Transparent conductive oxides for silicon heterojunction solar cells

TCM 2018, TCM-020.ID182 | P. Carroy, D. Muñoz, F. Métral, H. Fournier, J. Veirman, J.F. Lerat, P. Lefillastre

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OUTLINE

Introduction: presentation of the National Institute for Solar Energy (INES)

Silicon heterojunction (SHJ) solar cells

- Structure and operation
- Role of TCOs in SHJ cells
- SHJ solar cells and modules at INES

TCOs for SHJ cells

- Baseline TCO at INES
- Alternative TCO options
- Example of alternative TCO options tested at INES

Conclusions

INES (National Institute for Solar Energy) – CEA LITEN

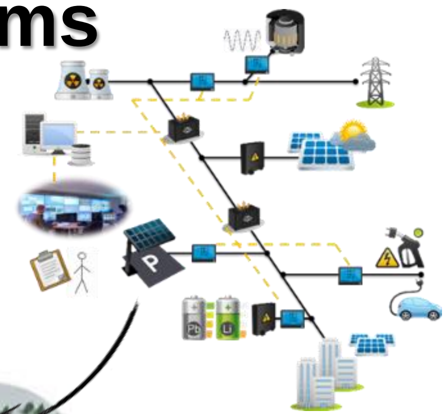
Covering the whole value chain, from material to systems including building integration and solar mobility

photovoltaic

material
cells
modules

systems

software & electronics
storage
grid
mobility & loading



building

Thermal systems
envelope
management

~ 450-500 persons

~ 70 patents a year

200 industrial partners

Budget **~ 60 M€**

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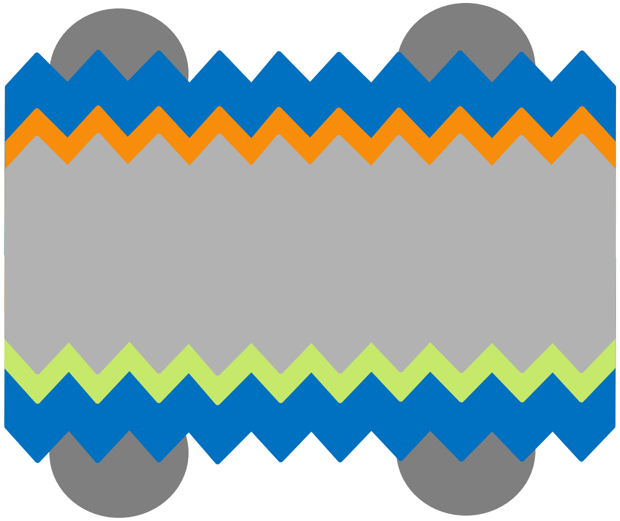
a-Si:H/c-Si heterojunction solar cell



- High η (25.1% [1], 26.7% IBC [2]) thanks to very high V_{OC}
- Bifacial device
- Low temperature (< 200ºC) processes
- Simple process
- Compatible with thin wafers

BUT:

1. **Very low conductivity of a-Si:H (<10^{-2} S/cm)**
   ➔ Lateral conduction is not enough for carrier collection (↓ **FF**)
2. **a-Si:H does not have antireflecting properties (↓ J_{SC})**

➔ **Need of TCOs!**

[1] D. Adachi et al., Applied Physics Letters, 107, 233506 (2015)
[2] K. Yoshikawa et al, Nat Energy. 2, 17032 (2017)

Role of TCOs in SHJ cells

Electrical requirements

1. **Carrier transport** to the metal contacts at the front and back side
2. **Low contact resistivity** with metal contacts and with a-Si:H layers

Optical requirements

1. **Antireflection** coating
2. **Transparence** 300-1200 nm, limited IR absorption

No degradation of the a-Si:H layers

1. **Soft deposition** conditions (T<200ºC, low ion bombardment…)
2. **Diffusion barrier** to metallic impurities (Cu…)

Adapted for module integration

1. **Stability** in time, no reaction with encapsulation material
2. **No ageing** with air/water…

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SILICON HETEROJUNCTION (SHJ) SOLAR CELLS

SHJ solar cells and modules at INES

Pre-industrial production line for silicon heterojunction solar cells

- <10h from wafer to cell
- Up to 2400 wafers/hour

→ **R&D with statistics**

Numerous industrial and institutional partners

MEYER BURGER | enel Green Power | AMPERE | HORIZON 2020 | DISC | AGENCE NATIONALE DE LA RECHERCHE ANR

→ **Versatile research**

Configuration	Record η
4 busbars (BB4)	22.8%
5 busbars (BB5)	23.1%
6 busbars (BB6)	23.1%
Busbar-less (BB0)	23.5%

