

High efficiency flexible solar cells on polymer foils: World record at the ETHZ

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Acknowledgements

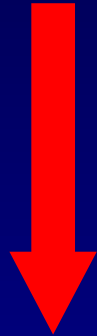
**Swiss Federal Office of Energy, Swiss National Science Foundation,
Swiss Federal Office of Science and Education for the EU project
METAFLEX**

ETH (Swiss Federal Institute of Technology) Zurich

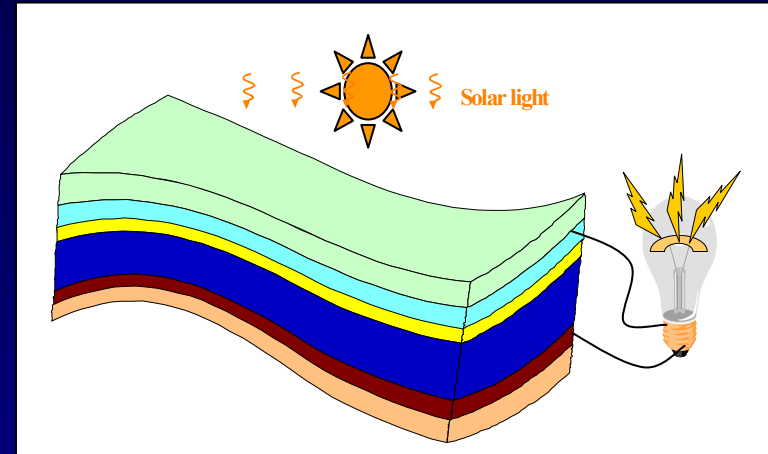
Thin Film Physics Group

www.tfp.ethz.ch

Flexible solar cells

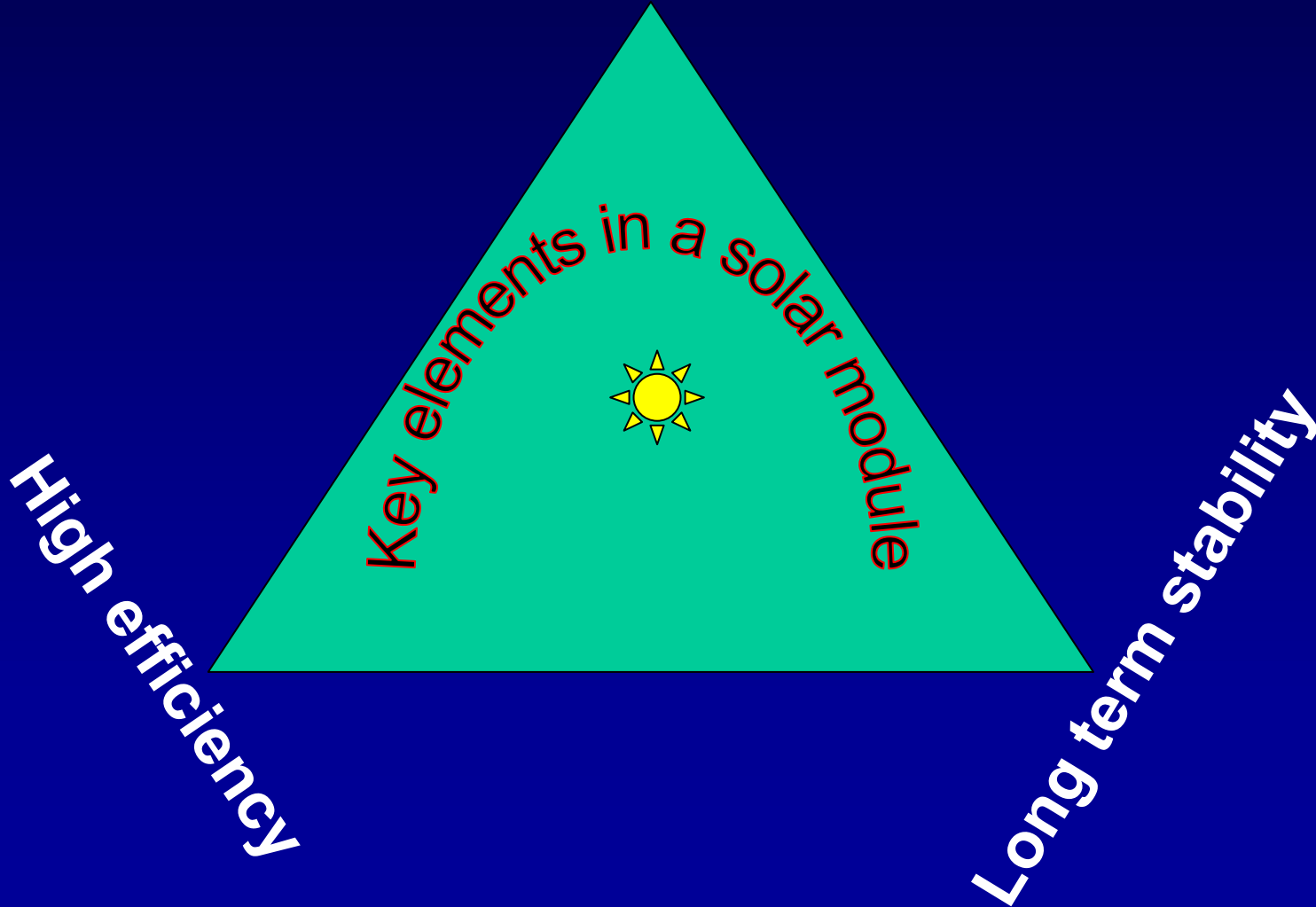


Practical solution provider



Solar cells: Viable solution provider

Cost effective / Low cost



Solar module cost \$ / W_p depends on:

- Processing and component costs \$ / m^2
- Efficiency and stability W_p / m^2
- Production volume W_p / Year
- Throughput
- Yield
- Waste

Important

High efficiency & long term stable performance

Outline

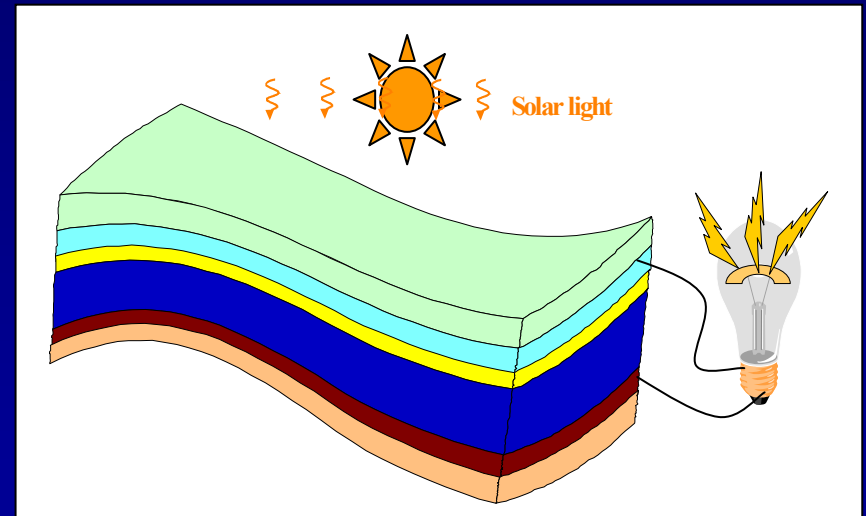
Overview of solar cells (PV)

Comparison of flexible solar cells

$\text{Cu}(\text{In,Ga})\text{Se}_2$ (called CIGS) solar cells

Applications

Outlook



Solar cells for terrestrial applications

Si- wafers

Si- thin film

CIGS thin film

CdTe thin film

TiO₂ (Graetzel)

Organic

Thin film solar cells

Material	Junctions	Efficiency
Amorphous Si	Triple	14.6% → 13%
CdTe	Single	16.5%
CIGS	Single	19.5%

Technology comparison

Solar cells on plastic foils

Base material	Cell efficiency (%)	Stability under light	Commercial availability
a-Si	6 – 12#	Degrades	Yes
CIGS*	8 – 14 (15 with AR coating ?)	Good	Not yet
CdTe*	6 – 11.4	Good	Not yet
Others	2 - 6	?	Not yet

Efficiency depending on number of junctions and substrate

***-ETHZ holds the efficiency world record**

Why thin film CIGS solar cells ?

Very high efficiency

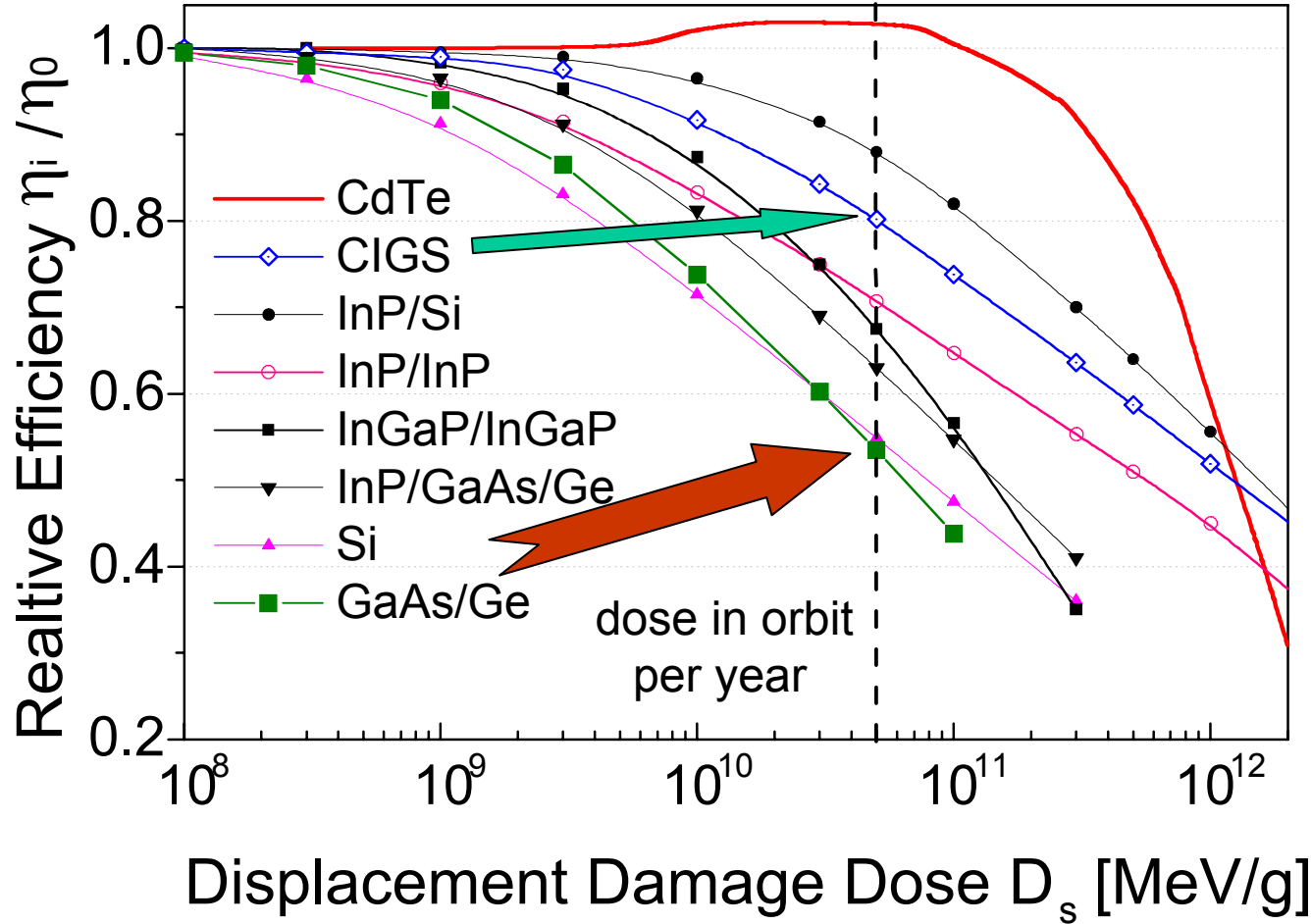
Highly stable performance for terrestrial and space applications

