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Improvement of Light Trapping in Thin-Film Silicon Solar Cells by Combining Periodic and Random Interfaces

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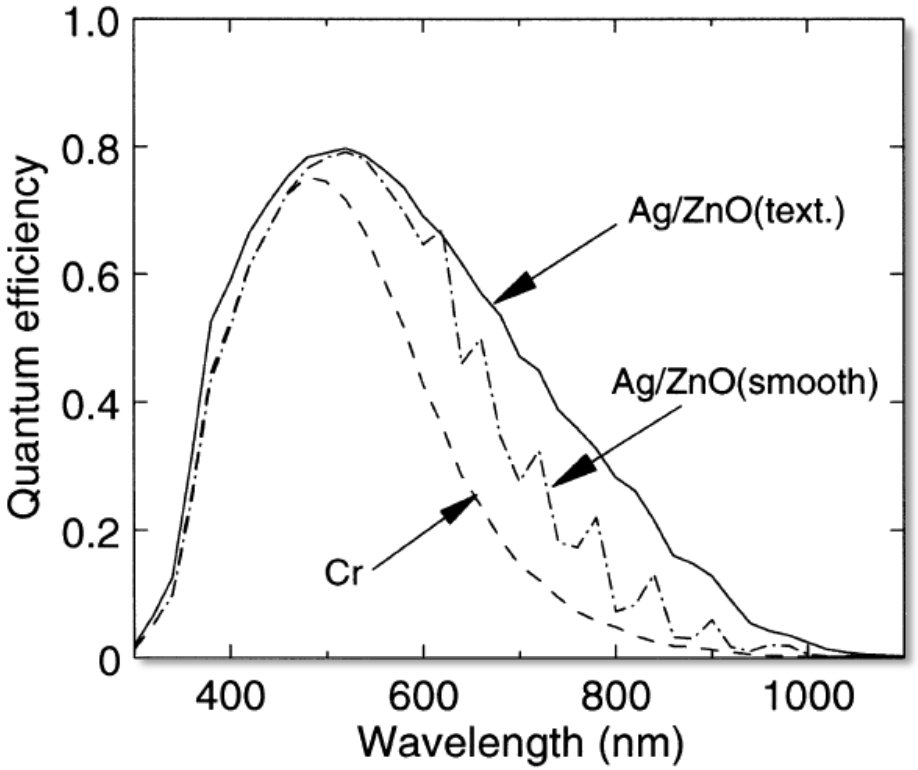
IEK5 – Photovoltaik, Forschungszentrum Jülich GmbH

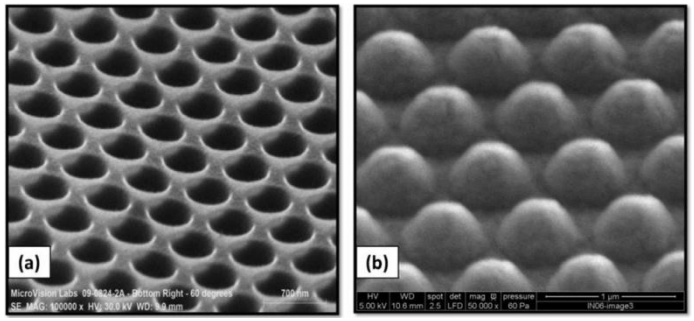
Motivation – Light Trapping in Solar Cells



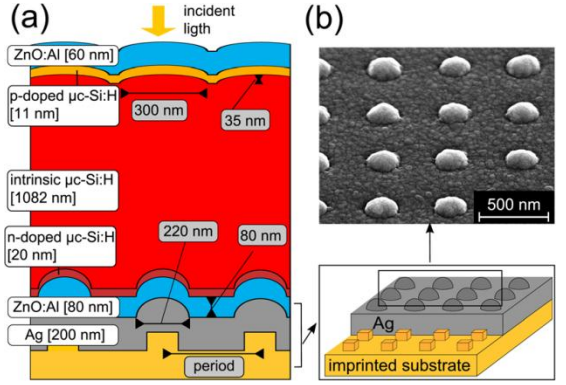
O. Vetterl et al., Solar Energy Materials & Solar Cells **62**, 97 (2000)

Motivation – Recent Work (examples)

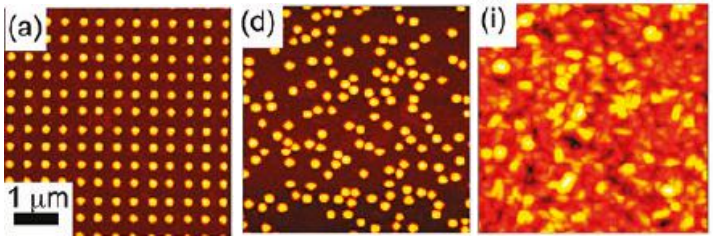
Bhattacharya et al.
Appl. Phys. Lett. 99, 131114 (2011)
"*A photonic-plasmonic structure for enhancing light absorption in thin film solar cells*"



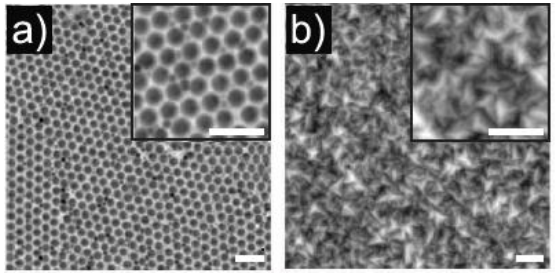
Paetzold et al.
Appl. Phys. Lett. 99, 181105 (2011)
"*Plasmonic reflection grating back contacts for microcrystalline silicon solar cells*"



Ferry et al., Nano Letters 11, 4239 (2011)
"*Optimized Spatial Correlations for Broadband Light Trapping Nanopatterns in High Efficiency Ultrathin Film a-Si:H Solar Cells*"



Battaglia et al., ACS Nano 6, 2790 (2012)
"*Light Trapping in Solar Cells: Can Periodic Beat Random?*"



Motivation – This Work

Common light-trapping concepts:

- Randomly textured interfaces
- Periodic gratings
- Periodic gratings with some disorder

Basic question:

- What is the best structure?

