Light management

UNIK 4450/9450 – Schedule

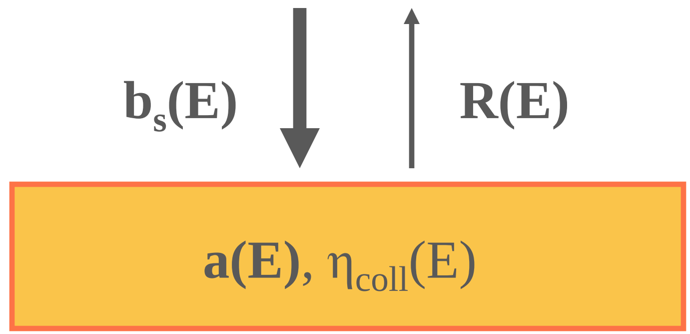
- 30/8 Solar cell fundamentals
- 6/9 Solar cell efficiency
- 13/9 Semiconductor theory
- 20/9 Generation
- 27/9 Recombination and lifetime
- 4/10 Silicon
- 11/10 Junctions
- 18/10 Solar cells
- 25/10 Silicon solar cells I (@IFE)
- 1/11 Silicon solar cells II
- 8/11 Alternative solar cells
- 15/11 Light trapping
- 22/11 Cancelled
- 29/11 Solar modules + Q&A

- Oral exam December 12th

~~Clever~~ student question:

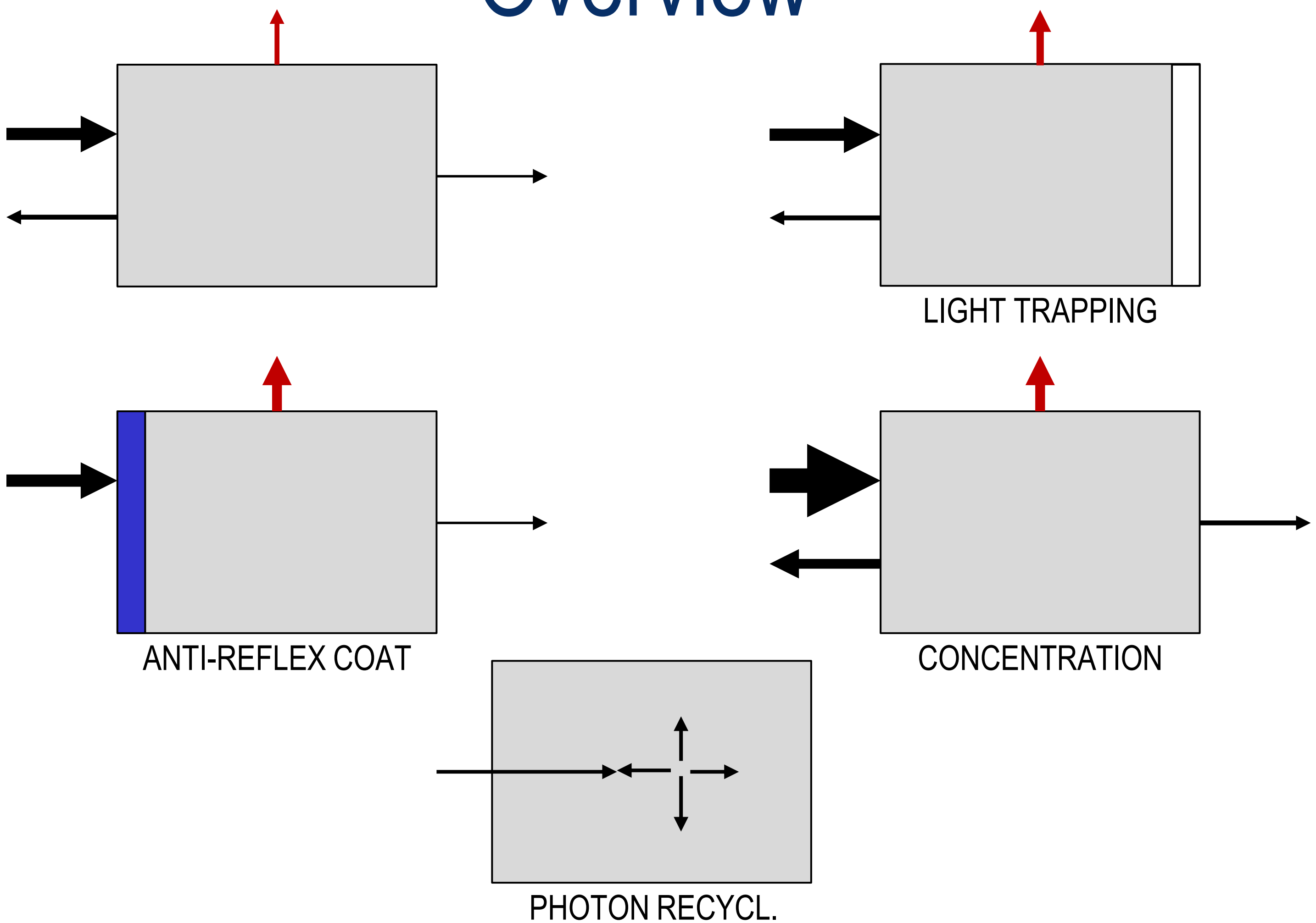
”Why do I care?”

Photogenerated current



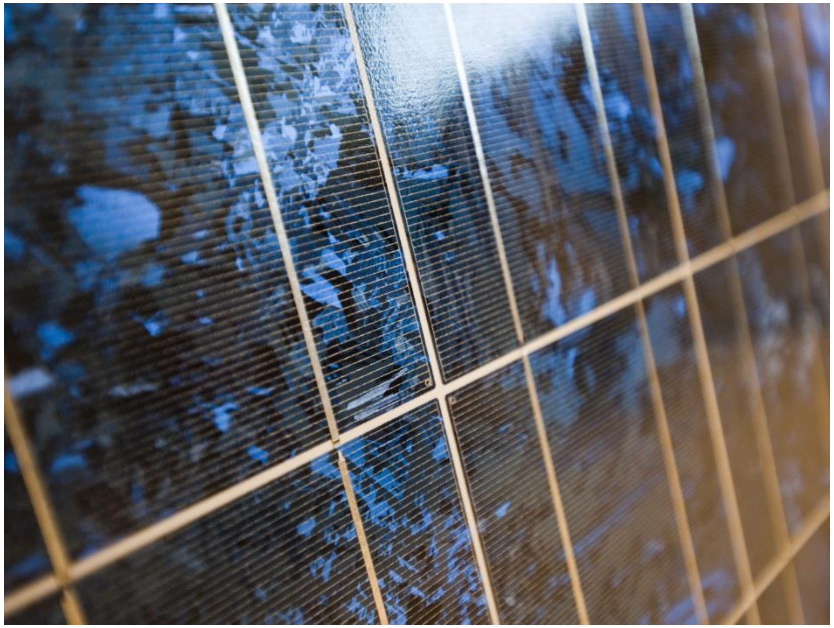
$$I_{SC}(E) = q \cdot A \cdot ([1 - R(E)] \cdot \eta_{coll}(E) \cdot a(E) \cdot b_s(E))$$

Overview

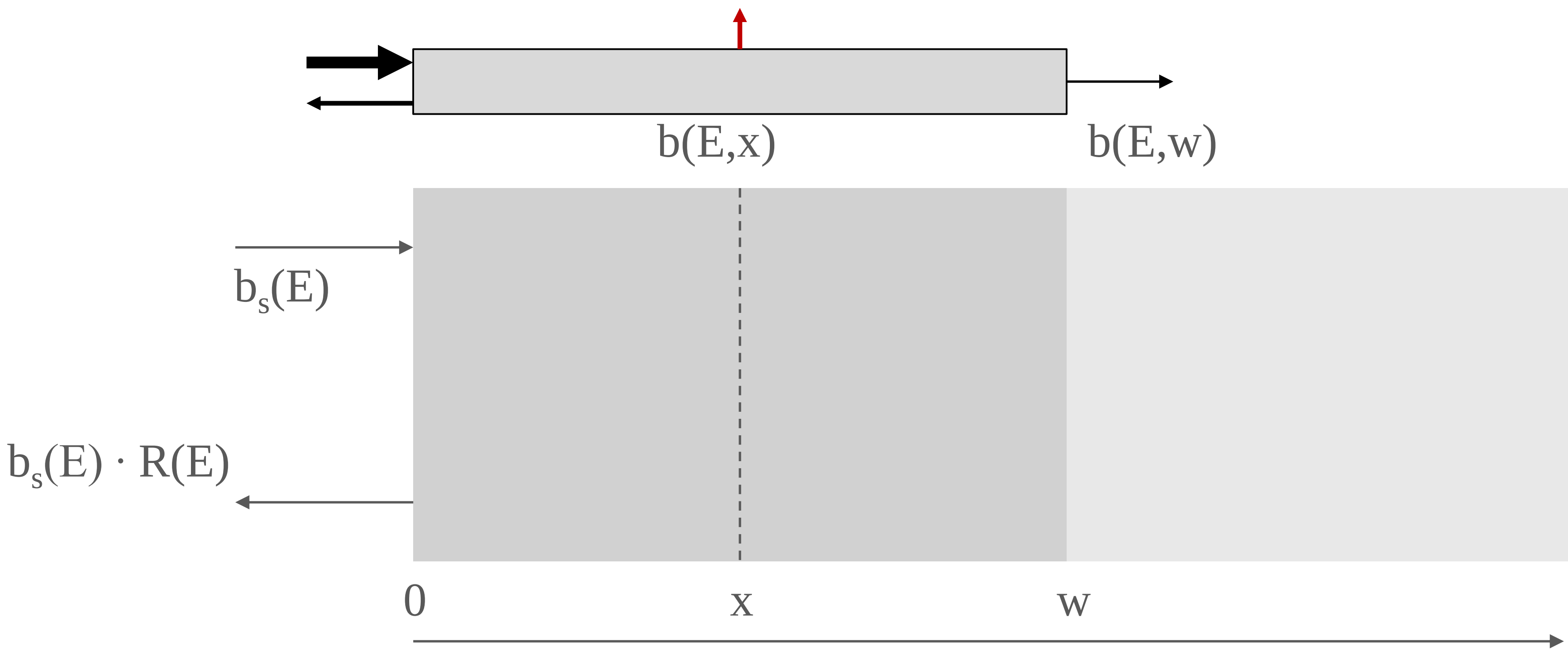

LIGHT TRAPPING
ANTI-REFLEX COAT
CONCENTRATION
PHOTON RECYCL.

Overview

- Basic theory
- Front side reflection
  - Anti-reflex coatings
  - Textures
- Light trapping
  - Rear side mirrors
    - Dielectric
    - Metallic
  - Geometrical
  - Diffractive
  - Plasmonic
- Concentration
- Photon recycling

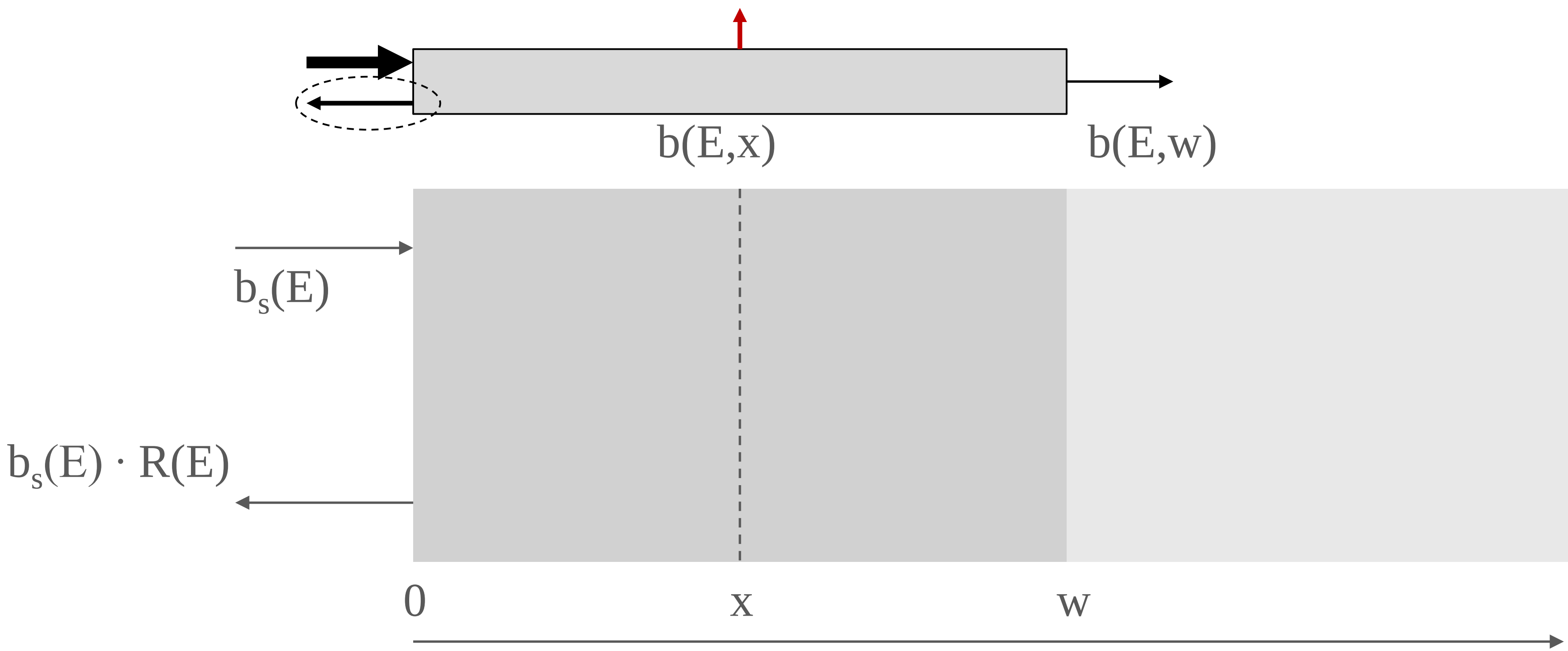


Optical model



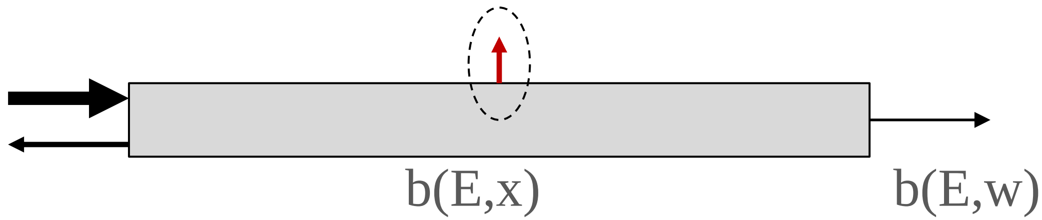
Reflected fraction

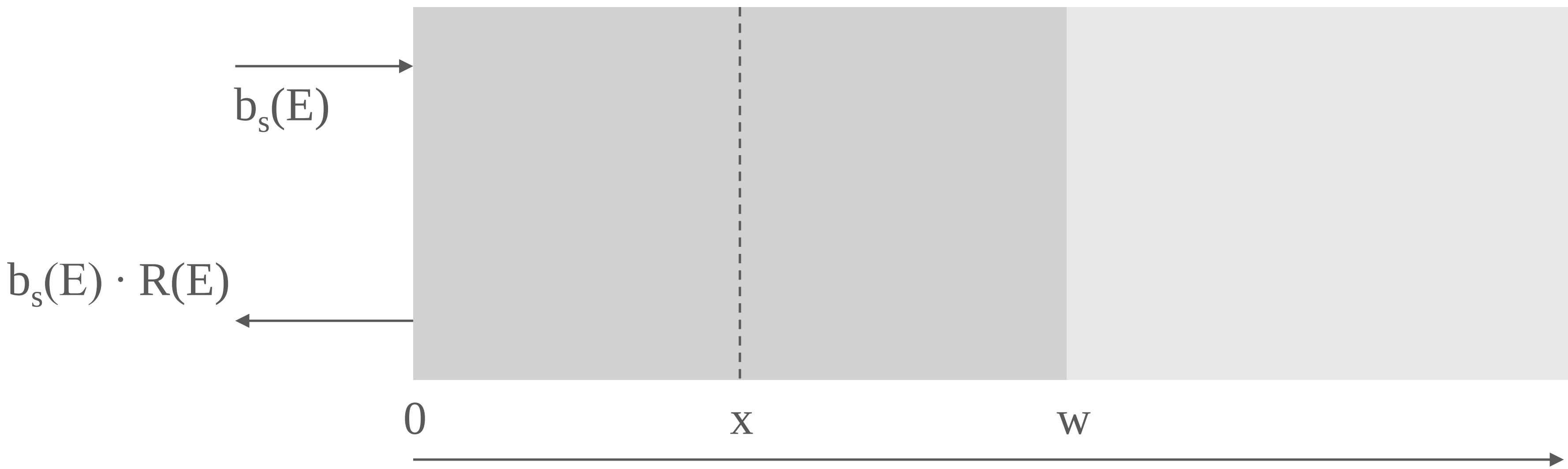
$$f_{refl} = b_s(E) \cdot R(E)$$



Absorbed fraction

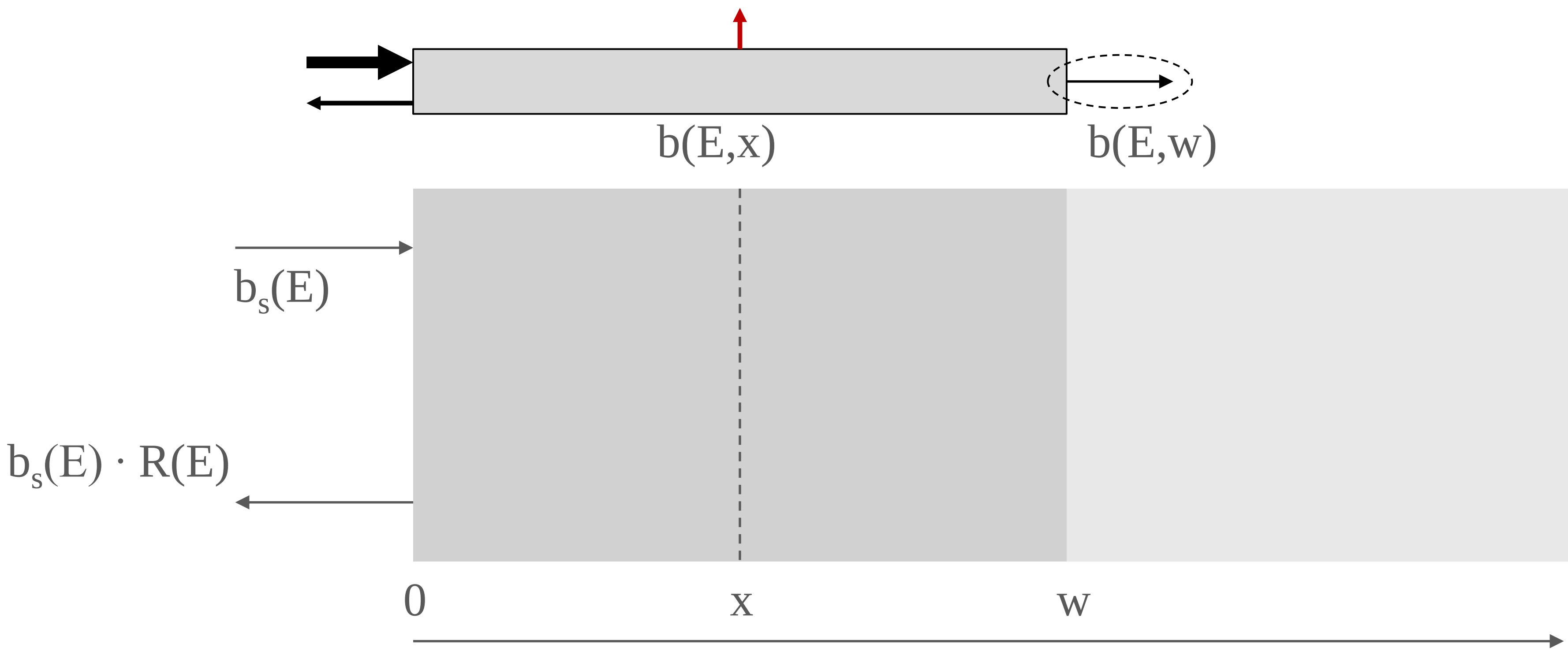
$$f_{abs} = 1 - R(E) - [b(E,w)/b_s(E)] \qquad = [1 - R(E)] \cdot (1 - e^{-\alpha(E)w})$$



