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TERASUN

Simplified processing of novel IBC-SHJ solar cells with MoO_x blanket layer: Modulated surface texturing for improved light in-coupling

K. Kovačević, Y. Zhao, P. Procel, L. Cao, E. Özkol, L. Mazzarella, O. Isabella

PVMD Delft University of Technology

9th of December 2025

Amsterdam, the Netherlands

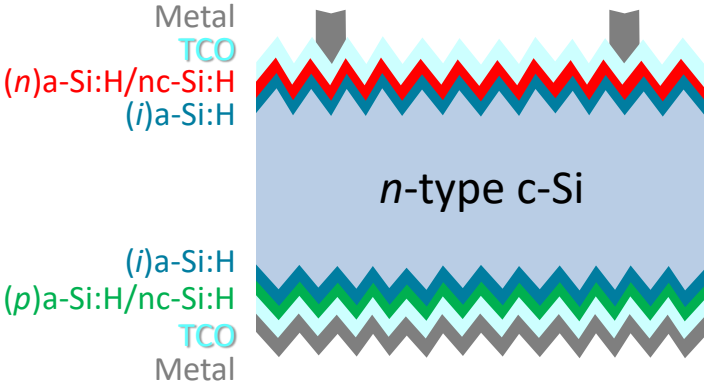
BCworkshop2025

TU Delft

Silicon heterojunction (SHJ) solar cells

Front/back-contacted (FBC)

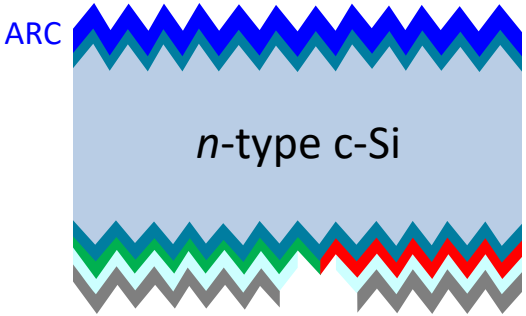
η = 27.08% [1]



Excellent passivation

Interdigitated-back-contacted (IBC)

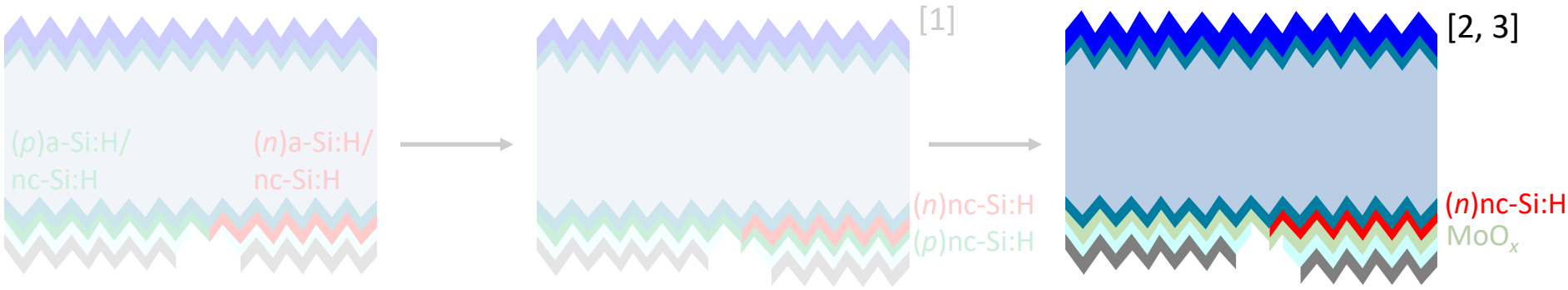
η = 27.3% [2]



Improved light in-coupling

[1] Z. Xie, et al., *Nature communications*, **16**, 9421 (2025)
[2] H. Wu, et al., *Nature*, **635**, 604 (2024)

Alternative structure and material choice



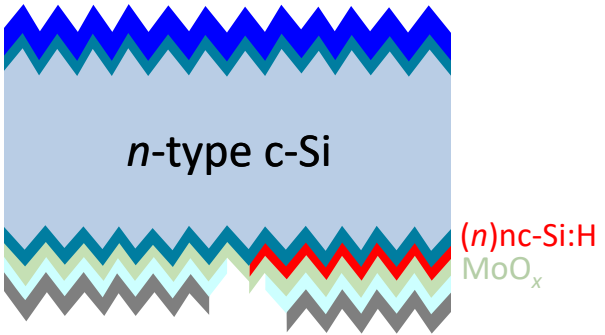
Improved light in-coupling
Lengthy fabrication process

Simple fabrication process
Low shunt resistance

Simple fabrication process
MoO_x with low lateral conductivity [4]
for high shunt resistance

[1] A. Tomasi, et al., *Nat. Energy*, **2**, 17062 (2017)
[2] P. Procel, et al., Patent, NL2033406B1 (2024)
[3] K. Kovačević, et al., *Prog. Photovolt. Res. Appl*, **33**, 209 (2024)
[4] L. Gerling, et al., *Sol. Energ. Mater. Sol. Cells,* **145**, 109 (2016)

IBC-SHJ solar cells with MoO_x blanket layer



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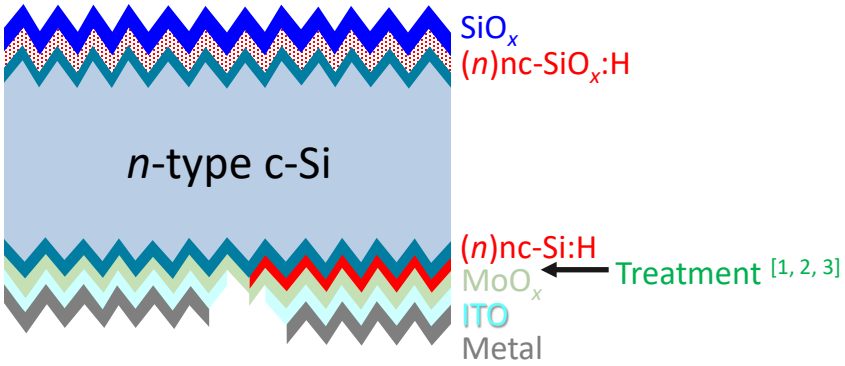
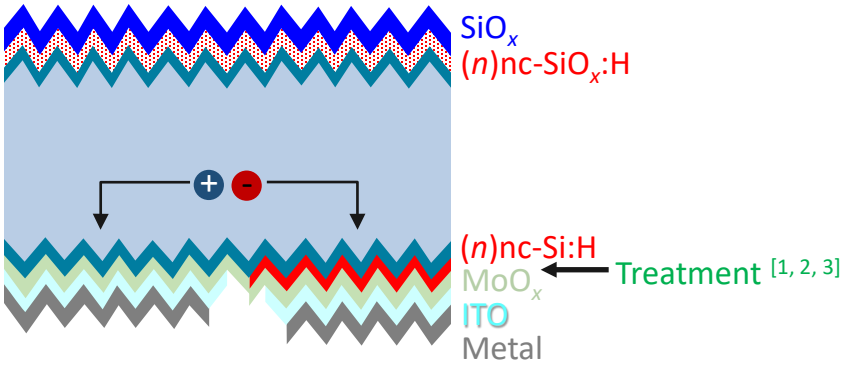


[1] L. Mazzarella, et al., Patent, NL2025744B1 (2022)
[2] L. Mazzarella, et al., *Prog. Photovolt. Res. Appl*, **29**, 391 (2020)
[3] L. Cao, et al., *Prog. Photovolt. Res. Appl*, **31**, 1245 (2022)

IBC-SHJ solar cells with MoO_x blanket layer

- η = 23.83% FBC-SHJ solar cells with MoO_x hole transport layer [3]
- Novel electron transport layer stack with (*n*)nc-Si:H and MoO_x [4, 5]



[1] L. Mazzarella, et al., Patent, NL2025744B1 (2022)
[2] L. Mazzarella, et al., *Prog. Photovolt. Res. Appl*, **29**, 391 (2020)
[3] L. Cao, et al., *Prog. Photovolt. Res. Appl*, **31**, 1245 (2022)
[4] P. Procel, et al., Patent, NL2033406B1 (2024)
[5] K. Kovačević, et al., *Prog. Photovolt. Res. Appl*, **33**, 209 (2024)

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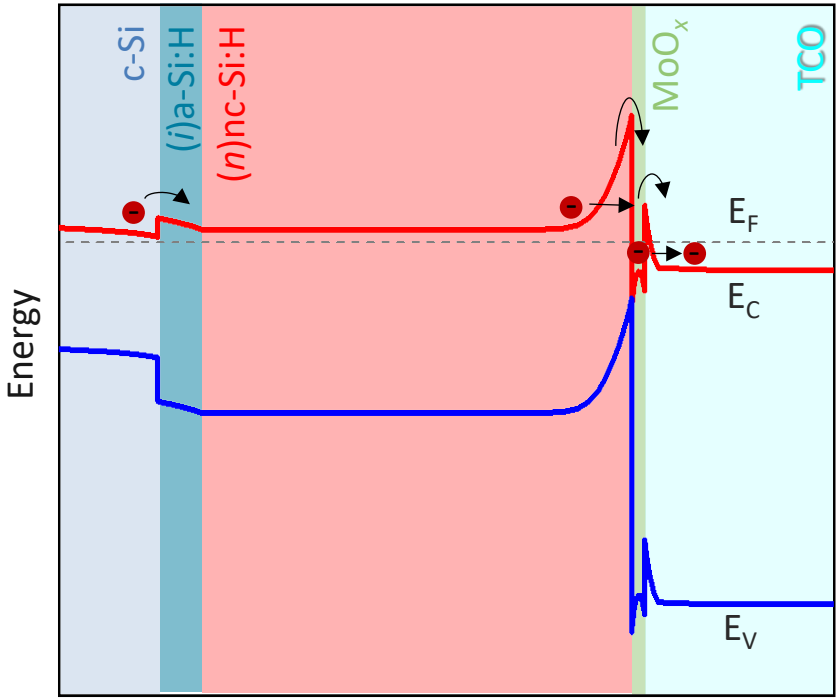

[1] L. Mazzarella, et al., Patent, NL2025744B1 (2022)
[2] L. Mazzarella, et al., *Prog. Photovolt. Res. Appl*, **29**, 391 (2020)
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[5] K. Kovačević, et al., *Prog. Photovolt. Res. Appl*, **33**, 209 (2024)

