The Abdus Salam International Centre for Theoretical Physics

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Winter College on Optics and Energy

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Anti-reflection and light-trapping

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Anti-reflection and light-trapping

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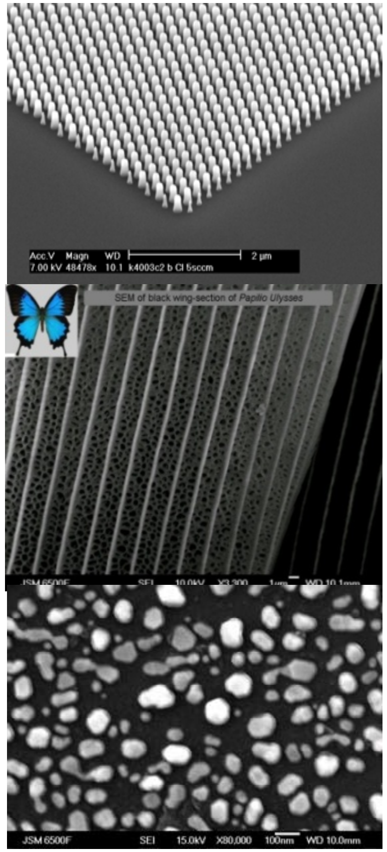

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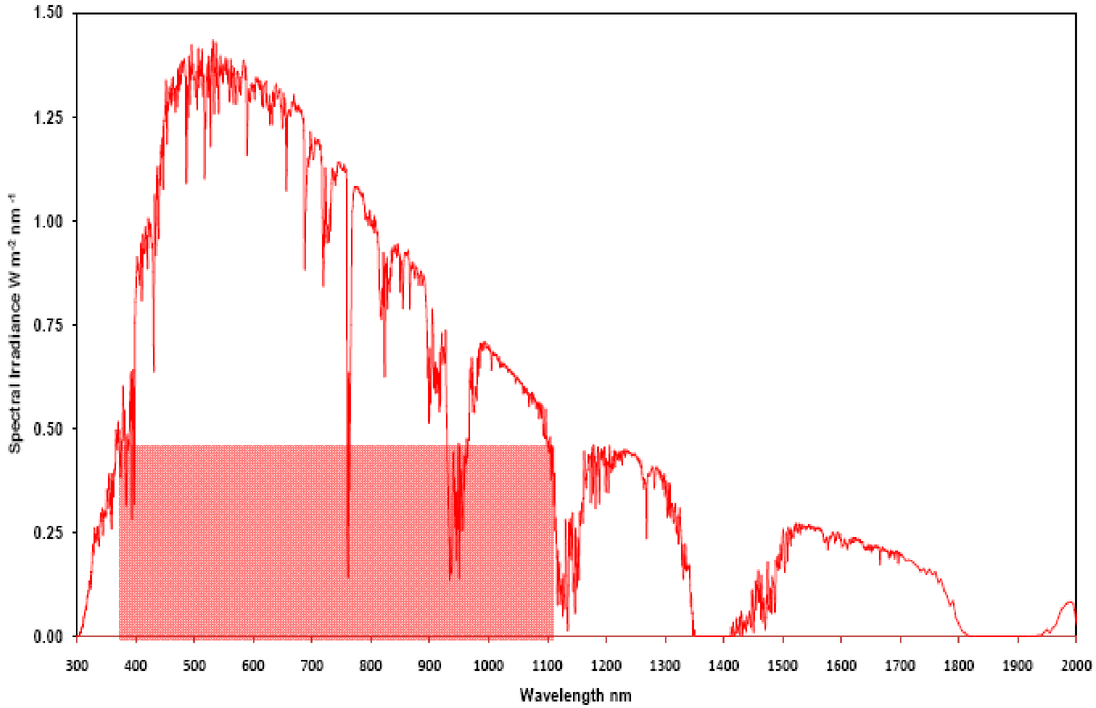
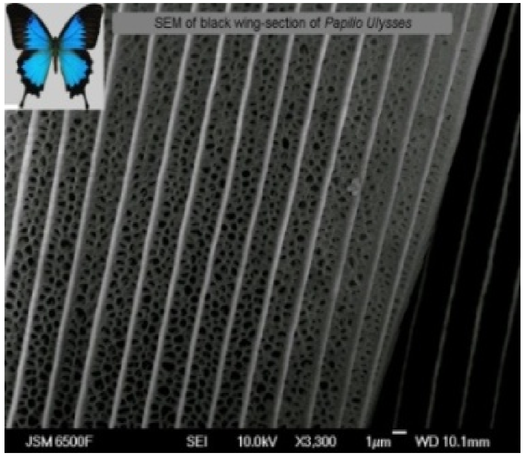
Challenge of Broadband



- laser-based photonic technologies can be 99.9% efficient over 100nm spectral range
- applying photonics to photovoltaics requires efficiency for 700nm of bandwidth.
- optimal solutions for AR and LT require spectral irradiance and IQE to be considered and dissordered (chirped) designs.

Biomimetics and Plasmonics



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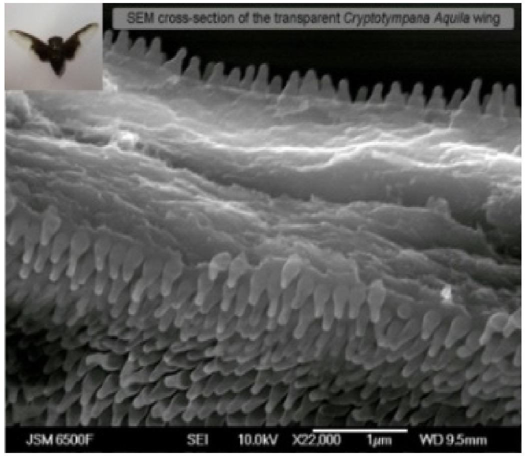

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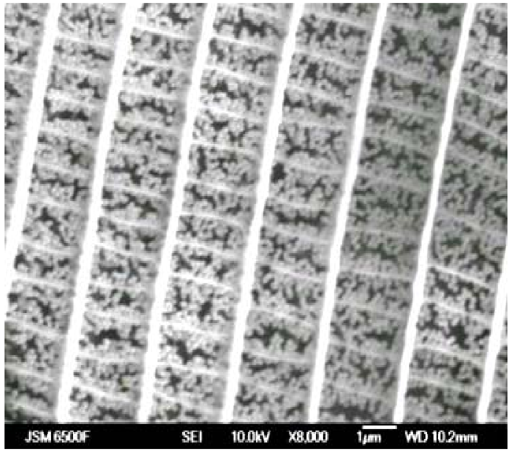

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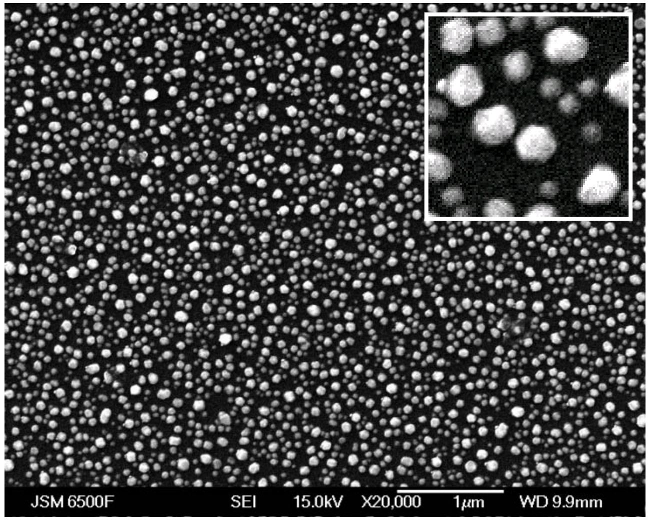

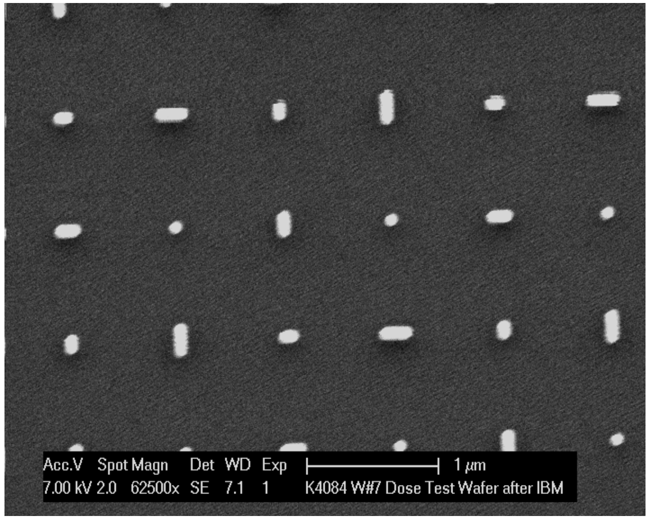

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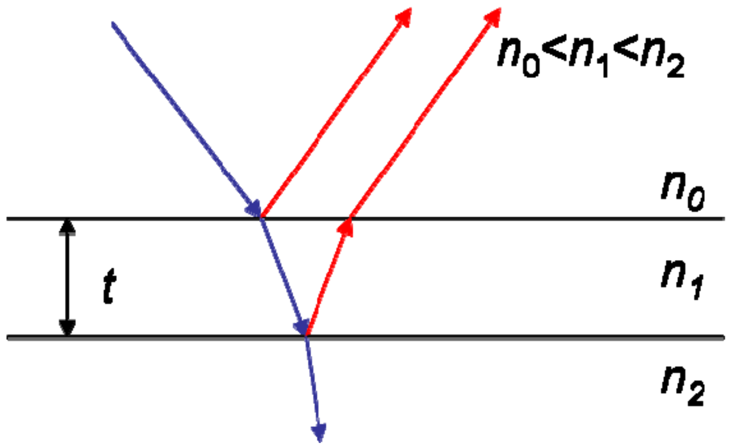
Anti-reflection

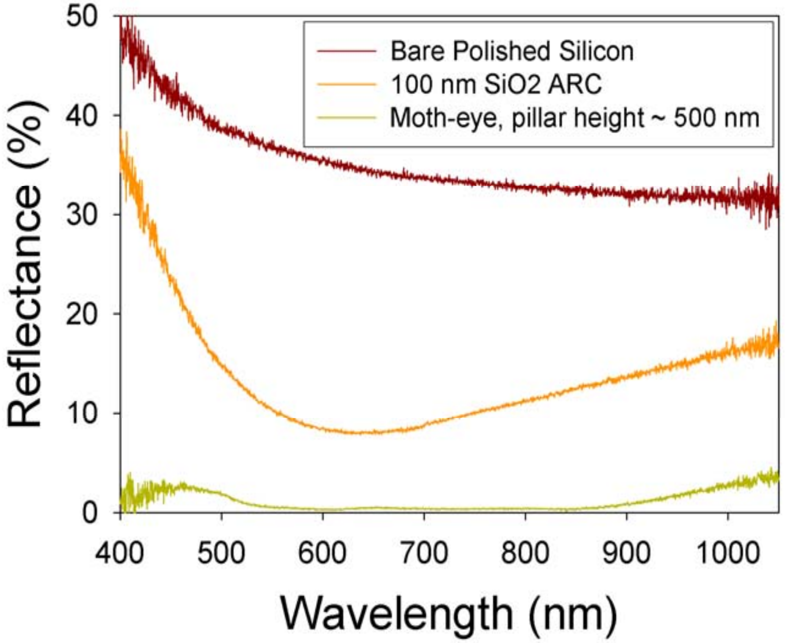
Single layer AR coating



• to reduce reflection a single thin film of quarter wavelength thickness (taking into account refractive index) uses interference to reduce intensity of reflected beem

• about 110nm of SiO_2 is simplest AR coating for Si

Single layer AR coating



- single layer ARCs are much better than bare surface (roughly half reflection)
- still, around 20% of light is still reflected

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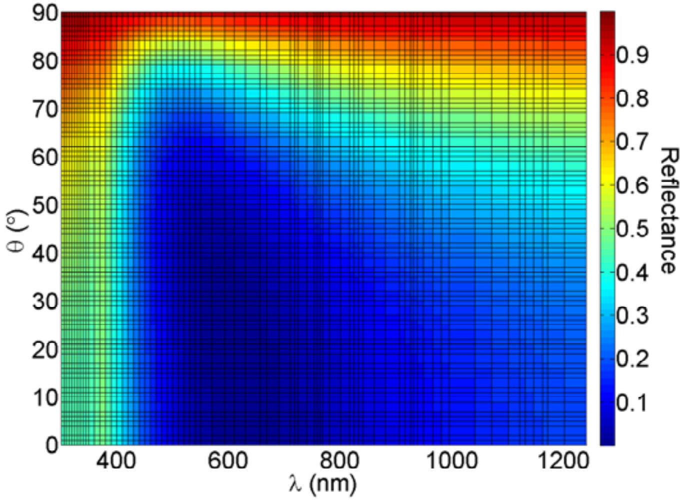
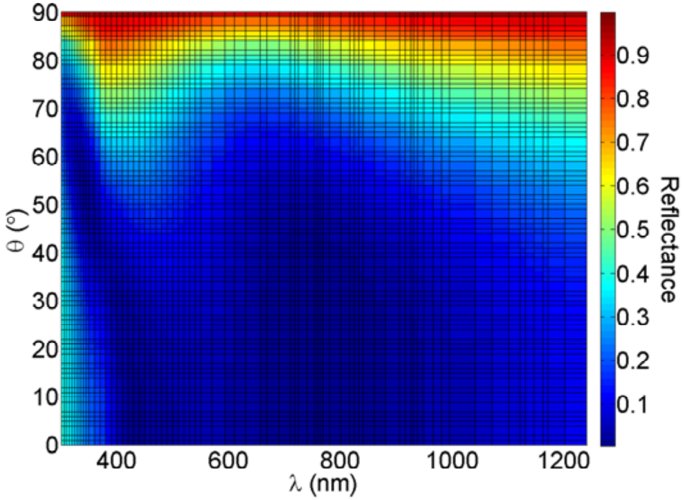
Double-layer AR coatings



CeO SLAR



ZnS,MgF_2 DLAR

- Double layer coatings can be used to broaden the AR effect and further reduce reflected intensity
- Ultimately there is only a small range of suitable materials (n) that do not absorb.

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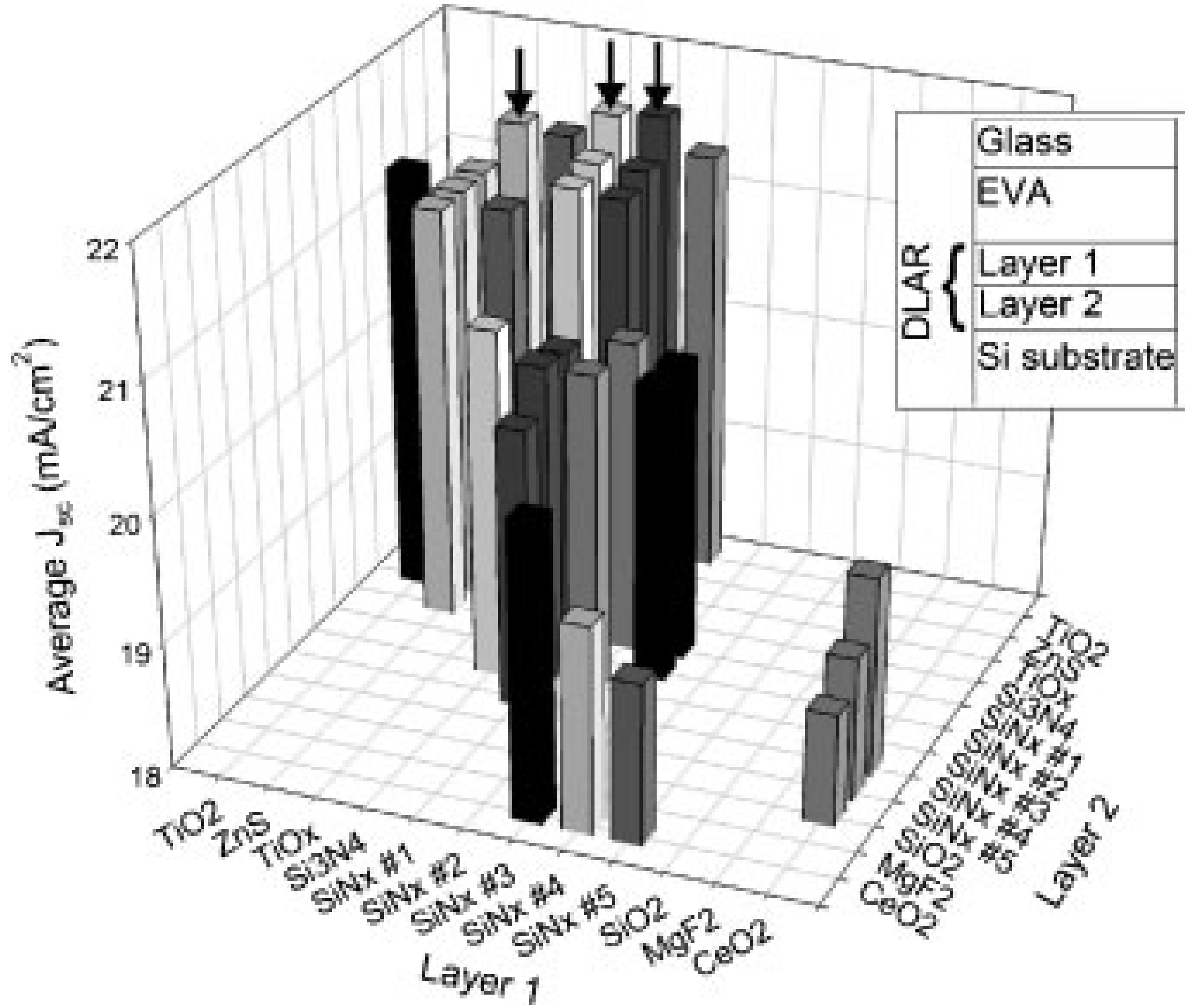
Double-layer AR coatings



