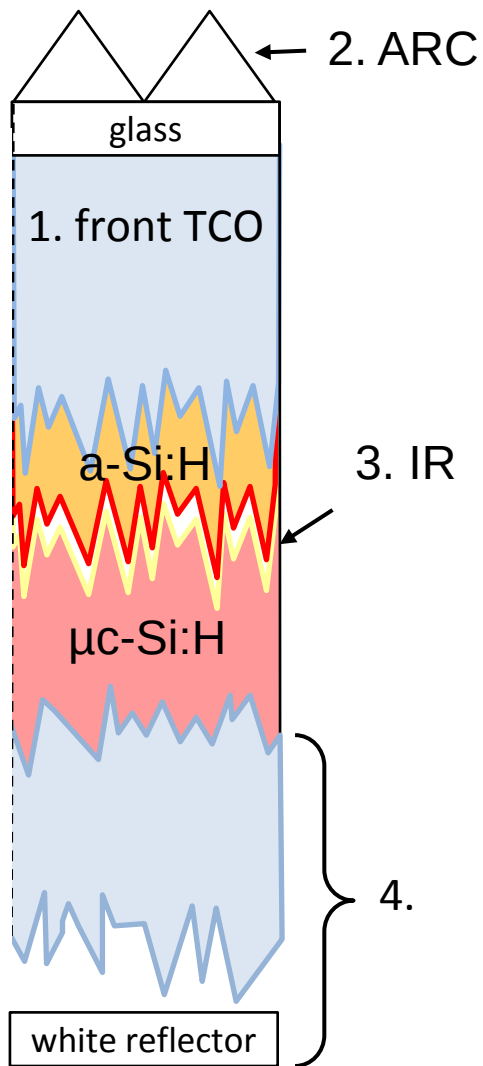




Influence on the opto-electronic properties of the different interfaces in thin-film silicon tandem solar cells

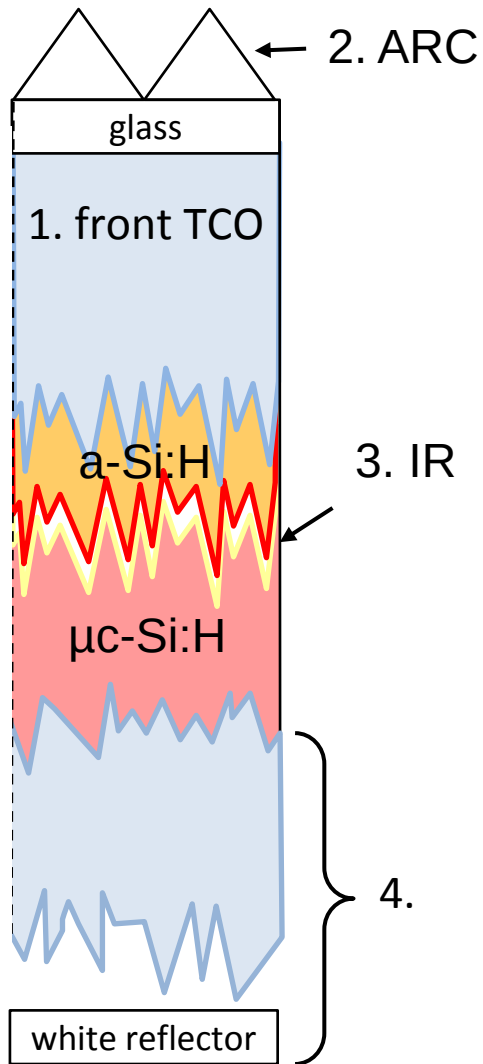
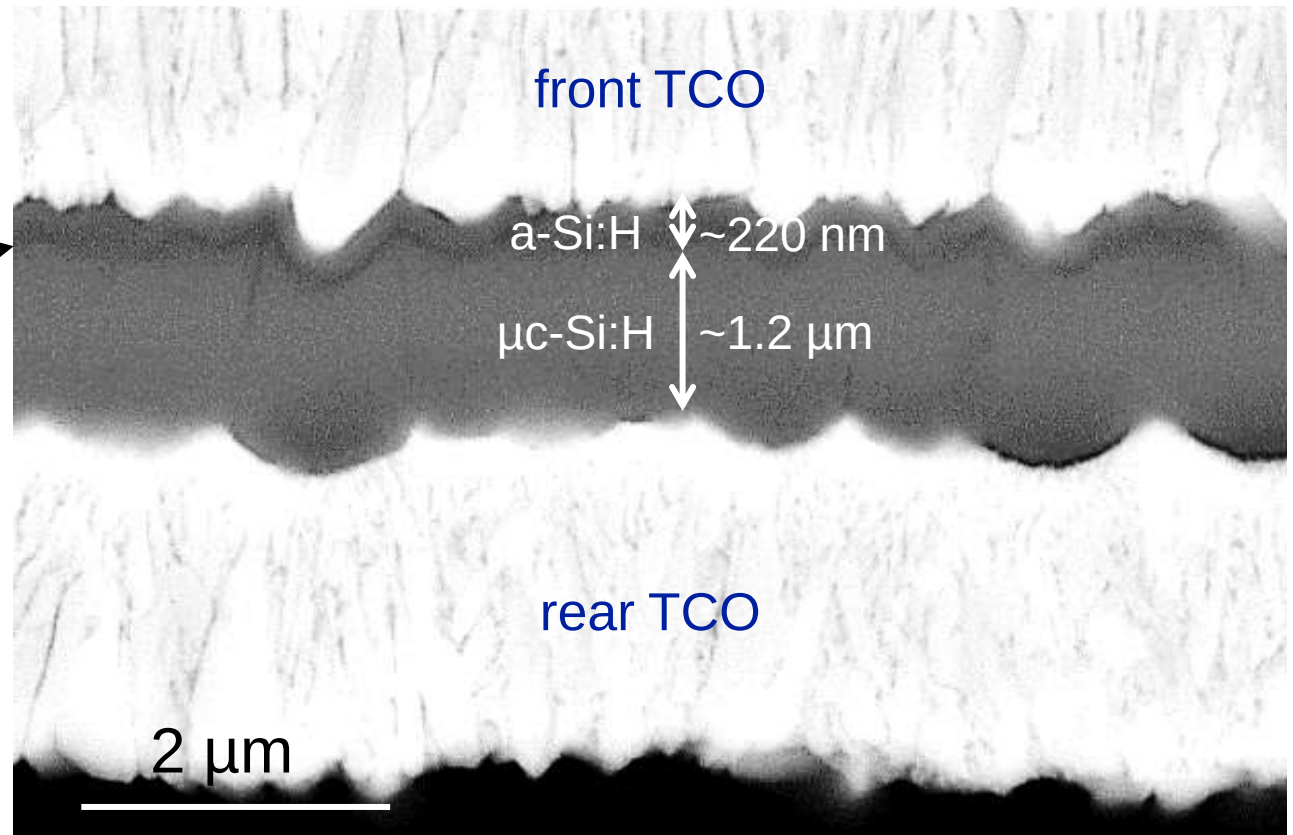
Etienne Moulin, Elmar Feuser, Björn Niesen, Franz-Josef Haug, Christophe Ballif
EUROREG-PV 1-3 Sept 2014

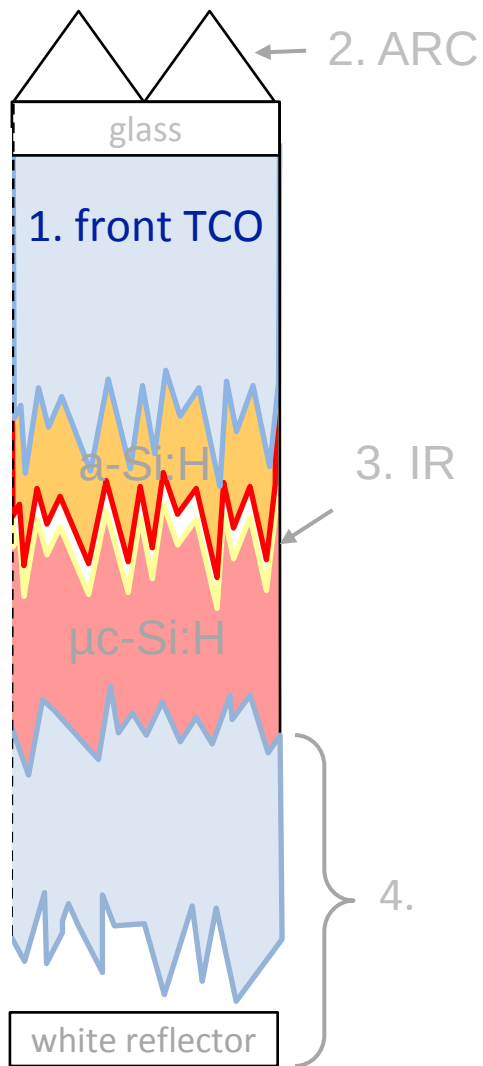
Outline



- 1. front-TCO/a-Si:H-cell interface
- 2. “glass”/air interface (ARC)
- 3. intermediate reflector (IR) for various front TCOs
 - Impact of IR on $EQE (= J_{sc})$
 - Impact of IR on electrical performance
- Best combination of 1., 2. and 3.
- 4. back reflector scheme (separate study)
- Conclusions

Micromorph cell design : a-Si:H / IR / μ c-Si:H

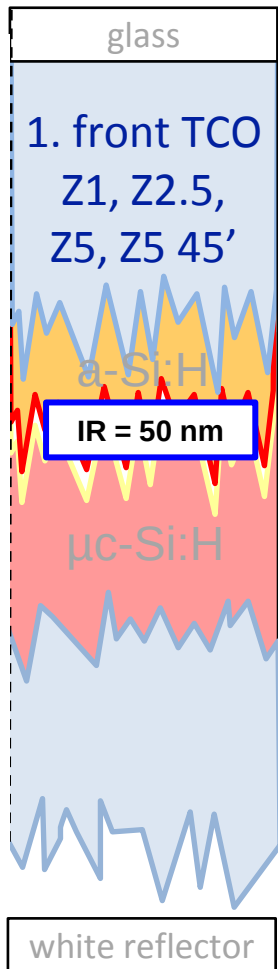




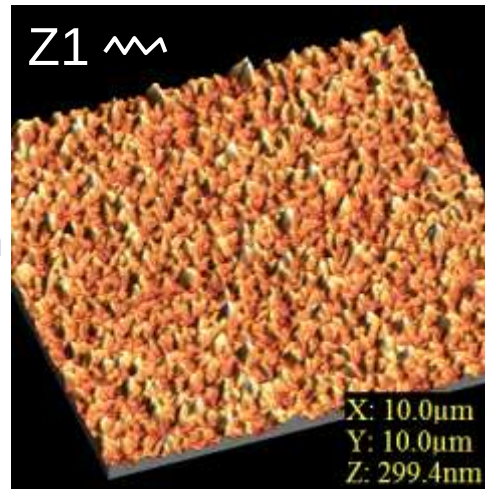
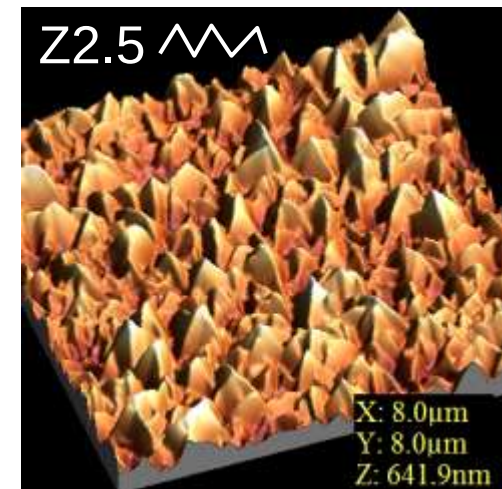
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1. front-TCO/a-Si:H-cell interface

Various front TCOs (LPCVD ZnO)

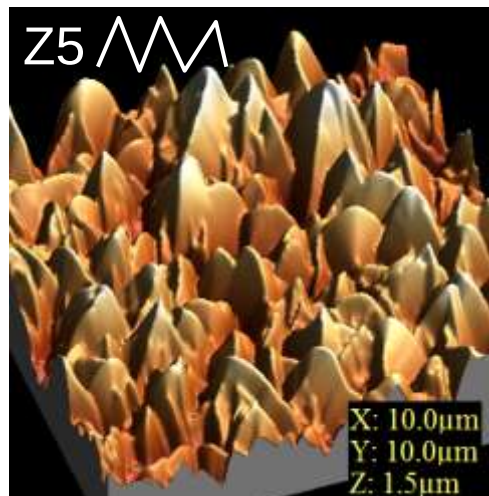
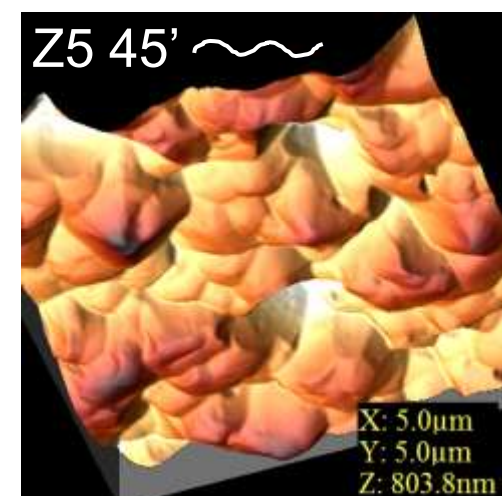


feature
size:
~200 nm



feature
size:
~500 nm

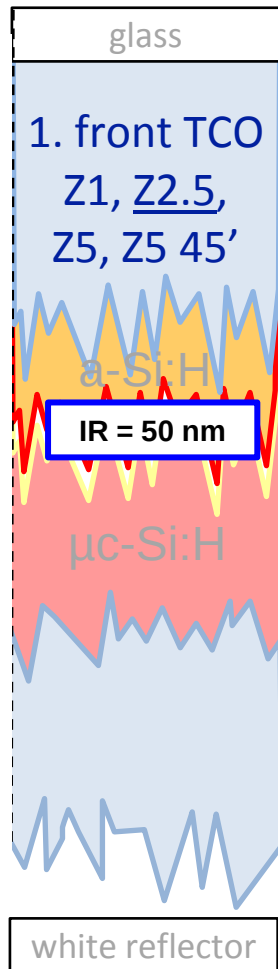
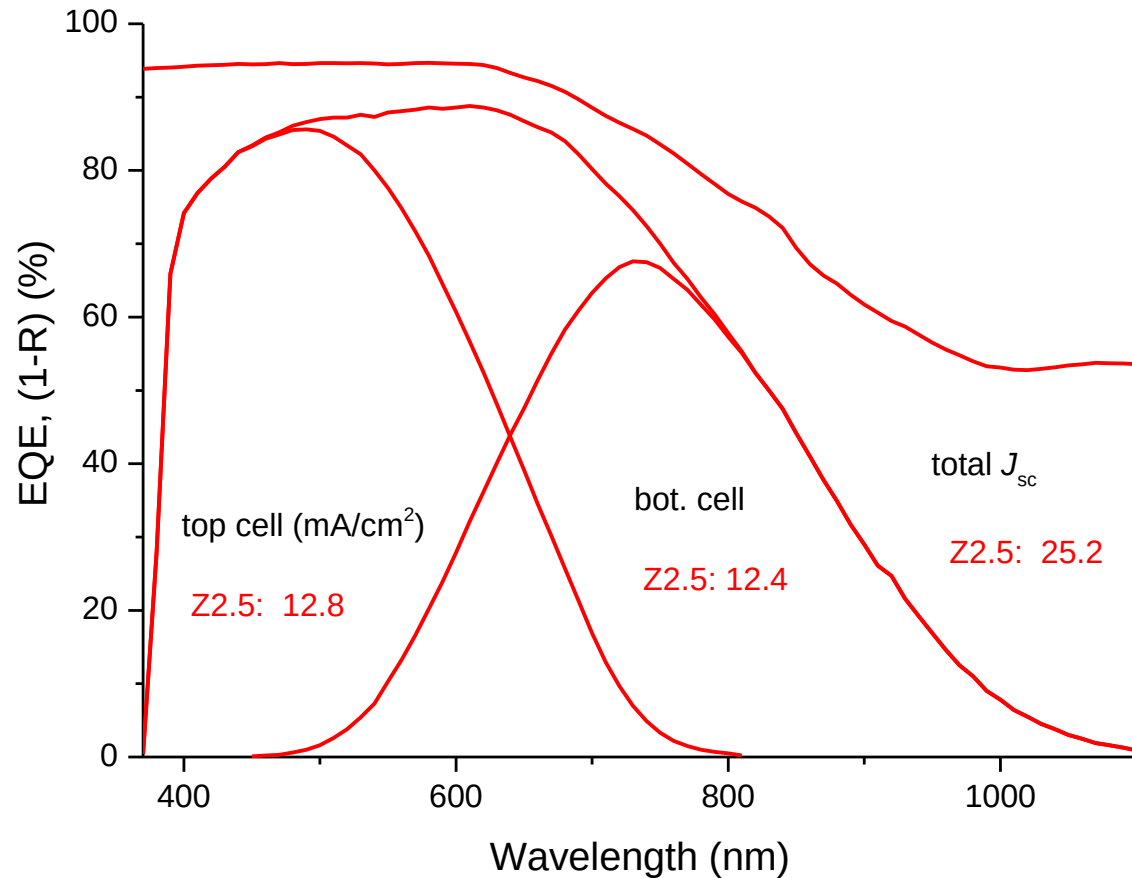
~1 μ m