410 W_P
72-cell module

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TCOs for SHJ cells

- **Baseline TCO at INES**
- **Alternative TCO options**
- **Example of alternative TCO options tested at INES**

Conclusions

Baseline TCO at INES

Sputtered In_2O_3:Sn (ITO)

- Industrial in-line sputtering tool by Meyer Burger: up to 2400 w/h
- In_2O_3/SnO_2 3 wt% rotary targets
- Simultaneous front and back side deposition

Limitations of sputtered ITO

1. Limited mobility
   - σ/T compromise → FF/J_{SC} compromise
   - $\sigma = qN\mu$
   - But: high N generates free carrier absorption (FCA)

   → need of **high μ material**
2. High ion bombardment induced by sputtering
   - Degradation of a-Si:H layers → V_{OC} and FF ↓

   → need of **soft deposition techniques**
3. Scarcity and costliness of In

   → need of **In-free TCOs** to ↓ costs

TCOS FOR SHJ SOLAR CELLS

Alternative TCO options

	PVD		CVD		
	Sputtering	RPD	MOCVD	ALD	AP-SALD
ITO:H	High-μ TCO	High-μ TCO, Low-damage			
In_2O_3:H	High-μ TCO	High-μ TCO, Low-damage		High-μ TCO, Low-damage	High-μ TCO, Low-damage
In_2O_3:W	High-μ TCO	WR; High-μ TCO, Low-damage			
ZnO:Al	In-free TCO		In-free TCO, Low-damage	In-free TCO, Low-damage	In-free TCO, Low-damage
ZnO:B	In-free TCO		In-free TCO, Low-damage	In-free TCO, Low-damage	In-free TCO, Low-damage

μ High-μ TCO   Low-damage   In In-free TCO

TCOS FOR SHJ SOLAR CELLS

Alternative TCO options tested on INES SHJ cells

	Sputtering	RPD	MOCVD	ALD	AP-SALD
ITO:H	**ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE**				
In_2O_3:H	**ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE**			ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE	
In_2O_3:W	**ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE**	ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE			
ZnO:Al	**ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE**			ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE	**ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE**
ZnO:B			ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE		

ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE → Tested on SHJ cells produced at INES