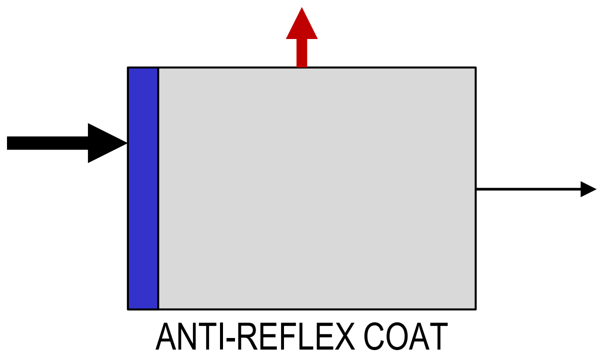


Transmitted fraction

$f_{trans} = [b(E,w)/b_s(E)] \qquad = [1 - R(E)] \cdot e^{-\alpha(E)w}$



Front side reflection

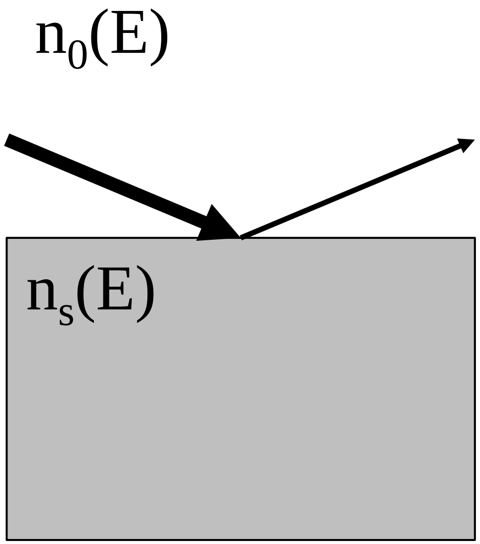


Reflected fraction

- Reflection at an interface

$$R = (n_0(E) – n_s(E)/n_0(E) + n_s(E))^2$$

- Calculated example
  - Air: n_0 = 1
  - Glass: n_s = 1.5
  - Reflection: R = $(0.5/2.5)^2$ = 4 %

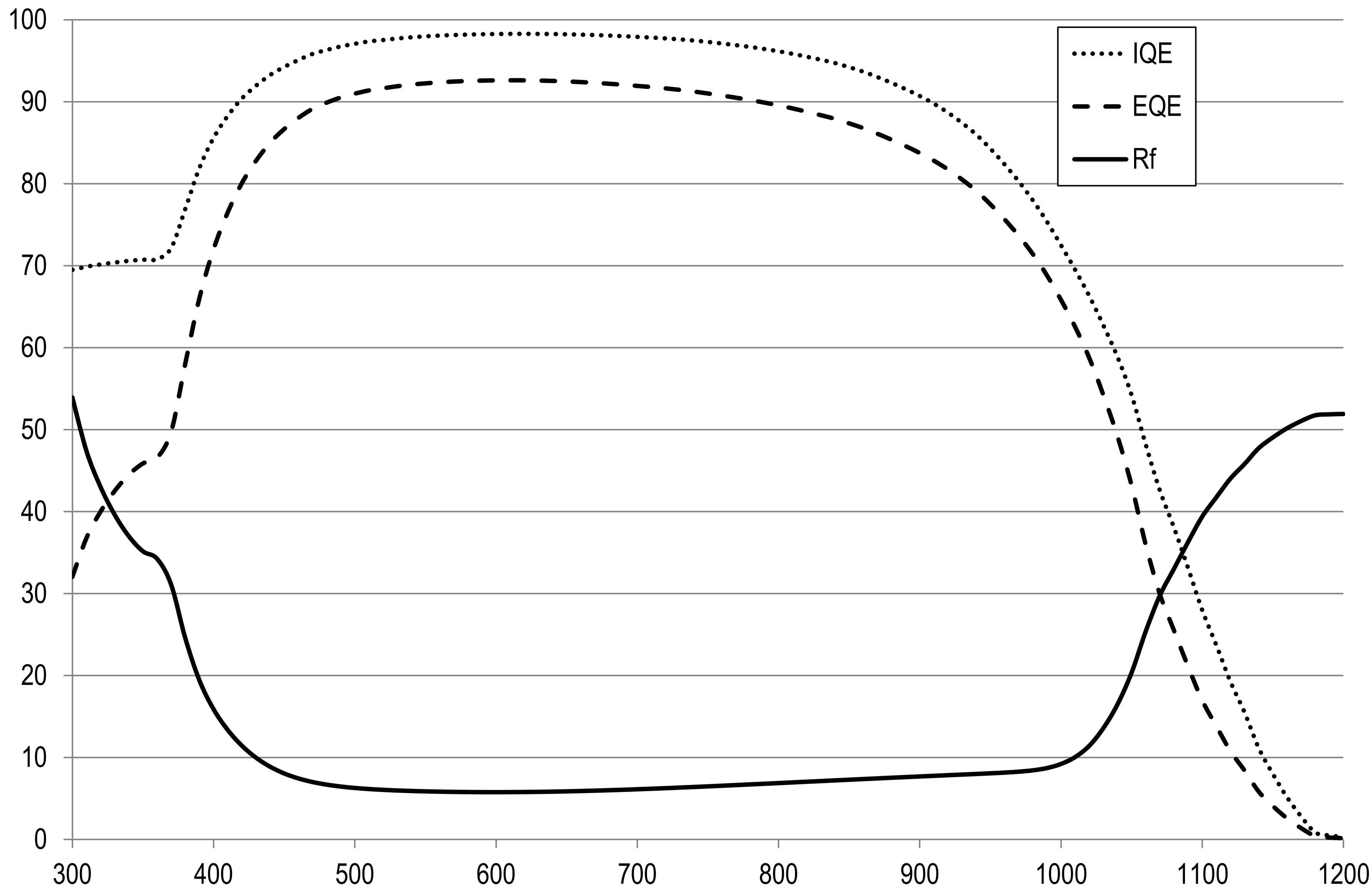


Minimizing reflection – ARC

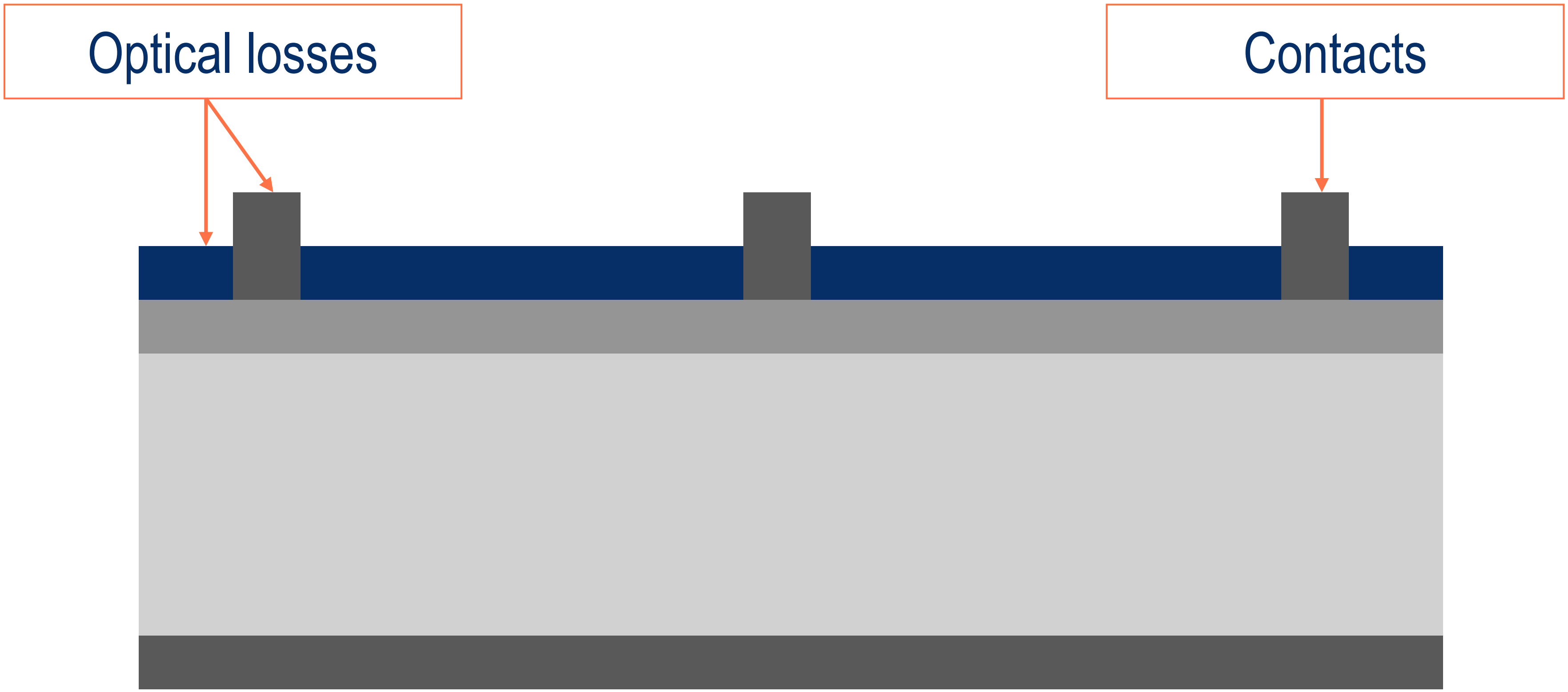
- Reflection at an interface

$$R = \frac{[(\eta_0 - \eta_s)^2 + (\eta_0\eta_s/\eta_1 - \eta_1)^2 \tan^2\delta_1]}{[(\eta_0 + \eta_s)^2 + (\eta_0\eta_s/\eta_1 + \eta_1)^2 \tan^2\delta_1}$$

where $\delta_1 = 2\pi\eta_1 d_1 \cos\theta_1 / \lambda$

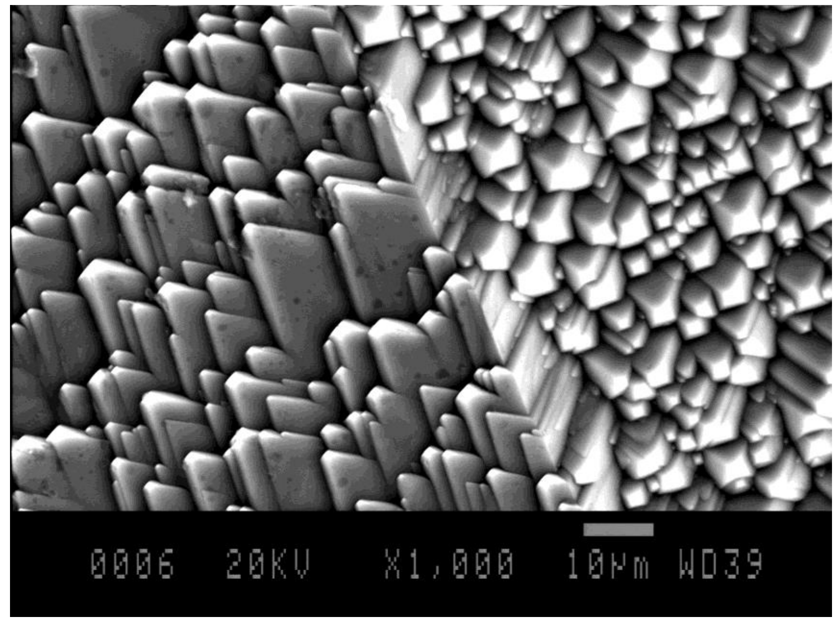


100
90
80
70
60
50
40
30
20
10
0
300
400
500
600
700
800
900
1000
1100
1200
IQE
EQE
Rf


Optical losses
Contacts

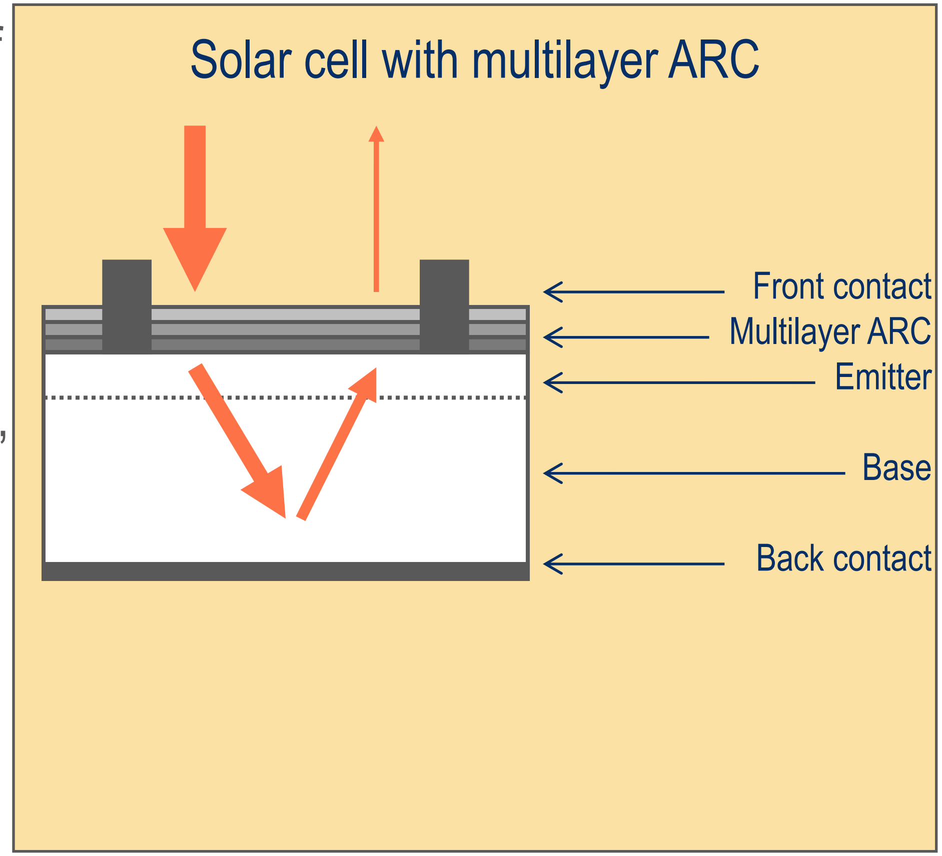
Texturing

- <u>Structure:</u> Typical feature sizes of several µm
- <u>Realization:</u> Wet chemical processes, possibly laser or plasma
- <u>Challenges:</u> -



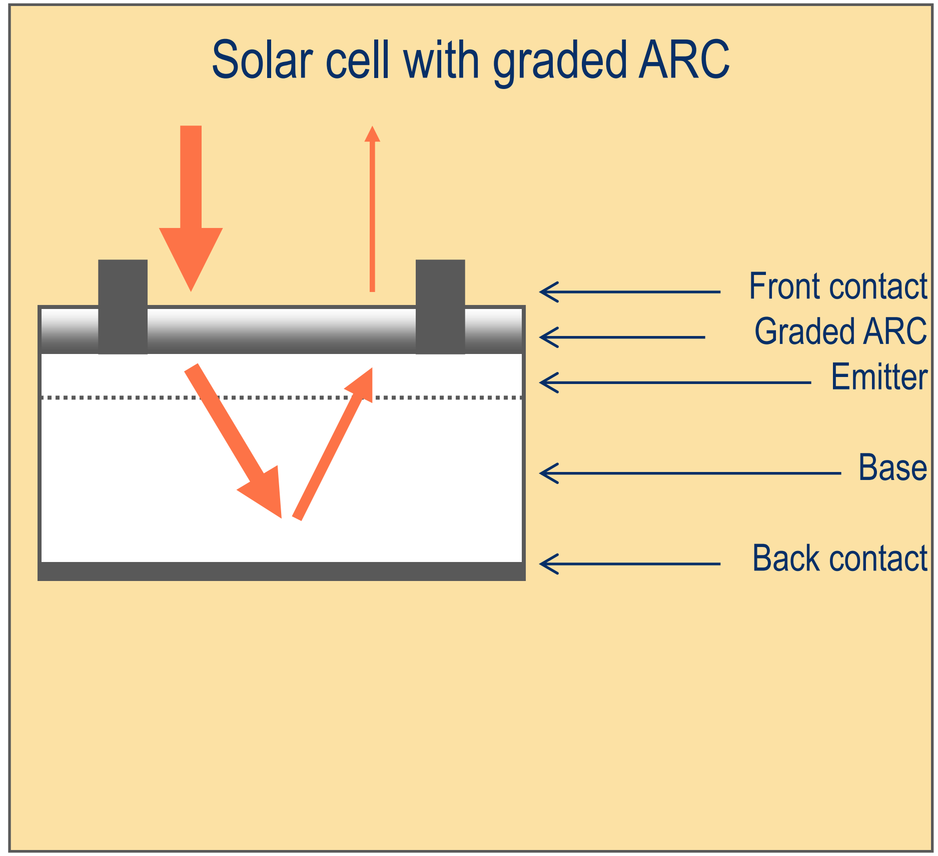
Multilayered anti-reflex coatings (ARCs)