Lightweight and flexible cells possible

Low cost potential

2 to 3 times higher radiation tolerance compared to conventional (Si or GaAs) solar cells in space

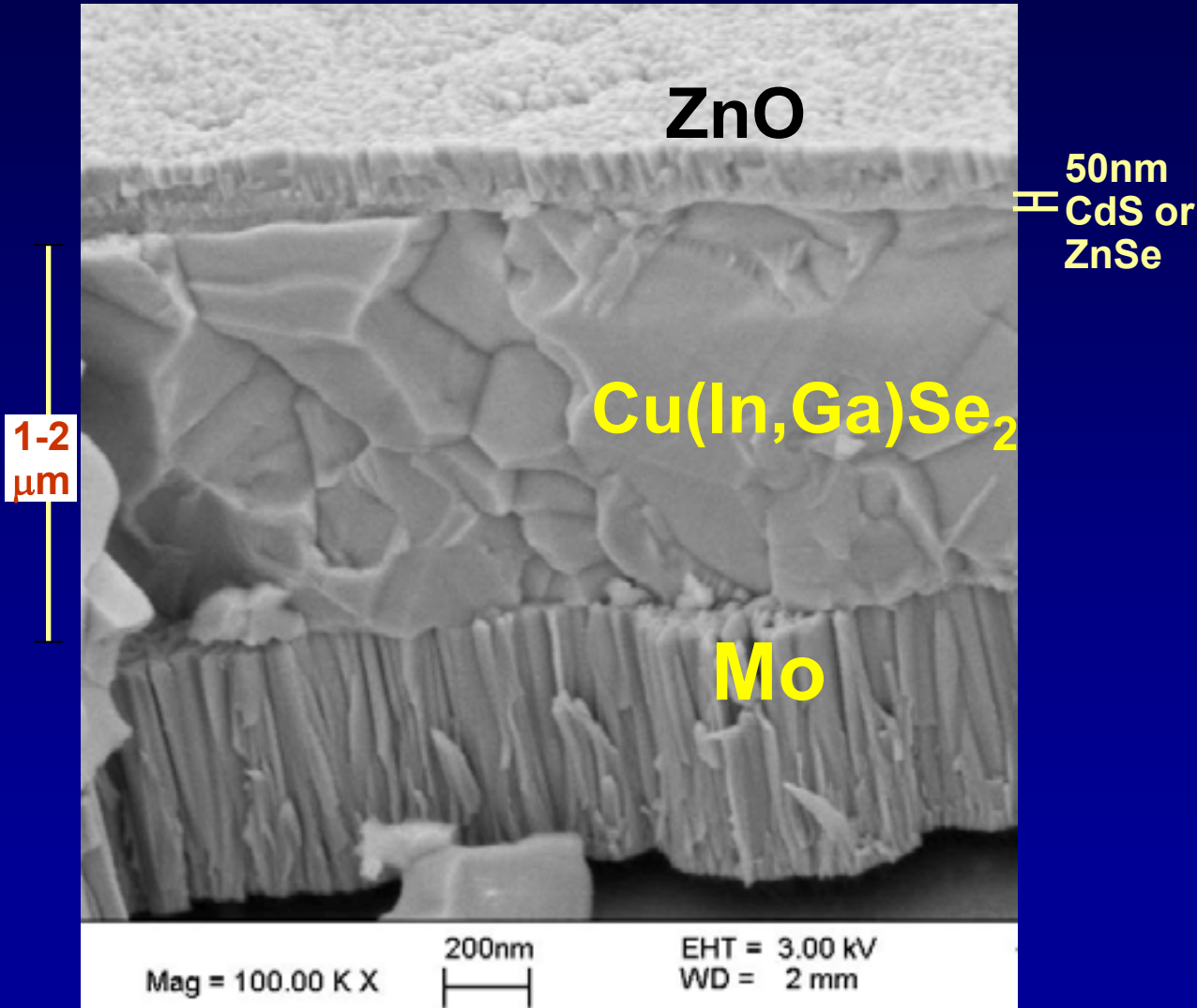
Space radiation (e- & p-) hardness of solar cells



CIGS has superior stability

NASA & Air Force, USA invested in flexible CIGS

CIGS Solar Cell Configuration



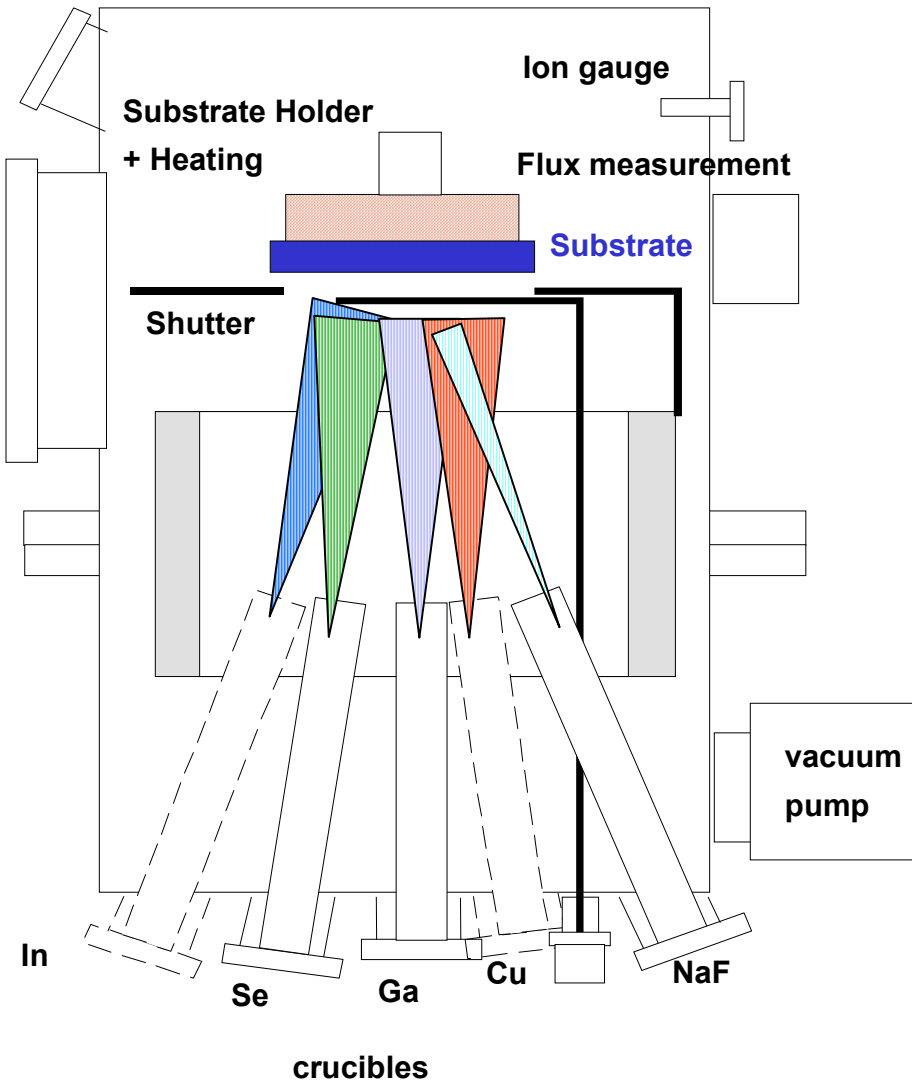
Sputtering
Chemical Bath

Co-Evaporation

Sputtering

Substrate
(Glass, Metal Foil,
Polymer)

Physical Vapor Deposition System for Cu(In,Ga)Se₂ Layers



Compound formation:

Reaction of evaporated elements

at the substrate

Process optimization:

**Evaporation flux of elements
(800 - 1300 °C)**

**Substrate temperature
(400 - 600 °C)**

Industrial production systems :

In-line deposition on 60 x 120 cm²

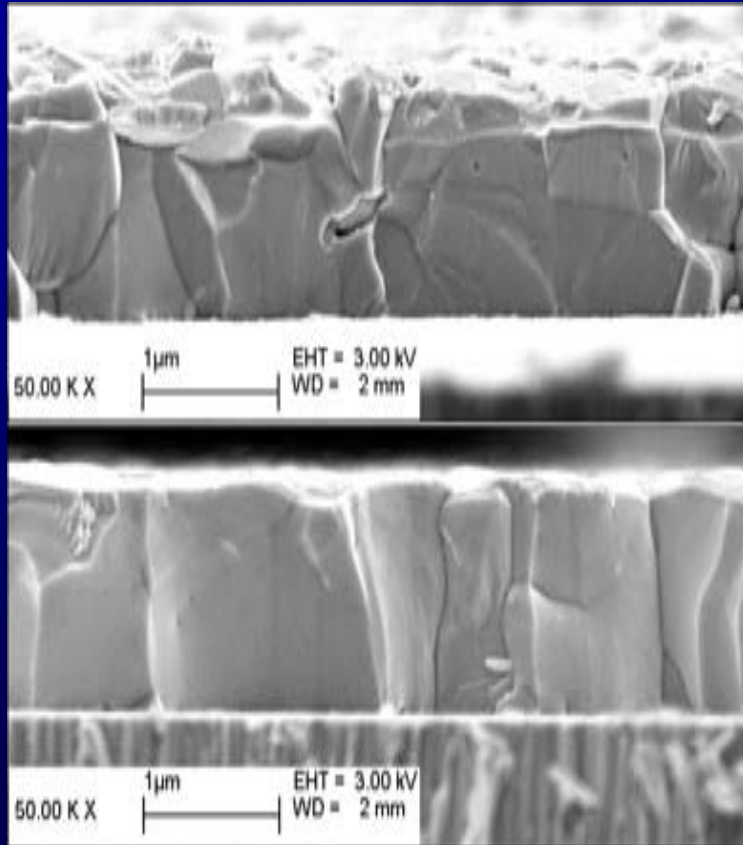
Roll- to- Roll deposition

CIGS absorber layer

Most important part of the solar cell

CuInSe₂ (1.04 eV) and CuGaSe₂ (1.67 eV)

Cu(In,Ga)Se₂ (1.25 eV)



Thickness of ~ 2 μm

Columnar large grains (~ 1 μm)

