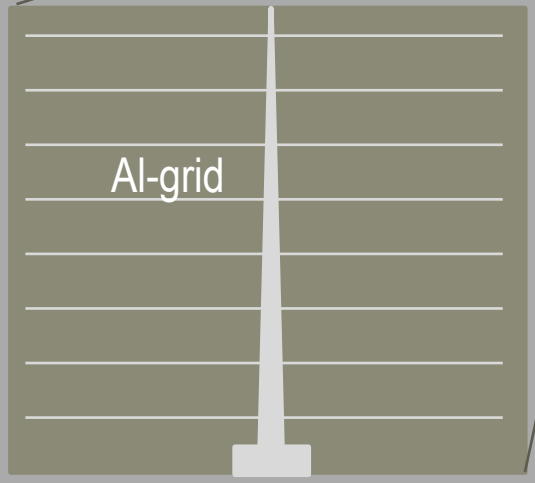
Module design



- Sheetresistance: 10 Ohms/sq
- Cell width: 5 mm
- Dead area loss: ~ 6%
- Encapsulation: 2 mm AR-glass + lamination material

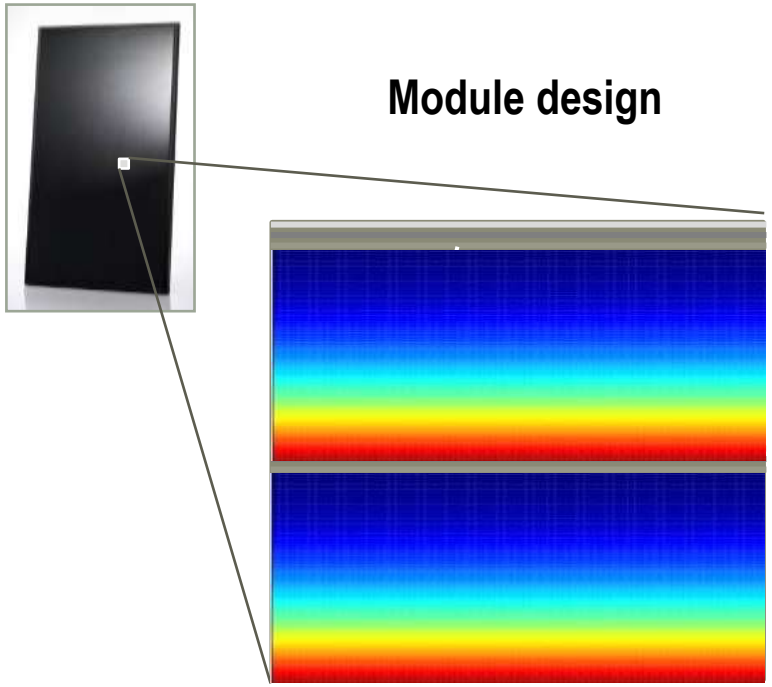
Cell design

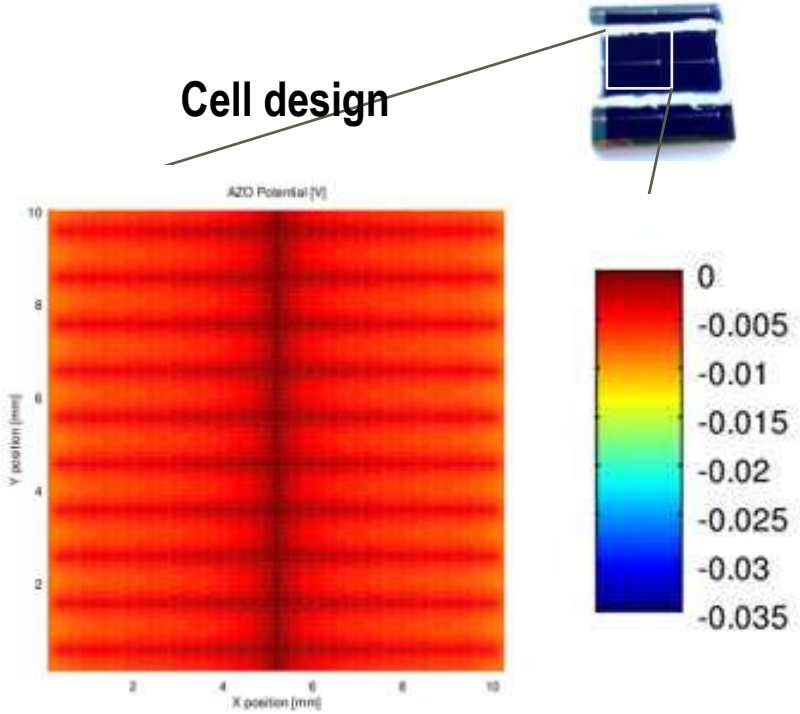




- Sheetresistance: 70 Ohms/sq
- Cell area: 10x10 mm^2
- Dead area loss: ~ 3%
- Encapsulation: MgF_2