- Nanostructure: Multilayered stack of deposited dielectric materials
- Realization: PECVD
- Challenges: Complexity, throughput, process stability

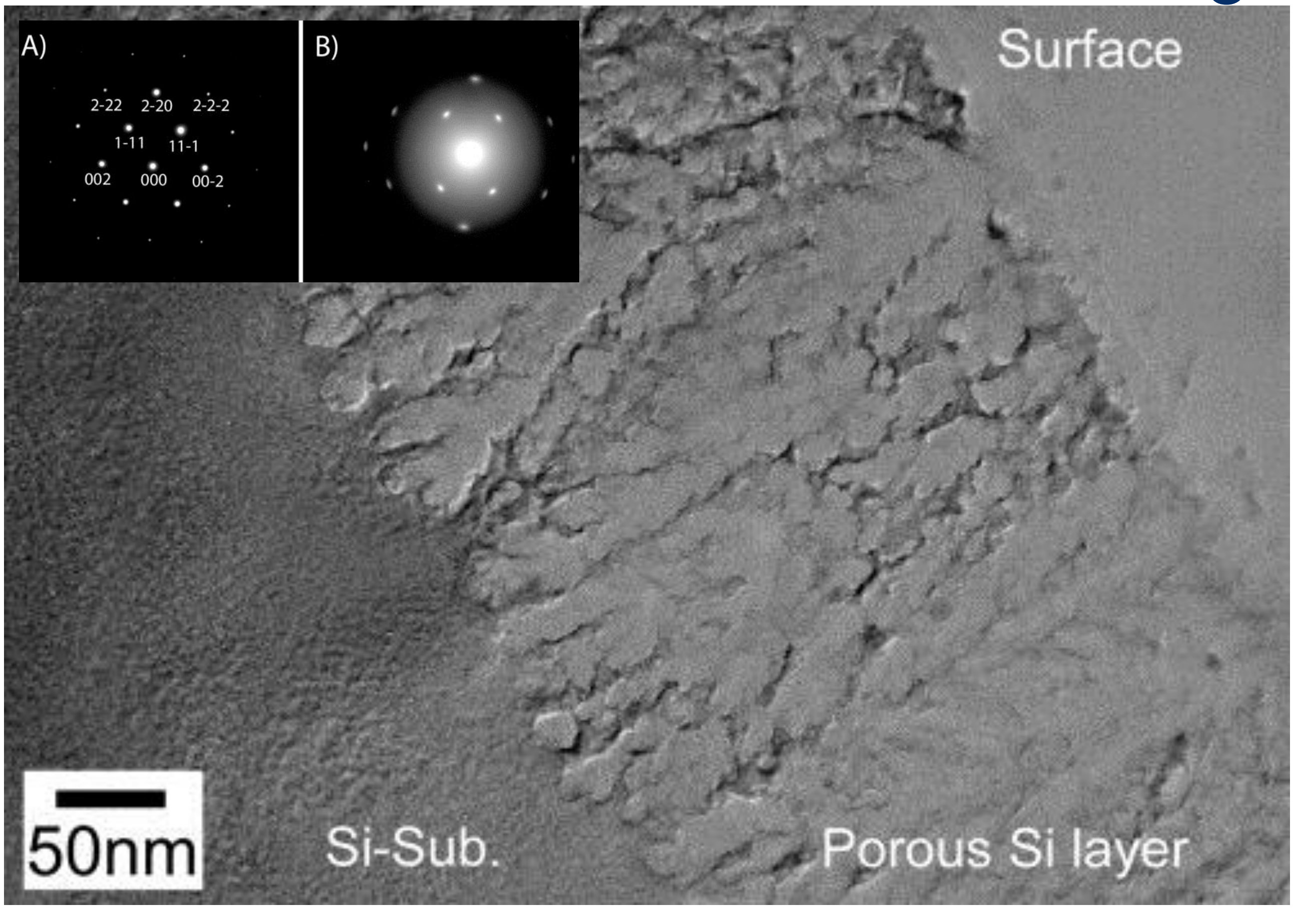


Graded anti-reflex coatings (ARCs)

- Nanostructure: Nanoporous silicon
- Realization: Electrochemical etching

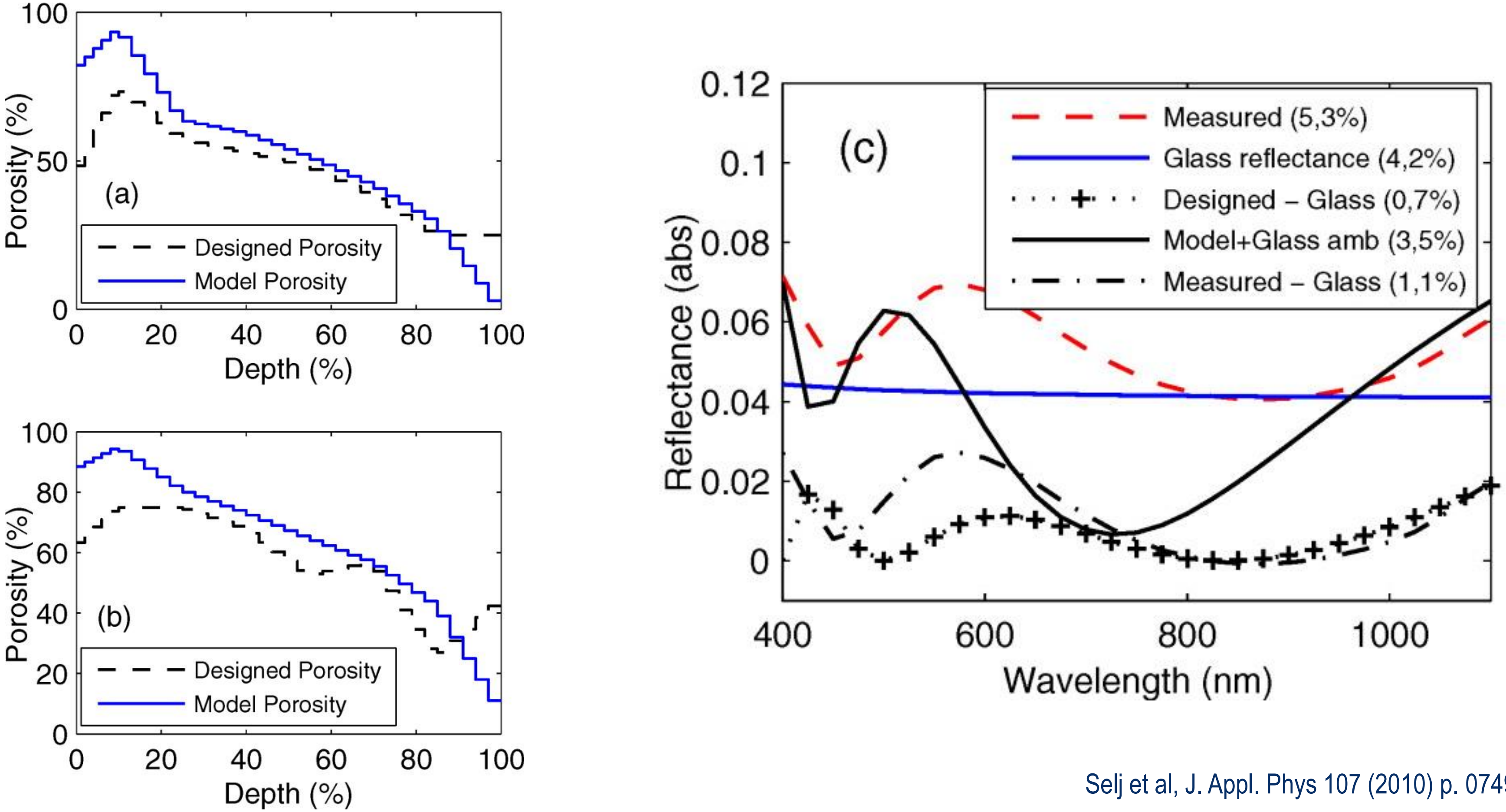


Graded anti-reflex coatings (ARCs)



Selj et al, J. Appl. Phys 107 (2010) p. 074904

Graded anti-reflex coatings (ARCs)



Selj et al, J. Appl. Phys 107 (2010) p. 074904

Graded anti-reflex coatings (ARCs)

- On the cool side:
  - The process works
  - Reproduceable, simple and fast process
- Is it really relevant for a solar cell?
  - High throughput
  - Surface passivation
  - Process issues
- Work in progress!

Issues for very thin solar cells

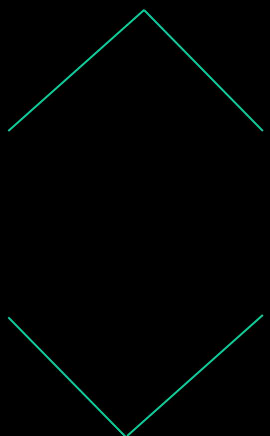
- Conventional textures consume a lot of silicon

- Front side textures excellent with respect to reflectance
  - KOH on <100>

- Preferred «smart cut» direction: <111>
  - Conventional processes unsuitable
    - KOH: <100>
    - Iso: saw damage
  - Plasma texturing an option

- Can we avoid texturing altogether?

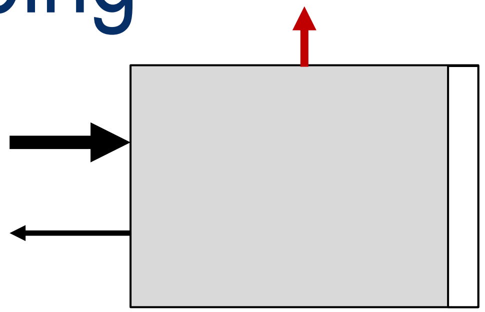
Issues for very thin solar cells



Structure			J_{ph} [mA/cm^2]		
Front side	Back side	Oxide	Al	Ag	Ideal
Pyramids	Planar	No	35.7	37.3	
Pyramids	Planar	Yes	37.7	37.9	
Pyramids	Pyramids	No	36.1	38.9	
Pyramids	Pyramids	Yes	39.4	40.0	
Pyramids	Pyramids	-			40.4
Planar	Cylinder	Yes	35.6	36.0	
Planar*	Cylinder	Yes	37.6	38.0	
Planar	Zigzag	Yes	37.3	37.7	
Planar*	Zigzag	Yes	39.3	39.7	

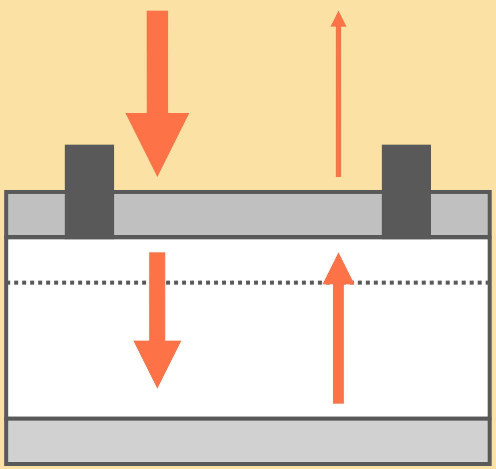
J. Gjessing et al. EUPVSEC (2011)

Light trapping

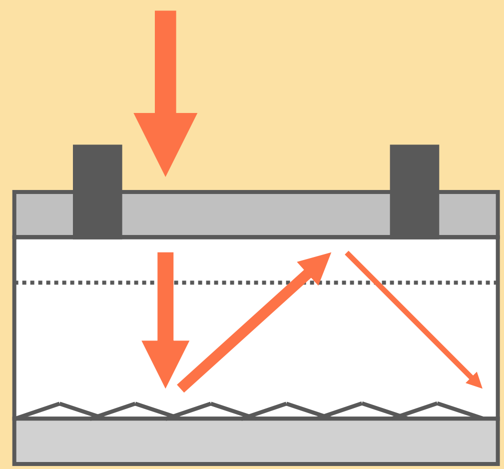


Light trapping

Rear reflection



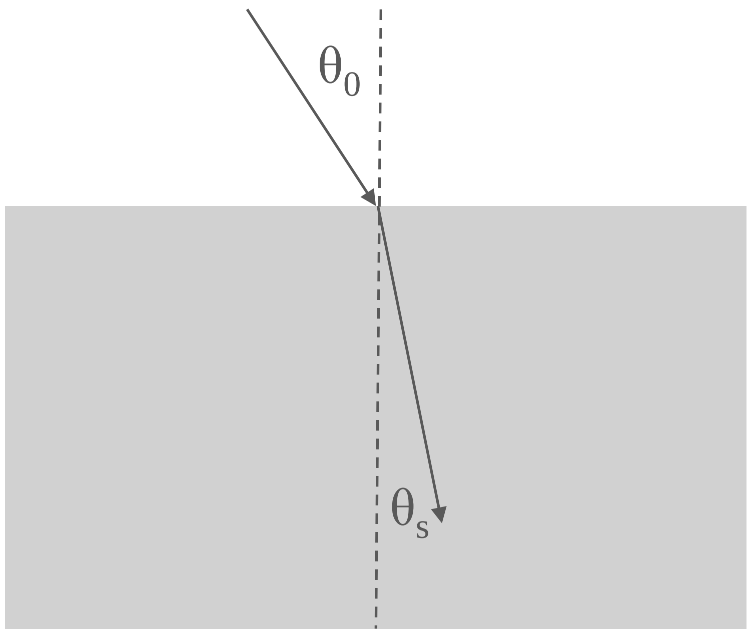
Light scattering



Refraction

- Refraction at interface (Snell's law)