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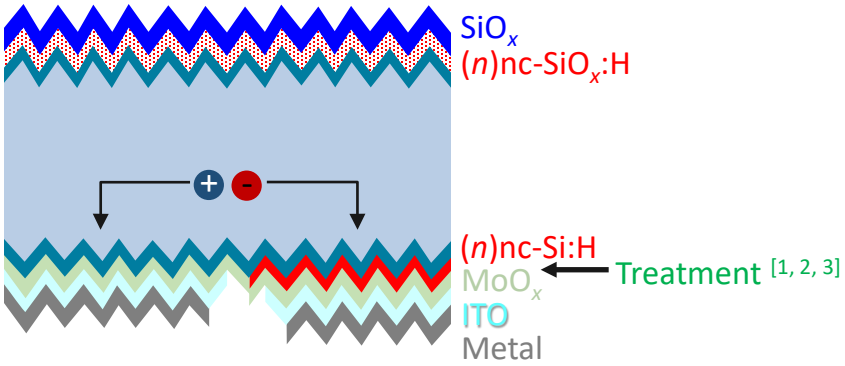
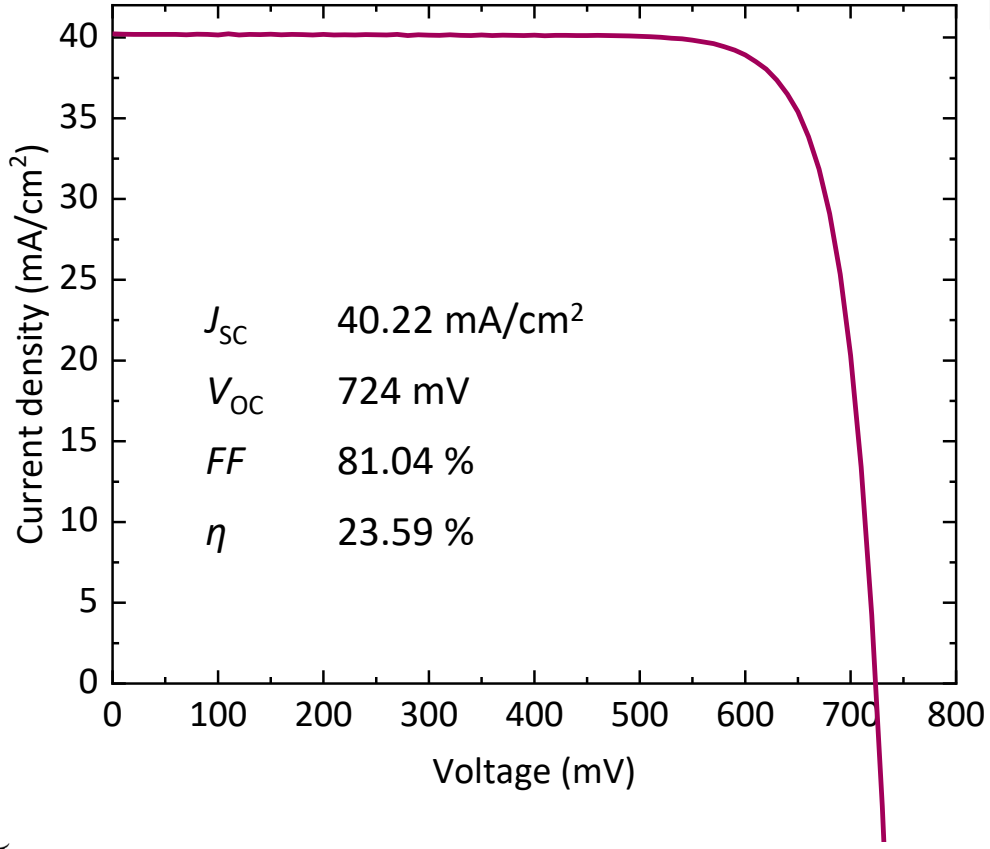


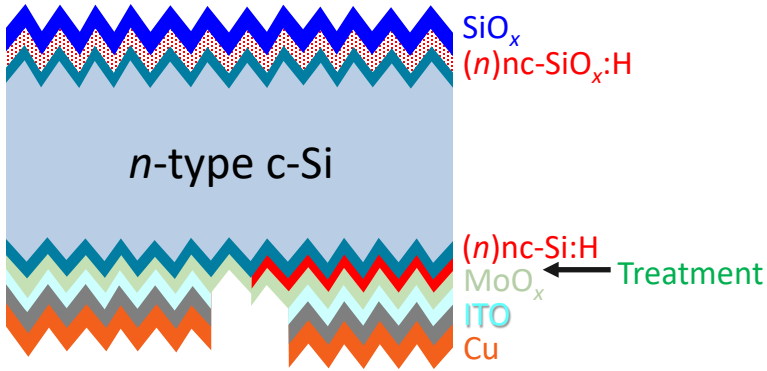
Minimized number of patterning steps, fast processing of MoO_x and high shunt resistance

[1] L. Mazzarella, et al., Patent, NL2025744B1 (2022)
[2] L. Mazzarella, et al., *Prog. Photovolt. Res. Appl*, **29**, 391 (2020)
[3] L. Cao, et al., *Prog. Photovolt. Res. Appl*, **31**, 1245 (2022)
[4] P. Procel, et al., Patent, NL2033406B1 (2024)
[5] K. Kovačević, et al., *Prog. Photovolt. Res. Appl*, **33**, 209 (2024)

Champion device



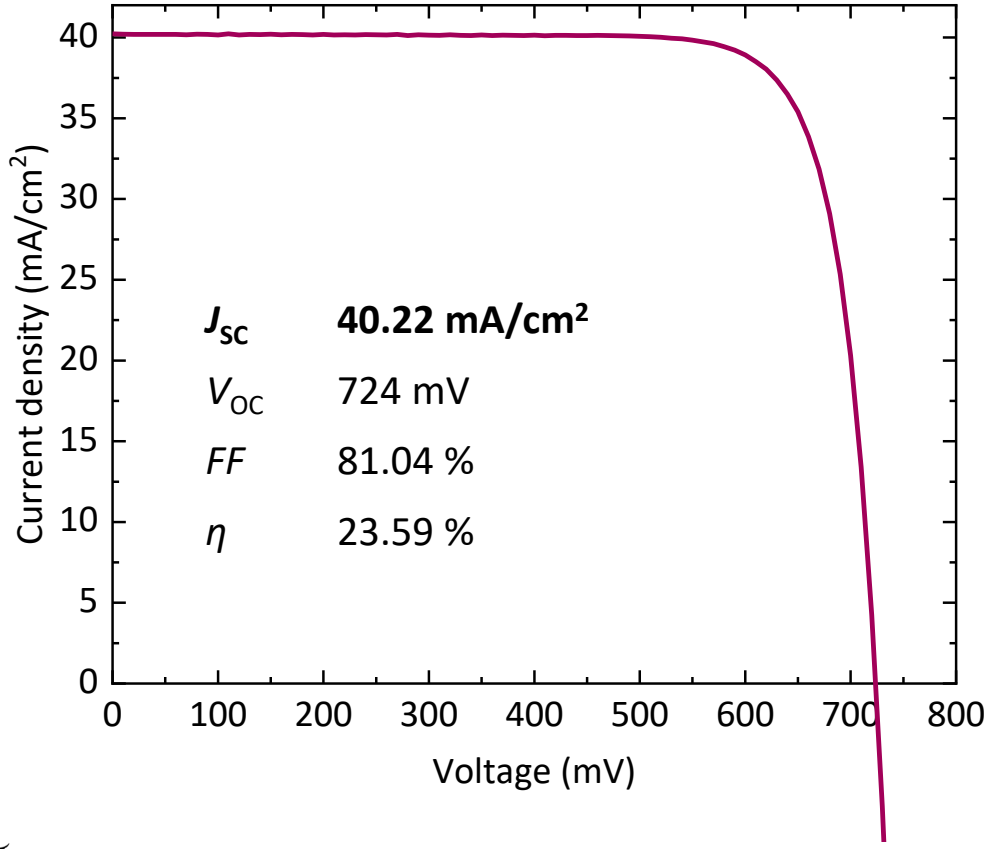
[1]



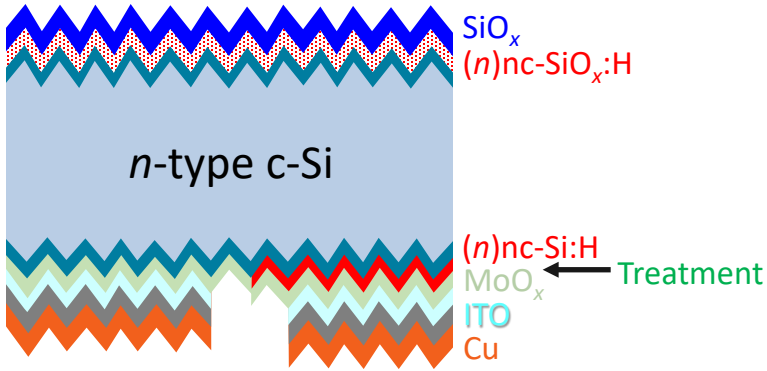
- Optimized electron and hole collection layer stack
- Electroplated Cu metalization

[1] K. Kovačević, et al., *Accepted for publication*

Champion device

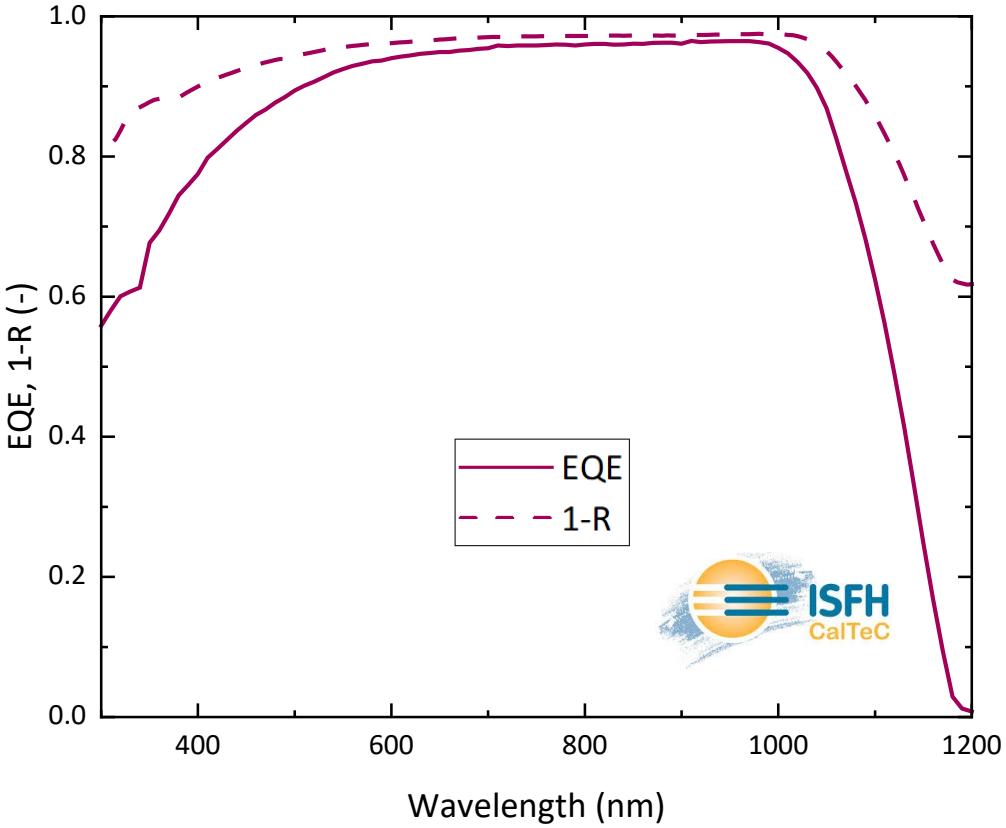


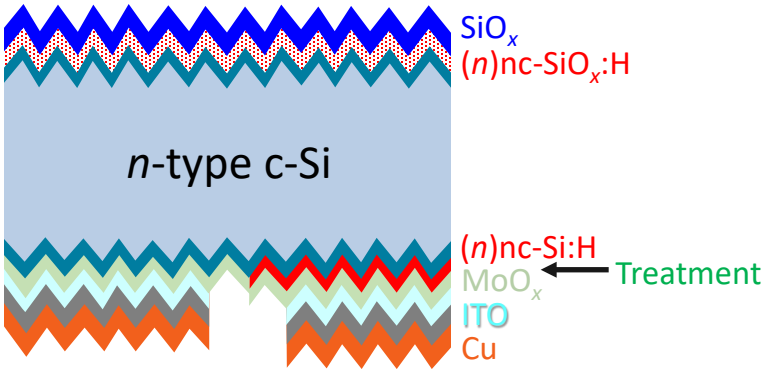
[1]