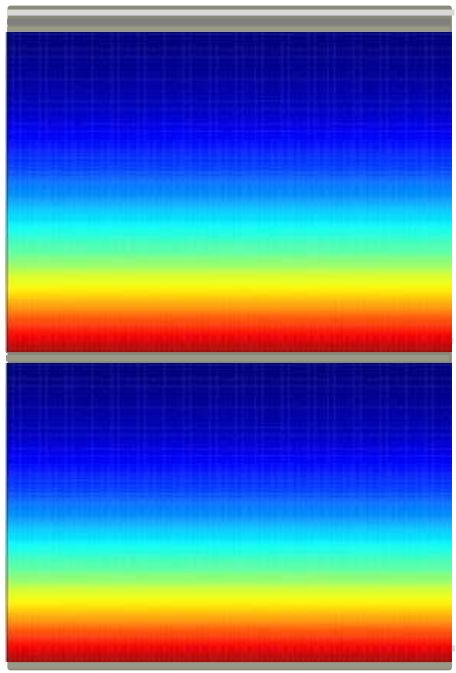
Cell toModuleLosses - FF

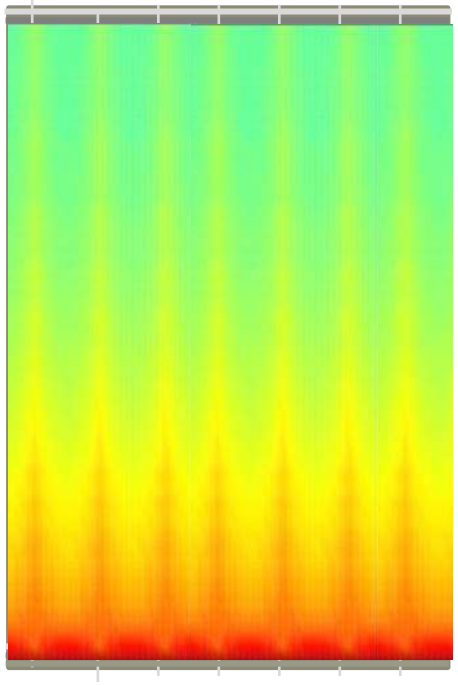


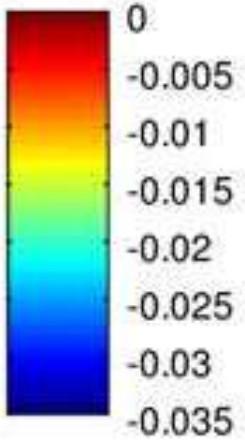


- **FF is reduced around 3 % units from cell to module**

Metalgrid – simulation

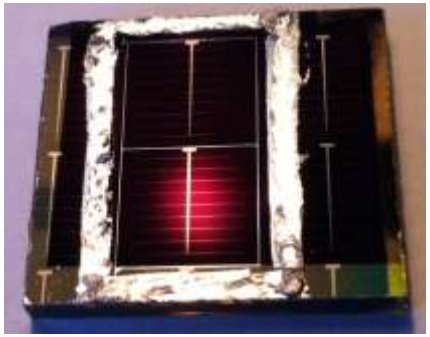


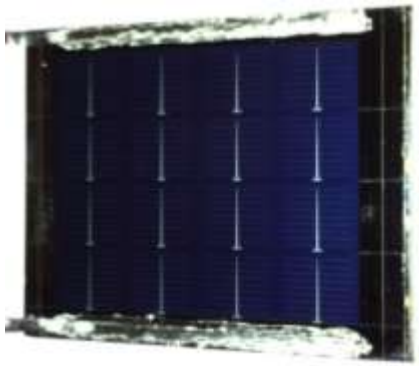




- 30 µm widelines
- 10 mm cell-width
- AZO – 70 Ohms/sq
- Grid-pitch 1.3 mm

METAL GRID EXPERIMENTAL RESULTS







Parameters	Record cell 1 cm^2	Record mini-module 16 cm^2	Record sub-module ~ 600 cm^2
Eff AA [%] (extconfirmed)	21.0*	18,7*	17,6*
Jsc [mA/cm^2]	35,7	35,3	33,5
FF [%]	77.6	75,6	73,4
Voc/cell [mV]	757	701	716