Try to outperform the common concepts by deeper understanding

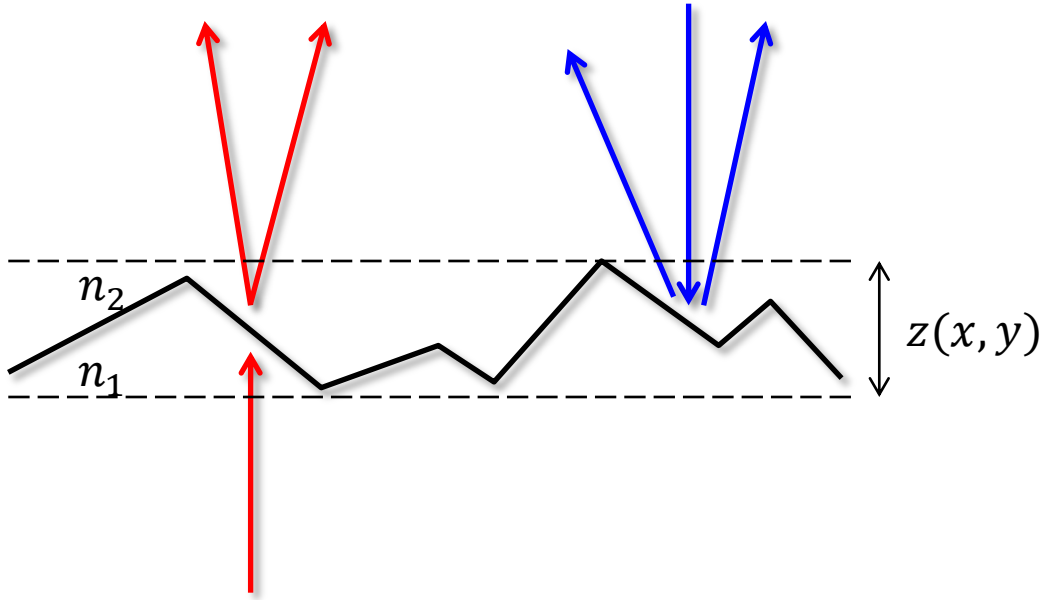
Scalar Model for Light-Trapping Efficiency

Transmission

$$\Delta\Phi = \frac{2\pi}{\lambda}(n_1 - n_2)z(x,y)$$

Reflection

$$\Delta\Phi = -\frac{2\pi}{\lambda}2n_2 z(x,y)$$



Angular Intensity Distribution:

$$AID(\Theta) \propto \sum_{k_x^2+k_y^2=k^2 \sin^2\Theta} \left|F\left\langle e^{i\Delta\Phi}\right\rangle\right|^2$$

where $F\langle \ldots \rangle$ denotes the Fourier transform

$k_x, \mathrm{k_y}$ denote the components of the wave vector

Scalar Model for Light-Trapping Efficiency

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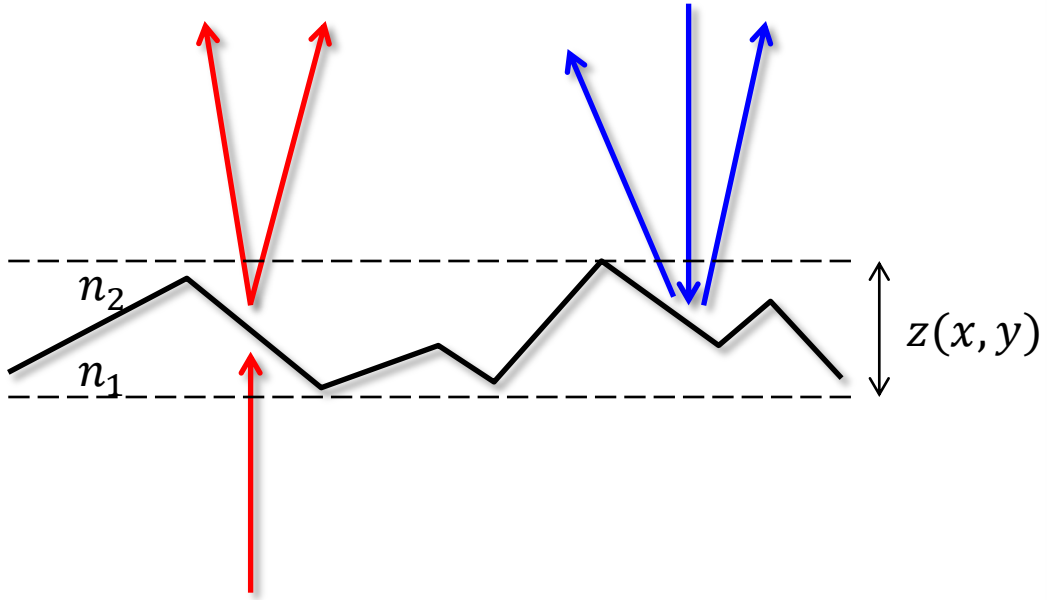

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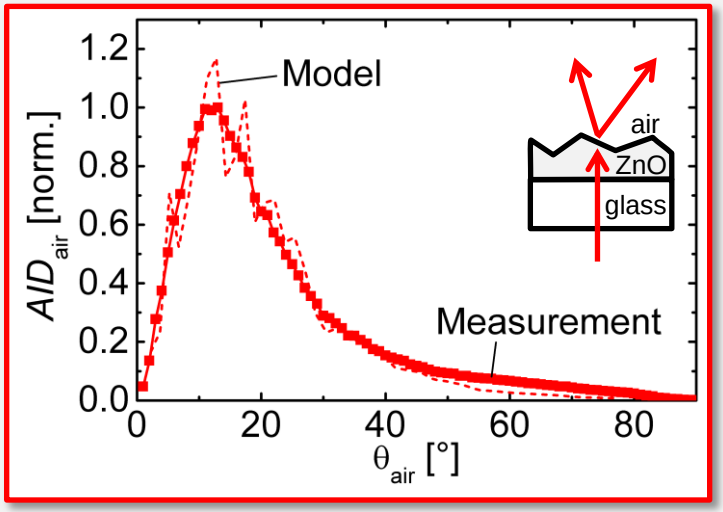
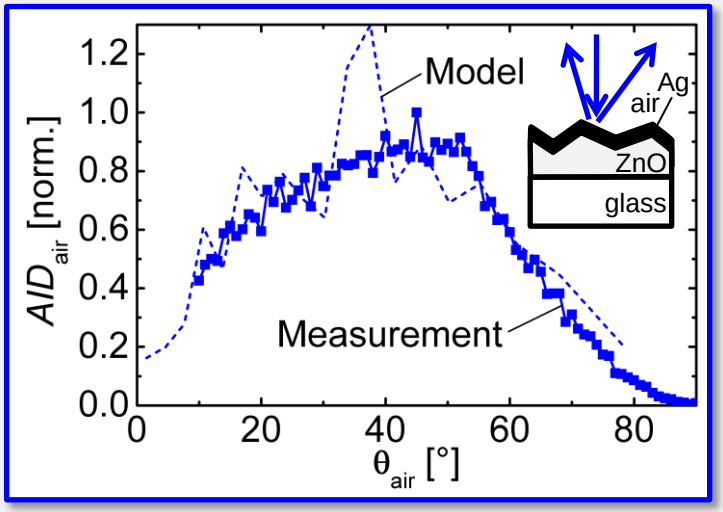
Experimental validation