~1 μ m

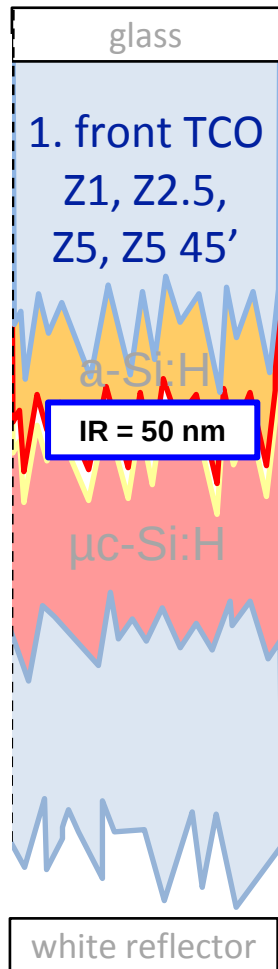
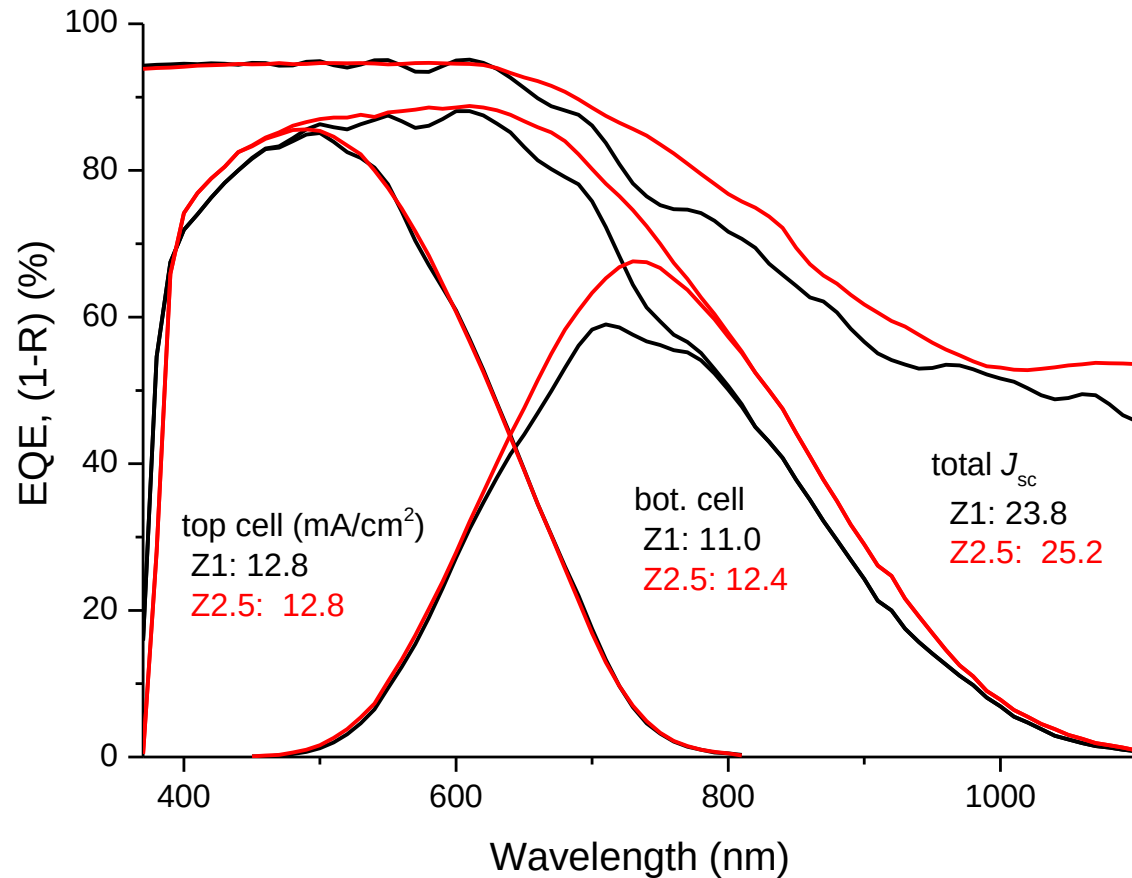
1. front-TCO/a-Si:H-cell interface

Impact of the front-TCO layer on EQE (J_{sc-top} , J_{sc-bot} , $J_{sc-total}$)



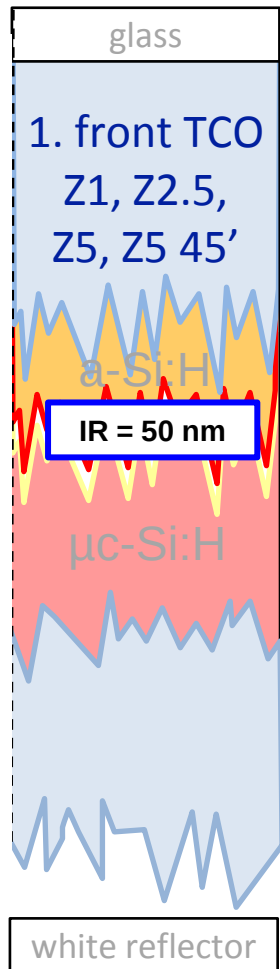
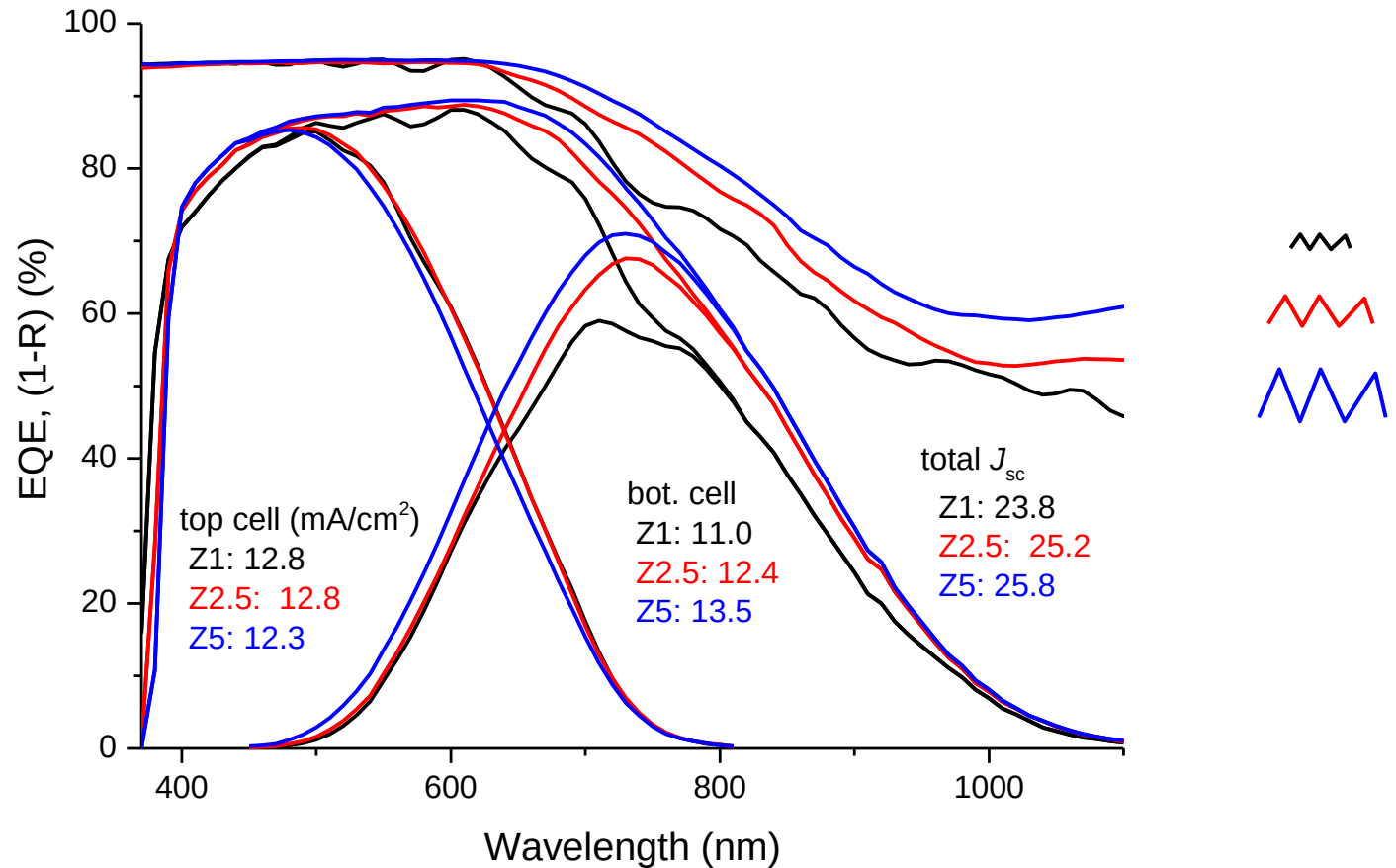
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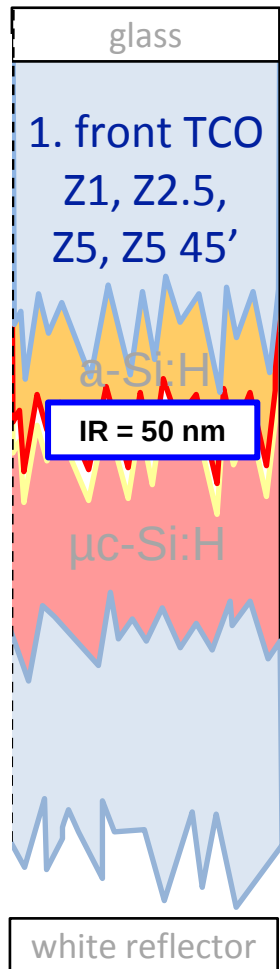
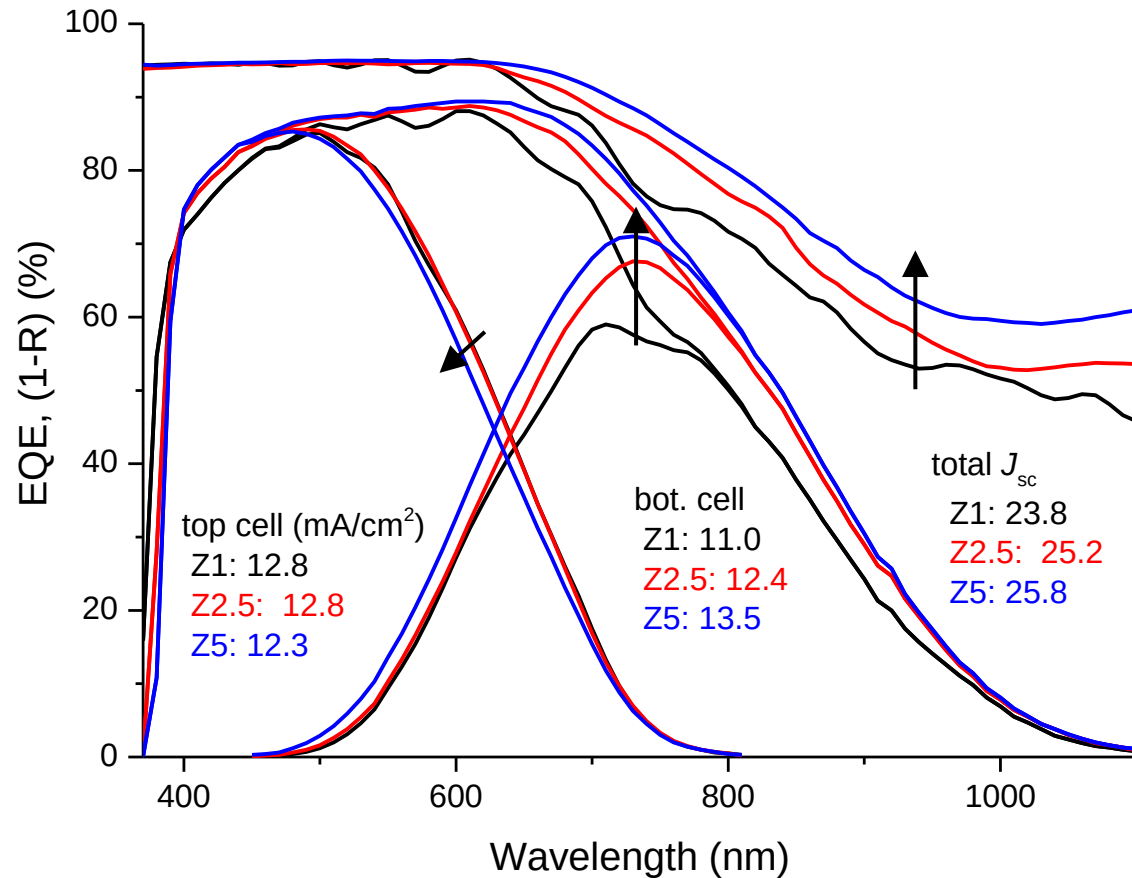
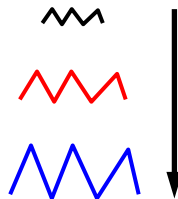
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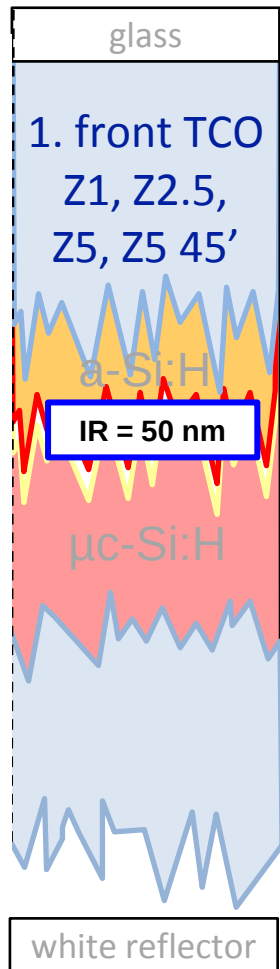
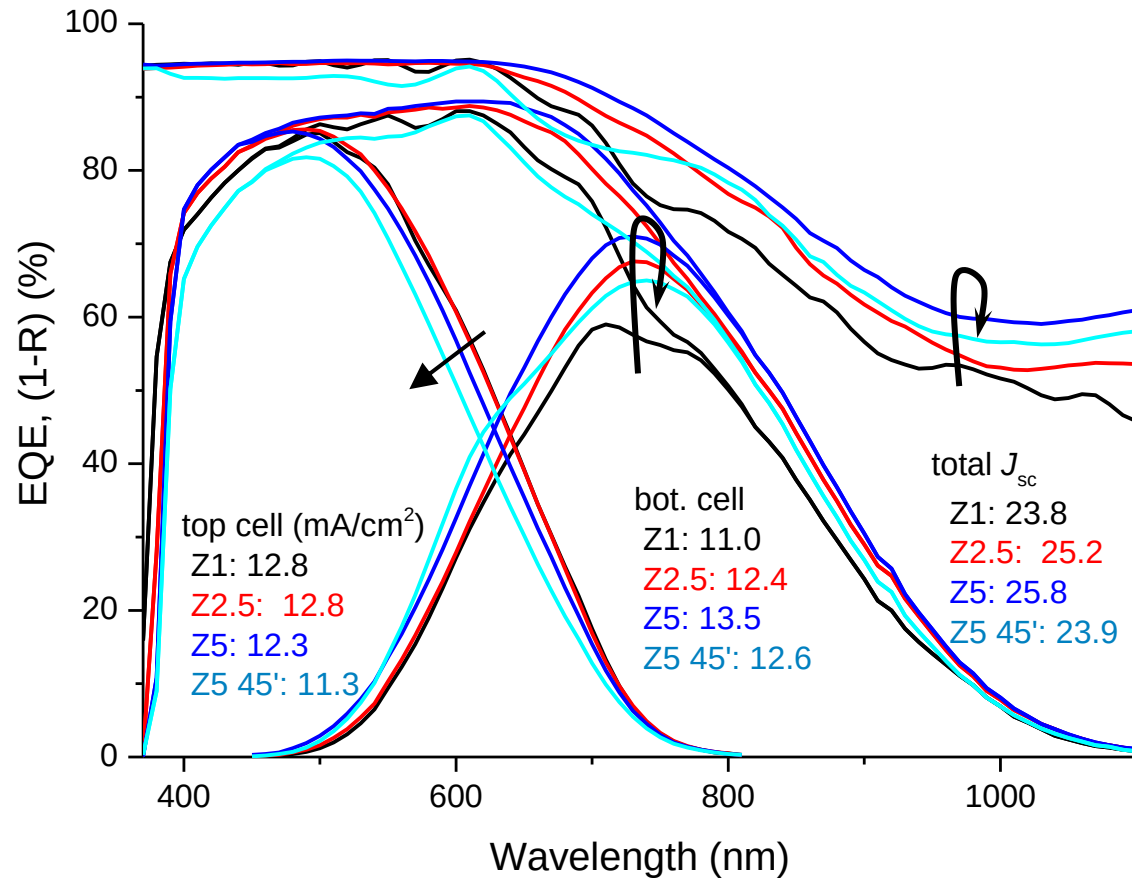
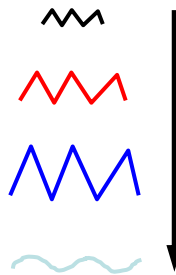
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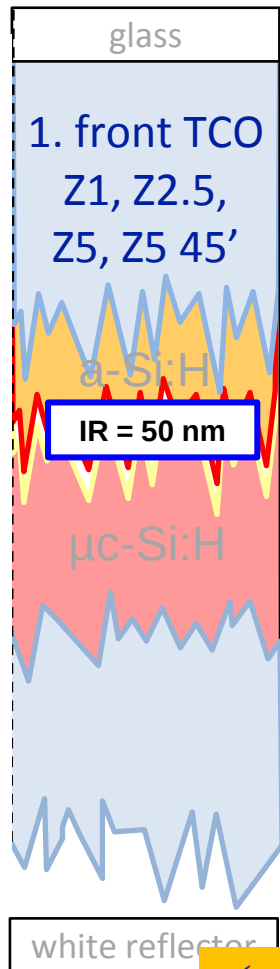
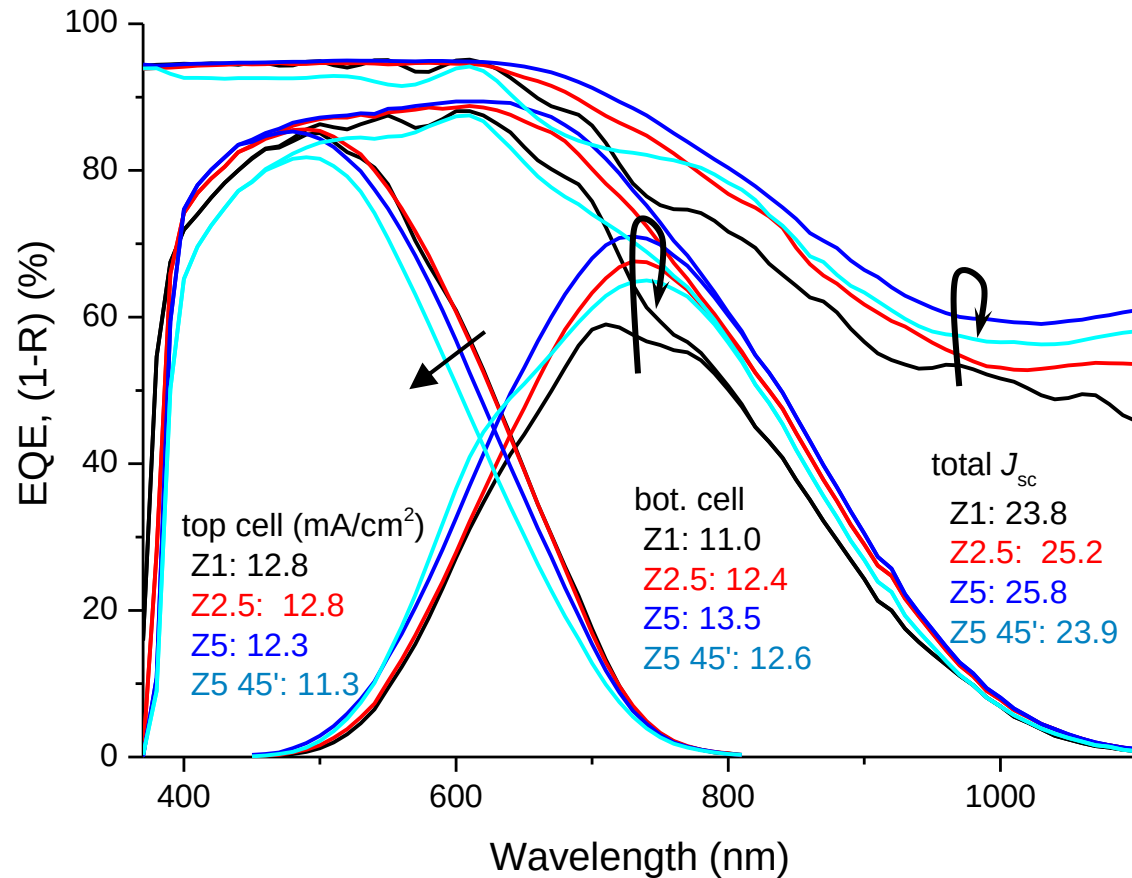
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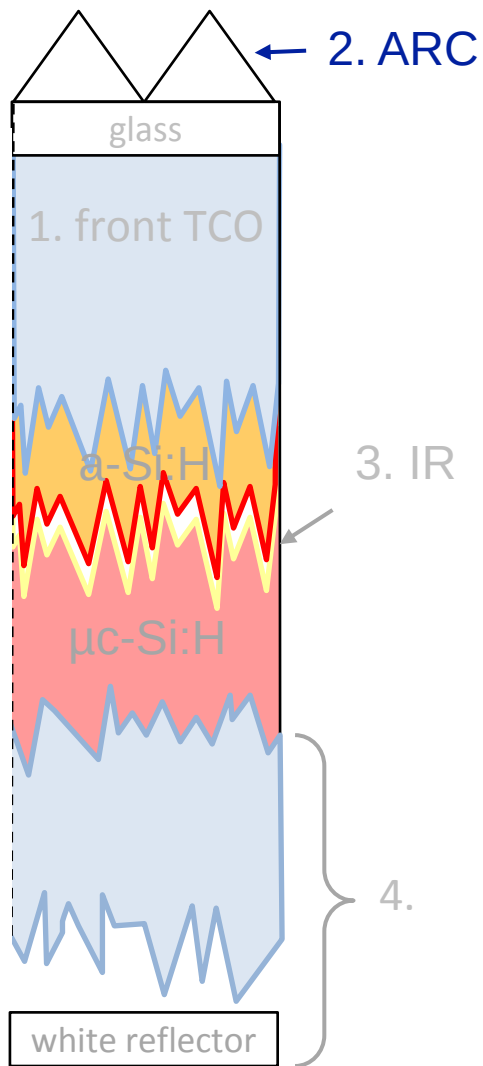