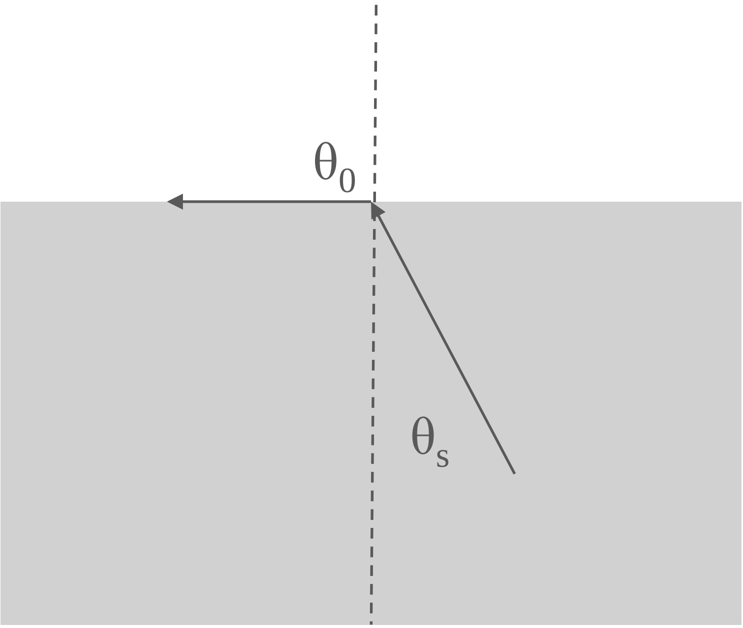
$$n_0 \sin\theta_0 = n_s \sin\theta_s$$



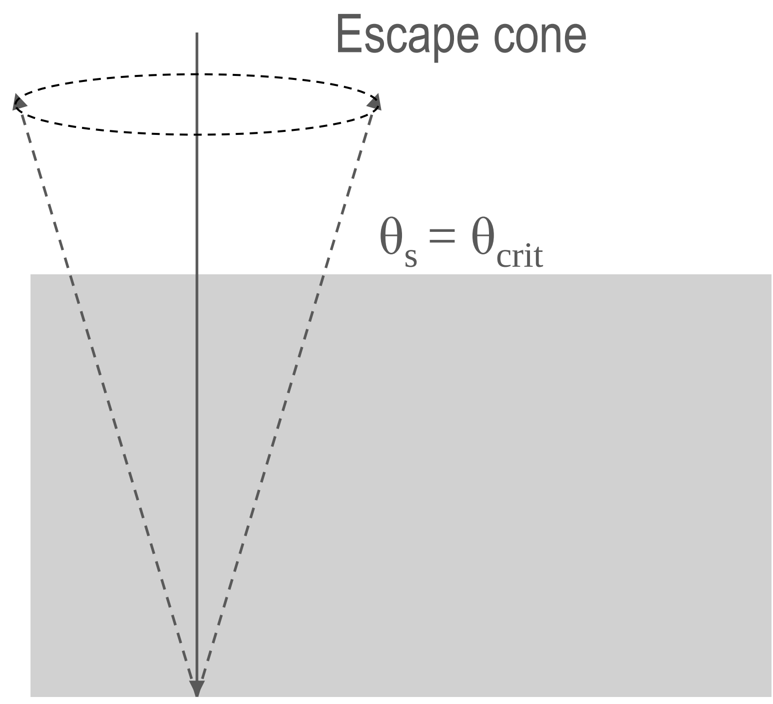
Total internal reflection

$$n_0 \sin 90^0 = n_s \sin\theta_{crit}$$

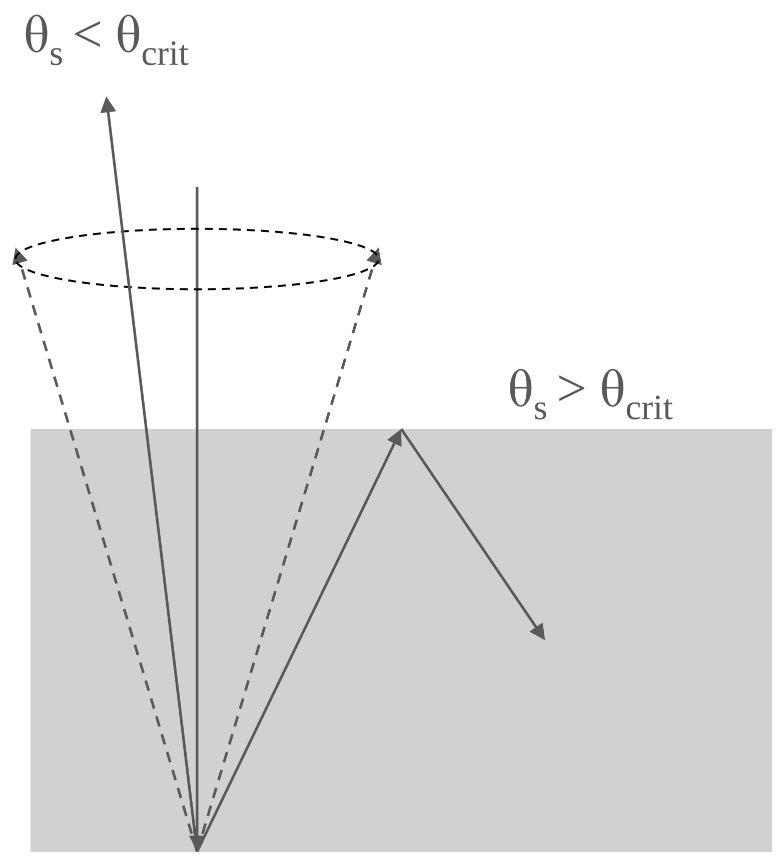
$$\theta_{crit} = \sin^{-1}(n_0/n_s)$$



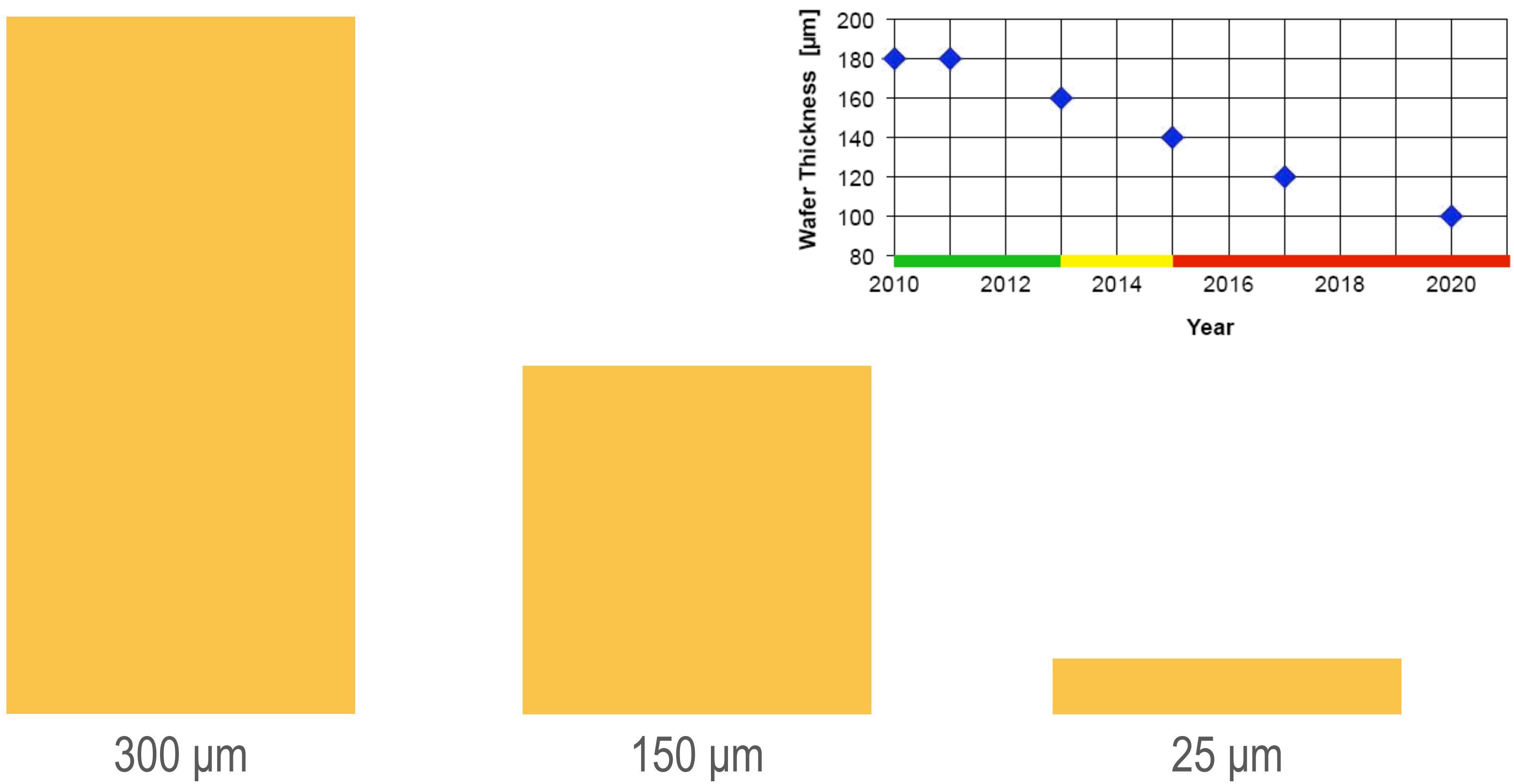
Total internal reflection

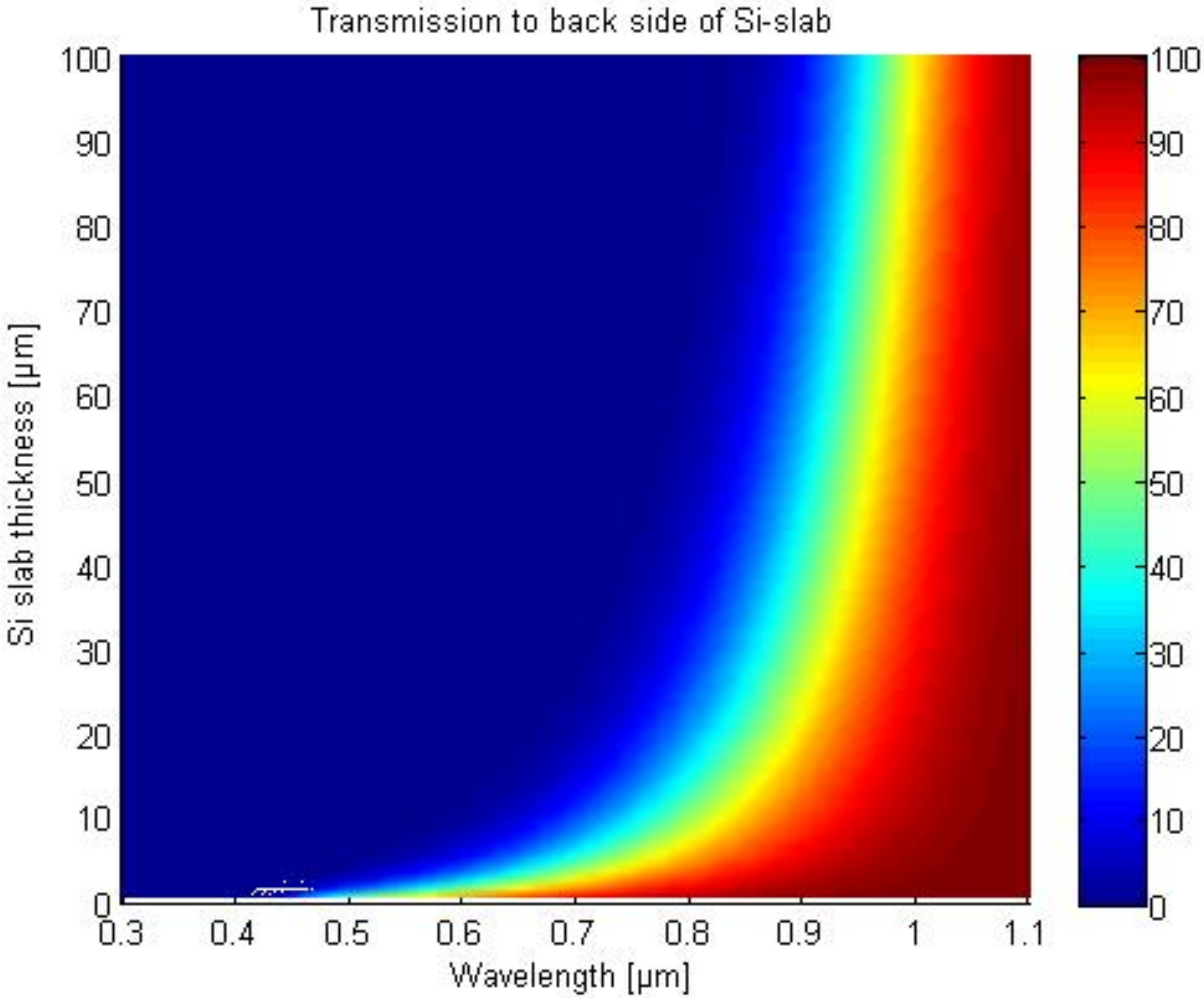


Total internal reflection



Thinner and thinner…

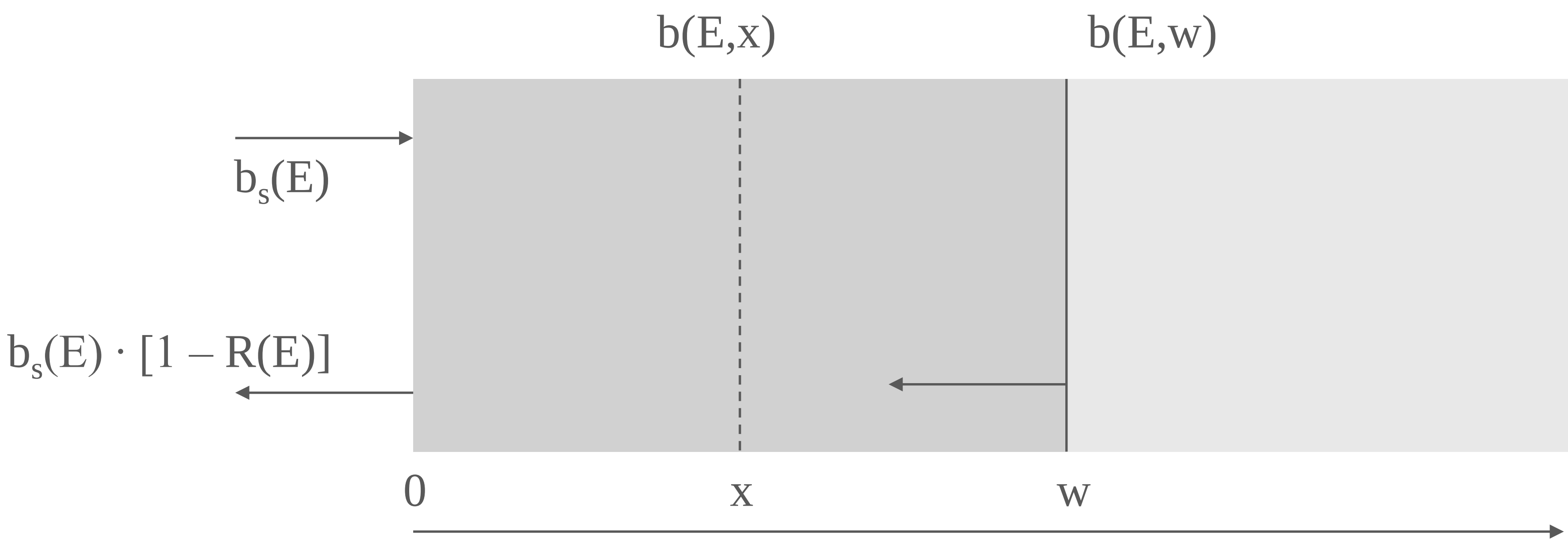



Transmission to back side of Si-slab
Si slab thickness [μm]
Wavelength [μm]
0
10
20
30
40
50
60
70
80
90
100
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1