[Boden and Bagnall, Prog. Photovolt: Res. Appl. 2009; 17:241–252]

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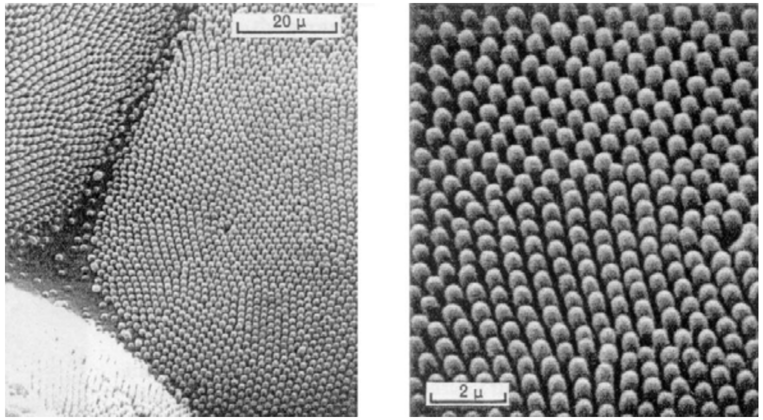
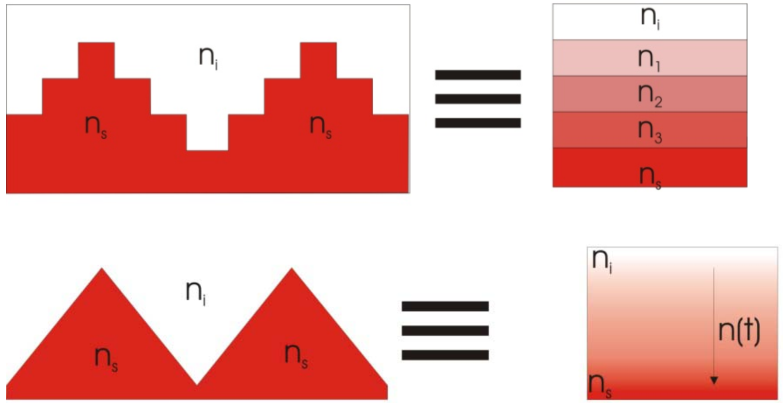
Biomimetic moth-eyes

- **Nanostructured corneal surface of some night moths**
  - **Improved eyesight**
  - **Less visible to predators**



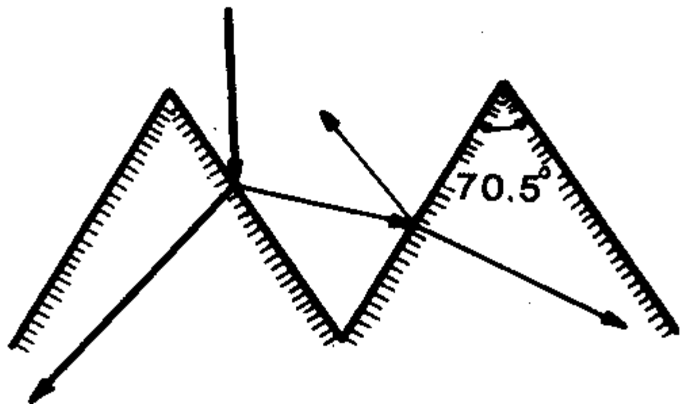
Bernhard, Endeavour vol 26, pp. 79-84, (1967)

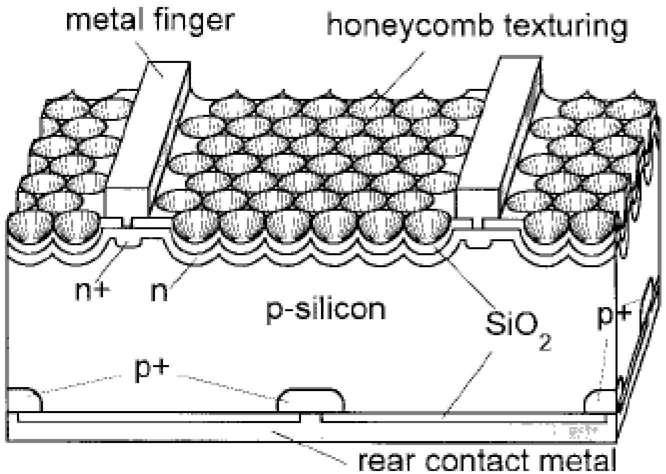
- **Arrays of <u>subwavelength</u> features**
- **Gradual change in refractive index from air into substrate**

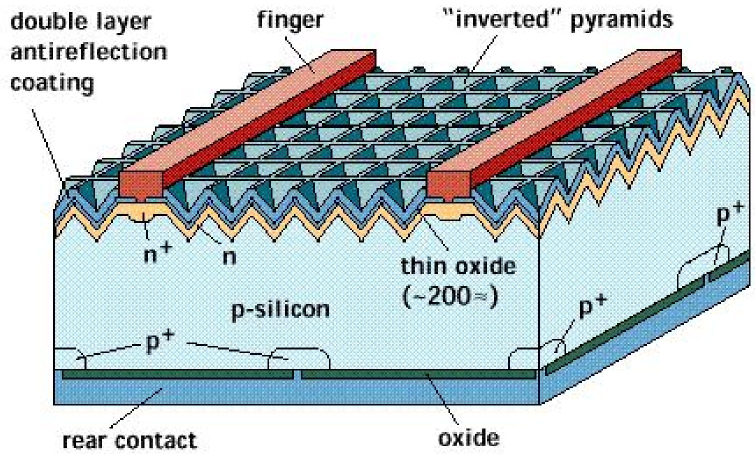


Micron-scale texturing

• micron –scale themes are based on the development of topographies that provide light with multiple opportunities to be absorbed
• reflectance can be as low as 1-2%
• easy to apply to C-Si (KOH etch)
• difficult to apply to other materials and thin materials (2-3 um)







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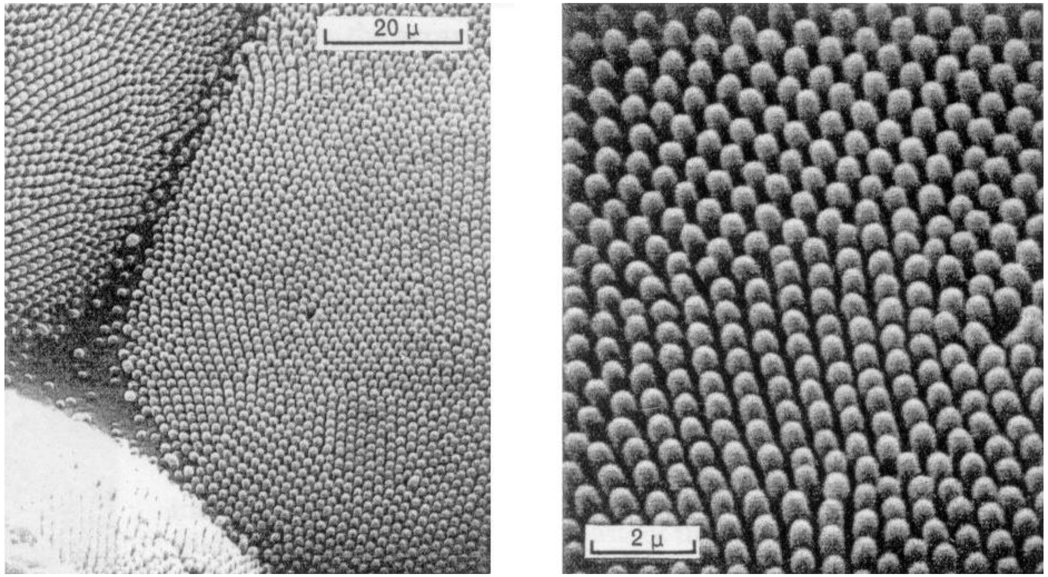
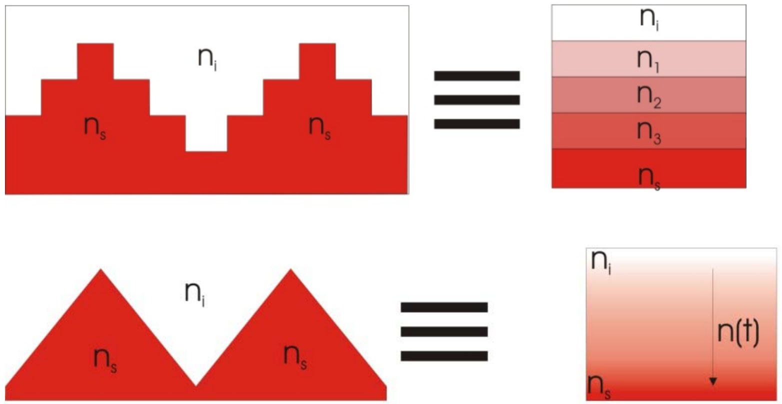
Biomimetic moth-eyes



Bernhard, Endeavour vol 26, pp. 79-84, (1967)

- Arrays of subwavelength features
- Gradual change in refractive index from air into substrate



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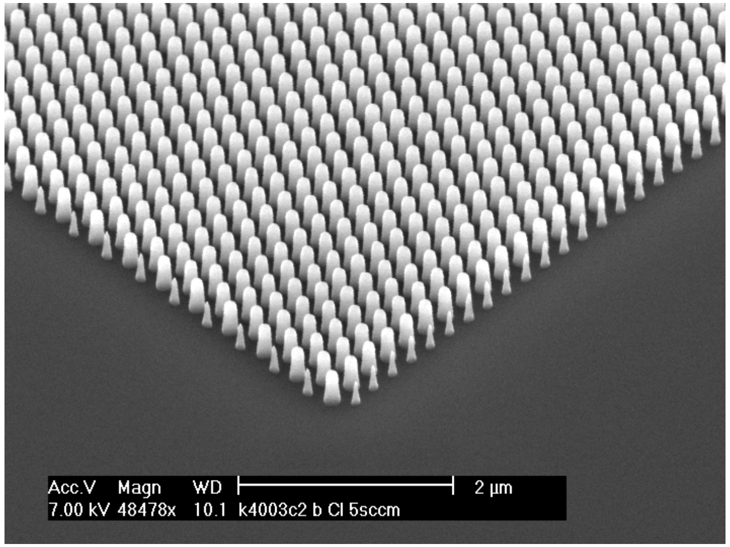
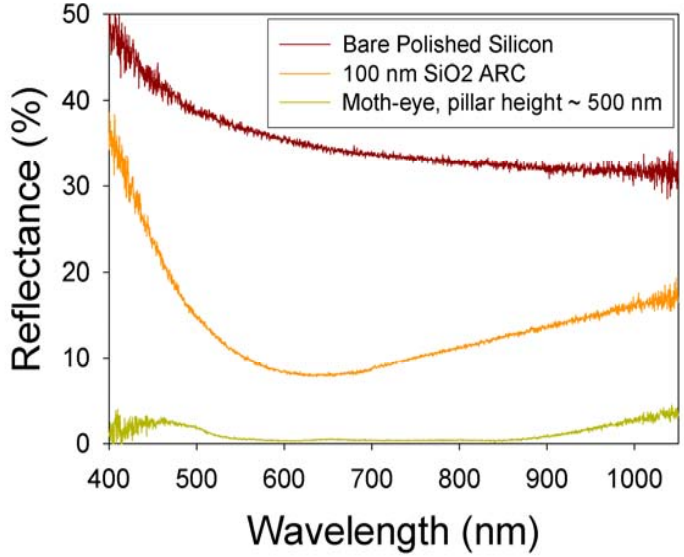
Biomimetic moth-eyes

• sub-wavelength patterning "creates a gradual change in refractive index and reduces reflection" – seen on moth-eyes

• our first structures were fabricated by e-beam and plasma etch





• first experimental results illustrates very low reflectance and evidence of structure that **can not be explained by effective medium theory**

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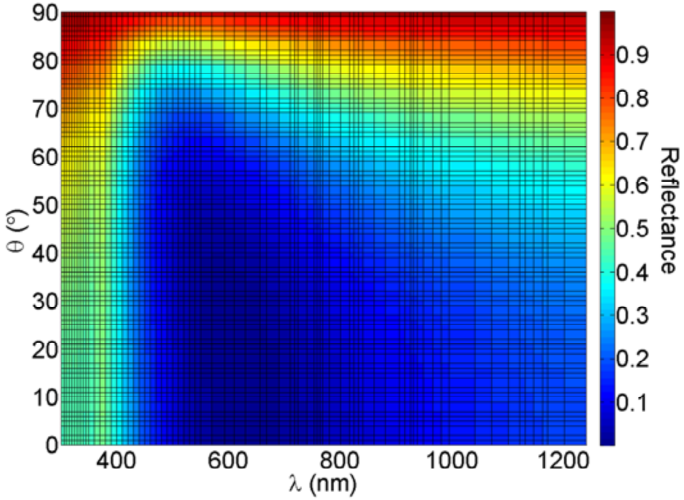
Biomimetic moth-eyes



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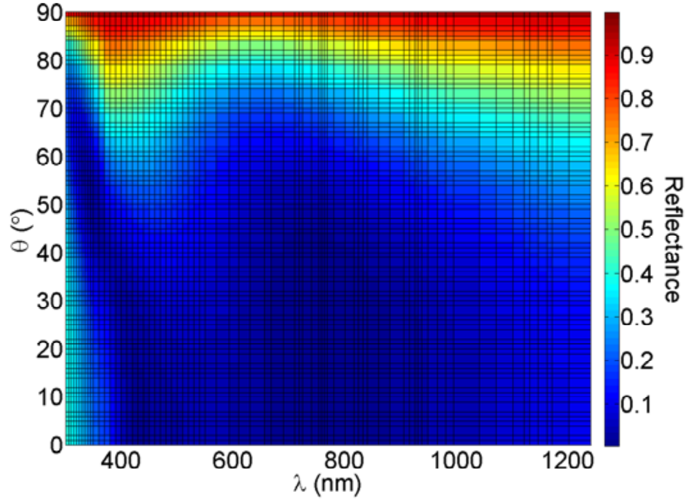
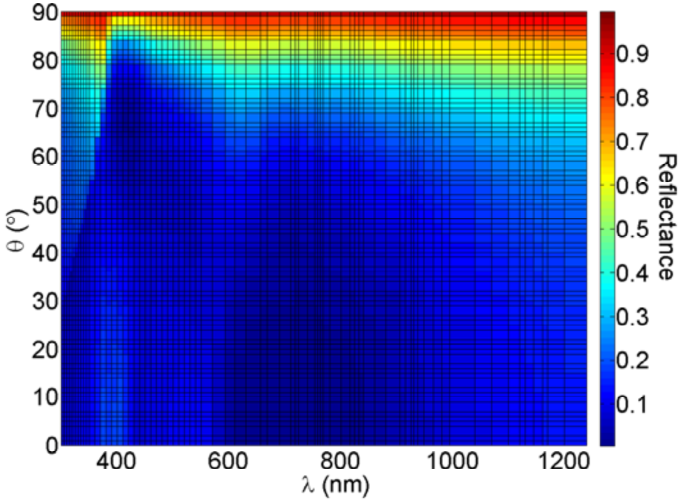
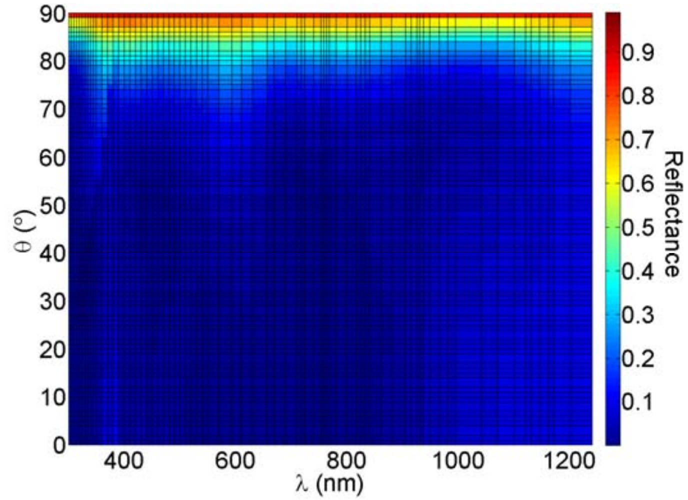


