

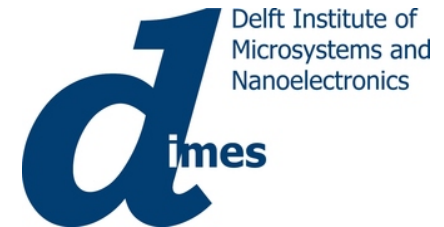
A versatile optical model for optimization of advanced solar cell concepts

Rudi Santbergen, PVMD, TU Delft, the Netherlands
Euroregional workshop on PV, September 1st 2014, Ljubljana

Introducing PVMD group

Photovoltaic materials and devices (PVMD)

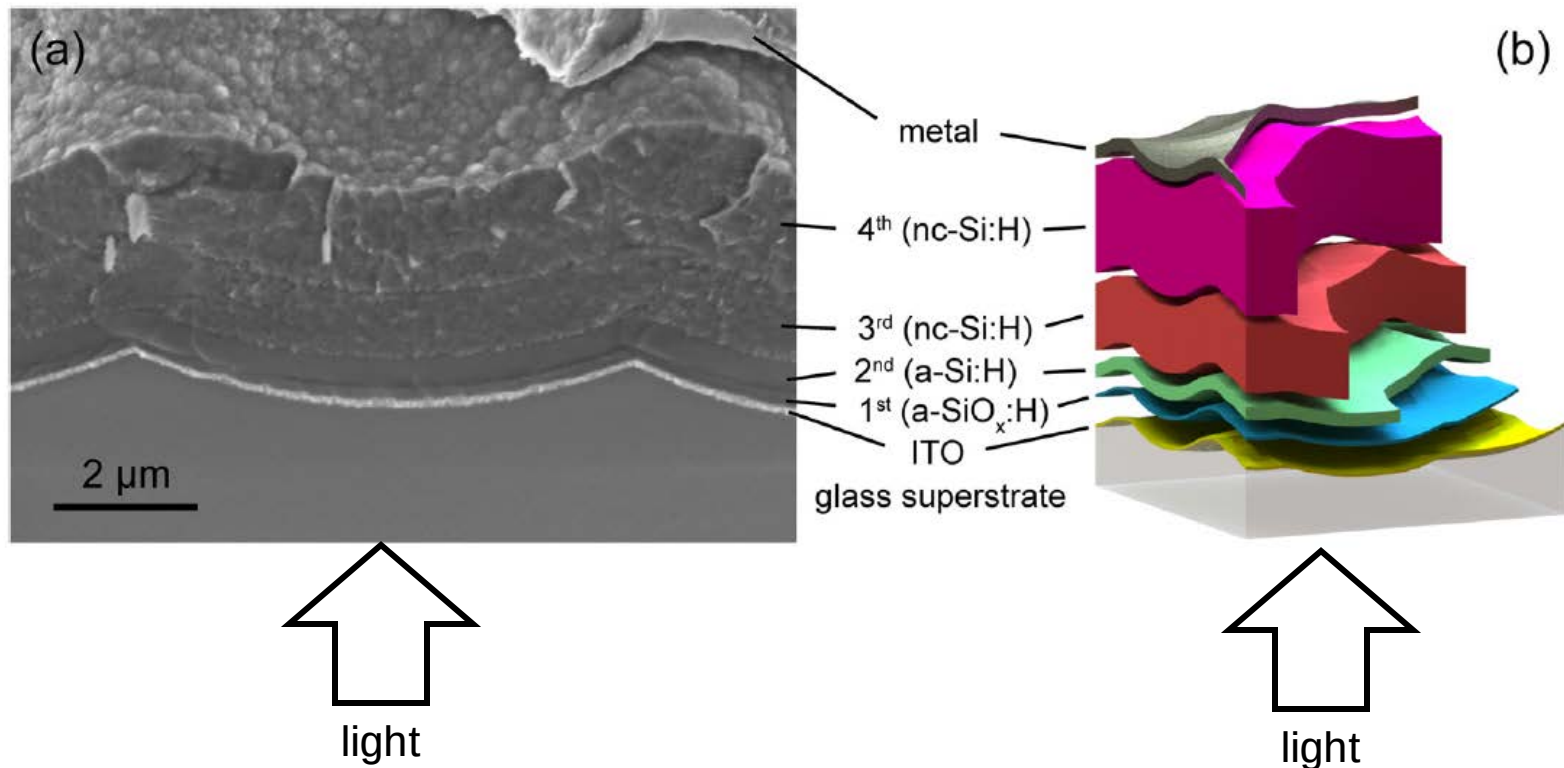
TU Delft → PVMD group (member of DIMES)



PVMD research: Thin-film Si (4J)

F. Si et. al., *Applied Physics Letters* (2014) **105** 063902

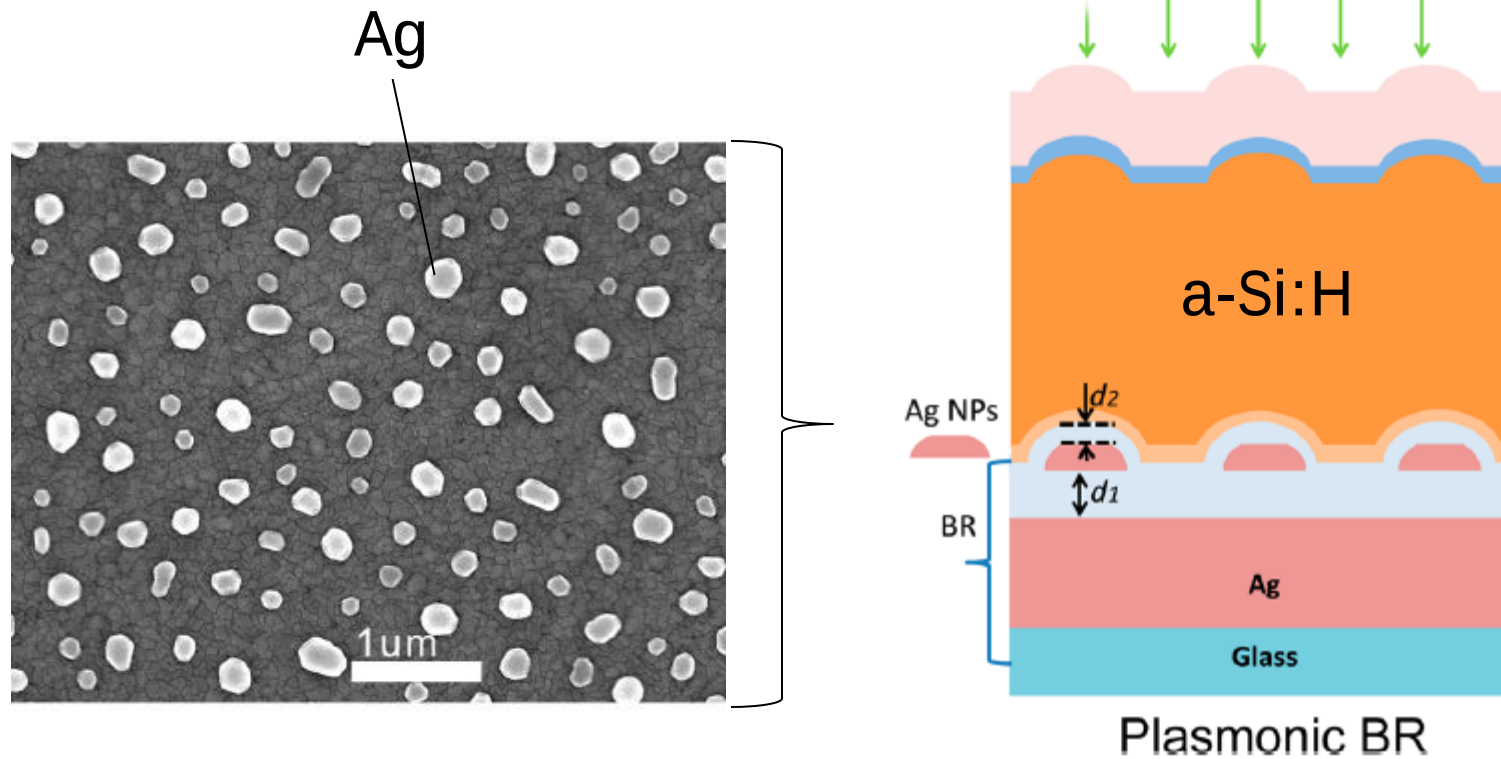
DOI: 10.1063/1.4892890



PVMD research: plasmonic light-trapping

H. Tan et. al., *Nano Letters* (2012) **12** 4070-4076

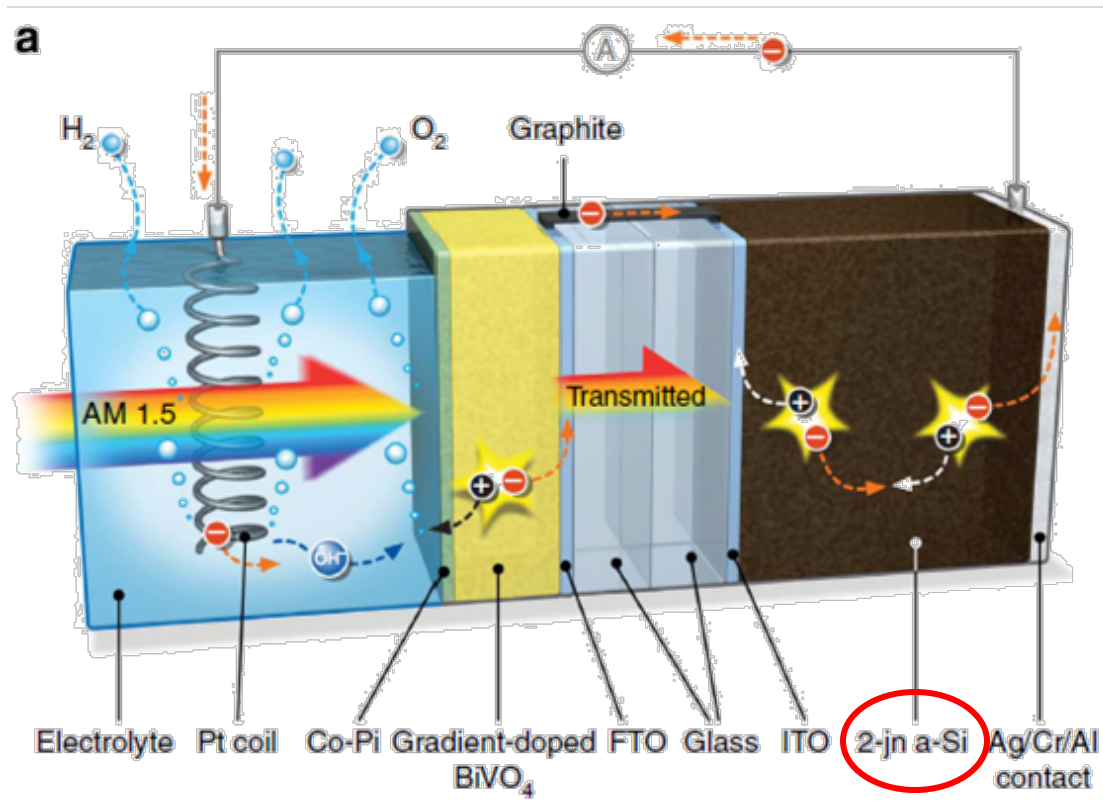
DOI: 10.1021/nl301521z



PVMD* research: solar water splitting

F. Abdi et. al., *Nature Communications* (2013) 4:2195

DOI: 10.1038/ncomms3195

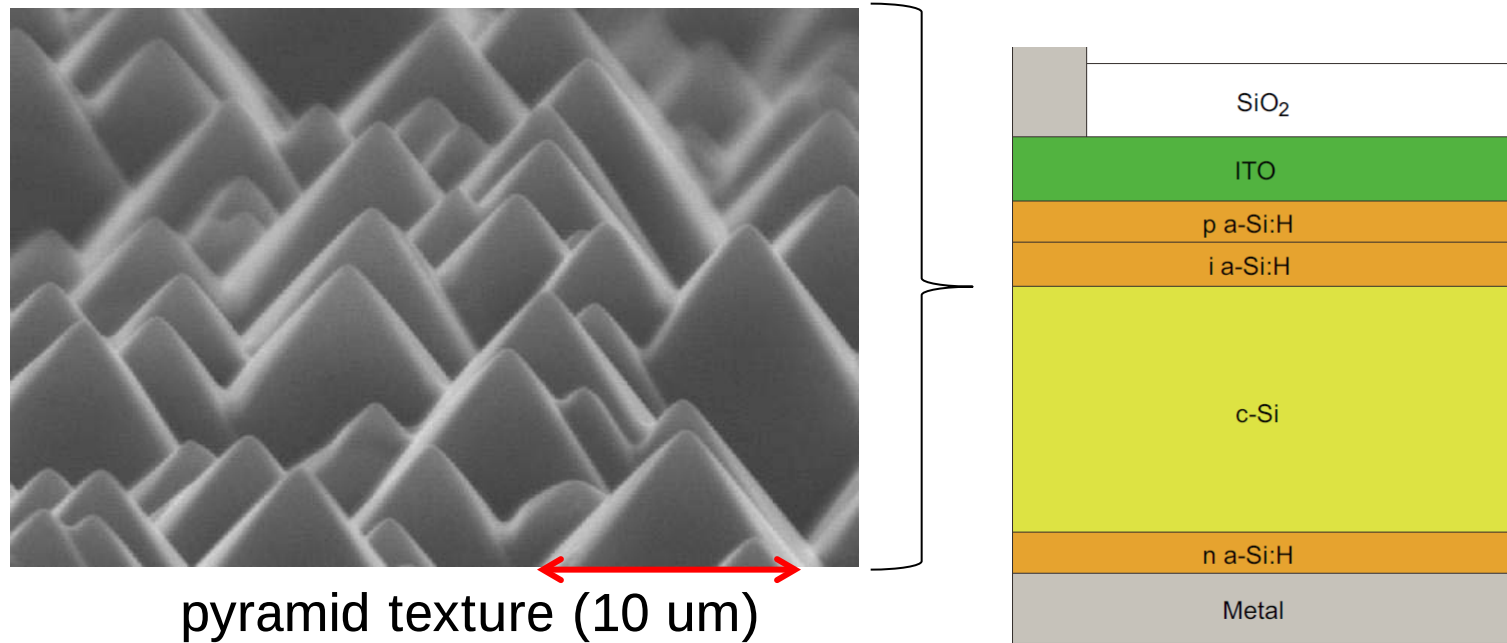


* in collaboration with MECS group (TU Delft)