ines INSTITUT NATIONAL DE L'ENERGIE SOLAIRE (boxed) → Presented here

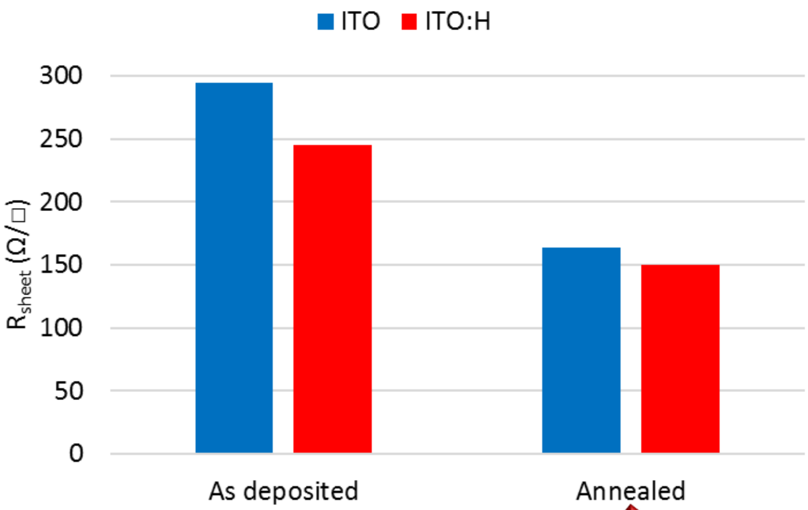
TCOS FOR SHJ SOLAR CELLS

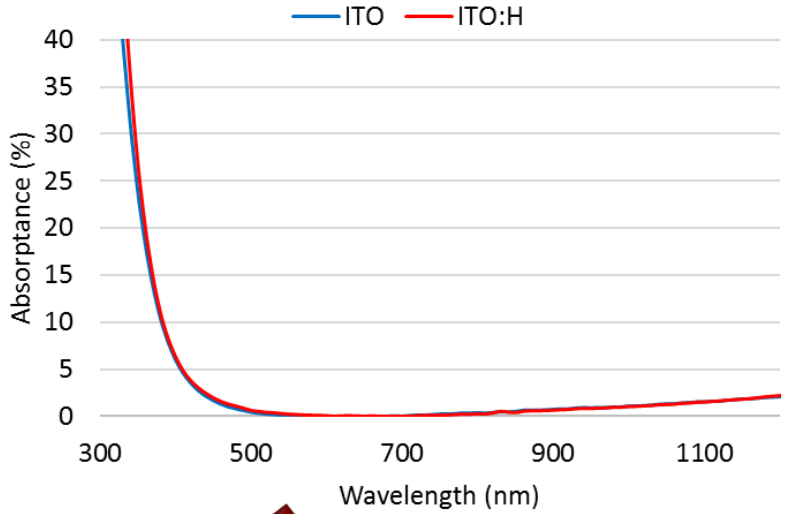
Alternative TCO options: sputtered ITO:H

In collaboration with MEYER BURGER

ITO:H:

- Slightly less resistive than ITO
- Similar absorptance as ITO, including in the near-IR





Bifacial BB0 cell results

	Voc (mV)	FF (%)	Jsc (mA/cm^2)	η (%)
ITO	731.1	79.99	37.93	22.16
ITO:H	731.2	**80.59**	37.90	**22.31**

Alternative TCO options: sputtered In_2O_3:H (IOH)

IOH

- Very low R_{sheet} thanks to very high μ
- Very low absorption thanks to limited N

R_{sheet} (Ω/□)	N (cm^{-3})	μ ($cm^2/V/s$)	$A_{300-1200nm}$ (%)
30	1.4E20	140	1.1

Electroplated BB4 cell results

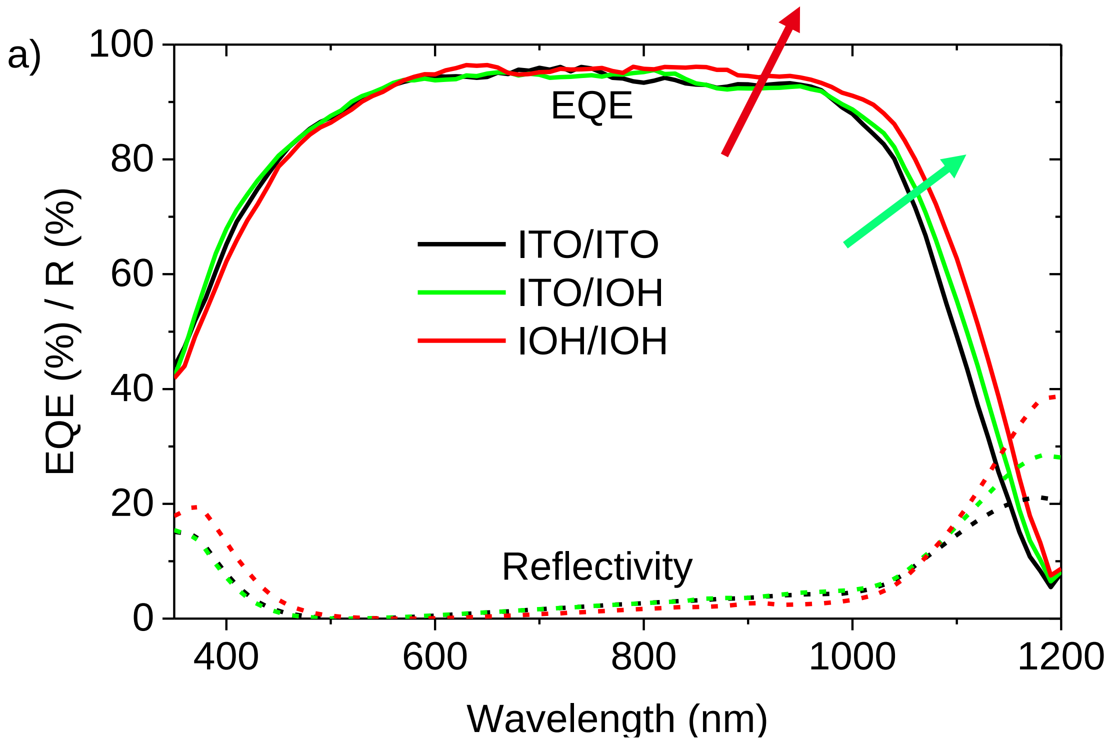
Front/back contact	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF (%)	η (%)
ITO/ITO	723.8	36.8	80.3	21.4
ITO/IOH	728.9	**37.4**	**79.2**	**21.6**
IOH/IOH	728.3	**37.5**	**79.4**	**21.7**

η ↑ with IOH thanks to significant J_{SC} ↑ and despite FF ↓ due to worse electrical contact

TCOS FOR SHJ SOLAR CELLS

Alternative TCO options: sputtered In_2O_3:H (IOH)

IOH: where is the current gain?