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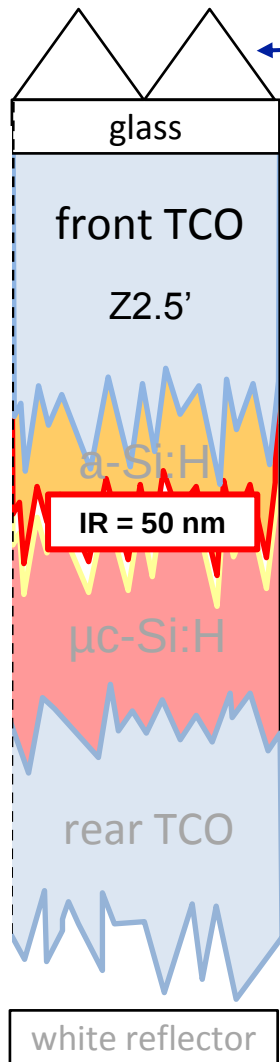


- ✓ small sharp features → light coupling
- ✓ large sharp features → light trapping (but weaker interplay with IR)
- ✓ smoothening → weaker light coupling and trapping

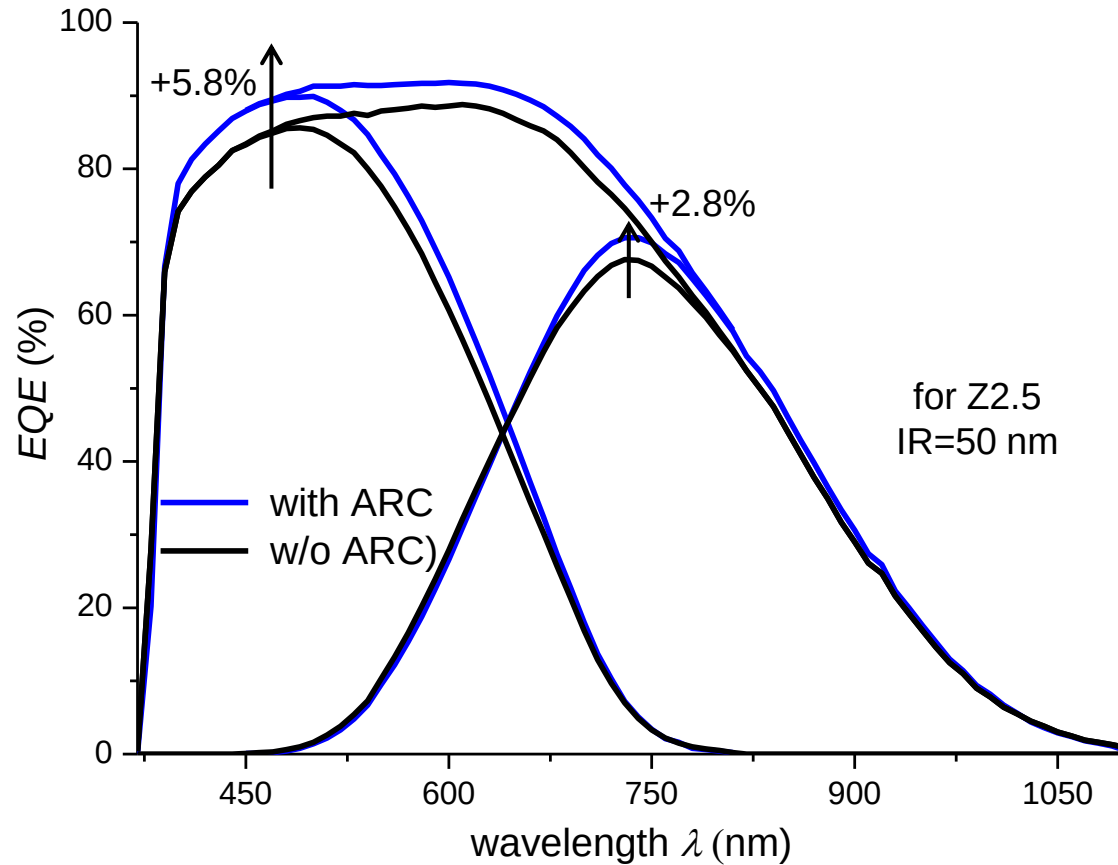


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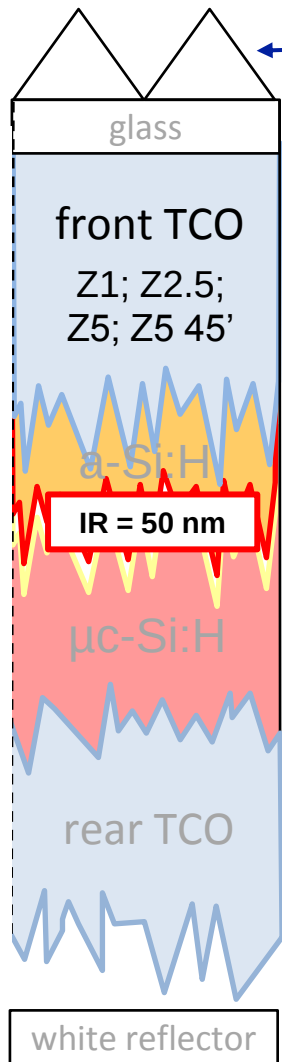
2. “glass”/air interface (ARC)



Impact of the ARC on EQE (J_{sc-top} , J_{sc-bot} , $J_{sc-total}$)



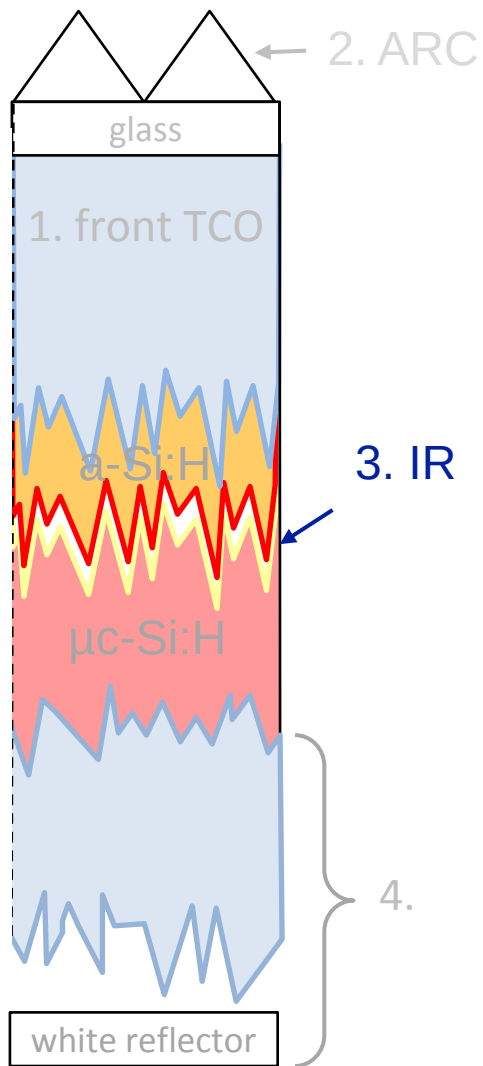
2. “glass”/air interface (ARC)