ZnS,MgF_2 DLAR



Moth-eye 250 nm

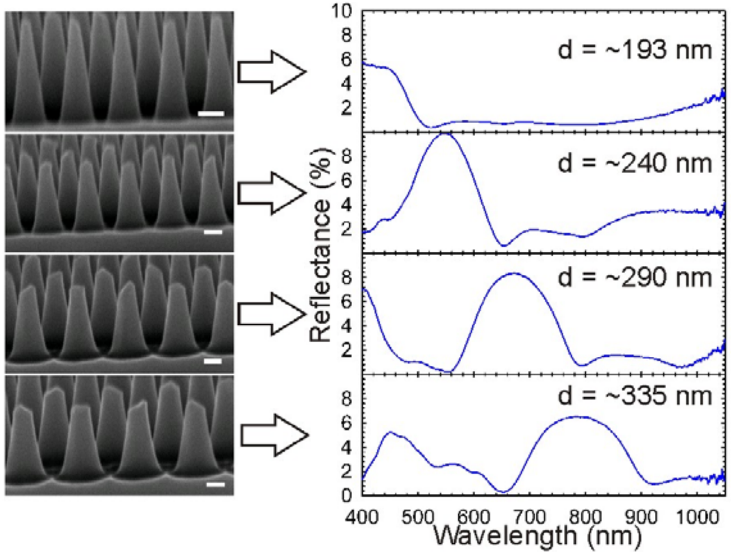


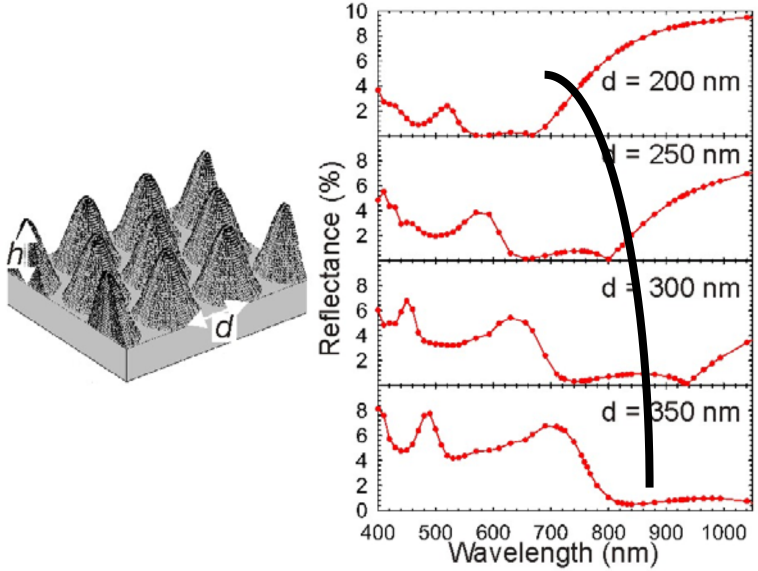
Moth-eye 500 nm

Tunable moth-eyes

• changing height, shape and period of pillar profiles on the reflectance of silicon moth-eye arrays.

• Study reveals a low reflectance band which shifts with array period.





• samples by nano-imprint lithography

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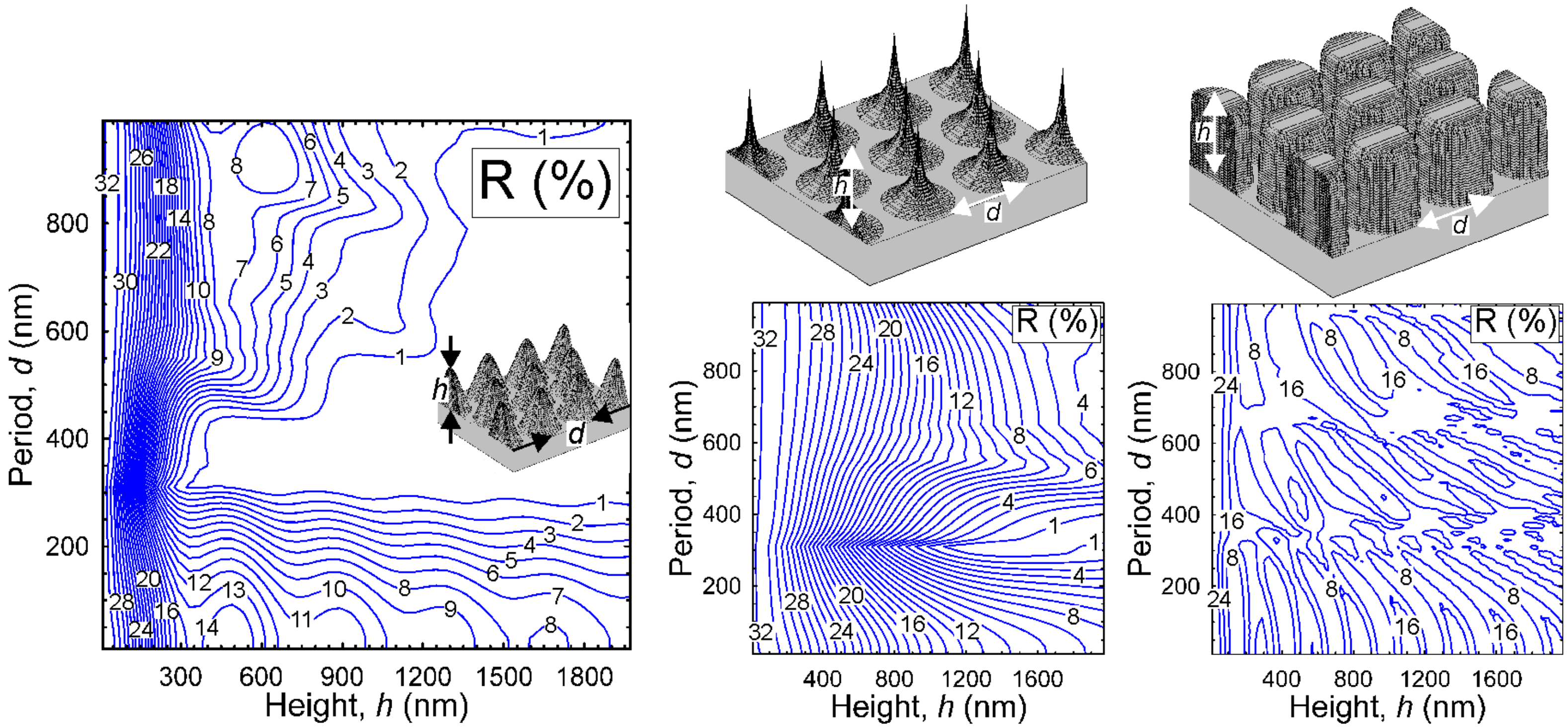
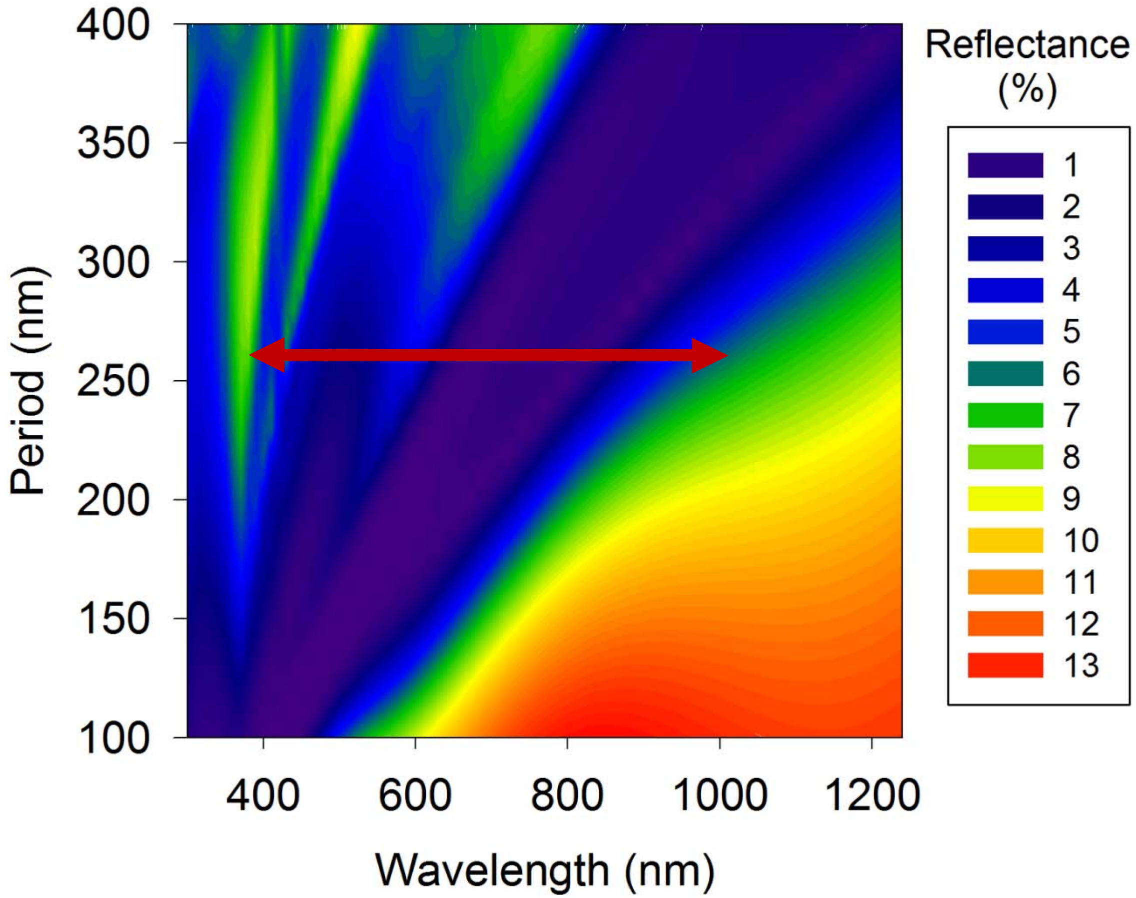
Biomimetic moth-eyes

- Pillar shape also has a dramatic effect on the reflectance properties.
- For highest performance pillar height, shape and array period should be optimized for the specific wavelength range of interest.



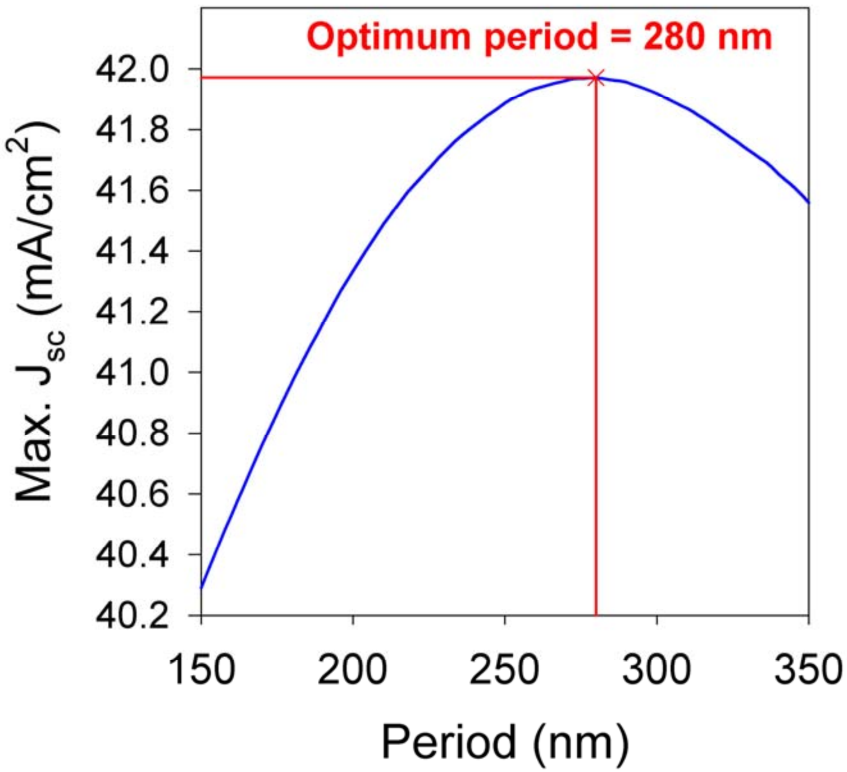
Design Detail....Period

Reflectance with period/wavelength (400nm height)



Biomimetic moth-eyes

Optimise periodicity by considering: R(λ)
QE (λ) and
AM1.5(λ)



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Design Detail....Period

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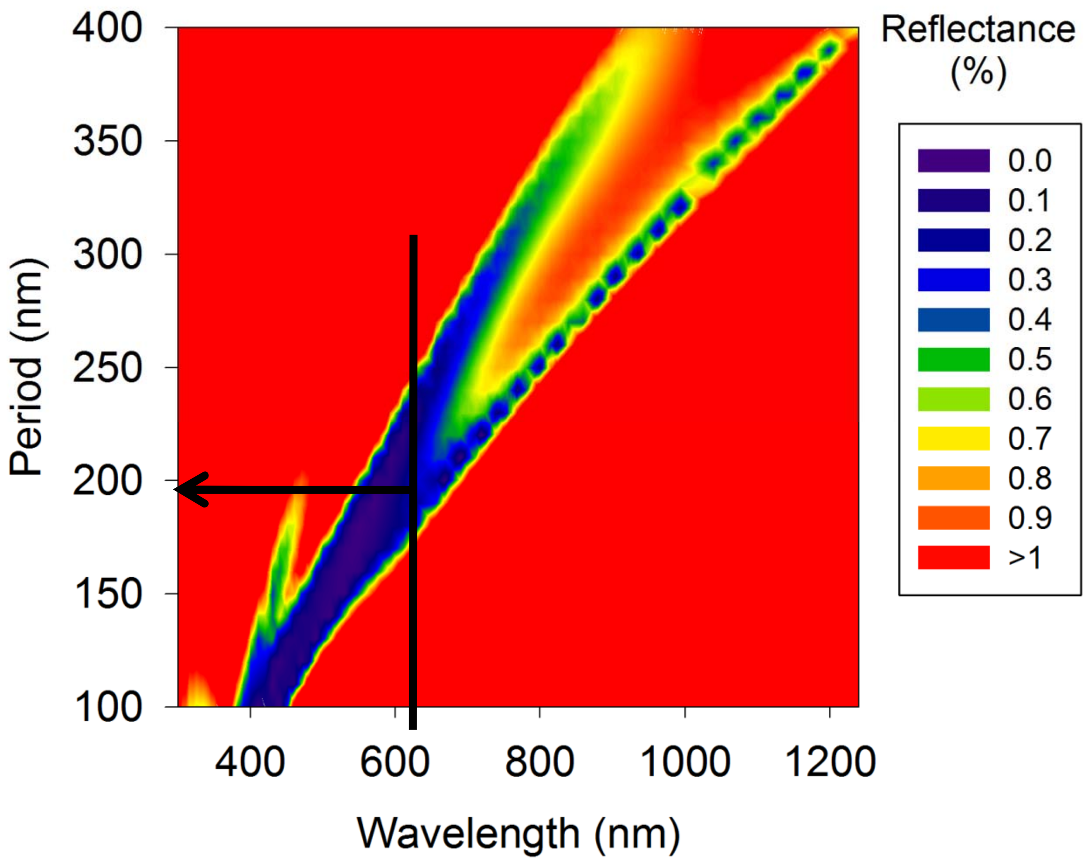

S. A. Boden and D. M. Bagnall, *Applied Physics Letters*, 93, 133108 (2008)

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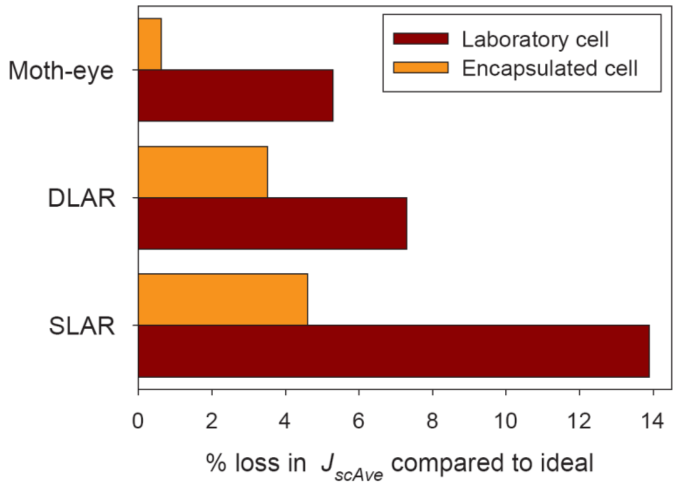
Sub-wavelength A/R