Smooth surface

Optimum band gap & grading

Optimum Cu/(In+Ga) composition

Low microstructural defects

Doping / Passivation with Na

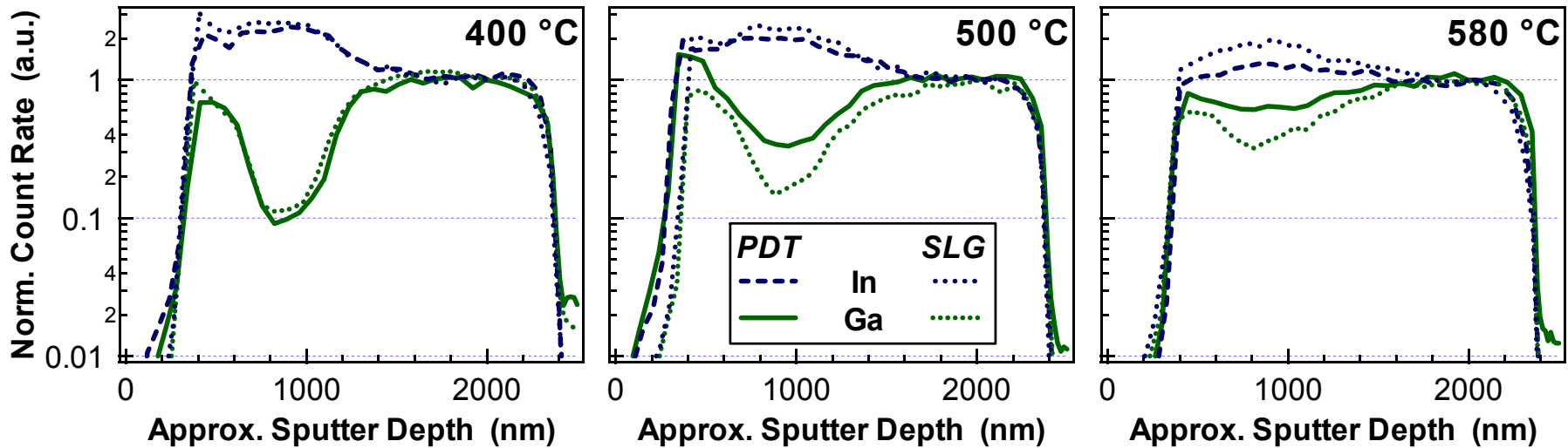
High efficiency @ 550 C

Lower efficiency @ 400 C

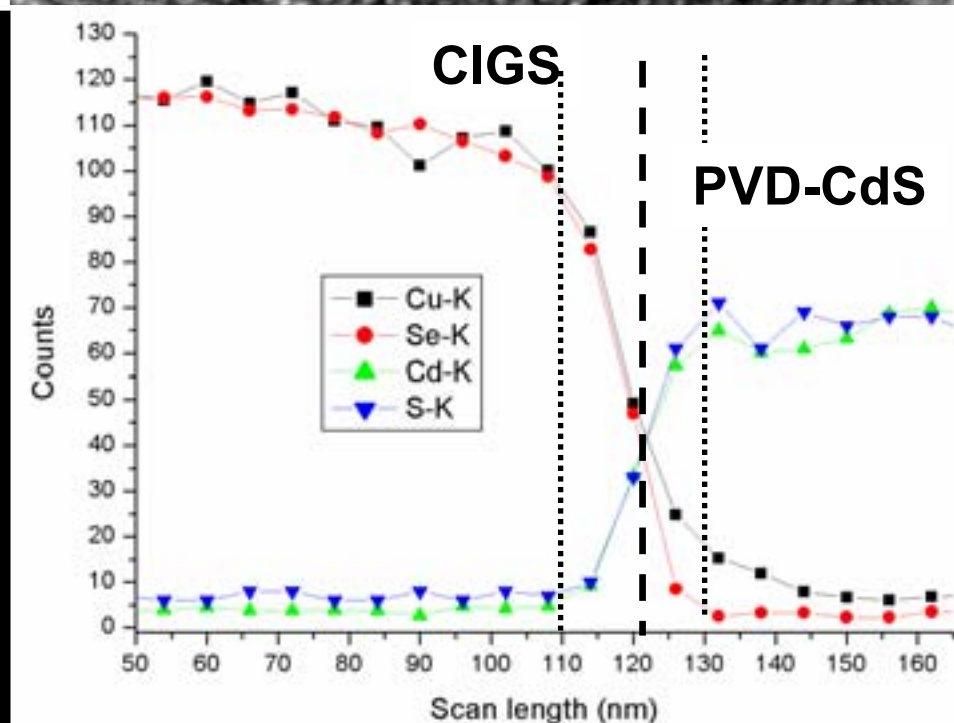
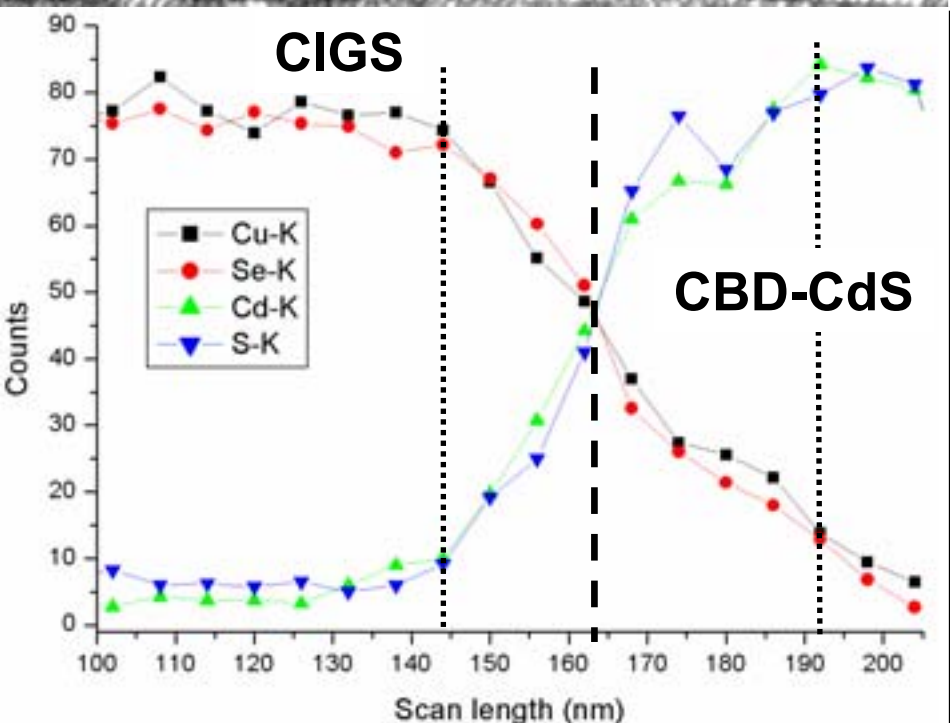
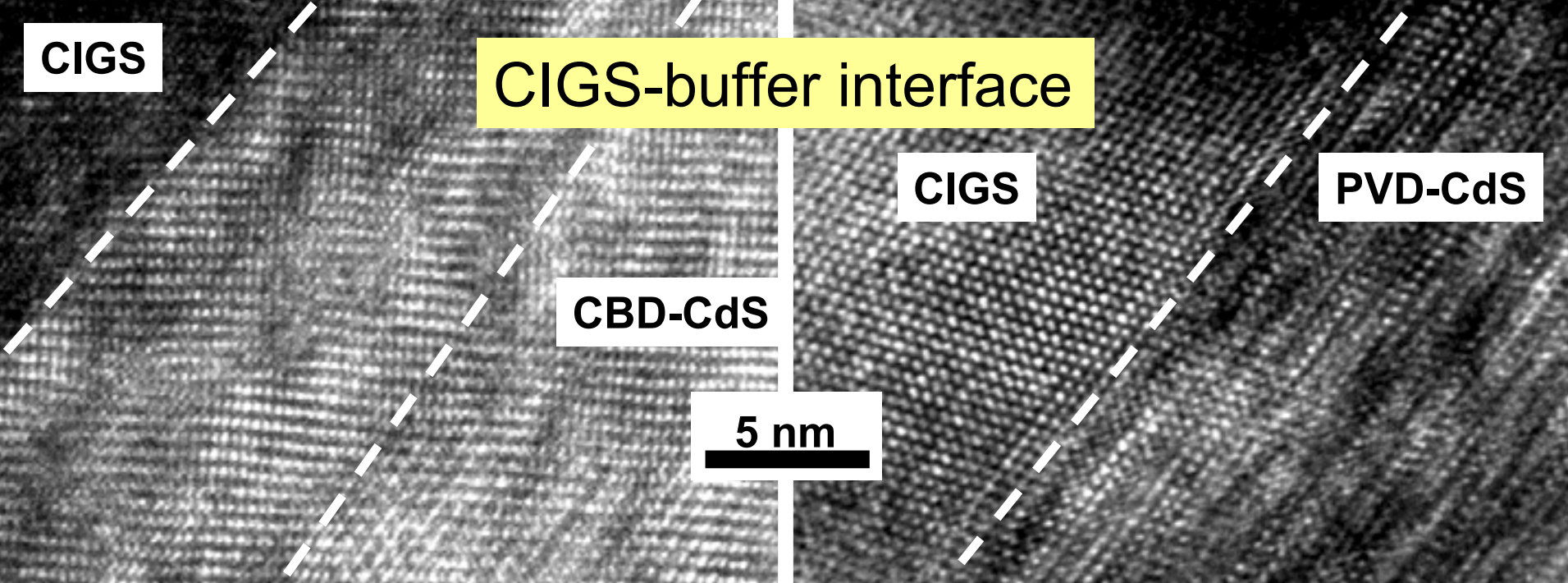
Different methods of CIGS deposition