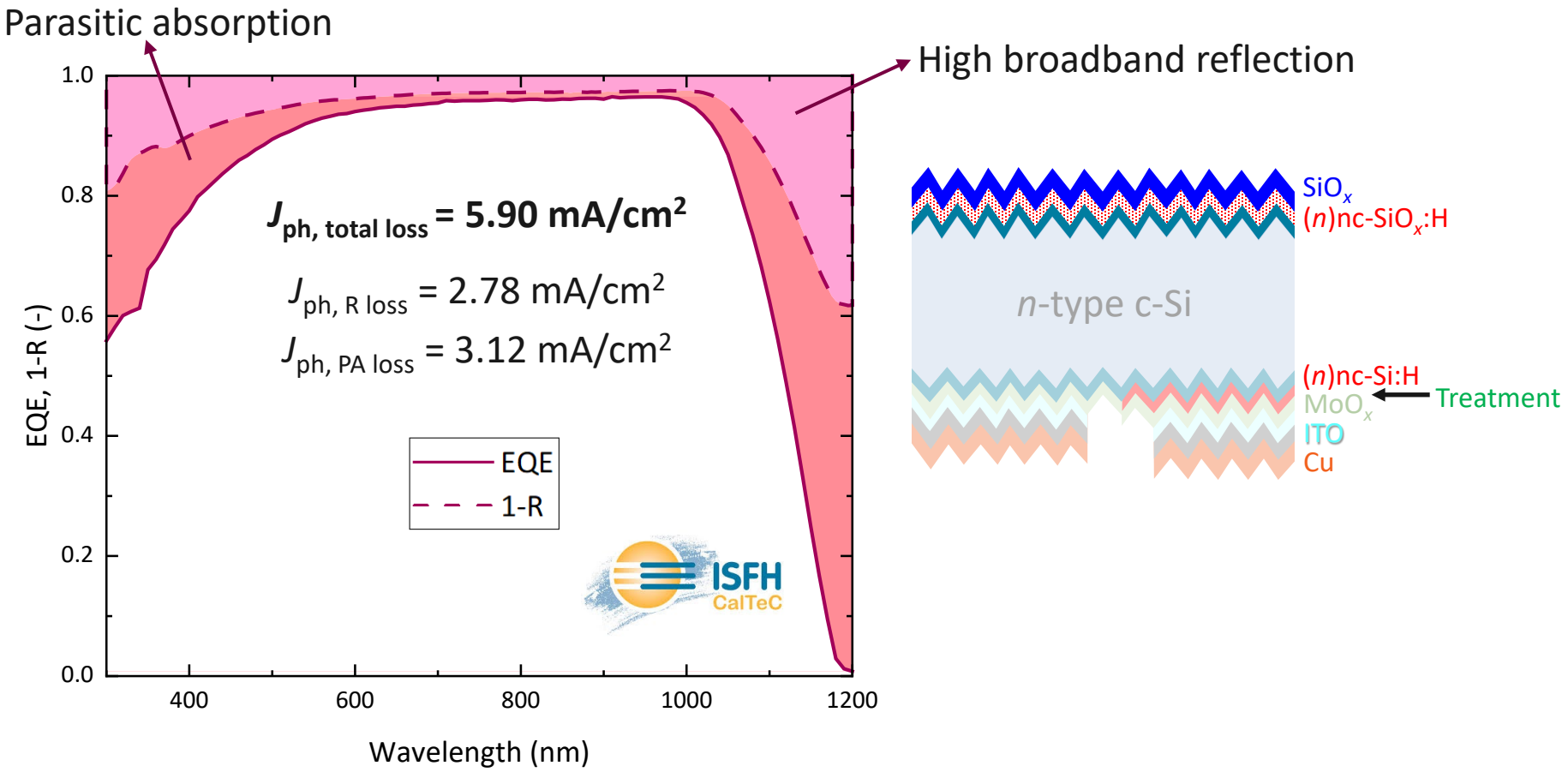
[1] K. Kovačević, et al., *Accepted for publication*

