3G rule for attending in person lectures at KIT:

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- ***geimpft* – vaccinated**
- ***genesen* – recovered**
- ***getestet* – tested**

Karlsruher Institut für Technologie

“Solar Energy” WS 2021/2022

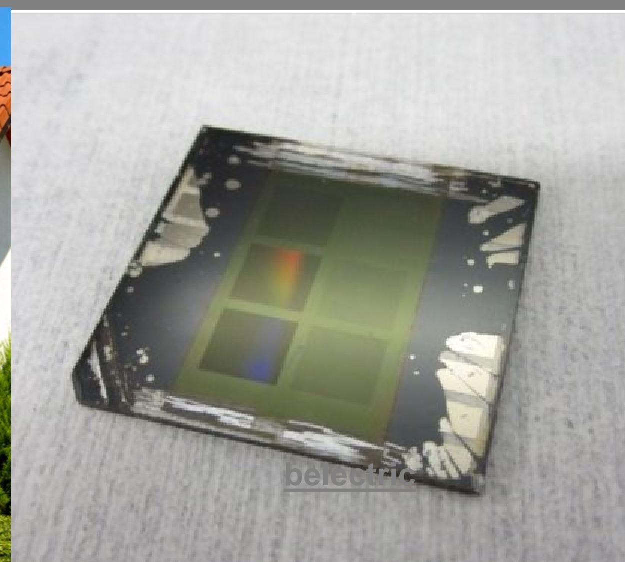
Lecture 15: Light management

Tenure-Track-Prof. Dr. Ulrich W. Paetzold

Institute of Microstructure Technology (IMT), Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen

Light Technology Institute (LTI), Engesserstrasse 13, Building 30.34, 76131 Karlsruhe

KIT Focus Optics & Photonics



Parts of the material used here have been kindly provided by Prof. T. Kirchartz, and Dr. D. Cheyns.

... nice picture! But …

... nice picture! But it should look like this!

OUTLINE

- **Light matters for PV**
  - **Light & solar cell operation principle**
  - Optics losses and their relation to the power conversion efficiency
- State-of-the-art light management in Si solar cells
  - Reducing light reflection
  - Light trapping
  - Avoiding shading and area losses
- Nanophotonic light management concepts
  - Nanophotonic light management in thin film Si solar cells
  - Nanophotonic light management in perovskite solar cells

What is light?

“In the beginning God created the heaven and the earth.
And the earth was without form, and void;
and darkness was upon the face of the deep.
And the Spirit of God moved upon the face of the waters.
And God said, Let there be light: and there was light.” Genesis, Chapter 1

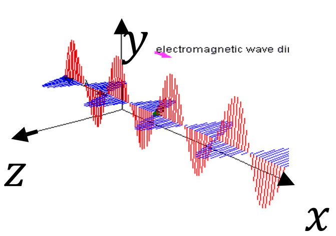
But what God ☺ really said was much more complex:

Light is a wave

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

$$\vec{\nabla} \cdot \vec{D} = \rho \qquad \vec{\nabla} \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{j}$$

Maxwell

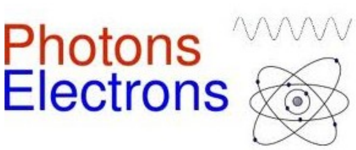


Wave properties:
EM radiation has a wave like behavior

... but light is a particle

$$\vec{E} = E_{max} \cos(kx - \omega t)\hat{j}$$

$$\vec{B} = \frac{E_{max}}{c} \cos(kx - \omega t)\hat{k}$$



Particle properties:
Light is emitted and absorbed as discrete packets of energy, i.e. quanta, called photons

Solar cell: Operating principle

- Solar cell as a diode:

Principles:

Light management

Jsc

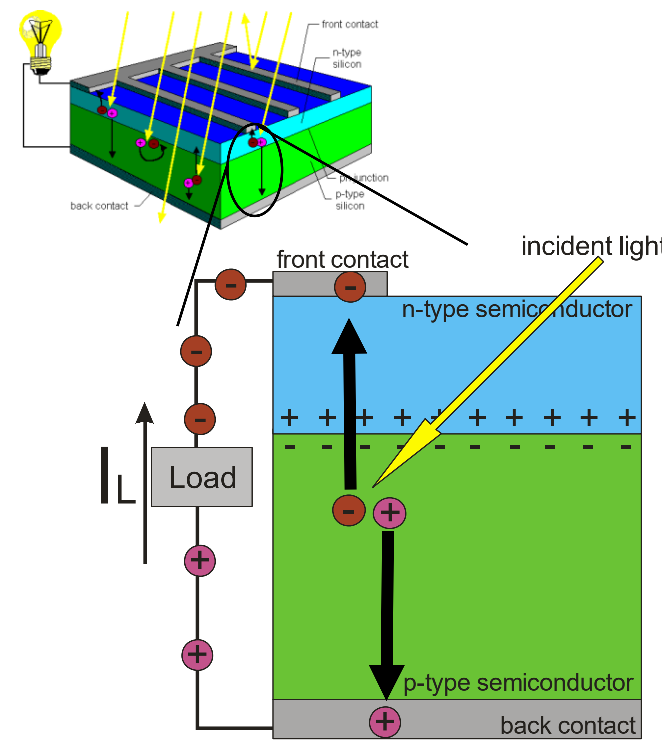
1. The active layer absorbs incident light
2. Charge carriers are created

Voc

FF

3. The p and n carriers are separated by the structural asymmetry (doping difference)
4. Collection of the separated carriers and the contacts

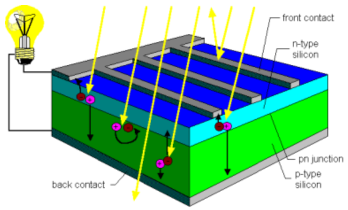
Electron management



Source: Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

Solar Cell Performance parameters

- J_{sc}, V_{oc} and FF

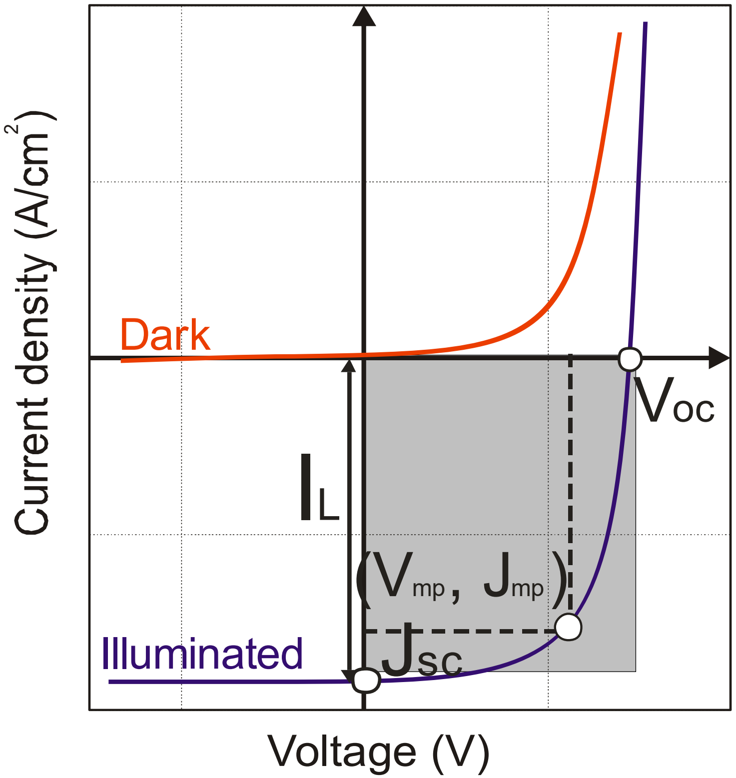


Fill factor

$$FF = \frac{V_{mp} \cdot J_{mp}}{V_{oc} \cdot J_{sc}}$$

Efficiency

$$\eta = \frac{V_{mp} \cdot J_{mp}}{P_{in}} = \frac{V_{oc} \cdot J_{sc} \cdot FF}{P_{in}}$$



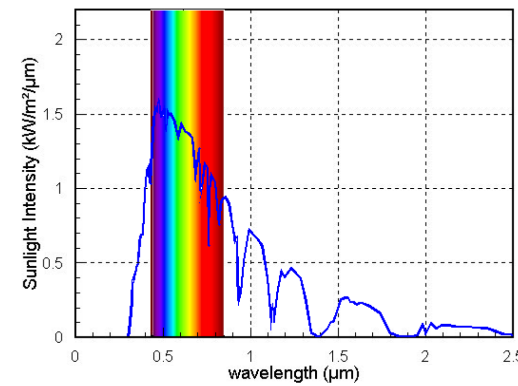
Source: Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

Solar Cell Performance parameters

Efficiency

$$\eta = \frac{J_{sc} \cdot V_{oc} \cdot FF}{P_{in}}$$

$$P = q \int_0^\infty \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda$$



Open circuit voltage

$$V_{oc} = \frac{k_B T}{q} \cdot \ln\left(\frac{J_{SC}}{J_0} + 1\right)$$

Fill factor

$$FF \approx \frac{qV_{OC}/k_B T - \ln(0.72 + qV_{OC}/k_B T)}{1 + qV_{OC}/k_B T}$$

Short circuit current density

$$J_{SC} = q \int_0^\infty EQE(\lambda)\, \Phi_{ph,\lambda} \mathrm{d}\lambda$$

$$J_{SC} = q \int_0^{E_G} A(\lambda)\, \Phi_{ph,\lambda} \mathrm{d}\lambda \times$$

optics of the solar cell

Which parameter relates most to optics ?

Relates directly to optics/light

Relates indirectly to optics/light

Solar Cell Performance parameters

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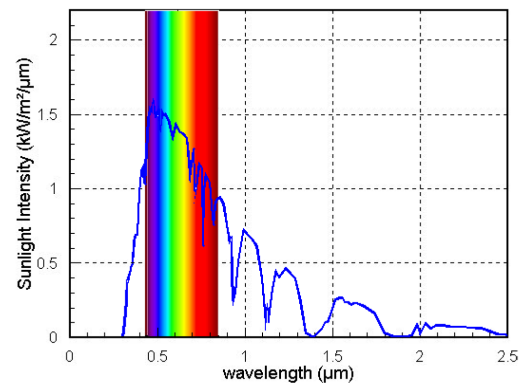
Efficiency

$$\eta = \frac{J_{sc} \cdot V_{oc} \cdot FF}{P_{in}}$$

Irradiated intensity

$$P_{in} = \int_0^{\infty} P(\lambda) d\lambda$$



Open circuit voltage

$$V_{oc} = \frac{k_B T}{q} \cdot \ln\left(\frac{J_{SC}}{J_0} + 1 \right)$$

Fill factor

$$FF \approx \frac{qV_{OC}/k_B T - \ln(0.72 + qV_{OC}/k_B T)}{1 + qV_{OC}/k_B T}$$

Short circuit current density

$$J_{SC} = -q \int_0^{\infty} EQE(\lambda)\, \Phi_{ph,\lambda} d\lambda$$

$$J_{SC} = -q \int_0^{E_G} \Phi_{ph,\lambda} d\lambda \times IQE_{opt} \times IQE_{el} \times (1 - R) \times \frac{A_f}{A_{tot}}$$

See also textbook p. 136.

Solar Cell Efficiency

If we discriminate the optical aspects in the device we get:

Photons

Charge carrier dynamics

$$\eta = \frac{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda}{\int_0^{\infty} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda} \times \frac{E_G \int_0^{E_G} \Phi_{ph,\lambda} \mathrm{d}\lambda}{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda} \times IQE_{el} \times (1 - R) \times \frac{A_f}{A_{tot}} \times IQE_{opt} \times \frac{eV_{OC}}{E_G} \times FF$$

Source: Textbook

OUTLINE

- **Light matters for PV**
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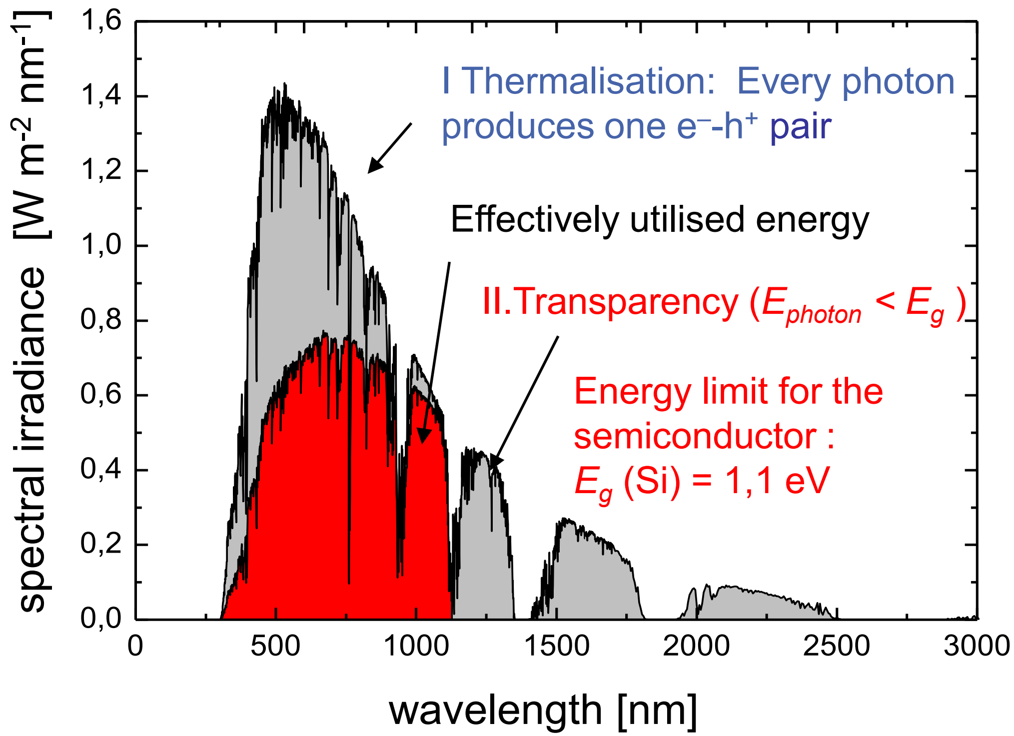
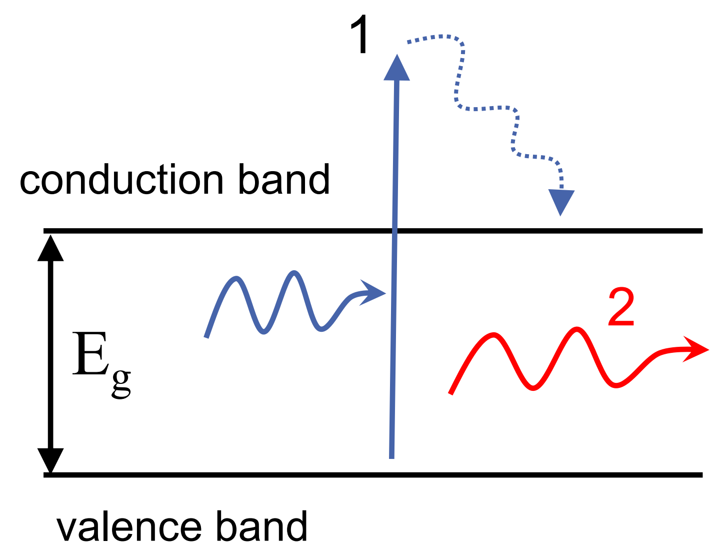
Solar Cell Efficiency