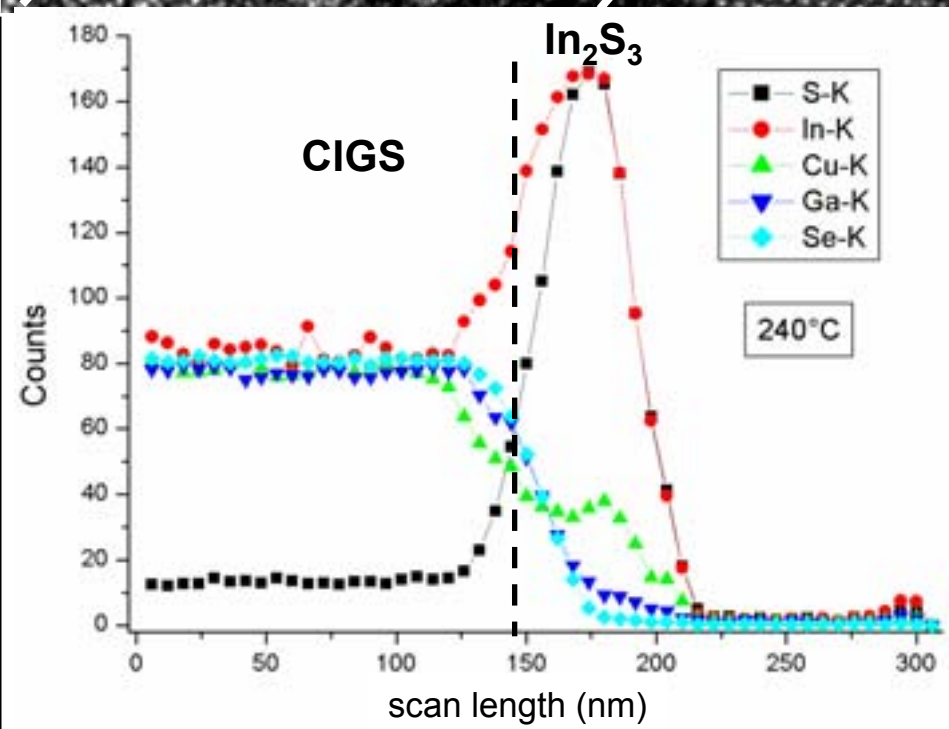
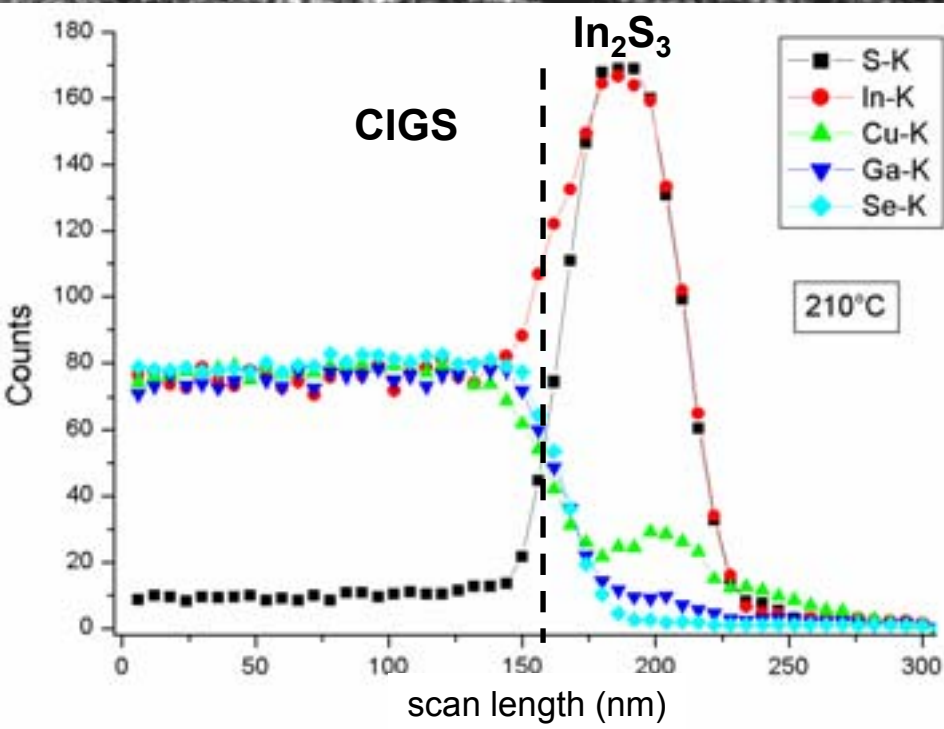
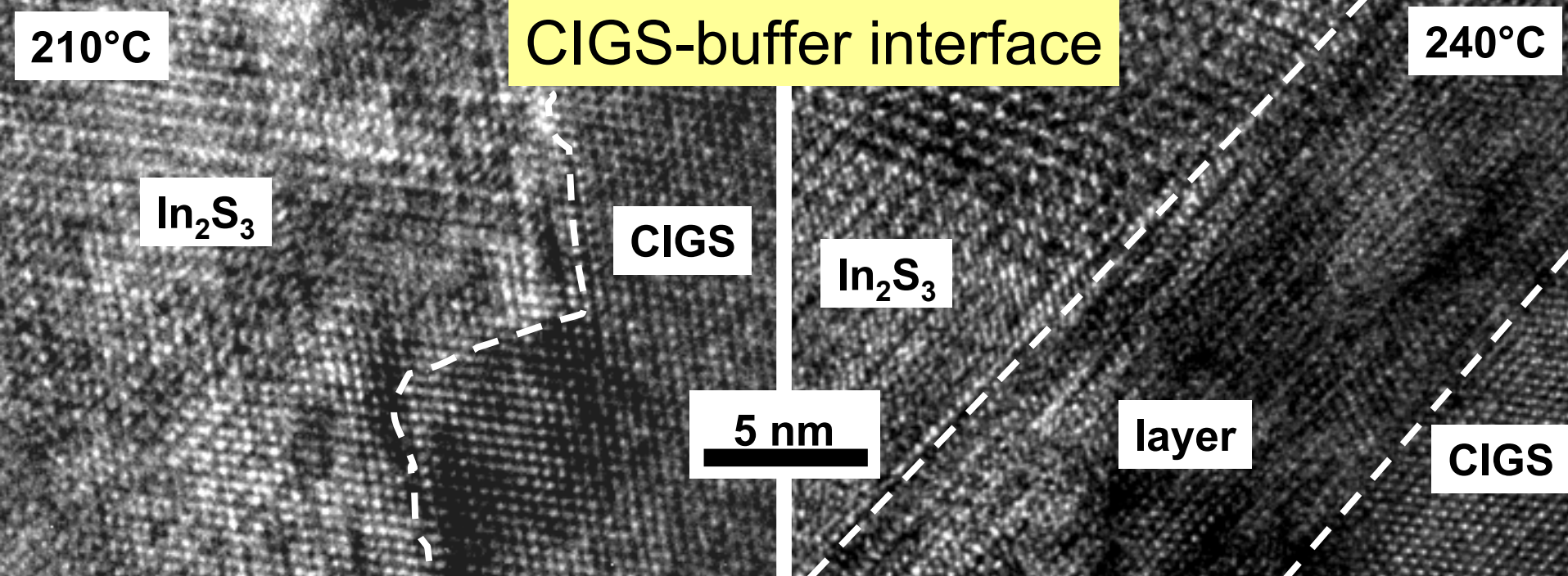
Relevance of Na effects: Band gap grading

SIMS

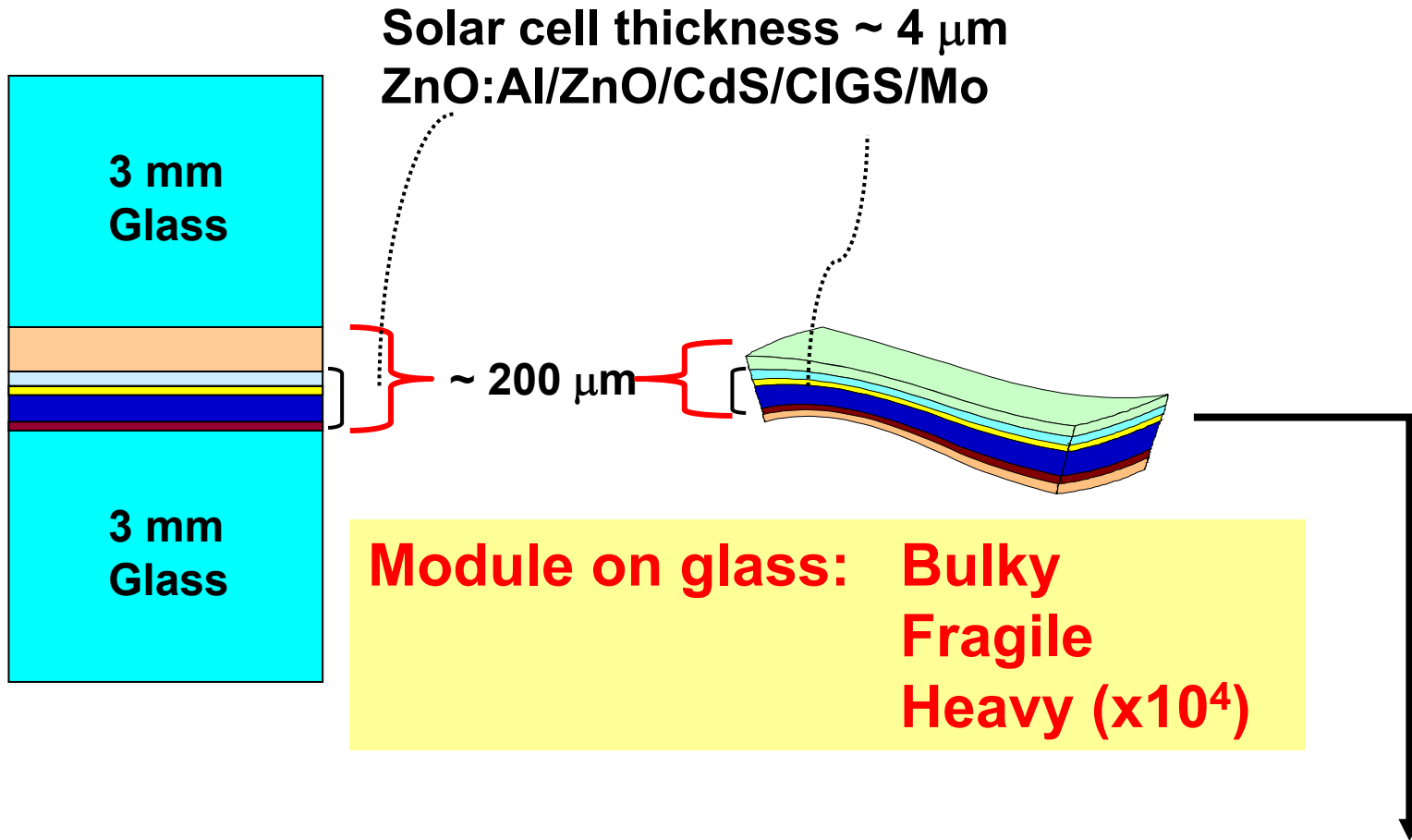


- **Ga notch: Inherent to 3-stage process**
- **Smoothed by In-Ga interdiffusion**
- ⇒ **$T_{\text{sub,max}} > 450 \text{ °C}$: More smoothing in PDT absorbers**
- ⇒ ***Na impedes In-Ga interdiffusion***





Substrate for CIGS solar modules: Glass vs foil



Flexible solar modules offer several advantages

CIGS solar modules: Industrial production

Pilot production-line & start-up

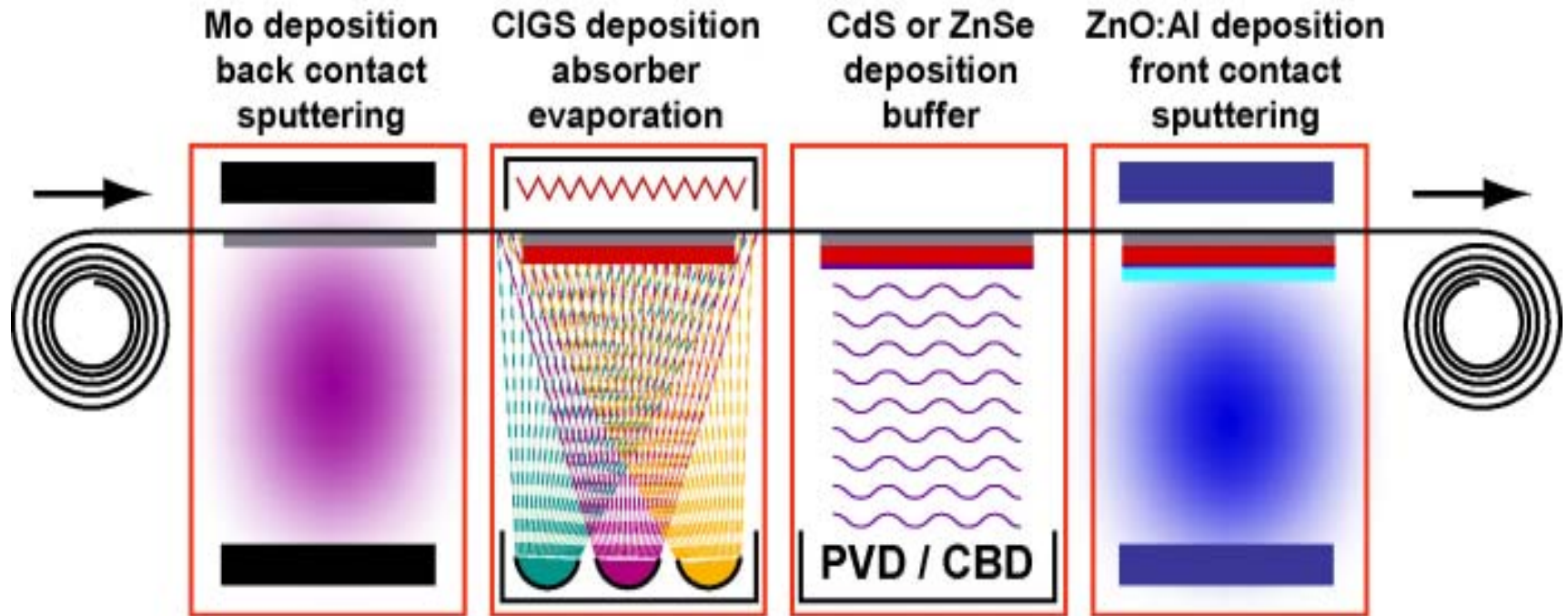
Shell Solar (USA, Germany)
Wurth Solar (Germany)
Showa Shell (Japan)
Sulfurcell (Germany)
ISET (USA)
Solibro (Sweden)
EDF-CNRS (France)
and

On glass

Global Solar (USA)
ISET (USA)
Solarion (Germany)
CIS Solar (Germany)
CIS Solartechnik (Germany)
Matsushita (Japan)
Nano Solar (USA)
Miasole (USA)
Magnolia solar (USA)
and....