↑ EQE in the near-IR range when replacing ITO by IOH

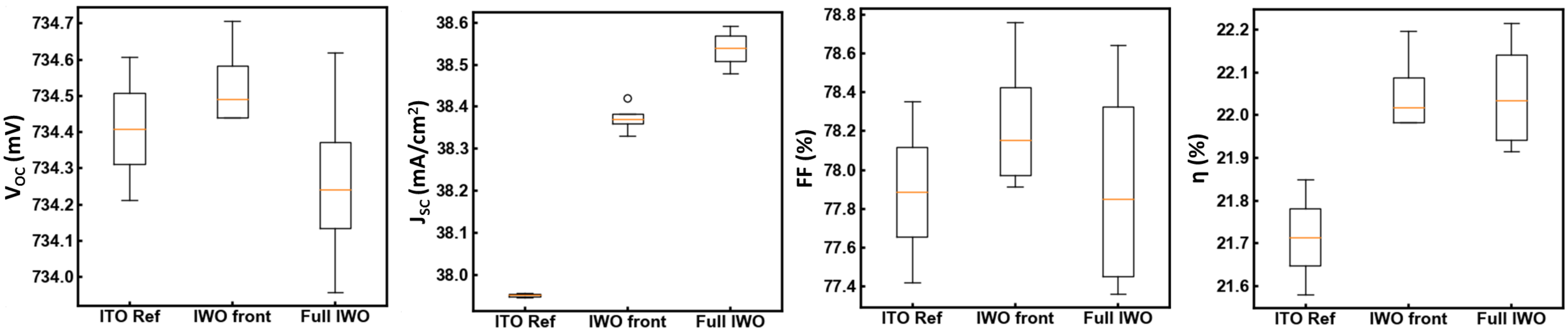
→ low N of IOH layers leading to lower FCA in the near-IR

TCOS FOR SHJ SOLAR CELLS

Alternative TCO options: sputtered In_2O_3:W (IWO)

IWO

- High-μ TCO: > 80 $cm^2/V/s$
- Developped by CSEM (Swiss Center for Electronique and Microtechnique) and integrated on INES SHJ cells in the framework of EU project AMPERE



G. Christmann et al., 35th EUPVSEC proceedings, to be published (2018)

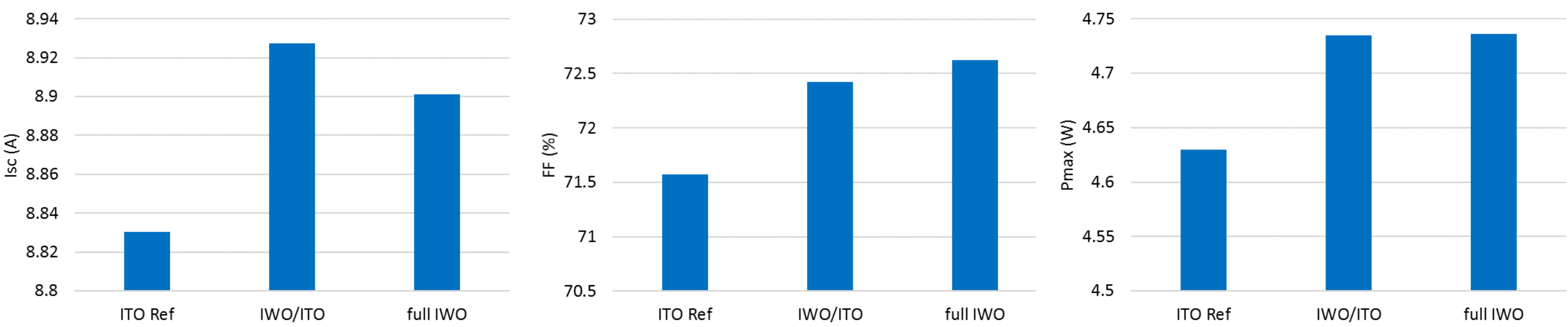
Strong J_{SC} ↑ with IWO as front TCO, even higher J_{SC} with double-side IWO application
Similar FF as ITO
→ Significant efficiency gain with IWO compared to ITO

TCOS FOR SHJ SOLAR CELLS

Alternative TCO options: sputtered In_2O_3:W (IWO)