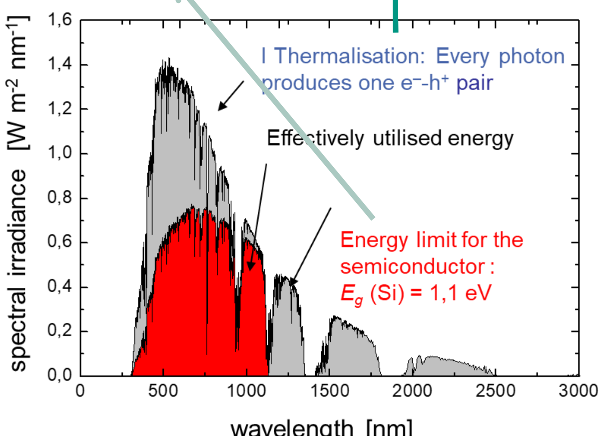


Solar Cell Efficiency

If we discriminate the optical aspects in the device we get:

Photons | Charge carrier dynamics

$$\eta = \frac{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} d\lambda}{\int_0^{\infty} \frac{hc}{\lambda} \Phi_{ph,\lambda} d\lambda} \times \frac{E_G \int_0^{E_G} \Phi_{ph,\lambda} d\lambda}{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} d\lambda} \times IQE_{el} \times (1-R) \times \frac{A_f}{A_{tot}} \times IQE_{opt} \times \frac{eV_{OC}}{E_G} \times FF$$



Termalization loss

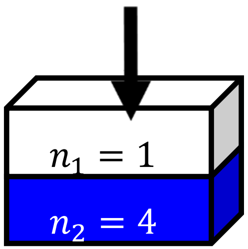
Sub band gap abs. loss

Reflectance at the surface

air/Si interface

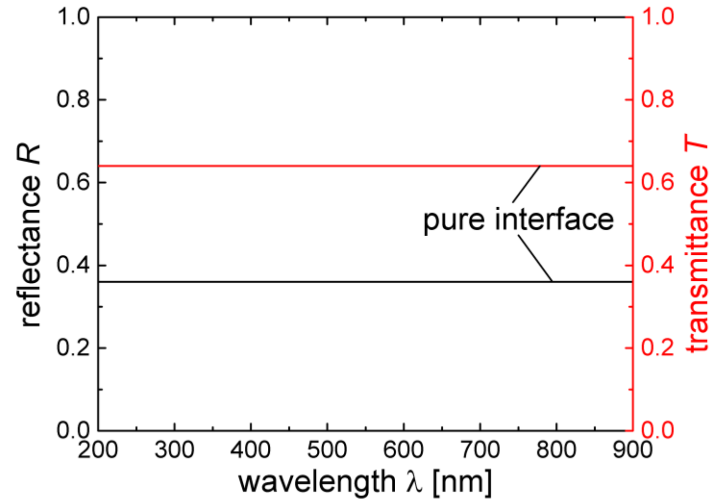
$n_{air} = 1$

$n_{Si} = 4$



$$R = \left(\frac{n_{top} - n_{bot}}{n_{top} + n_{bot}} \right)^2$$

$$T = \frac{4 n_{top} n_{bot}}{\left(n_{top} + n_{bot} \right)^2}$$



Strategies to overcome:

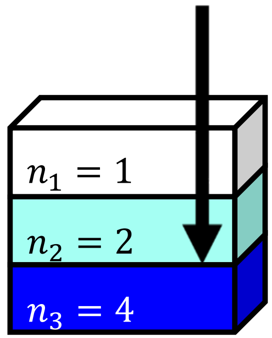
1. Anti reflection coatings
2. Microtextures which enforce multiple incidences on the surface
3. Nanotextures which induce a gradual matching of the refractive index.

Source: Slide adapted from Karsten Bittkau (Forschungszentrum Juelich)

Reflectance at the surface

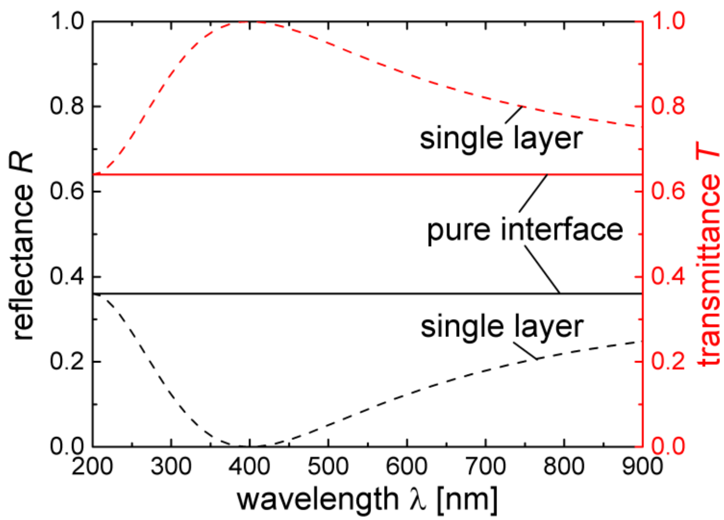
single layer ARC

$n_{air} = 1$, $n_{Si} = 4$
$n_{ARC} = 2$



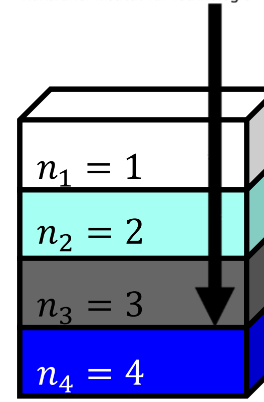
$$n_{ARC} = \sqrt{n_{top} \times n_{bot}}$$

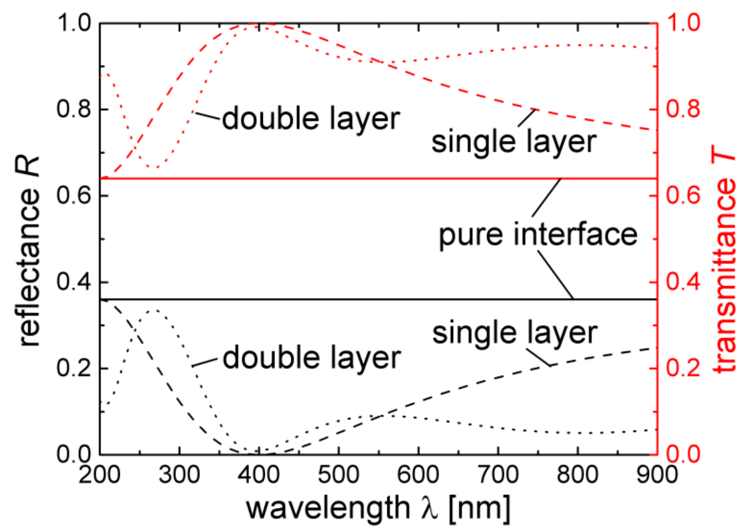
+ interference effects!



multi-layer ARC

- further improvement

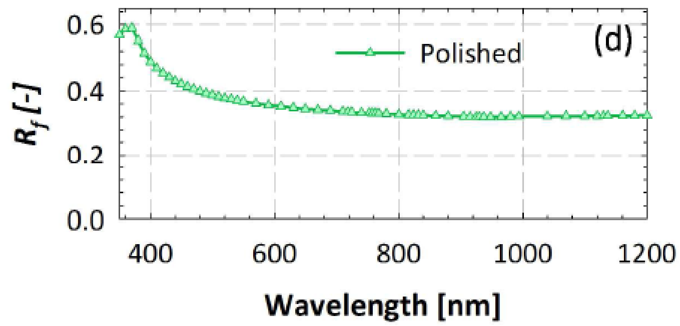




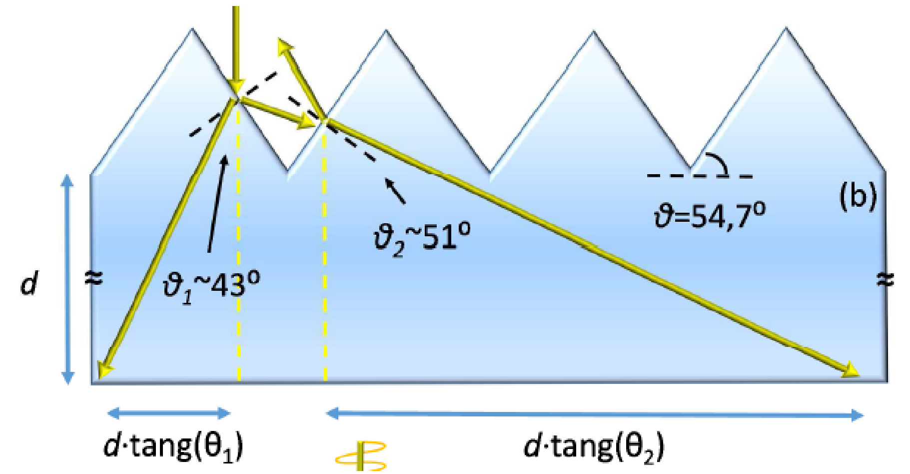
Source: Slide adapted from Karsten Bittkau (Forschungszentrum Juelich)

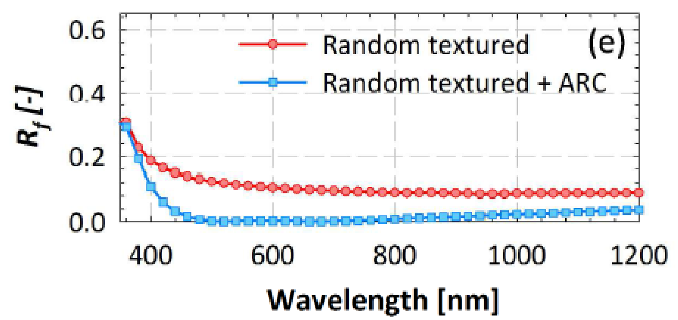
Reflectance at the surface

Textured interfaces reduce reflectance by multiple incidences



dimension of texture >> wavelength of light

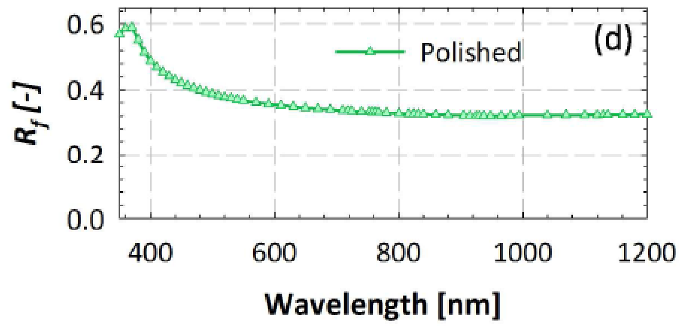




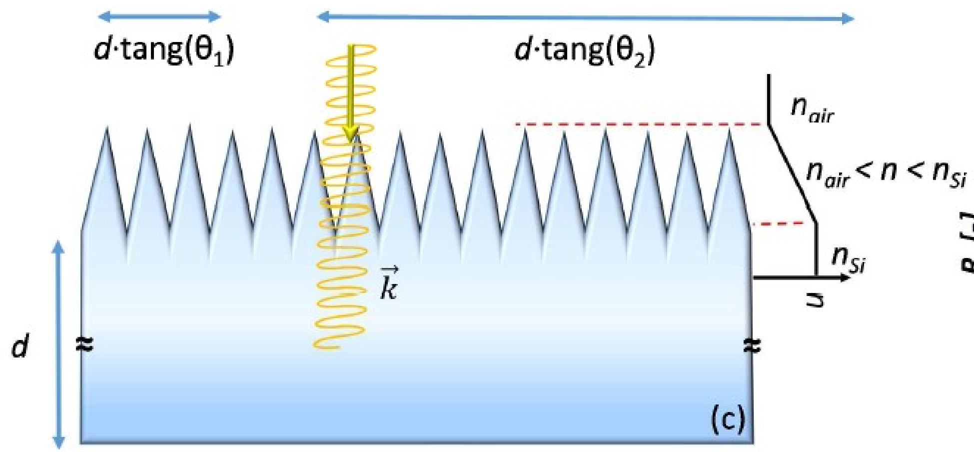
Source: Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

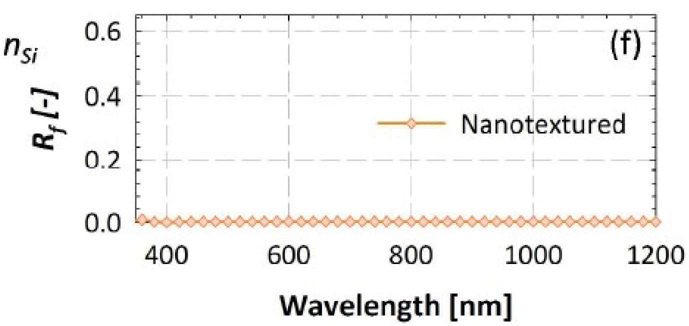
Reflectance at the surface

Nanoscale textures can reduce reflectance by “effective medium ARC”



dimension of texture << wavelength of light





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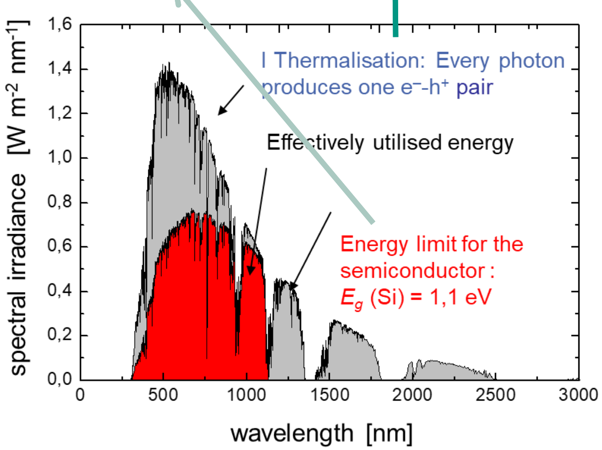
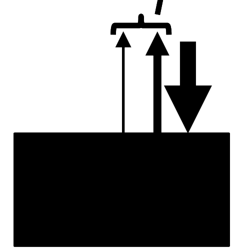
Solar Cell Efficiency