PVMD research: c-Si wafer based (HIT)

D. Zhang et. al., *Sol. Ener. Mat. & Sol. Cells* (2013) **117** 132

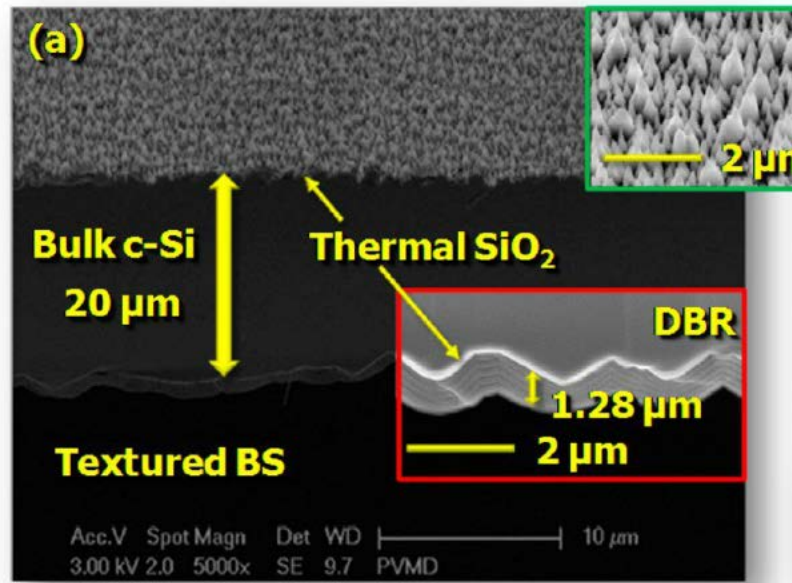
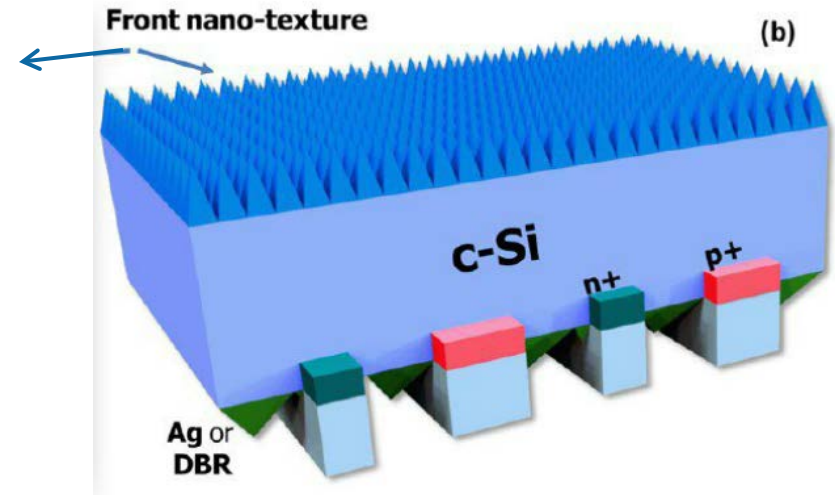
DOI: 10.1016/j.solmat.2013.05.044



PVMD research: ultra-thin c-Si

A. Ingenito et. al., *ACS Photonics* (2014) **1** 270-278

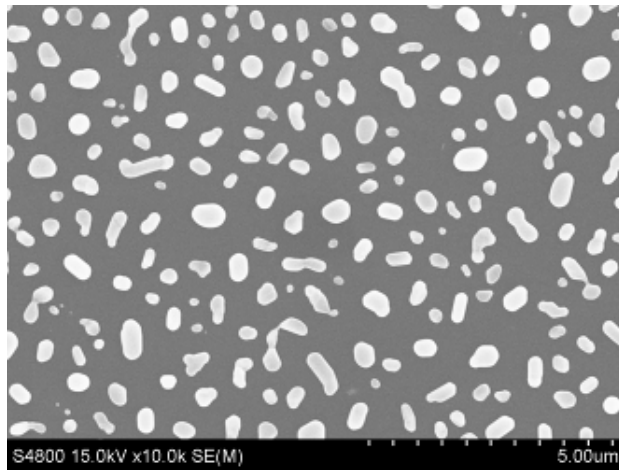
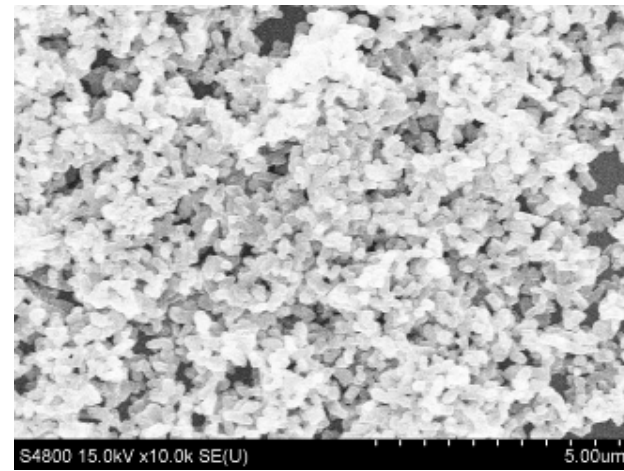
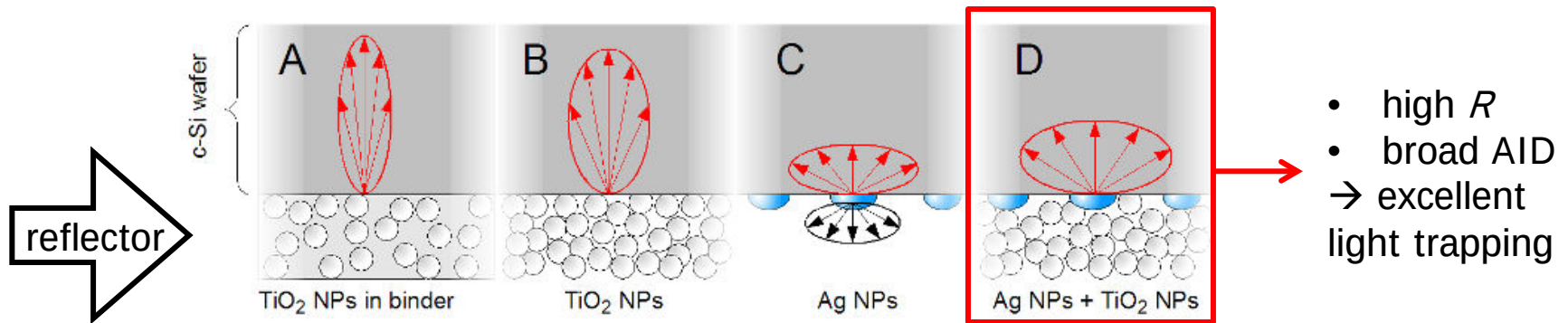
DOI: 10.1021/ph4001586



PVMD research: plasmonic white paint

R. Santbergen et al. 39th IEEE PVSC (2013)

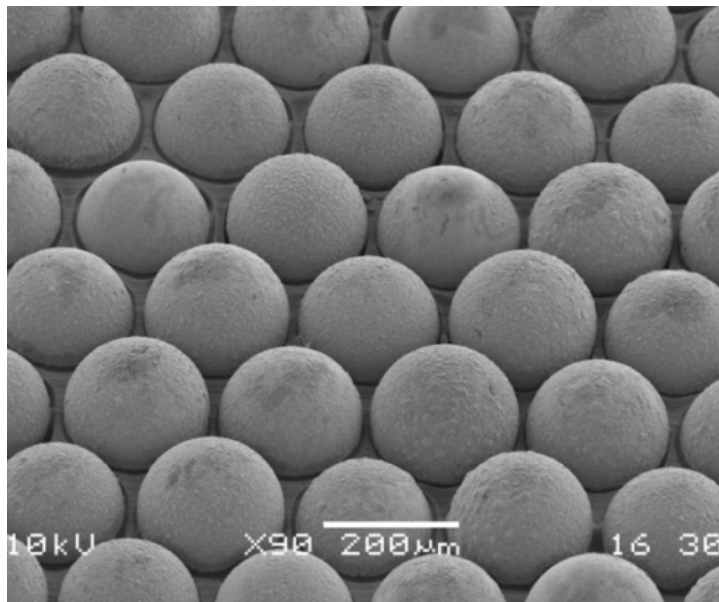
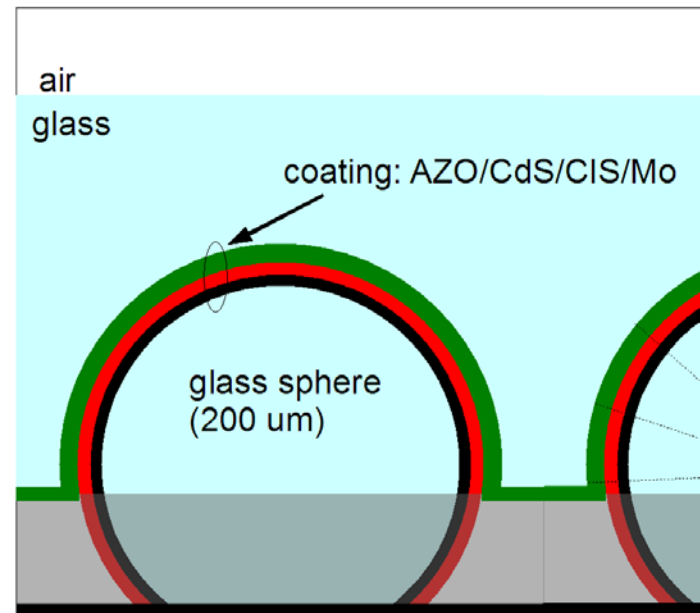
DOI: 10.1109/PVSC.2013.6744092



PVMD* research: CIGS coated micro beads

V. Geyer et al., *Thin-Solid Films* **516** (2008) 4651-4655

DOI: 10.1016/j.tsf.2007.05.083

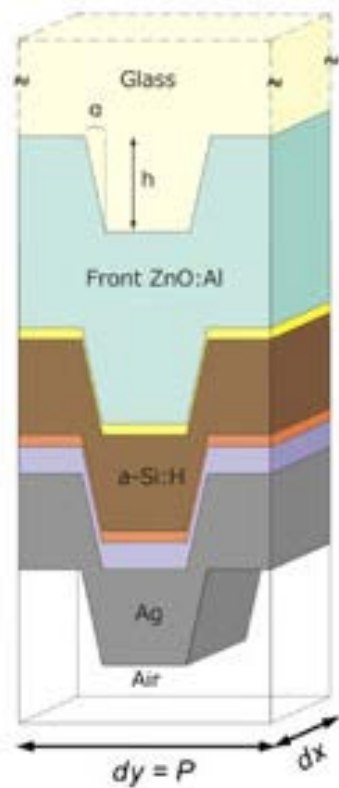
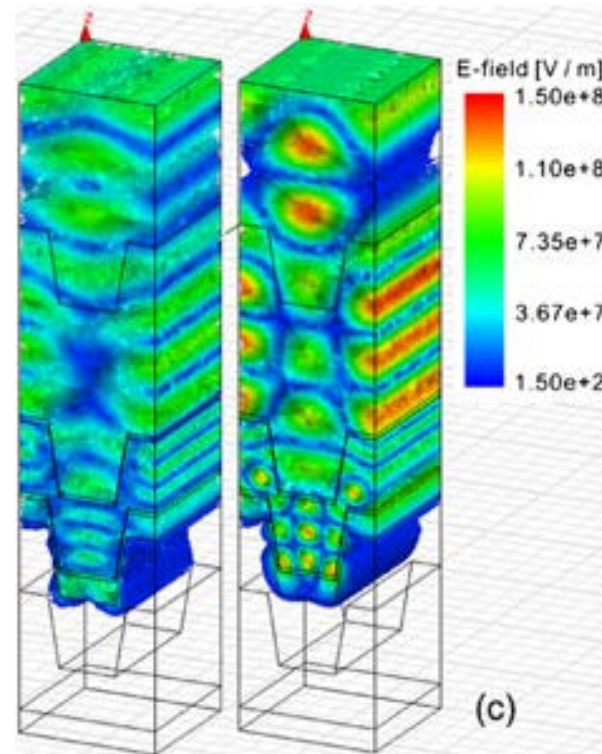


* in collaboration with Scheuten (Dutch glass & PV company)

PVMD research: solar cell simulation

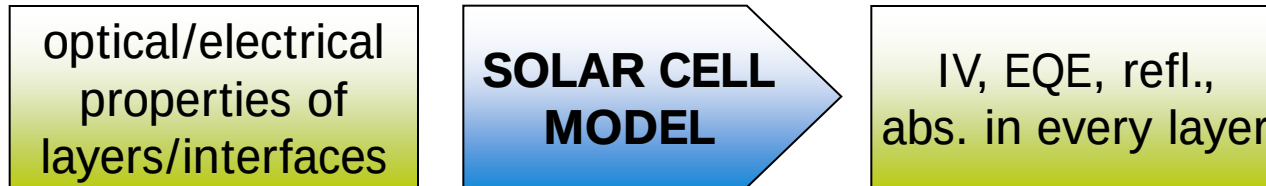
O. Isabella et. al., *Prog. Photovolt.* **21** (2013) 94-108