IWO: gain confirmed in module

- 1-cell mini-modules for this 1st test
- 2 modules/condition



Potential: +7-8 W in a 72-cell module

TCOS FOR SHJ SOLAR CELLS

Alternative TCO options: sputtered ZnO:Al (AZO)

In collaboration with MEYER BURGER

AZO
- Cheap In-free material
- High R_{sheet} due to low µ
- Slightly higher absorption than ITO

R_{sheet} (Ω/□)	N (cm^{-3})	µ ($cm^2/V/s$)	$A_{300\text{-}1200nm}$ (%)
200-300	2.5-3E20	7-14	3

Slightly lower J_{SC} with AZO

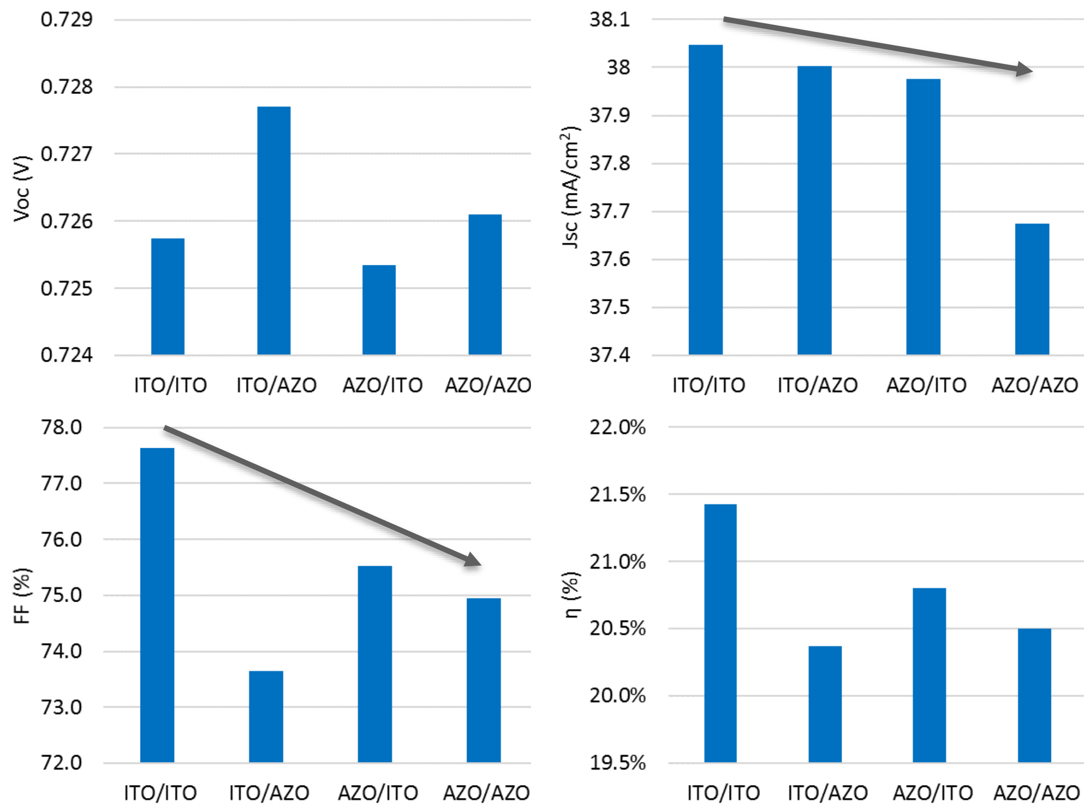
FF ↓↓ with AZO, especially when integrated at the back

→ η ↓ with AZO

But: **acceptable performance with front AZO** only

What about stability?