J. Gjessing

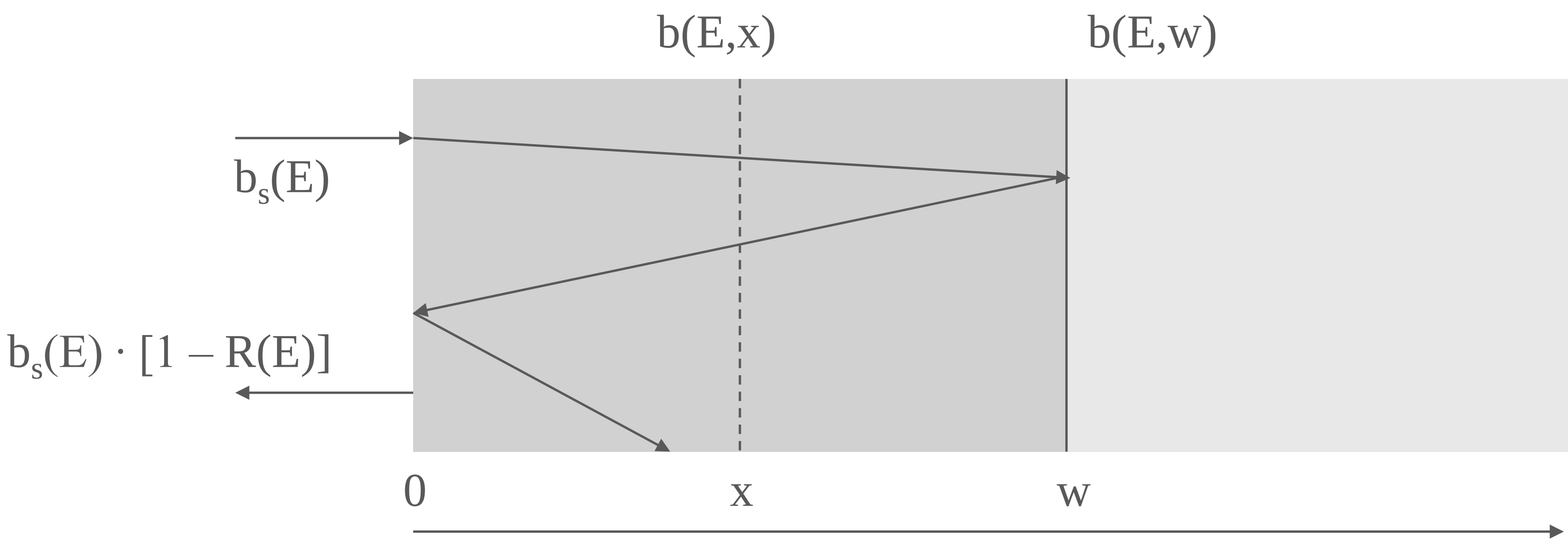
Light confinement – rear mirrors

- Path length enhancement: $\langle l \rangle = 2w$



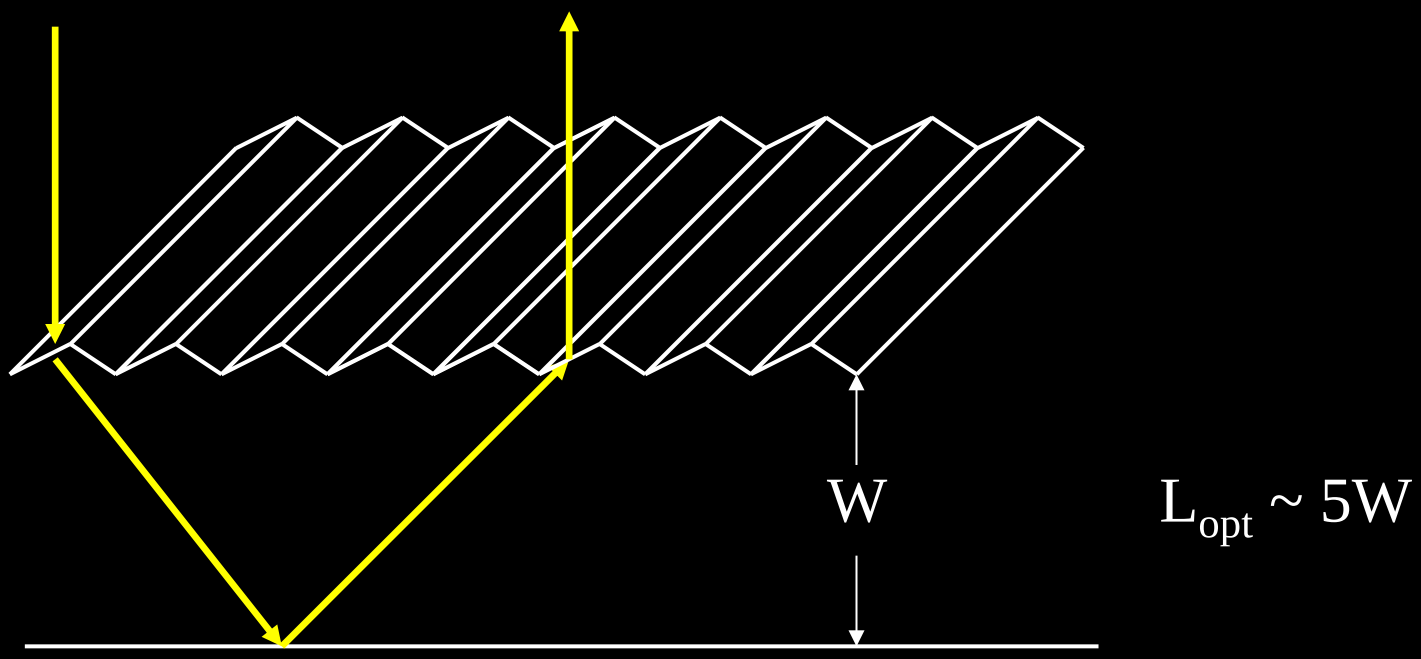
Light confinement – random scattering

- Path length enhancement: $\langle l \rangle \sim 4 n_s^2 w$



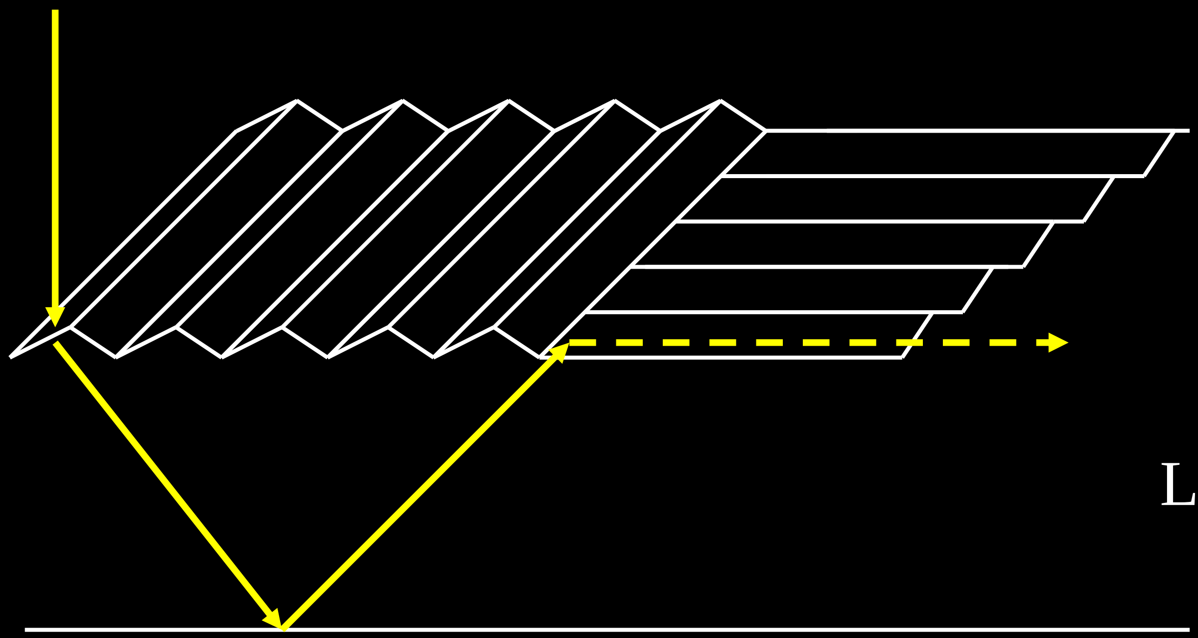
Geometric light trapping

- Symmetry can reduce optical path length



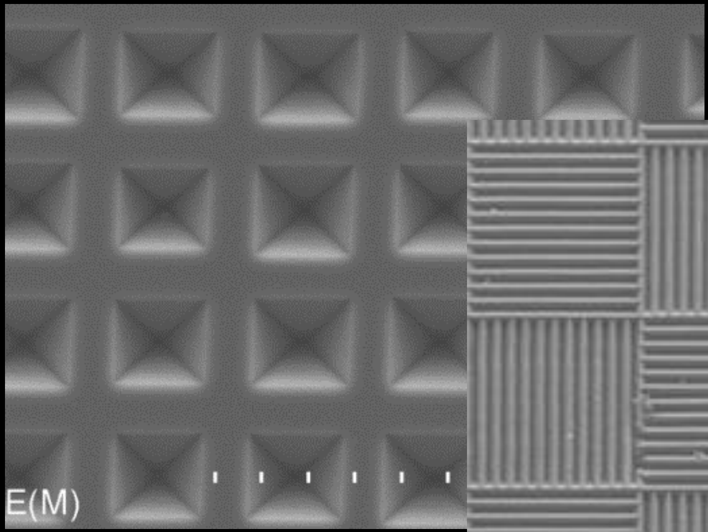
Geometric light trapping

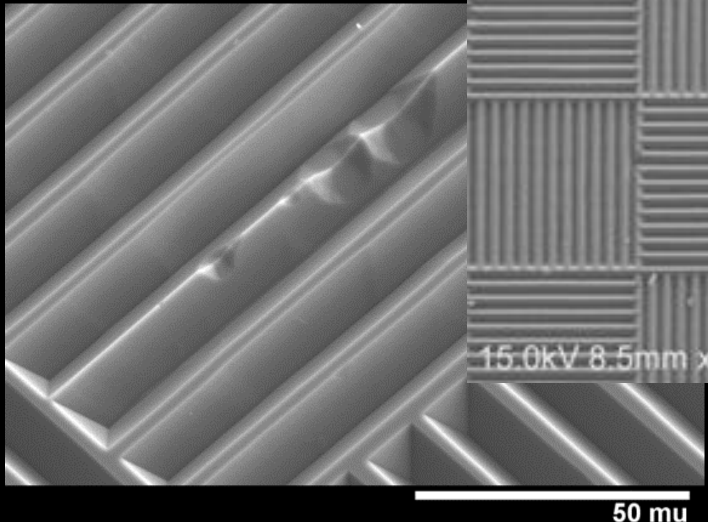
- Breaking symmetries – ”patch” structures

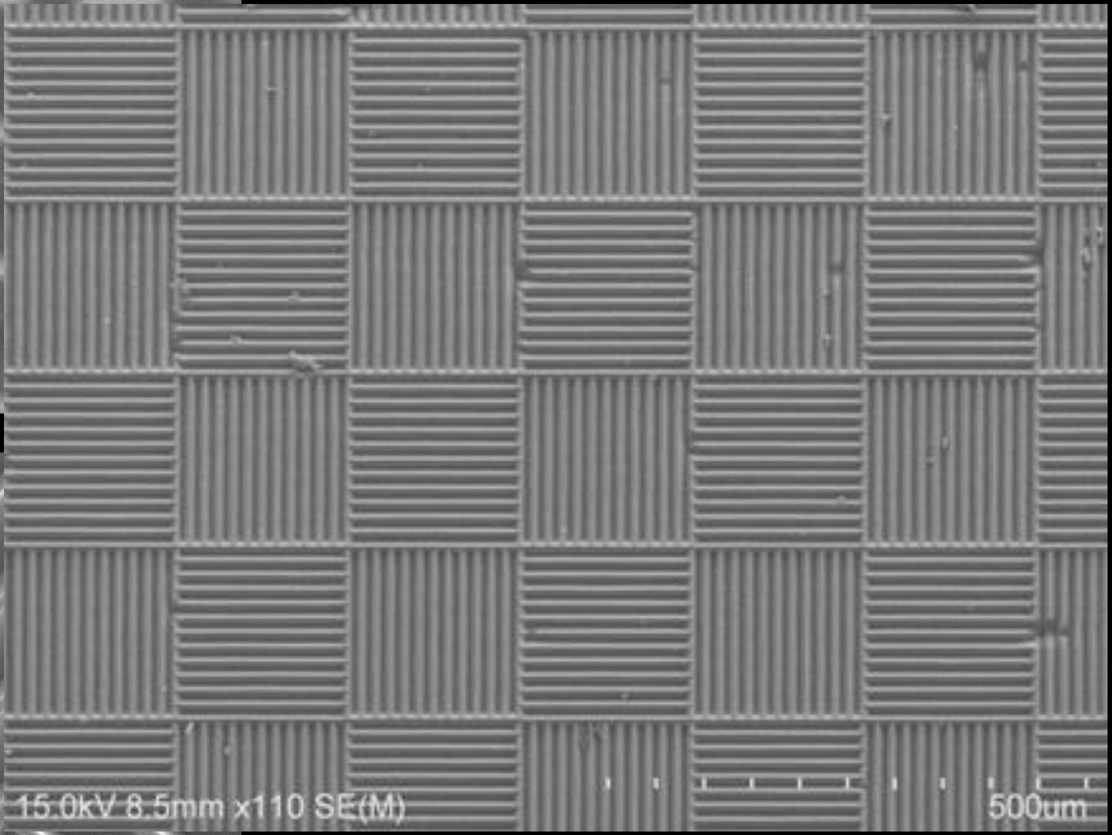


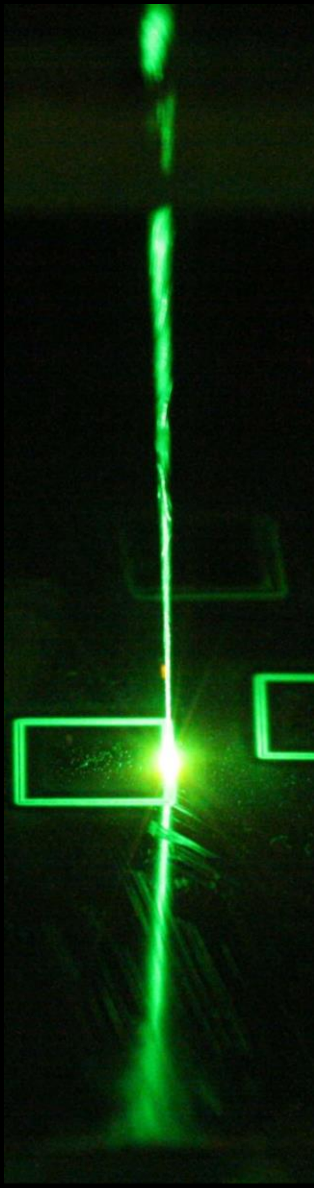
$L_{opt} \sim 10W+$

Masking + laser ablation



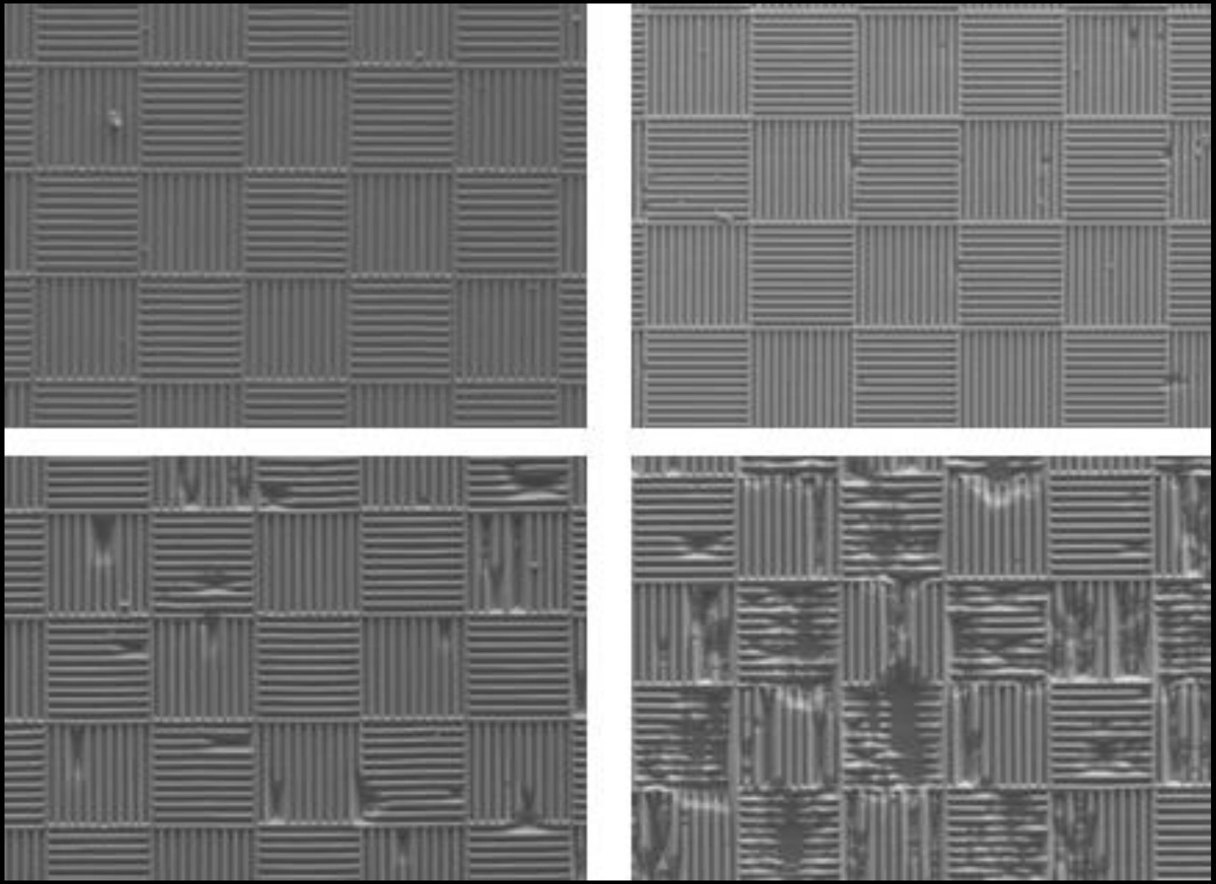






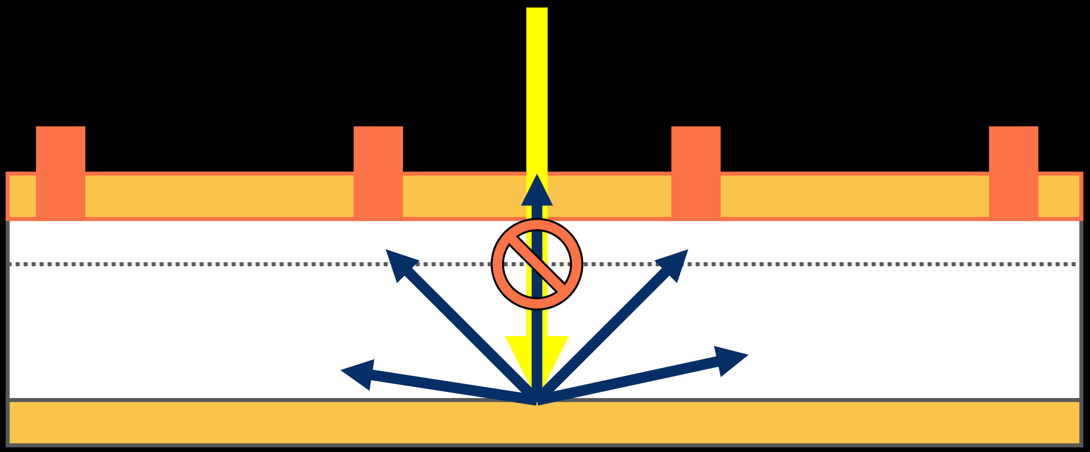
J. Thorstensen PhD thesis 2013, PIP

Masking + laser ablation



J. Thorstensen PhD thesis 2013, PIP

If we could choose…

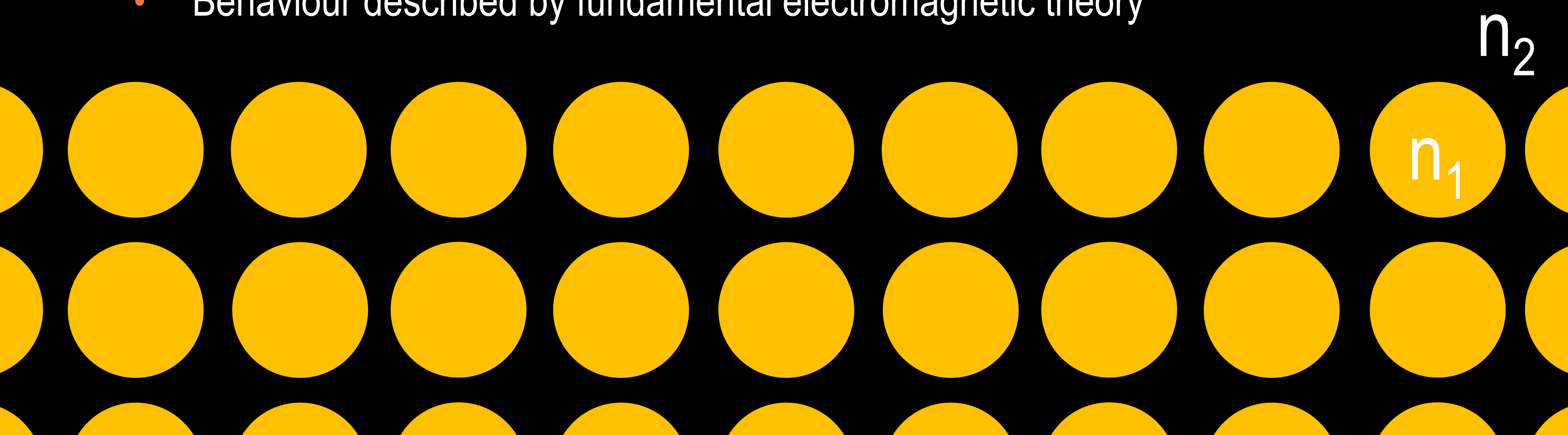


Photonic crystals

- Periodic material structures
  - Refractive index contrast
  - Sub-wavelength feature size

- Can exhibit unique optical properties, including
  - Effective scattering into higher orders
  - High (broadband) reflectance

- Behaviour described by fundamental electromagnetic theory

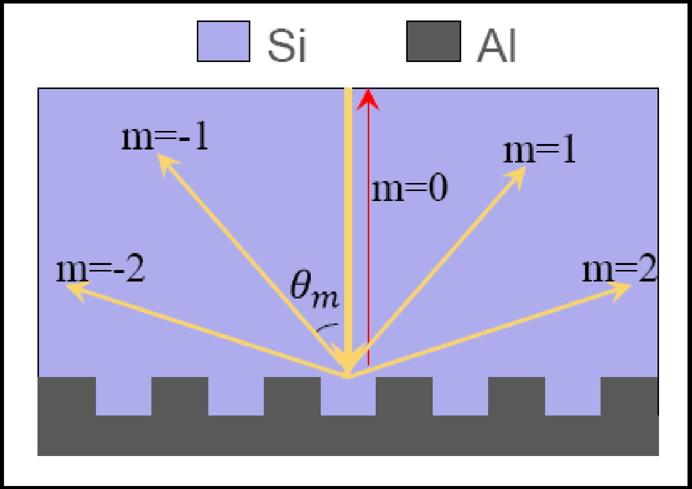


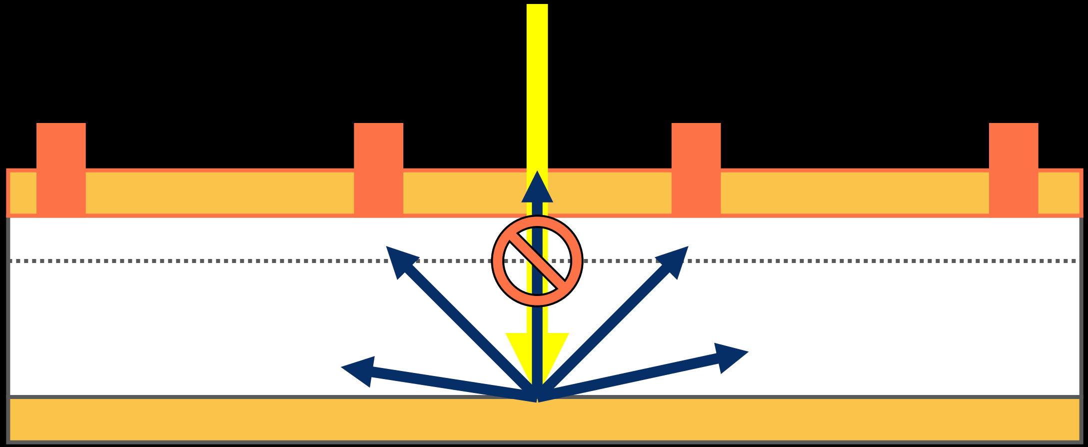
2D photonic crystals (2DPCs)

- Exhibit the desired properties
- Diffraction angles and efficiencies can be optimized

$$\sin(\theta_m) = \sin(\theta_i) + m\lambda/\Lambda n_0$$

- Effective scattering possible with thin structures
- Bandwidth requirements relaxed at rear side
- Metal absorption an issue