DOI: 10.1002/pip.1257



Solar cell simulation

Importance of simulations

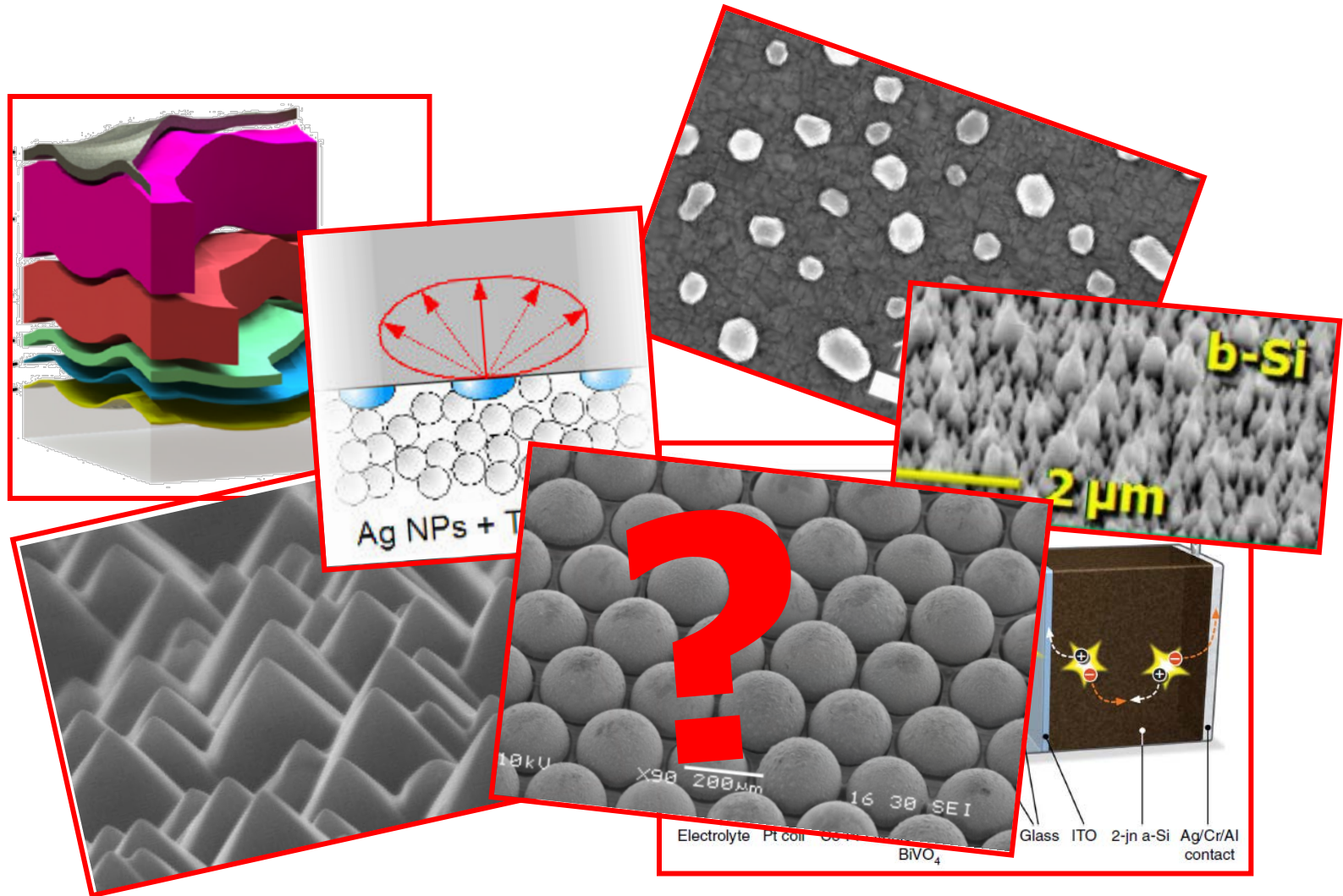


- gives more insight (in loss mechanisms)
- fast optimization of complex designs

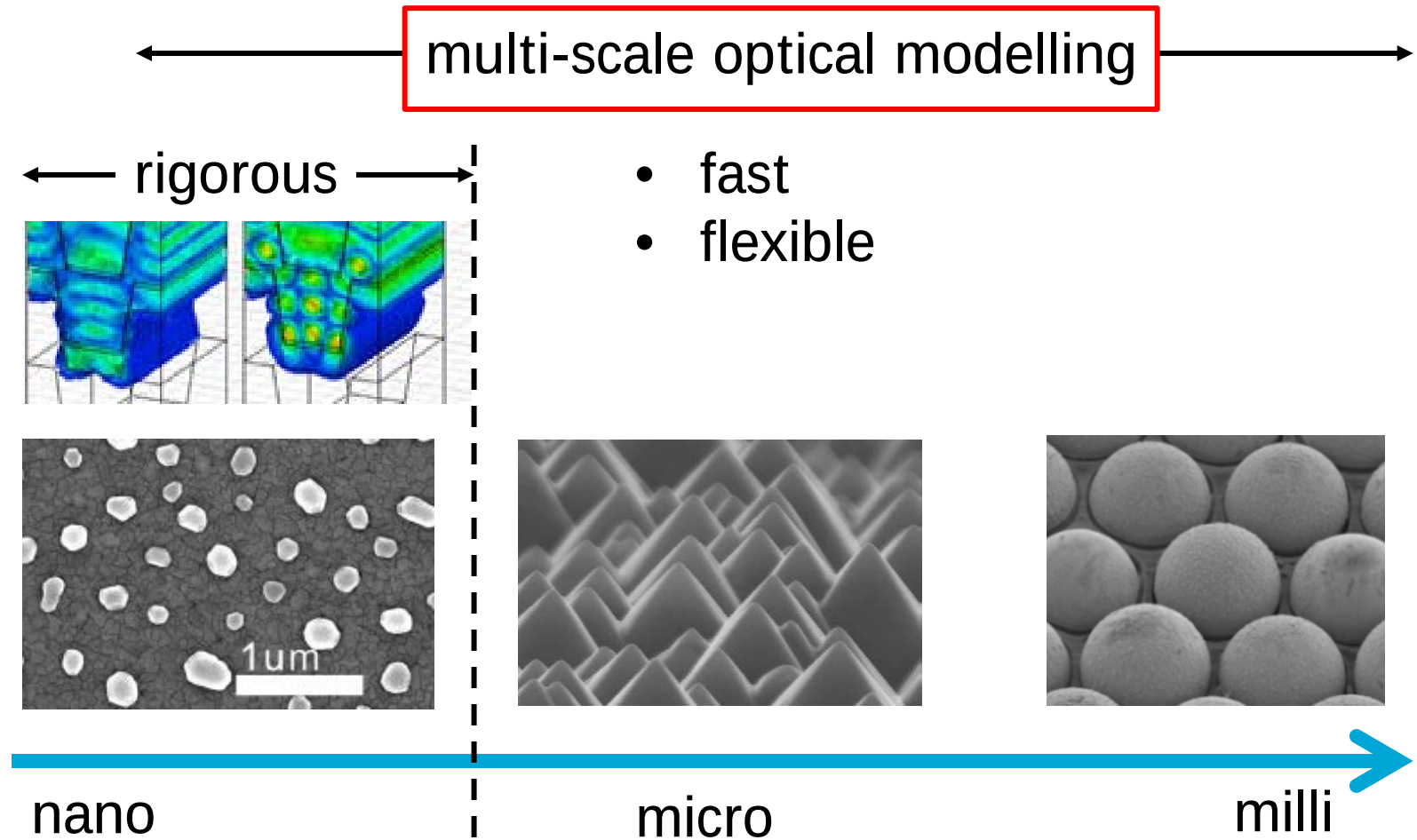
Solar cell model has 2 parts

- optical model → photon absorption profile
- electrical model → charge transport

How to simulate



Objective

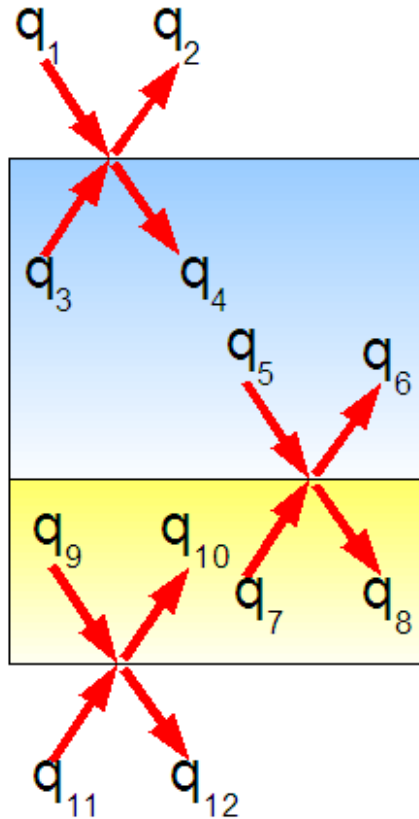


Outline

- Basic optical model
 - coherence of light
 - plasmonic TF-Si solar cells
- Extended model
 - pyramid textured c-Si solar cells
- Ray-tracing
 - CIGS coated glass beads
- Summary

1. Basic model

Net-radiation method



$$\begin{aligned}
 q_1 &= 1 \\
 q_2 &= r_1 q_1 + t_1 q_3 \\
 q_3 &= \tau_1 q_6 \\
 q_4 &= t_1 q_1 + r_1 q_3 \\
 q_5 &= \tau_1 q_4 \\
 q_6 &= r_2 q_5 + t_2 q_7 \\
 q_7 &= \tau_2 q_{10} \\
 q_8 &= t_2 q_5 + r_2 q_7 \\
 q_9 &= \tau_2 q_8 \\
 q_{10} &= r_3 q_9 + t_3 q_{11} \\
 q_{11} &= 0 \\
 q_{12} &= t_3 q_9 + r_3 q_{11}
 \end{aligned}$$

intensity at every interface
can be written in one set
of **linear** equations

solve

$$\begin{aligned}
 R &= q_2 \\
 A_1 &= q_4 - q_3 + q_6 - q_5 \\
 A_2 &= q_8 - q_7 + q_{10} - q_9 \\
 T &= q_{12}
 \end{aligned}$$

R. Santbergen et. al., *Optics Express* **21** (2013) A262-A267

DOI: 10.1364/OE.21.00A262

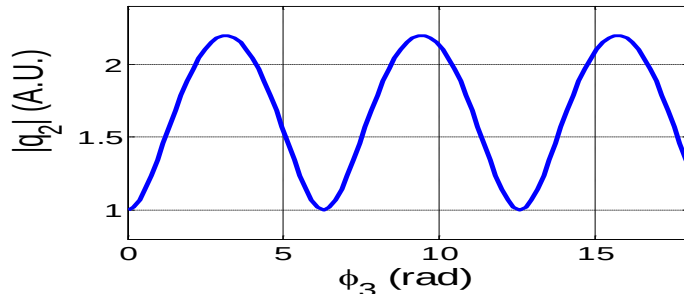
Interference or no interference?