Transmission



Reflection



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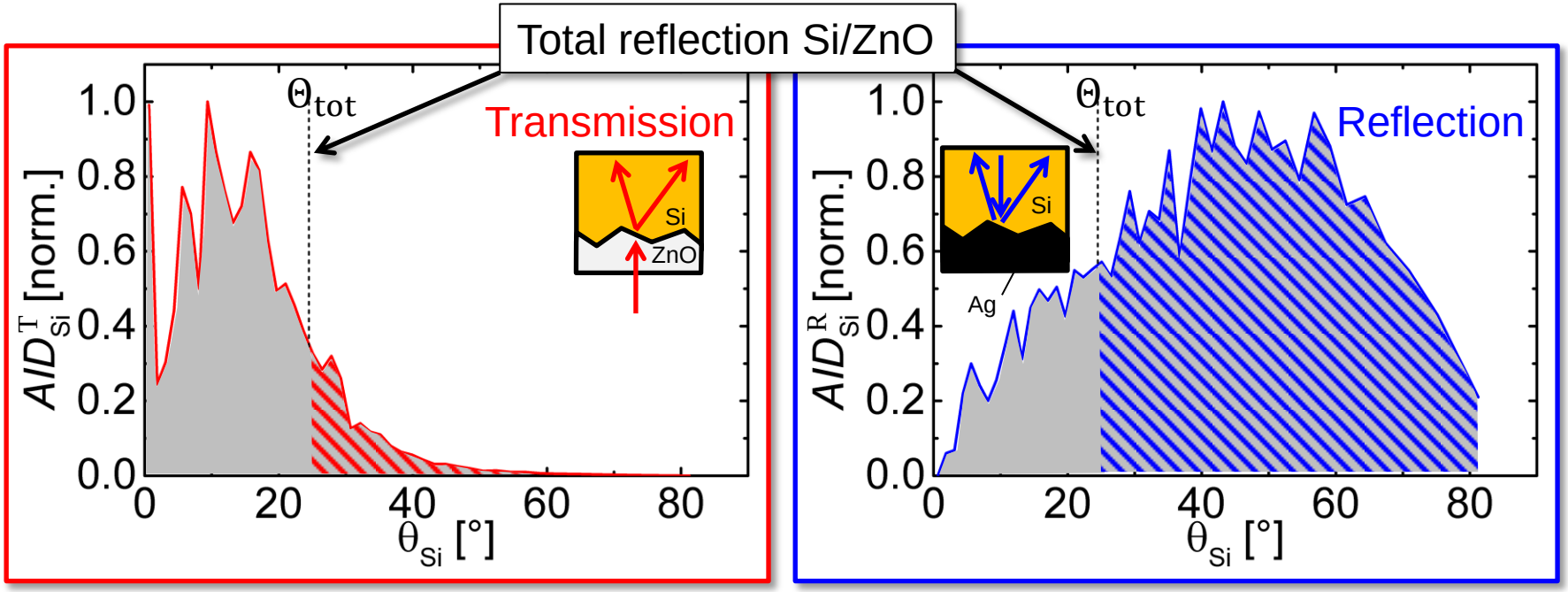


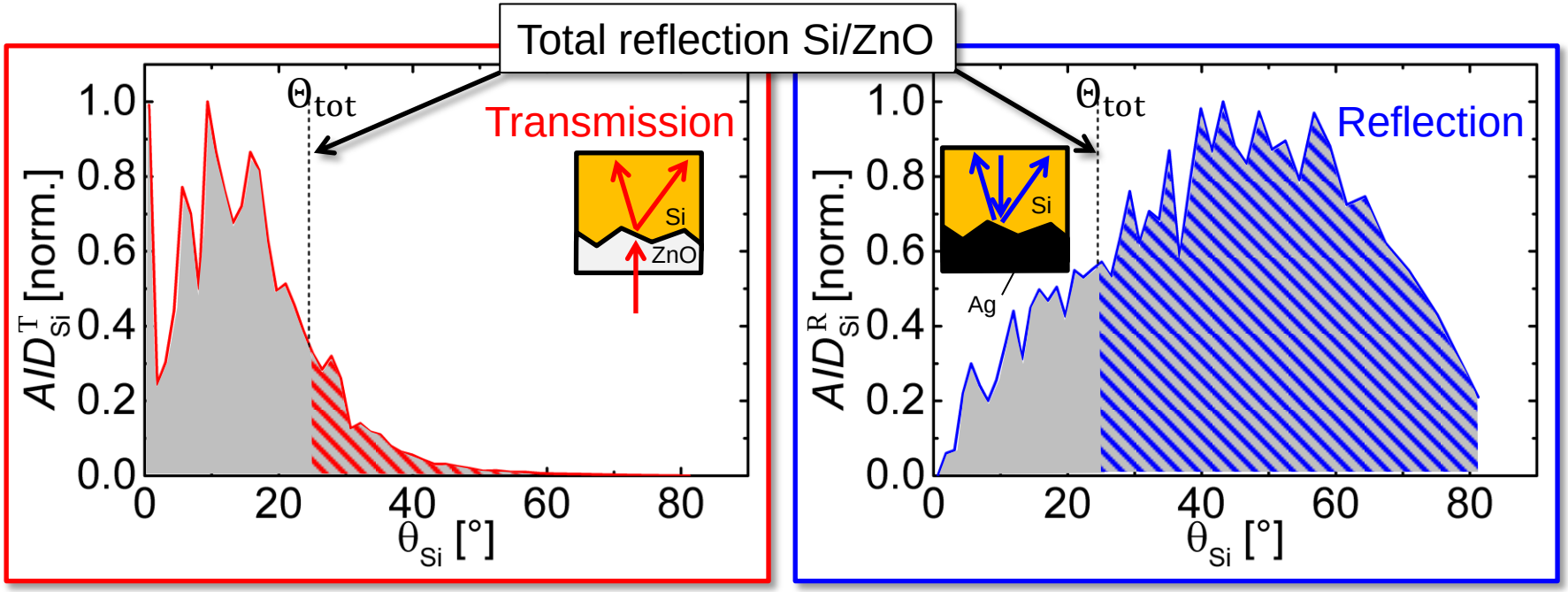
Light-**T**rapping **E**fficiency (*LTE*):