Bifacial BB0 cell results



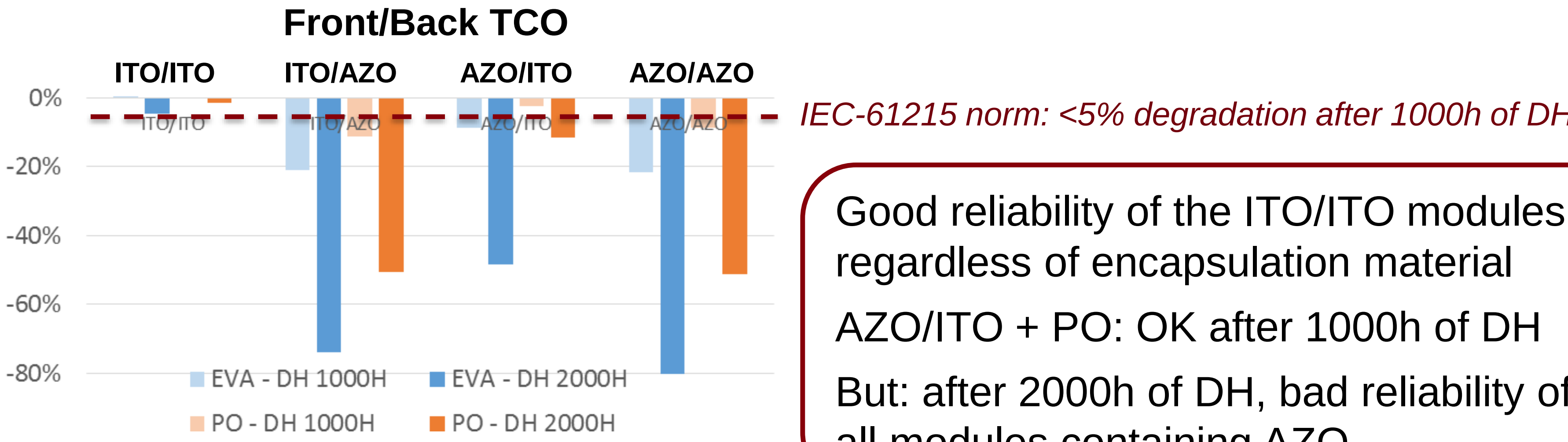
TCOS FOR SHJ SOLAR CELLS

Alternative TCO options: sputtered ZnO:Al (AZO)

In collaboration with MEYER BURGER

AZO: module reliability

- 4-cell mini-modules
- 4 TCO configurations: ITO/ITO, ITO/AZO, AZO/ITO, AZO/AZO
- 2 different encapsulations: polyolefin (PO) vs ethylene-vinyl acetate (EVA)
- module degradation after 1000h and 2000h damp-heat test (85ºC, 85% humidity)



Good reliability of the ITO/ITO modules regardless of encapsulation material

AZO/ITO + PO: OK after 1000h of DH

But: after 2000h of DH, bad reliability of all modules containing AZO

TCOS FOR SHJ SOLAR CELLS

Alternative TCO options: spatial ALD AZO (SALD AZO)

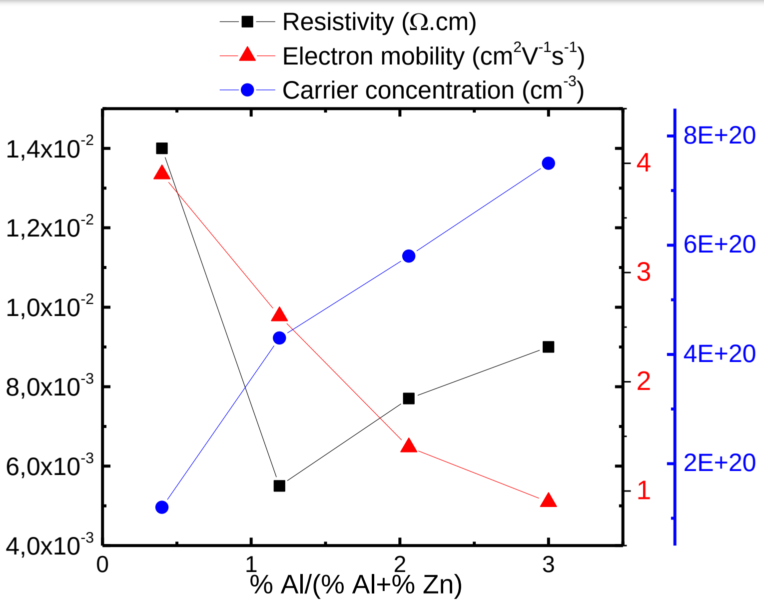
AP-SALD AZO

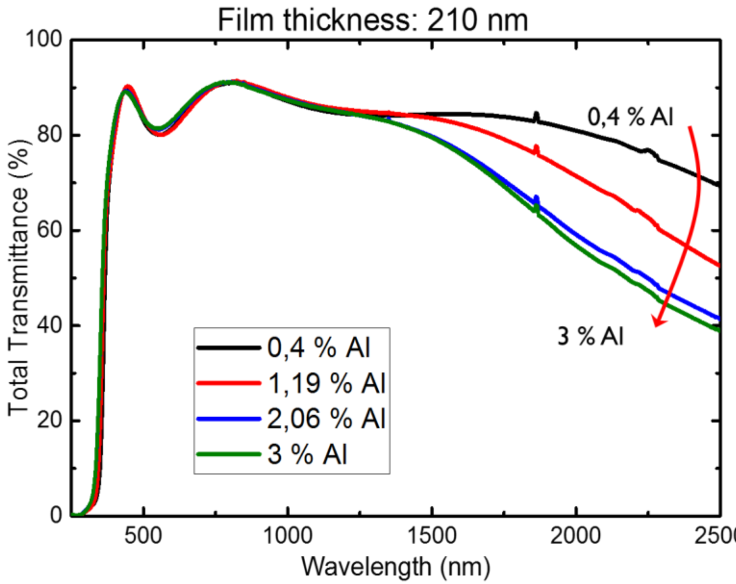
Developped by LMGP (Materials and Physical Engineering Laboratory) in the framework of ANR DESPATCH project