Impact of the ARC on EQE (J_{sc-top} , J_{sc-bot} , $J_{sc-total}$)

		top	bot.	total
~	Z1	5.5%	3.4%	4.6%
^^	Z2.5	5.8%	2.8%	4.3%
^^^	Z5	6.5%	1.6%	4.0%
~~~~	Z5 45'	6.3%	4.6%	5.4%

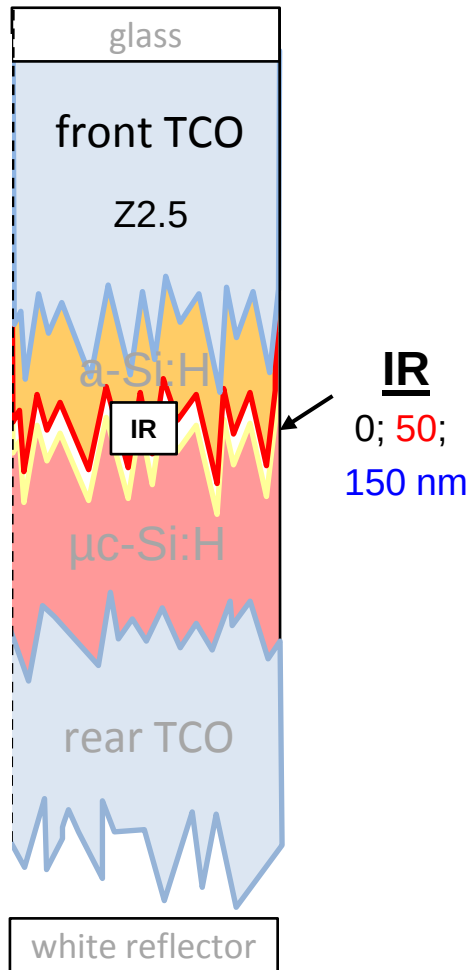
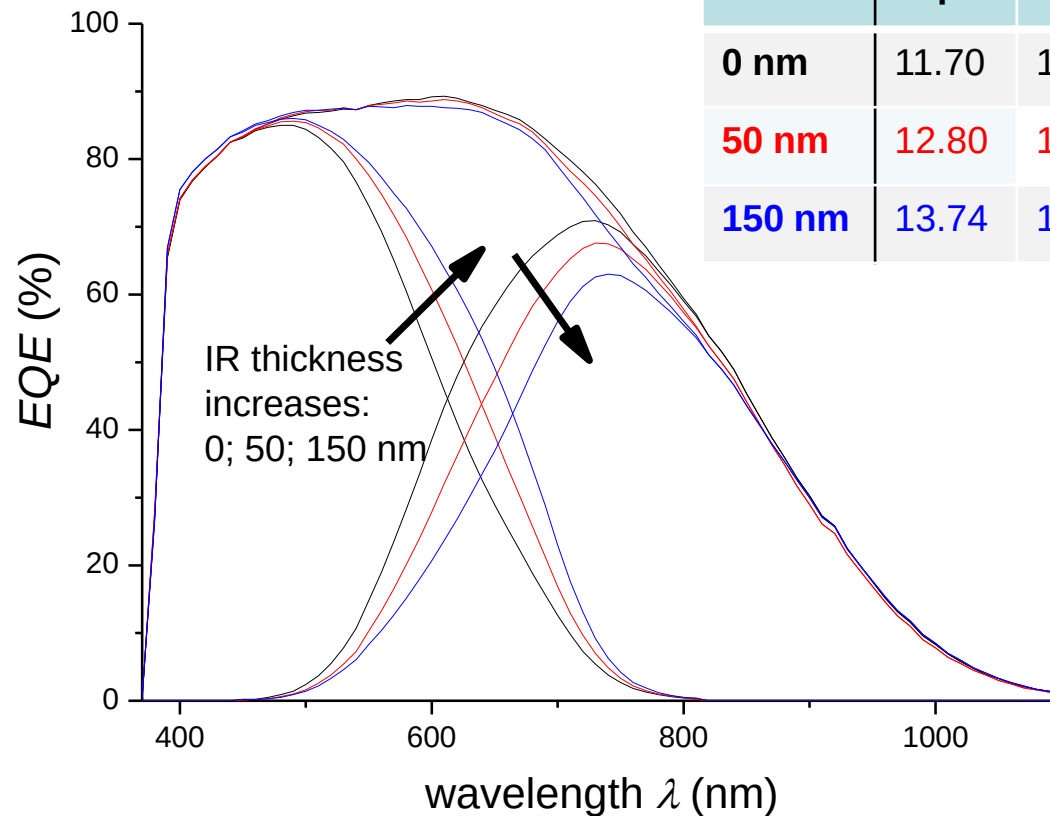
- ✓ Gain in  $J_{sc-top}$  ~6%, irrespective of the front-TCO texture
- ✓ Gain in  $J_{sc-bot}$  stronger for low-light-trapping front-TCO textures
- ✓ Same conclusion for  $J_{sc-total}$



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# Impact of the IR on *EQE*

Effect of the IR thickness on  $J_{sc-top}$ ,  $J_{sc-bot}$  and  $J_{sc-total}$

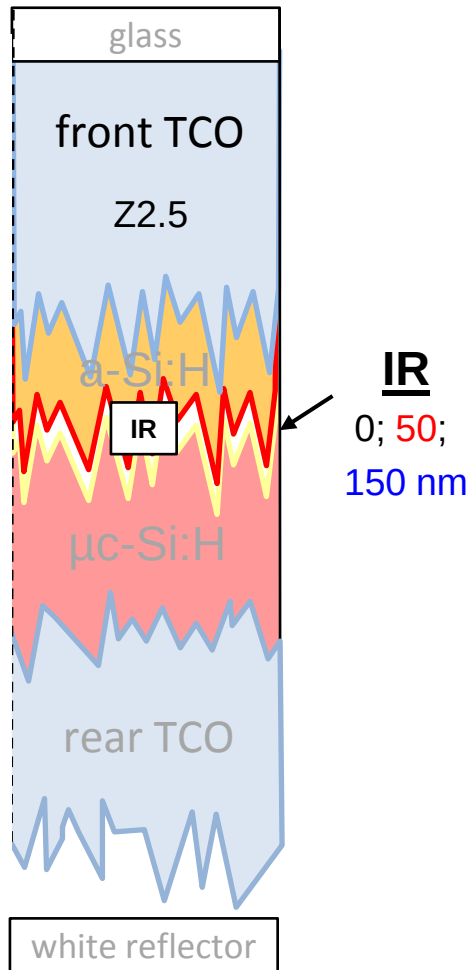
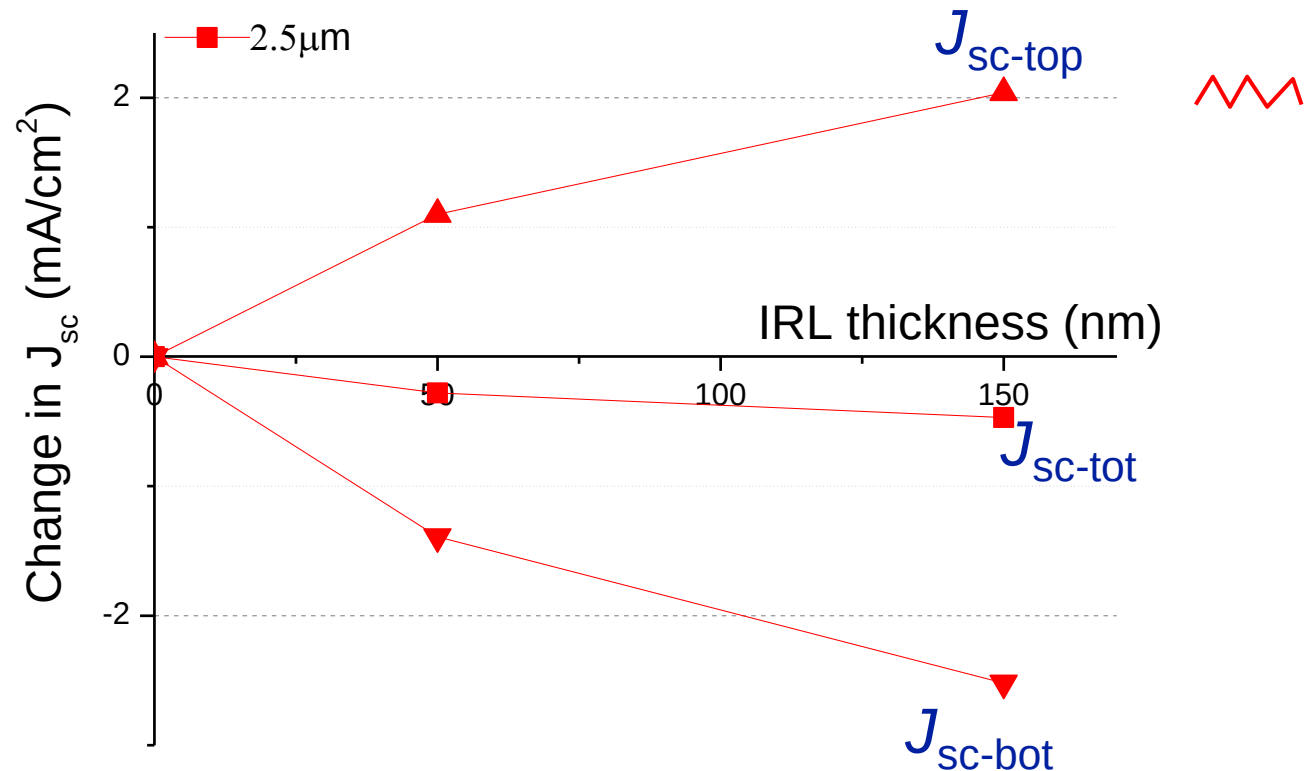


SOIR	Top	Bottom	Total
0 nm	11.70	13.83	25.52
50 nm	12.80	12.44	25.24
150 nm	13.74	11.31	25.05



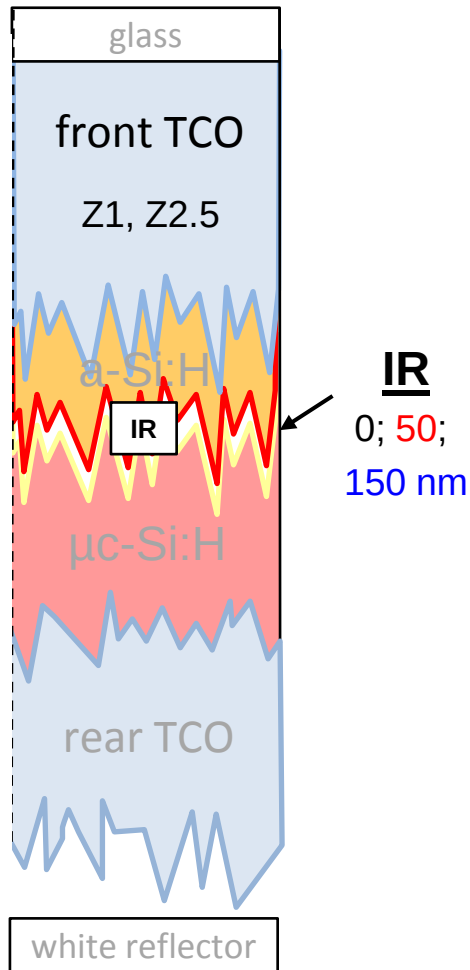
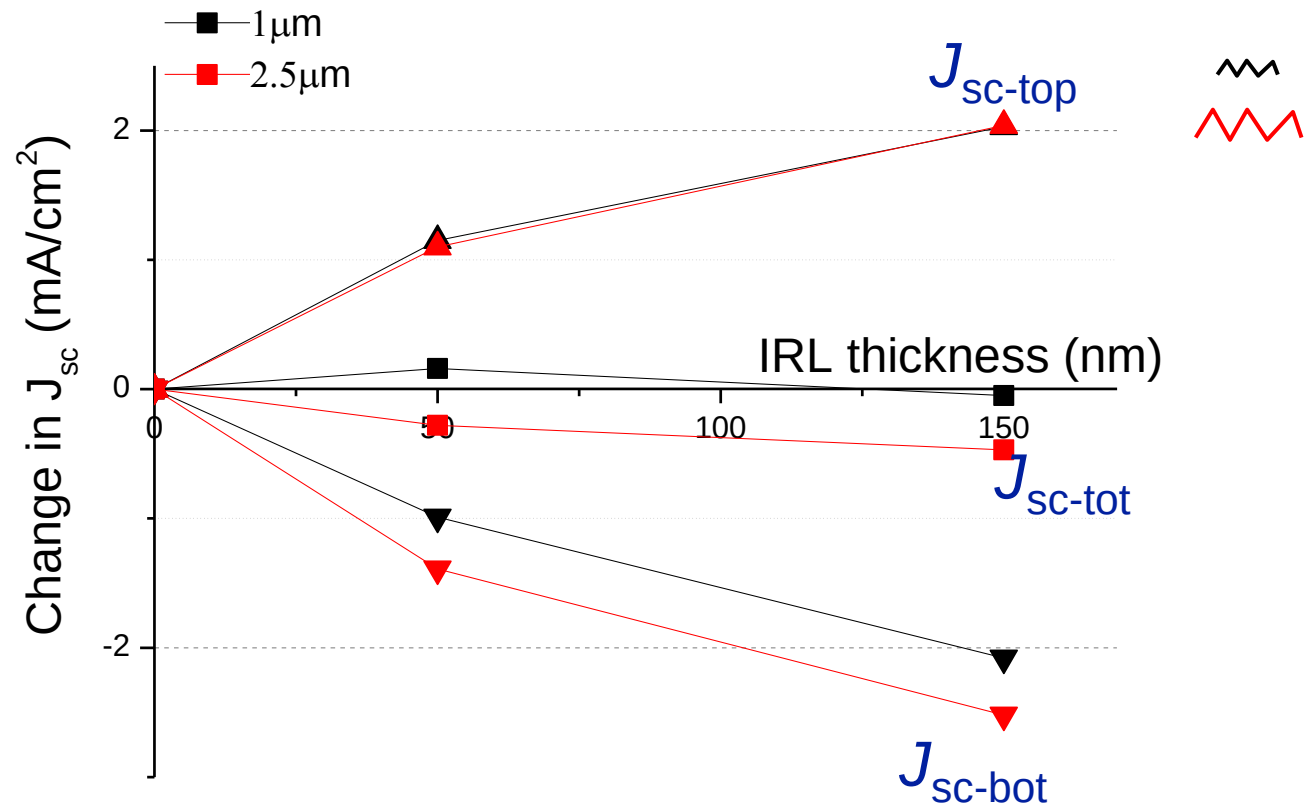
# Impact of the IR on $EQE$

Effect of the IR thickness on  $J_{sc-top}$ ,  $J_{sc-bot}$  and  $J_{sc-tot}$



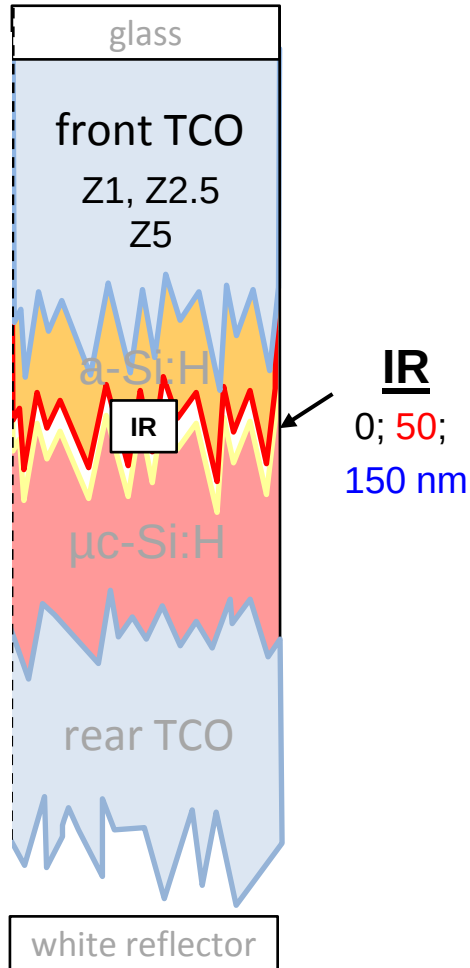
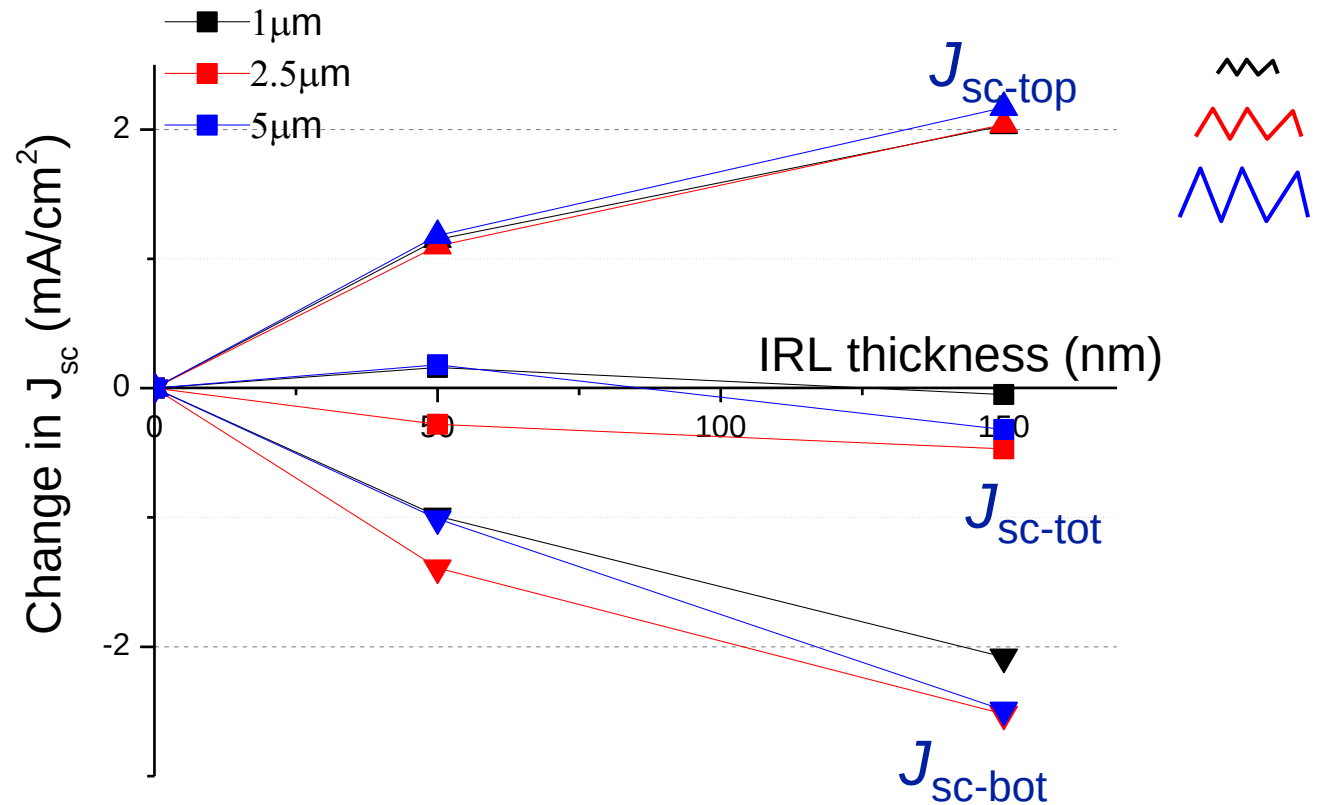
# Impact of the IR on $EQE$ , for different front TCOs

Effect of the IR thickness on  $J_{sc-top}$ ,  $J_{sc-bot}$  and  $J_{sc-tot}$



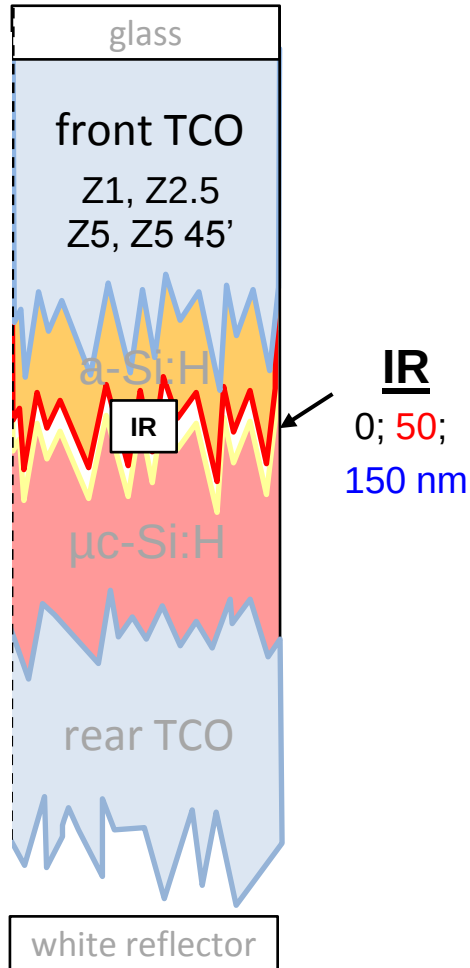