• moth-eye AR schemes are promising for thin film solar cells

• requires self-assembly/cheap fabrication

• nanoscale roughened surfaces might already be doing the job for some thin films

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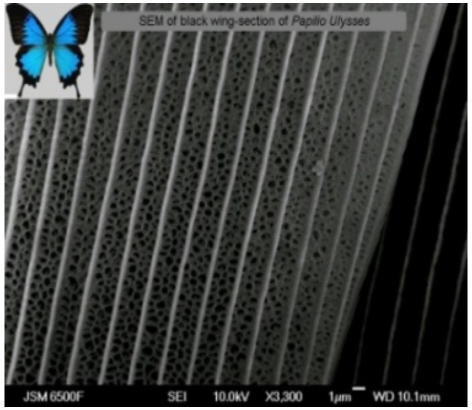
Other biomimetics

- Meanwhile, many other natural systems offer interesting prospects

- Each represents considerable challenge to fabricate or model



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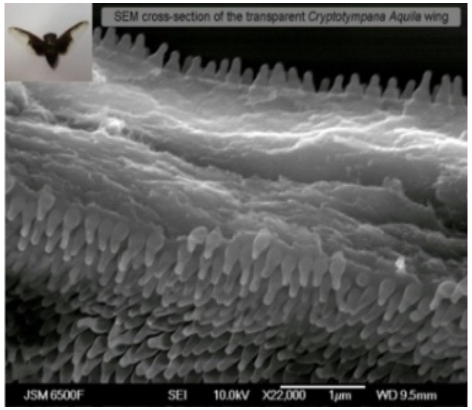

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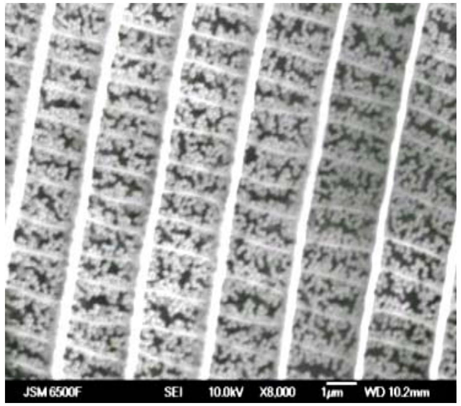

white

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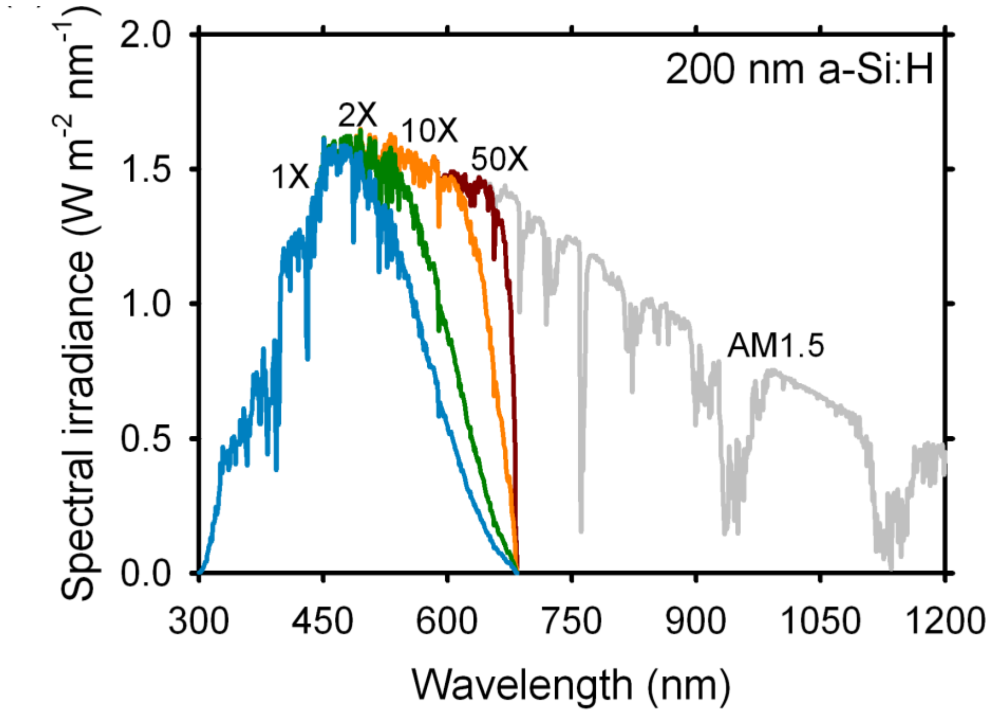
Light-trapping

The case for light-trapping



- light-trapping can help all devices (enhance absorption or carrier collection, use less material)
- For a-Si, p-Si light-trapping is essential – but can it be improved?

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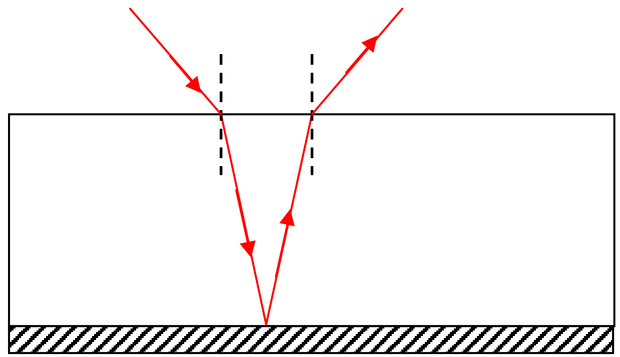
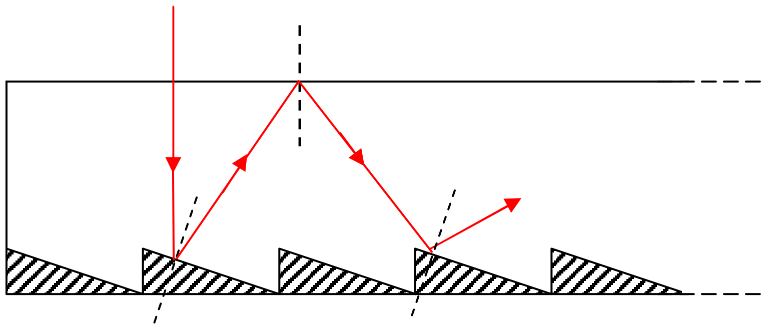
Classic solutions

• ensure reflection from the back surface of the solar cell (doubles the effective path – but in the highly symmetric scheme remaining light is decoupled at surface

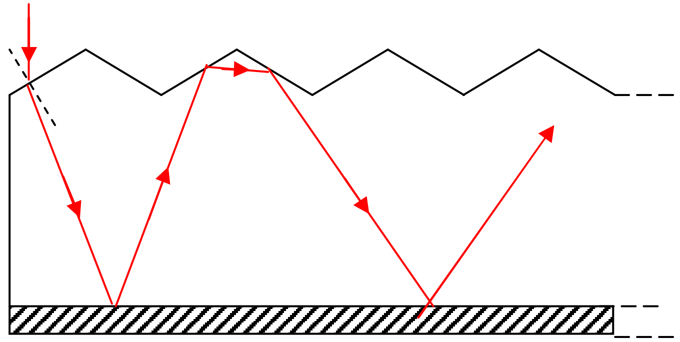


• asymmetric back-reflector ensures multiple reflections (but hard to manufacture)

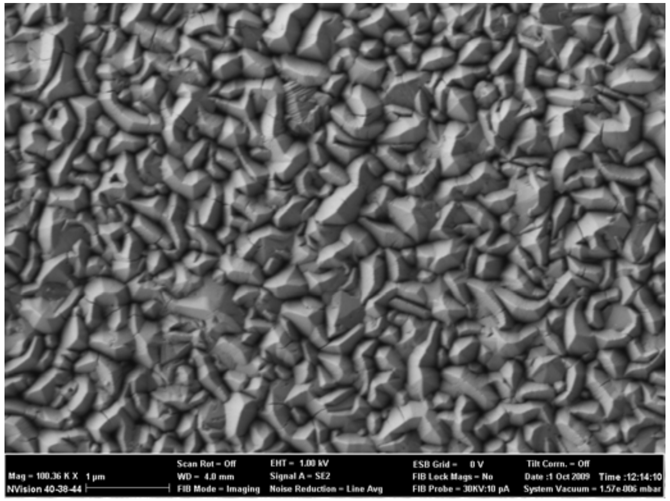
•R. H. Morf, in *Diffractive Optics for Industrial and Commercial Applications*, edited by Jari Turunen and Frank Wyrowski, Akademie Verlag GmbH, Berlin (1997) p361-389



• diffuse scattering schemes can increase path-lengths by as much as 20x, but with some escape-cone losses

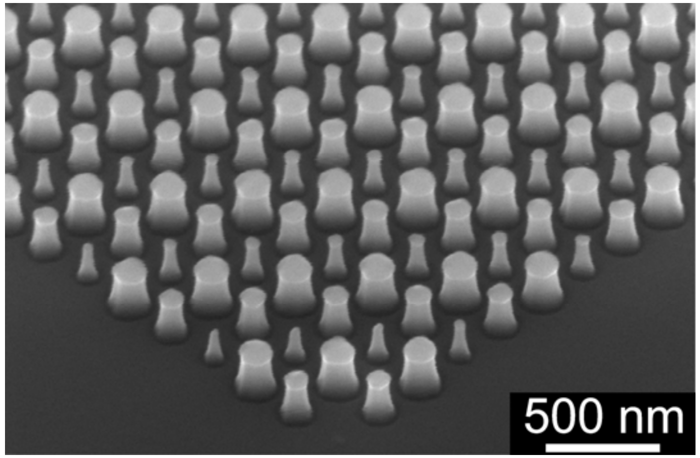


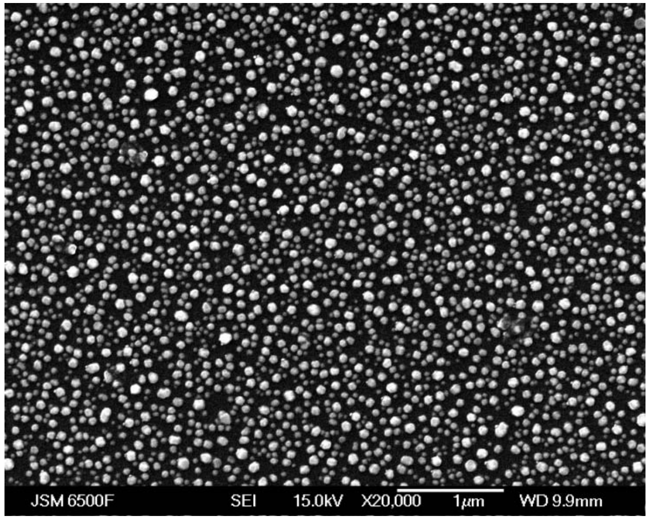
Light-trapping mechanisms



Texturing
(Lambertian scattering)

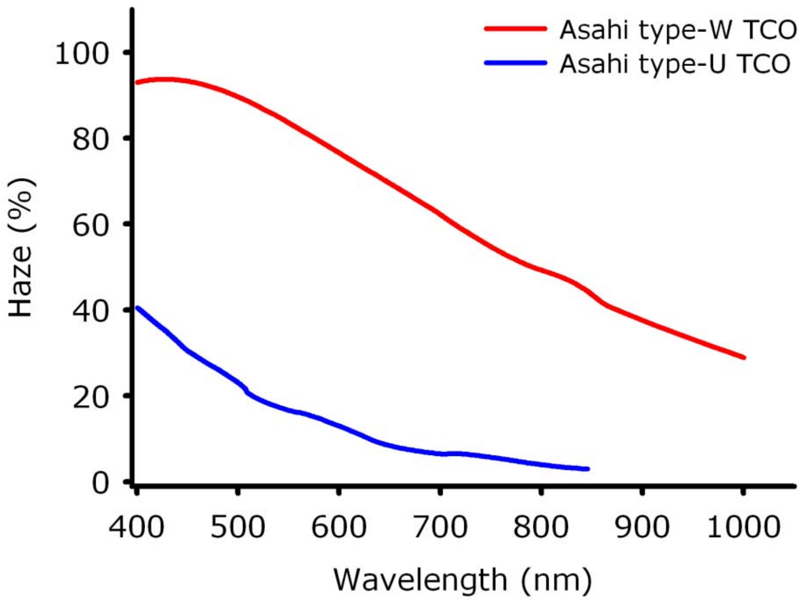
Periodic structures
(diffraction, photonics)

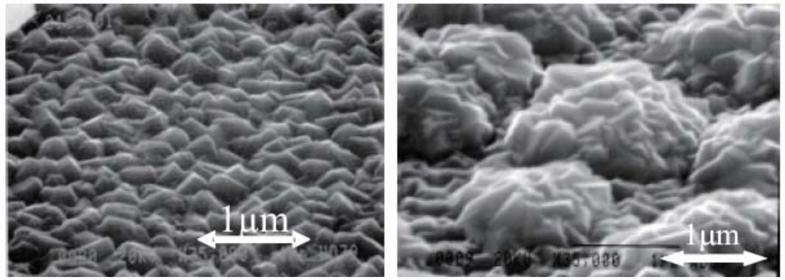




Plasmonic
(preferential scattering)

Textured Surface





Asahi type-U TCO   Asahi type-W TCO

[N.Taneda, T. Oyama and K. Sato, Proceedings of Intenational PVSEC-17, 2007]

- Textured TCO on glass can be readily provided by appropriate growth or etching regime
- Asahi “U” type is commercial product for a-Si devices
- Required to provide optimum scattering 500-700nm wavelengths
- Classically measured by **“haze”** value

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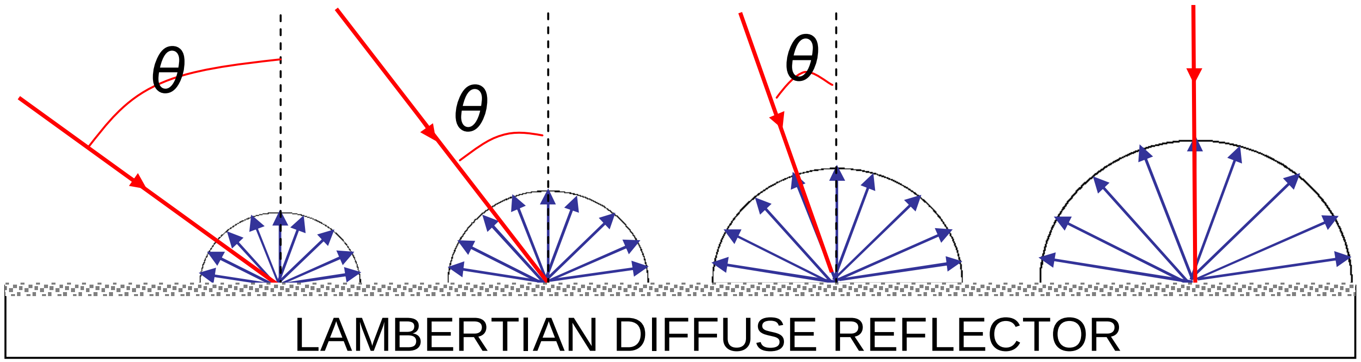
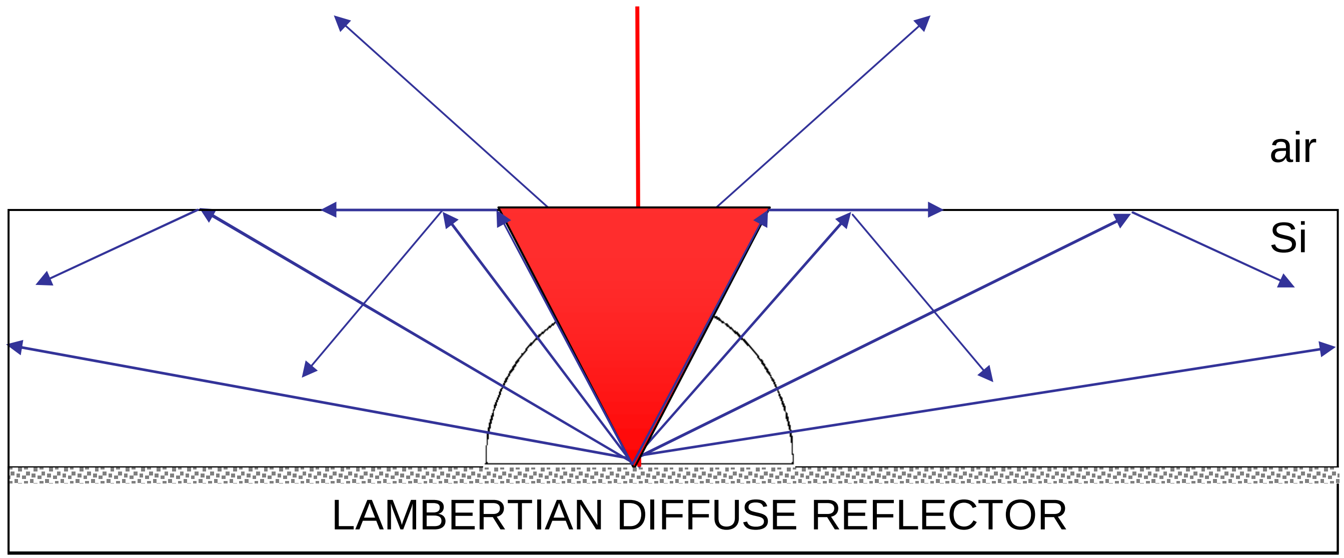
Lambertian Scattering

$$I_{diffuse} = k_d I_{light} \cos\theta$$



- Incoming light is scattered equally in all directions
- Viewed brightness is independent of viewing direction
- Brightness <u>does</u> depend on direction of illumination