Front layer stack optimization

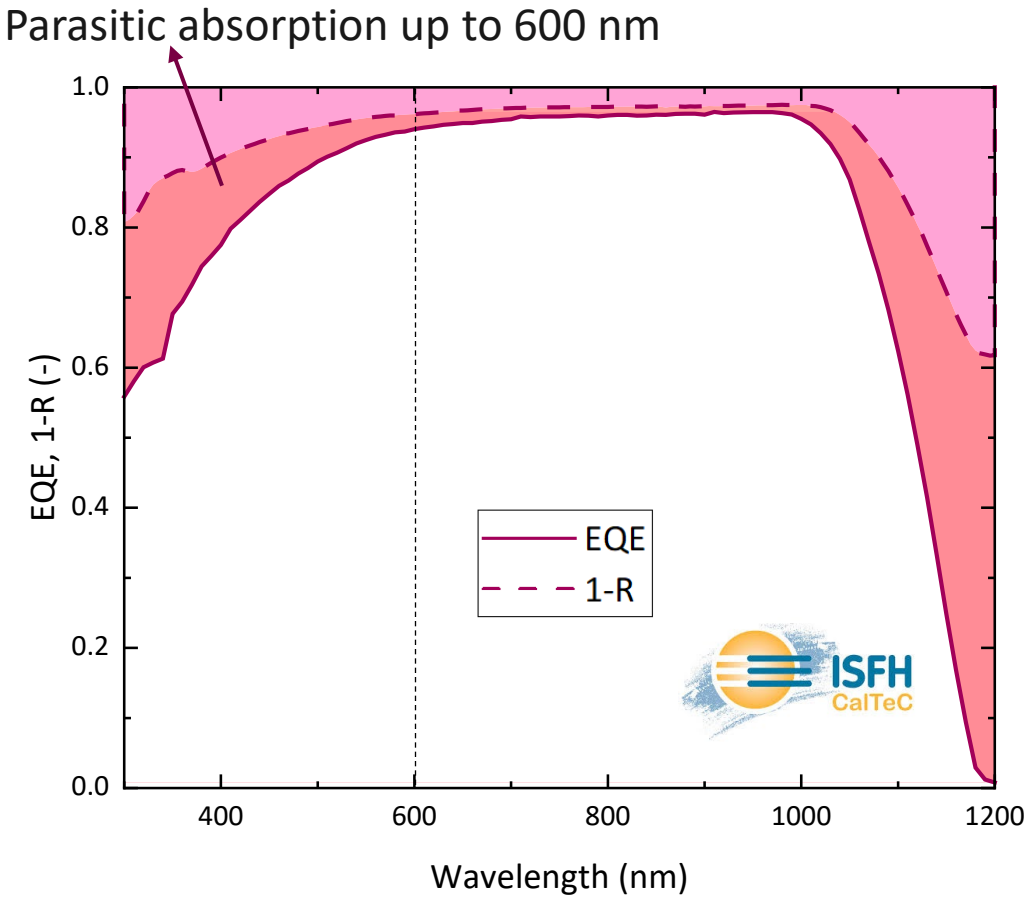


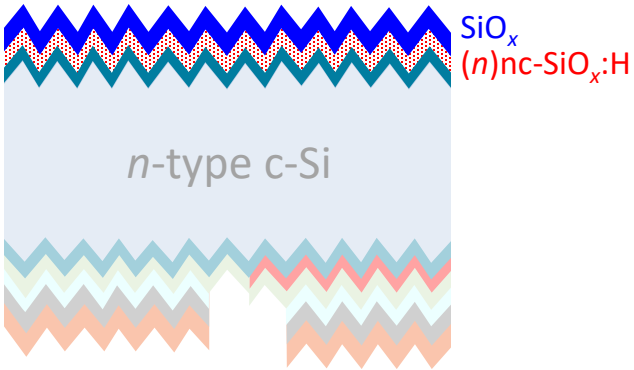


Front layer stack optimization



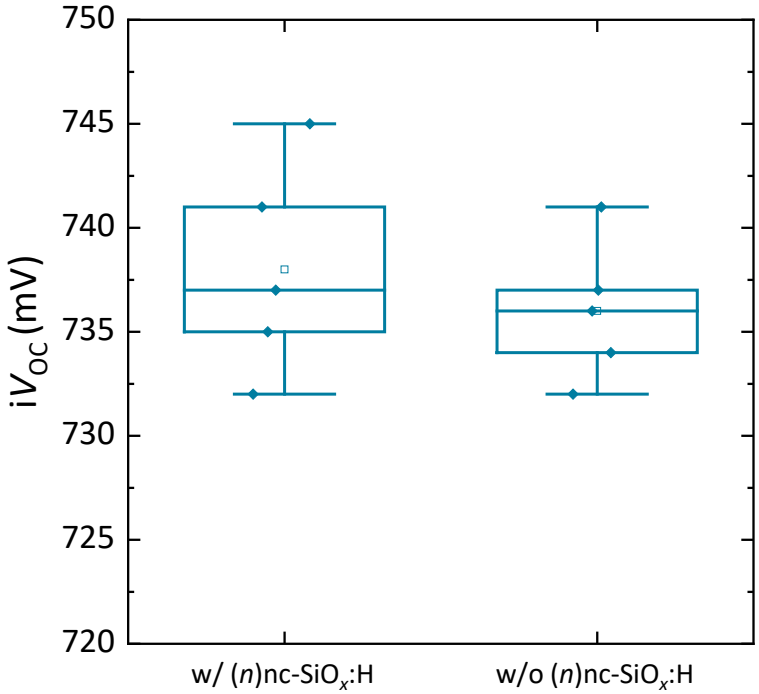
Front layer stack optimization

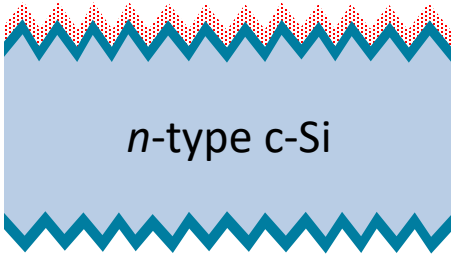




- Simulated $J_{ph,\ PA\ loss}$ from (*n*)nc-SiO$_x$:H up to 1 mA/cm^2

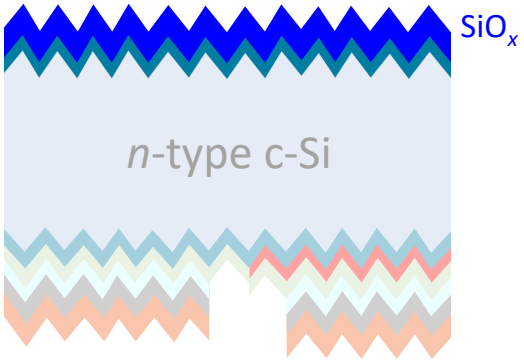
Front layer stack optimization





- Average iV_{OC} > 735 mV for both stacks

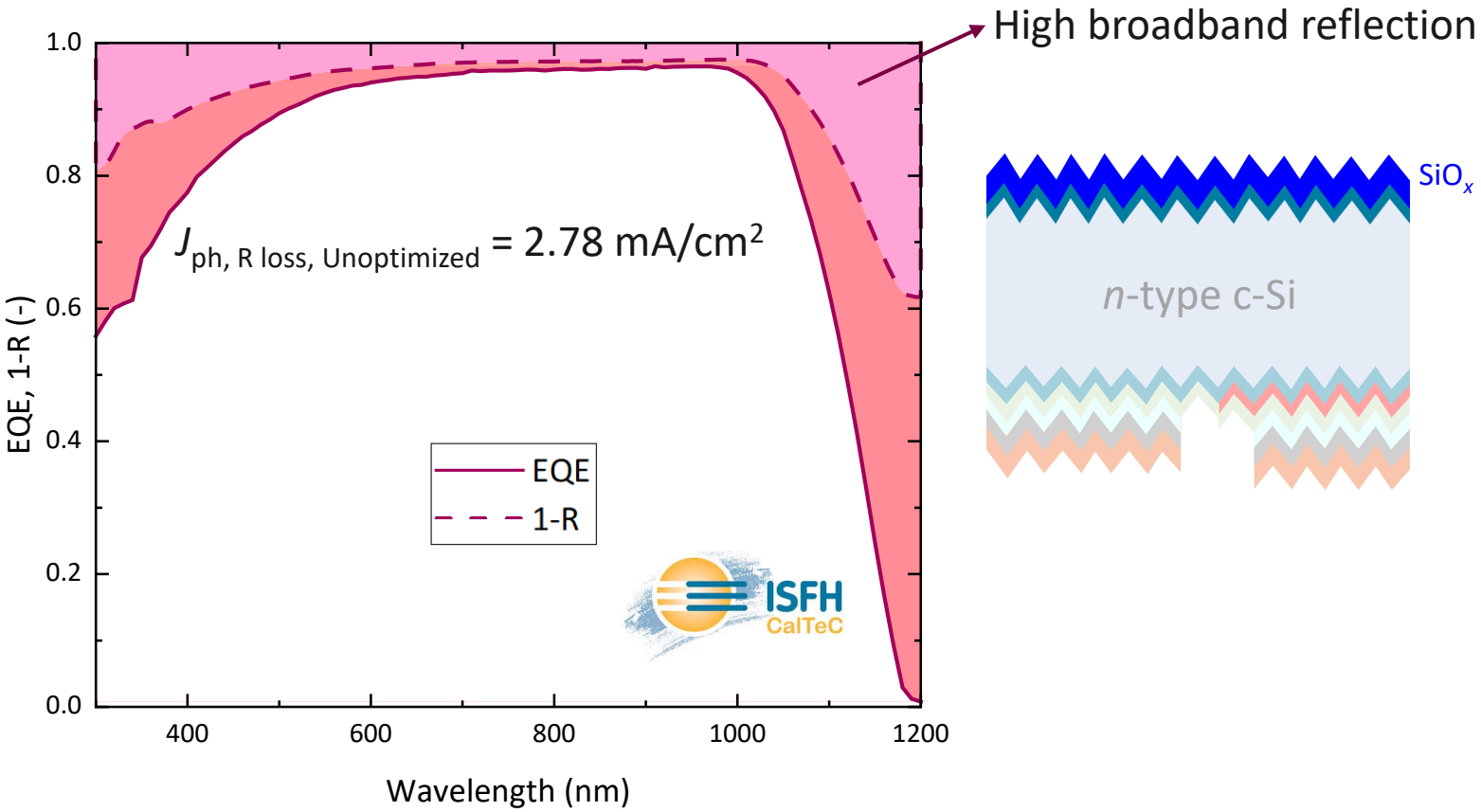
Front layer stack optimization



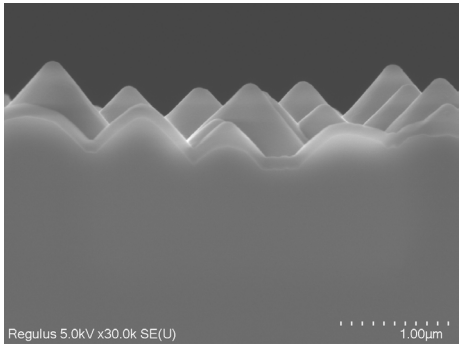
Without (*n*)nc-SiO$_x$:H:

- Reduced $J_{ph,\ PA\ loss}$
- Comparable experimental iV_{OC} for simplified stack

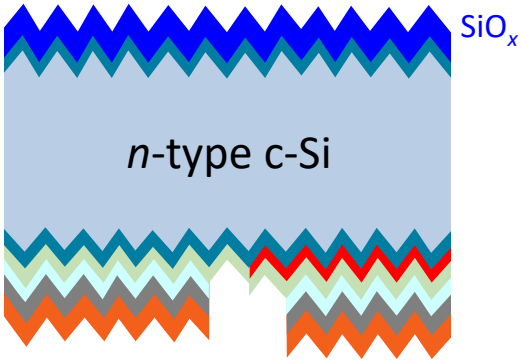
Front layer stack optimization



Reducing reflection losses



Double-layer anti-reflection coating (DLARC)
SiN_x + dense SiO_x



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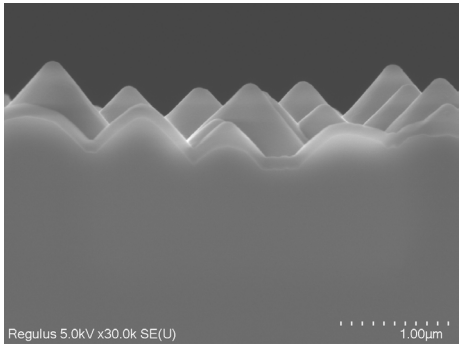
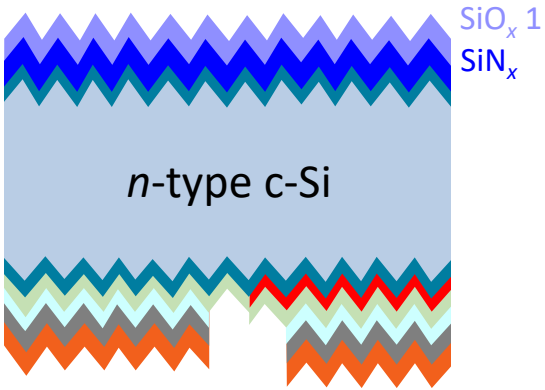
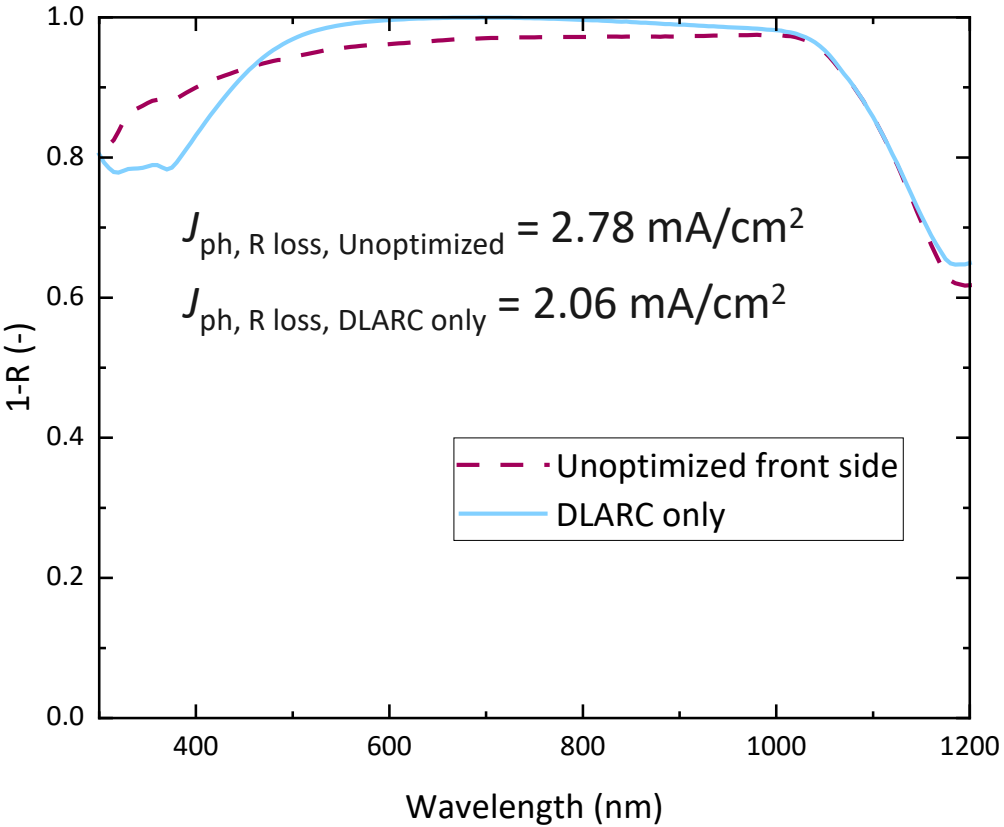
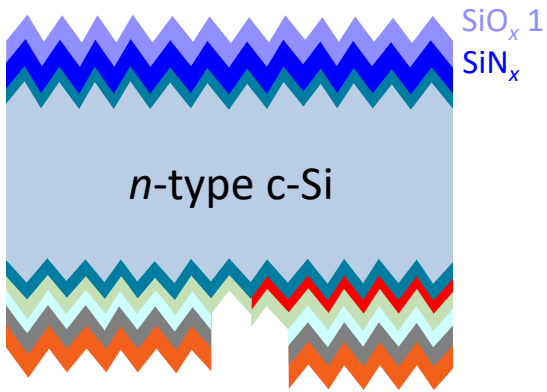


Double-layer anti-reflection coating (DLARC)
SiN_x + dense SiO_x (SiO_x 1)



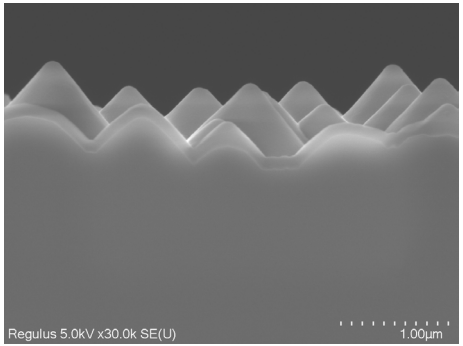
Reducing reflection losses





- (Still) high reflection losses in short wavelength range

Reducing reflection losses



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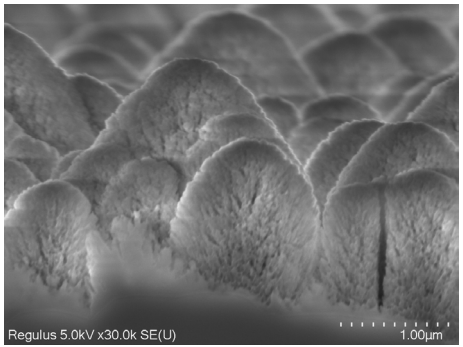
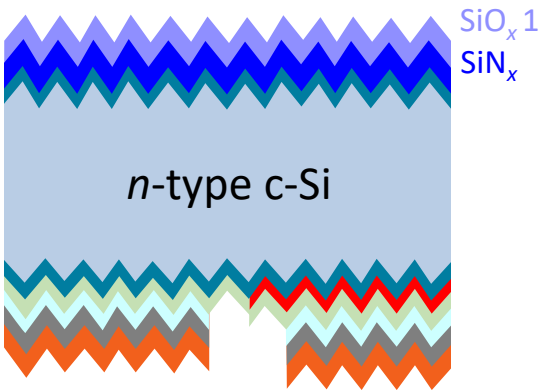


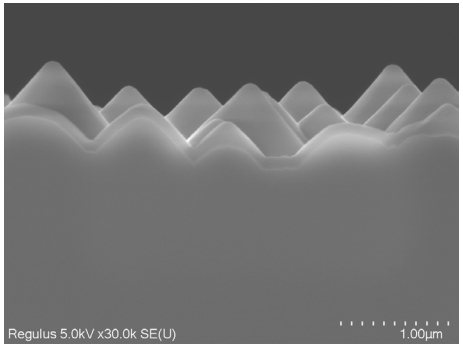
Double-layer anti-reflection coating (DLARC)
SiN_x + dense SiO_x (SiO_x 1)



SiO_x-based modulated surface texture (SiO_x-MST) [1]
Porous SiO_x

[1] G. Yang, et al., *Sol. Energ. Mater. Sol. Cells,* **186**, 9 (2018)

Reducing reflection losses



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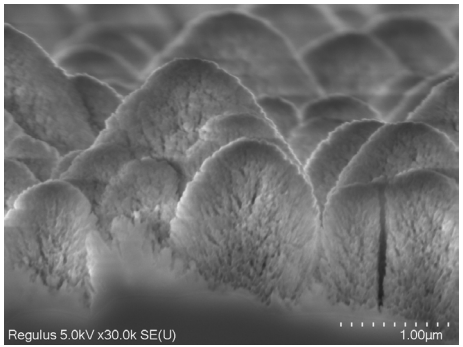