$LTE_{\mathrm{T}} =$ 

$LTE_{\mathrm{R}} =$ 

Total system: $LTE = (LTE_{\mathrm{T}} + LTE_{\mathrm{R}})/2$

Scalar Model for Light-Trapping Efficiency



Light-**T**rapping **E**fficiency (*LTE*):

$$LTE_{\mathrm{T}} = \frac{\int_{\Theta_{tot}}^{90^\circ} AID_{\mathrm{Si}}^{\mathrm{T}}(\Theta)\,d\Theta}{\int_{0^\circ}^{90^\circ} AID_{\mathrm{Si}}^{\mathrm{T}}(\Theta)\,d\Theta}$$

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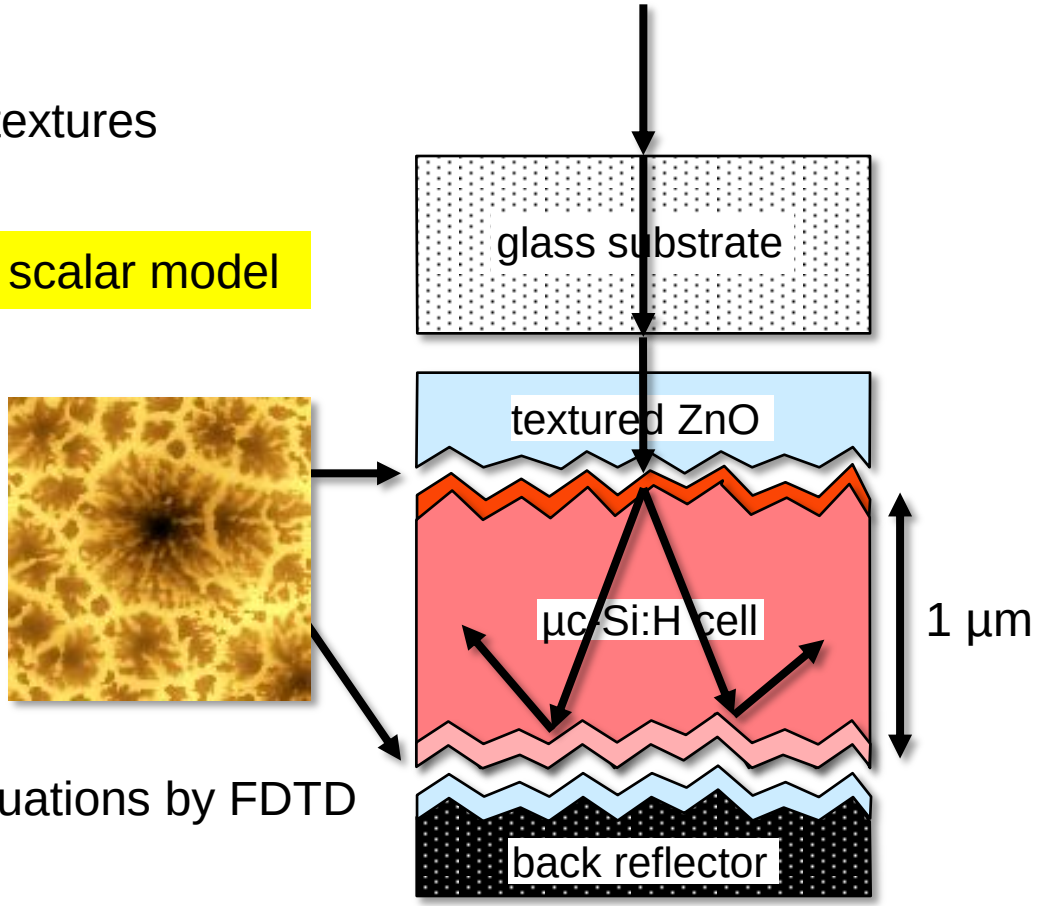
Total system: $LTE = (LTE_{\mathrm{T}} + LTE_{\mathrm{R}})/2$