Light-trapping

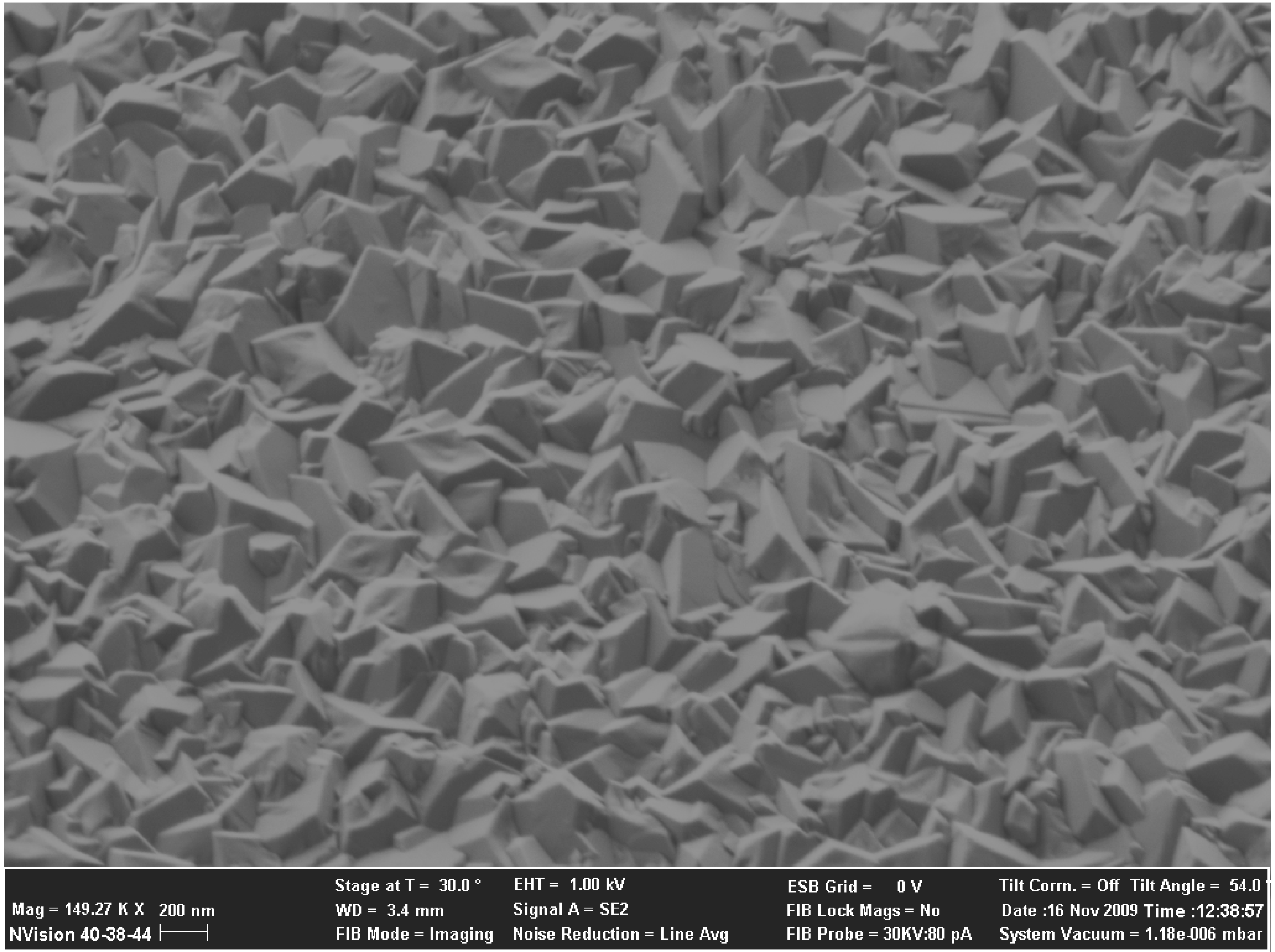


- Fraction of light reflected by total internal reflection = $1-\frac{1}{n^2}$

- For Si, n=3.4. Therefore, **91%** of light is reflected back into the cell each time it reaches the top surface
- "**escape cone**" losses account for **9%**
- Overall, the path length can be increased by about a **factor of 50**

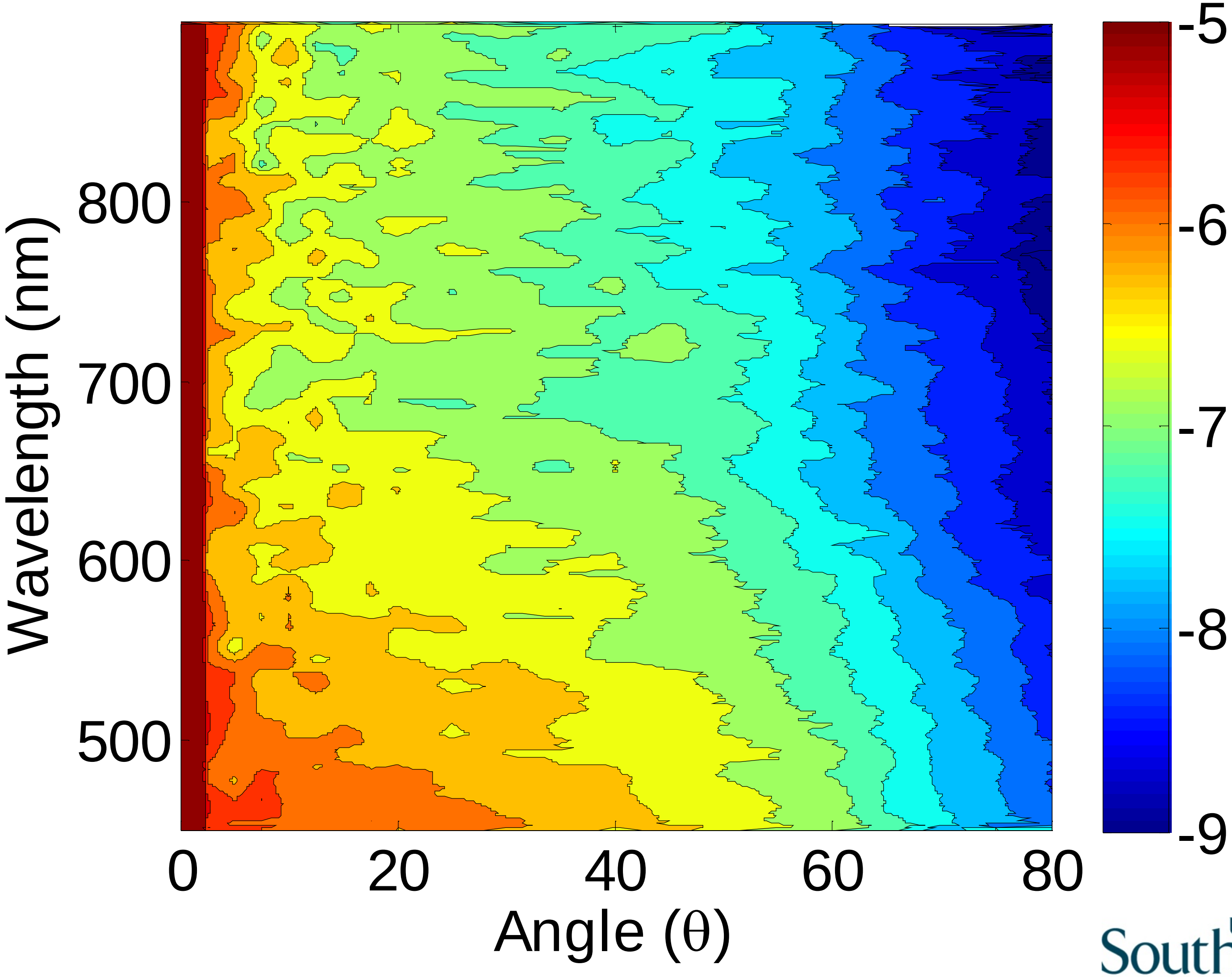
Textured TCOs

Asahi “U” type



White-light angular scattering

Asahi “U” type



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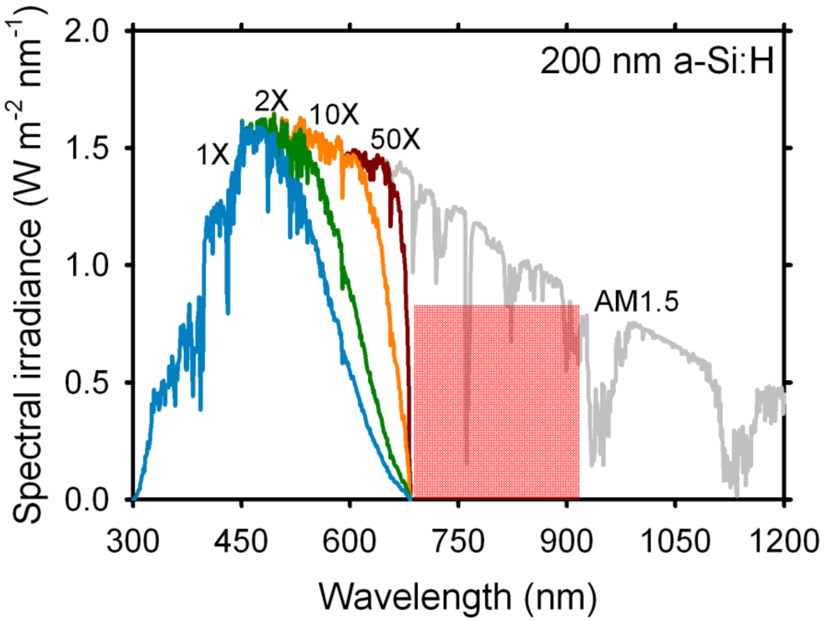
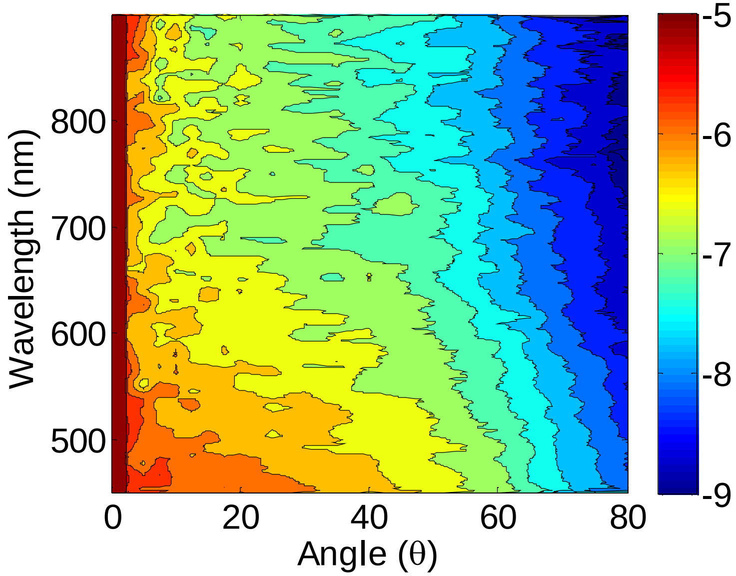
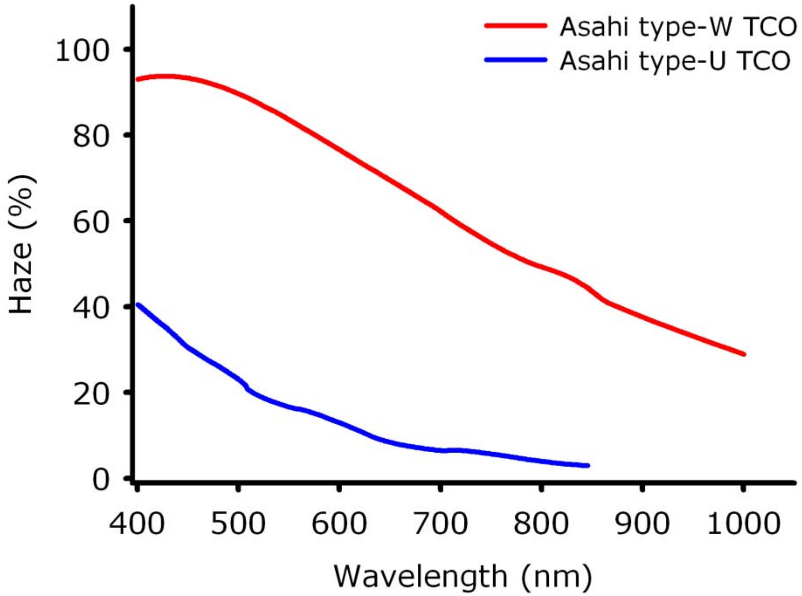
Feature size dependence

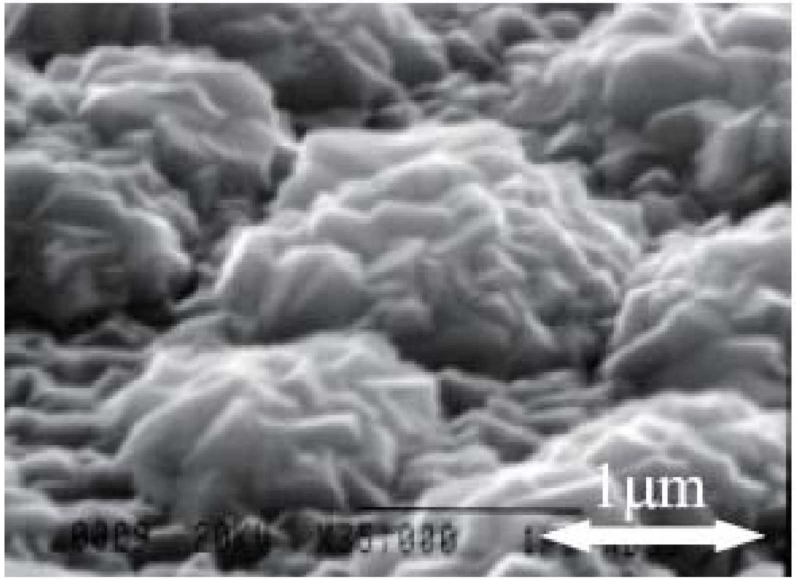
- The main problem with texturing is that long-wavelength scattering requires large feature size
- Large features sizes are difficult to grow on
- Commercial designs represent a compromise between optical performance and device performance
- Asahi “U-Type” is used for a-Si
- Rougher surfaces are required for **“micromorph” devices**