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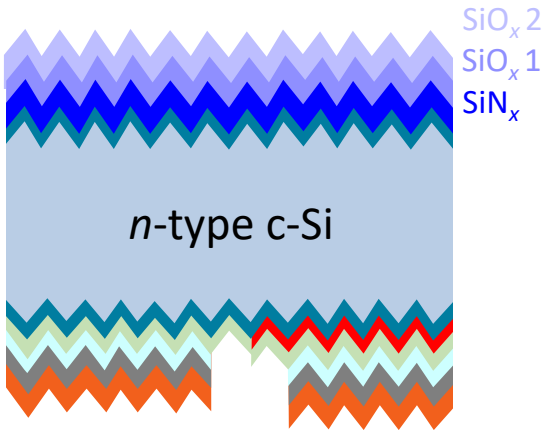
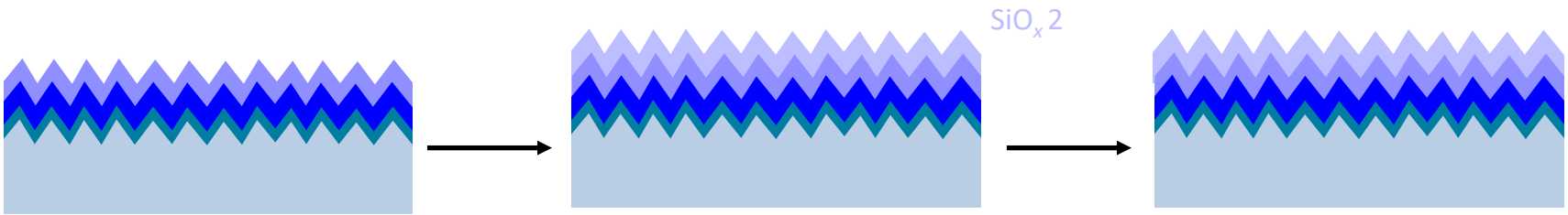


SiO_x-based modulated surface texture (SiO_x-MST) [1]
Porous SiO_x (SiO_x 2)

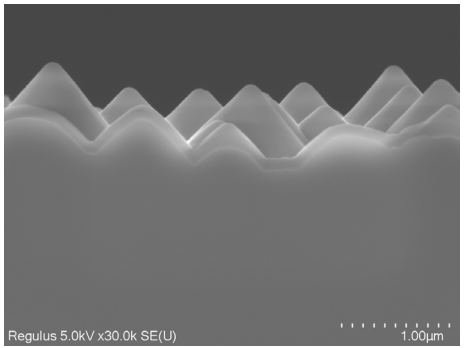
[1] G. Yang, et al., *Sol. Energ. Mater. Sol. Cells,* **186**, 9 (2018)

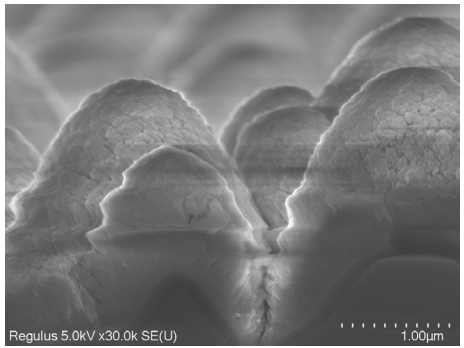
Making of SiO_x-MST [1]

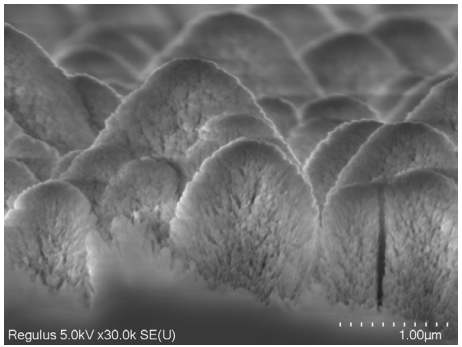


Low SiH_4 PECVD deposition of SiO_x

HF etching of SiO_x

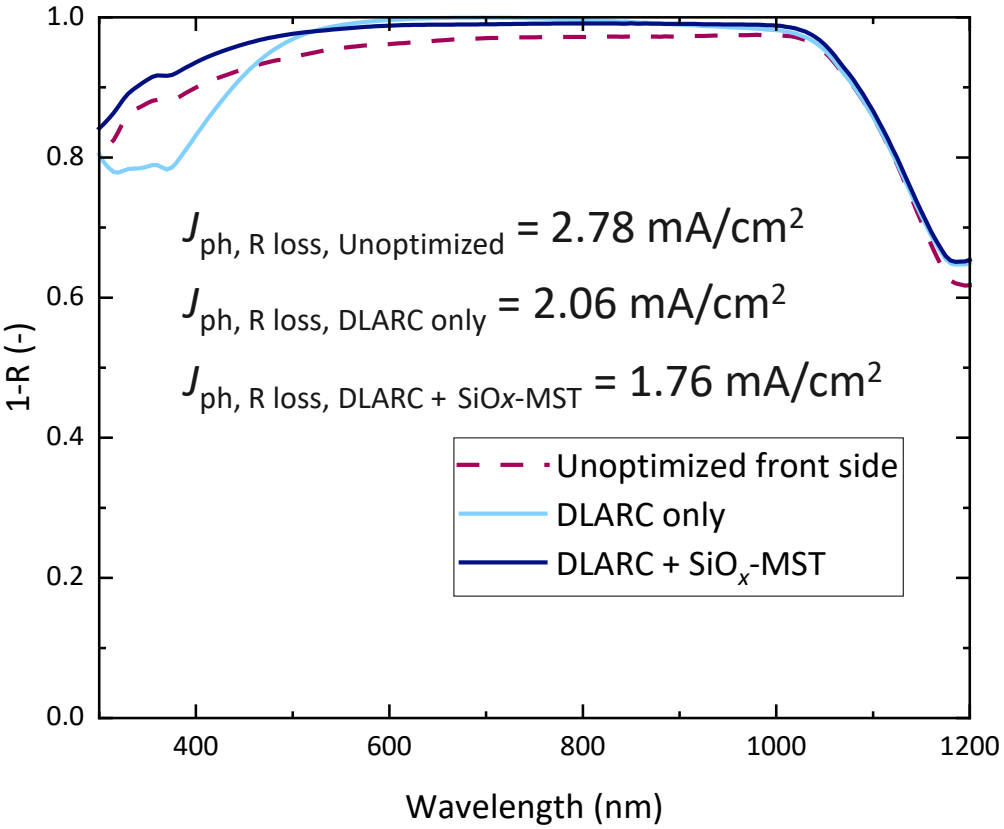


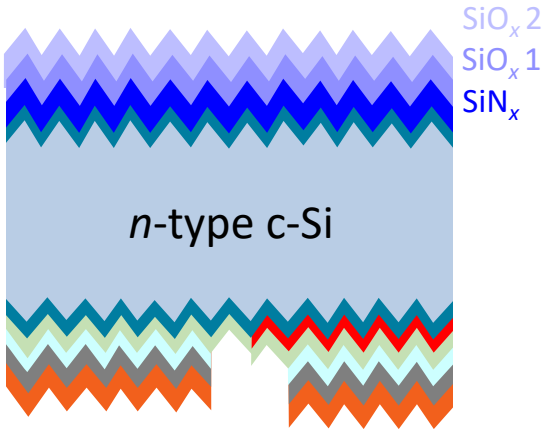




[1] G. Yang, et al., *Sol. Energ. Mater. Sol. Cells,* **186**, 9 (2018)

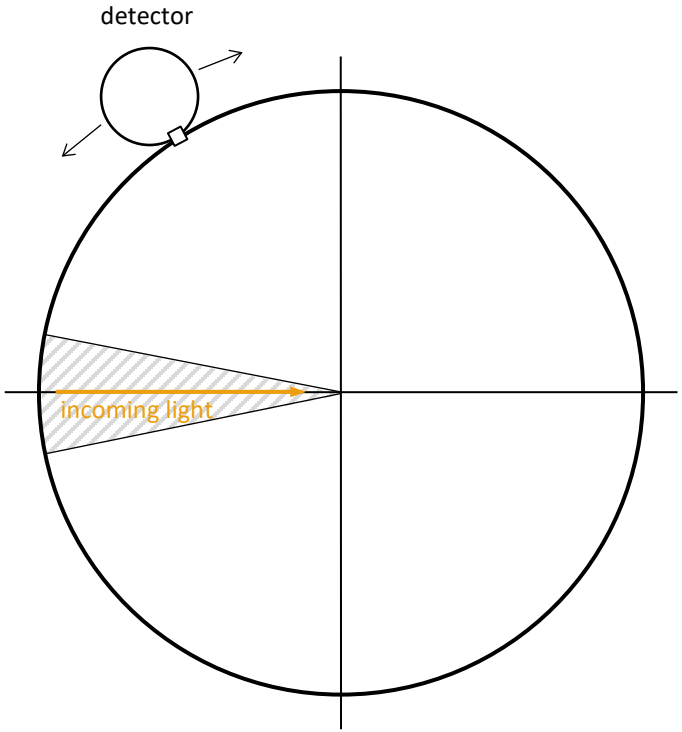
Reducing reflection losses





- Reduced reflectance across extended range of wavelengths (> 1 mA/cm^2 gain)
- Does SiO_x-MST influence angular reflectance?

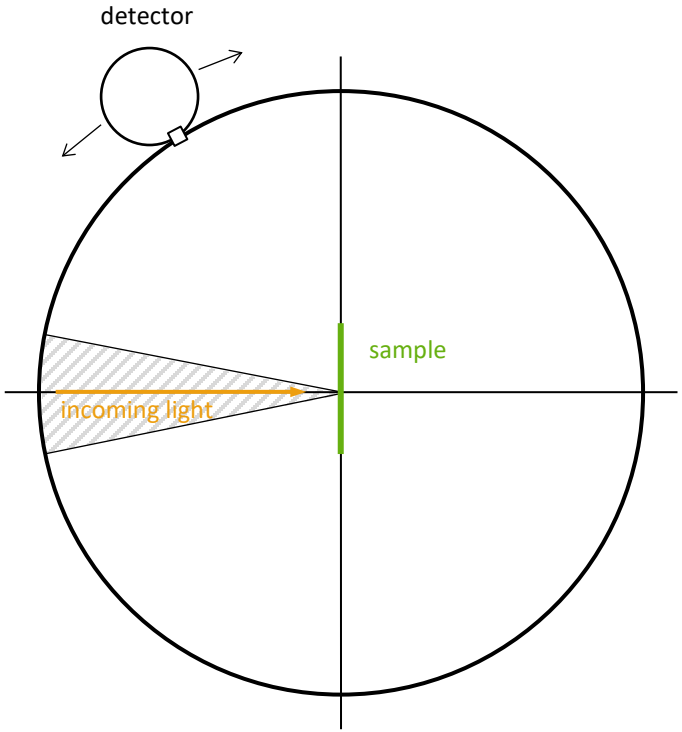
Angular intensity distribution (AID) in reflectance



Absolute reflectance transmittance accessory (ARTA) [1]

[1] Perkin Elmer

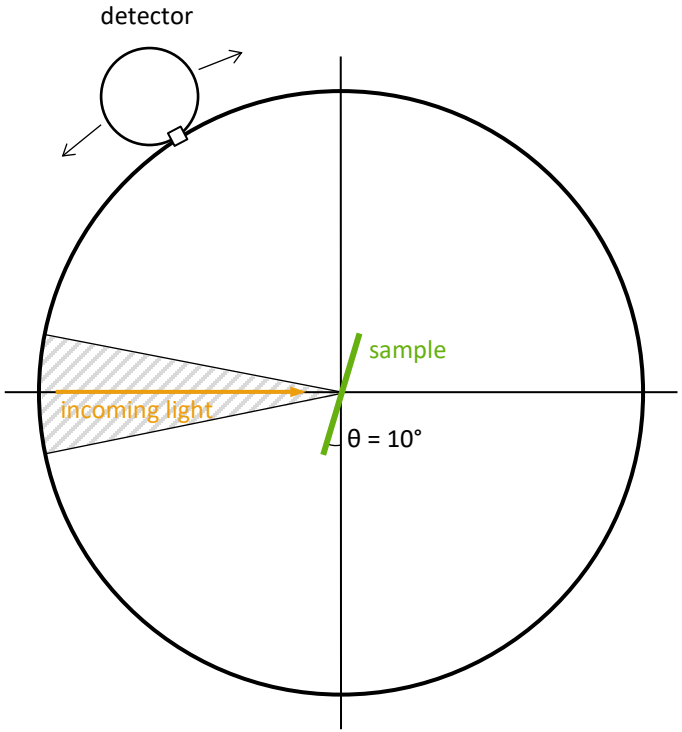
Angular intensity distribution (AID) in reflectance