Validation of the Model

Create a large variety of artificial textures

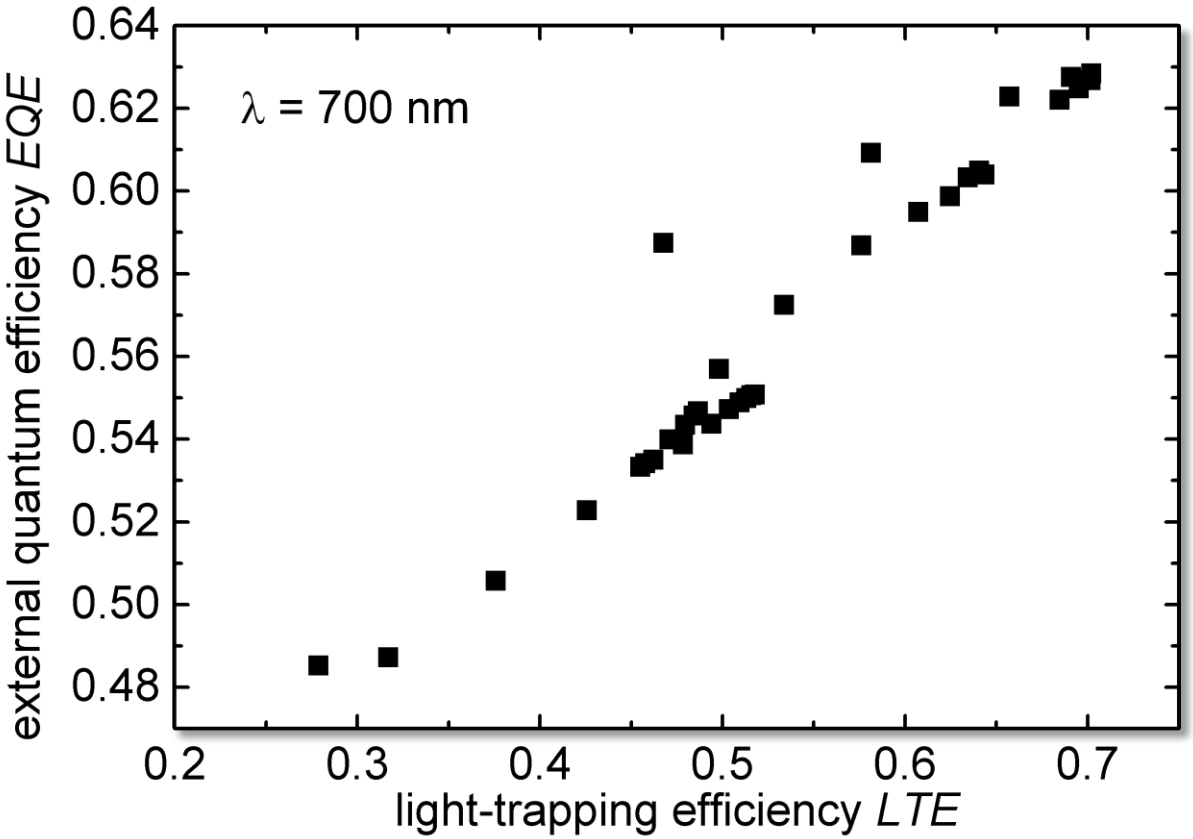
Calculate *LTE* for each texture by scalar model



Rigorous solution of Maxwell's equations by FDTD

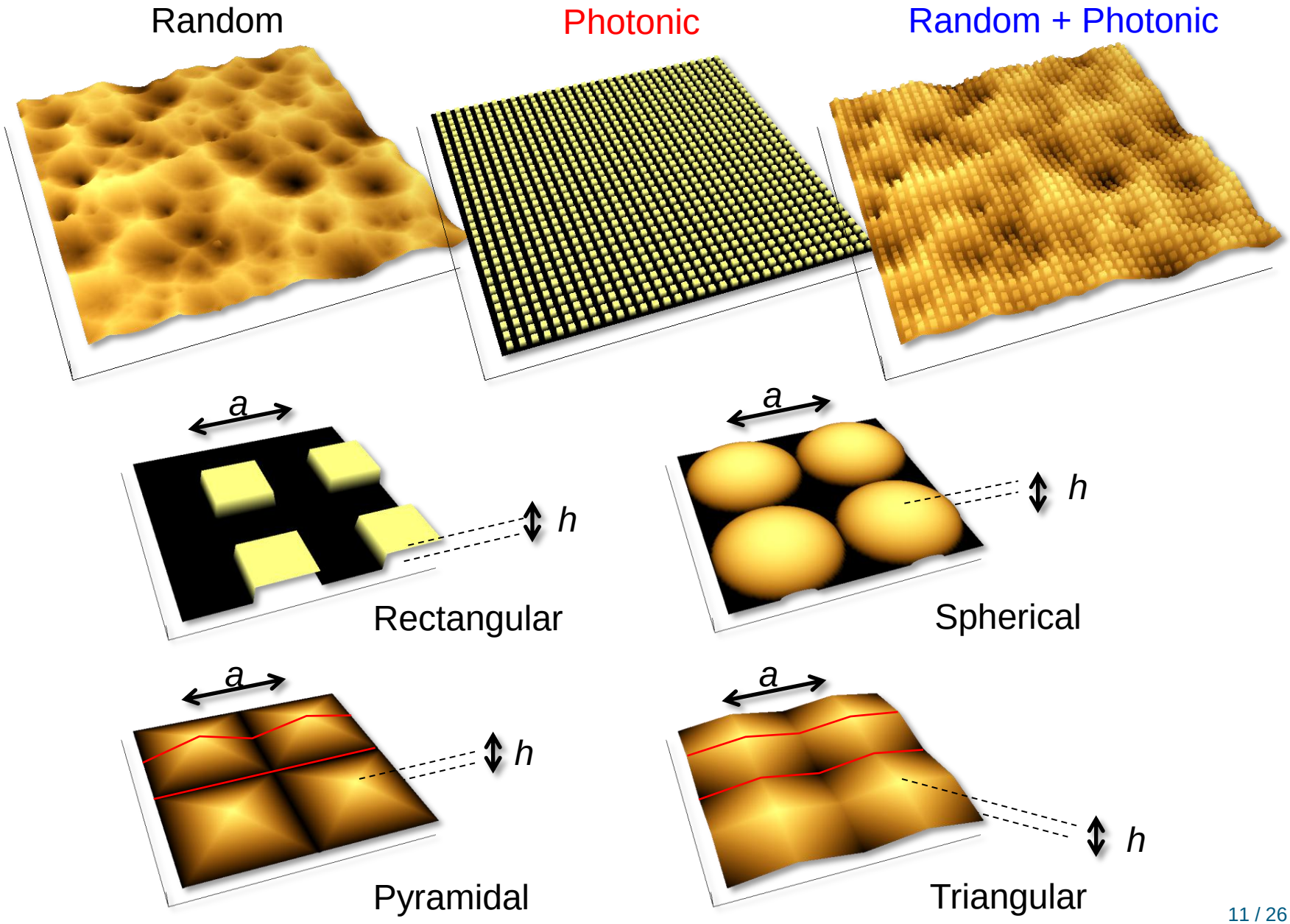
Absorptance in silicon layer (*EQE*)