Light-trapping for longer wavelengths





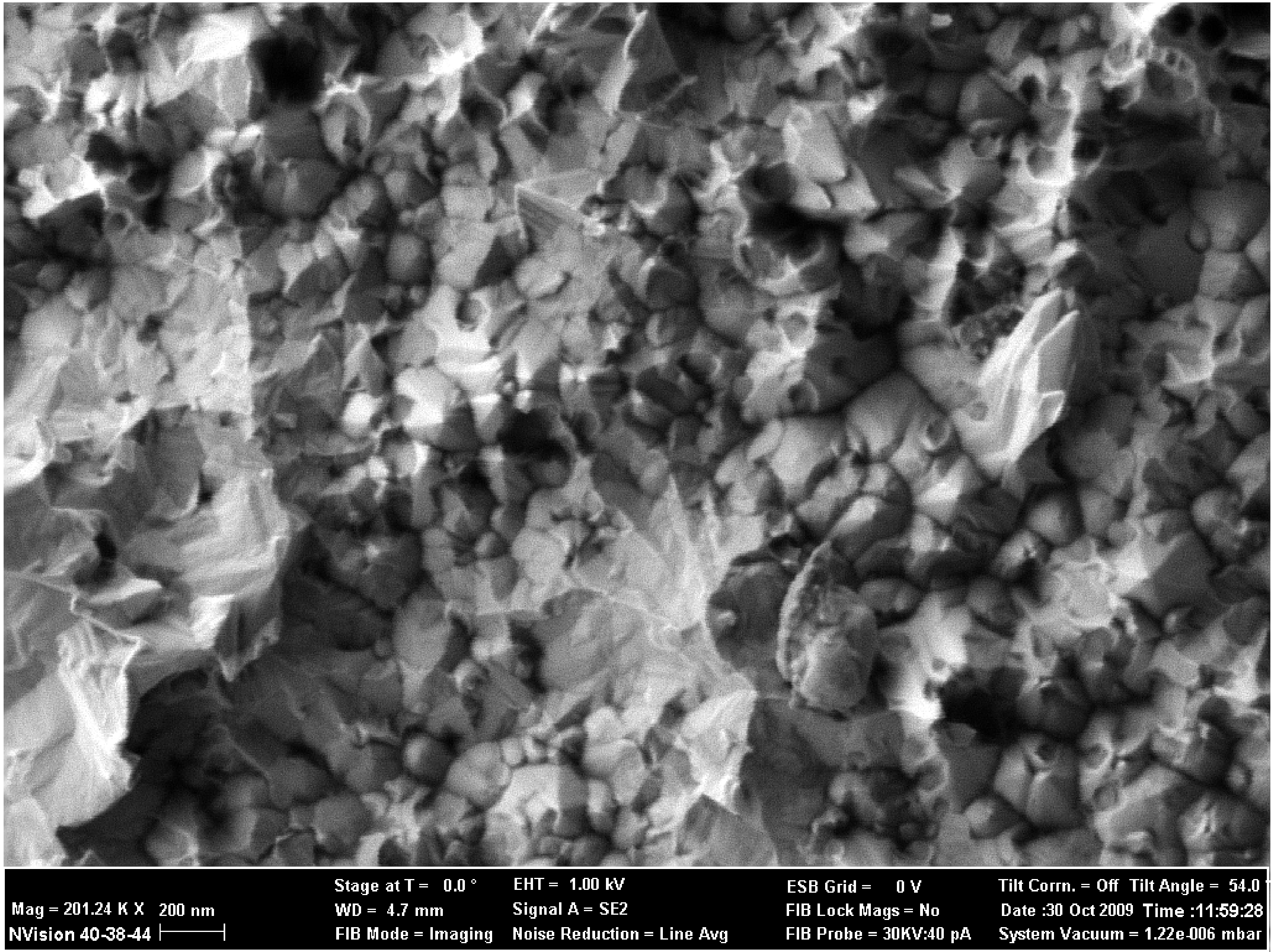
Asahi type-W TCO

[N.Taneda, T. Oyama and K. Sato,
Proceedings of Intenational PVSEC-17, 2007]

- Can metal nanoparticles offer an alternative scattering mechanism?

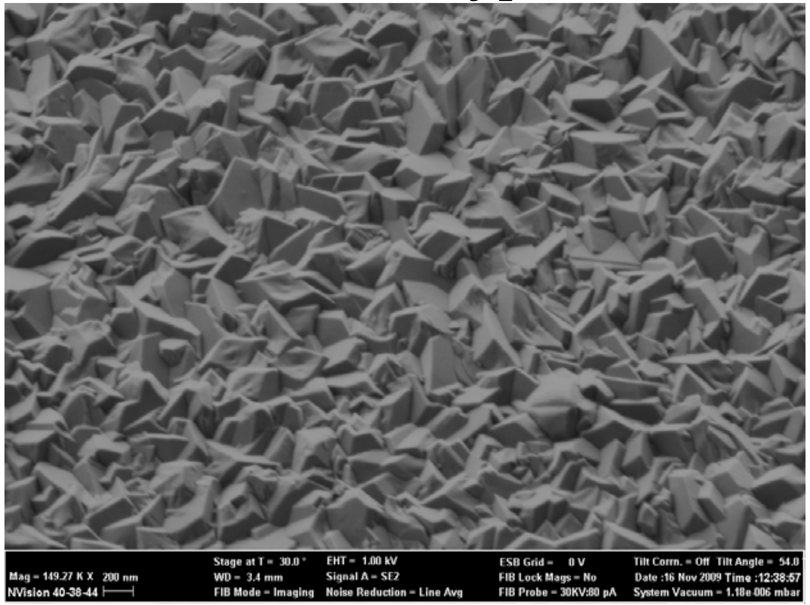
White-light angular scattering

EPV 386

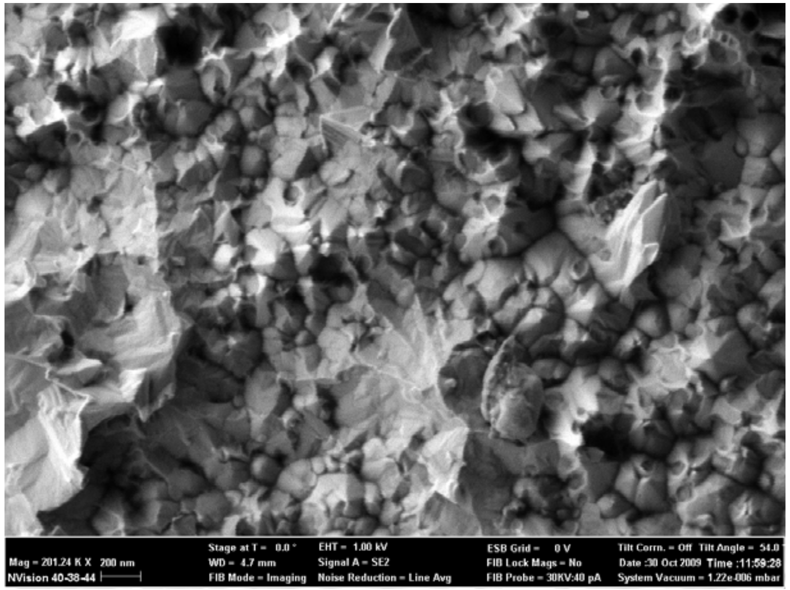


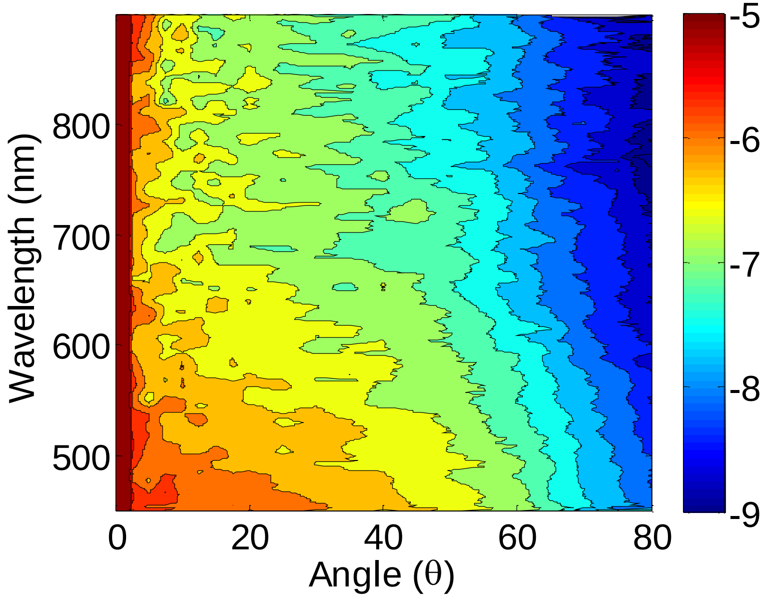
White-light angular scattering

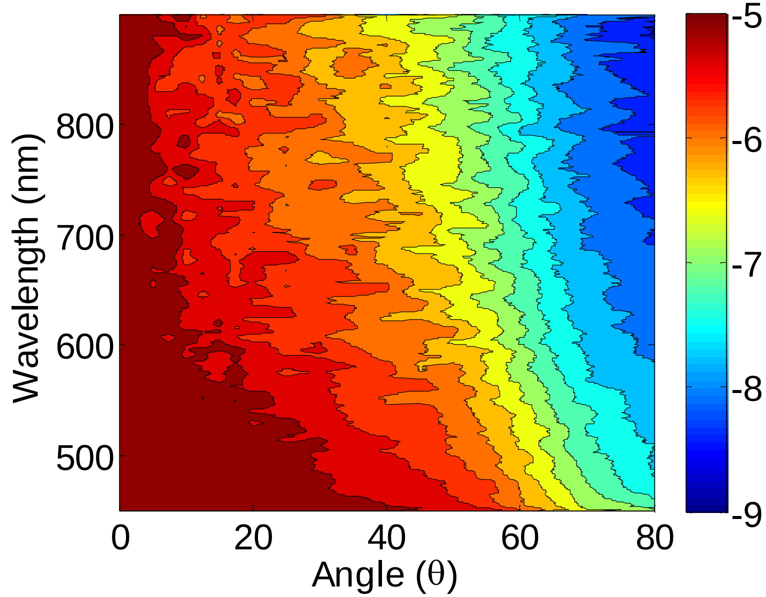
Asahi “U” type



EPV 386







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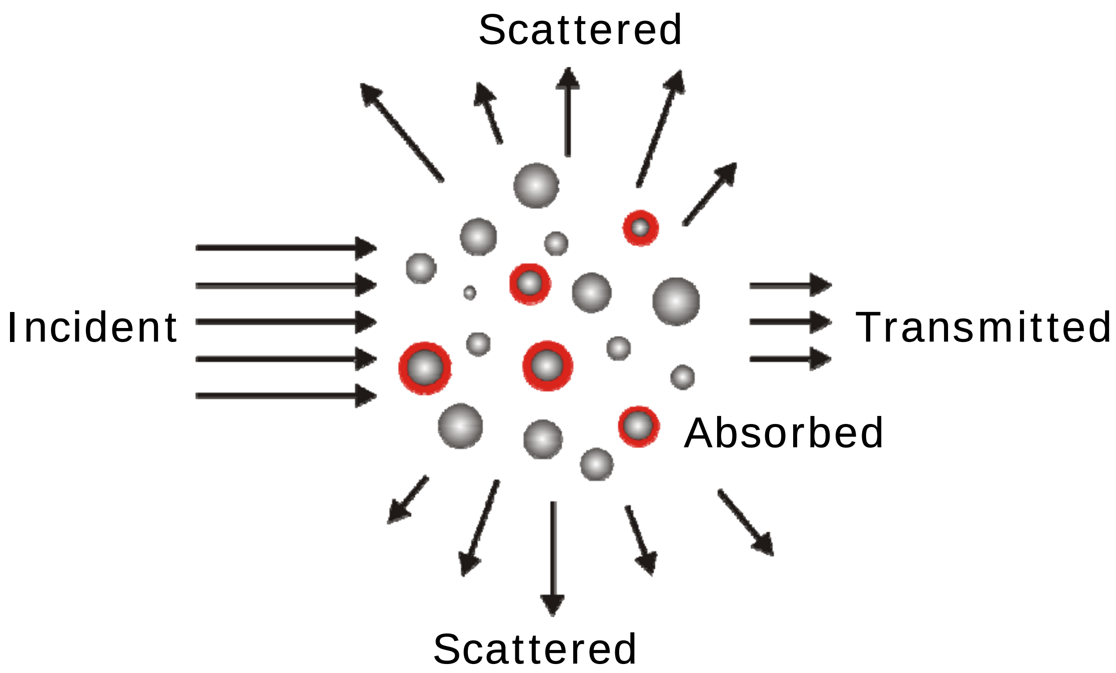
Plasmonic Light-trapping

Can metal nanoparticles offer an alternative scattering mechanism?

Plasmonic light-trapping

- The interaction of light with metal nanoparticles can lead to the generation of localised surface plasmons (LSP).



Extinction = Scattering + Absorption

Simulations

Spheres : Mie theory codes (BHMIE and BHCOAT)
(Bohren and Huffmen)

Spheroids : Separation of variables (SVM)
(Voshchinnikov and Farafonov)

Prisms etc : Discrete Dipole Analysis (DDA) (DDSCAT)
(Draine and Flatau)

(refractive index data taken from Palik)

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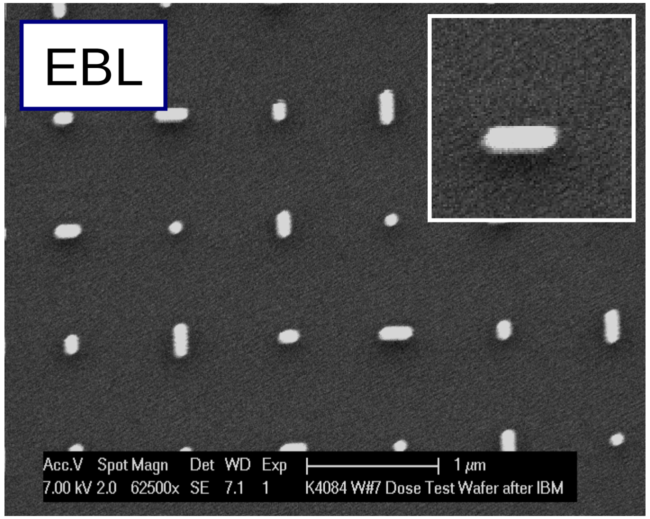
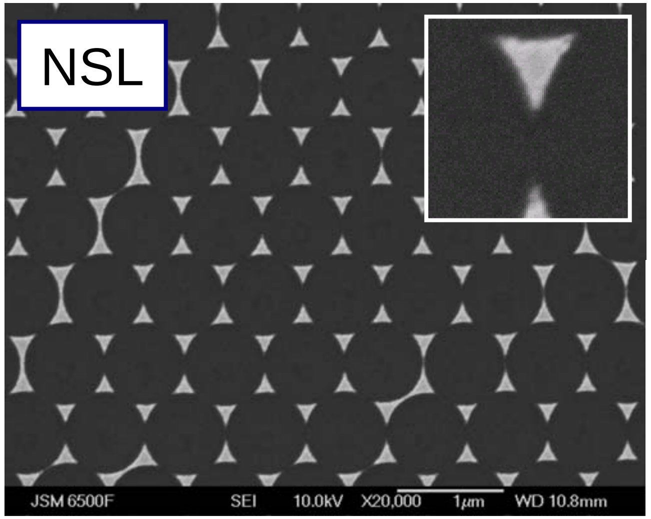
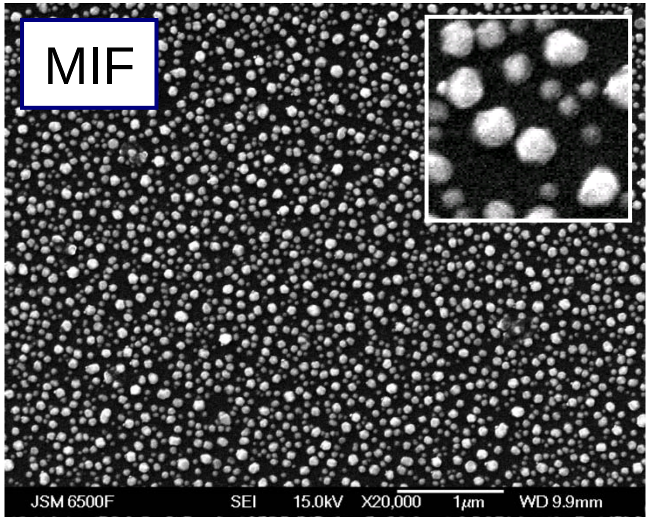
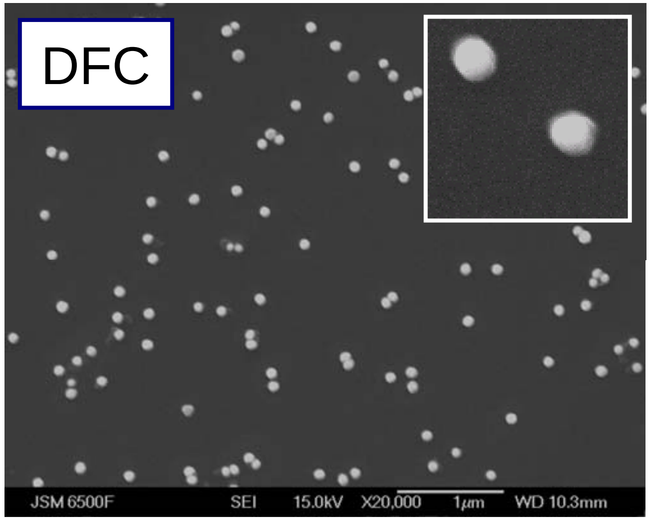
Fabrication of metal nanoparticles