$$q_2 = r_1 q_1 + t_1 q_3$$

q can represent:
electric field strength or intensity



complex number: $\tilde{E} = E \cdot e^{i\varphi}$



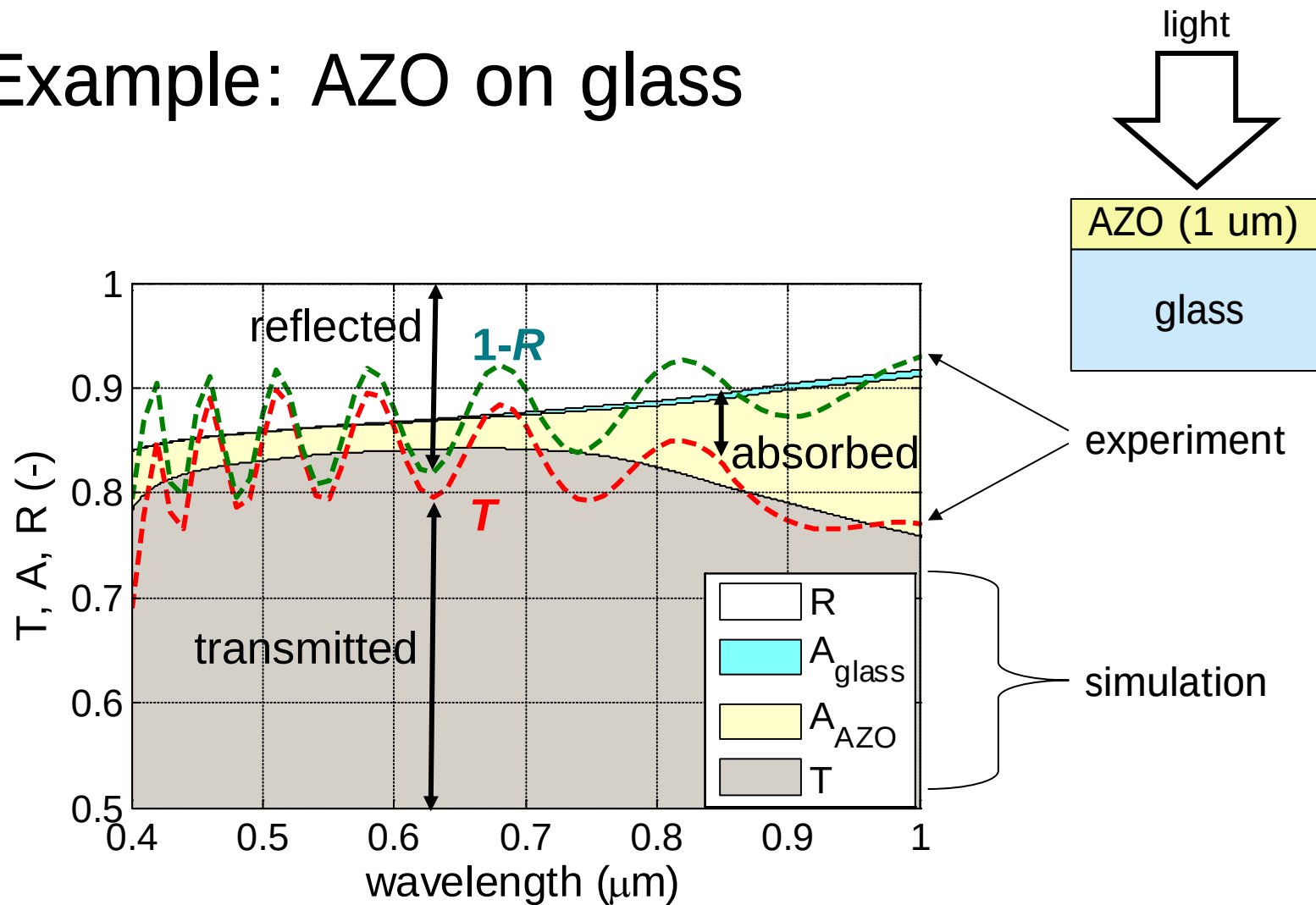
interference included



real number

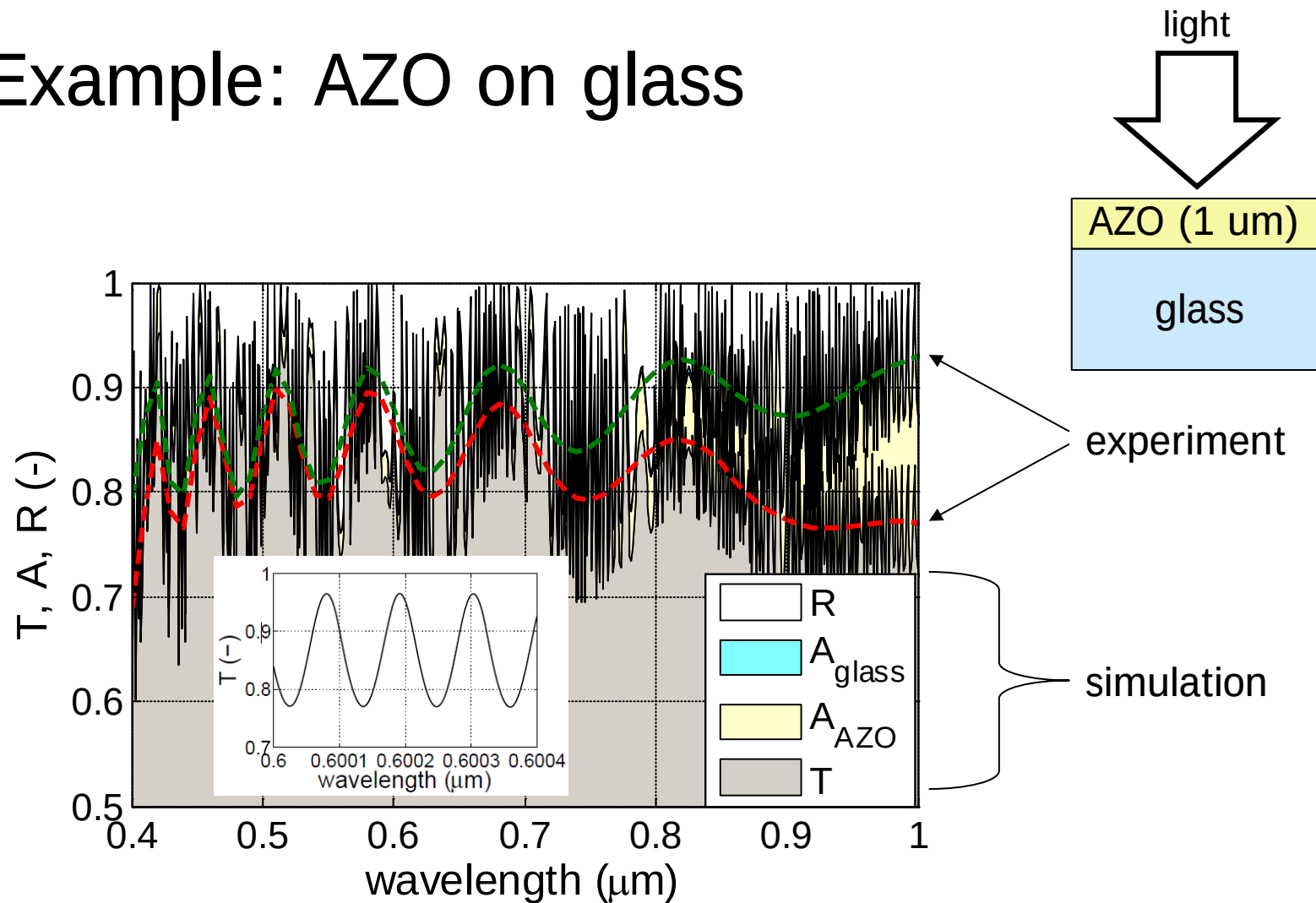
interference not included

Example: AZO on glass



q is intensity $\rightarrow$ no interference in AZO or glass

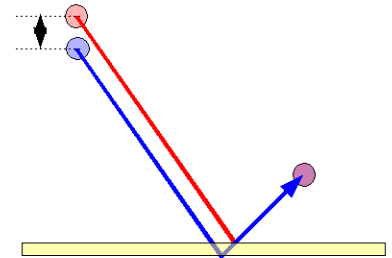
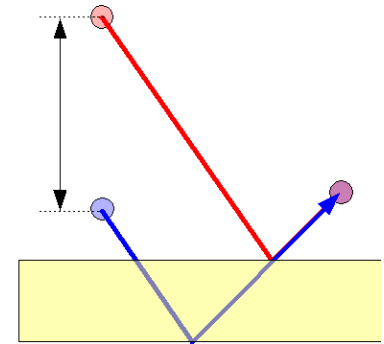
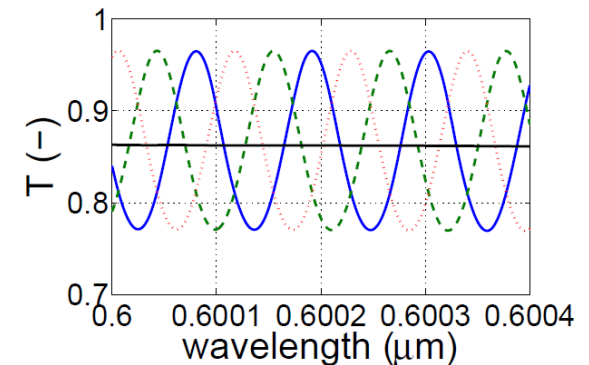
Example: AZO on glass



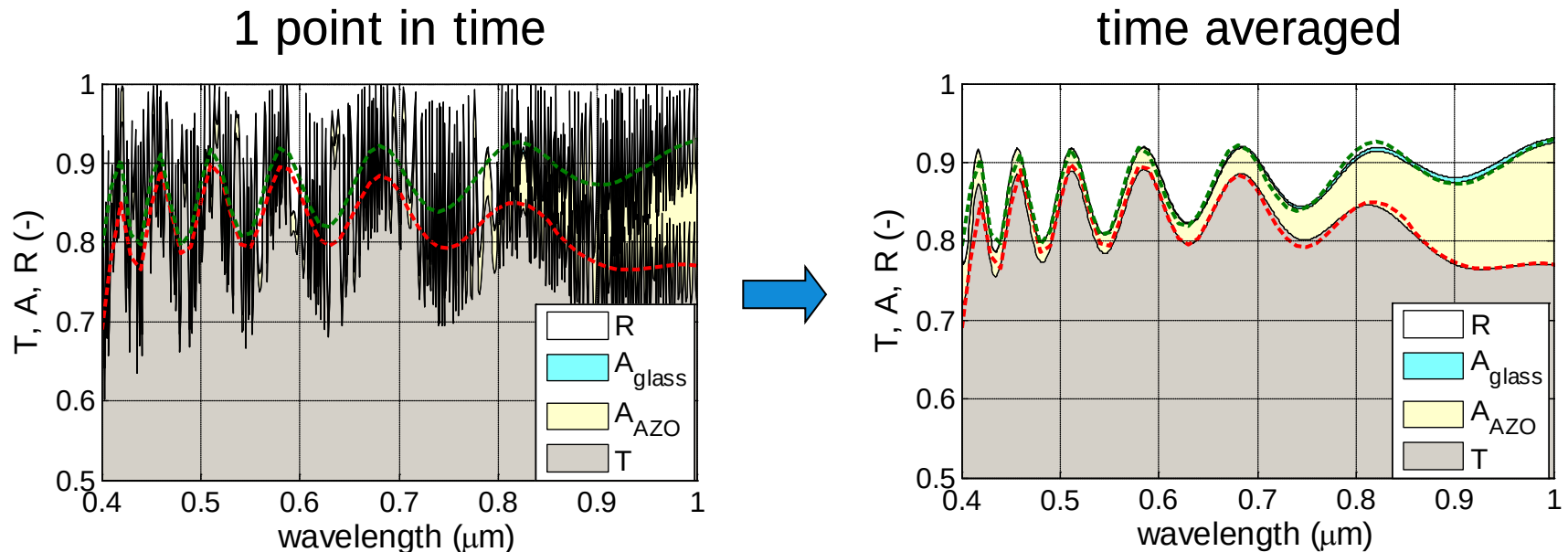
q is E-field $\rightarrow$ interference in both AZO and glass

Thick versus thin

- interference is caused by recombination of two parts of a wave
- for thick layers, two parts are separated more than the coherence length of the light
- interpretation: no stable phase relation $\rightarrow$ any measurement will give a time average
- calculate time average in model

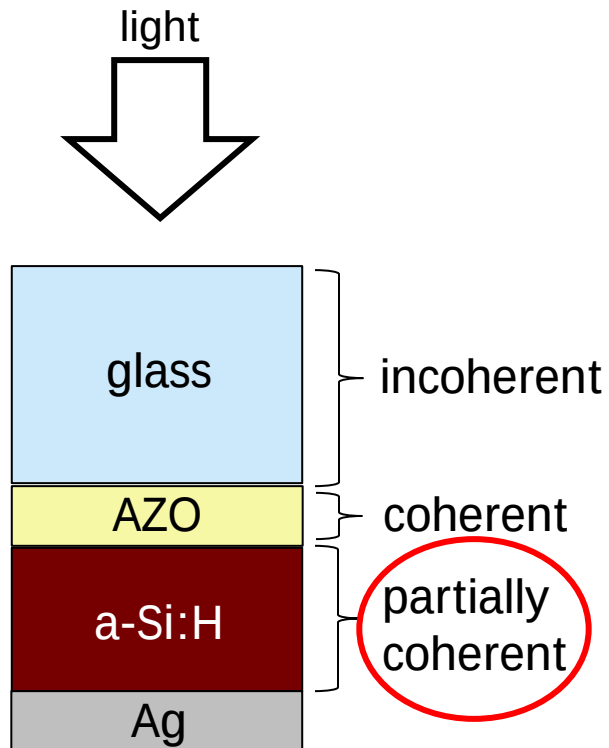
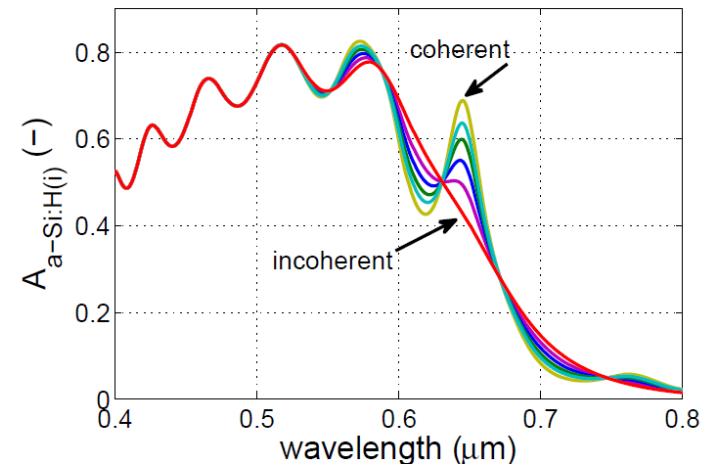
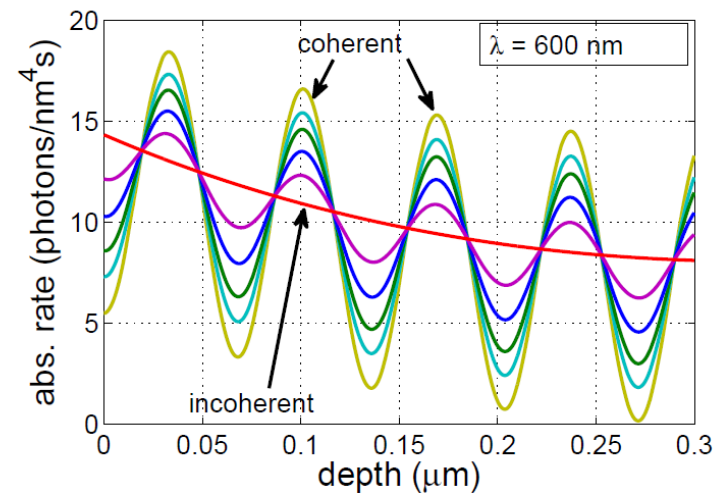


Example: AZO on glass



- 'time averaging' mimics reality → good agreement with experiment
- no separate coherent and incoherent calculation → keeps it simple