AGENCE NATIONALE DE LA RECHERCHE ANR

- Cheap In-free material
- Low-damage deposition method
- Fast and easily scalable deposition method
- High R_{sheet} due to very low µ
- High transmission in the 300-1200 nm range

Learn more on SALD AZO:
V. Nguyen, TCM030,
Wednesday 17th at 17:40





V.H. Nguyen et al, J. Renew. Sustain. Energy 9, 21203 (2017)

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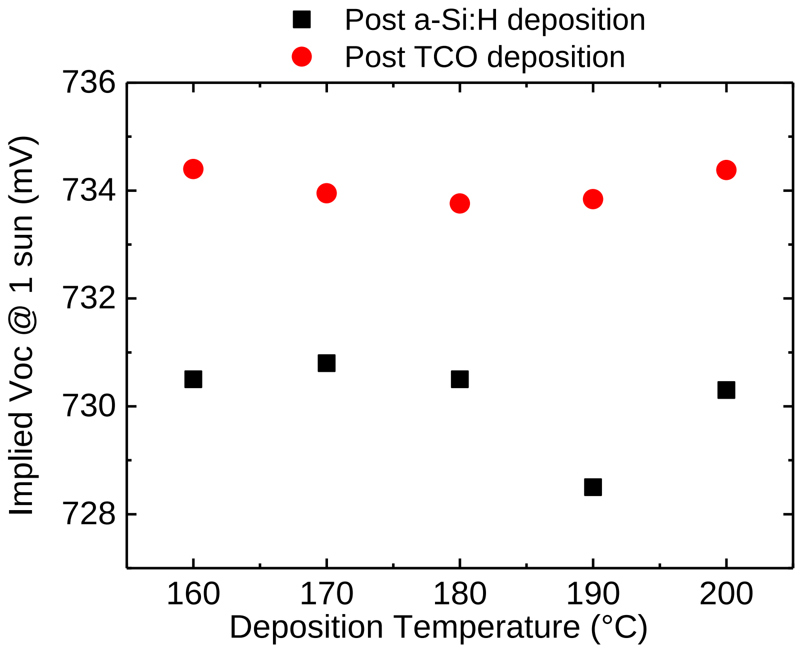
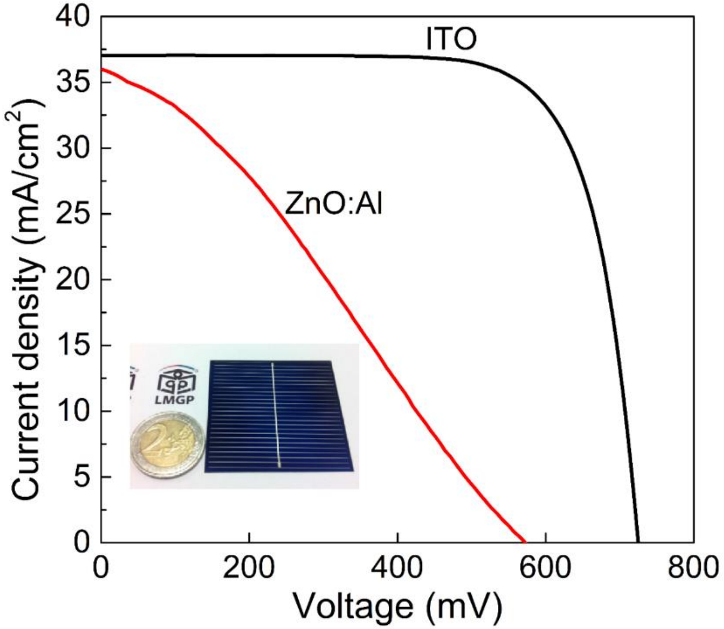
Alternative TCO options: spatial ALD AZO (SALD AZO)