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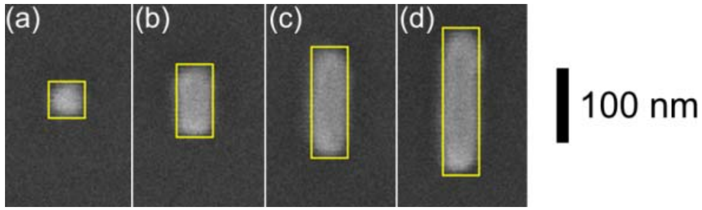
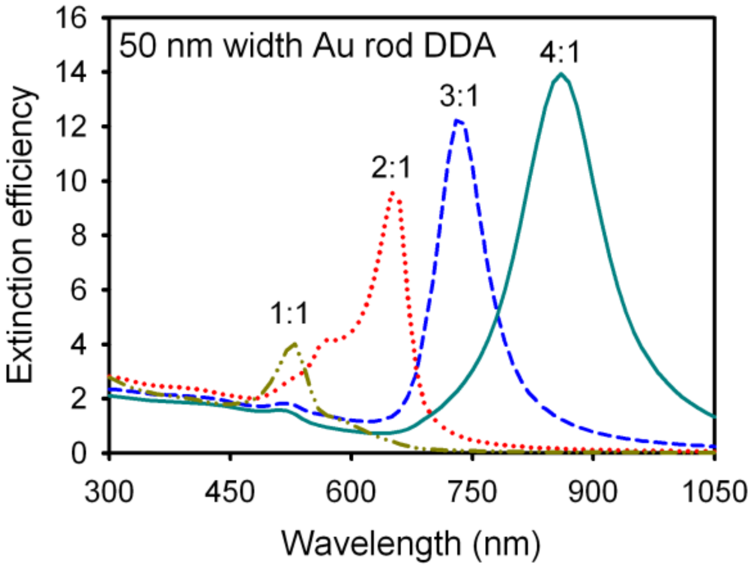
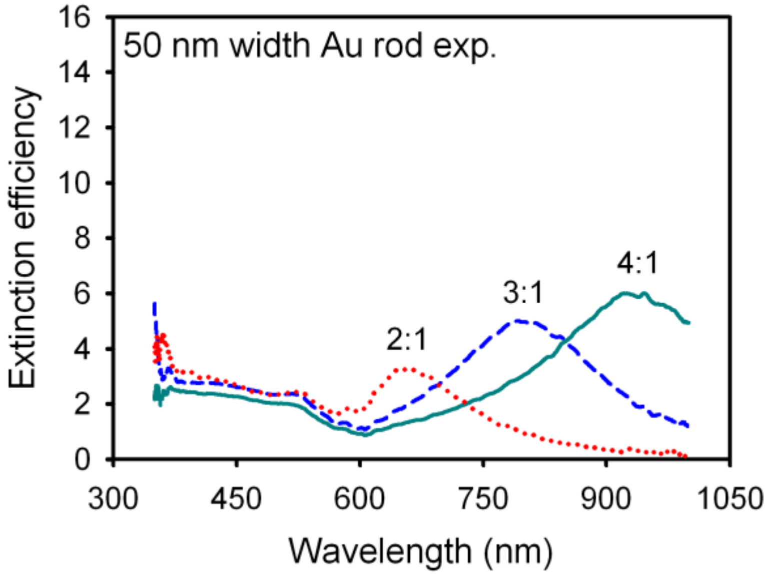
Electron-beam lithography: aspect ratio



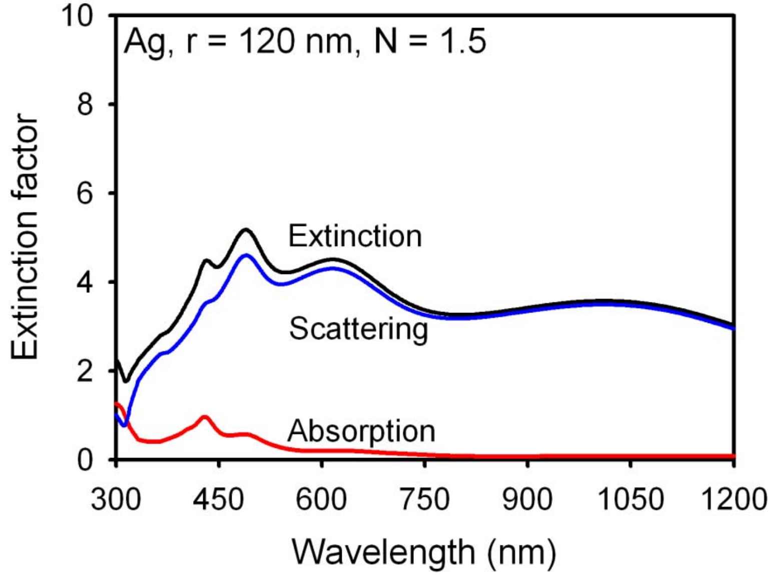




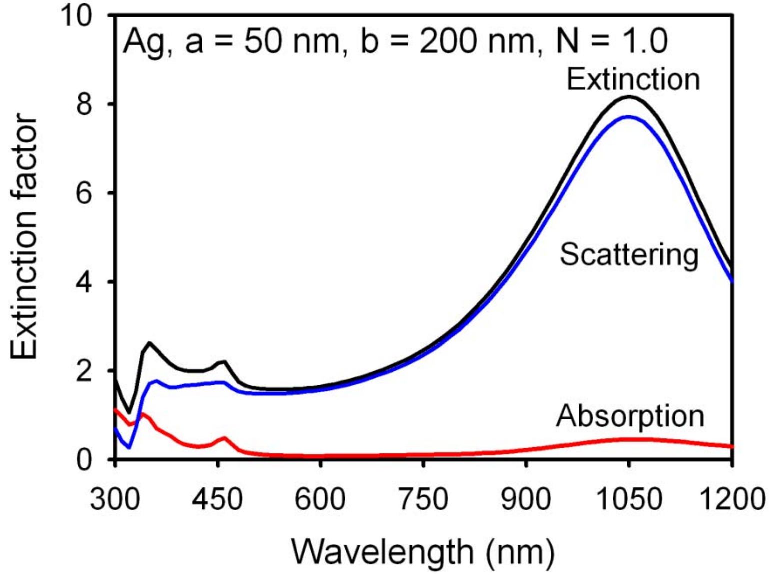
- rectangles can be produced (chemically) and offer excellent extinction at near bandedge

Optimized scattering

<u>Spheres</u>



<u>Spheroids</u>



Small particles are highly absorbing, large particles highly scattering

Absorption : good for organic, bad for inorganic

Scattering : good for all pv (part of light-trapping scheme)

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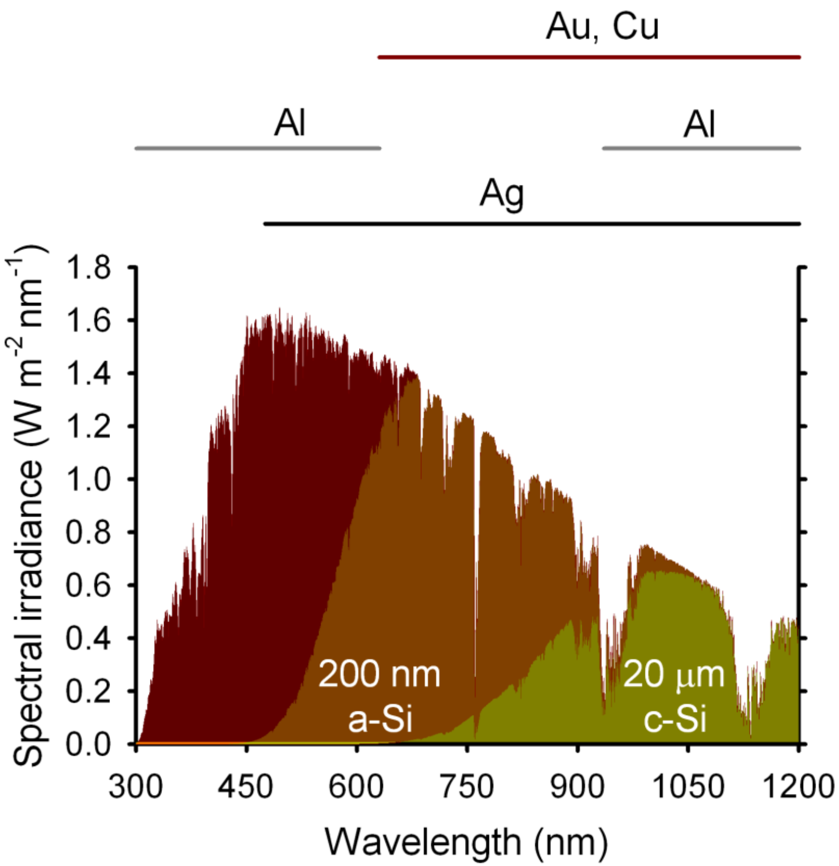
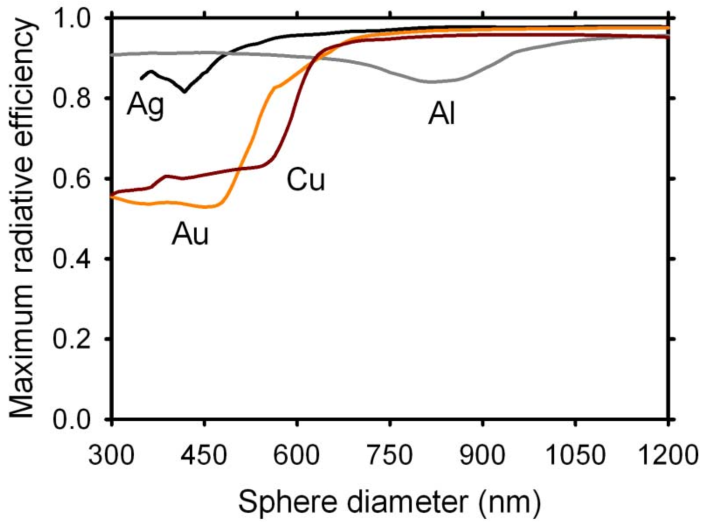
Choice of metal

Qrad > 0.9



Spectrum present at rear of two devices



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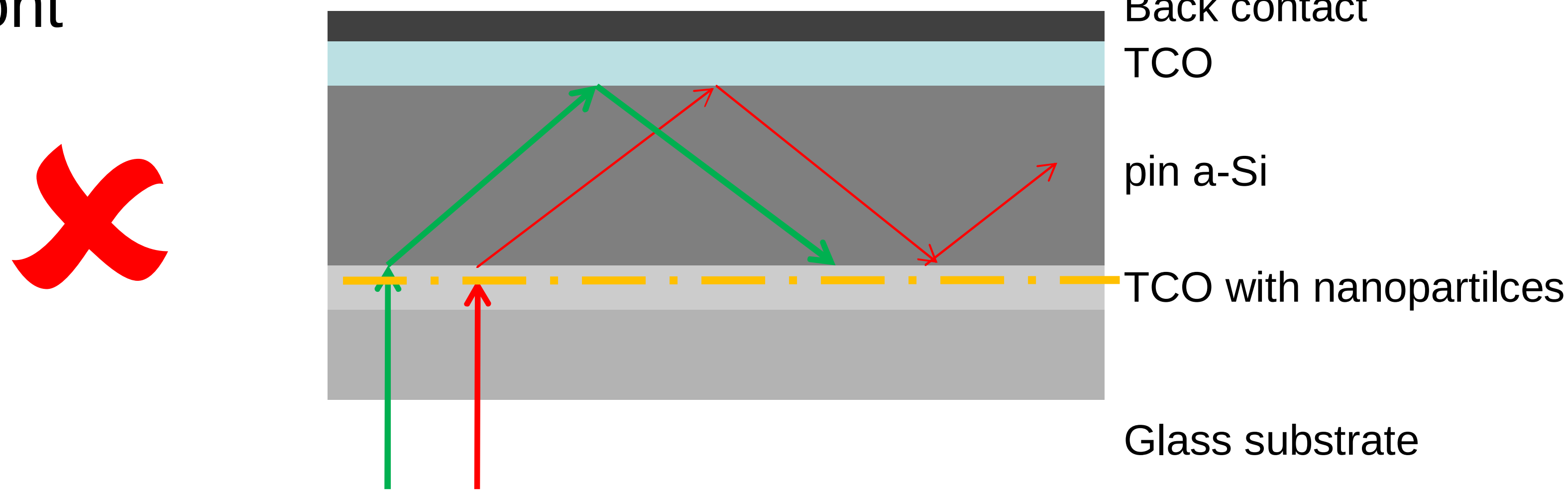
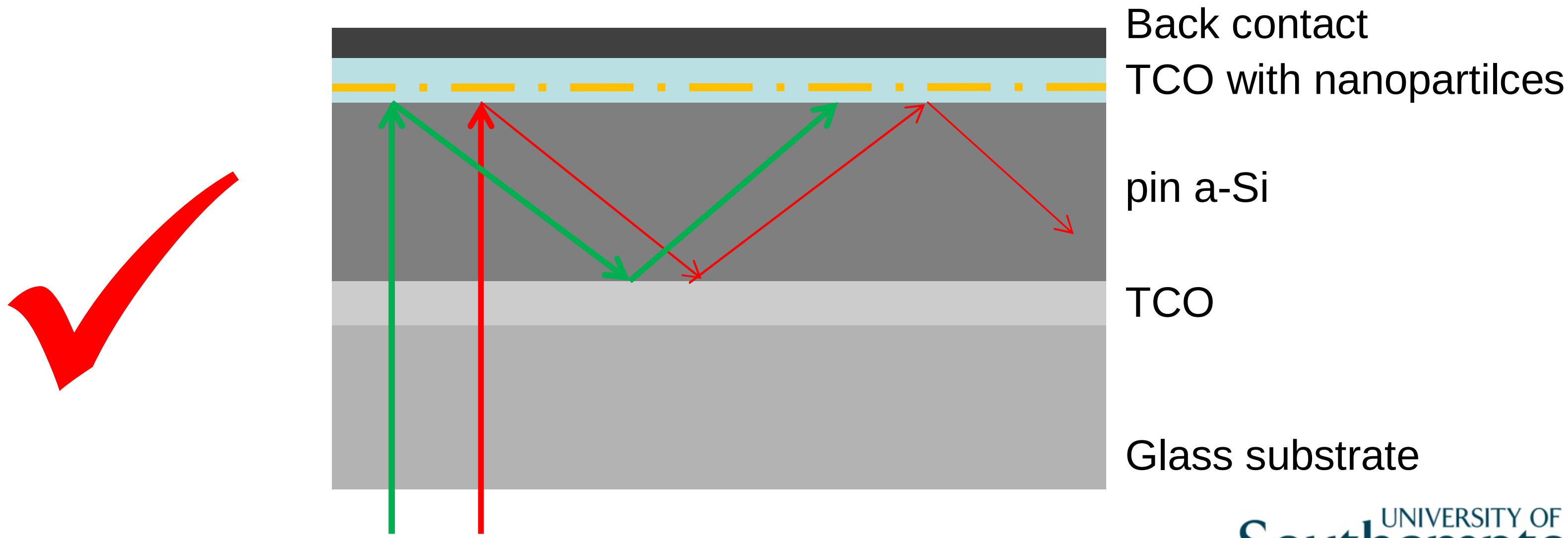
“Plasmonic” a-Si:H solar cells

Front



Back



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Design Rules

You should make sure you :

- chose a particle size and shape that **maximises scattering** in the region of low absorption (i.e. the band edge)
- **minimise absorption** in the metal across entire spectral range (assuming multiple scattering events small absoprtion will be multiplied 10 fold)
- **select the metal carefully**
- insert the **plasmonic layer at the back of the device** (short wavelength absorption is unavoidable, avoids surface reflection)
- use **large asymmetric particles** as this produces high scattering efficiency at long wavelengths
- **spread the particles about** (coupling leads to loss)
- **randomly distribute particles** (avoid diffraction) or else take diffraction into account.
- **randomly orientate particles** (polarization) or else have vertical & horizontal features
- understand that your metal nanoparticles change the optical properties of the TCO they sit in (consider reflection and coupling to back contact and antireflection)