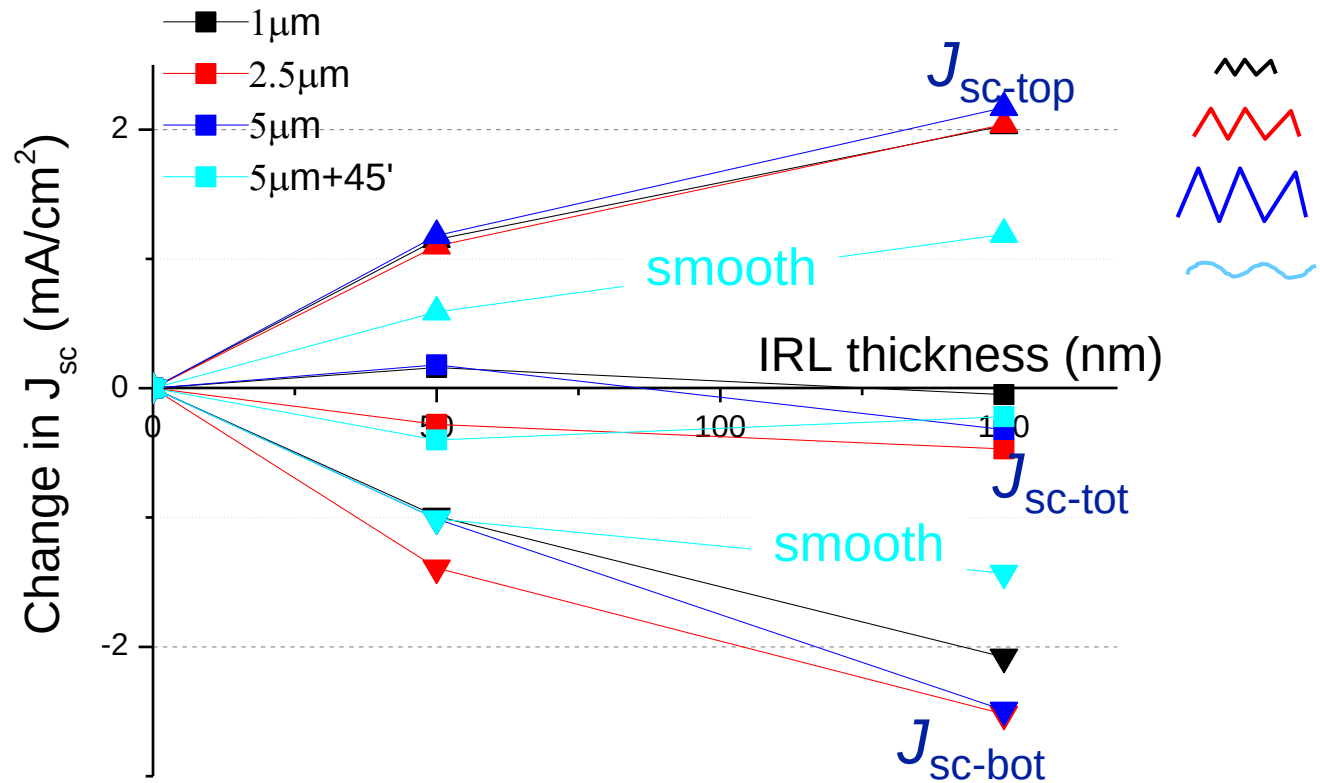
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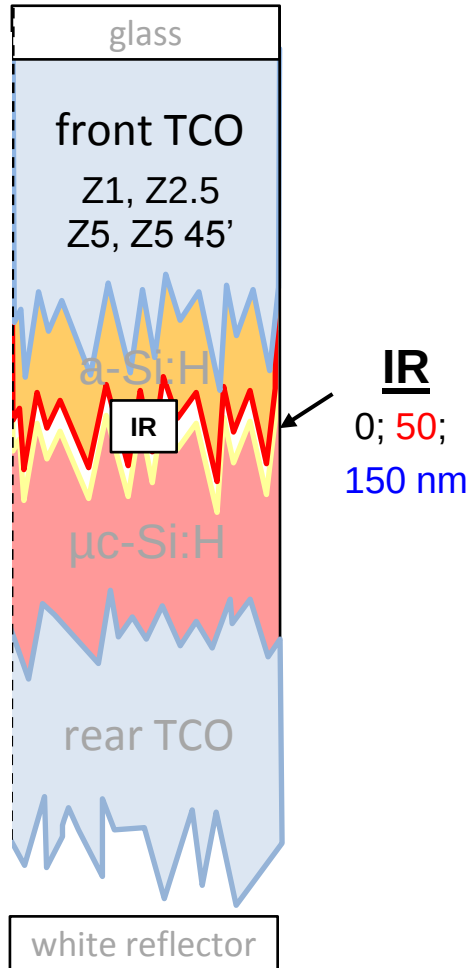
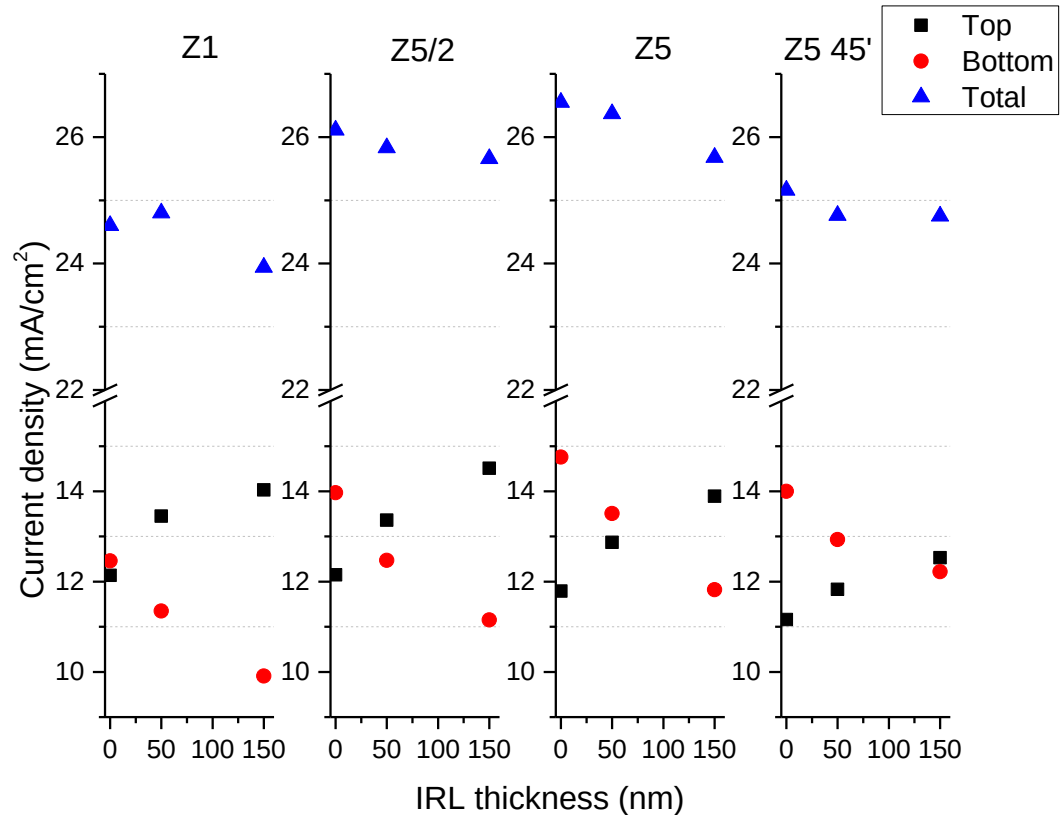
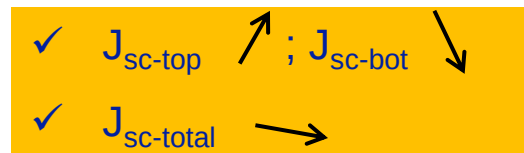
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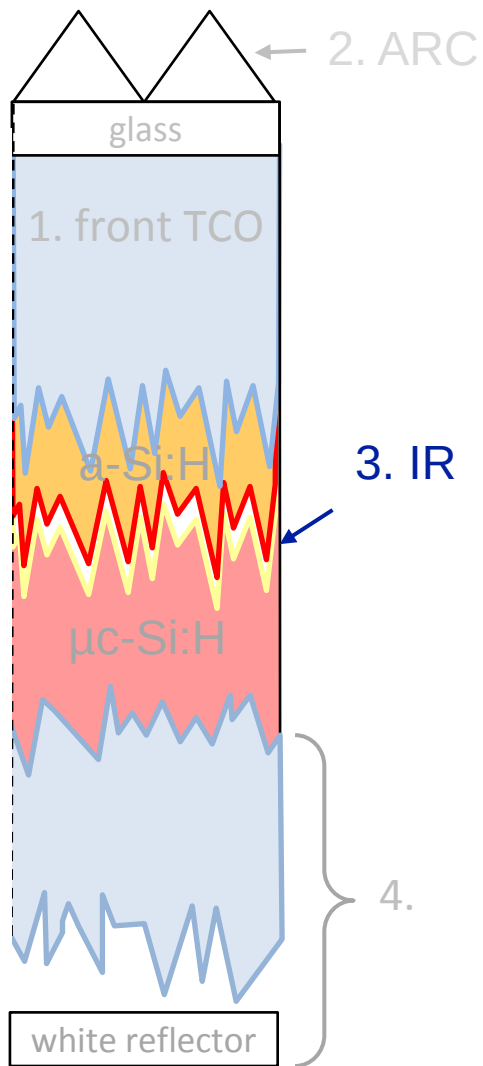


- ✓ SOIR efficiency lower for smoother (Z5 45') front TCOs
- ✓ Same trends for *relative* changes in  $J_{sc}$

# Impact of the IR on $EQE$ , for different front TCOs

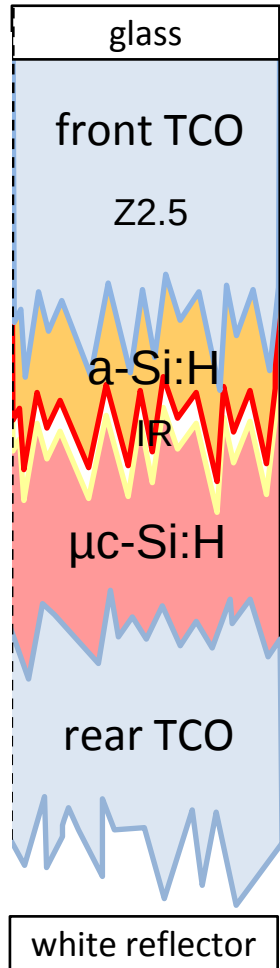
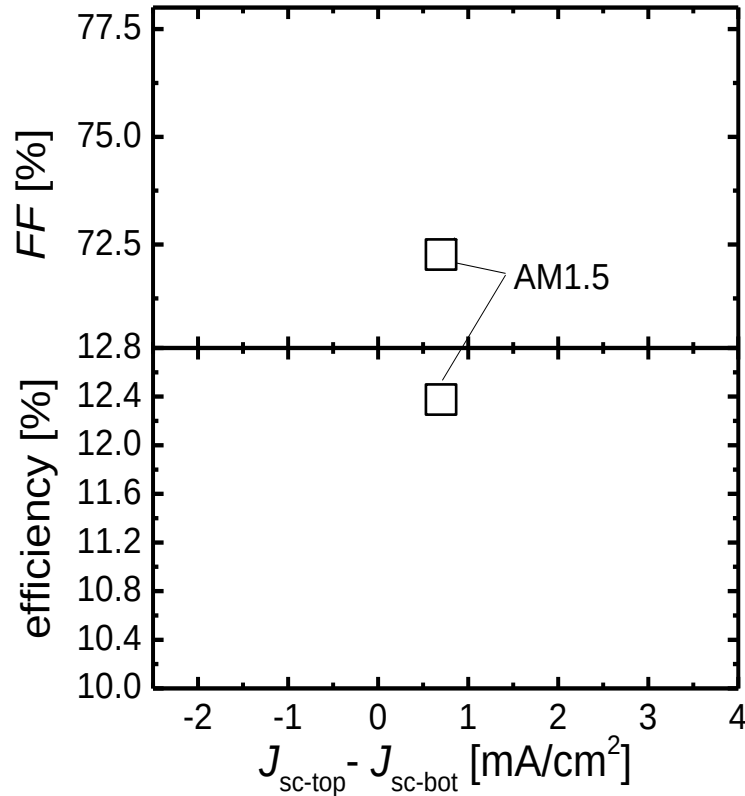
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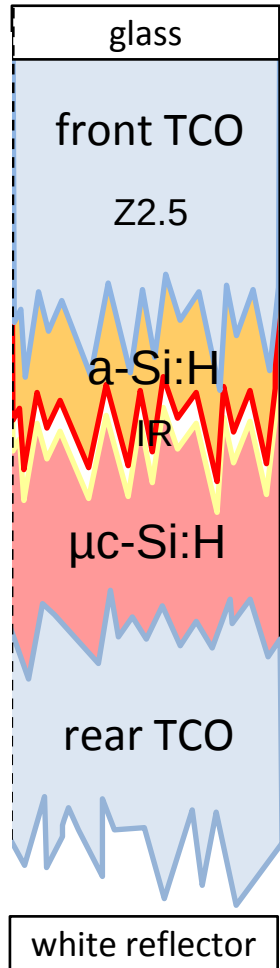
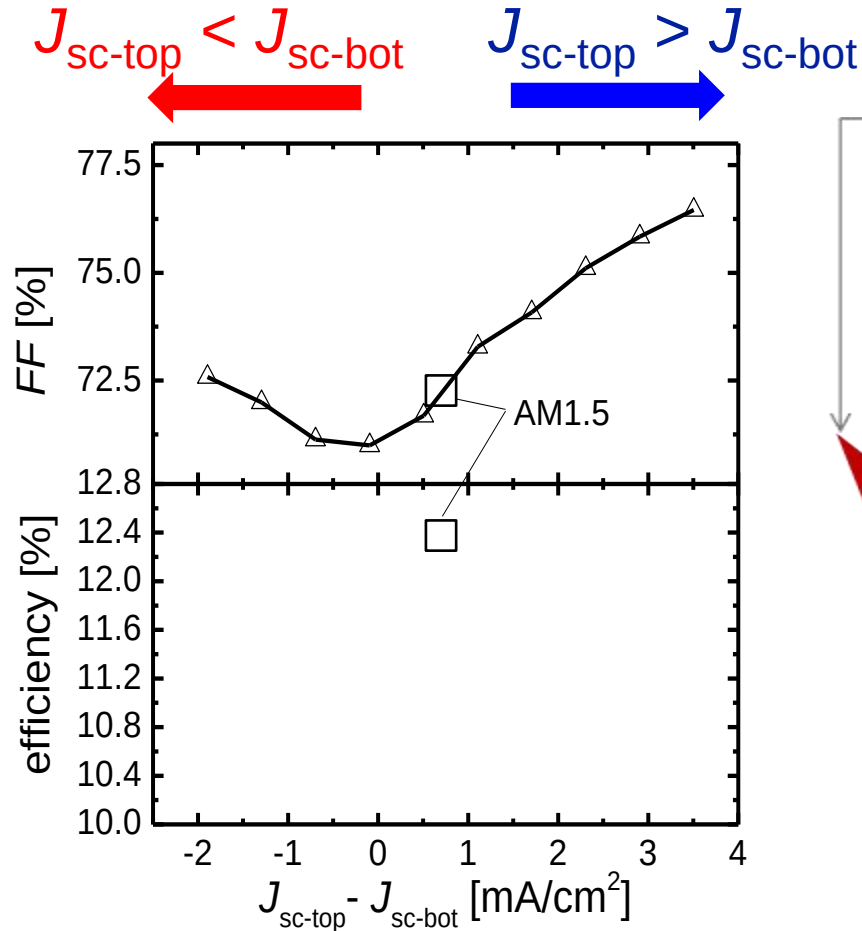
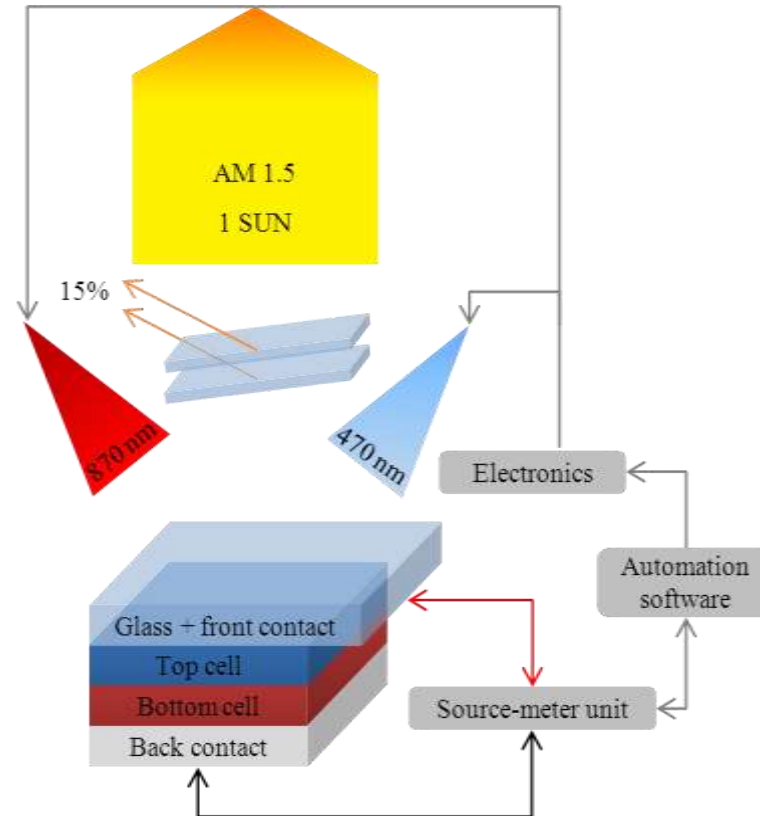


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# Micromorph cells ... under AM1.5 and ... under various illumination spectra

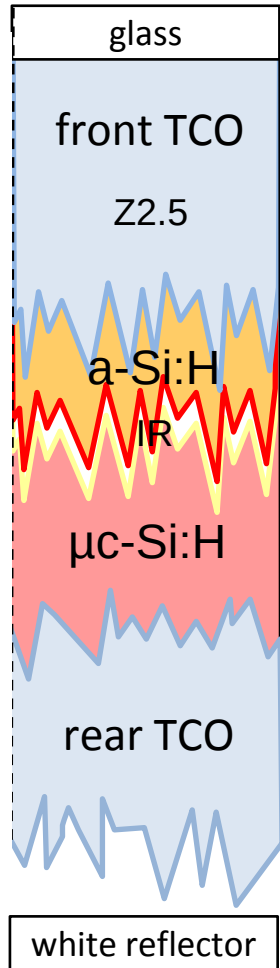
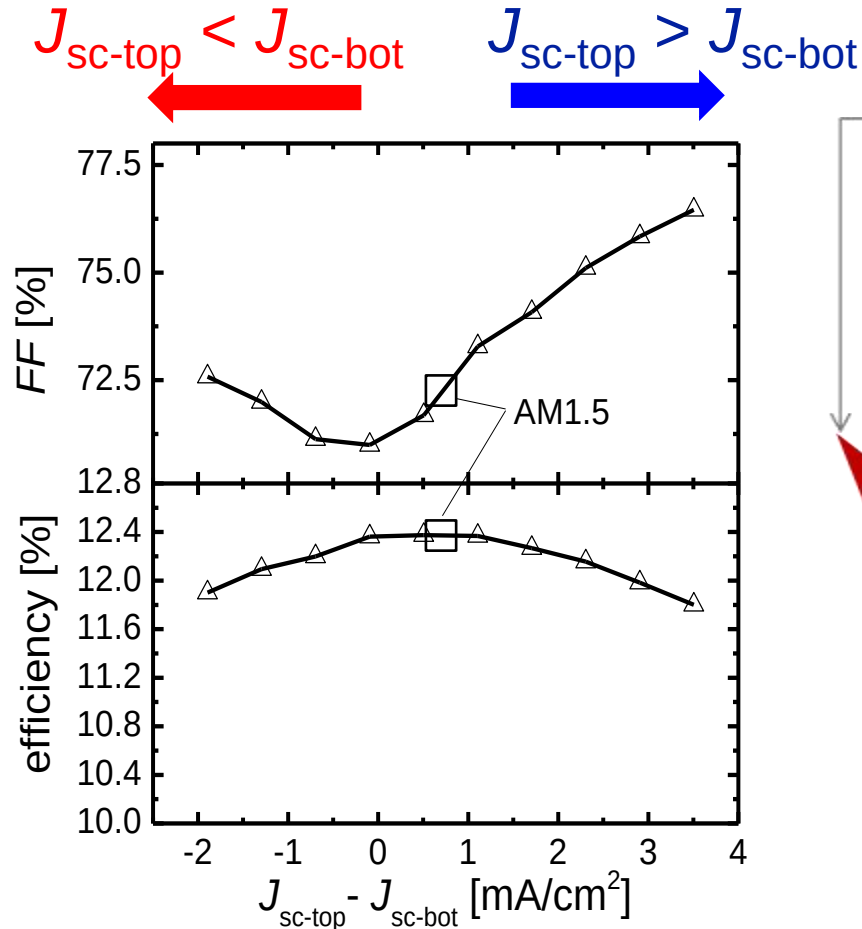
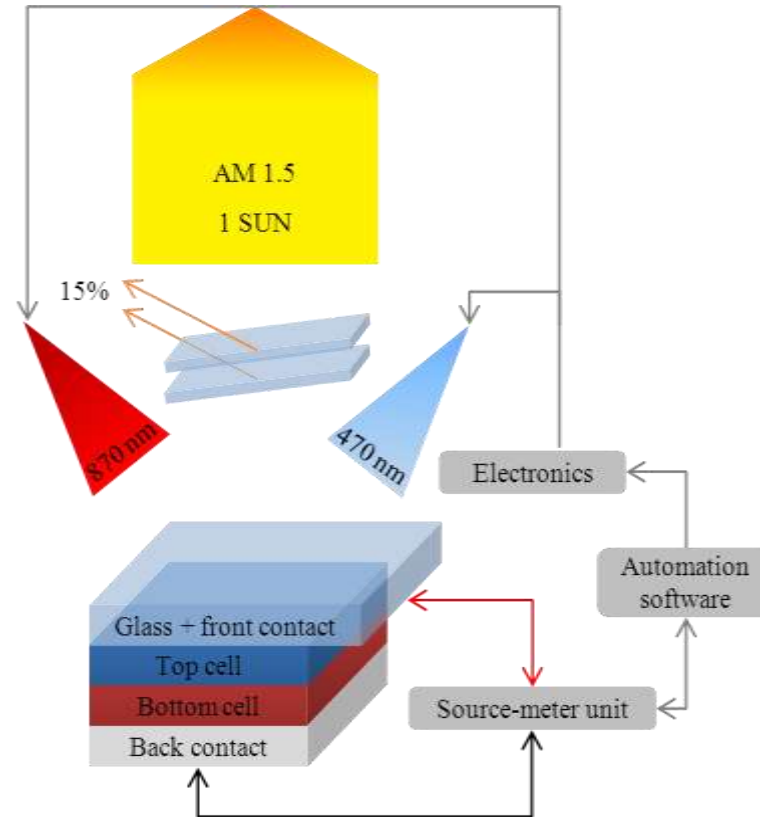


# Micromorph cells ... under AM1.5 and ... under various illumination spectra



Current Matching Machine¹ (CMM)

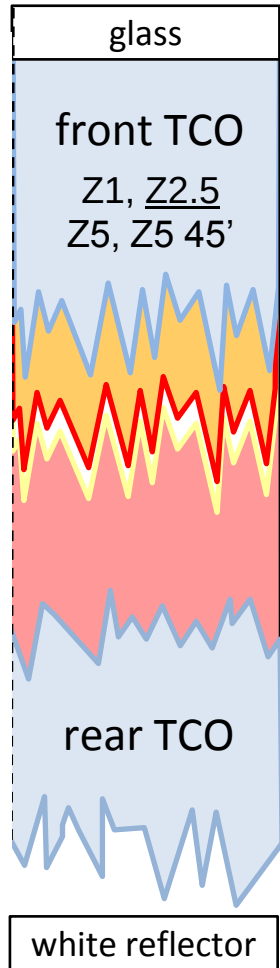
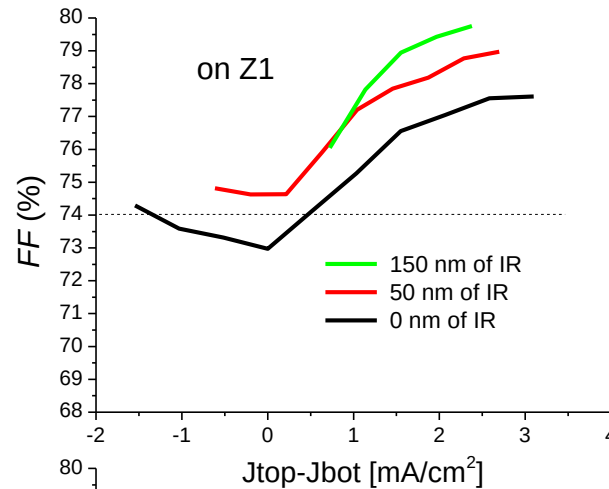
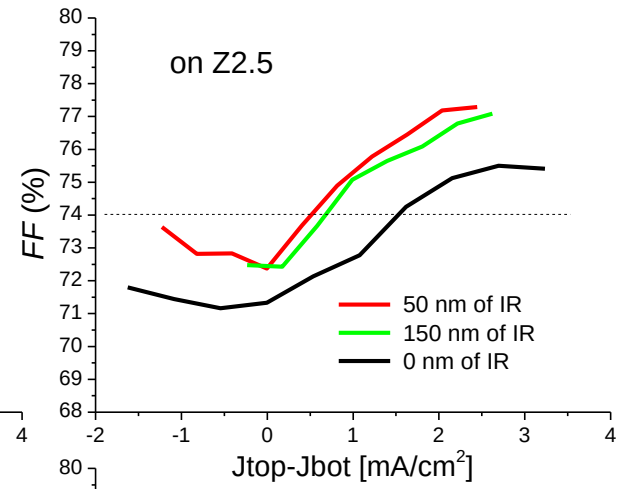
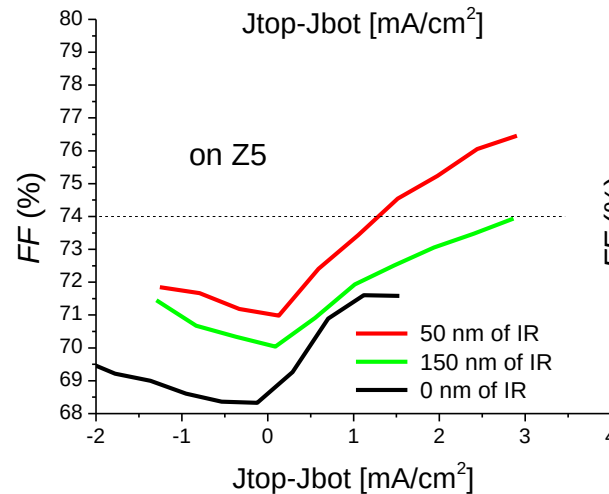