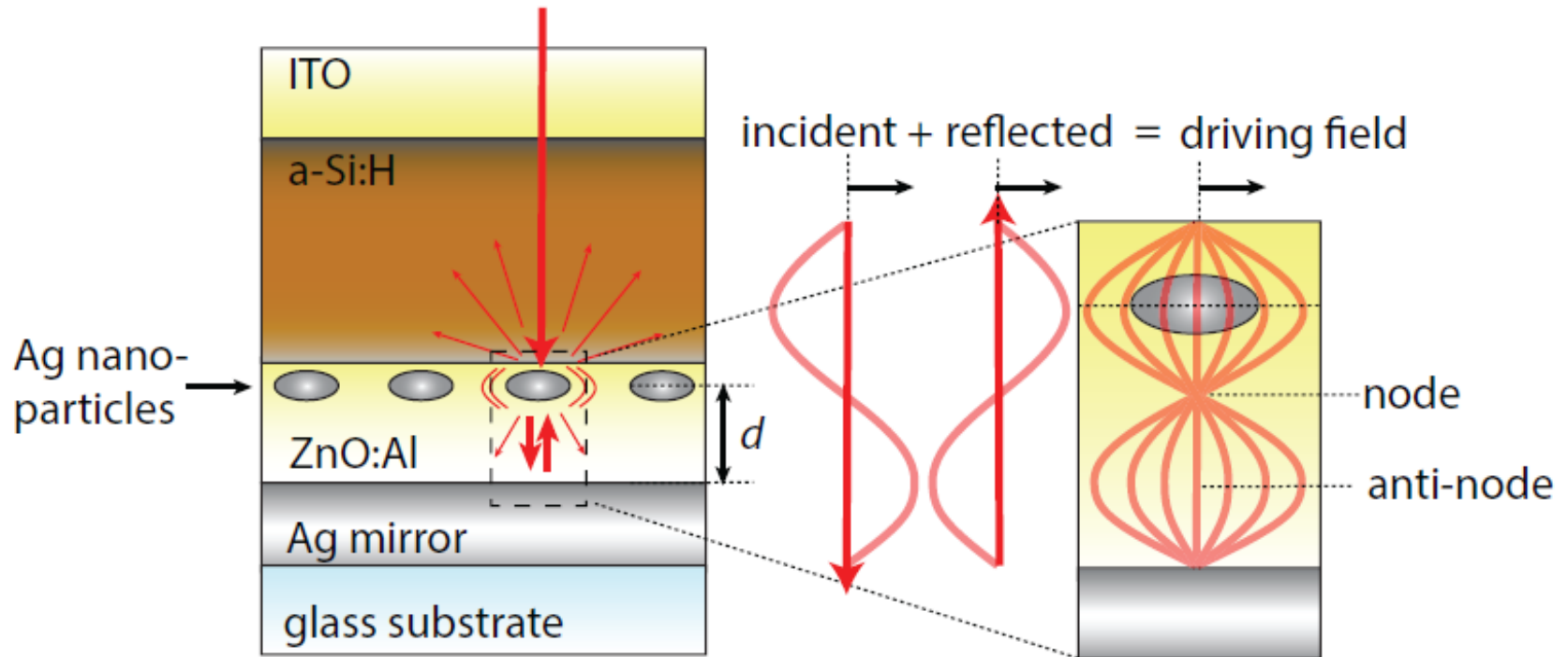
Partial coherence



R. Santbergen et. al., *Optics Express* **21** (2013) A262-A267

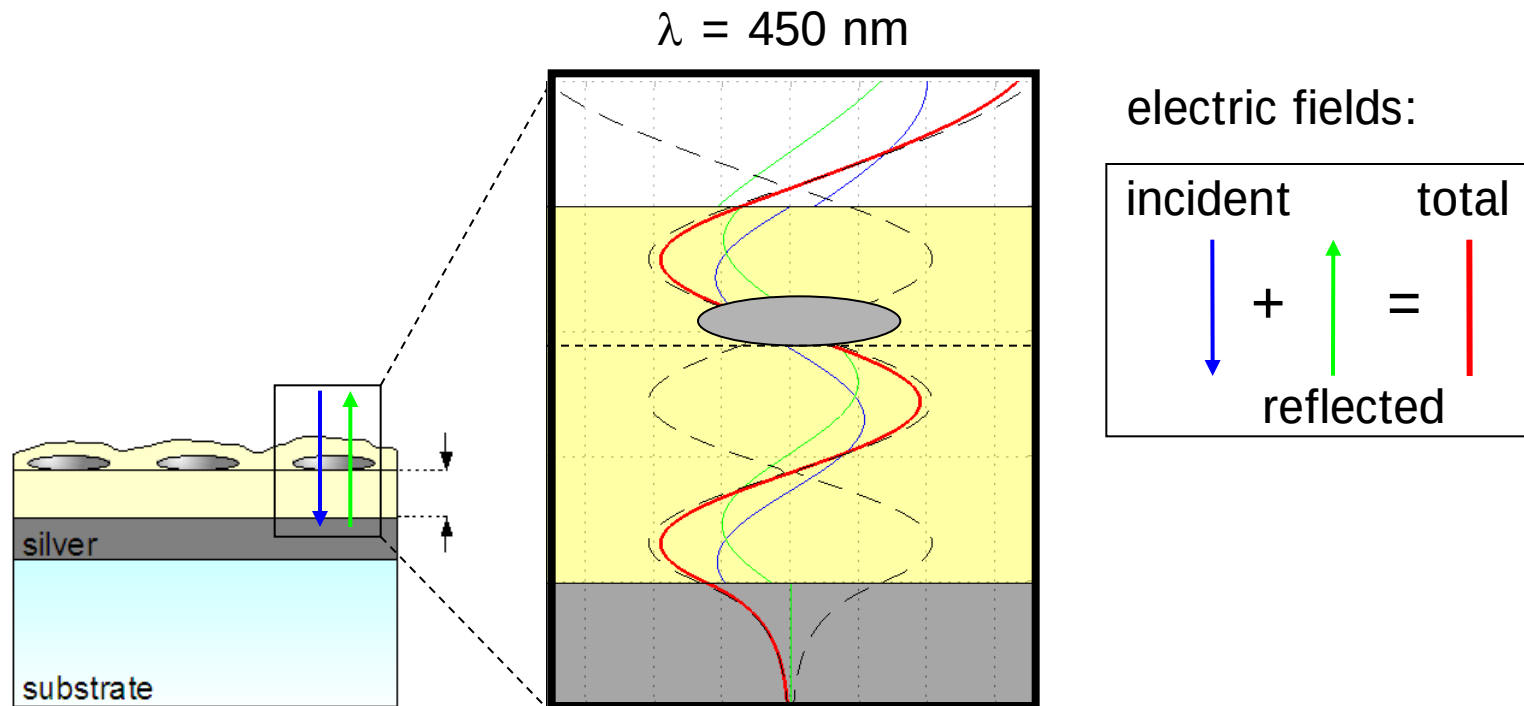
DOI: 10.1364/OE.21.00A262

Plasmonic nanoparticles



What is the ideal distance: Ag NPs $\leftrightarrow$ mirror?

Driving field in plasmonic BR



- TOTAL field drives plasmon resonance
- NP at node $\rightarrow$ zero driving field
- NP at anti-node $\rightarrow$ double driving field

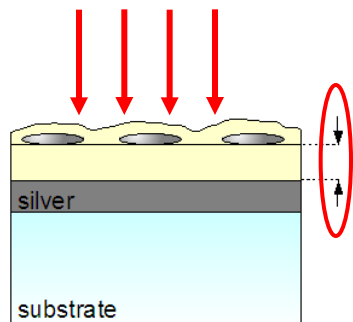
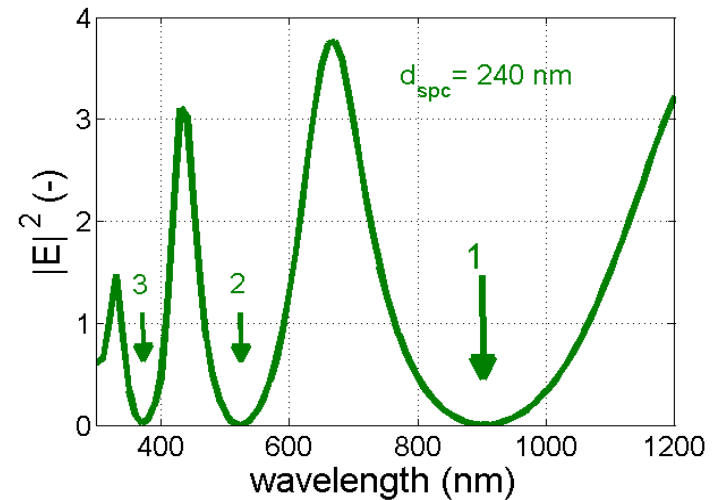
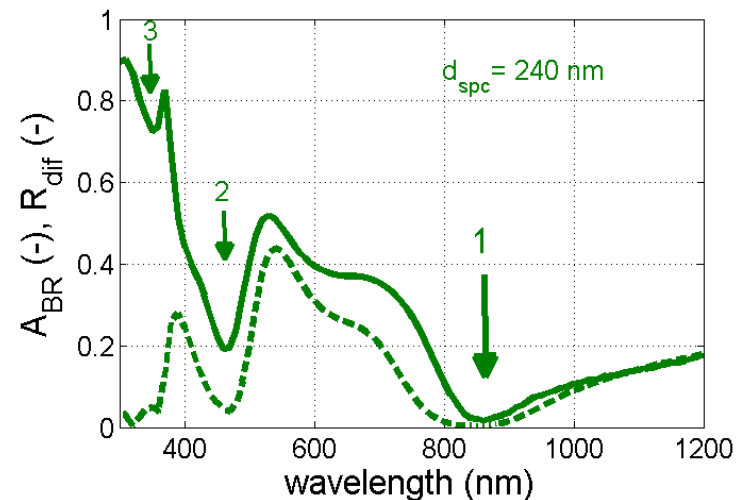
Experimental validation

calculated

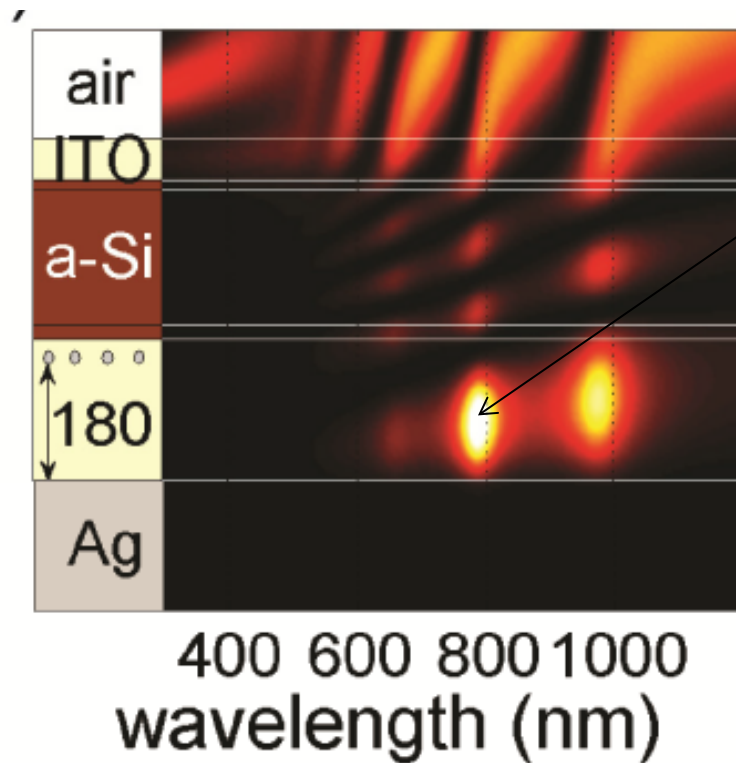
driving field at NP

measured:

- absorbance $A_{BR}(=1-R_{tot})$
- diffuse reflectance R_{dif}



Driving field in a-Si:H solar cells



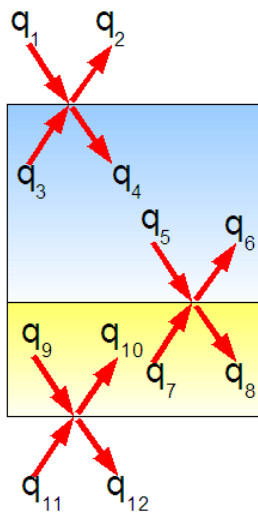
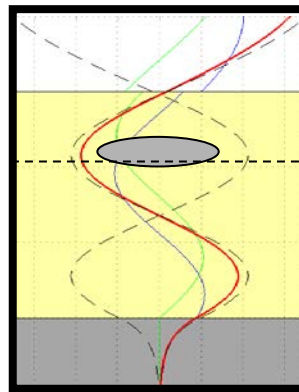
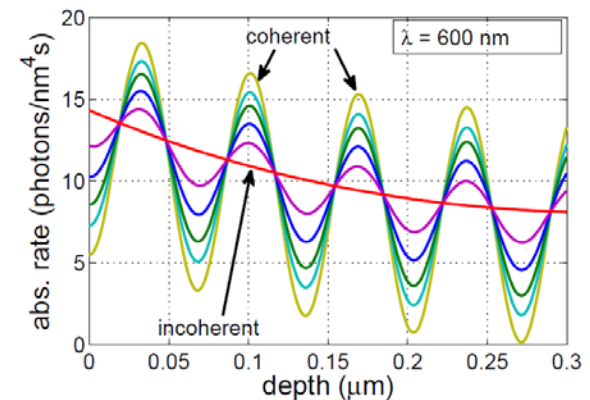
- 'sweet spots' in rear TCO
- depends on layer thicknesses
- up to 14 fold enhancement
- stronger plasmonic scattering