If we discriminate the optical aspects in the device we get:

Photons | **Charge carrier dynamics**

$$\eta = \frac{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda}{\int_0^{\infty} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda} \times \frac{E_G \int_0^{E_G} \Phi_{ph,\lambda} \mathrm{d}\lambda}{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda} \times IQE_{el} \times (1 - R) \times \frac{A_f}{A_{tot}} \times IQE_{opt} \times \frac{eV_{OC}}{E_G} \times FF$$





Termalization loss

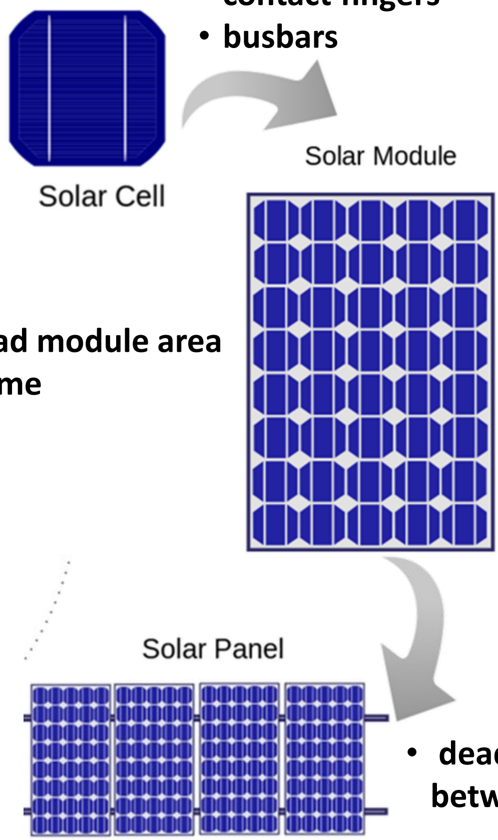
Sub band gap abs. loss

Reflection

Losses of active area

Silicon solar cell technology

- contact fingers
- busbars



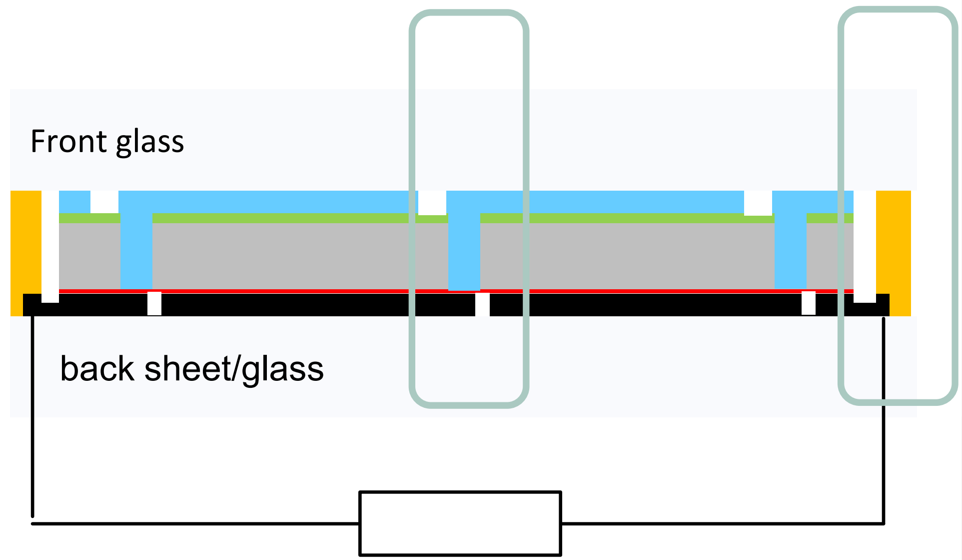
- dead module area
- frame

- dead area between modules

Thin-film solar cell technologies

Area loss interconnection

Area loss frame



Source: https://commons.wikimedia.org/w/index.php?curid=34961018

Solar Cell Efficiency

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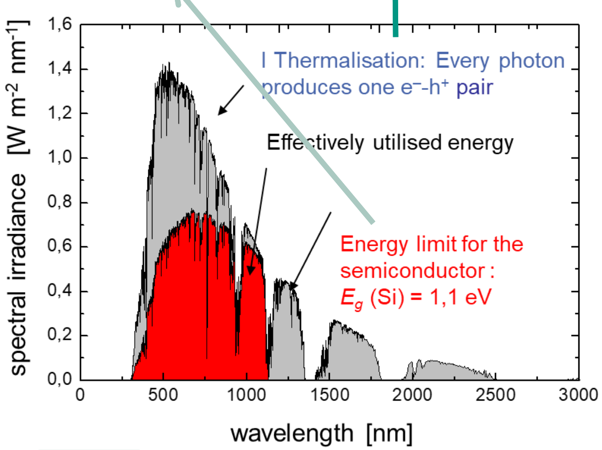
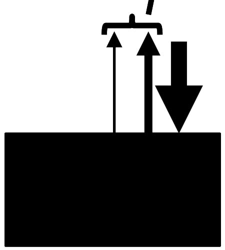




Termalization loss

Sub band gap abs. loss

Reflection

Area loss / shadowing

Imperfect light absorption

Lambert-Beer law

intensity in a medium:

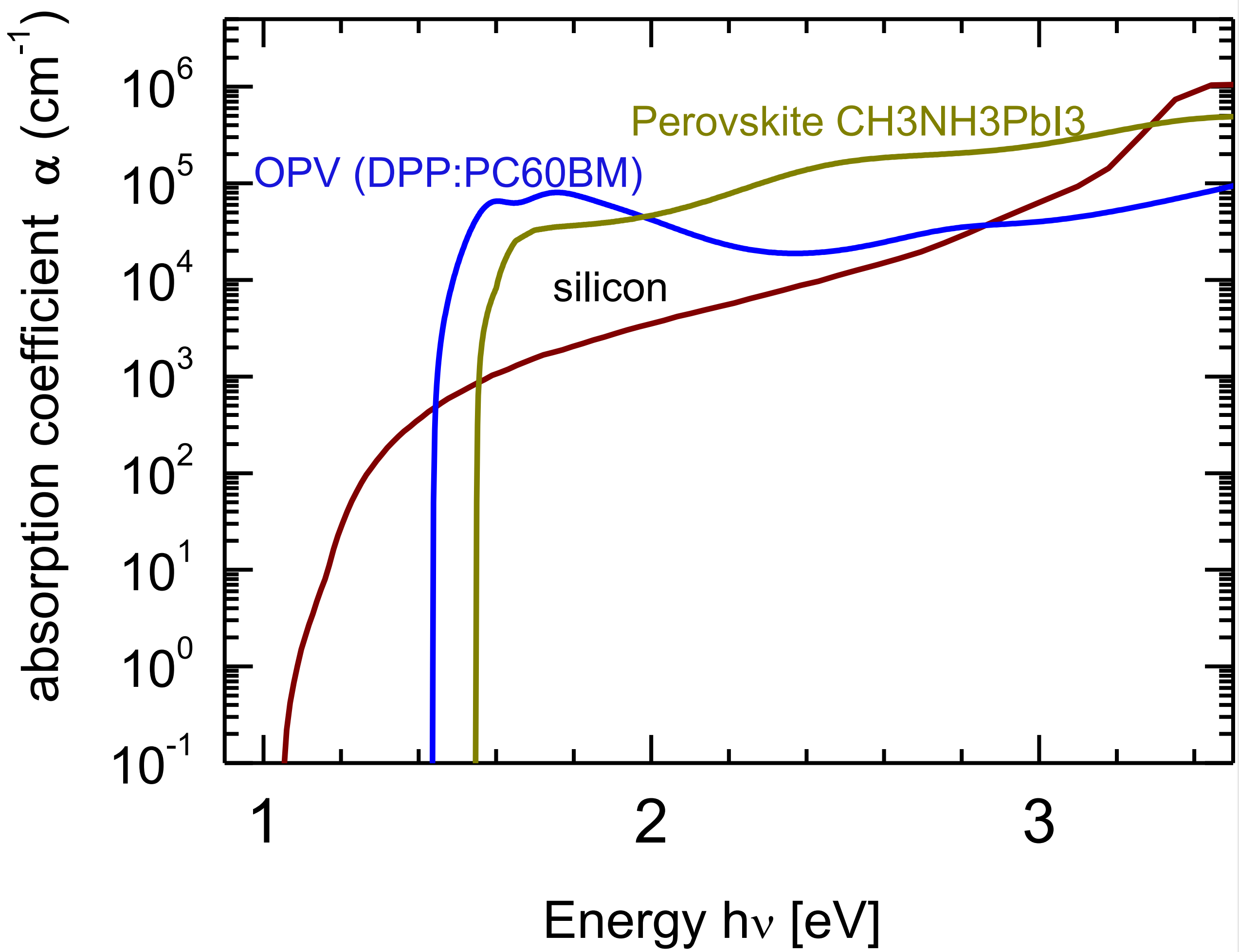
$$I(x) = I_0 e^{-\alpha x}$$

α : absorption coefficient

Absorption of a single pass

$$A(E) = 1 - e^{-\alpha(E) d}$$

d : thickness of the solar cell



Imperfect light absorption

Lambert-Beer law

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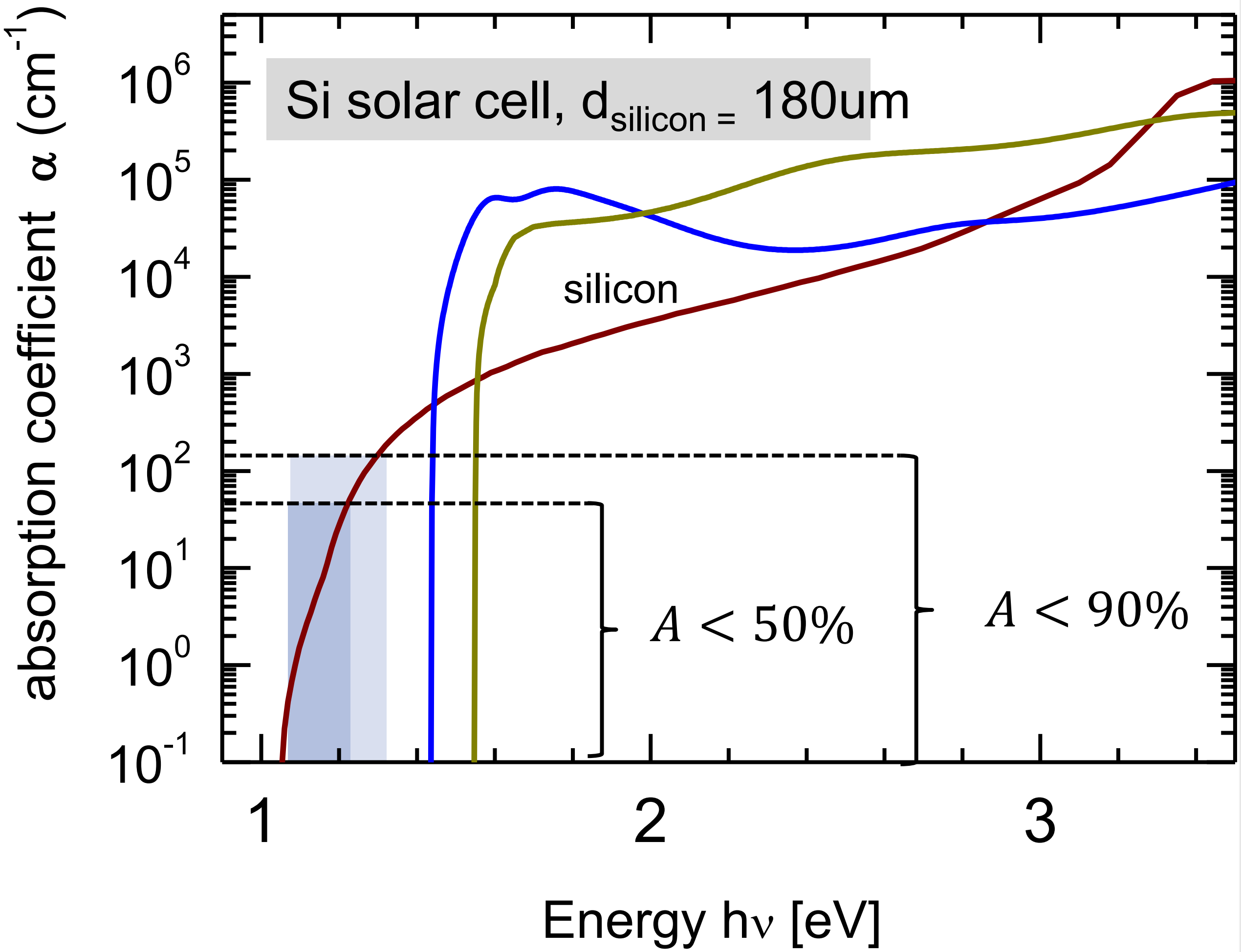