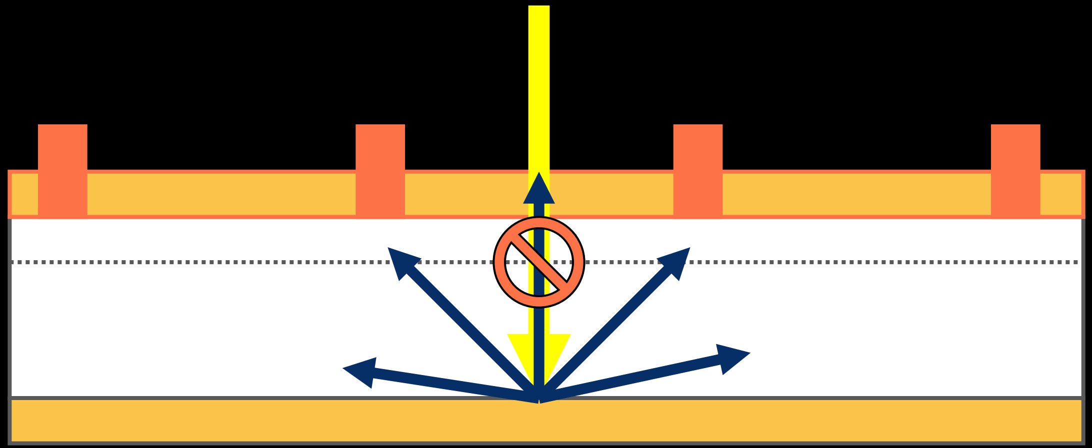


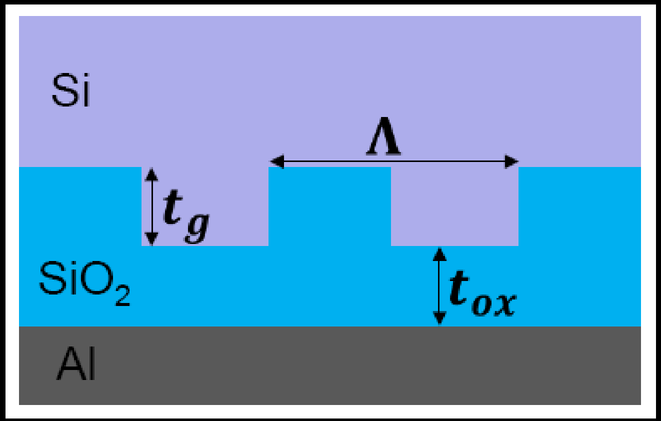


J. Gjessing, Aa. Sudbø

Modeling of 2DPCs

- Tools:
  - Rigorous electromagnetic modeling required when feature sizes are close to λ
  - RCWA
- Model:
  - Structured silicon filled with low index dielectric (SiO_2)
  - Separation of metal added (Ag or Al)
  - All relevant dimensions varied





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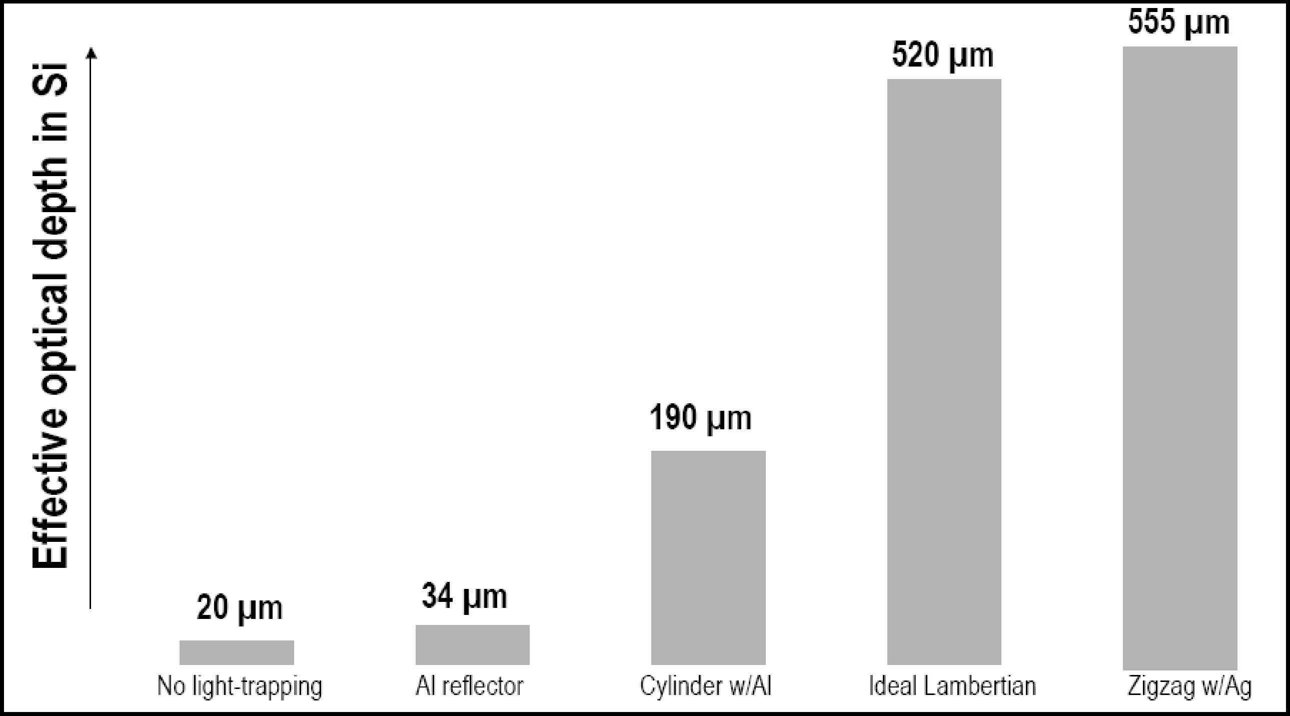
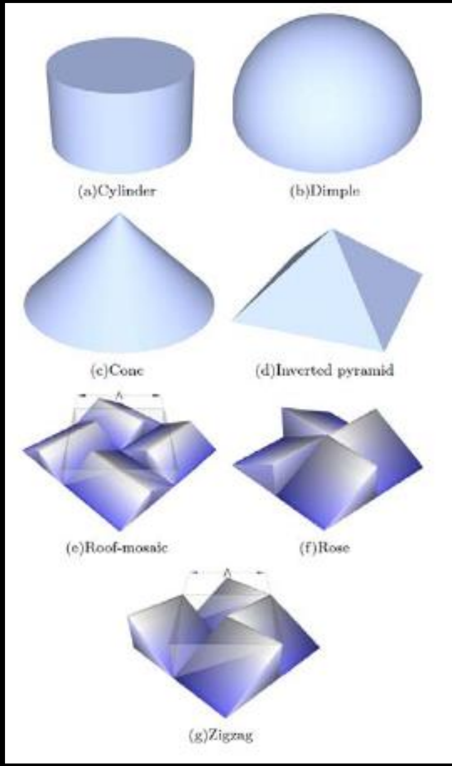
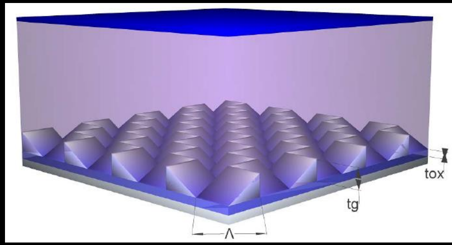
Current understanding

- Many different geometries investigated
- Full structures modeled
- Dimension control more important than unit cell structure
- Asymmetry highly beneficial



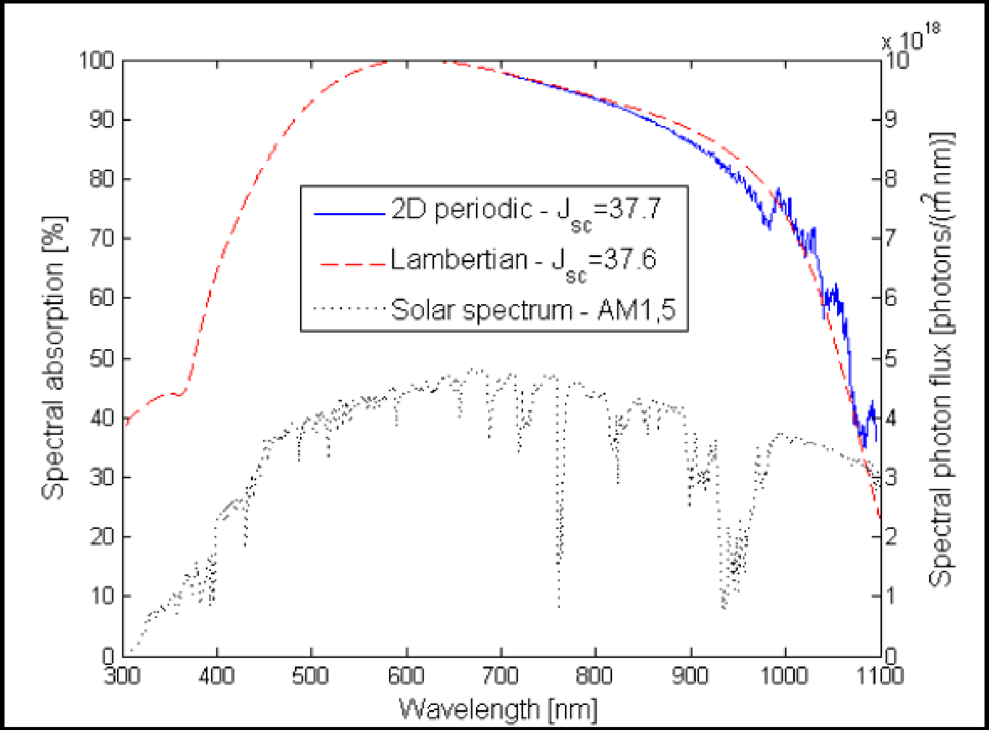




J. Gjessing et al., J. Appl. Phys (2011)
J. Gjessing et al., JEOS (2011)

Current understaning

- 2D light trapping structures can be extremely effective!



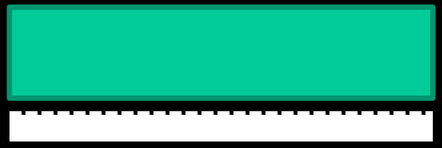
J. Gjessing et al., J. Appl. Phys (2011)
J. Gjessing et al., JEOS (2011)

Synthesis of large-area 2DPCs

- Focus: from laboratory to real world application
  - Demonstrators fabricated using lithographic techniques

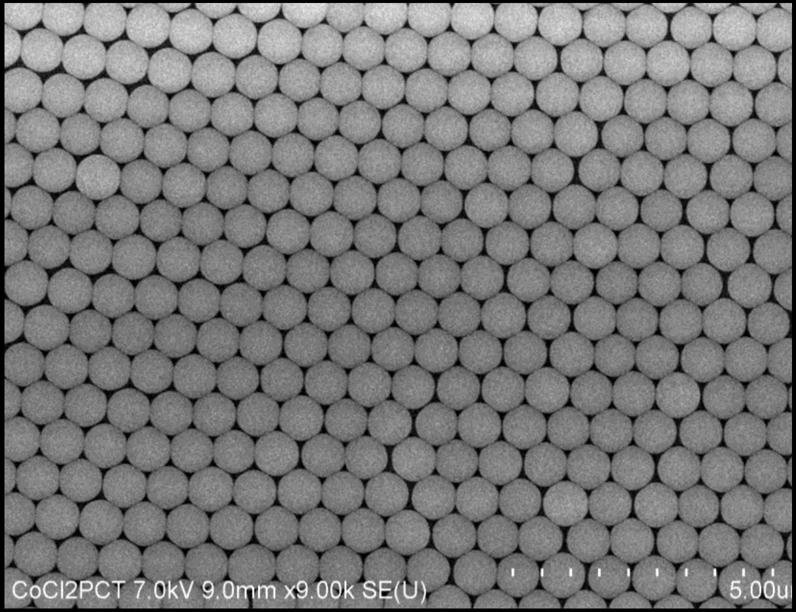
- Can we enable large area, low cost nanopatterning?
  - Nano-imprint lithography
  - Interference lithography
  - Self-assembly

- Potentially easier to address backsheet than the silicon wafer itself.



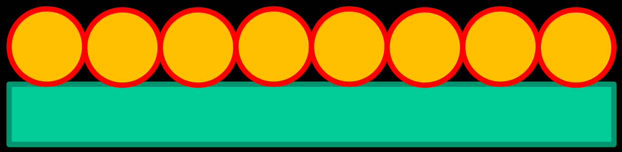
J. Gjessing et al. "2D back-side diffraction grating for improved light trapping in thin silicon solar cells", Optics Express 18 (2010) p. 5481
E. Haugan et al. Energy Proc.