Validation of the Model

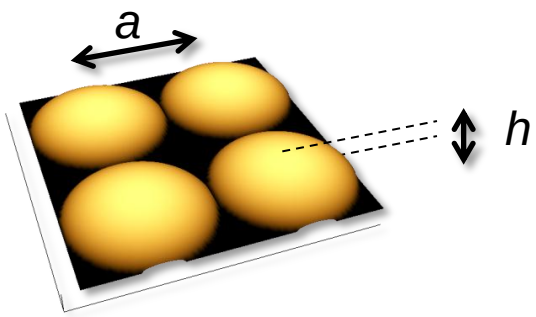


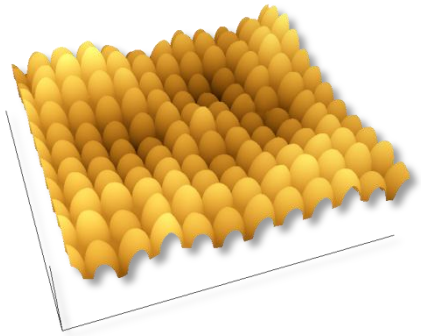
LTE from scalar model has a high predictive power

Photonic Random Textures



Optimization of Structure





Photonic texture

Photonic random texture

Initial Topography (10 µm x 10 µm)	
Flat interface	AFM measurement of “Jülich ZnO”

Varied Parameters	
grating constant *a*	0 nm – 800 nm
structure height *h*	0 nm – 800 nm
wavelength λ	600 nm – 900 nm

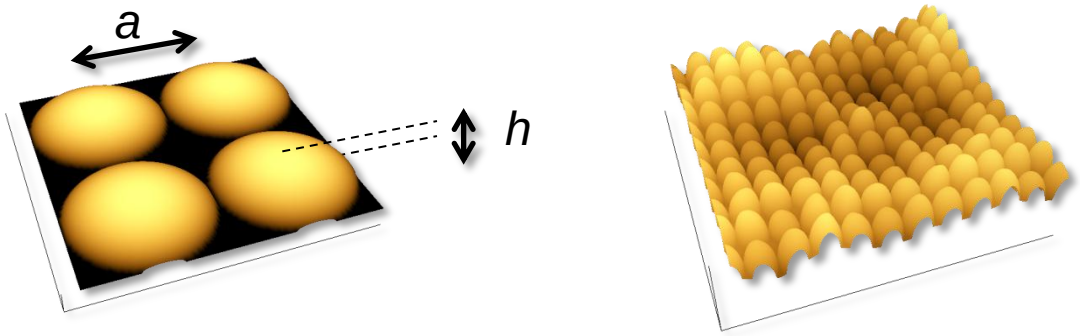
Calculate *LTE* for each texture and wavelength

- Solar cell is broadband device

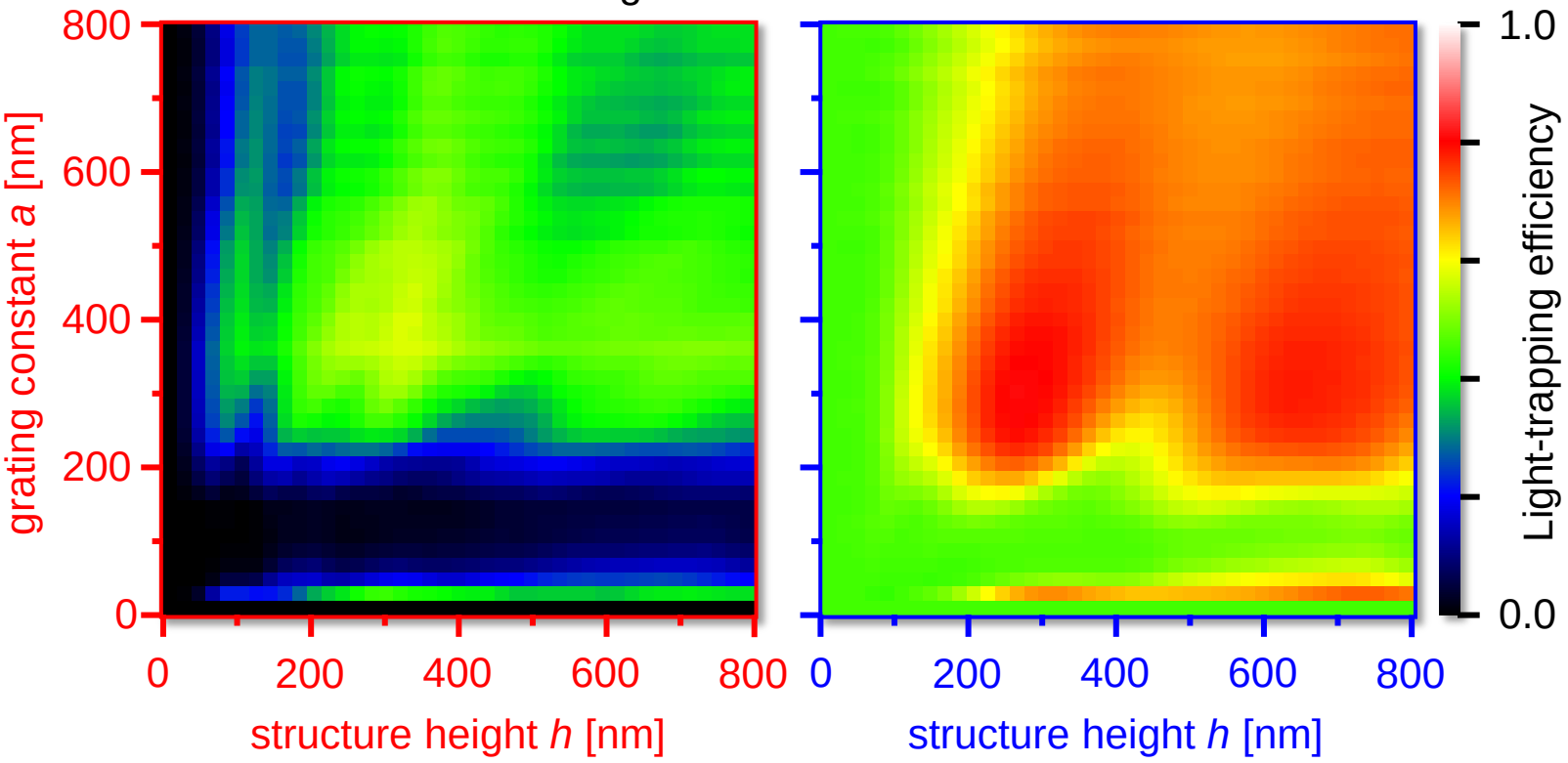
Take the spectral average

- Photonic structures are resonant

Optimization of Structure



average λ = 600 nm – 900 nm



Optimization of Structure

		a [nm]	*h* [nm]	Light-trapping efficiency [%]
reference	Random	-	-	45.7
photonic textures	Rectangular	360	160	33.1
	Spherical	360	320	57.4
	Pyramidal	800	780	44.5
	Triangular	600	700	87.8
photonic random textures	Rectangular + Random	320	180	69.3
	Spherical + Random	300	260	80.6
	Pyramidal + Random	720	700	83.4
	Triangular + Random	660	800	91.3