Imperfect light absorption

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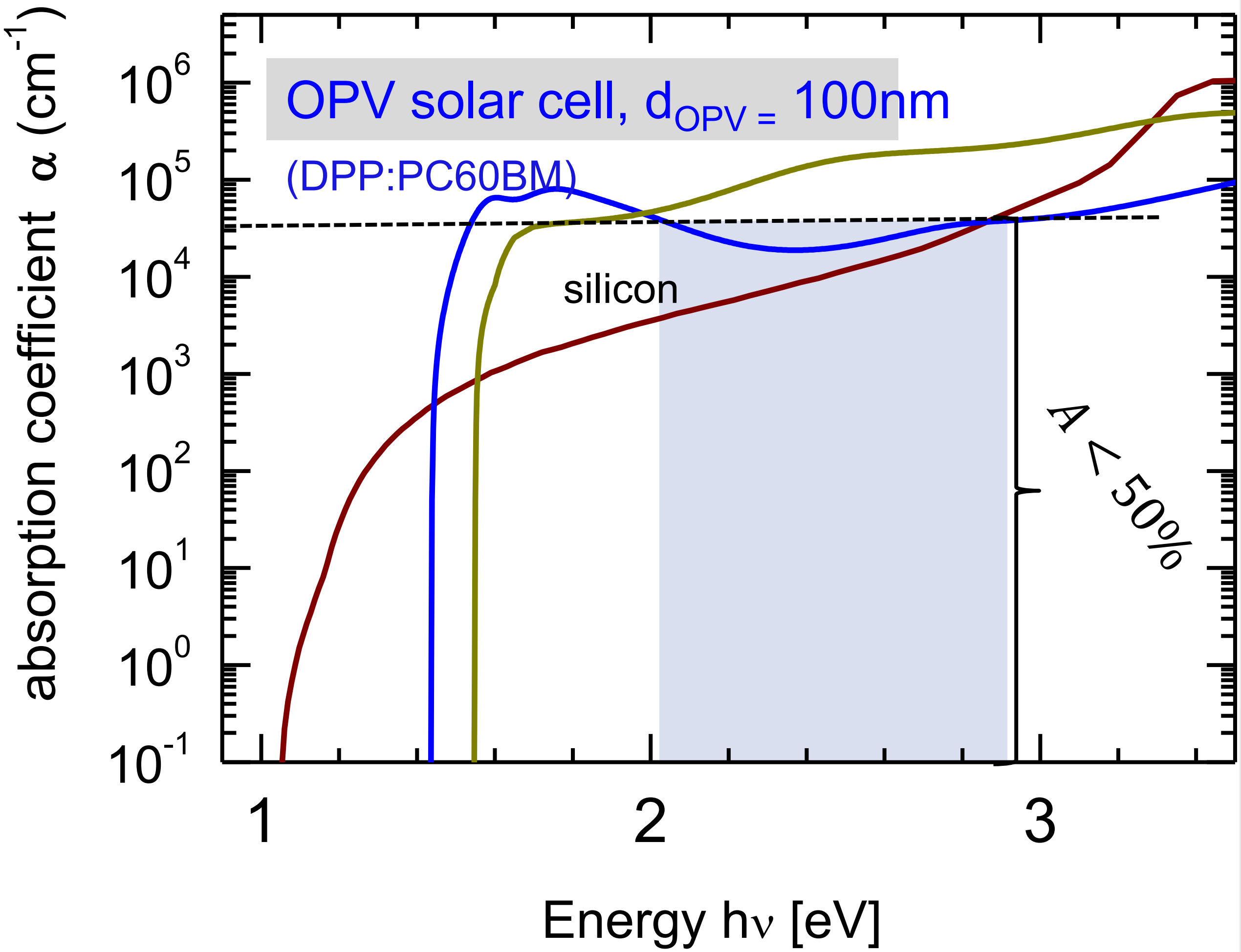

Imperfect light absorption

Karlsruher Institut für Technologie

Lambert-Beer law

<u>intensity in a medium:</u>

$$I(x) = I_0 e^{-\alpha x}$$

α : absorption coefficient

<u>Absorption of a single pass</u>

$$A(E) = 1 - e^{-\alpha(E) d}$$

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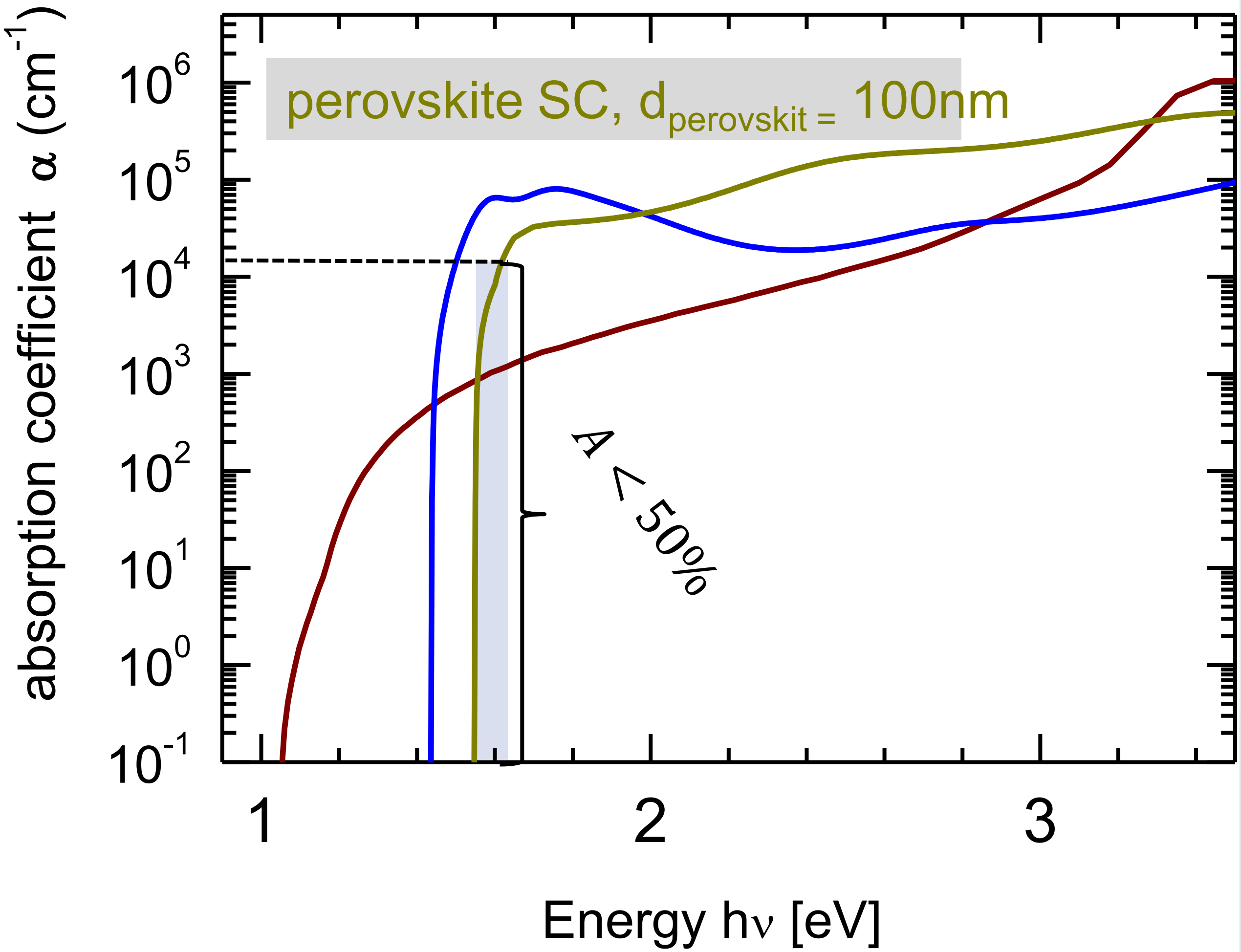
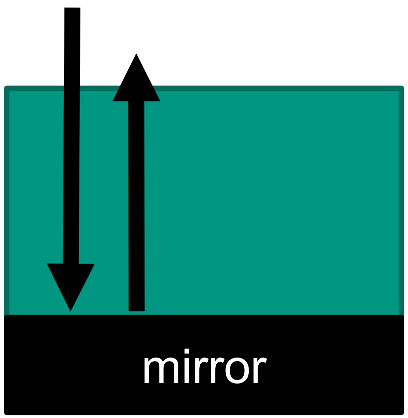


Imperfect light absorption

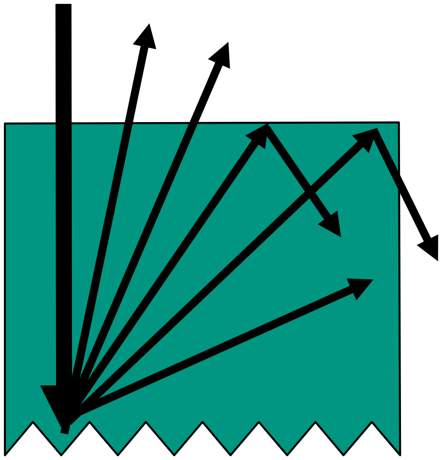
Strategies to improve light absorption are called “LIGHT TRAPPING”

1. Back Reflector



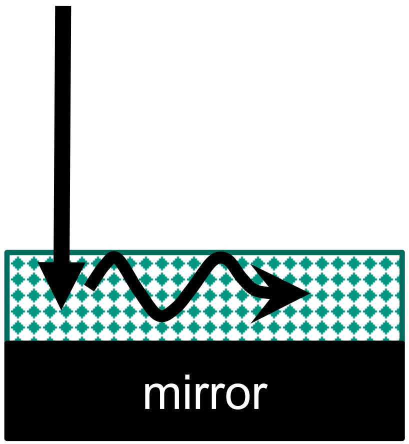
- double the light path

2. Light scattering



- increase light path by scattering angle
- total internal reflection for
  $\alpha_{sca} > \alpha_{critica}$, $\alpha_{critica} = \text{asin}(n1/n2)$

2. Light guiding



- Coupling to waveguide modes (requires thin absorbers)
- Coupling via diffraction or nanophotonics

Solar Cell Efficiency

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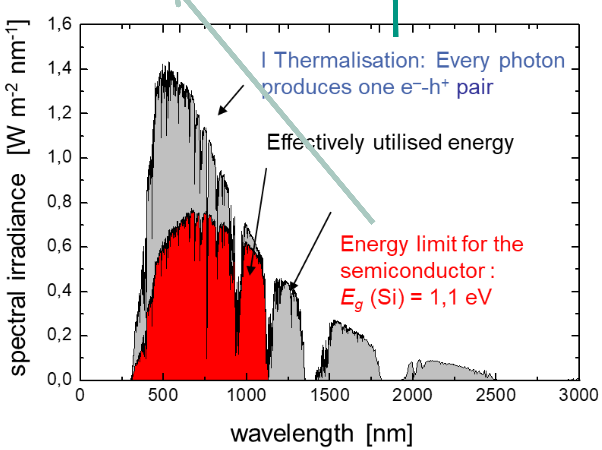
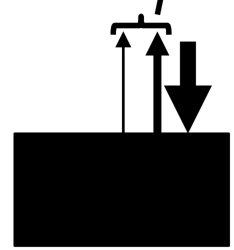
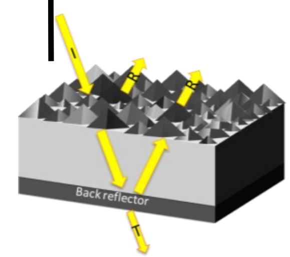
If we discriminate the optical aspects in the device we get:

Photons | **Charge carrier dynamics**

$$\eta = \frac{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda}{\int_0^{\infty} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda} \times \frac{E_G \int_0^{E_G} \Phi_{ph,\lambda} \mathrm{d}\lambda}{\int_0^{E_G} \frac{hc}{\lambda} \Phi_{ph,\lambda} \mathrm{d}\lambda} \times IQE_{el} \times (1-R) \times \frac{A_f}{A_{tot}} \times IQE_{opt} \times \frac{eV_{OC}}{E_G} \times FF$$







Termalization loss	Sub band gap abs. loss	Imperf. collection	Reflection	Area loss / shadowing	Imperfect abs	Voc loss	FF loss

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Solar Cell Efficiency

If we discriminate the optical aspects in the device we get:

Photons

Charge carrier dynamics

$$\eta = \frac{\int_0^{\lambda_g} P(\lambda)d\lambda}{\int_0^{\infty} P(\lambda)d\lambda} \times \frac{E_g \int_0^{\lambda_g} N(\lambda)d\lambda}{\int_0^{\lambda_g} P(\lambda)d\lambda} \times \eta_{col} \times (1-R) \times \left(\frac{S_{act}}{S_{tot}}\right) \times \eta_{\alpha} \times \frac{qV_{OC}}{E_g} \times FF$$

NOTE AGAIN! Light management influences the current generation but also the charge carrier dynamics!

Open circuit voltage

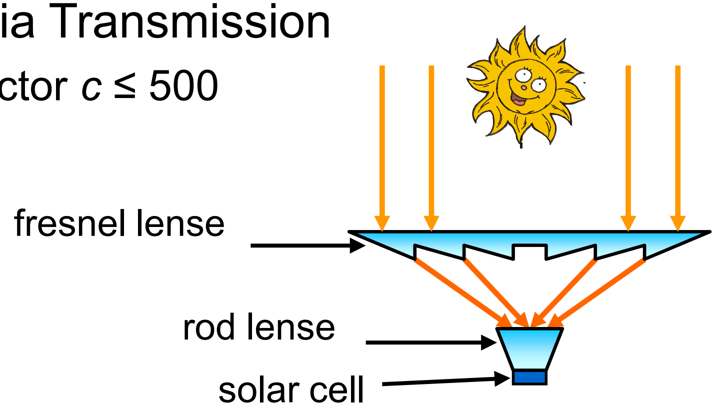
$$V_{oc} = \frac{k_B T}{q} \cdot \ln\left(\frac{J_{SC}}{J_0} + 1\right)$$

Concentration Photovoltaics

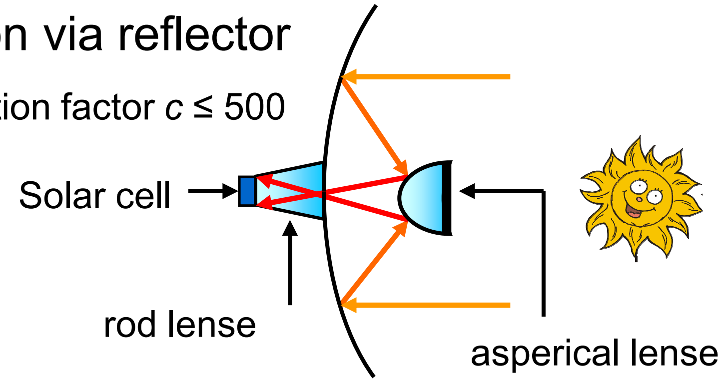
Example for impact of light management on Voc!