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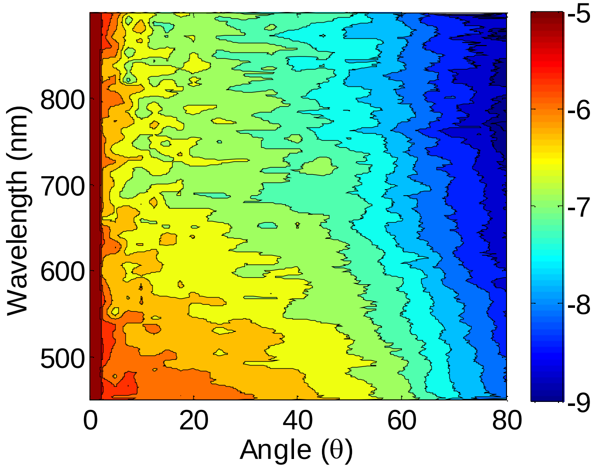
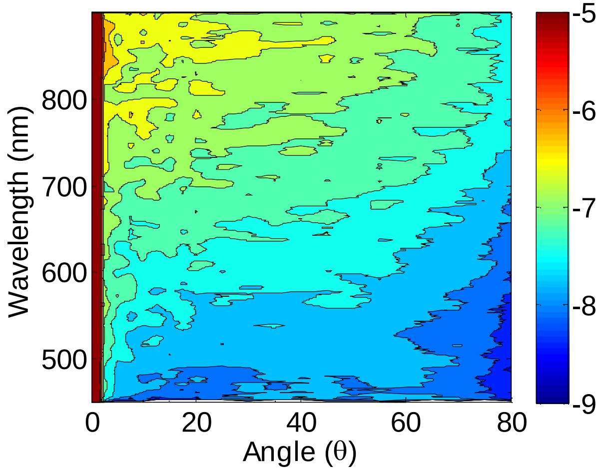
Conclusions

- Plasmonic enhancement of an inorganic thin film solar cell has yet to be demonstrated
- First thin film "plasmonic devices" will exploit scattering in conjunction with texturing





- Enhanced absorption may feature in organic systems (will be harder to use for inorganic)
- Second generation of inorganic plasmonic devices might utilise preferential scattering and diffraction to allow ultra-thin devices

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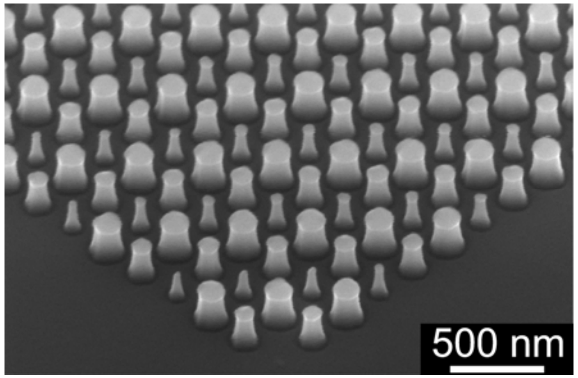
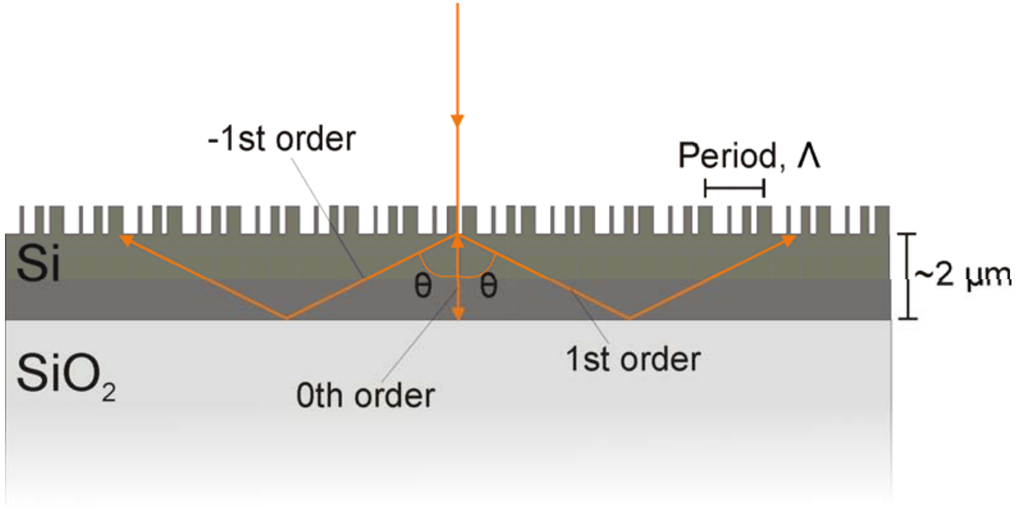
Photonic Light-trapping

“Photonic” light-trapping

- We’ve looked at random scattering and plasmonic scattering
- The third light-trapping technique could be diffraction
- Techniques commonly used in photonics for coupling in waveguides





- We have found that blazed diffraction gratings can be effective (90%) for 200nm spectral range
- rather expensive to produce for little benefit

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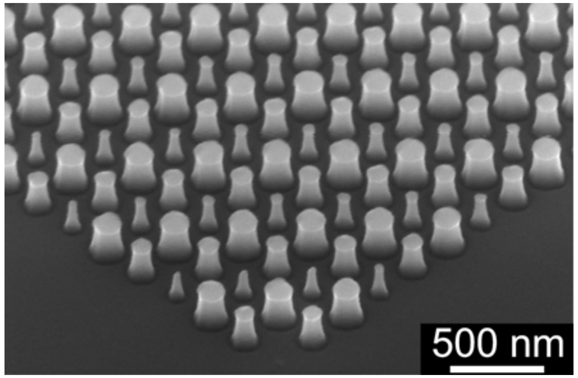
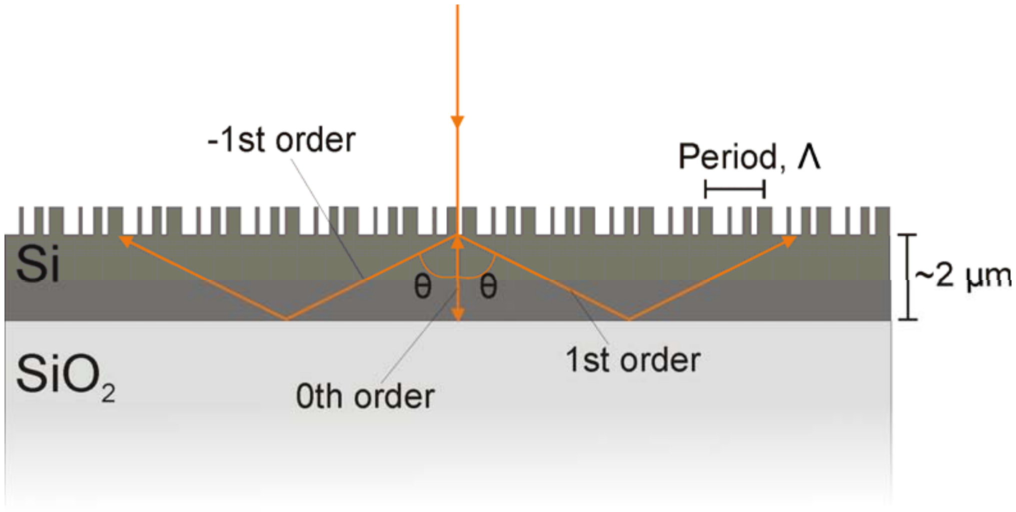
"Photonic" light-trapping

- We've looked at random scattering and plasmonic scattering
- The third light-trapping technique could be diffraction





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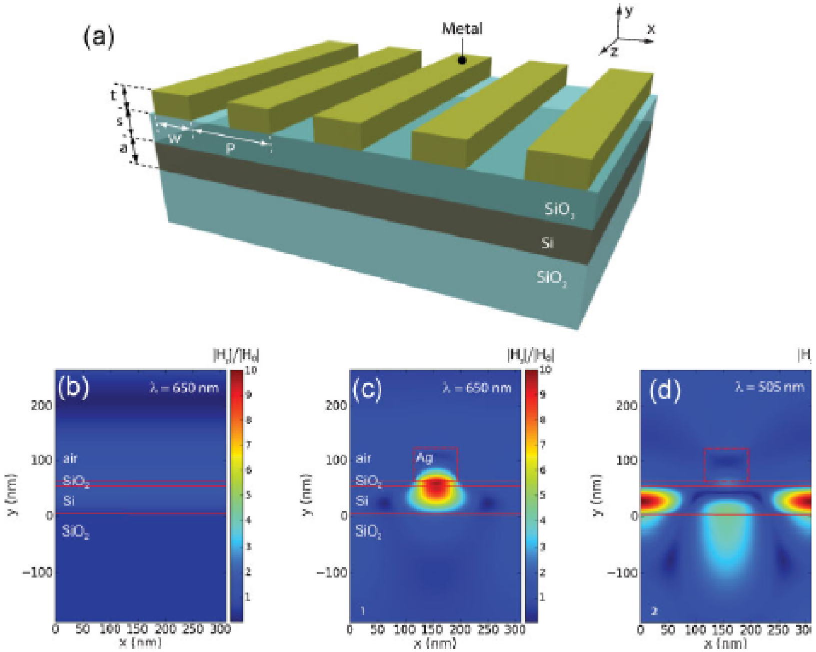
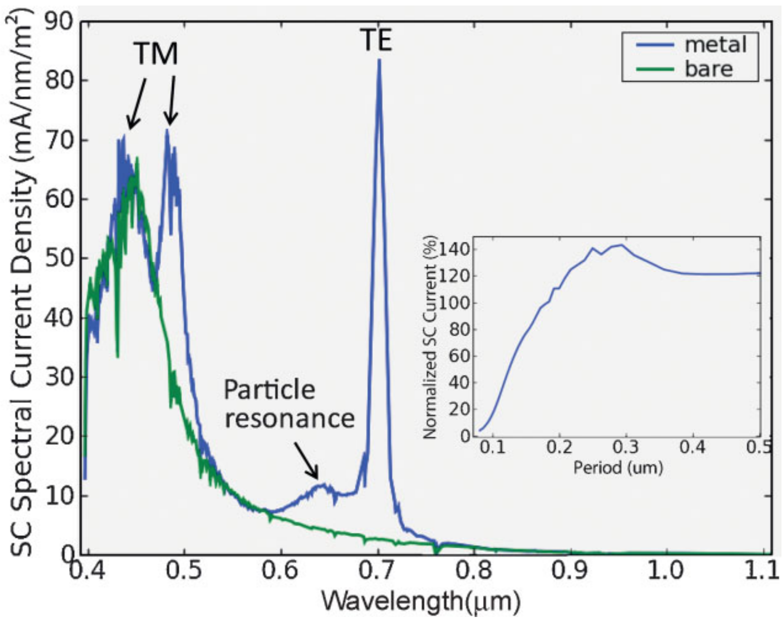
Plasmonic + Photonic Light-trapping

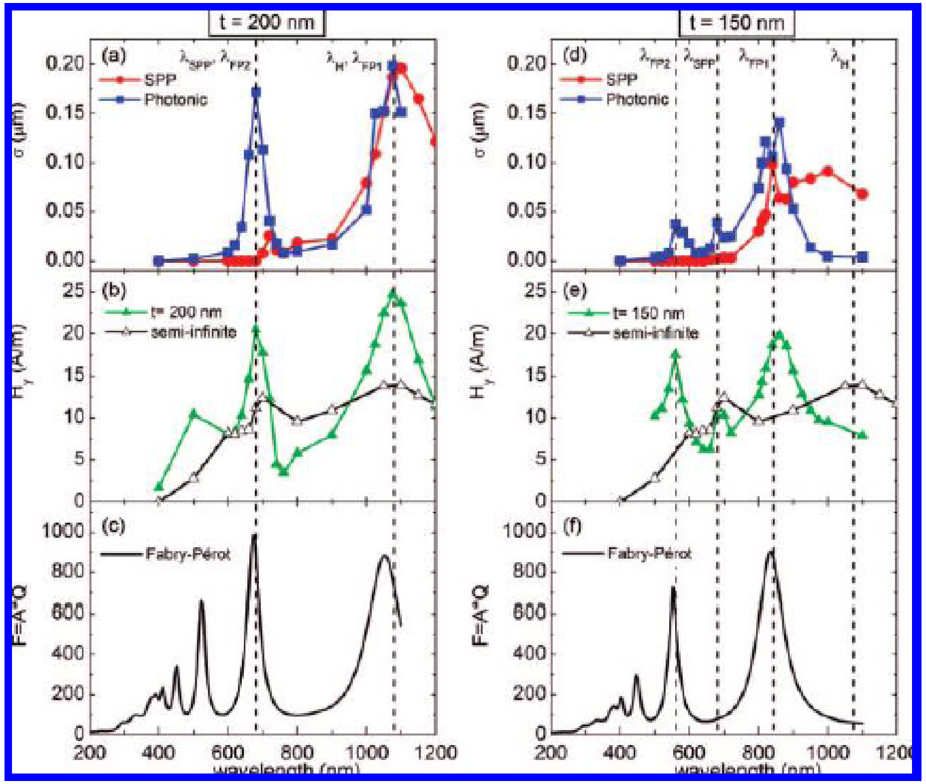
Gratings

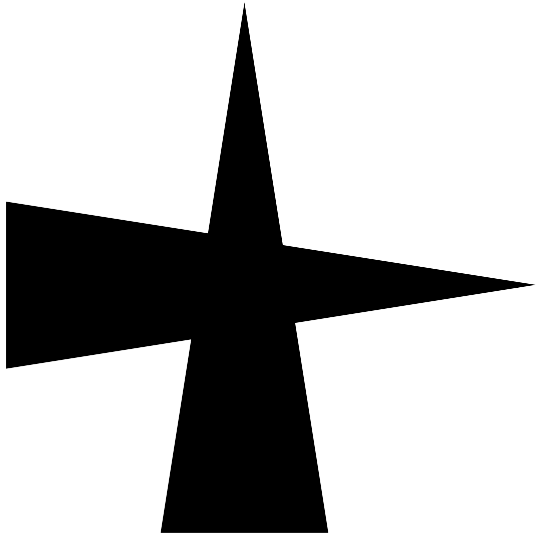


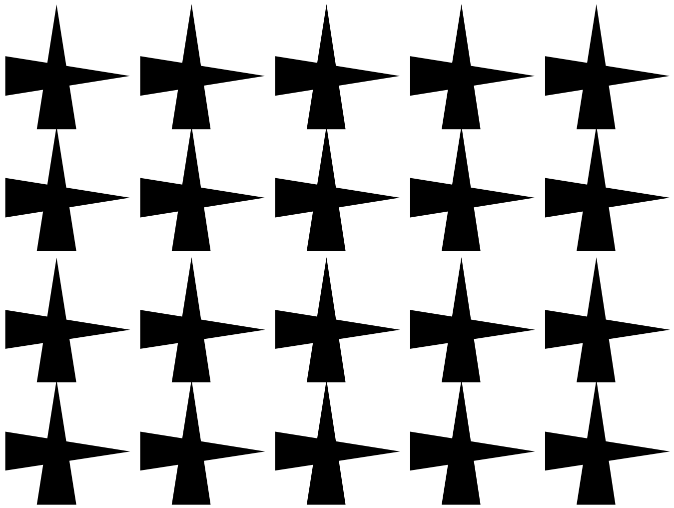
Stanford University



Grating Plasmonics



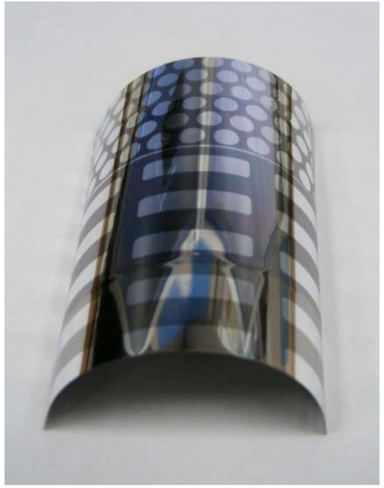


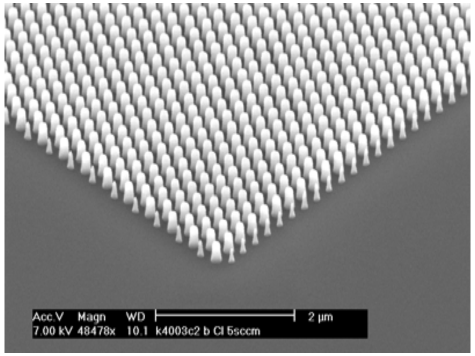


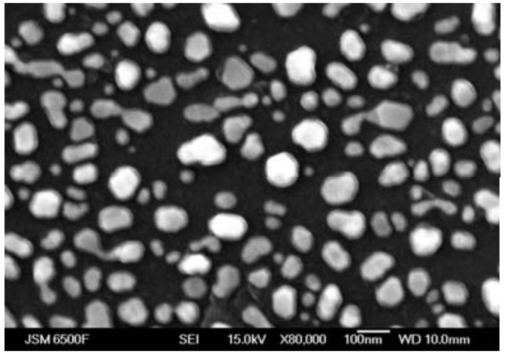
Attwater group

Conclusions

- Nanotechnology and photonics increasingly important to PV
- Challenges are
  - "self-organised" fabrication
  - integration into fabrication sequence
  - reliability reproducibility of nano processes







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