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Random texture always benefits from photonic structure

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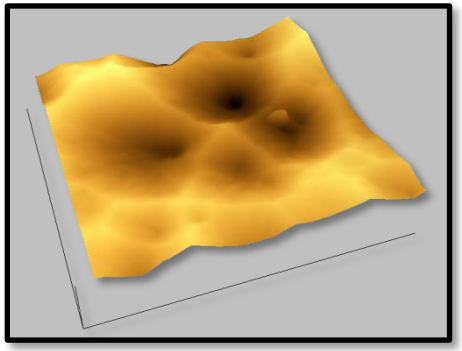
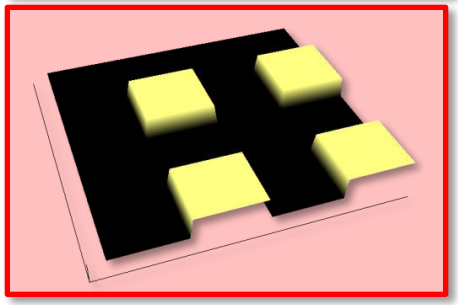
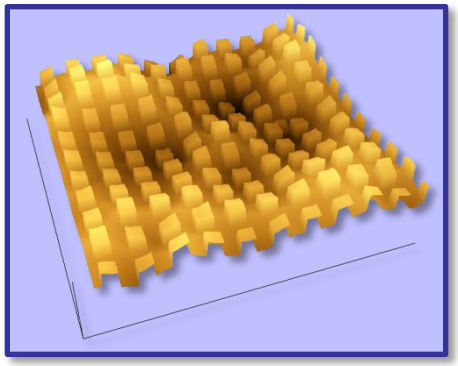
Photonic structure always benefits from random texture

Light Scattering Process







What is different between photonic and random textures?

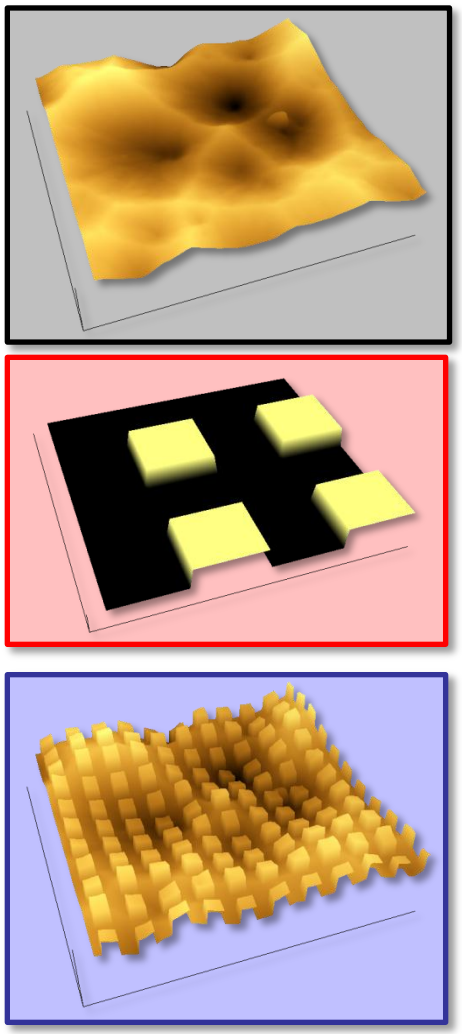
- Photonic structures have well-defined diffraction orders
- Random structures scatter into broad angular distribution

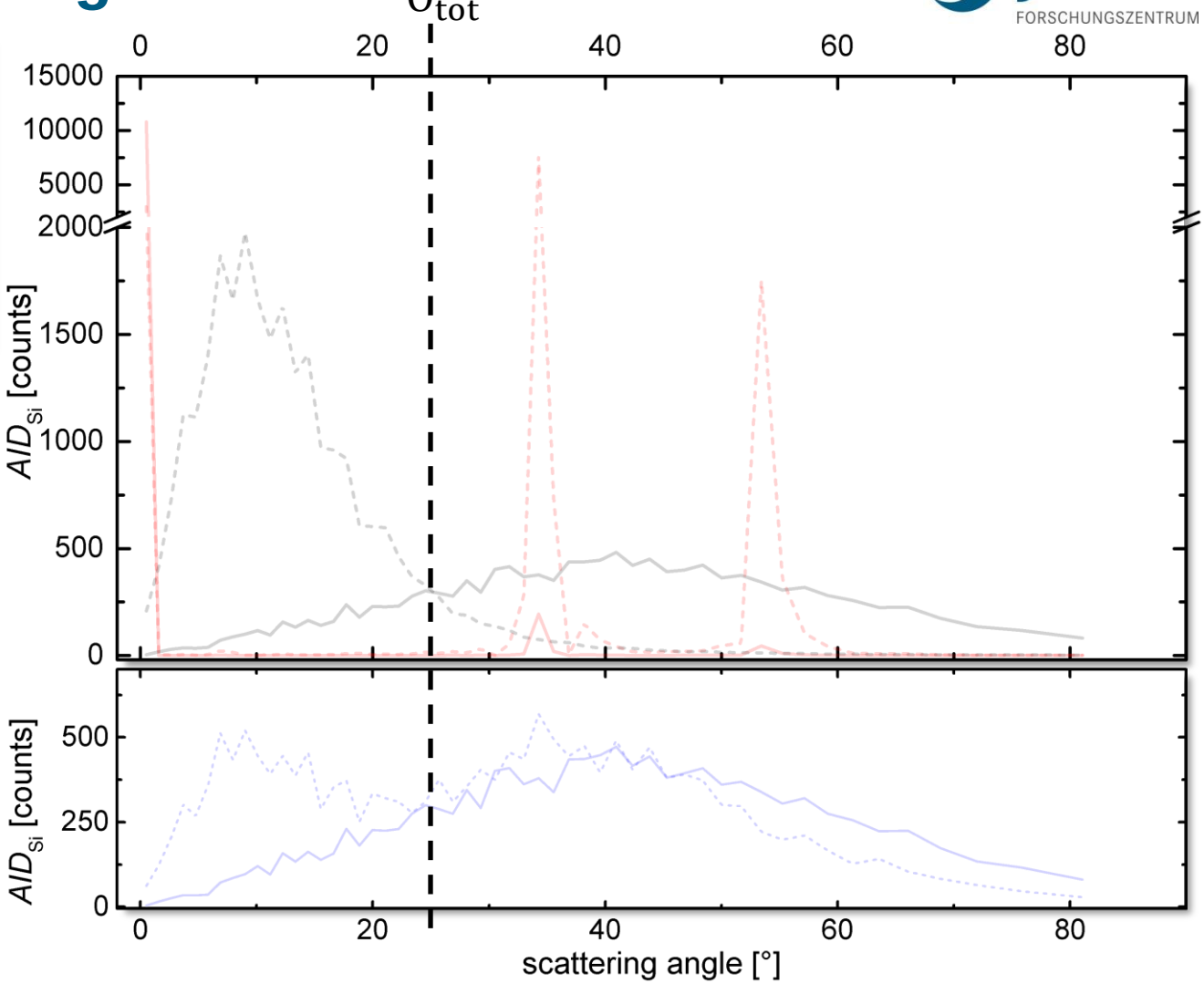
How are the efficiencies for transmission and reflection?