On flexible foils
(Mostly on metals)

Roll-to-roll deposition on metal or polyimide foil



Modules -> Need scribing and patterning for interconnections

Good for industrial production !

Difficult in R&D labs!

Why thin film solar cells on flexible substrates ?

Roll to roll deposition process for industrial production

Reduction of manufacturing time and cost

Low energy pay back time

Novel applications of *light-weight and flexible* solar cells

Roofs and facades in buildings

Portable source of power

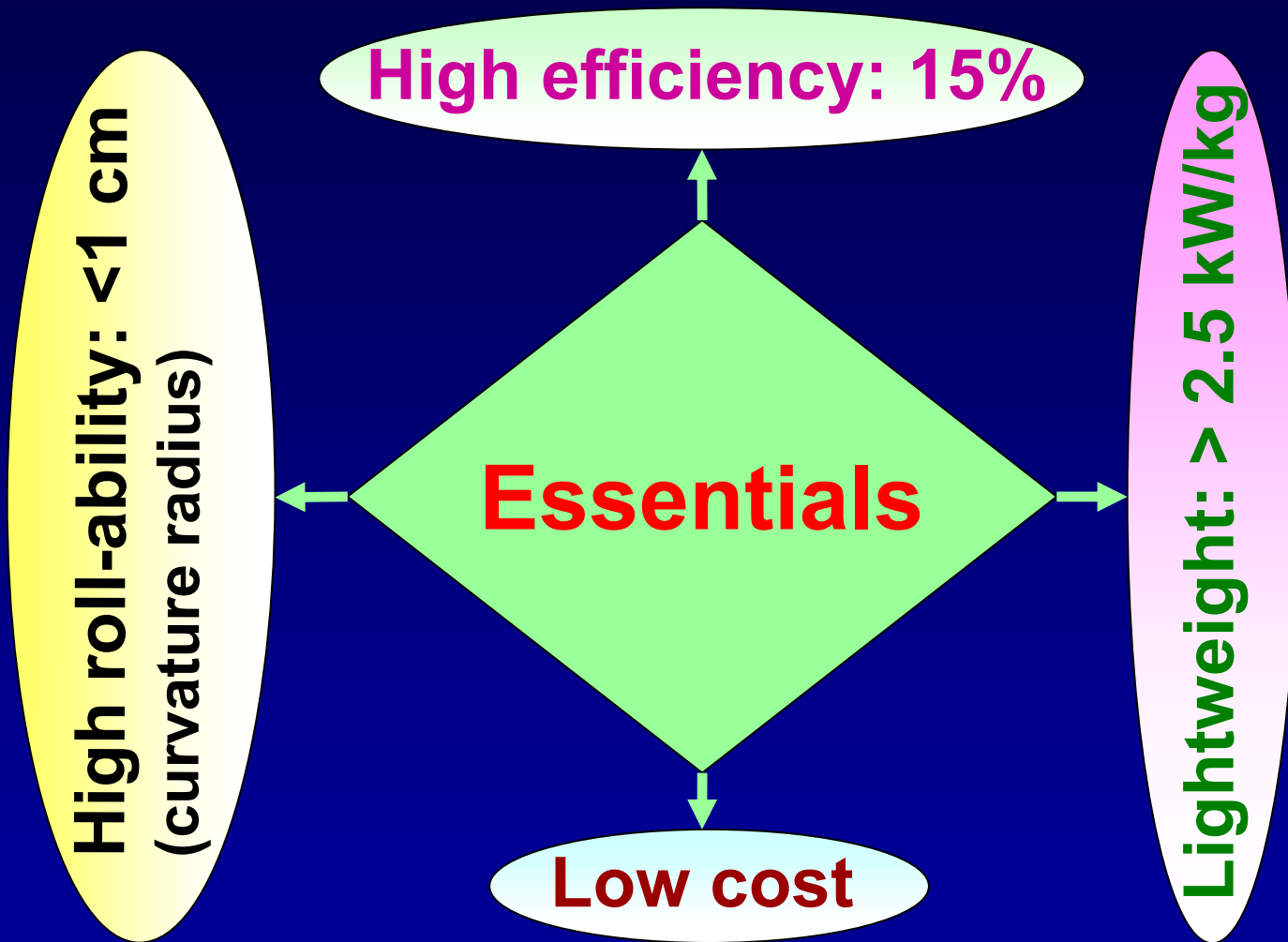
Consumer electronics, smart cards, etc.

Value added products

Automobiles & boats

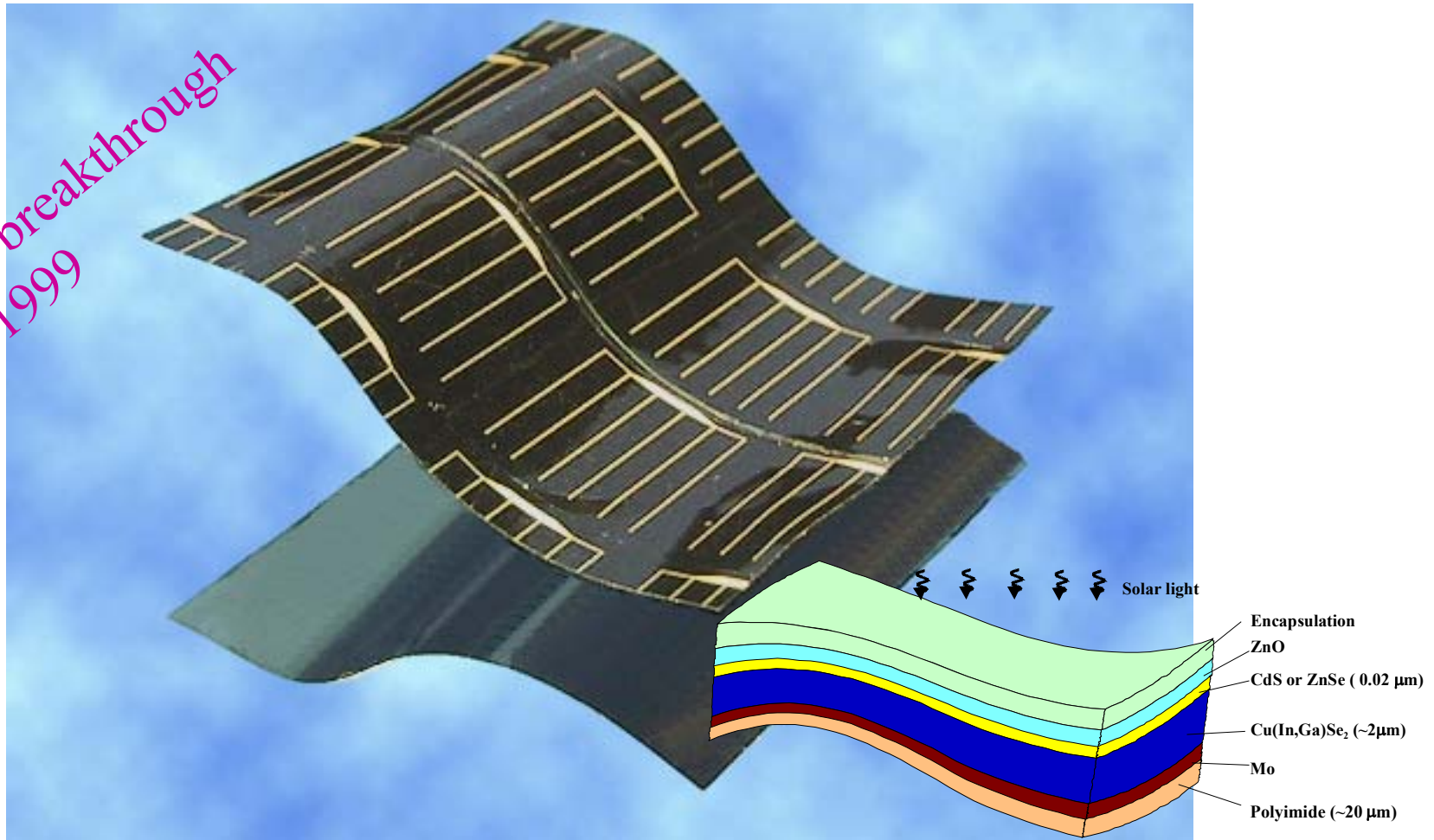
Space applications

Application requirements



Flexible CIGS solar cells on polyimide developed at ETHZ

First breakthrough
in 1999



12.8% World Record efficiency (total area, no AR)

Detachable Solar Power Jacket

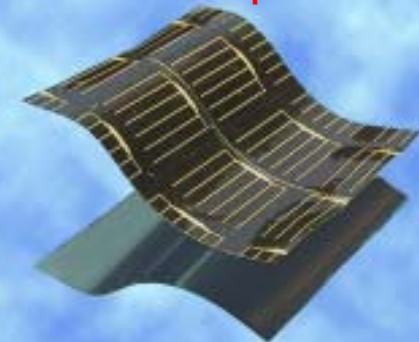


Artist's imagination (M. Leopold)

Imagination → Reality

Not straightforward !

Solar cell developed at ETHZ



Dream did not come true

But

Another breakthrough.....