Pattern definition

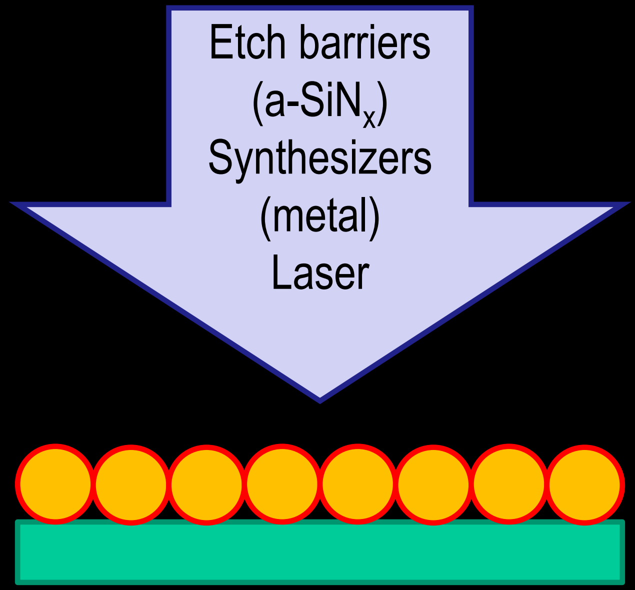


E. Haugan et al. Energy Proc.

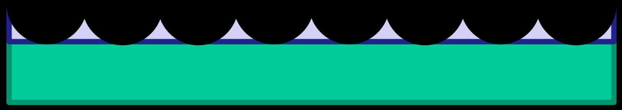
Pattern definition



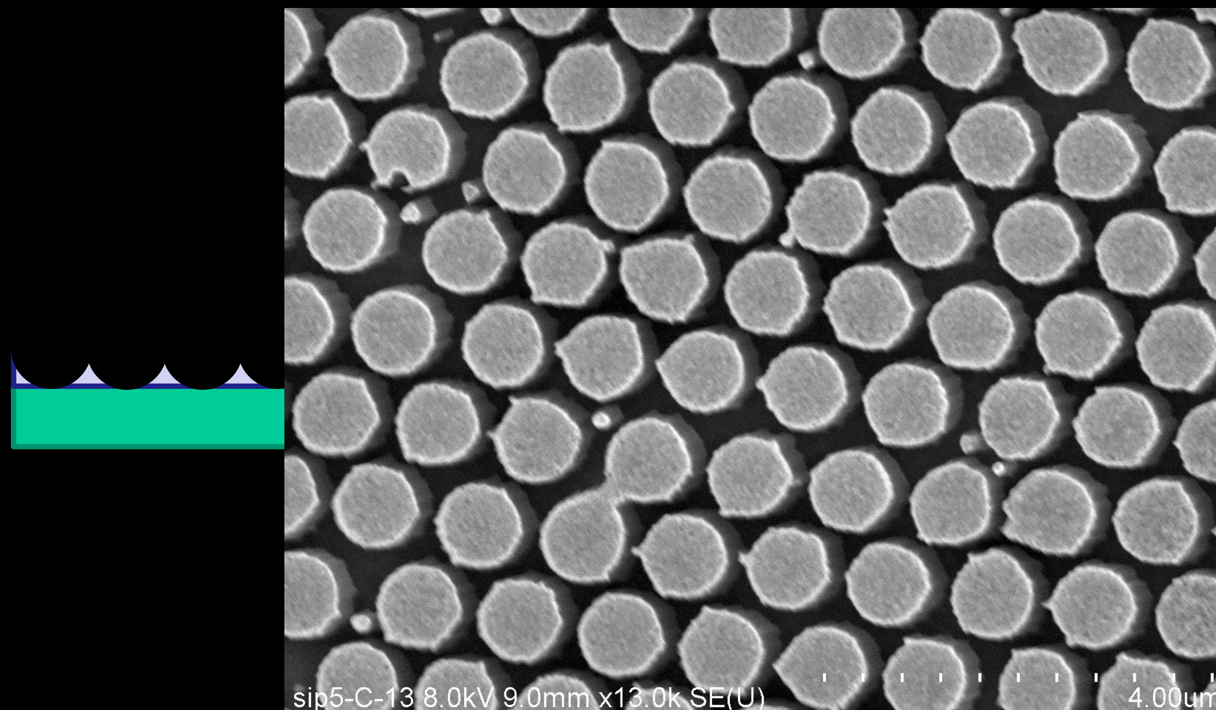
Making the 2DPCs



Making the 2DPCs

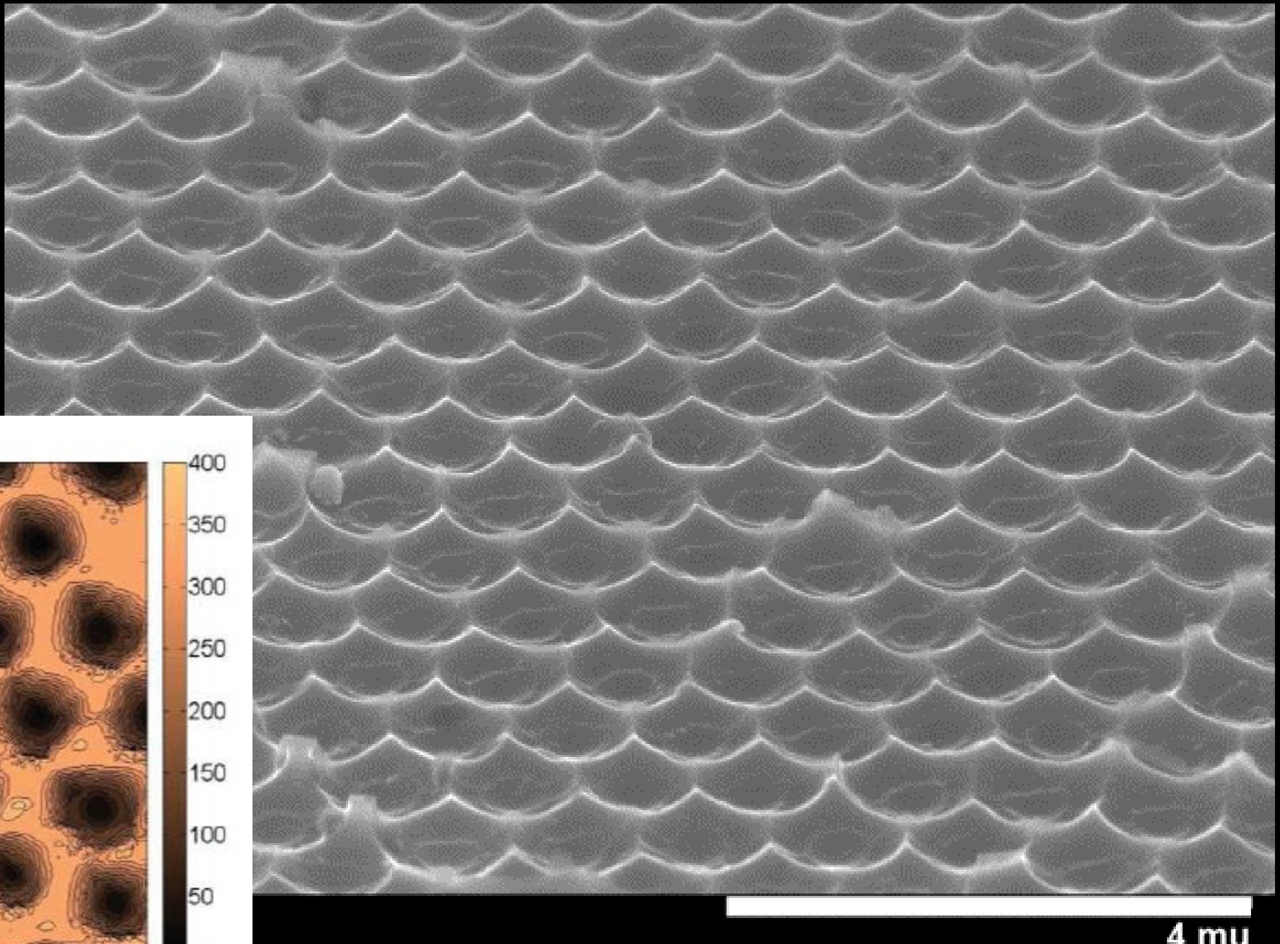


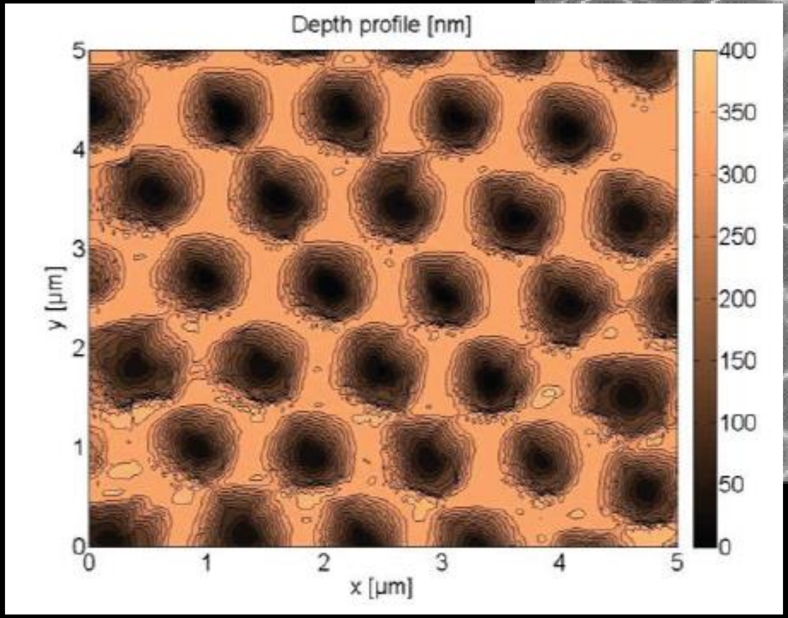
Making the 2DPCs



E. Haugan et al. Energy Proc.

Self-assembly + laser ablation





J. Thorstensen PhD thesis 2013

Self-assembly + laser ablation

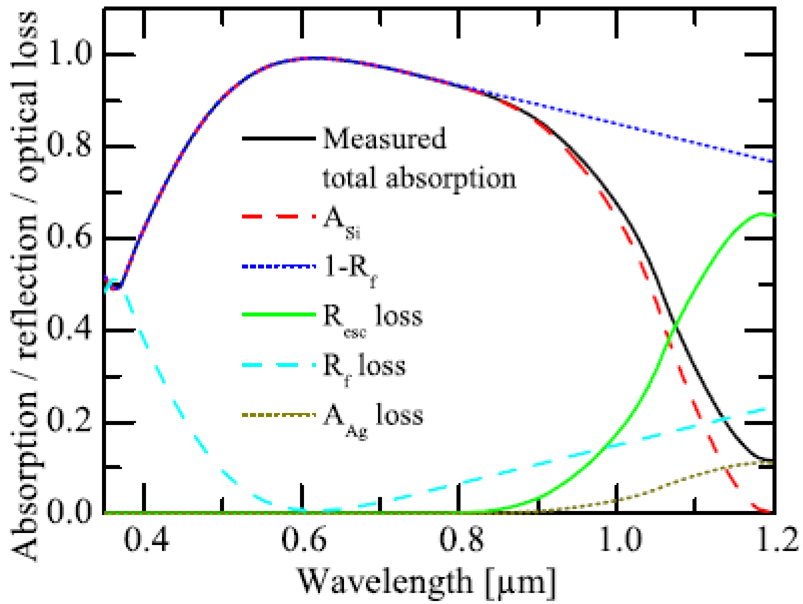
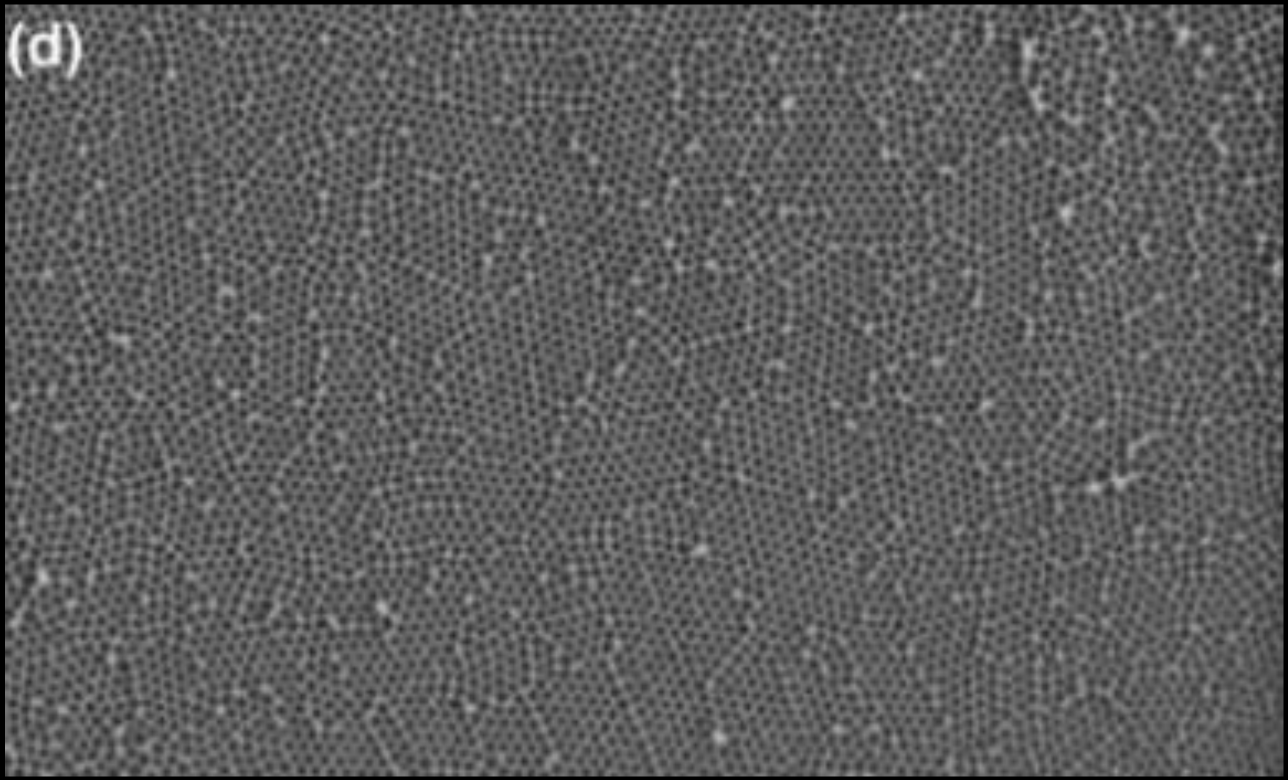


Fig. 4. Optical losses for a 28-μm-thick cell with a planar front side and dimples on the rear side as found using the model described in Section II-B.

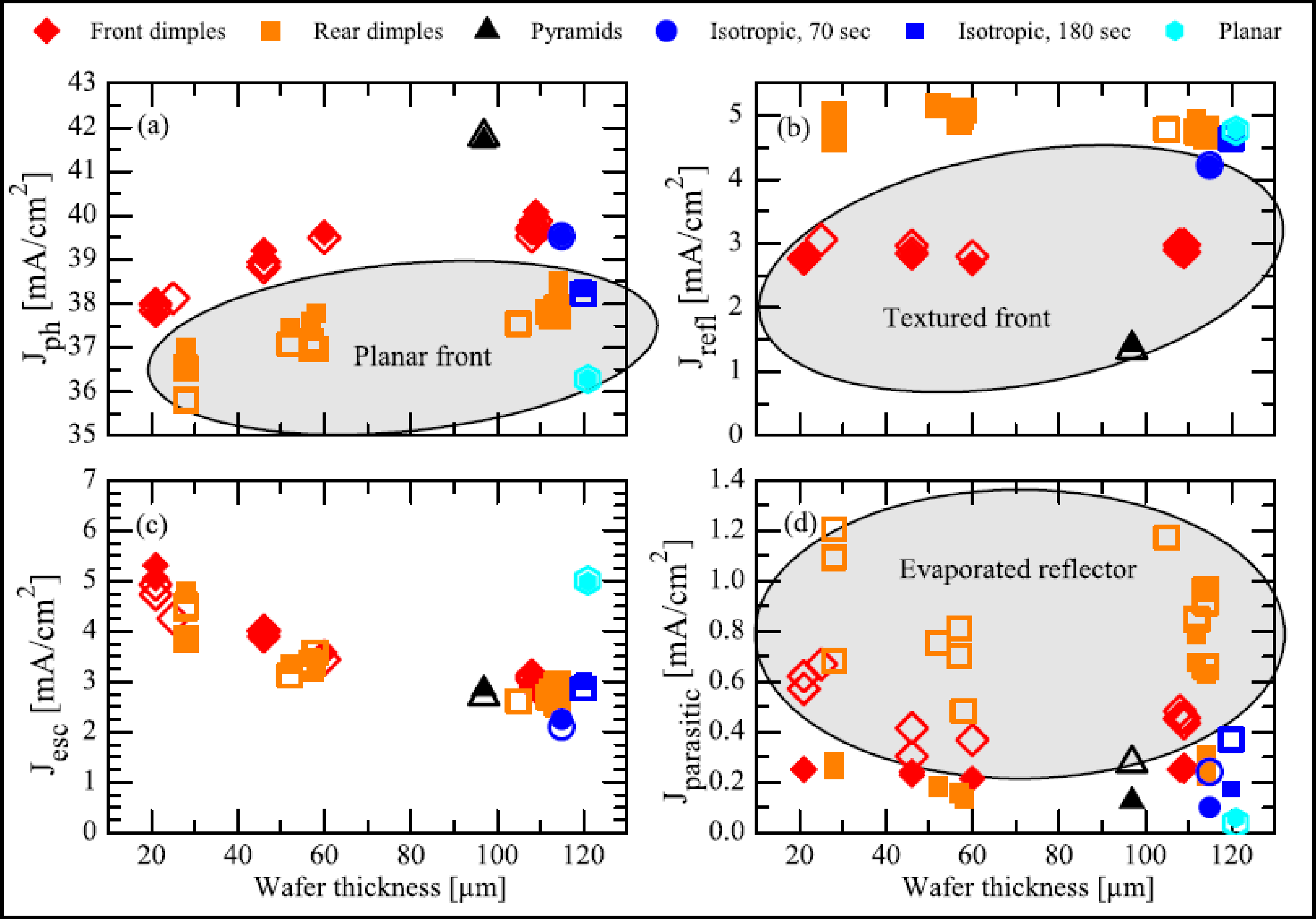
J. Thorstensen PhD thesis 2013, IEEE J-PV