- Concentration via Transmission

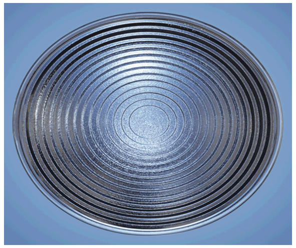
  concentraction factor $c \leq 500$



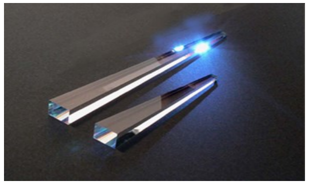
- Concentration via reflector
  - concentraction factor $c \leq 500$



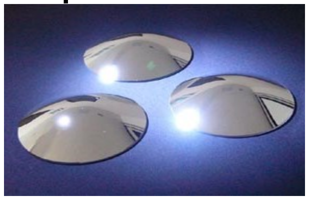
Fresnel lense



Rod lense



asperical lense



Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

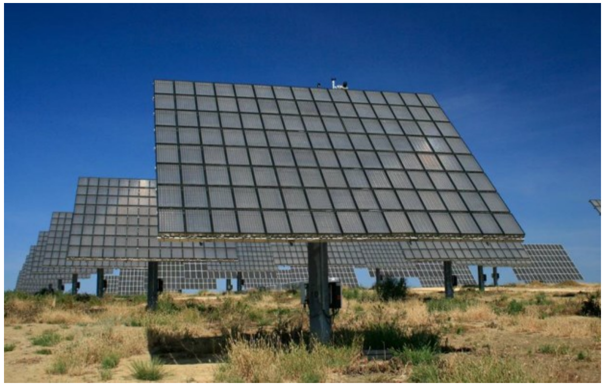
Concentration Photovoltaics

Example for impact of light management on Voc!

- Concentration via transmission

SolFocus Inc.

- Concentration via reflector



Concentrix Solar GmbH

Slide adapted from Prof. Uwe Rau (Forschungszentrum Juelich)

Concentration Photovoltaics

Example for impact of light management on Voc!

Concentration factor c: Multiple of the incident intensity of the sun (p_{sun} = 1000W/m²)

=> $j_{SC}^{c} = c\, j_{SC}^{0}$ concentrated *short circuit current density increases with c*

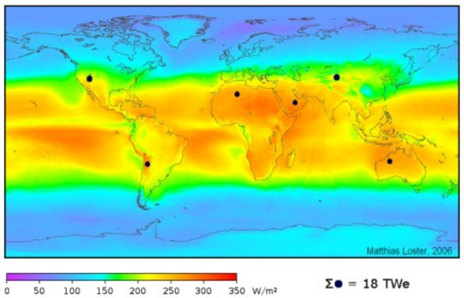
=> $$V_{OC}^{c} \approx \frac{n_{id} kT}{q} \ln\left(\frac{c\, j_{SC}^{0}}{j_0}\right) = V_{OC}^{0} + \frac{n_{id} kT}{q} \ln c = V_{OC}^{0} + \Delta V_{OC}$$

concentrated Voc increases.

=> $$\eta^{c} = \frac{p_{max}}{p_{in}^{c}} = \frac{j_{SC}^{c} V_{OC}^{c} FF^{c}}{p_{in}^{c}} = \frac{c\, j_{SC}^{0} V_{OC}^{c} FF^{c}}{c\, p_{in}^{0}} = \frac{j_{SC}^{0} V_{OC}^{c} FF^{c}}{p_{in}^{0}}$$

increase in efficiency only due to increase in Voc (increase in Jsc cancels out).

Slide adapted from Prof. Uwe Rau (Forschungszentrum Juelich)



Human mankind consume 18TW per year (2013), for solar cells with 8% efficiency this is the consumed area!

Karlsruher Institut für Technologie

EVALUATION BREAK

The evaluation of the lecture will be performed online. An invitation with the link will follow per mail. *Please contribute and help us to improve the lecture!*

- Solar Energy

(https://onlineumfrage.kit.edu/evasys/public/online/index/index?online_php=&p=EUEFM&_ga_8KKDCKF6WY=GS1.1.1610446757.1.1.1610446816.0&_ga=GA1.1.764319627.1610446757&rl_anonymous_id=%22b8160e93-4991-4352-a149-8486066f2bcf%22&rl_user_id=%22wfkrfy45wb86dgzd5ozcgbn31o%22&rl_trait=%7B%7D&ONLINEID=980905406939747108594626568855563770472 70)

Source: https://www.ez2c.de/ml/solar_land_area/

OUTLINE

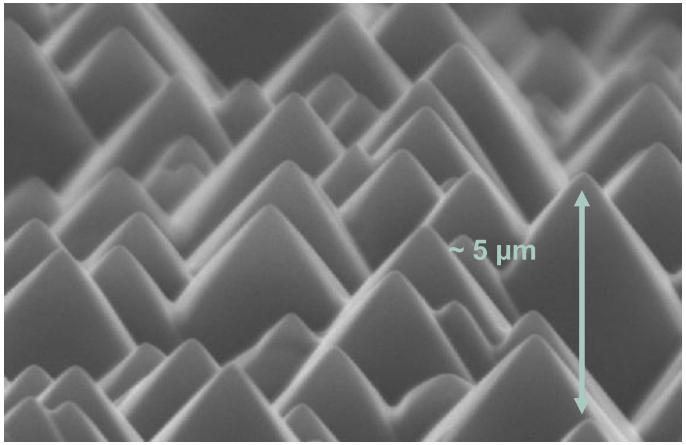
Karlsruher Institut für Technologie

- Light matters for PV
  - Light & solar cell operation principle
  - Optics losses and their relation to the power conversion efficiency
- **State-of-the-art light management in Si solar cells**
  - Reducing light reflection
  - Light trapping
  - Avoiding shading and area losses
- Nanophotonic light management concepts
  - Nanophotonic light management in thin film Si solar cells
  - Nanophotonic light management in perovskite solar cells

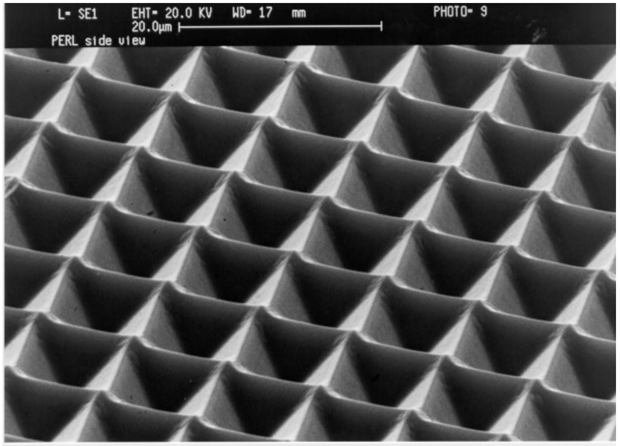
Reducing light reflection

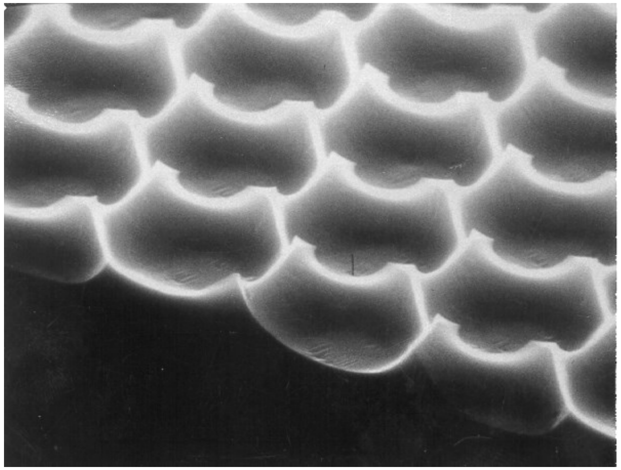
Random pyramid texturing by alkaline etching

Etching of Si in KOH or NaOH:
Etch rate depends on crystallographic planes
→ formation of pyramids



Improved periodic pyramides w. lithography





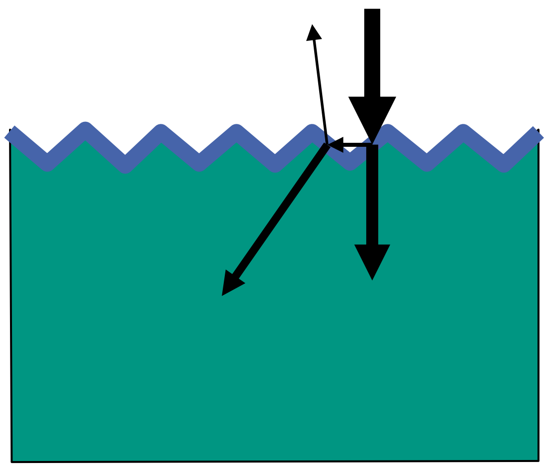
Sourcehttp://www.pveducation.org/

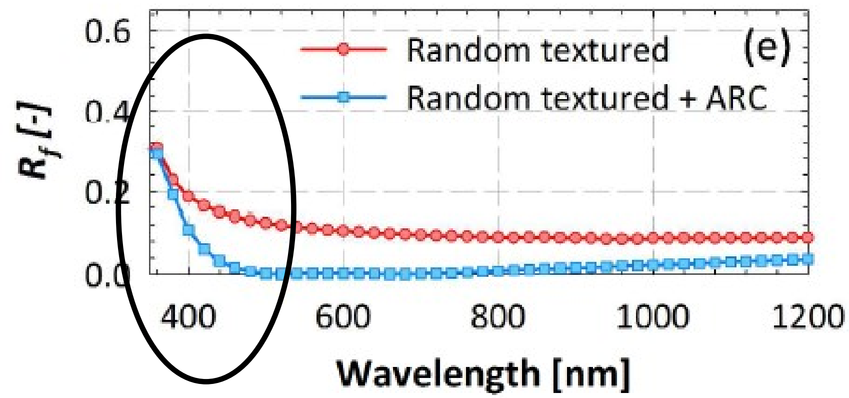
Reducing light reflection

Additionally, ARCs are deposited on top of the etched pyramids.

$n_{top(glass)} = 1.4$
$n_{Si} = 3.5$

Optimal RI for an ARC: $n_{ARC}(\lambda) = \sqrt{n_{Si}(\lambda) n_{top}(\lambda)} = 2.2$





Blue !

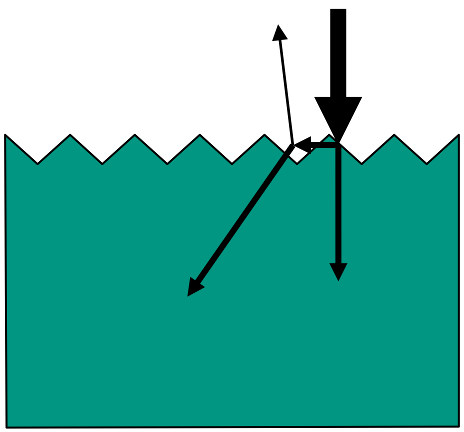
<u>Commonly used (for mono Si)</u>:

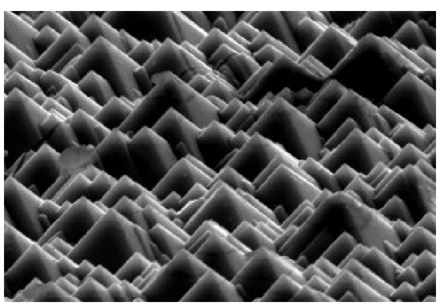
Pyramid texturing
80nm SiN ARC
[R(600nm) ~ 0]

Light trapping

The textured front surface of So solar cells also scatter incident light

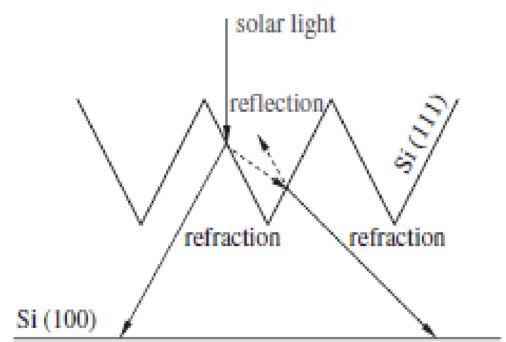
-> increase optical path





Textured surface:

- *Multiple reflections*: more impacts, more harvested photons
- *Refraction*: Longer path of the photons in the absorbing medium



T. Yagi et al. / Solar Energy Materials & Solar Cells 90 (2006) 2647–2656

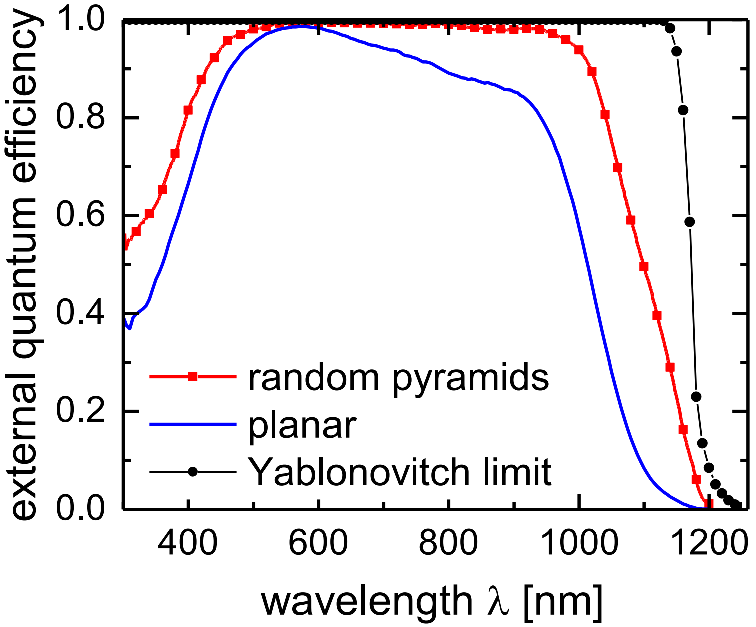
Light management in Si solar cell

For an exemplary state-of-the-art Si solar cell

Jsc increase significantly:

36mA/cm2 -> 42mA/cm2

(planar) (pyramids)



There is a limit – the Yablonovitch limit ?