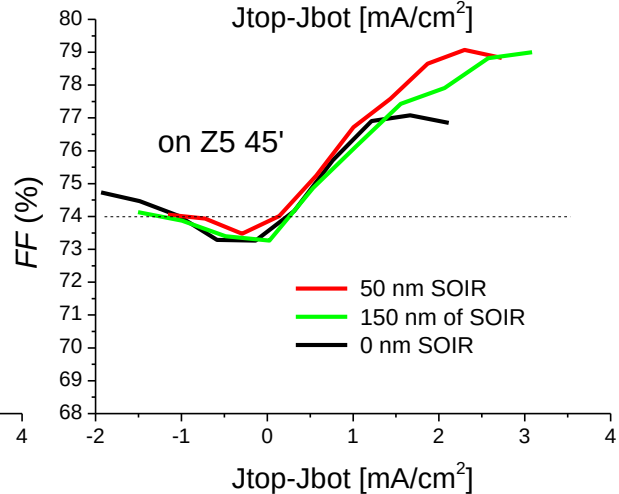
# Micromorph cells ... under AM1.5 and ... under various illumination spectra



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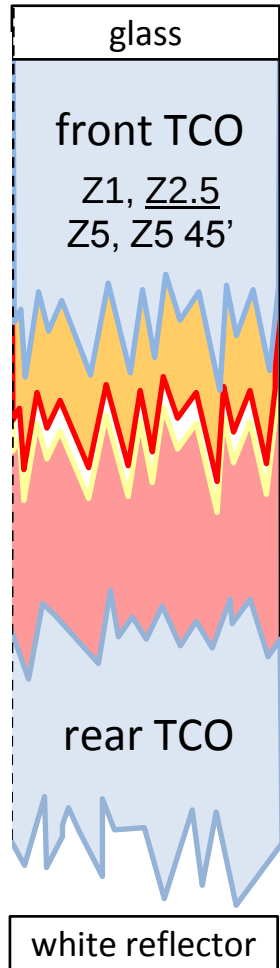
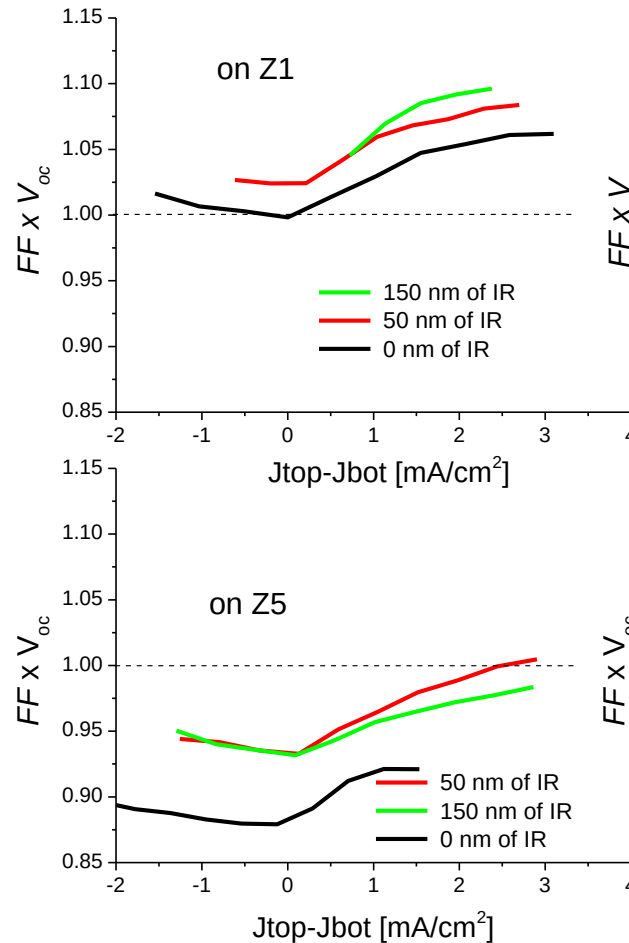
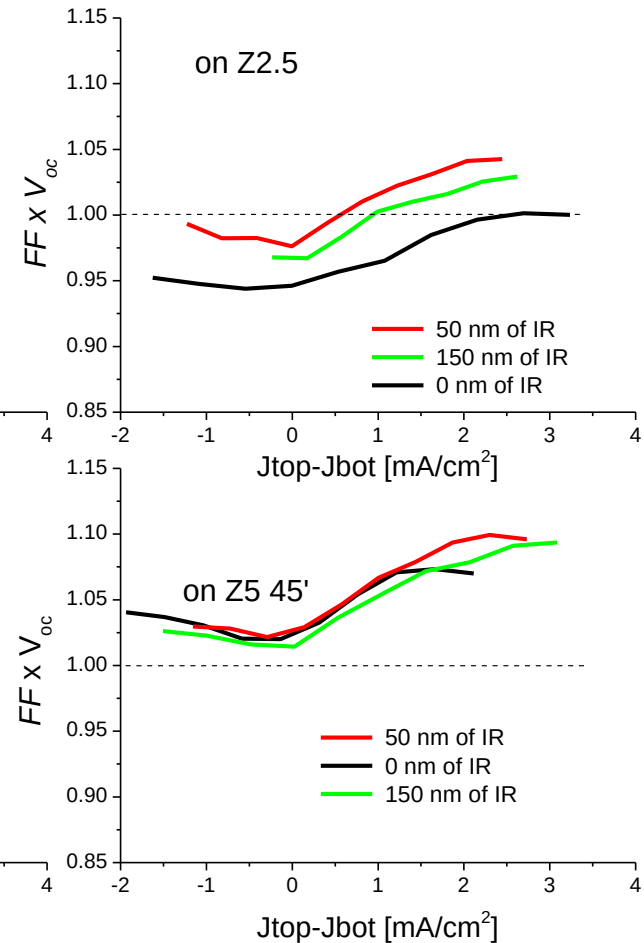
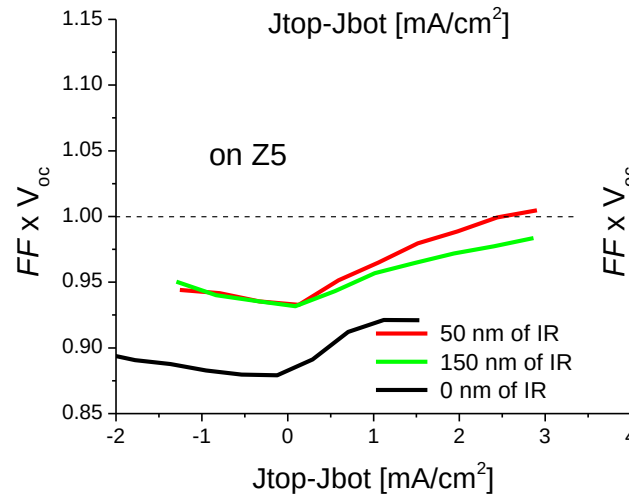
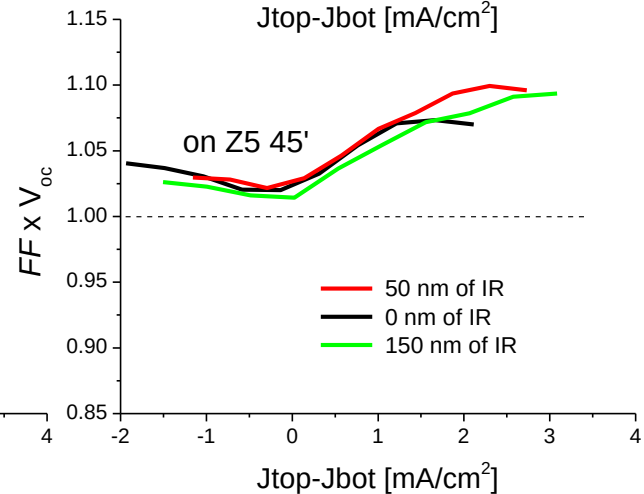
# Impact of the IR on FF for different front TCOs

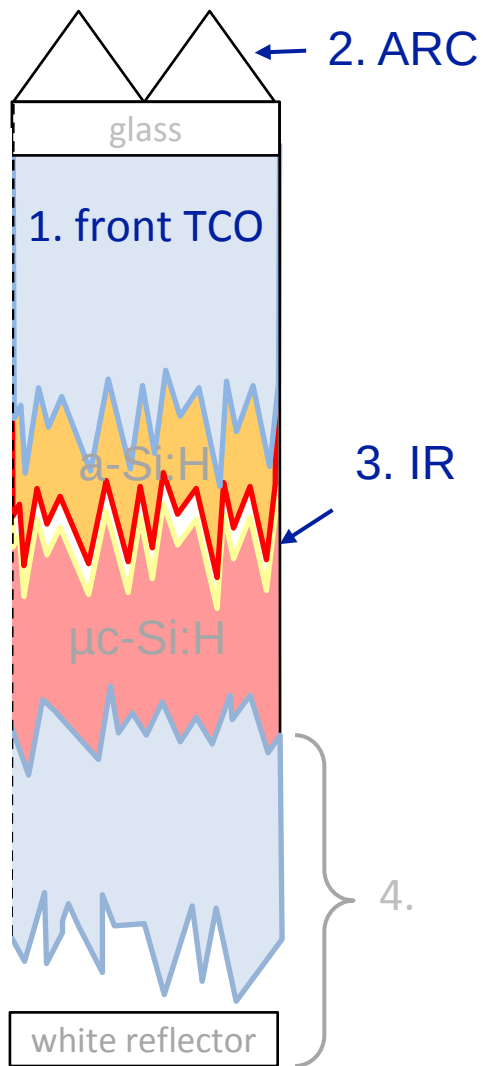
## Impact of the IR thickness on *FF* under various illumination spectra



# Impact of the IR on $FF \times V_{oc}$ for different front TCOs

## Impact of the IR thickness on $FF \times V_{oc}$ under various illumination spectra

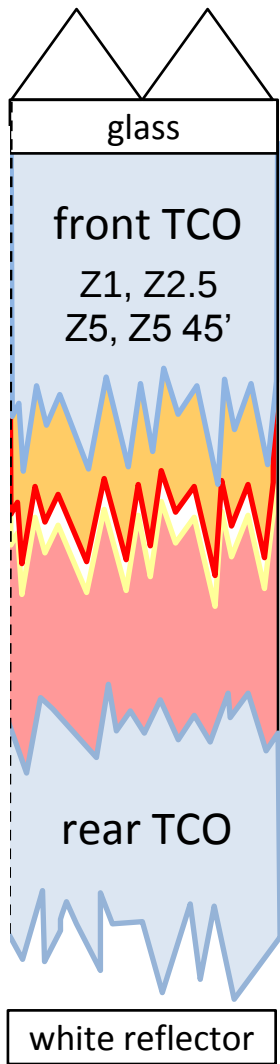
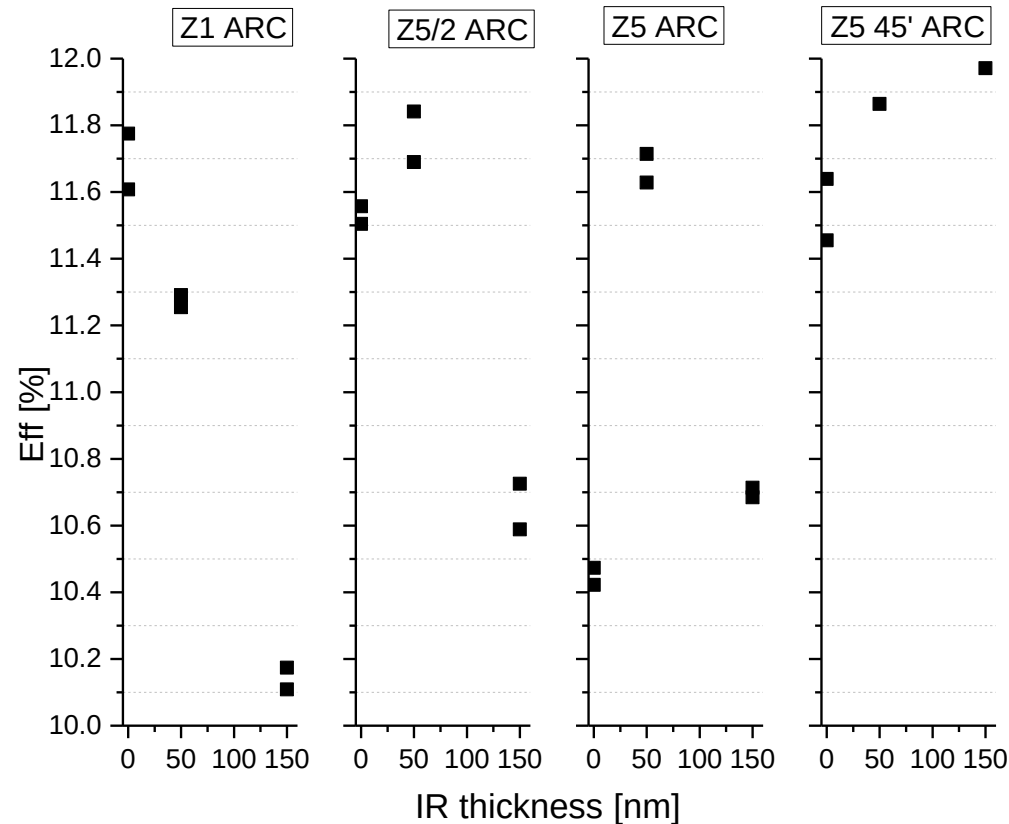




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- **Best combination of 1., 2. and 3.**
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# Summary/overview of the cells performances

## Power conversion efficiency with ARC, under AM1.5



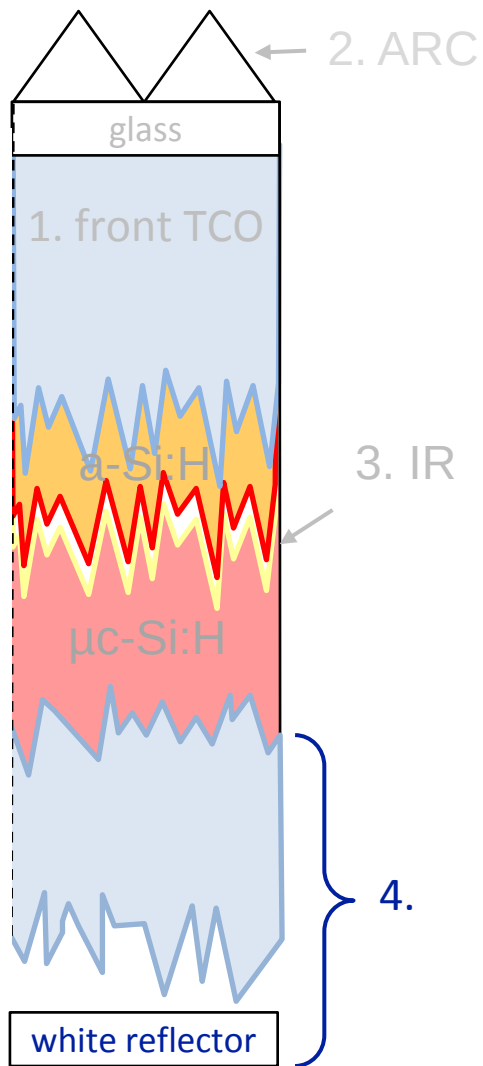
Highest eff. on  
Z5 45' (smooth)  
and Z2.5

Z1:  
 $J_{sc-bot}$  too small

Z2.5:  
good compromise

Z5: too rough →  
low electric perf.

Z5 45':  
- acceptable  $J_{sc}$   