New world record of highest efficiency

Flexible and lightweight CIGS solar cells on plastic

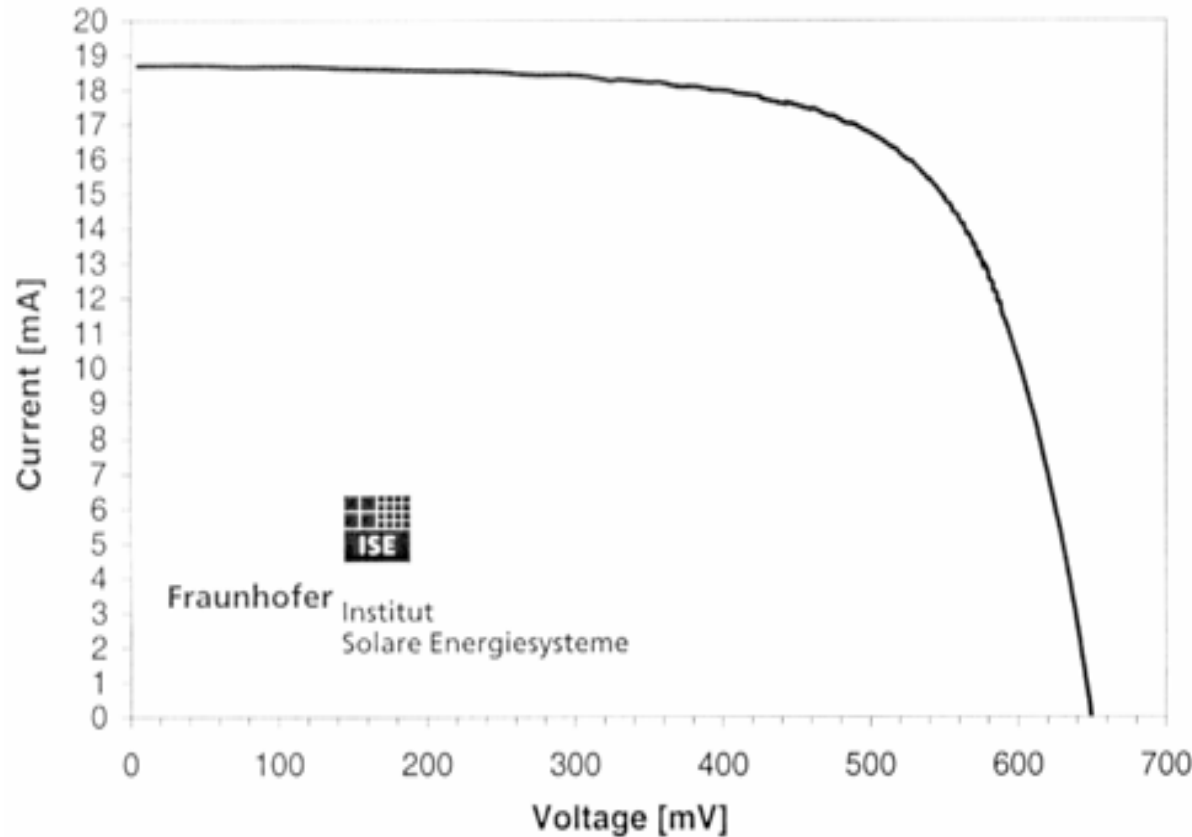


CIGS solar cells developed with an innovative process

Independently certified efficiency of 14.1%

New world record of highest efficiency

Flexible and lightweight CIGS solar cells on plastic



$$V_{oc} = 649.4 \text{ mV}$$

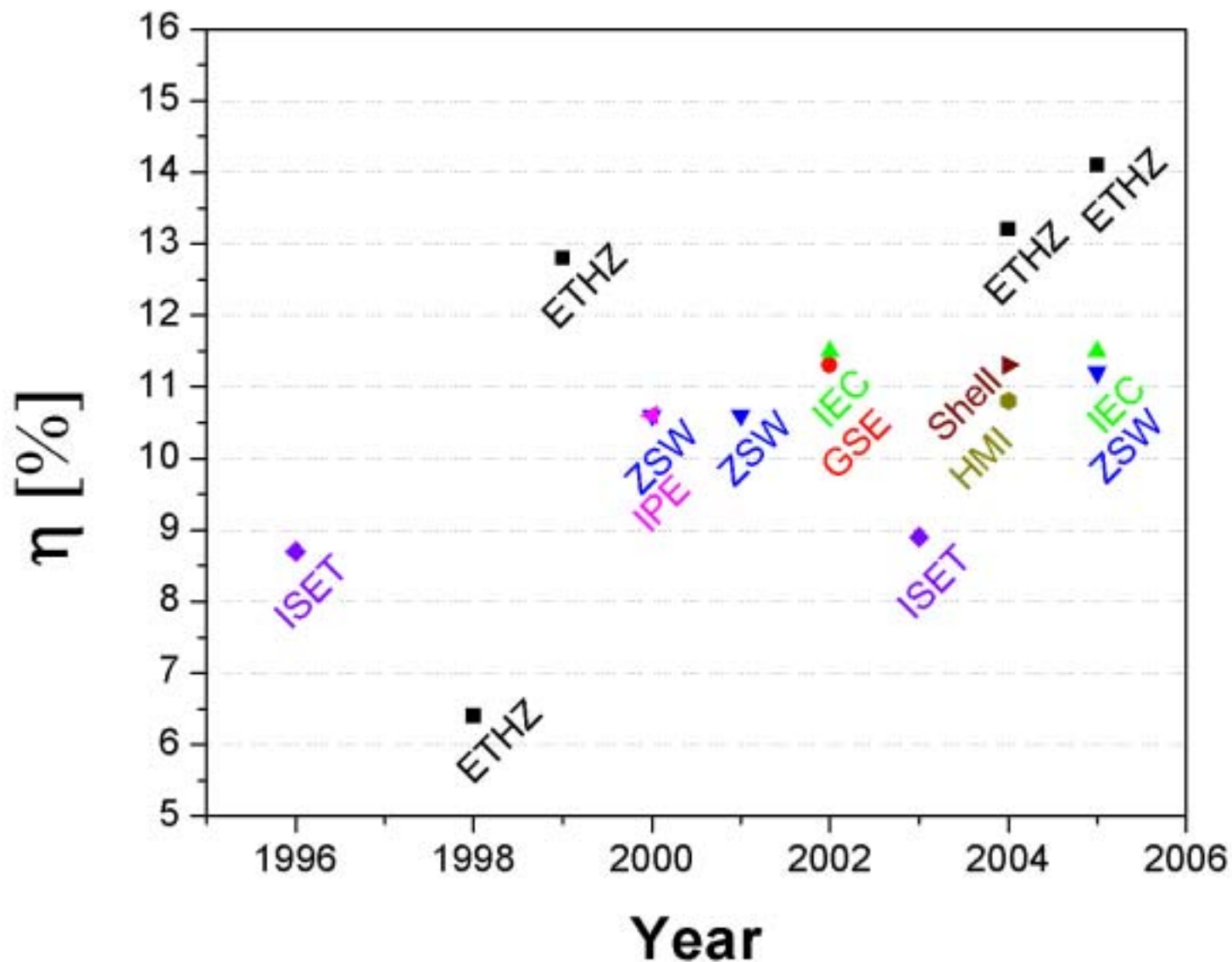
$$J_{sc} = 31.48 \text{ mA/cm}^2$$

$$FF = 69.1\%$$

$$\eta = 14.1\%$$

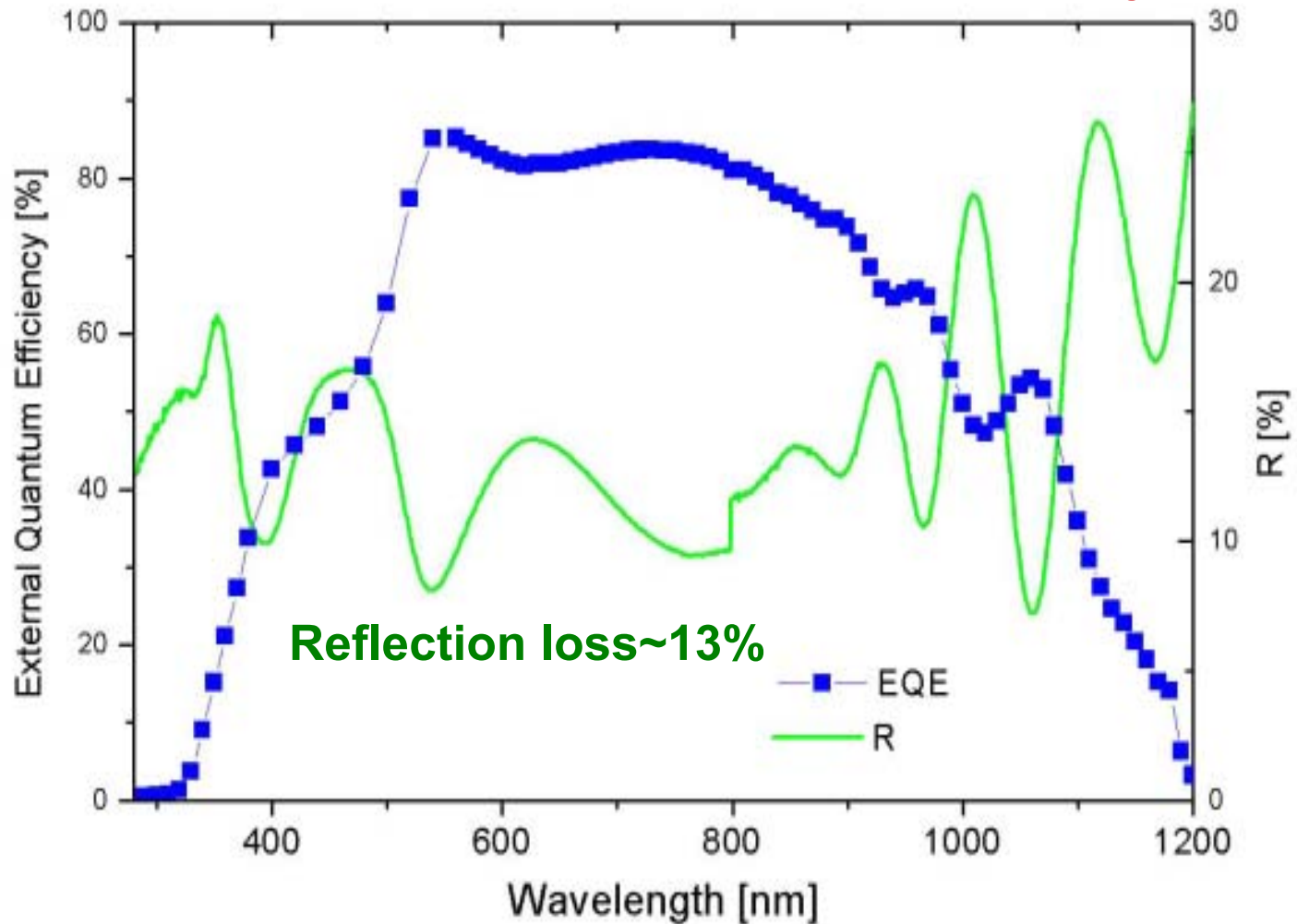
Certified efficiency: Total area, AM1.5 illumination, no AR coating