R. Santbergen et. al., *Optics Express* **22** (2014) A1023

DOI: 10.1364/OE.22.0A1023

Conclusions basic model

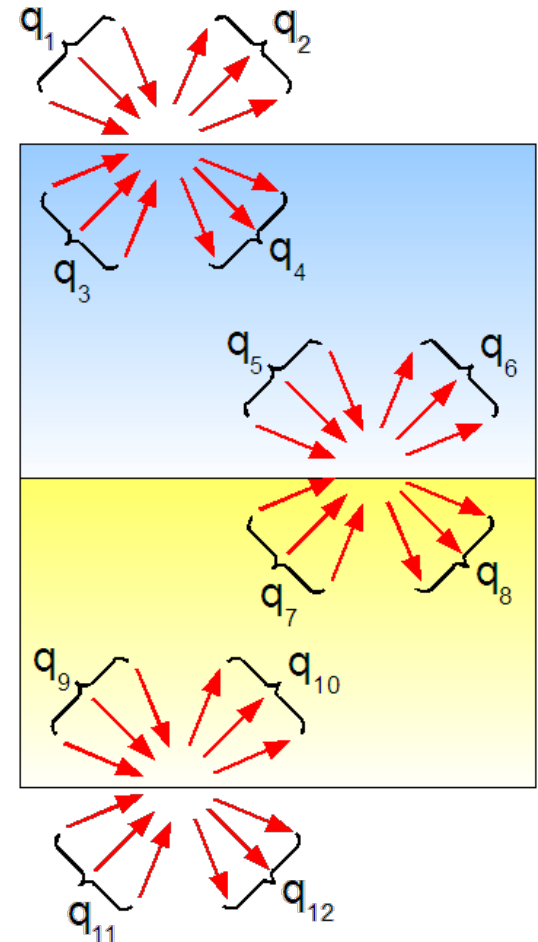
- simple model for multi-layers
 - coherent
 - incoherent
 - partly coherent
- calculate absorption profile and E-field strength
- tool for optimizing plasmonic solar cells



2. Extended model

Modelling light scattering

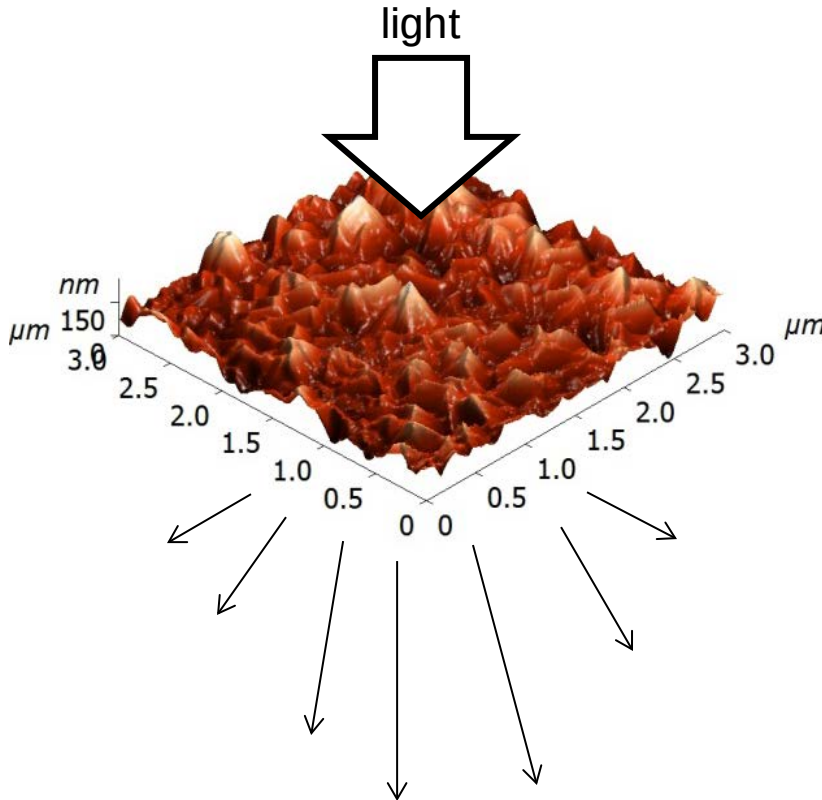
- every flux is replaced by a set of 'sub-fluxes'
- reflection coefficients are replaced by matrices $\mathbf{r}$
- solve set of equations to find R , A and T
- external model needed to determine matrices



R. Santbergen et. al., *Solar Ener. Mater. & Sol. Cells* **92** (2008) 432

DOI: 10.1016/j.solmat.2007.10.005

Scalar scatter model

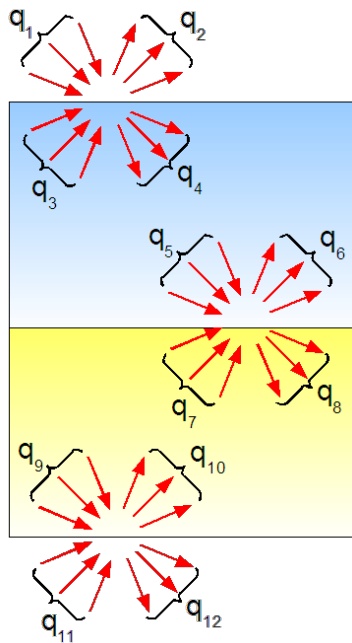
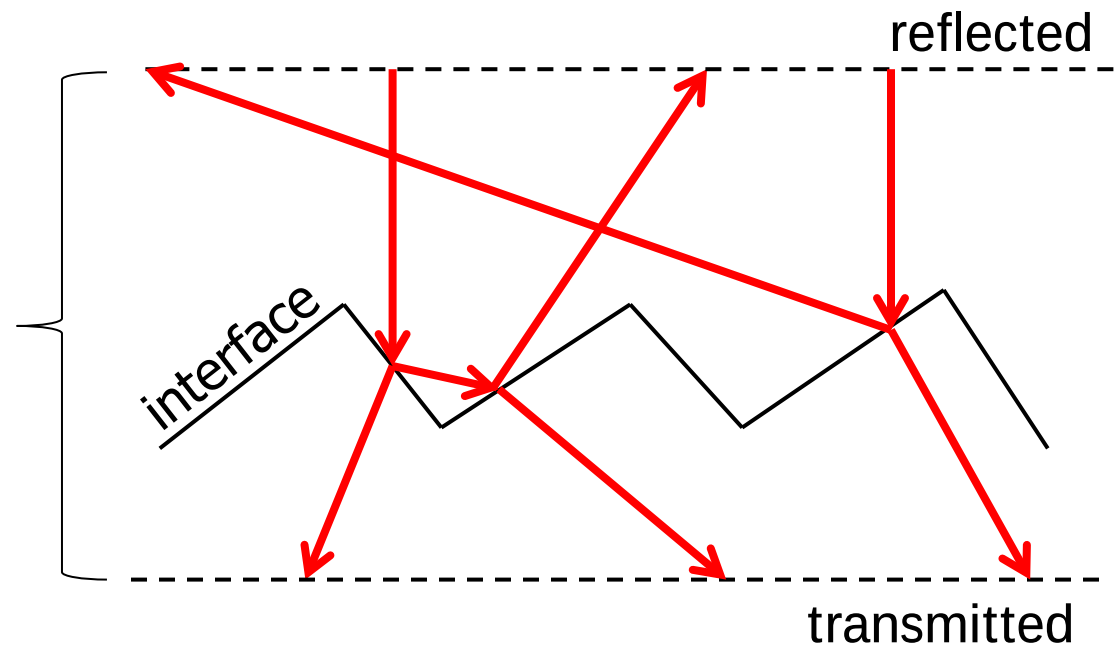


- scattering = diffraction
- AFM scan $\rightarrow$ angular distribution of scattered light
- Fourier transform $\rightarrow$ fast
- accurate for features $< \lambda$
- limited fixed R , T

K. Jäger et. al., *J. Appl. Phys.* **111** (2012) 1

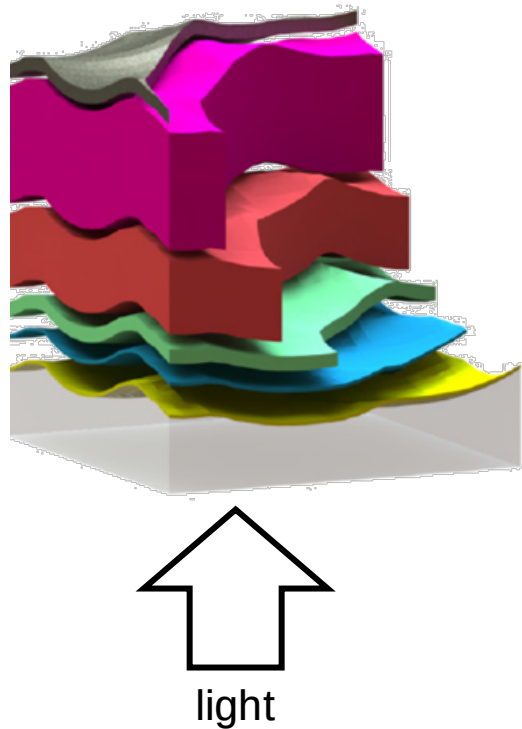
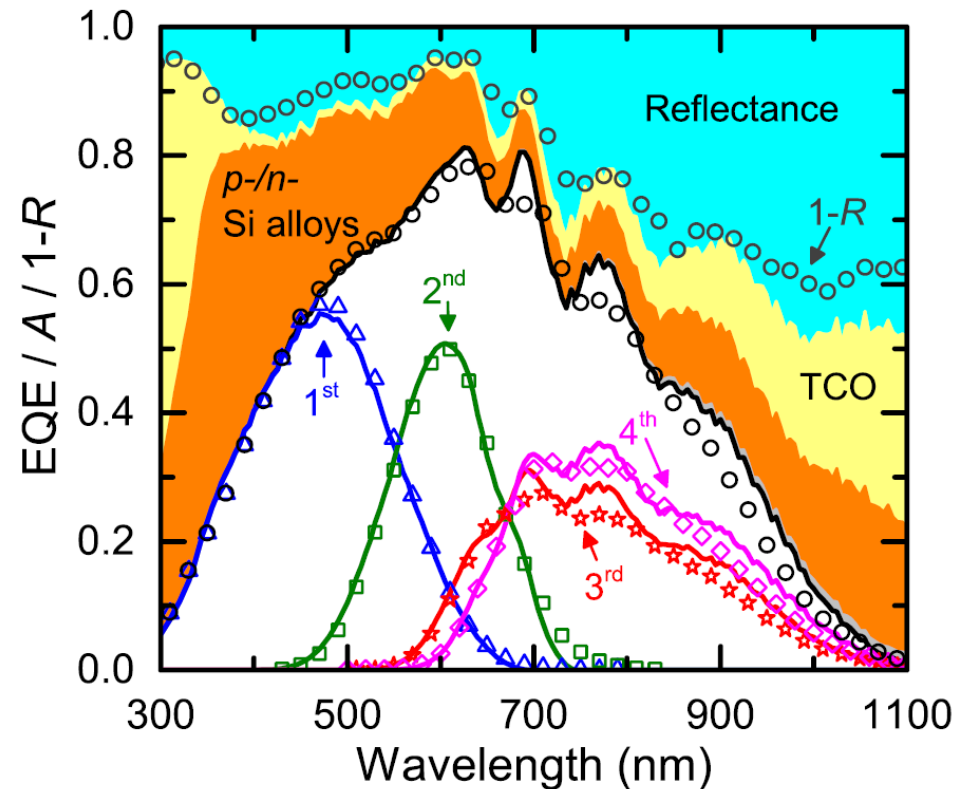
DOI: 10.1063/1.4704372

Ray-tracing model



- scattering = reflection & refraction
- accurate for large features ($>\lambda$)
- can model anti-reflective effect of texture

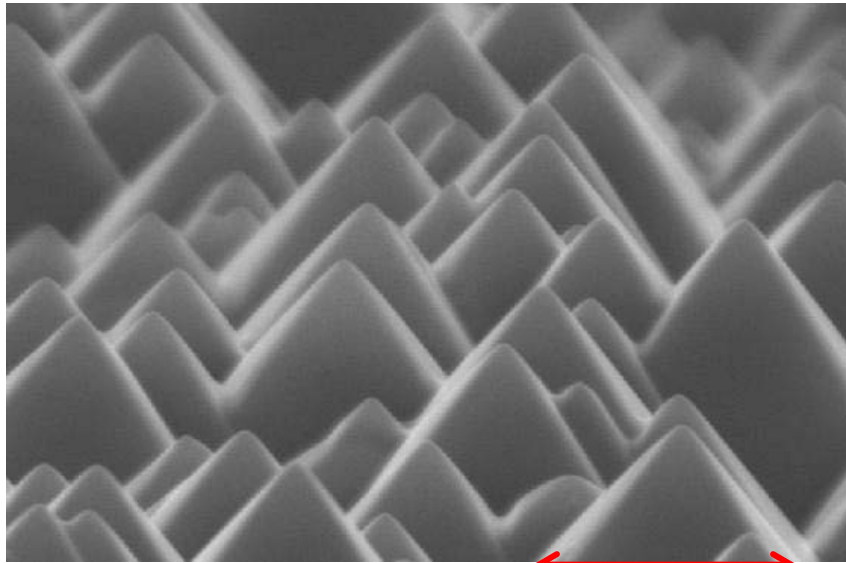
TF-Si solar cell on textured glass (4J)



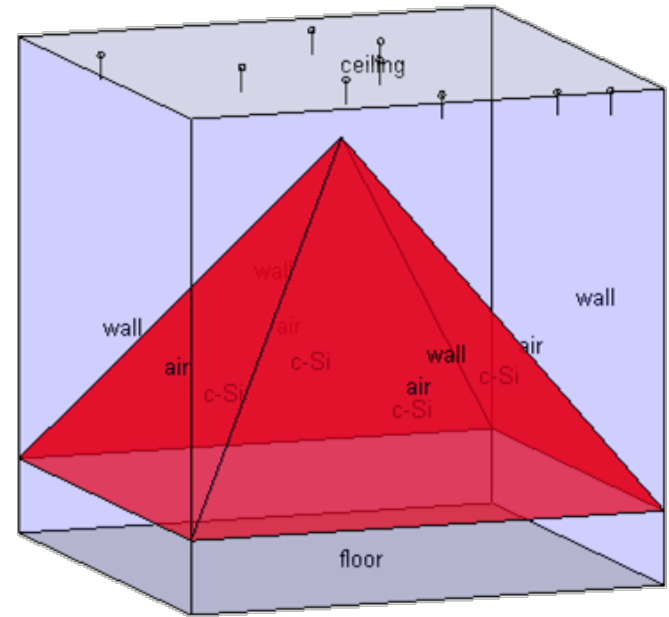
F. Si et. al., *Applied Physics Letters* (2014) **105** 063902