AP-SALD AZO: application on CEA-INES SHJ solar cells

Quasi-steady-state photoconductance measurement



Light I(V) measurement



i-V_{OC} slightly ↑ after AZO deposition

➡ No degradation of the passivation with SALD AZO

But: very poor cell performance due high series resistance

V.H. Nguyen et al, J. Renew. Sustain. Energy 9, 21203 (2017)

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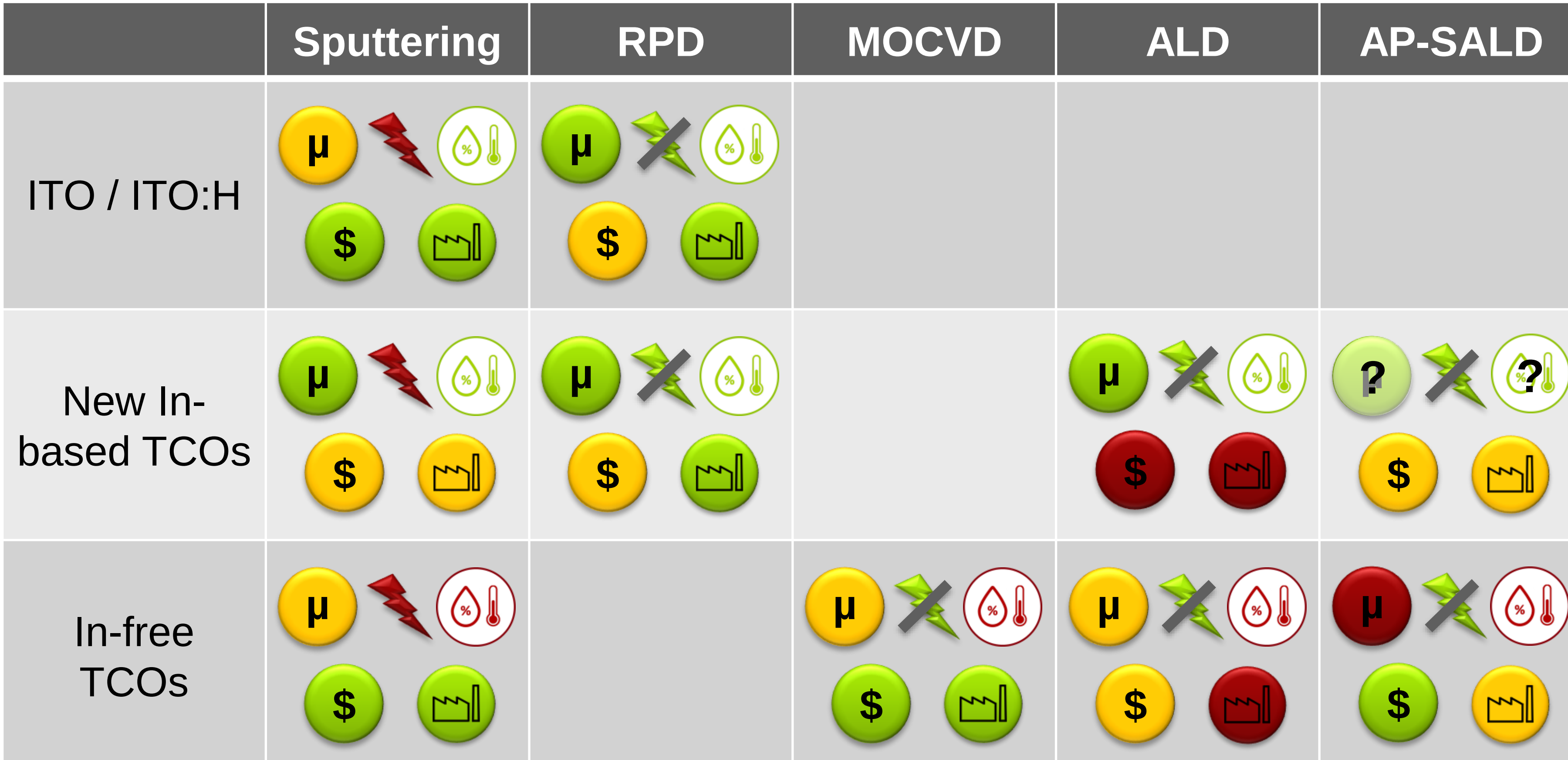
CONCLUSIONS



μ Mobility Bombardment Reliability $ Cost Compatibility with mass production

Best alternative to sputtered ITO: new In-based TCOs by RPD

Thank you for your attention!

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