Self-assembly + laser ablation

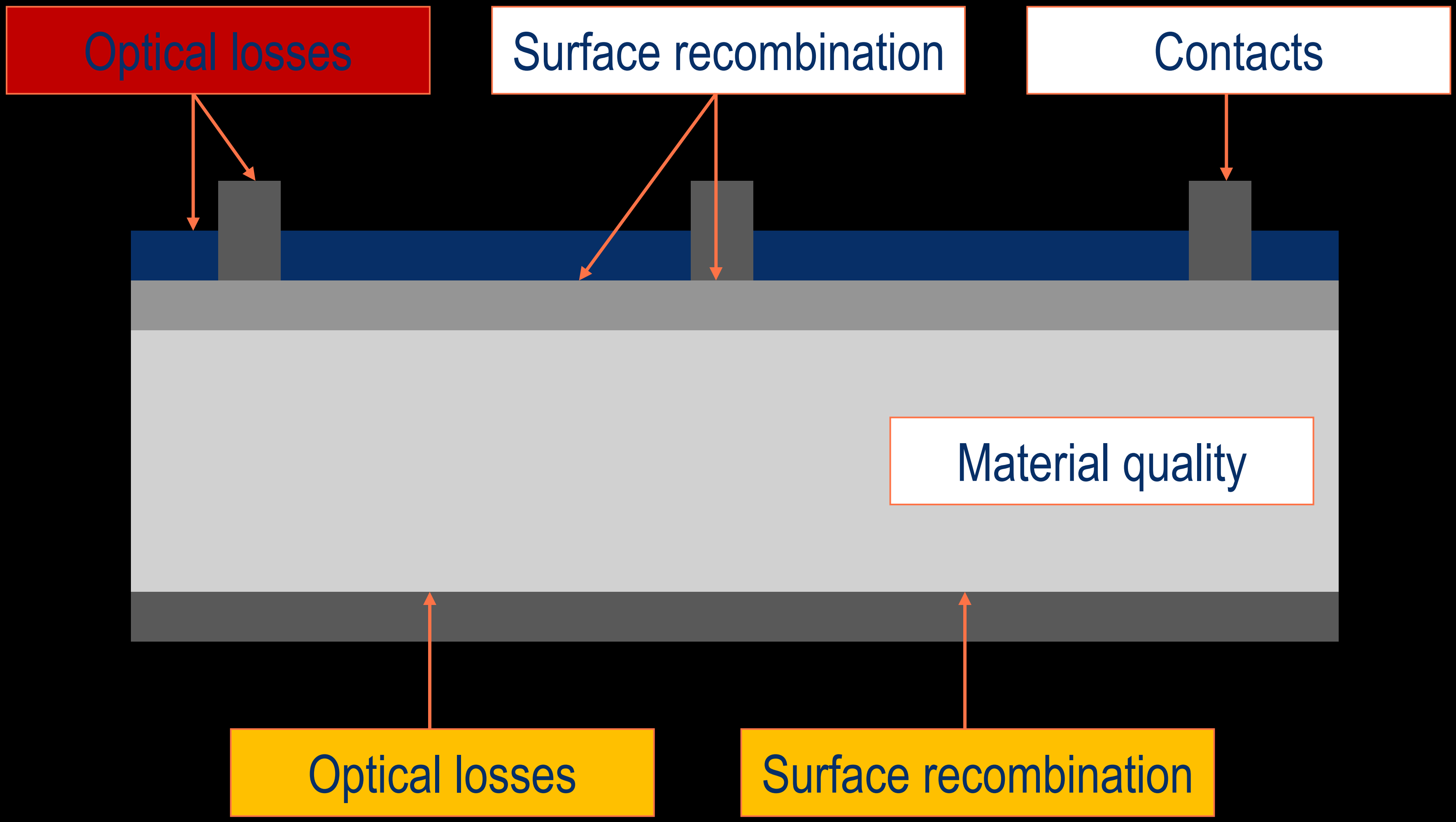


J. Thorstensen PhD thesis 2013, IEEE J-PV

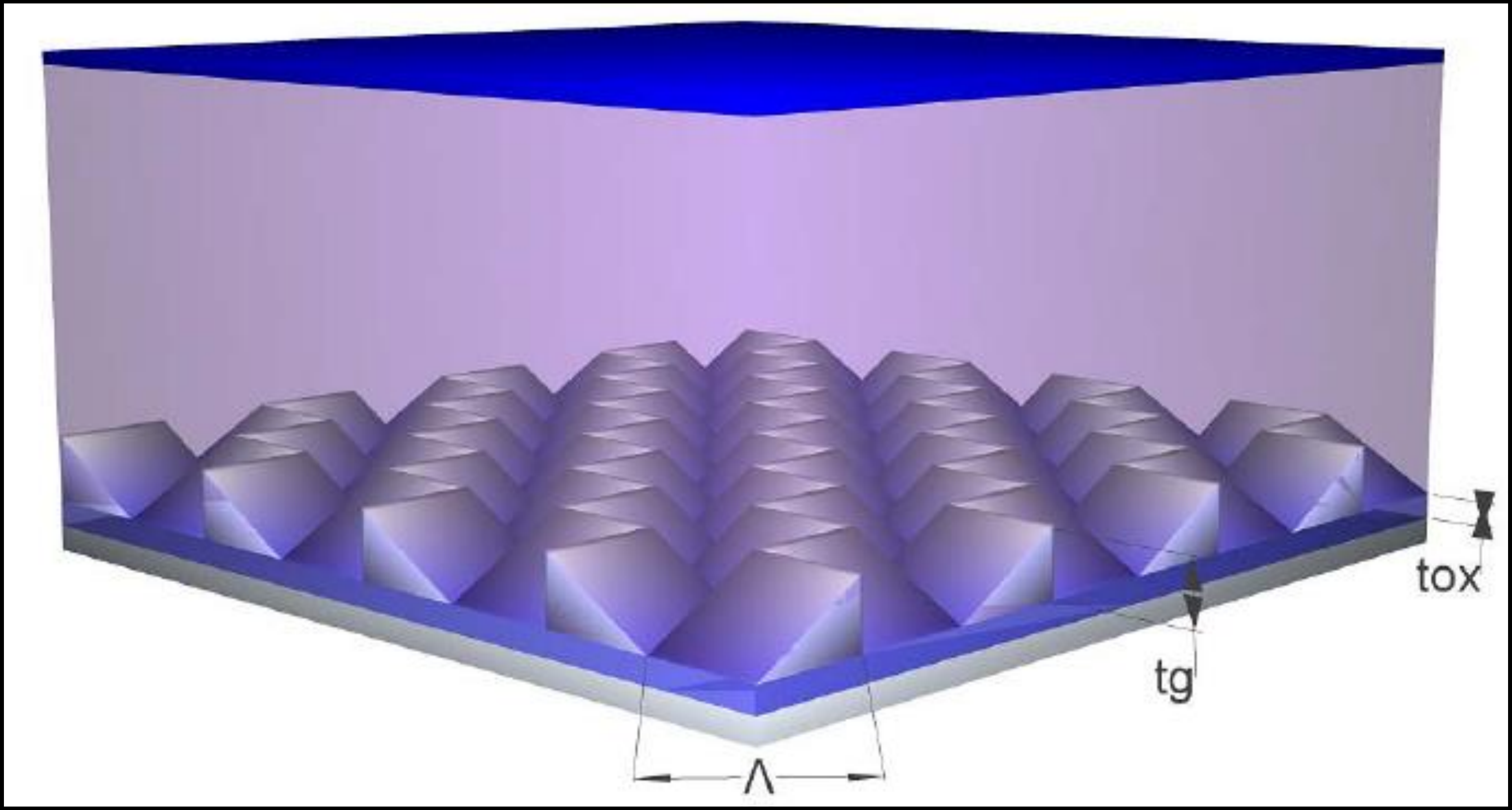
Light trapping – evaluation



J. Thorstensen PhD thesis 2013, IEEE J-PV

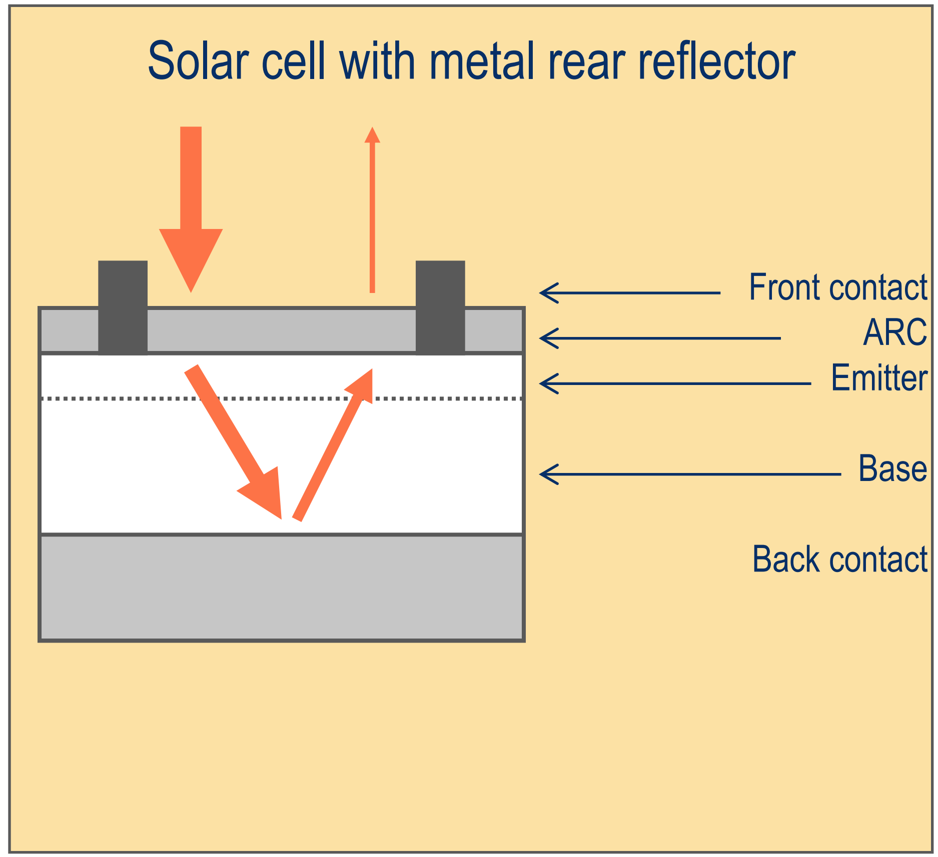

Optical losses
Surface recombination
Contacts
Material quality
Optical losses
Surface recombination

Light trapping solar cell



Metallic rear reflector

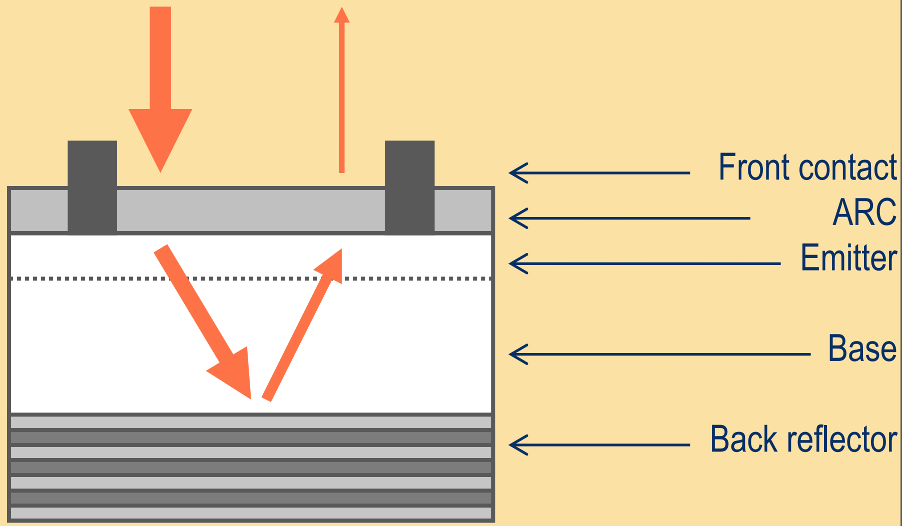
- Realization: Screen-printing, sputtering, evaporation
- Advantage: Multiple functionality in one material/process
- Disadvantage: R < 100%



Distributed Bragg reflectors (DBRs)

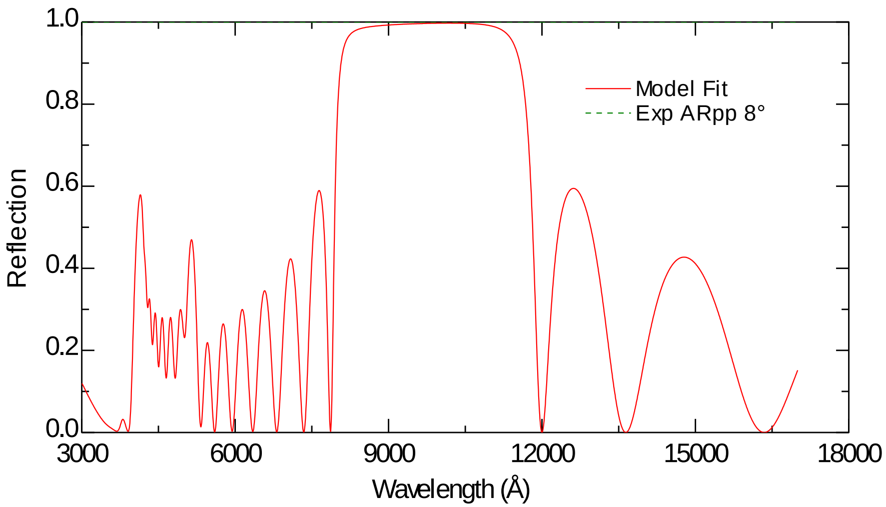
- Nanostructure: Nanoporous silicon
- Realization: Electrochemical etching, PECVD

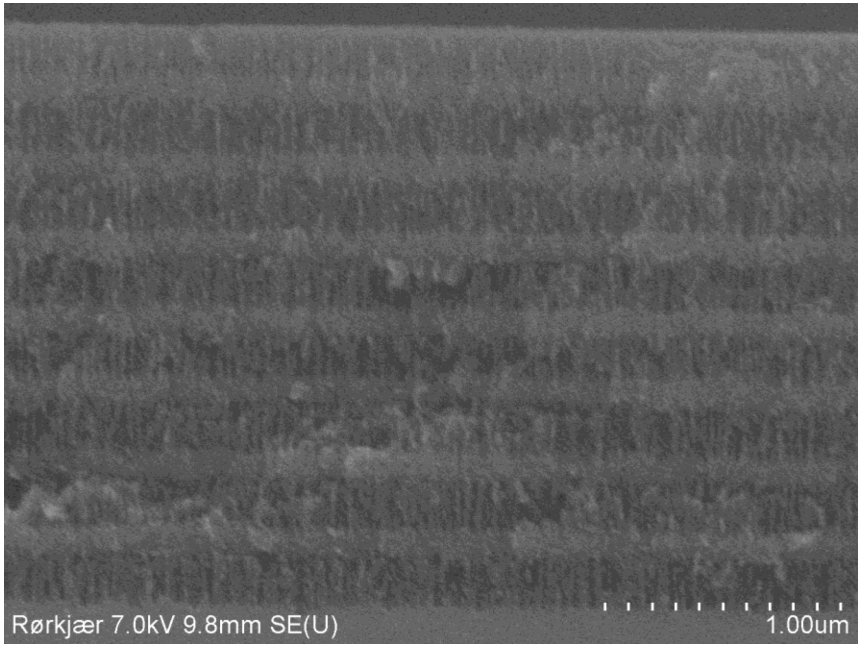
Solar cell with DBR rear reflector



Distributed Bragg reflectors (DBRs)

15-layer 40 % and 76 % porosity stack



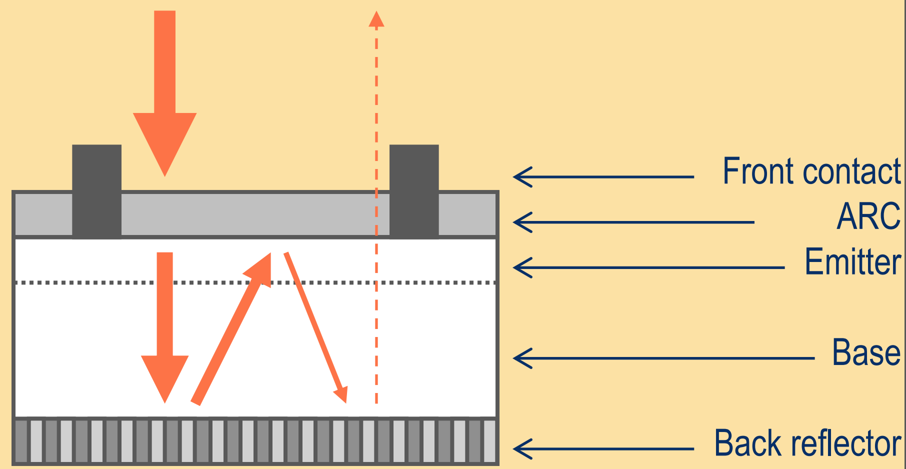


S. Rørkjær – M.Sc thesis (NTNU) 2010

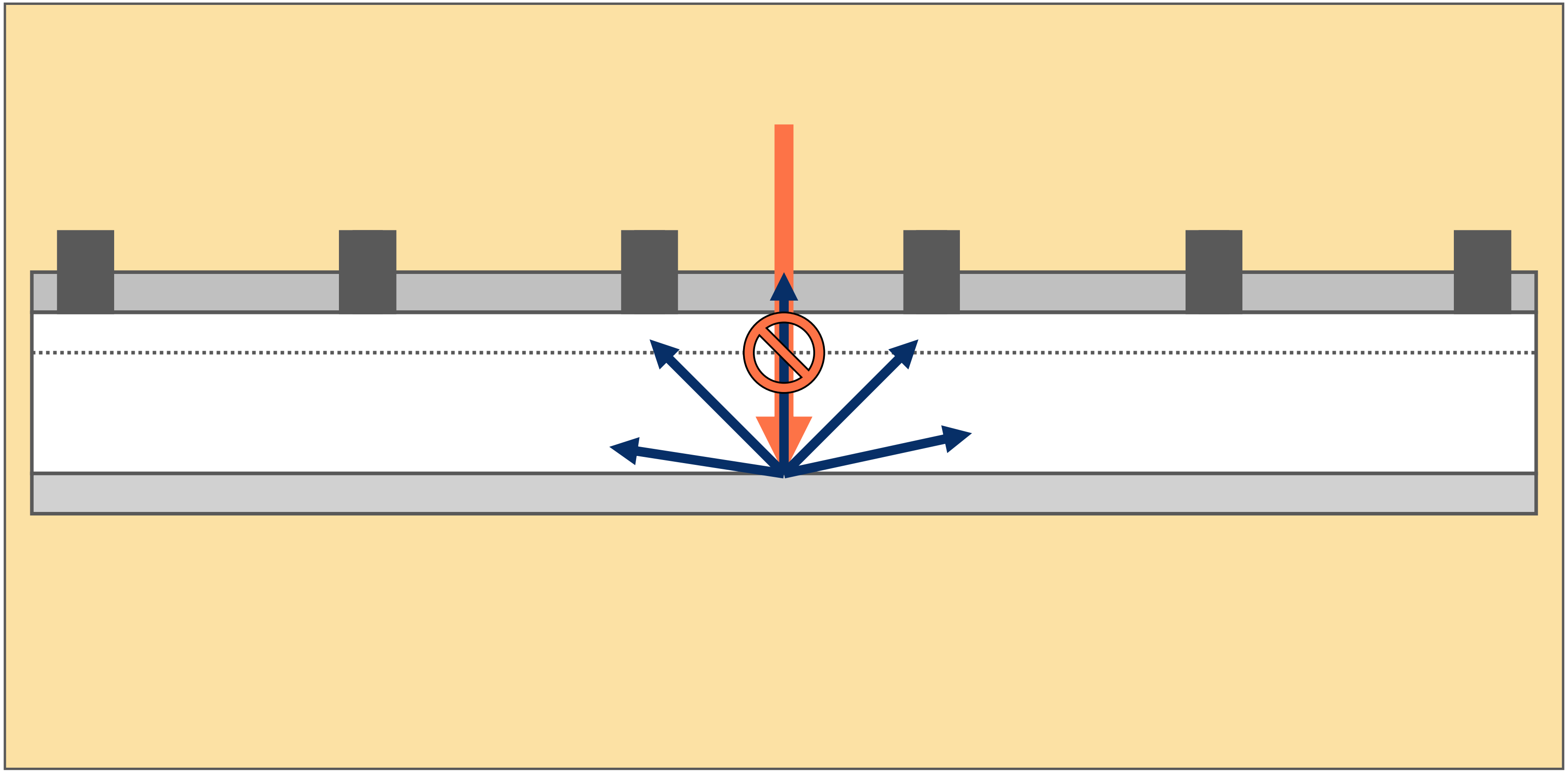
Photonic crystals

- Nanostructure: 1D, 2D and 3D periodic structures
- Realization: electrochemical etching, nanopatterning, colloidal crystals

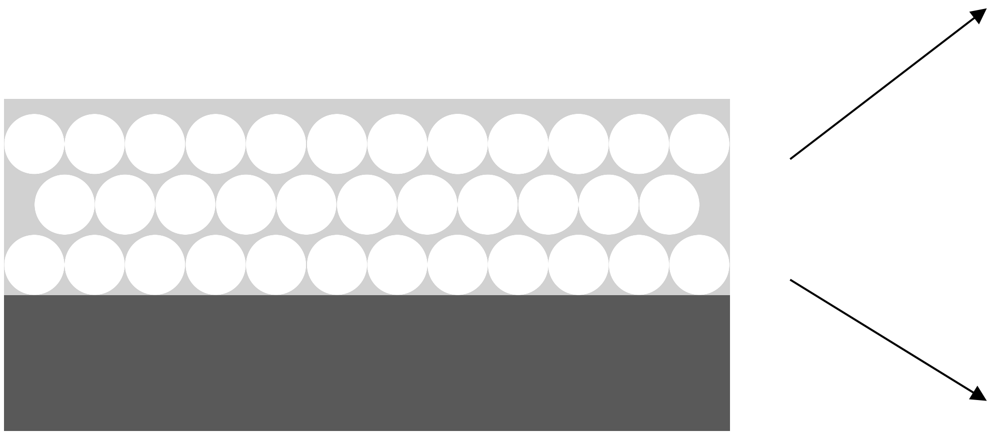
Solar cell with photonic crystal reflector

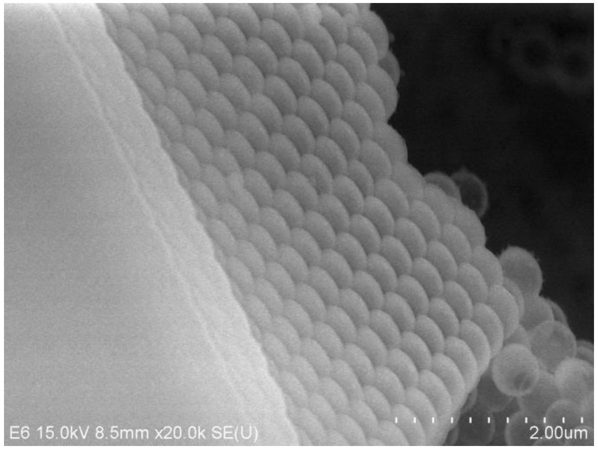


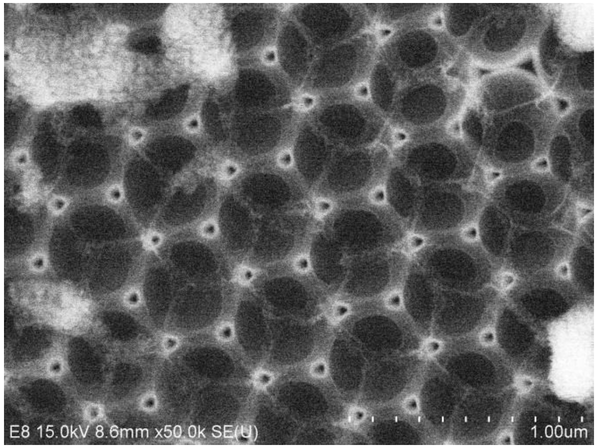
Photonic crystals



Self-ordered photonic crystals





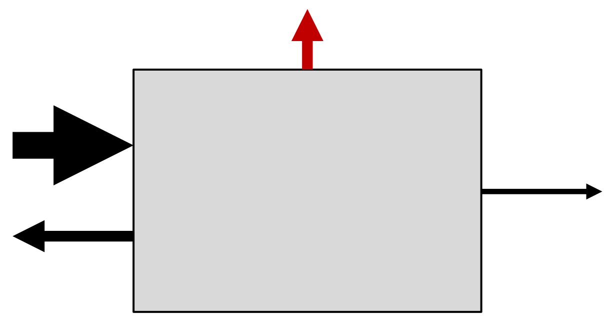


H. Granlund, Master thesis (NTNU) 2009

Photonic crystals

- On the cool side:
  - High, broadband reflection obtainable
  - Scattering
- Is it really relevant for a solar cell?
  - Manufacturability
  - Low cost, large-area, sub-micron structuring
- Work in progress!

Concentration

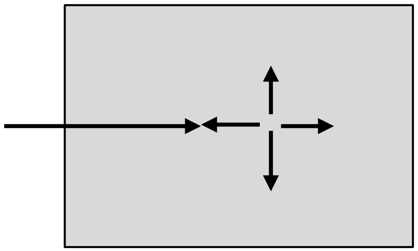


The effect of concentration

- Irradiance: $b_s(E)$
- Concentrated irradiance: $X \cdot b_s(E)$

- J_{sc} => $X \cdot J_0$
- V_{oc} => $\sim V_{oc}(1) + (kT/q) \cdot \ln X$

Photon recycling



PHOTON RECYCL.