Is says: "... The maximum light path enhancement factor is **$4 n^2 d$."**

=> $A = 1 - \exp(-\alpha < w >) \approx \alpha < w >= 4n^2 \alpha d$

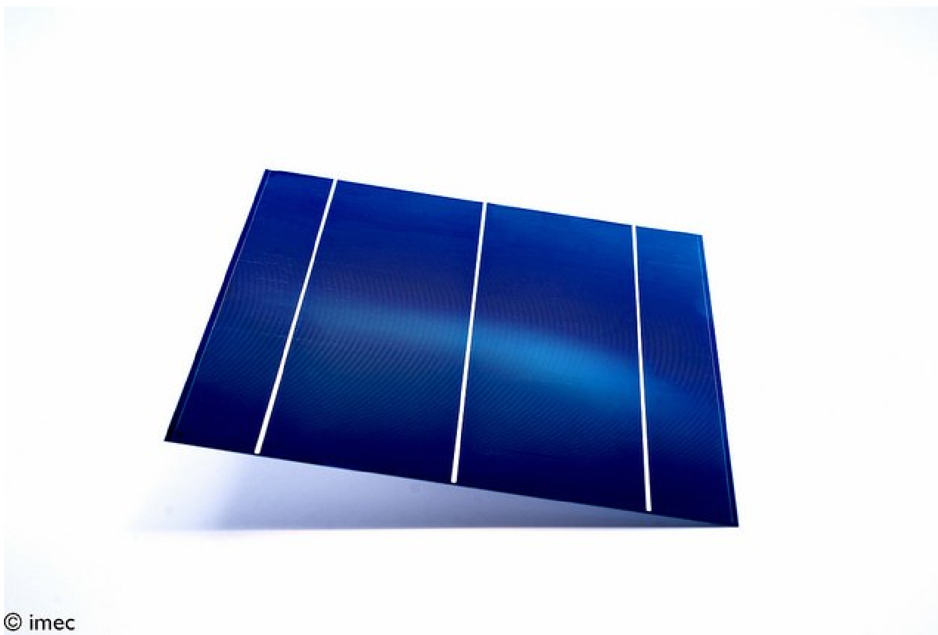
Avoiding shading and area losses

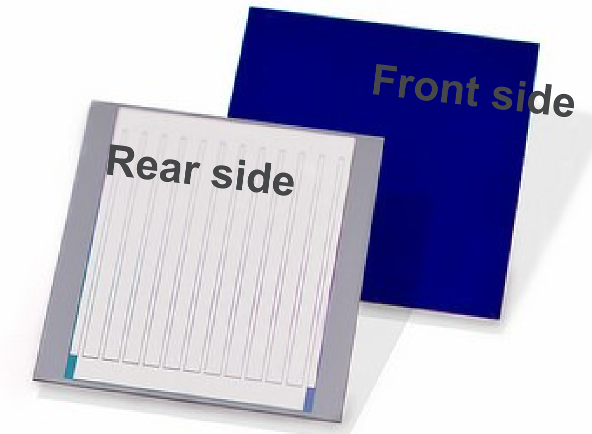
Shading losses - the challenge of designing metal contacts

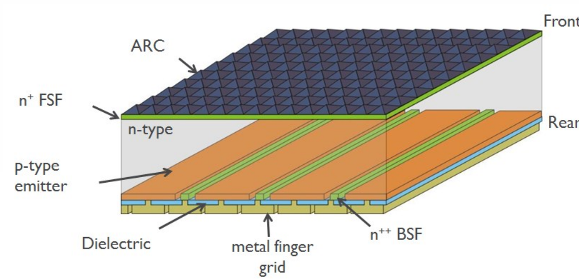
Minimise metallised areas...
but without losing from series resistance

→

All contacts on rear-side
but process becomes very complex



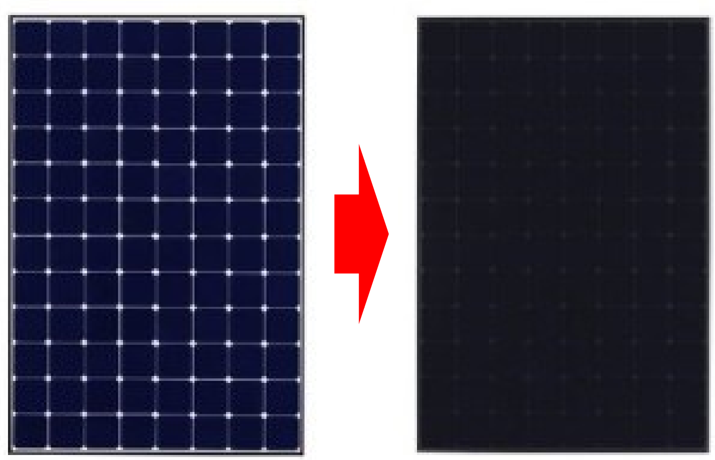




Avoiding shading and area losses

Advancing module design

- *Using interdigitated back contact solar cells we obtain black modules*
- *Record power conversion efficiency of such a SI solar 23.8% (Panasonic)*



This is already close to our goal:

OUTLINE

- Light matters for PV
  - Light & solar cell operation principle
  - Optics losses and their relation to the power conversion efficiency
- State-of-the-art light management in Si solar cells
  - Reducing light reflection
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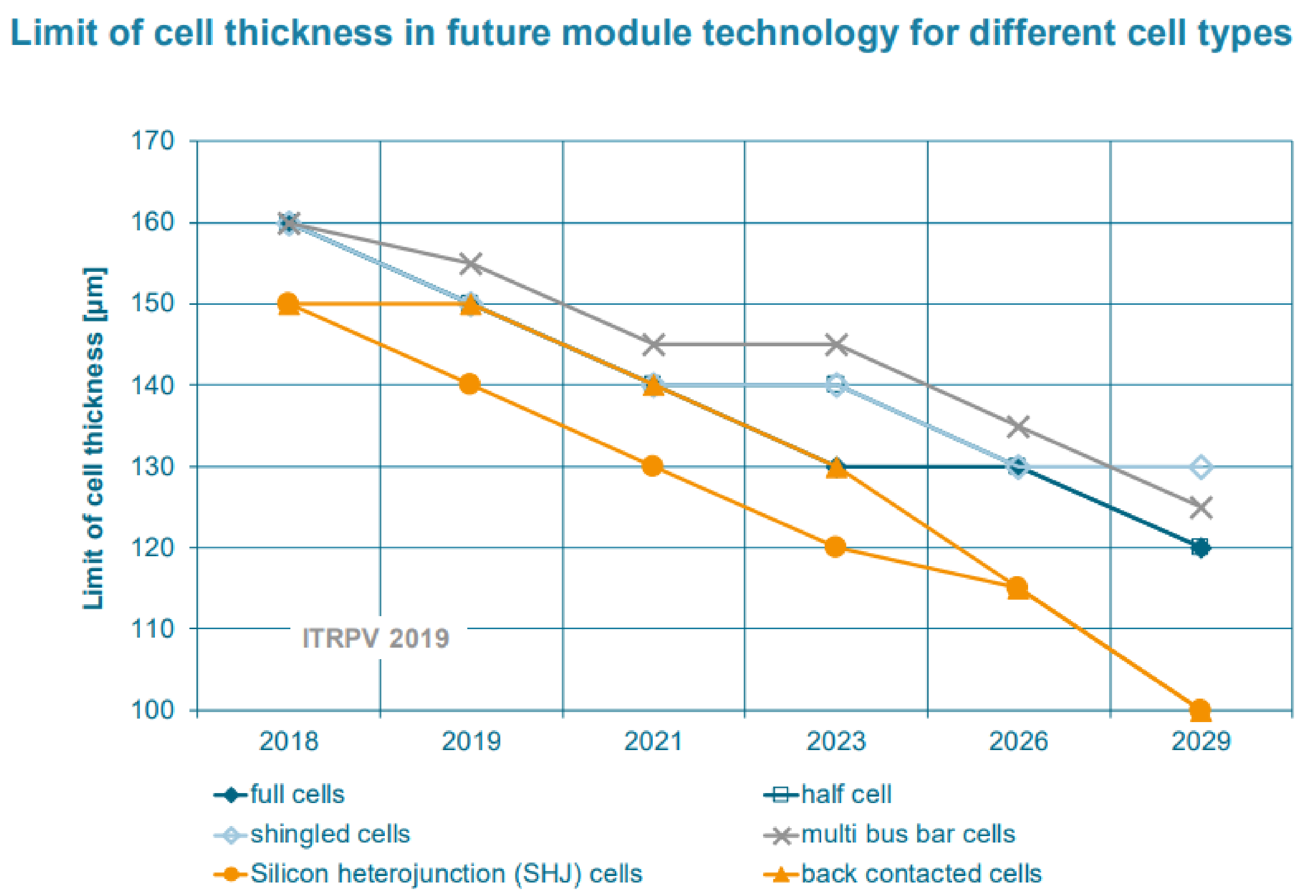
  - Avoiding shading and area losses
- **Nanophotonic light management concepts**
  - Nanophotonic light management in thin film Si solar cells
  - Nanophotonic light management in perovskite solar cells

Towards thin Si

- Crystalline silicon wafers (c-Si) are an expensive component of the Si solar cell
- Trend of going towards thinner Si wafers (ITRPV)



Source: ITRPV 2018.

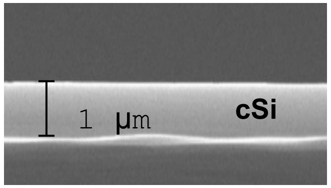
But Si is a poor absorber

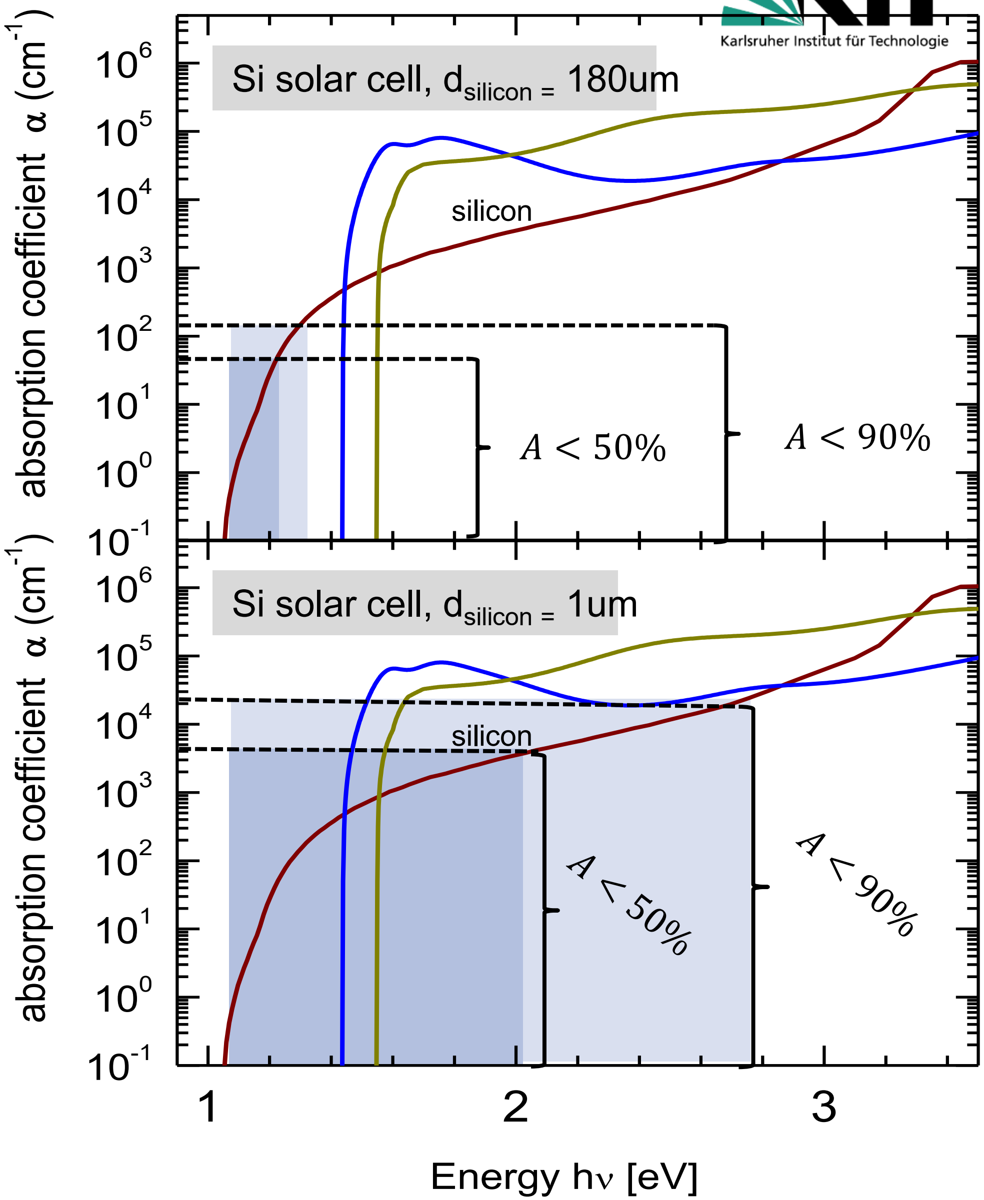
In order to reduce costs one would like to go for thin Si films < 50um

- **<u>Let us look in the future:</u>**

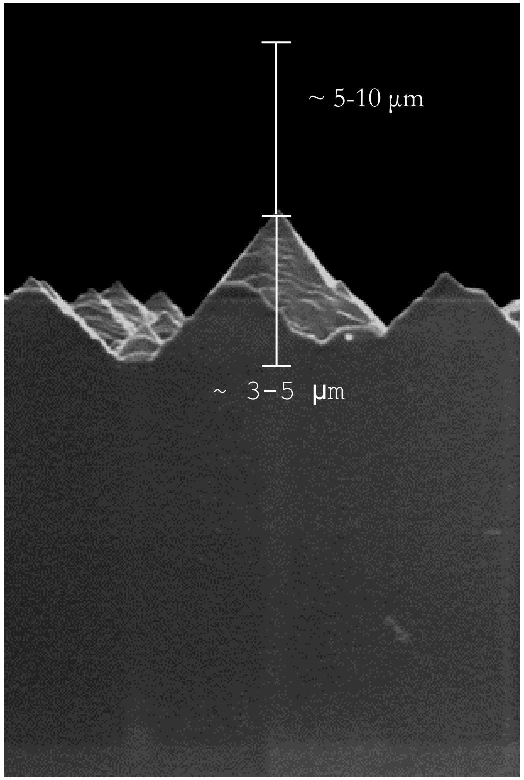
Epifoil (~ 40µm)

Epifree (~ 1µm)





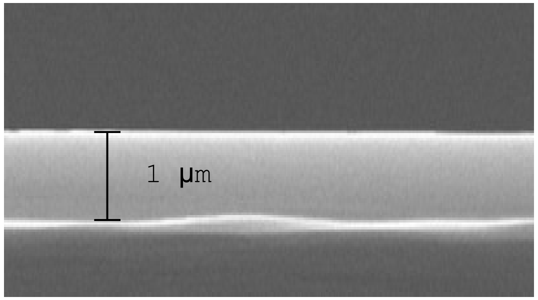
Conventional light management is not compatible with thin Si



Random pyramid texturing

Advanced light trapping for ultra-thin film technologies is needed!