DOI: 10.1063/1.4892890

Textured c-Si wafer



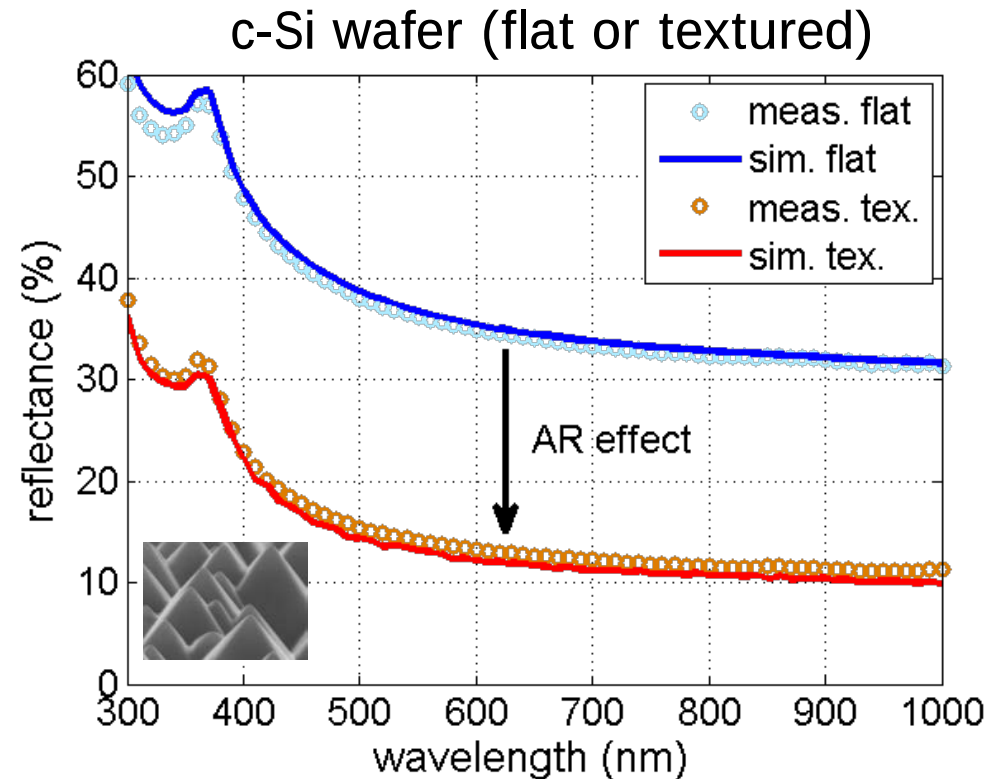
pyramid texture (10 μm)



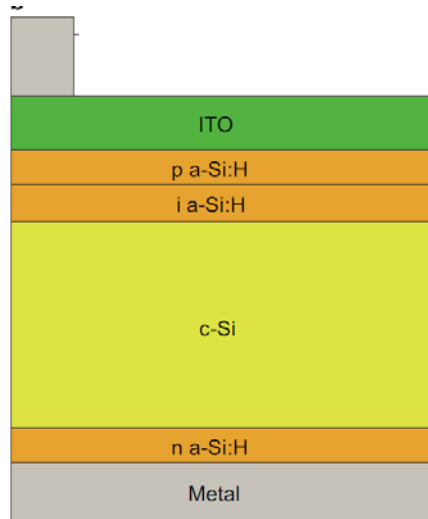
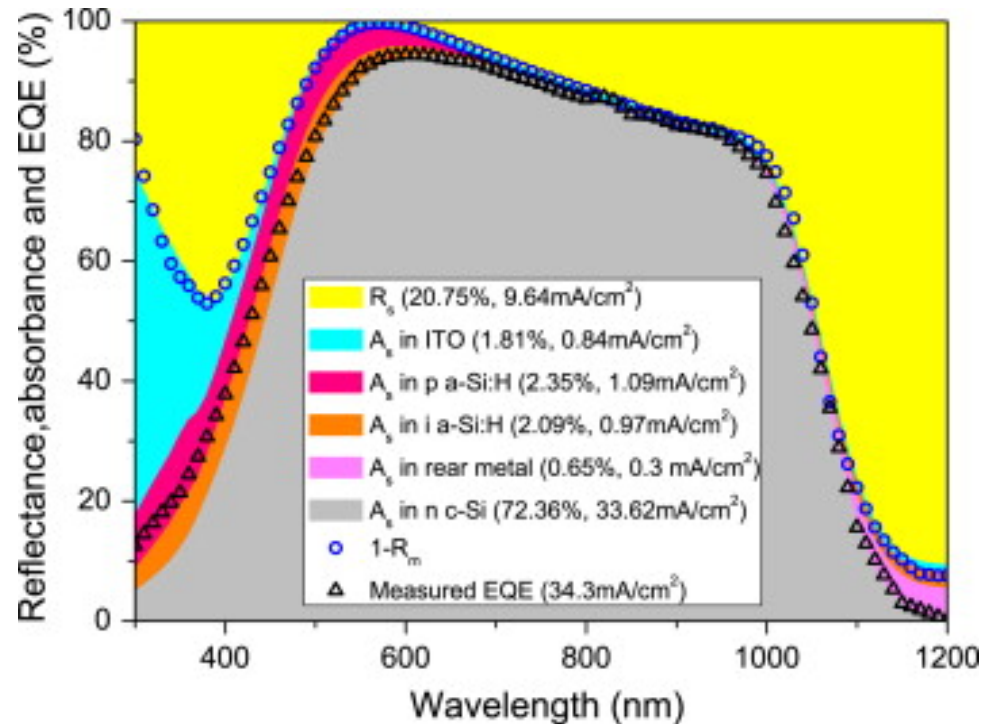
- Approximate pyramid texture as single pyramid
- Periodic boundary conditions to simulate periodic array

Anti-reflective effect of texture

- measurement: textured interface has lower reflectance than a polished one
- simulation: gives very good agreement

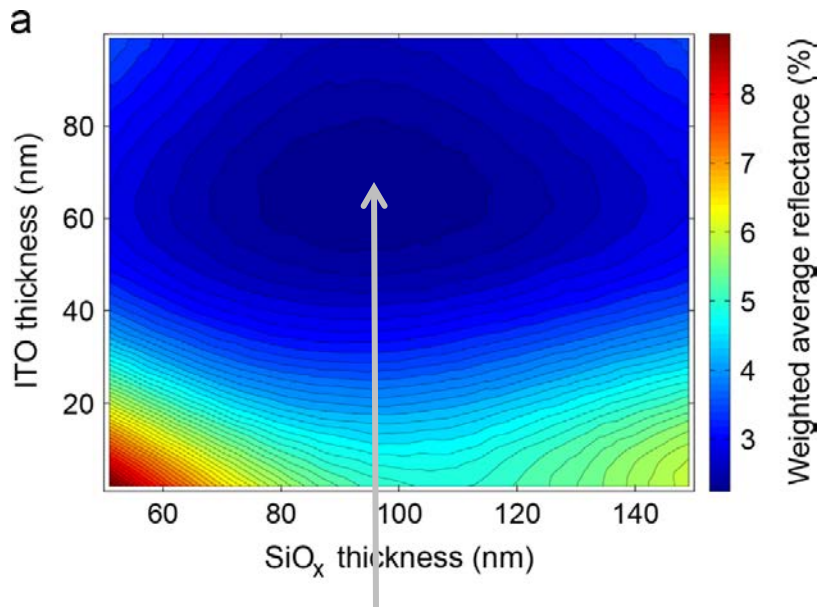


Double layer AR-coating on HIT cell



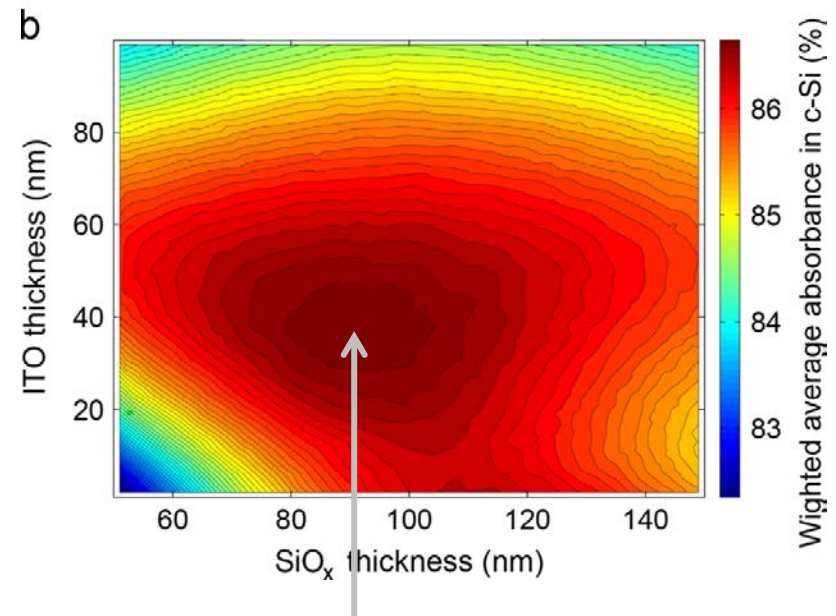
- thin-film optics for a-Si:H and ITO layers
- excellent agreement
- optimize thickness double layer anti-reflective coating (DLARC)

Optimizing DLARC on texture



minimum reflection:

- ITO 70 nm
- SiO_x 100 nm



maximum abs. in c-Si:

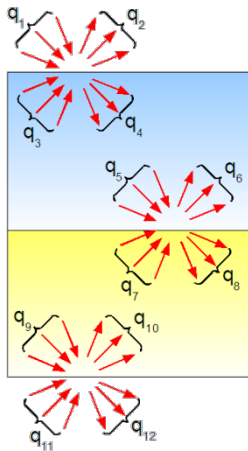
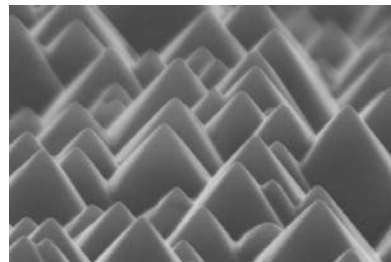
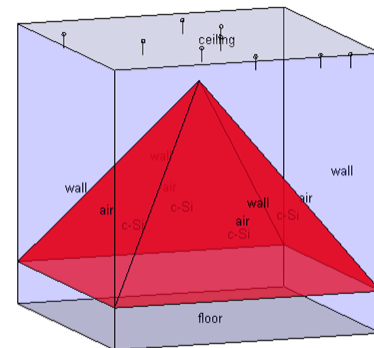
- ITO 40 nm
- SiO_x 90 nm

D. Zhang et. al., *Sol. Ener. Mat. & Sol. Cells* (2013) **117** 132

DOI: 10.1016/j.solmat.2013.05.044

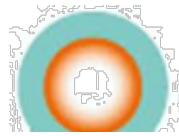
Conclusions extended model

- basic method was extended (scalar scatter, ray-tracing)
- suitable for both large and small scale texture
- optimized DLARC on textured HIT cell



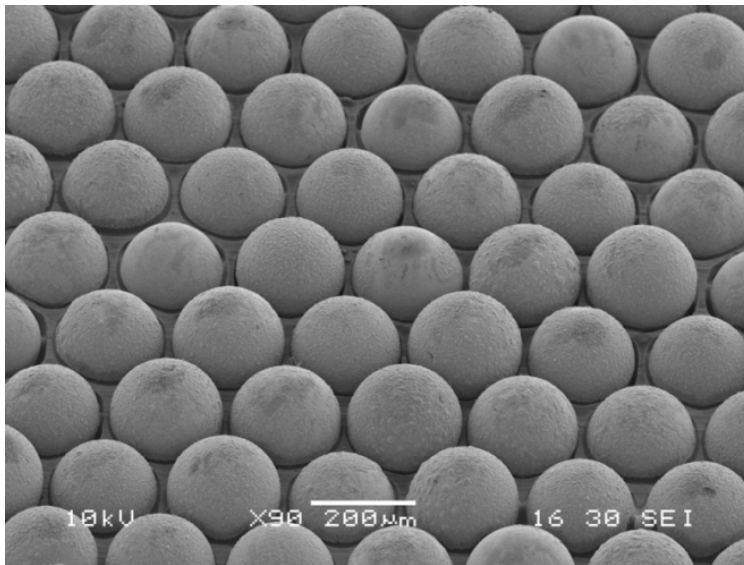
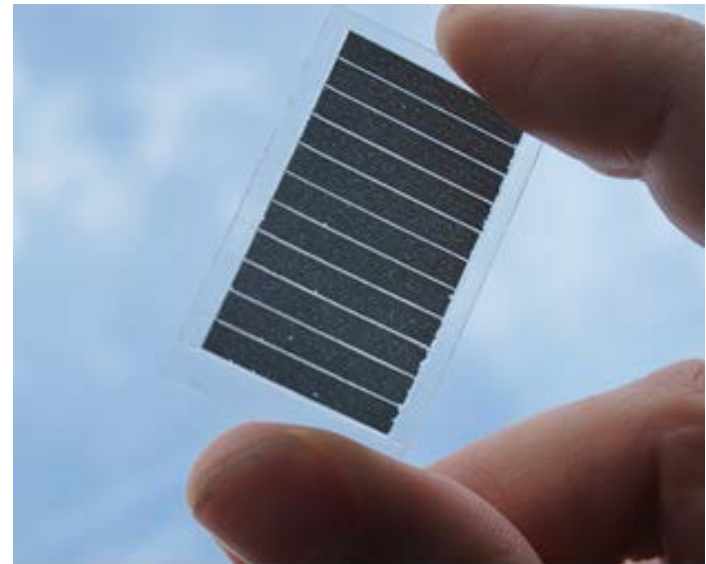
3. Ray-tracing (stand alone)