CONCLUSION

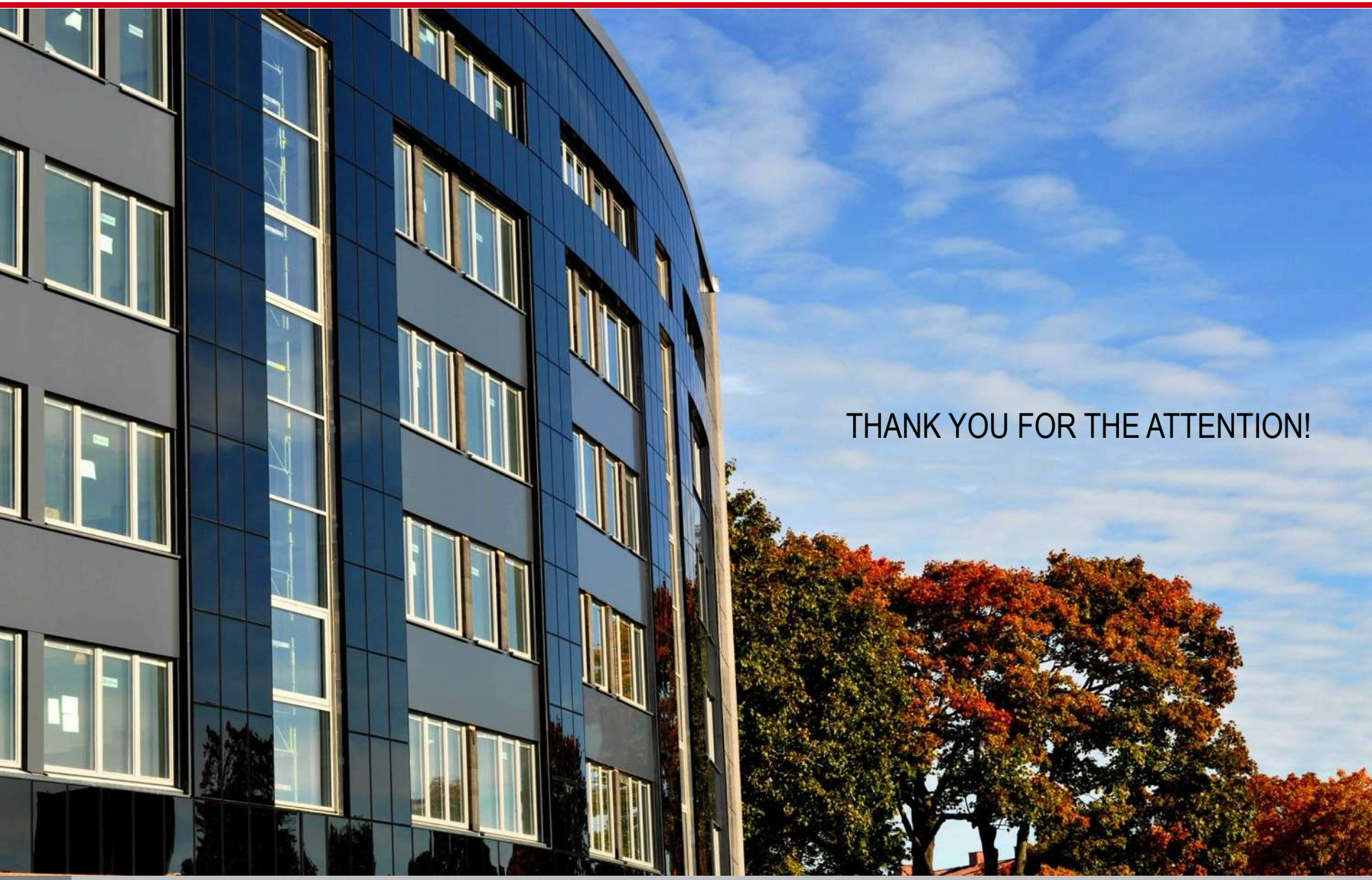
SOLIBRO CIGS PV module technology havedemonstrated> 16 % total area efficiency

There is a substantialfurther potential – approaching 20 % - possible, by

- Improved CIGS bulk and heterointerface quality (K, Rb, Cs,…..)
- Passivatedpoint back contacts
- Light capturingstructures and thinabsorbers
- Reducedparasitic absorption in windowlayers
- Reducedlabcell-to-modulelosses

Wewilltogether to realize this potential in the new EU project ARCIGS-M

Uni-Uppsala (coordProf Marika Edoff), Uni-Ljubljana, Solibro Research, and IMEC, CNRS, UCL, LIN-INL, TNO, Midsummer, Obducat, EDF, AC-CS, AMMR


THANK YOU FOR THE ATTENTION!