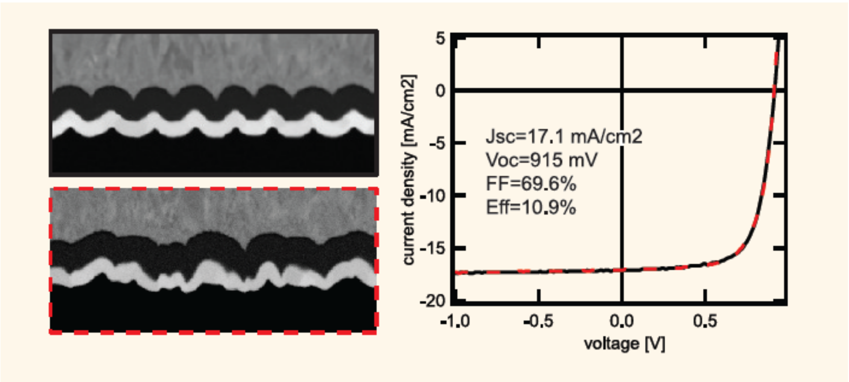
-> NEED TO GO NANO



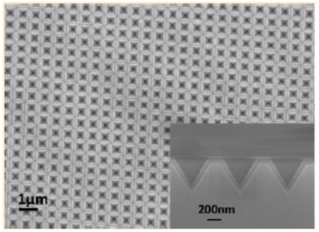
Ultra-thin c-Si films

Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

Heavy recent research activities on nanoscale light management



Corsin Battaglia et al., *ACS Nano*, 2012, 6 (3), pp. 2790–2797



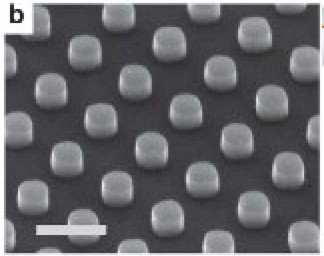
NANO LETTERS

Letter

pubs.acs.org/NanoLett

Efficient Light Trapping in Inverted Nanopyramid Thin Crystalline Silicon Membranes for Solar Cell Applications

Anastassios Mavrokefalos, Sang Eon Han, Selcuk Yerci, Matthew S. Branham, and Gang Chen*

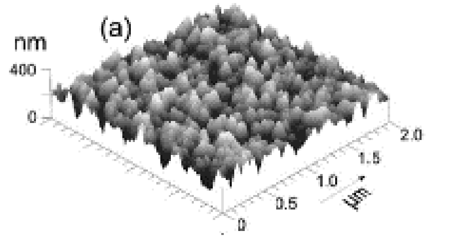


nature COMMUNICATIONS

OPEN

ARTICLE

Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators

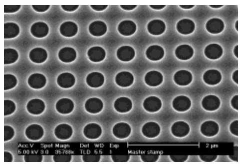


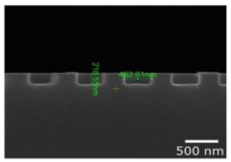
Black nonreflecting silicon surfaces for solar cells

Svetoslav Koynov,[a)] Martin S. Brandt, and Martin Stutzmann
Walter Schottky Institut, Technische Universität München, 85748 Garching, Germany

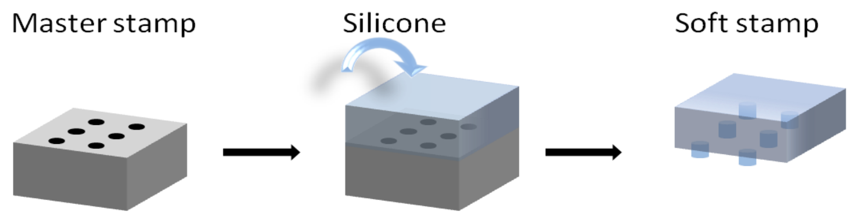
Fabrication of NanoTextures

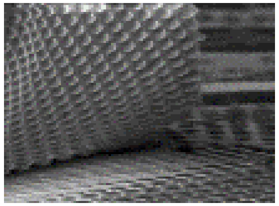
Nanoimprint lithography (NIL)



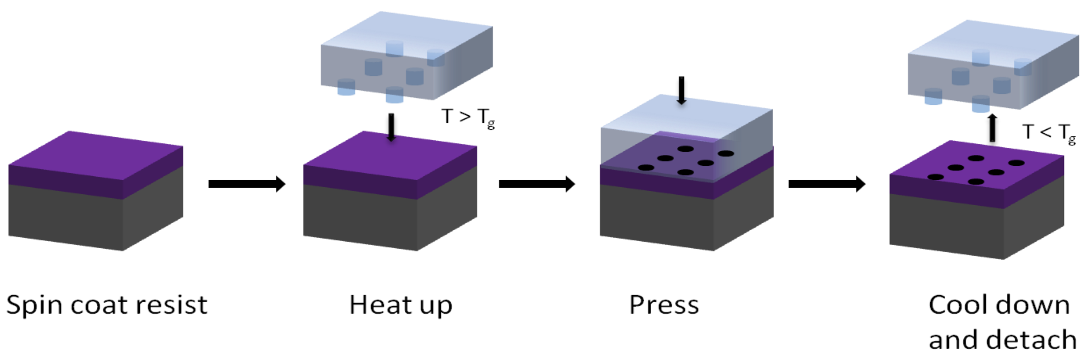


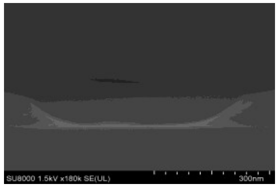
1. Soft stamp fabrication



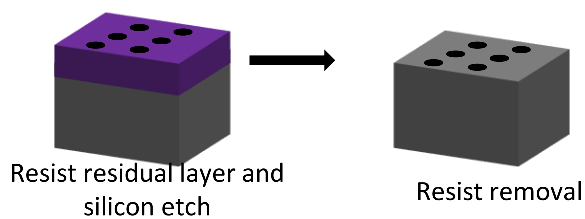


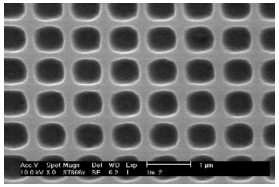
2. Nanoimprint





3. Pattern transfer





Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

Fabrication of NanoTextures

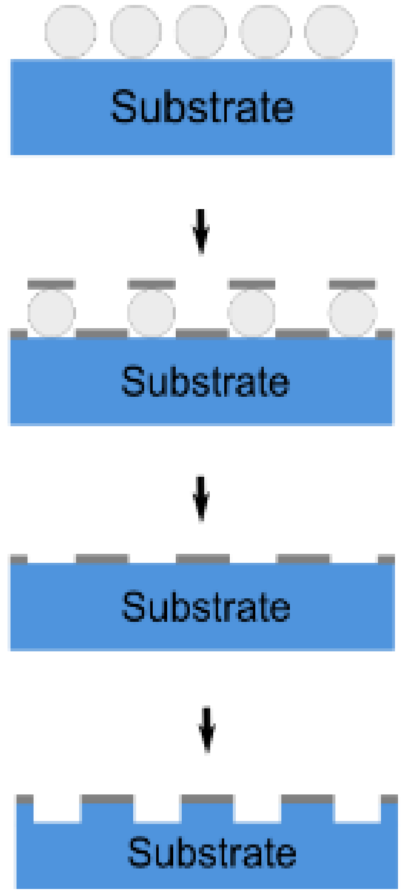
Hole mask colloidal lithography (HCL)

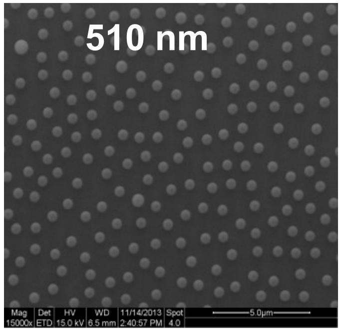
1. Adsorption of PS beads

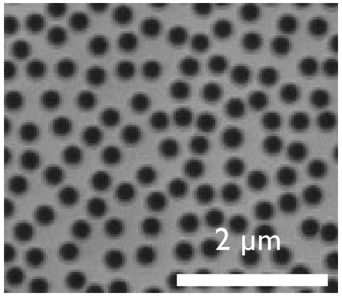
2. Etch mask deposition

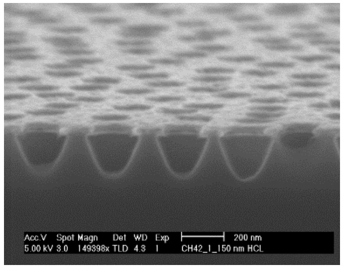
3. PS bead removal

4. Pattern transfer





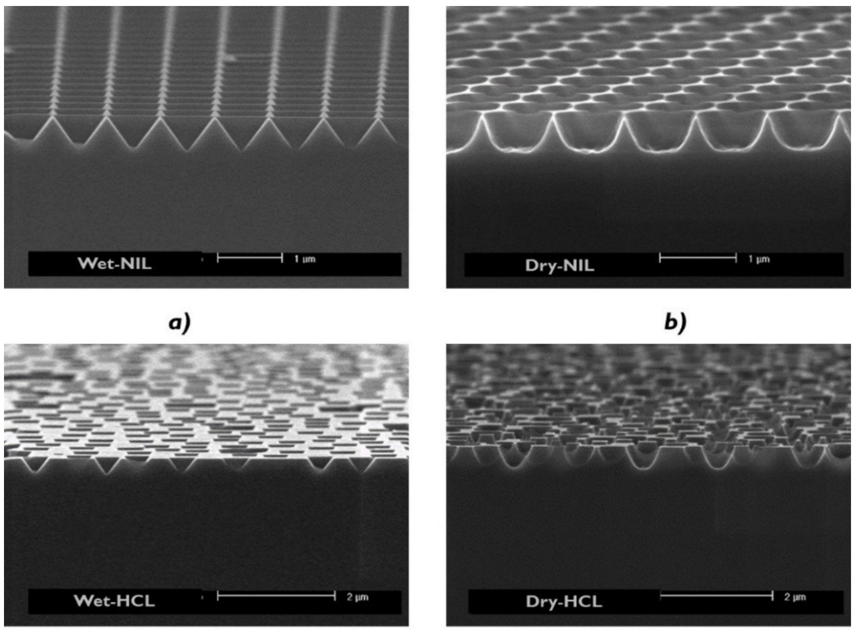




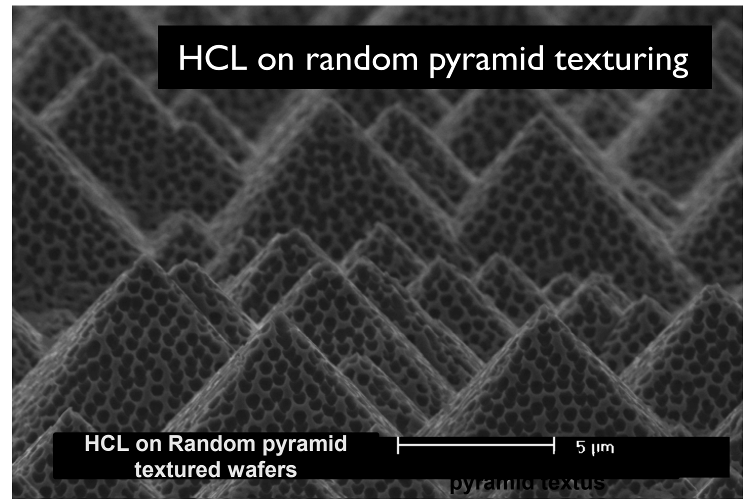
Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

Fabrication of NanoTextures

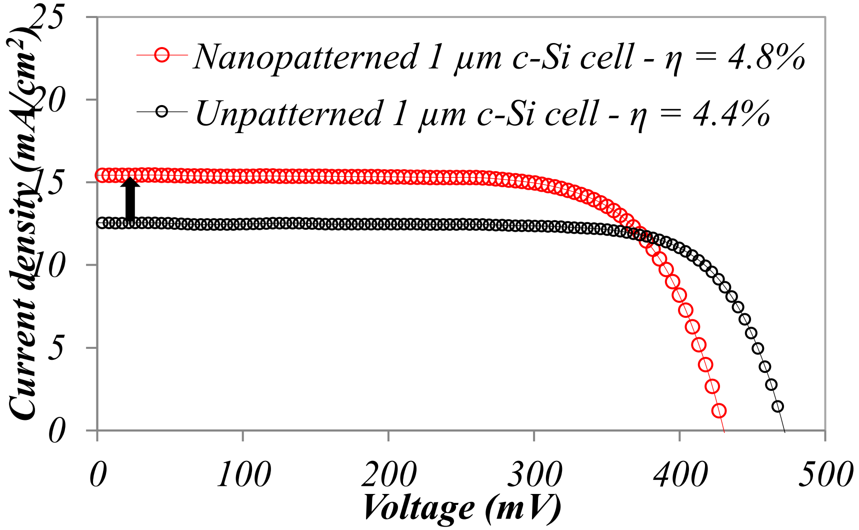
Large variety of nanostructures successfully transferred into Si.