Sunrise concept



Scheuten

- glass beads coated with Mo/CIGS/CdS/AZO
- coating in compact reactor (1 kg beads → 3 m² PV module)

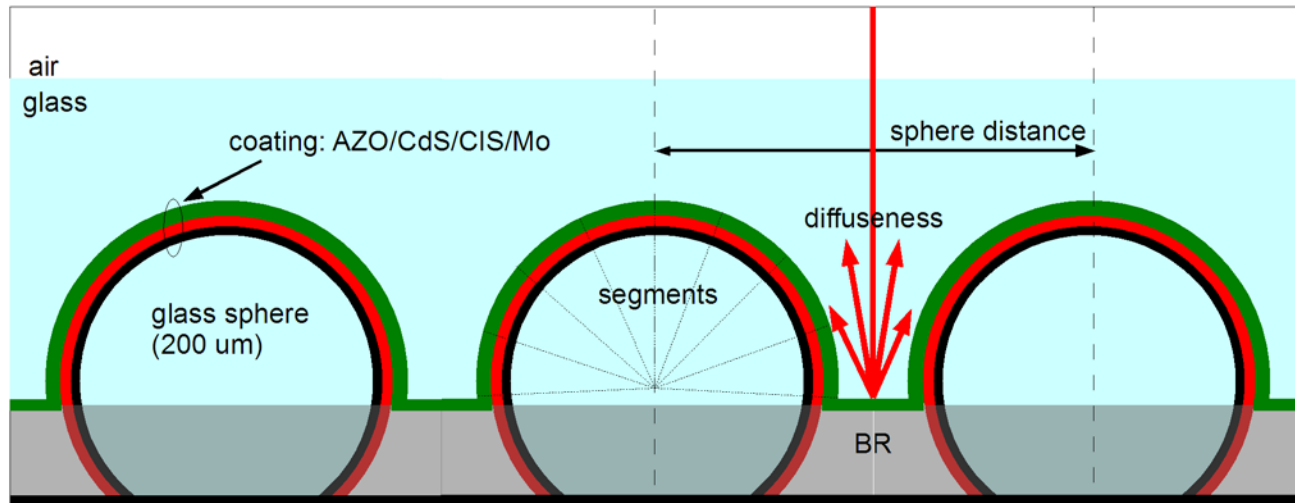


V. Geyer et al., *Thin-Solid Films* **516** (2008) 4651-4655

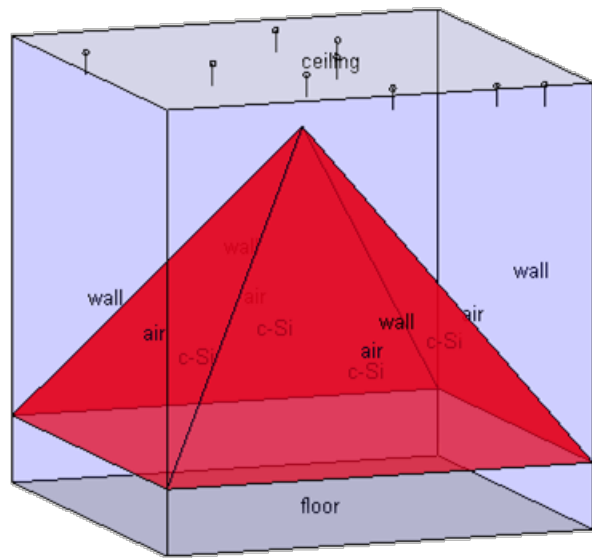
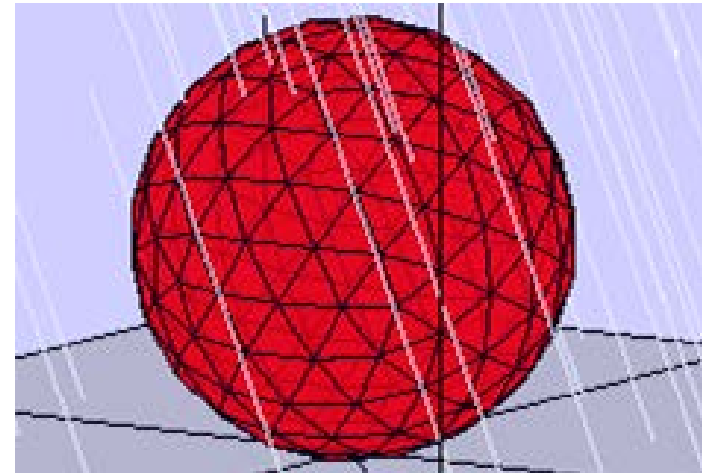
DOI: 10.1016/j.tsf.2007.05.083

Back reflector

- AZO front contact, Mo contacts metal back reflector (BR)
- light reflected by BR is trapped in glass
- optimum sphere density? → optical simulations

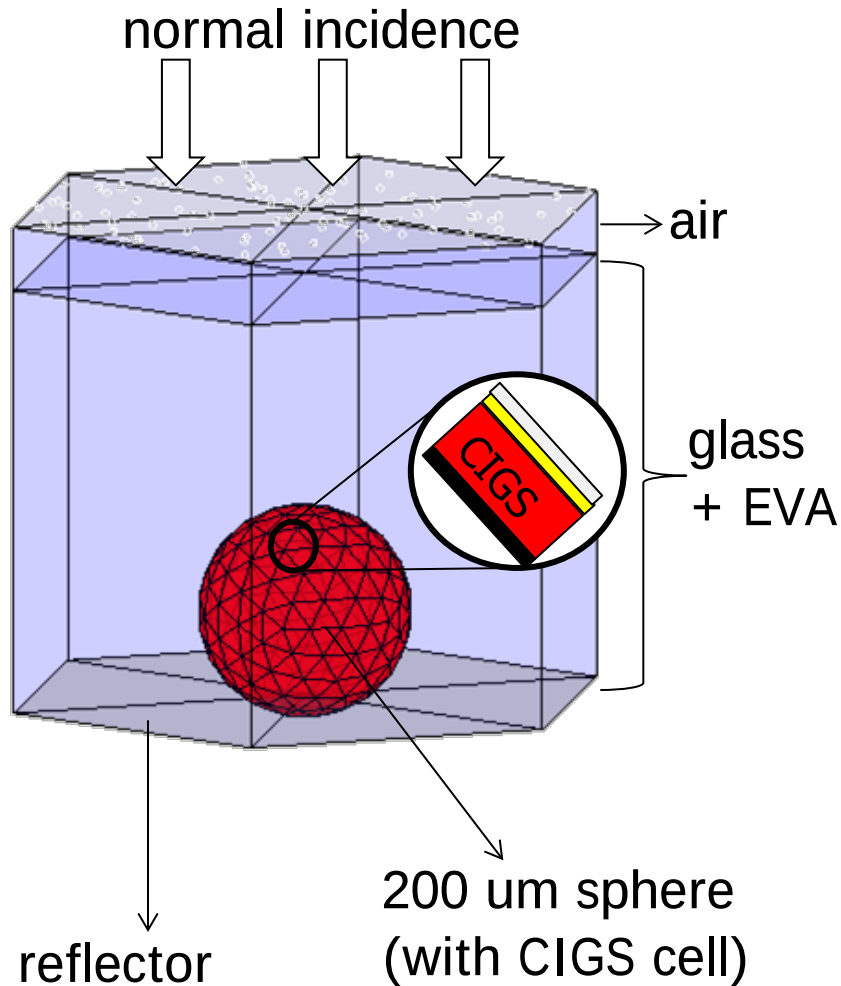


Ray-tracing module



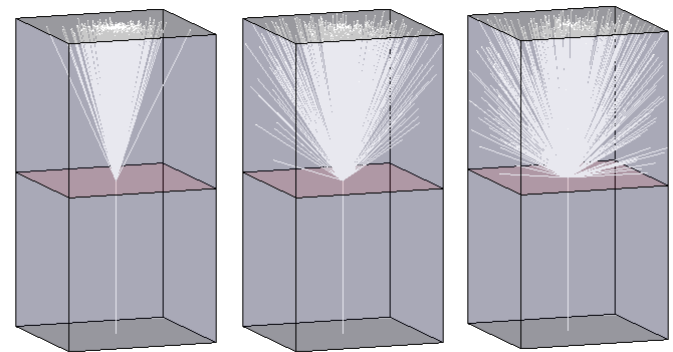
- ray-tracing module: AID calculation → stand-alone
- thin-film optics: AR-coating → Mo/CIGS/CdS/AZO

Hexagonal array



Vary:

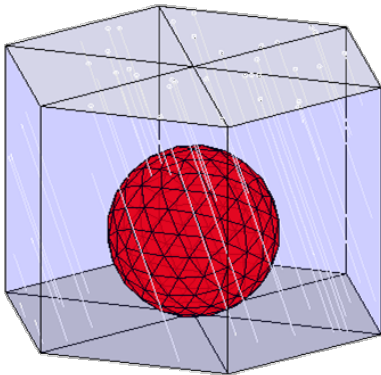
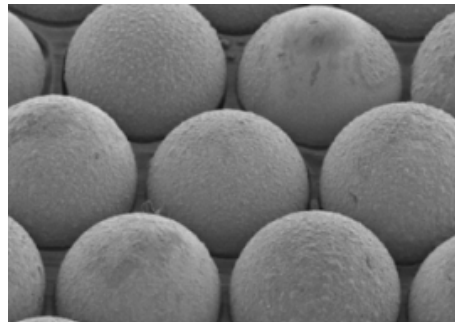
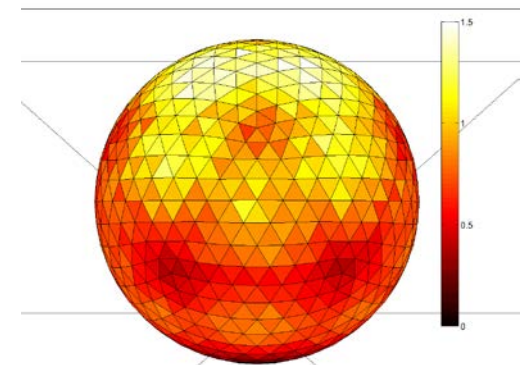
- sphere-sphere distance
- diffuseness of reflector



more specular $\leftrightarrow$ more diffuse

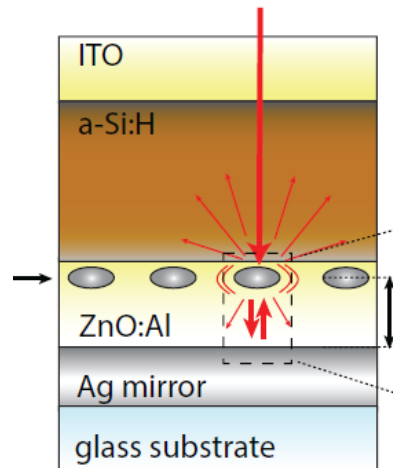
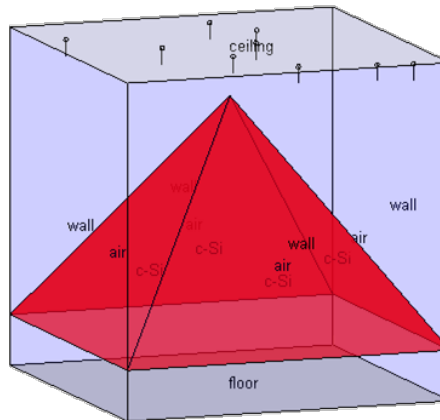
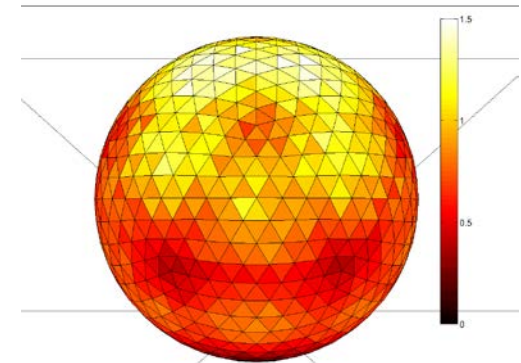
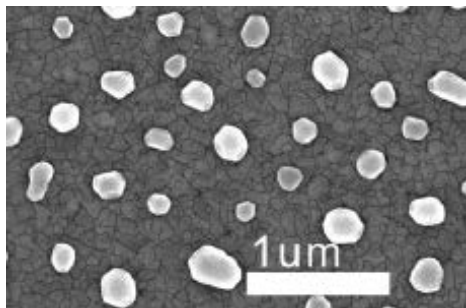
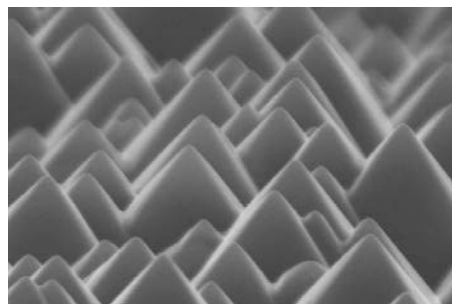
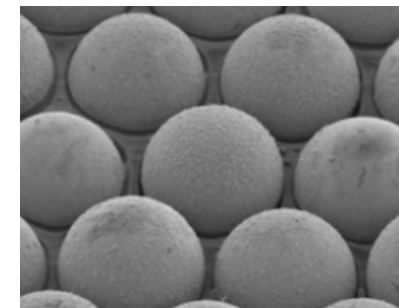
Conclusions ray-tracing

- Ray-tracing model AID → stand alone
- complex geometries + thin-film optics
- tool for optimizing Sunrise concept (CIGS coated spheres)



Summary

Summary



nano

micro

milli

Acknowledgements

- colleagues



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