- excellent  
electric perf.

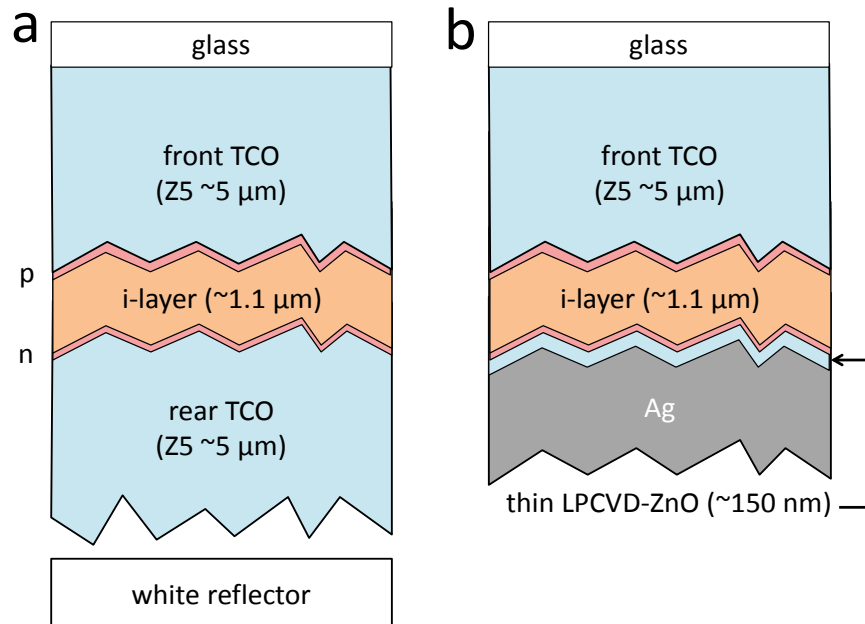
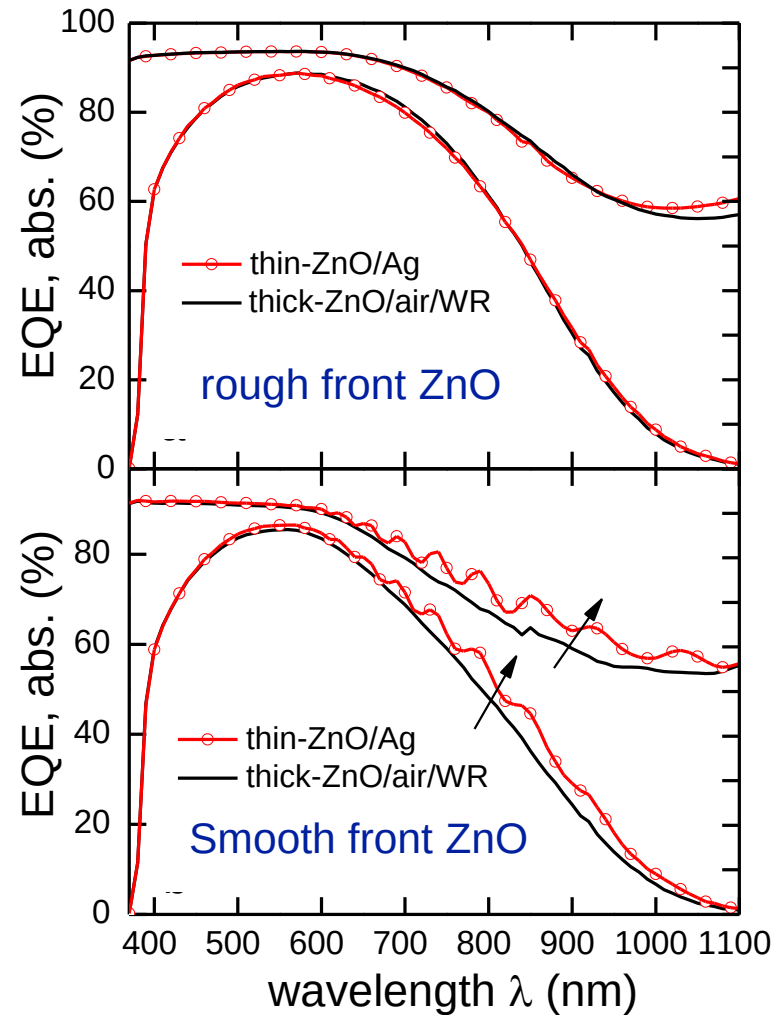


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# Impact of the back contact

## State-of-the-art versus ZnO(~150nm)/Ag

### Single-junction $\mu\text{c-Si:H}$ cells



✓ Thin-ZnO/Ag provides a better light trapping for smooth front-TCO textures

# Impact of the back contact

Front-electrode	BR design	Voc (mV)	FF (%)	Jsc (mA/cm ² )	η (%)
State-of-the-art front TCO (Z5 45')	thick-ZnO/air/WR	543	<b>67.9</b>	<b>24.1</b>	<b>8.9</b>
	thin-ZnO/Ag	538	<b>70.5</b>	<b>24.6</b>	<b>9.3</b>
Smooth front TCO (Z5 80')	Thick-ZnO/air/WR	554	<b>69.4</b>	<b>22.4</b>	<b>8.6</b>
	thin-ZnO/Ag	550	<b>72.8</b>	<b>23.5</b>	<b>9.4</b>

## Conclusions:

- ✓ Thin-ZnO/Ag provides a significant eff. boost
- ✓ New optimized config. with smoother front ZnO

# Conclusions

- Impact of the front-TCO surface texture: (4 different textures evaluated)
  - sharp features → good light coupling
  - large features → good light trapping (lower efficiency of IR)
  - smooth texture → weakening of the light-coupling and trapping properties.
- ARC: larger gain for low-light-trapping front-TCO textures
- Intermediate reflector (IR) for various front TCOs