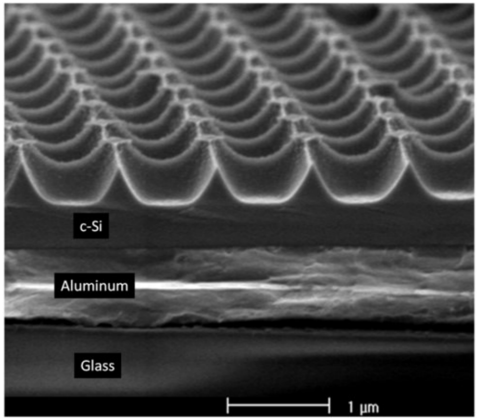


c) d)



Solar cell integration: 1 um epifree





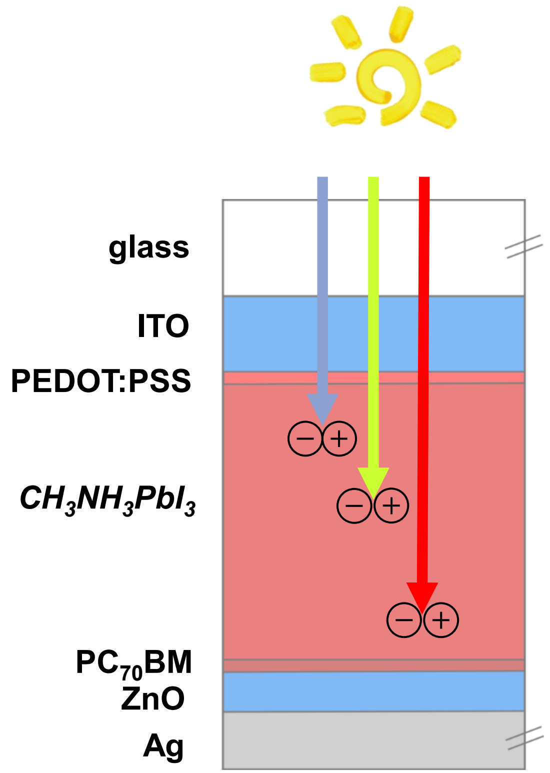
Texturing	J_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	η [%]
Flat	12.5	471	75	4.4
Nanopatterned	15.5	434	72	4.8

C. Trompoukis et al., Appl. Phys. Lett. 101, 103901 (2012)

- Increase in current
- Voc decreased due to material degradation from dry etching
- Increased efficiency

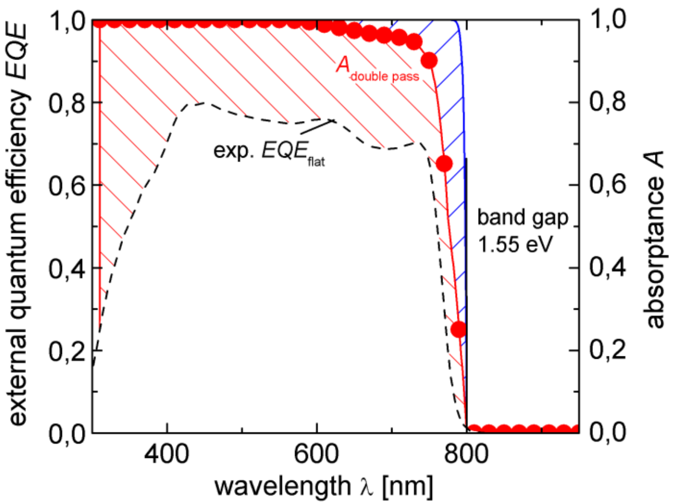
Slide adapted from Christos Trompoukis, Valerie Depauw (imec)

Nanophotonic Light Management in Perovskite Solar Cells



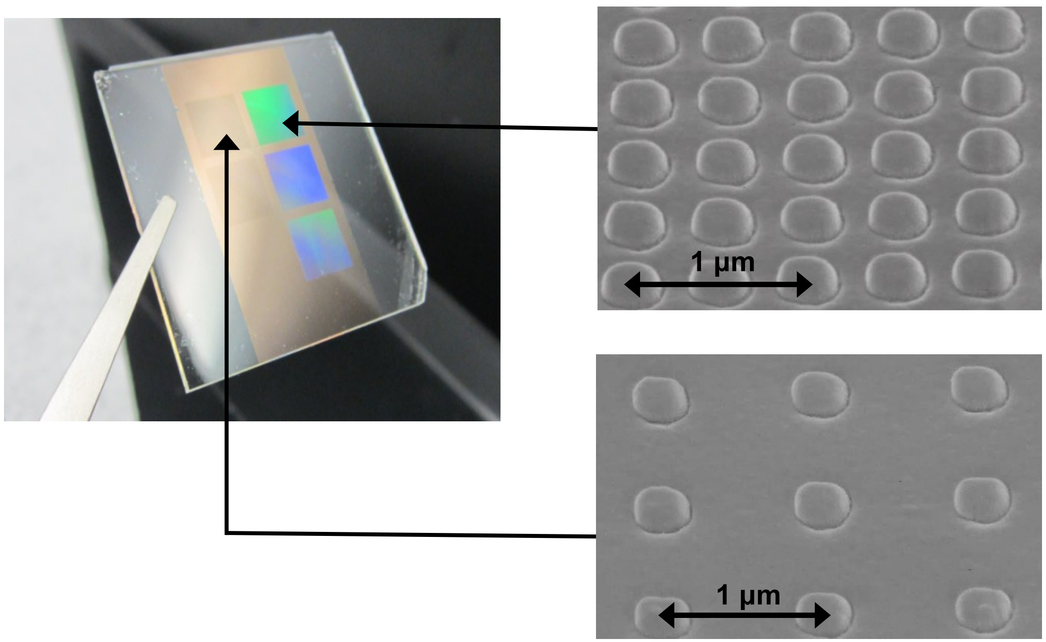
Perovskite Solar cells:

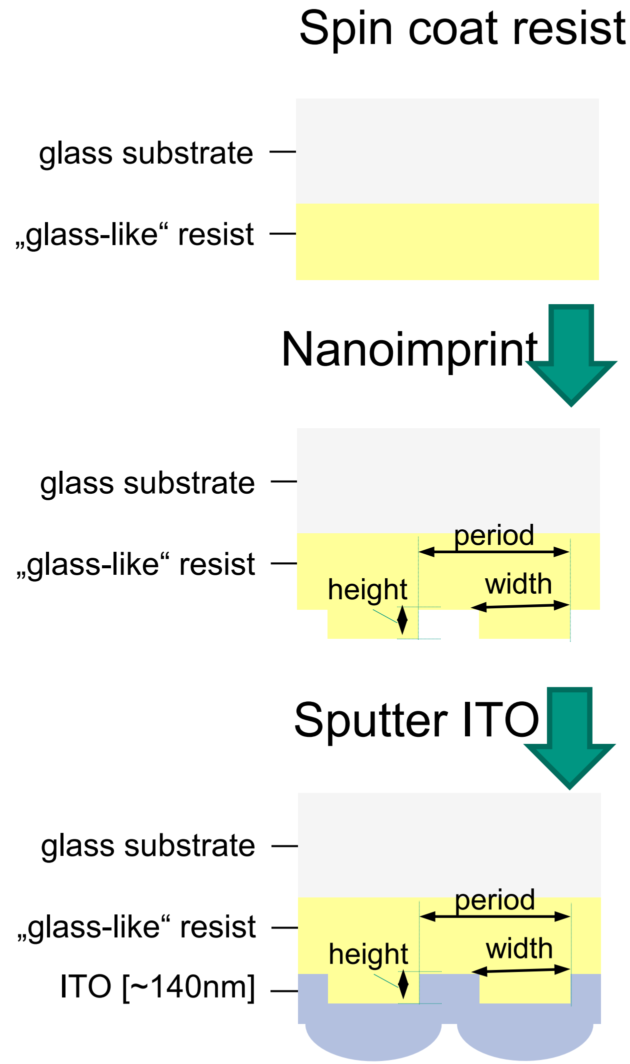
- ***Perfect charge carrier collection***
- ***Perfect absorption ($E>E_g$)*** +
- ***Poor light incoupling*** +



Nanophotonic electrodes

Fabricated by nanoimprint lithography

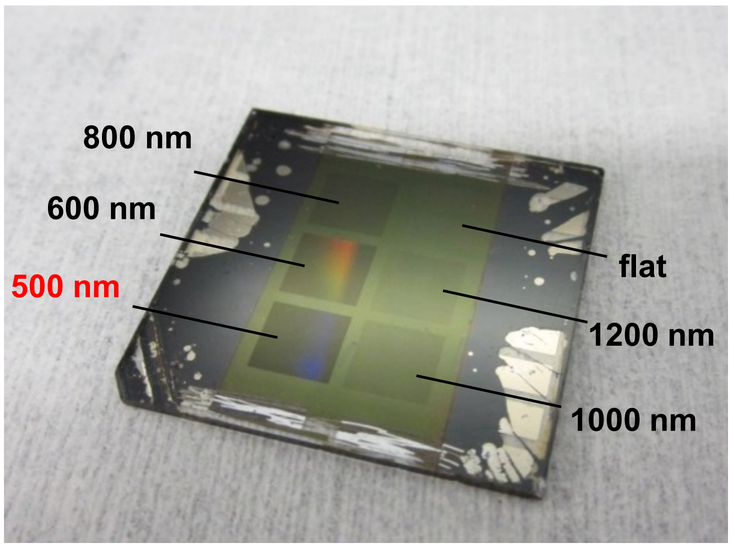


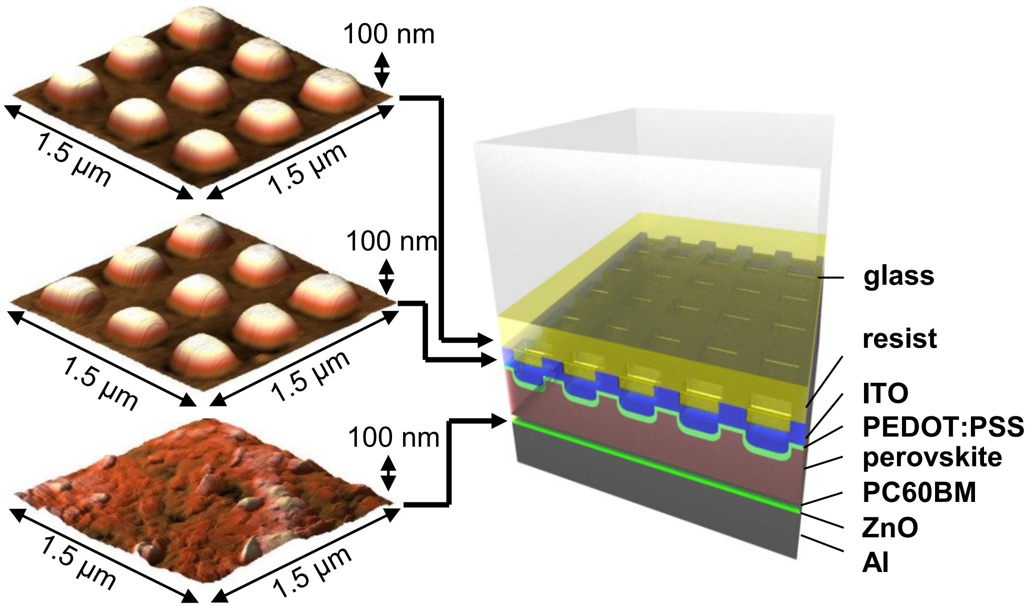


Source: U. W. Paetzold et al., Applied Physics Letters, 106 173101 (2015).

Nanophotonic electrodes

Prototype Solar Cells

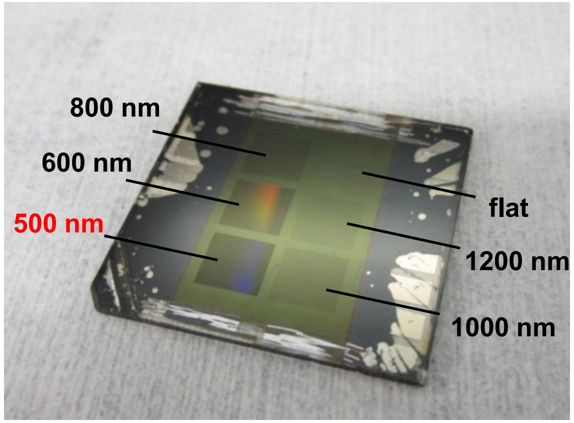




Source: U. W. Paetzold et al., Applied Physics Letters, 106 173101 (2015).

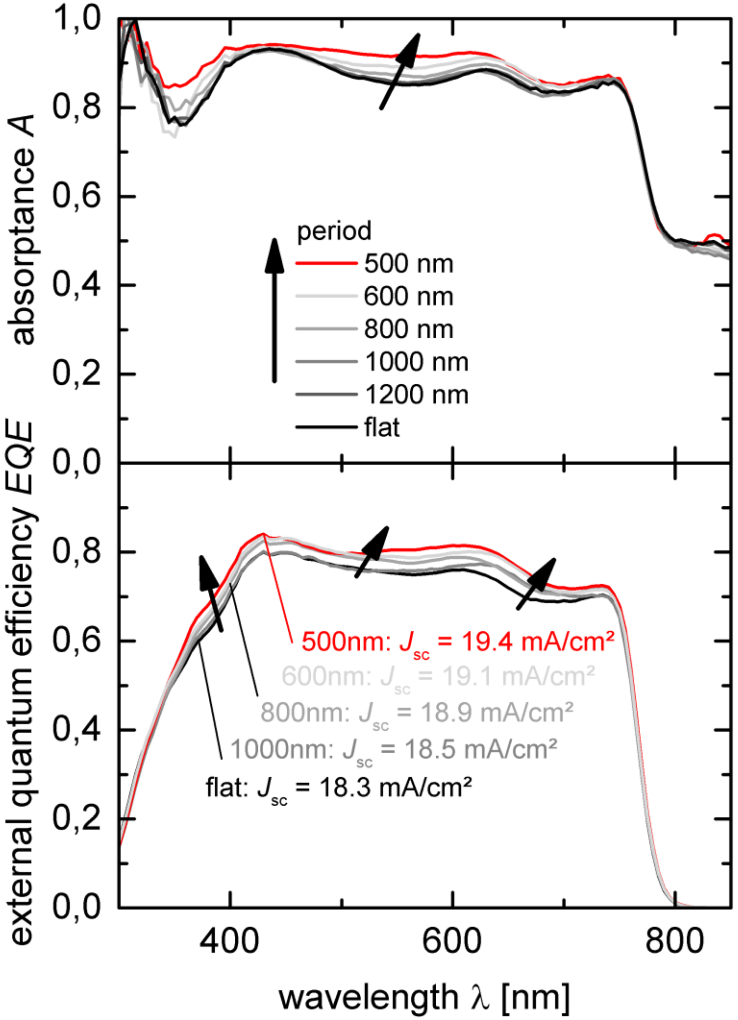
Nanophotonic electrodes

Prototype Solar Cells



	FF	V_{OC} [V]	J_{SC} [mA/cm²] (calc. from EQE)	η [%]
Flat	0.59	0.89	18.3	**9.6**
Nanophotonic (period 500 nm)	0.59	0.87	19.4	**9.9**

- Reduced reflection -> light management
- Still far away from the optimum!



Source: U. W. Paetzold et al., Applied Physics Letters, 106 173101 (2015).

Take Away Messages

- Light matters for PV !
- Optics influence directly the Jsc, but indirectly also the Voc and FF!
- Key optical losses which require light management are:
  - Reflection
  - Shading
  - Poor absorption => Light trapping
- State-of-the-art light management in Si solar cells
  - Reducing light reflection => textured front surface + ARC
  - Light trapping => textured front surface
  - Avoiding shading and area losses => IBC solar cells
- Nanotechnology for next generation light management is in focus of state-of-the-art research
  Examples:
  - Nanotextures for thin film cSi solar cells
  - Nanophotonic electrodes for improved light incoupling in perovskite solar cells

Quick Test

- Discriminate the optical aspects that influence the power conversion efficiency of a solar cell.
- How does light managment / optics of a solar cell correlate with (1) short-circuits current density, (2) open-circuit voltage, (3) fill factor?
- Why does the open-circuit voltage of a concentrated solar cell increase with the concentration coefficient? (Derive the correlation!)
- Explain state-of-the-art light management in Si solar cells with regard to (1) light incoupling, (2) light trapping, and (3) reducing inactive areas.
- How does nanophotonic light management differ from conventional light management?