Progress in flexible CIGS solar cells on polymer foils



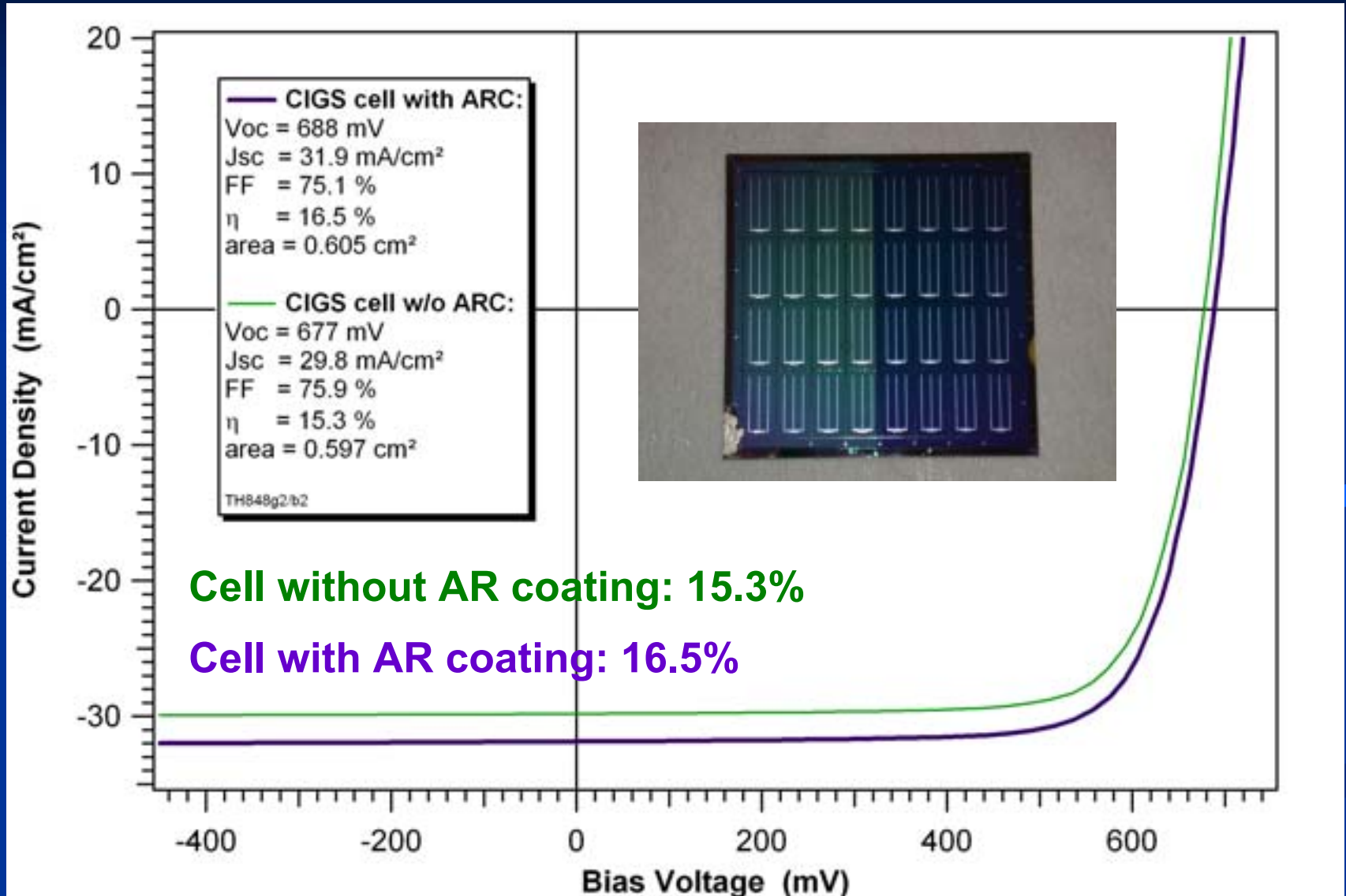
Efficiency improvement from 14% to >15%

Spectral dependence of quantum efficiency



Apply anti reflection coating!

Efficiency improvement due to anti-reflection coating



**The challenge ?
Exploit the full potential of thin
film technology...**



**Monolithically inter-connected
solar modules**

Monolithically connected CIGS solar modules

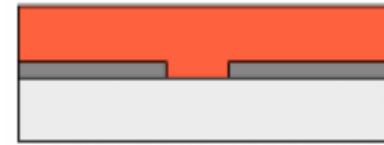
Mo back contact deposition by sputtering



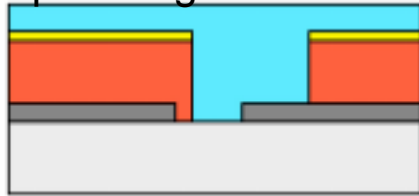
Scribing of Mo by laser beam



CIGS absorber deposition by vacuum evaporation



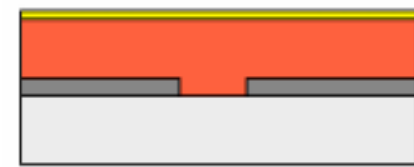
ZnO:Al Front contact deposition by sputtering



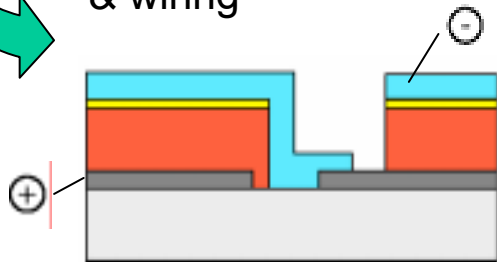
Patterning of buffer/CIGS by mechanical scribing



CdS or ZnS buffer deposition by chemical method

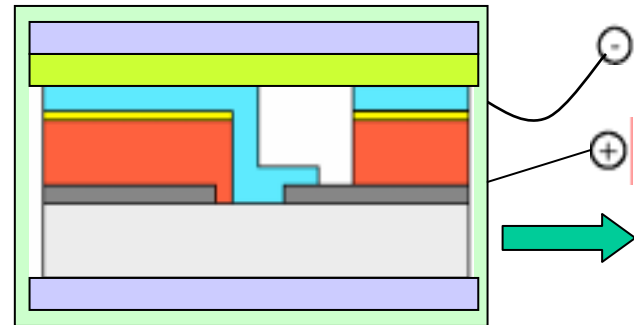


Patterning of front contact & wiring



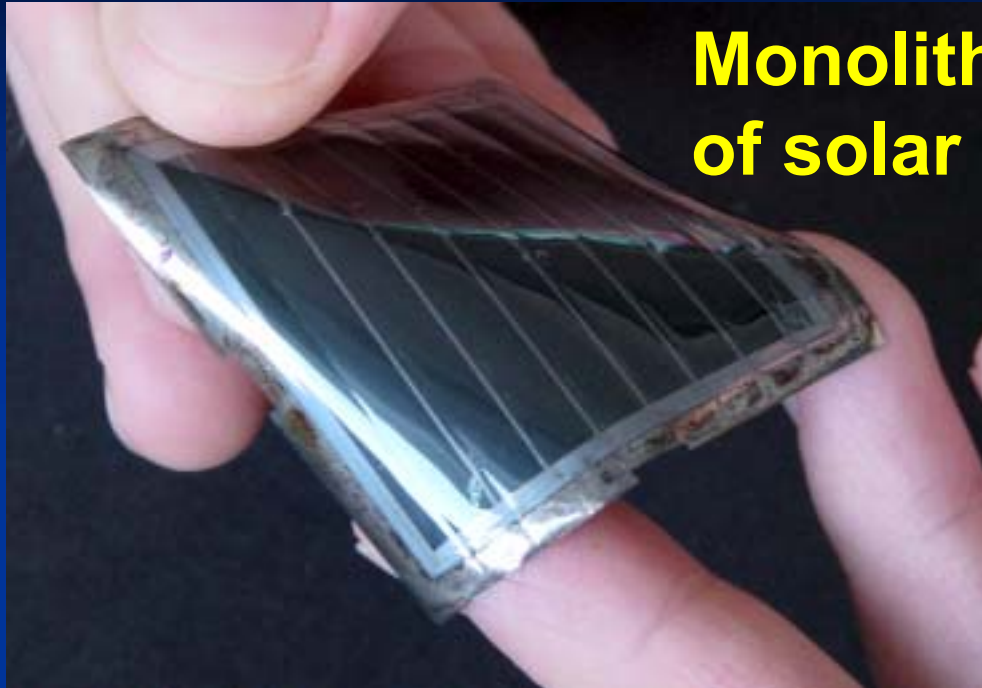
ZnO:Al (1 μm)
CdS or ZnS (0.03 μm)
CIGS (2 μm)
Mo (1 μm)
Substrate

Encapsulation & Lamination

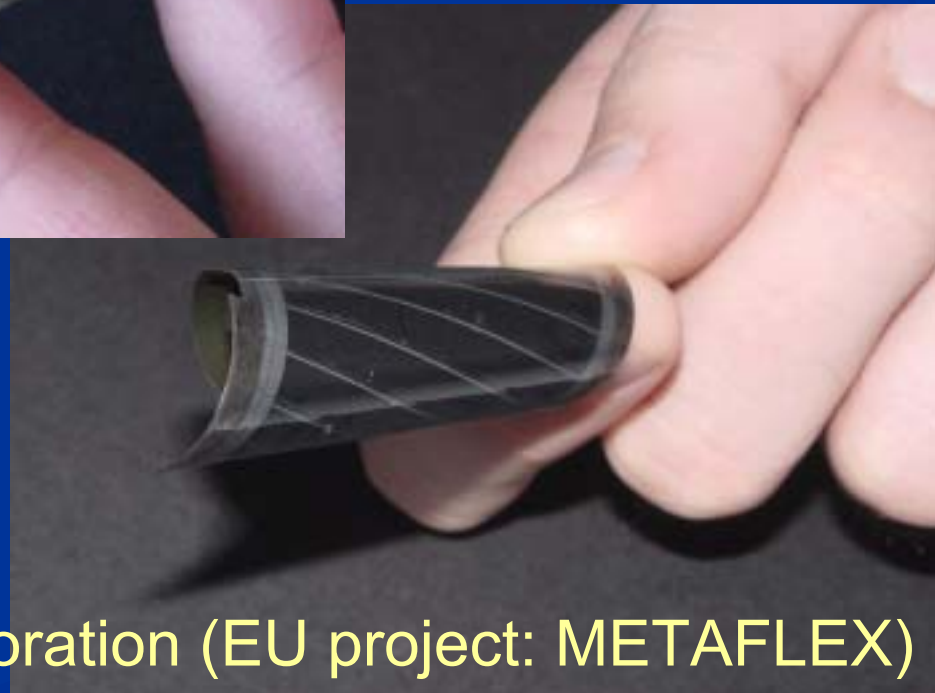


Technology development needed !

Flexible CIGS module on plastic foil



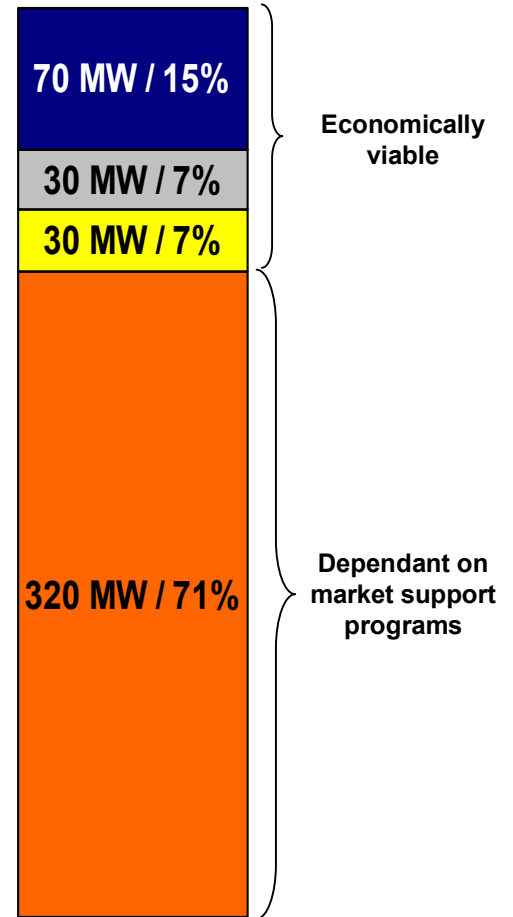
**Monolithic inter-connection
of solar cells**



ETHZ and ZSW collaboration (EU project: METAFLEX)

Applications...

Main terrestrial solar electricity market segments



Market in 2002

Solar Plane with Solar Cells ??