Absolute reflectance transmittance accessory (ARTA) [1]

[1] Perkin Elmer

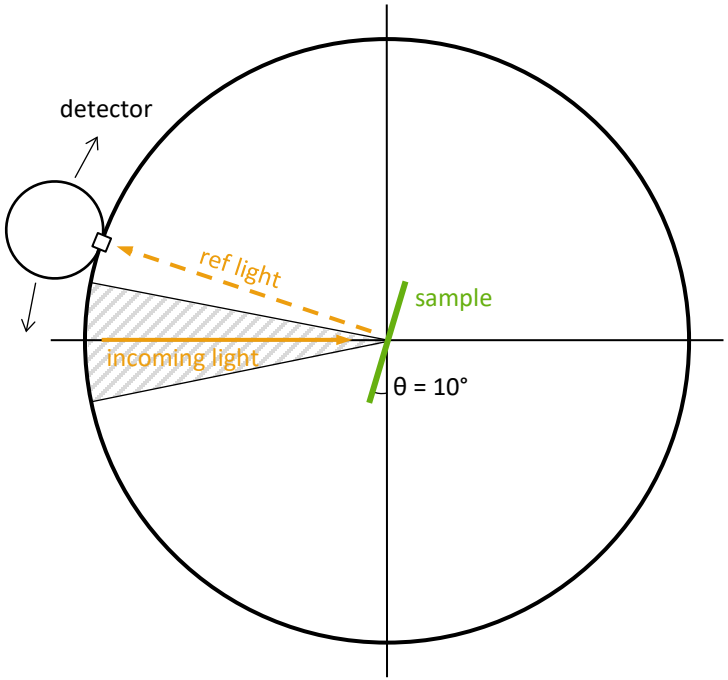
Angular intensity distribution (AID) in reflectance



Absolute reflectance transmittance accessory (ARTA) [1]

[1] Perkin Elmer

Angular intensity distribution (AID) in reflectance



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[1] Perkin Elmer

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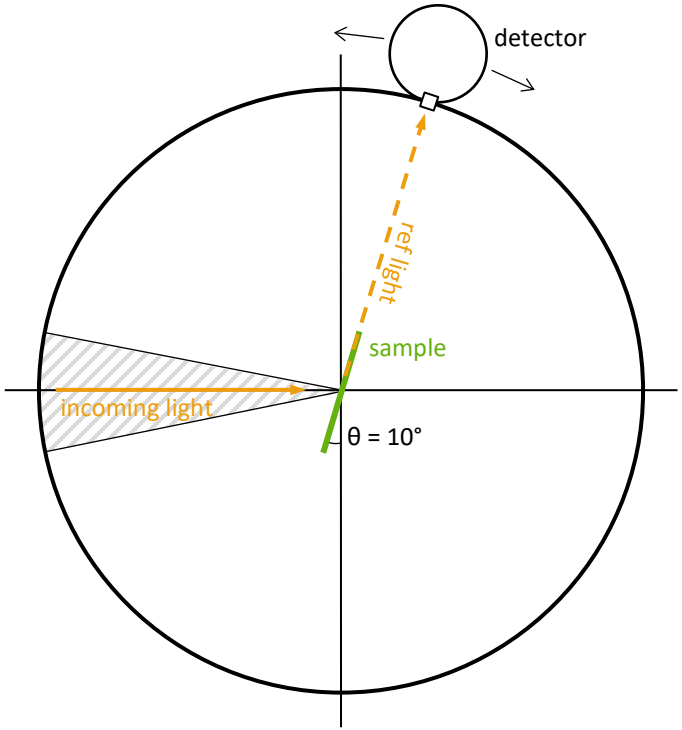

Absolute reflectance transmittance accessory (ARTA) [1]

[1] Perkin Elmer

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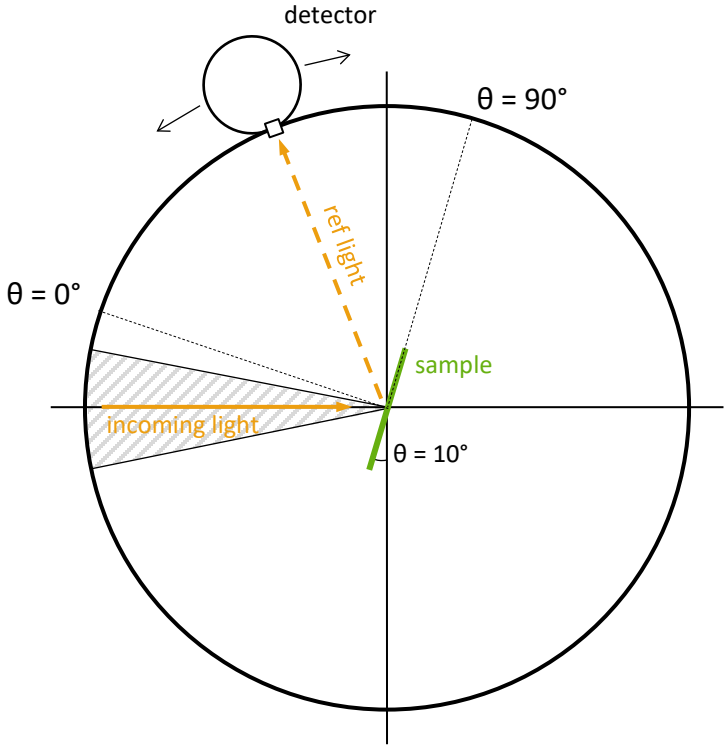

Absolute reflectance transmittance accessory (ARTA) [1]

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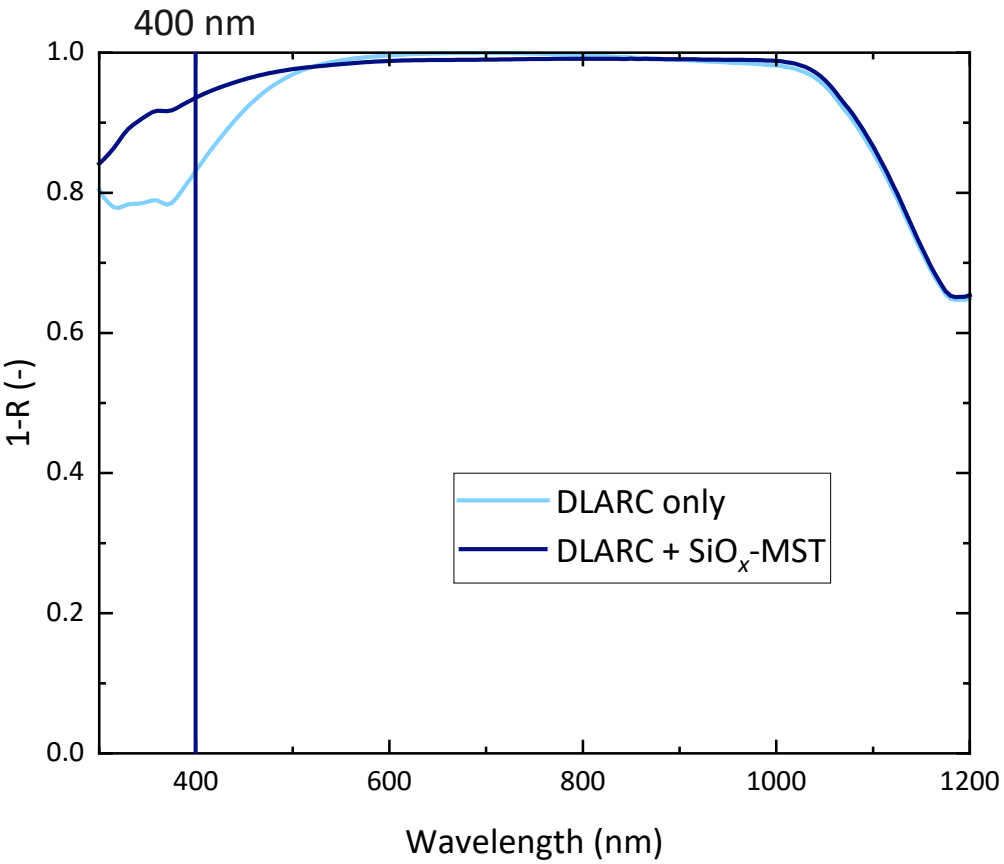
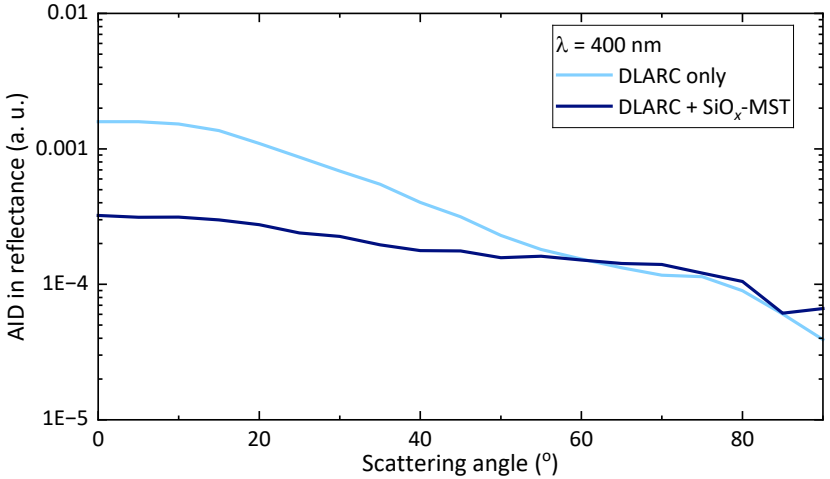
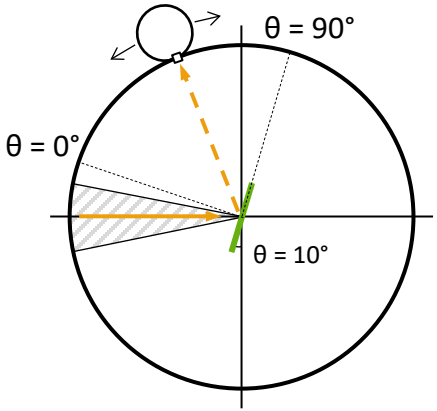
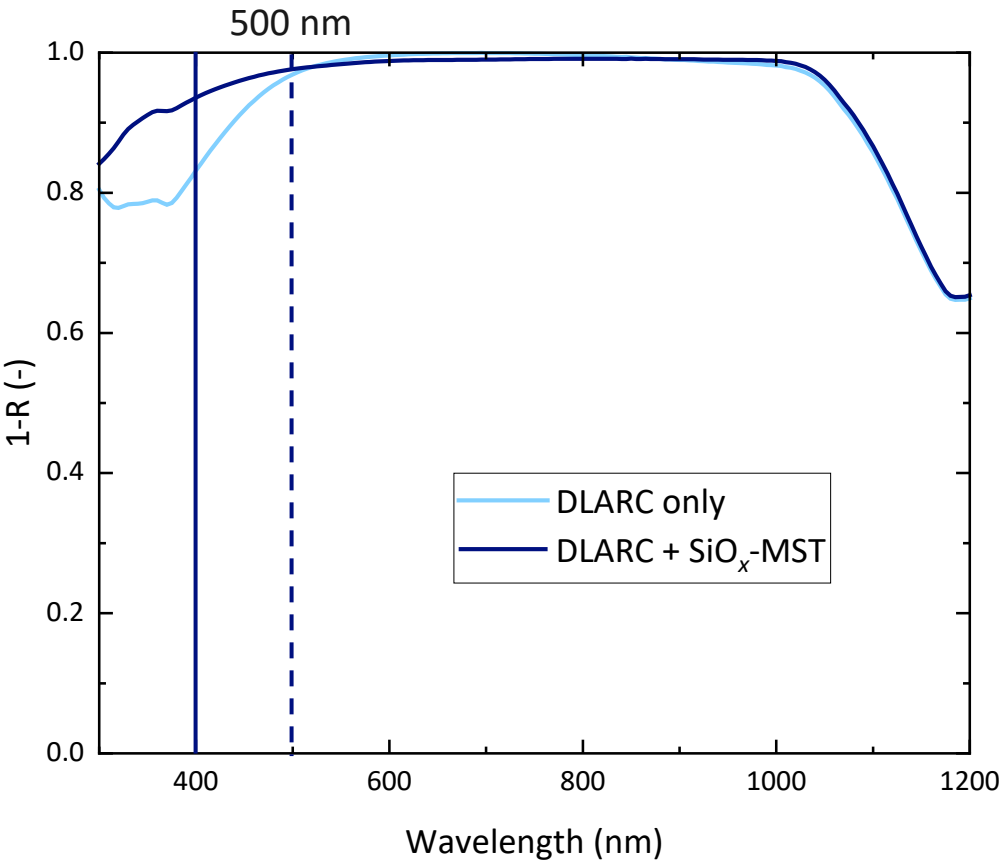
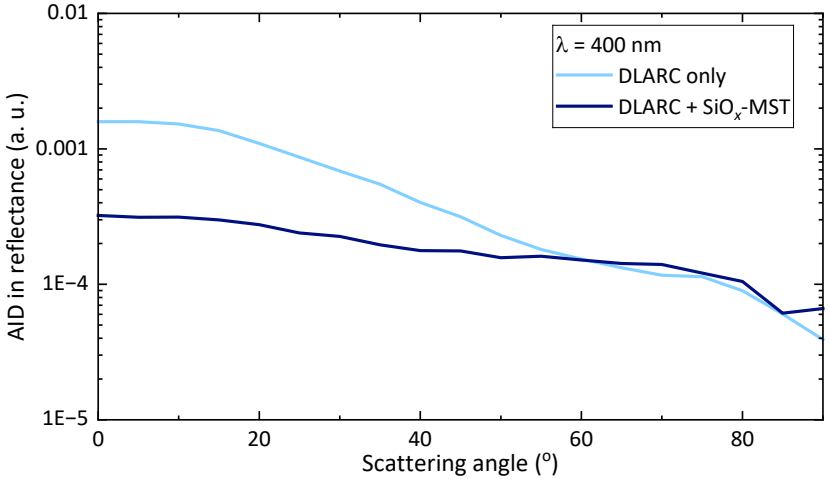