  - $J_{sc-top} \uparrow$  ;  $J_{sc-bot} \searrow$  ;  $J_{sc-total} \rightarrow$  (reflection loss at the IR interface)
  - FF varies with varying irradiance spectrum
  - → IR leads to a gain in “intrinsic” FF (shunt quenching).
  - → small features and smooth texture provide the best electrical cell performance
- Best combination of interfaces identified and well understood
- Back reflector: sp-ZnO(~150nm) / Ag provides a better ...
  - FF (higher lateral conductivity)
  - $J_{sc}$  (better light trapping)... than ZnO(~2μm) / WR

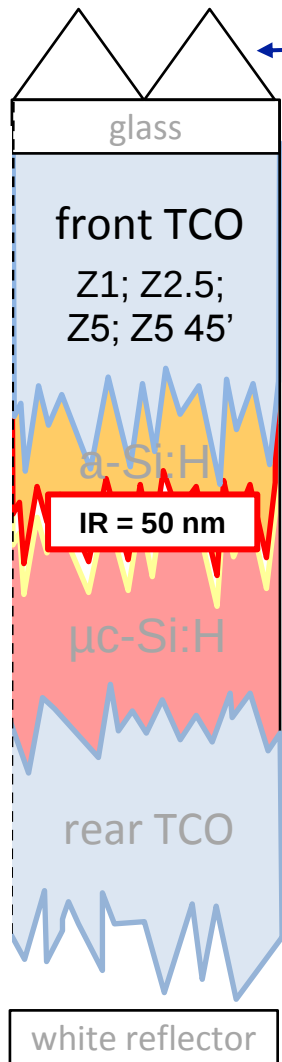
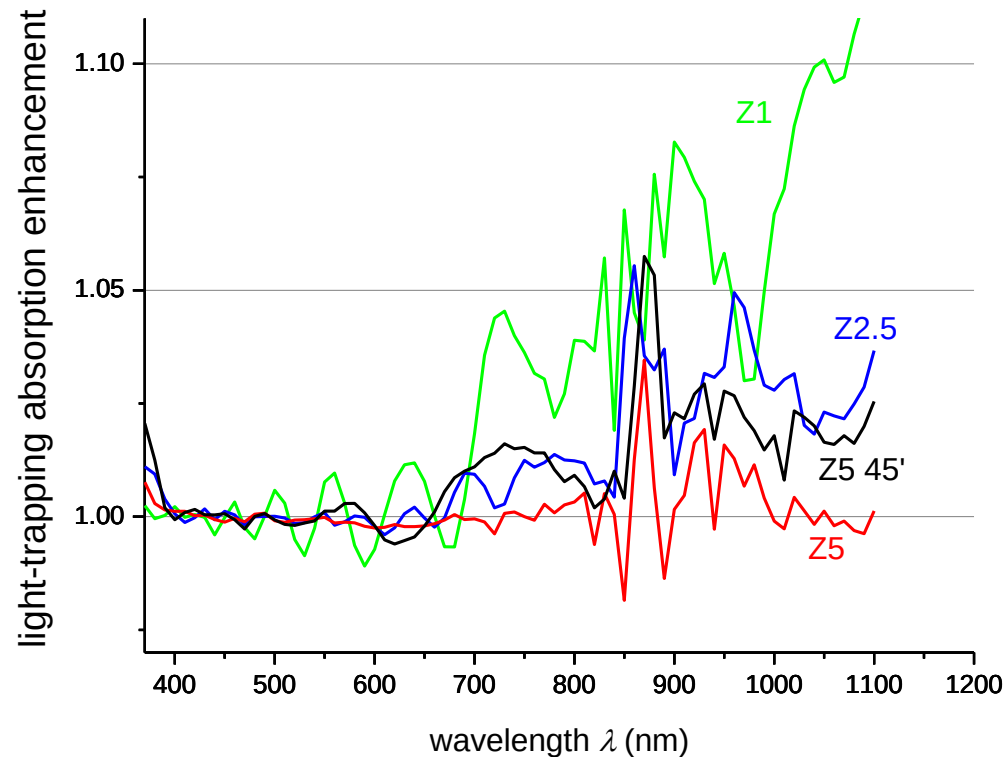


Thank you for your attention

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## 2. “glass”/air interface (ARC)

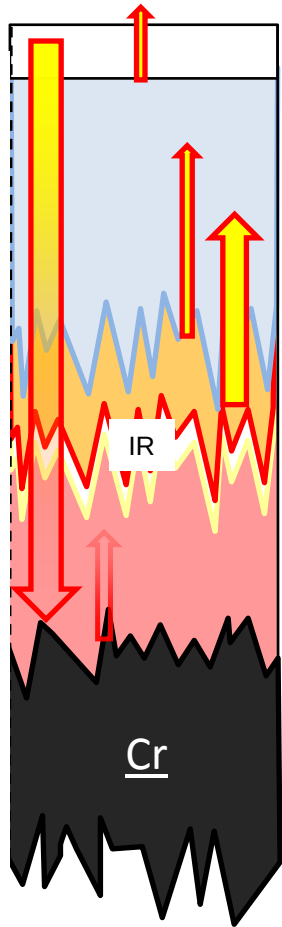
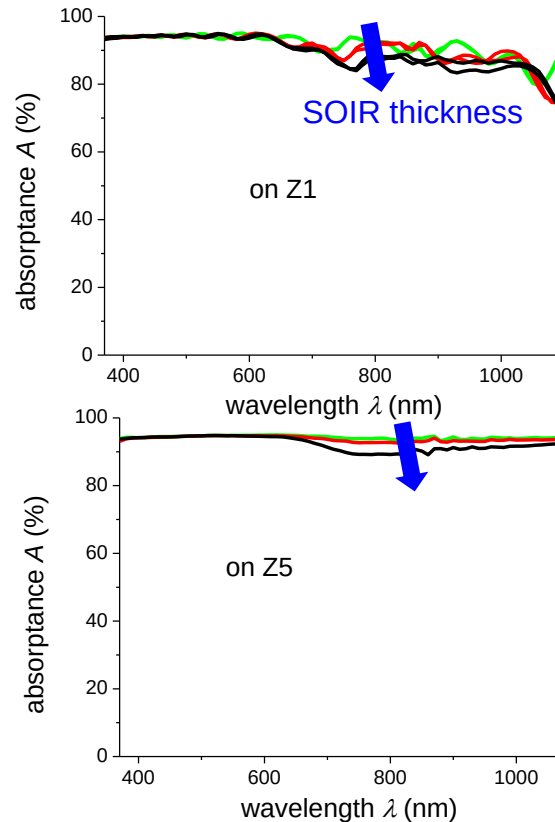
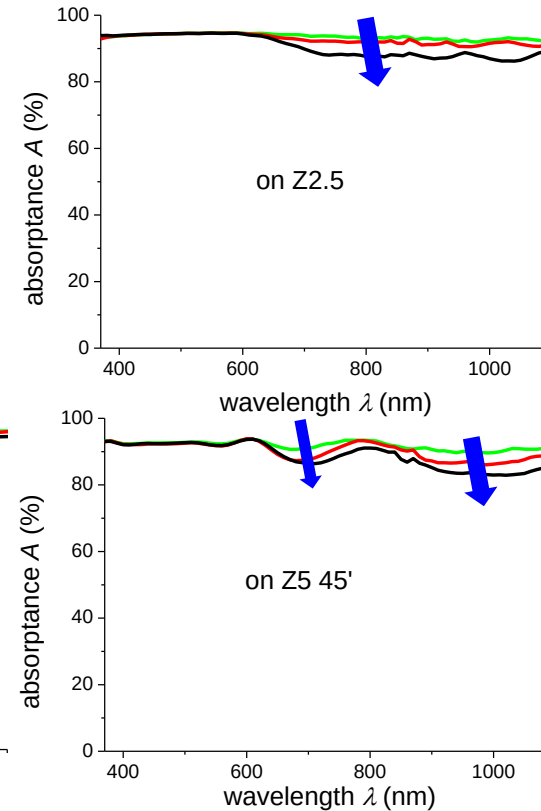
← ARC    Impact of the ARC on the light-trapping improvement



✓ Highest light-trapping gain with ARC for Z1 (no initial light-trapping ability)

# Optical loss at the SOIR interfaces

Effect of the IR thickness on the reflection loss, for different front TCOs



✓ Reflection loss increases with SOIR thickness

# Optical loss at the IR interfaces

Effect of the IR thickness on the reflection loss, for Z5 45' (no IR)