Solar plane developed by Mike Garton, mike@iastate.edu

Lightweight and flexible can help to fly!

But high efficiency needed...

Portable Power for Laptops

Conventional technology: Available but not suitable

Si wafer: Very heavy (2.5 – 3.5 kg)
with (~14% efficiency)

Power requirement:
10 – 50 Watt

a-Si films: Very large area
($>0.66 \text{ m}^2$ with 6% efficiency)

Potential of CIGS flexible
technology:

Very lightweight (10 times lighter)
&

Compact (50% less area needed)



Solar cell applications: Portable power



C-Si wafer based cells: Efficient but heavy, rigid, fragile...

Portable solar modules



**~\$ 25 million - projects
on flexible solar cells**

DARPA, USA announcement in 2004



**U.S. demand for batteries
in military & aerospace:
\$930 million in 2002
\$1,221 million in 2009**

Source: Frost & Sullivan, New York (<http://mae.pennet.com>)

Flexible CIGS modules from Global Solar, USA



Courtesy: <http://www.itnes.com/product>, <http://www.globalsolar.com/>

Solar cell applications: Tents (mostly based on a-Si)



Iowa Thin Film Technologies



www.oksolar.com



www.mpl.ird.fr



www.solarintegrated.com (solar cells from Uni-Solar)

Solar cell applications: Buildings



Solar factory, Gelsenkirchen DE



Solarsail, Münsingen
(www.solarsail.ch)

Imagine rural and urban buildings with flexible PV

Solar Refrigerators: Portable or Fixed

Power requirement: 10 – 80 watts



www.global-merchants.com

Coleman® Exponent® FLEX 5 –Foldable Solar Charger

Efficient chargers: c-Si wafer based



Very heavy !

Solar powered refrigerator for medicine & food

So heavy !

Why not lightweight ?



PV module

Cool box

Photograph Source: Unknown, Sorry!!

Power output from solar module*

12% efficiency means 120 watt from 1 m² surface area exposed to sun

Lower efficiency means larger area needed

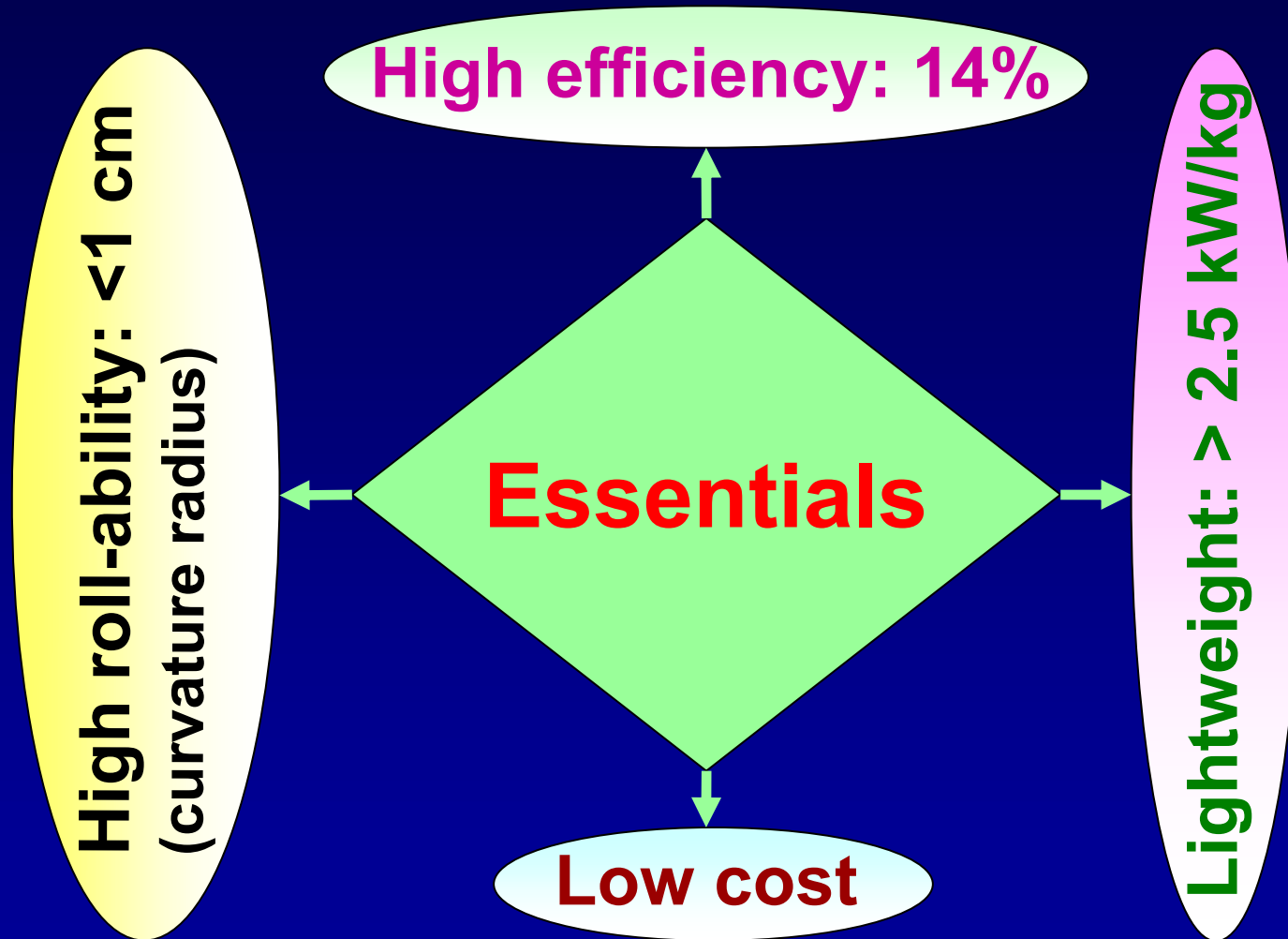
Efficiency*	Area need for 20 W
12% (CIGS)	0.166 m ² (0.3 X 0.55 m ²)
6%	0.332 m ² (0.3 X 1.1 m ²)
3%	0.664 m ² (0.3 X 2.2 m ²)

*- Under AM1.5 illumination

Importance of efficiency to meet the power requirement

Module efficiency (%)	Deliverable output power (W) from 1 m ² module		
	Incident solar energy (W/m ²)		
	1000 (Sunny)	500	200 (Cloudy)
15	150	75	30
10	100	50	20
5	50	25	10

ETHZ solar cell: Unique combination of 4 attributes in 1 device



ETH (Swiss Federal Institute of Technology) Zurich

Thin Film Physics Group

www.tfp.ethz.ch

Outlook

**Higher efficiency, lightweight
and flexible solar modules**



**Larger area scale-up
production**

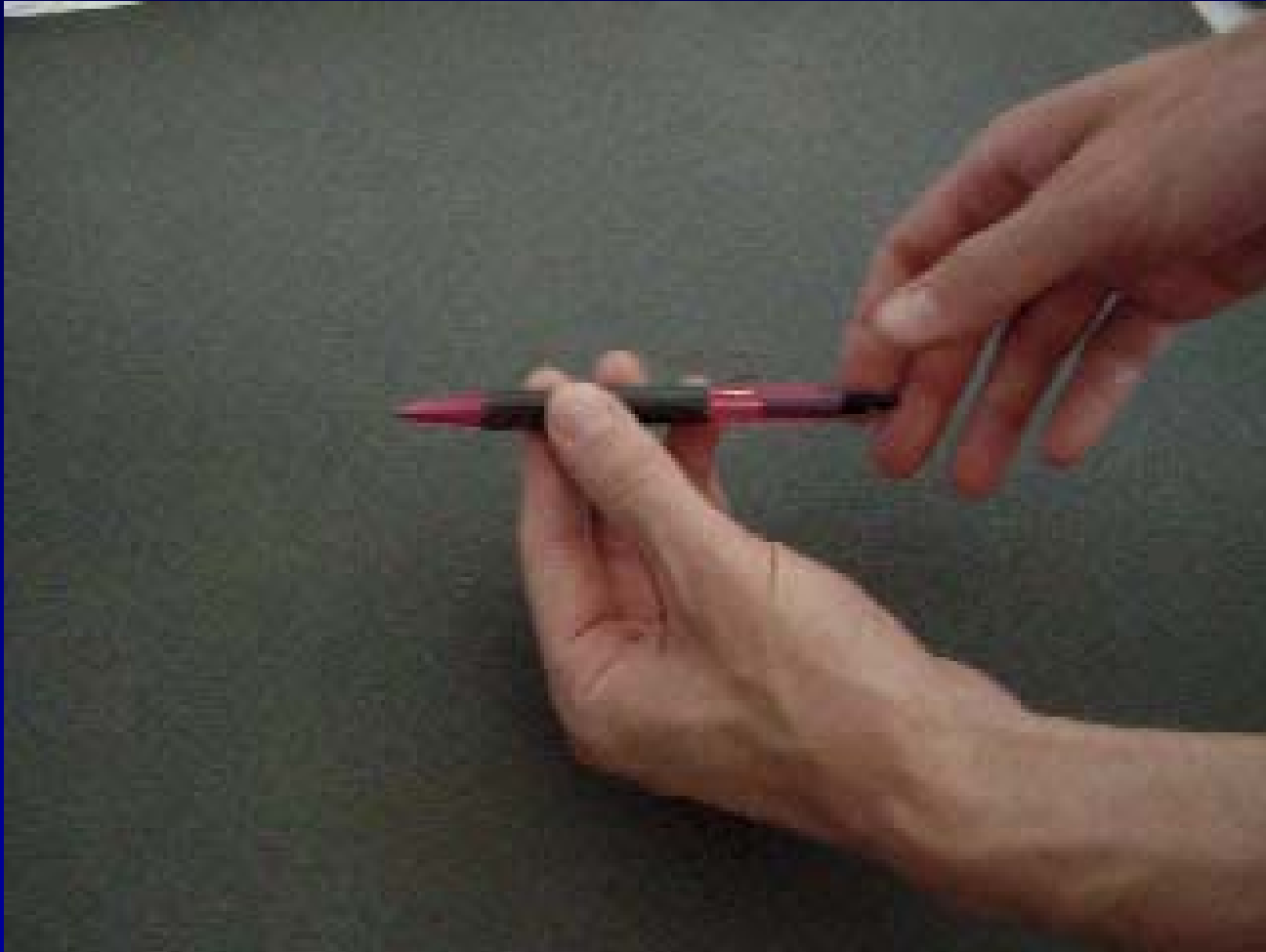


Applications



Cost reduction

R&D to industrial manufacturing & viable solutions



ETH (Swiss Federal Institute of Technology) Zurich

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Innovative R&D to industrial manufacturing

Flexible CIGS on plastic foil of 30 x 30 cm² area

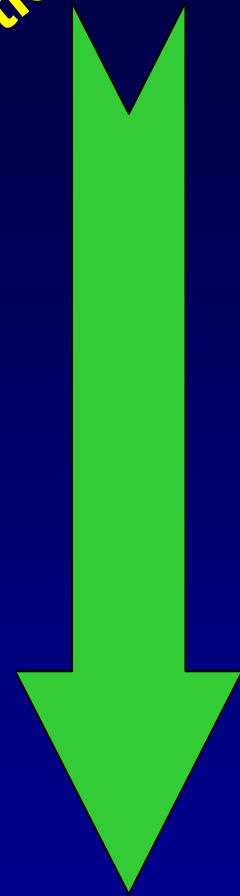


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Challenge
Transfer of research excellence to industrial production



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