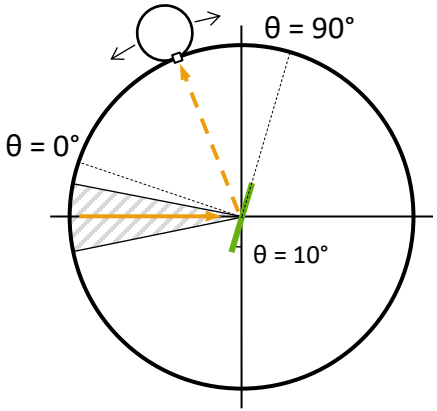




Angular intensity distribution (AID) in reflectance







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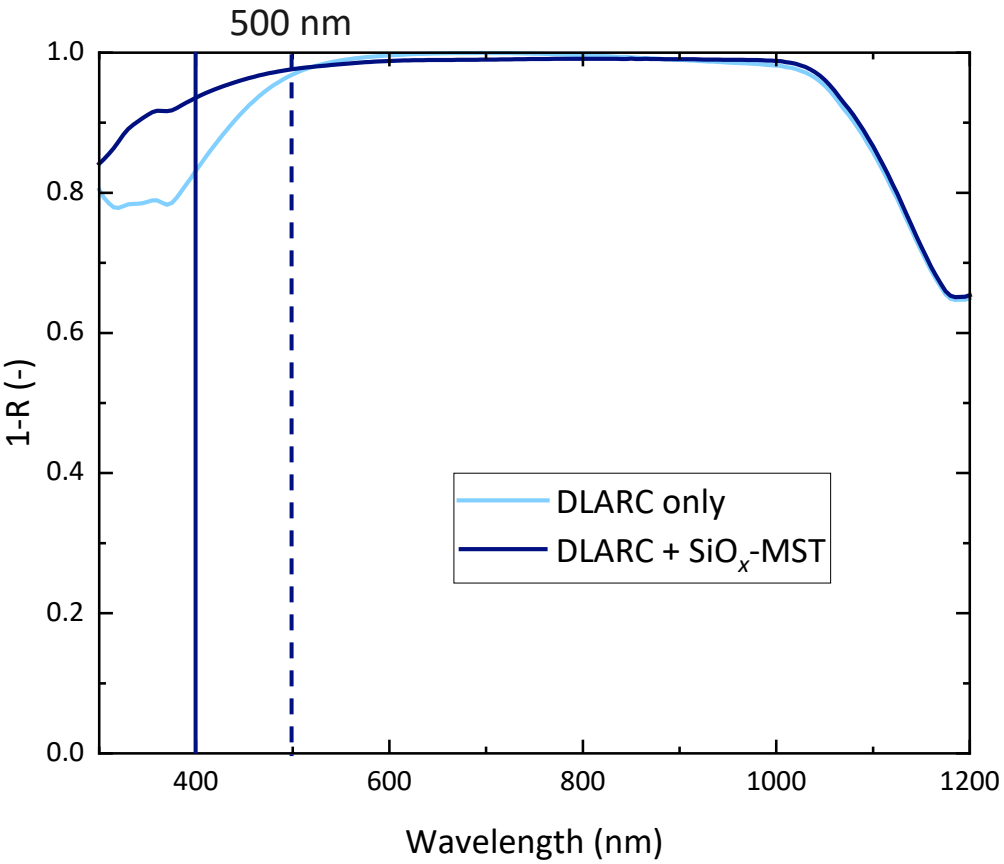

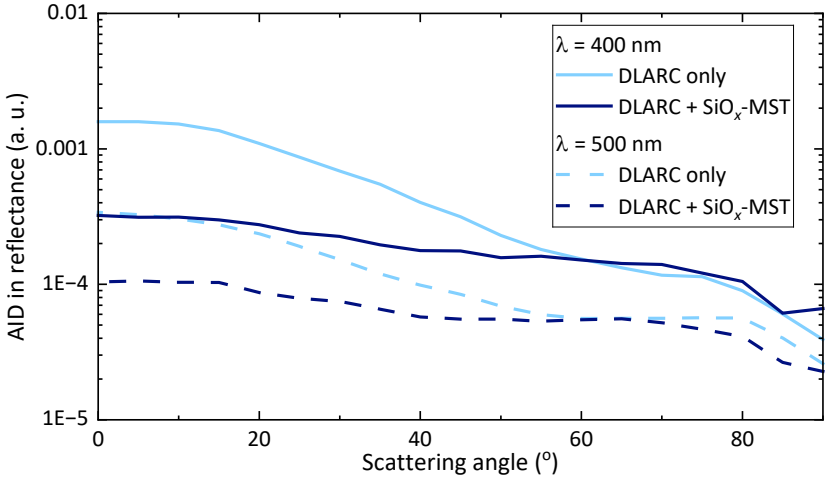

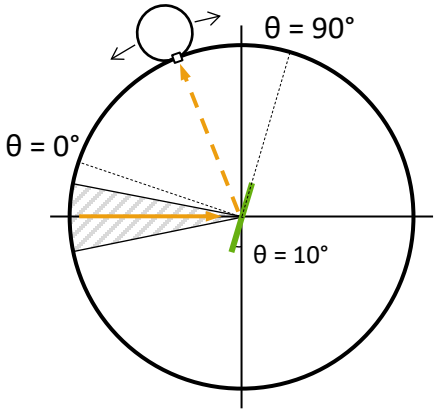

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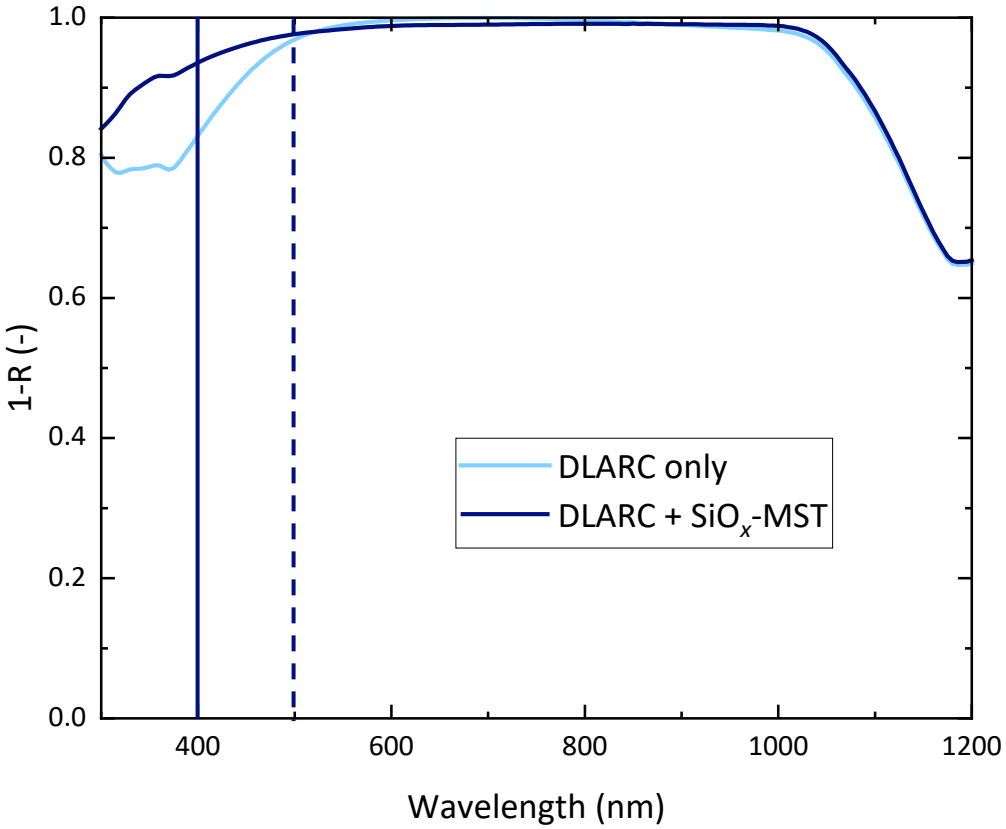
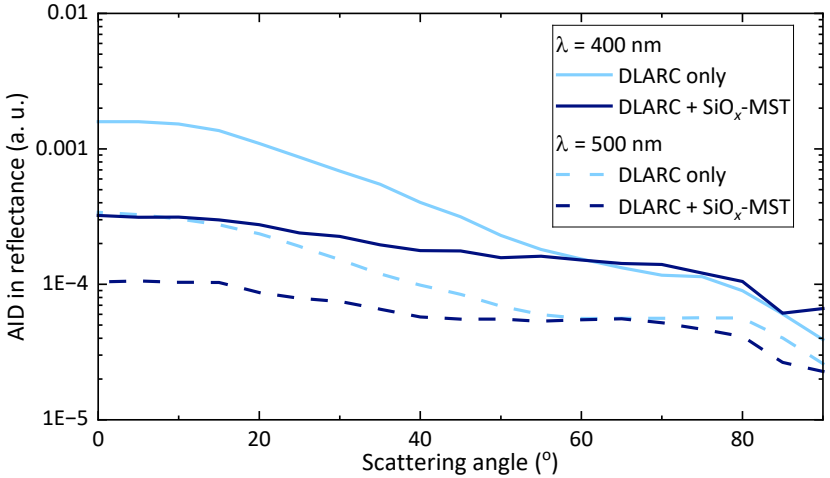
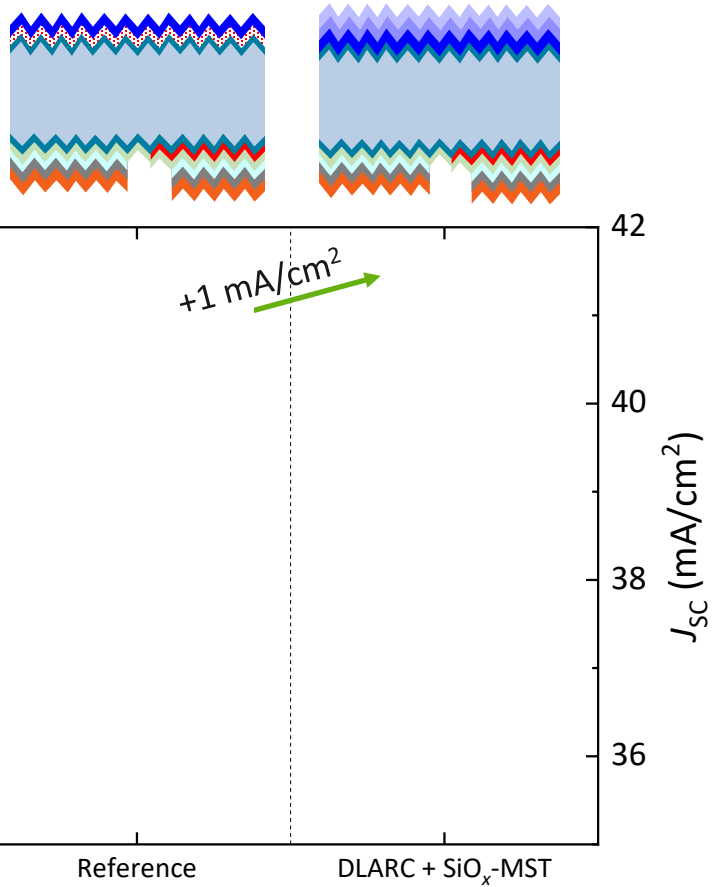




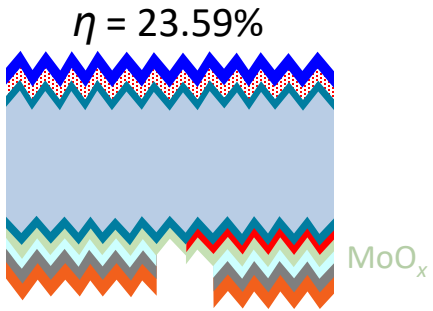
- Nanofeatures of SiO_x-MST enable more even reflectance from different angles

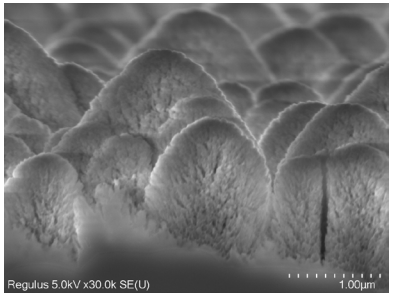
Solar cells with improved light management

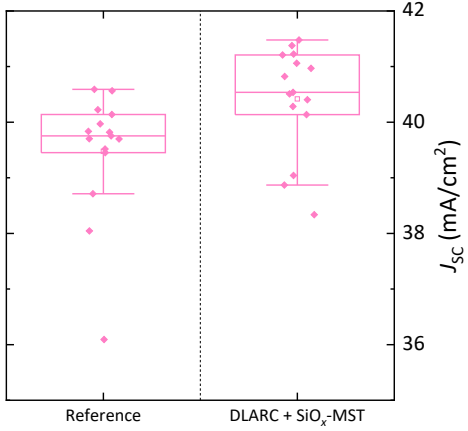


Conclusion

- Novel IBC-SHJ solar cells with MoO_x blanket layer
  - Simple fabrication, faster processing and high shunt resistance
- Combining DLARC and SiO_x-MST for optimized light in-coupling
  - Reduced reflectance across extended range of wavelengths and angles
  - Best-to-best +1 mA/cm^2 J_{SC} gain







Thank you for your attention!

TU Delft Institutes

Urban Energy

e-Refinery

AgTech

TU Delft Climate Action Programme

TERASUN

PVMD funding

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Rijksdienst voor Ondernemend Nederland

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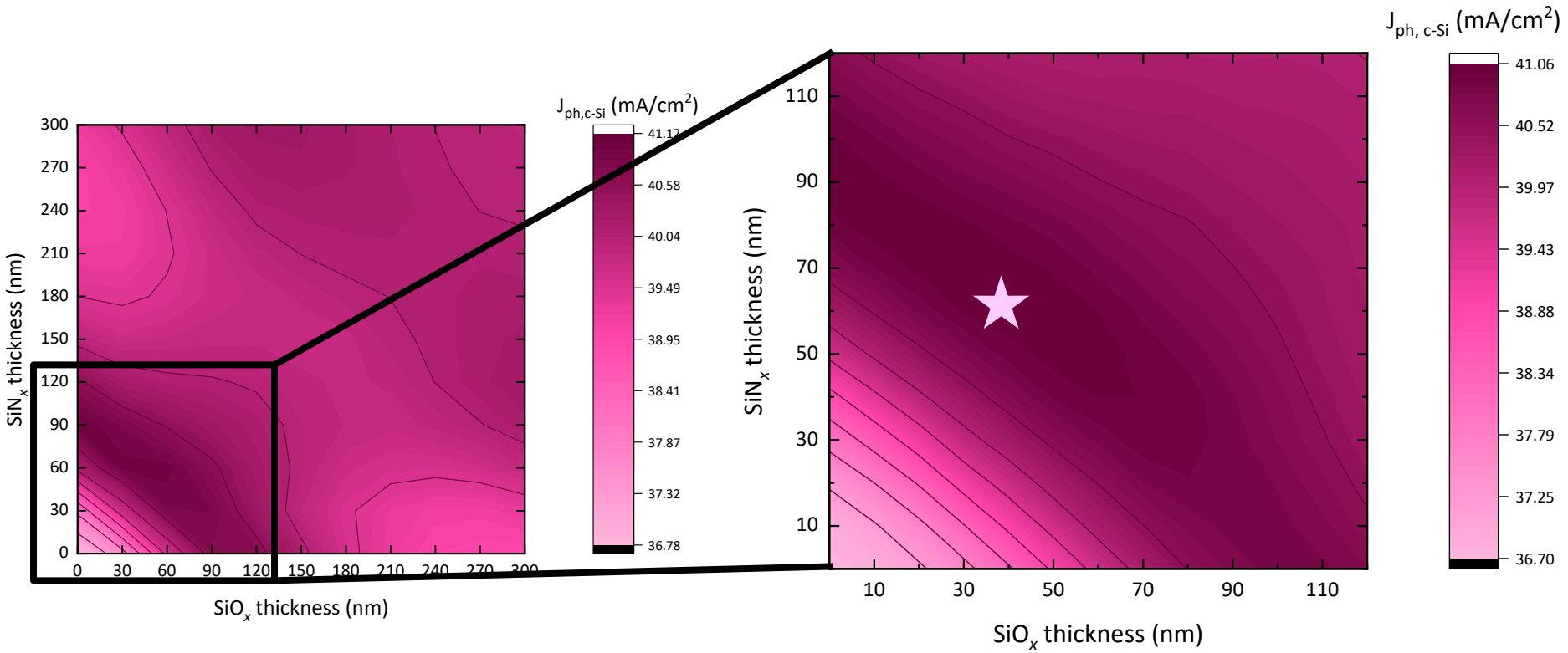
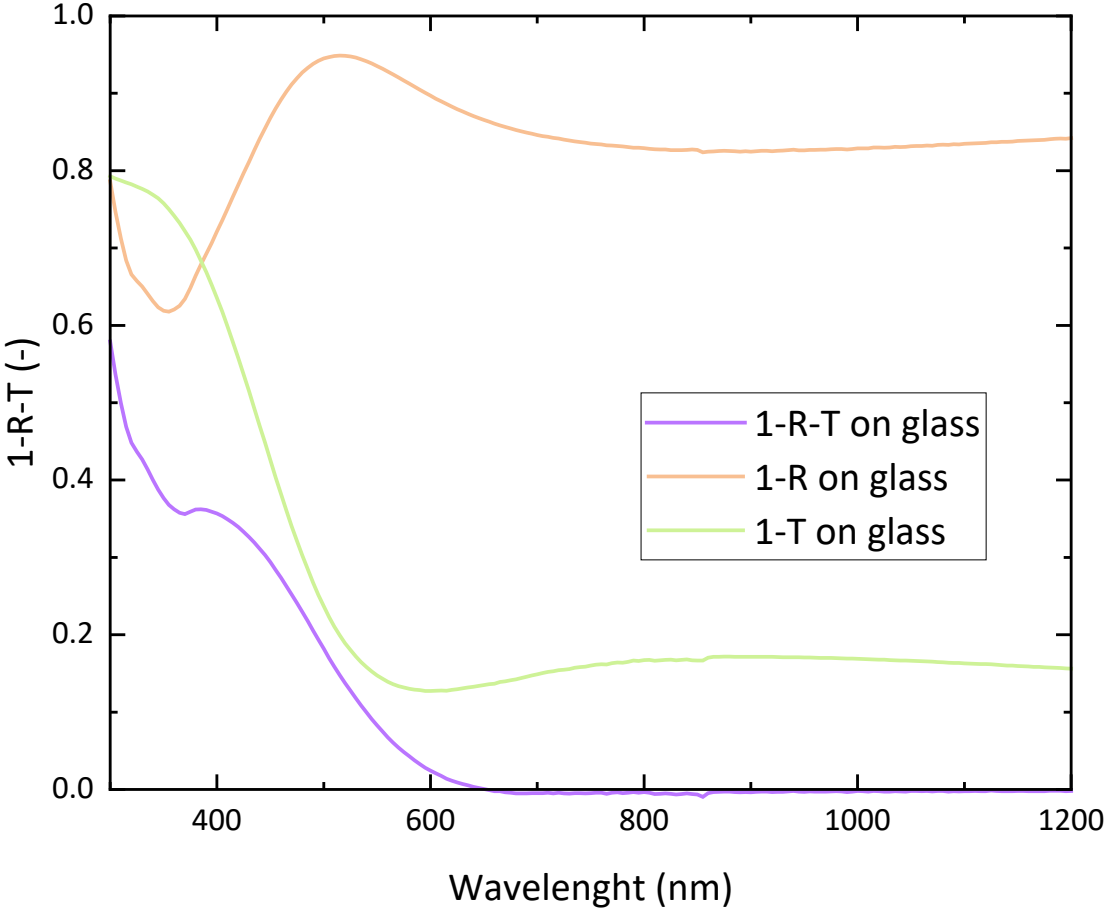
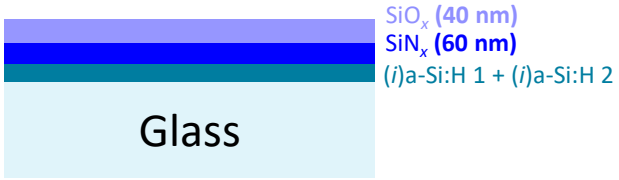
Reducing reflection losses



Reflectance and transmittance of the stack





Symmetrical samples without FSF