Is a photonic random texture more photonic or more random?

Calculate *AID* in silicon for transmission and reflection for the three different textures

Light Scattering Process





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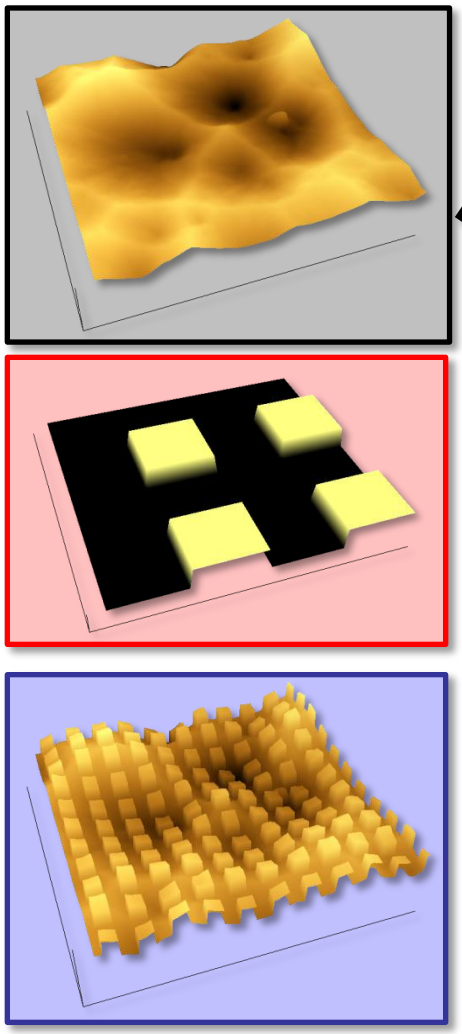

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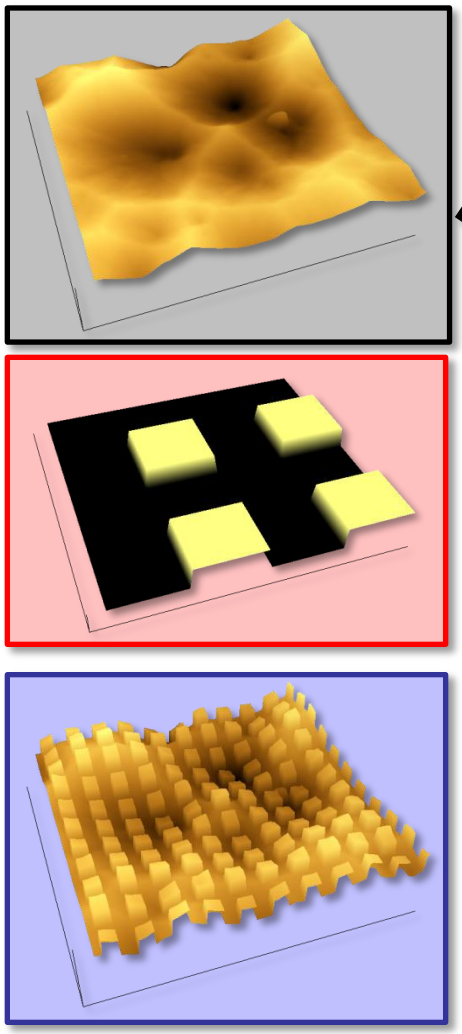

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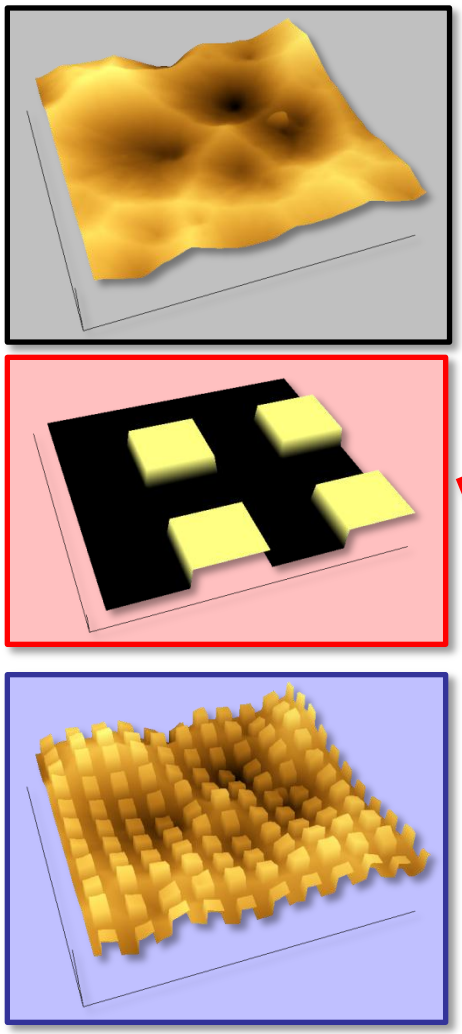

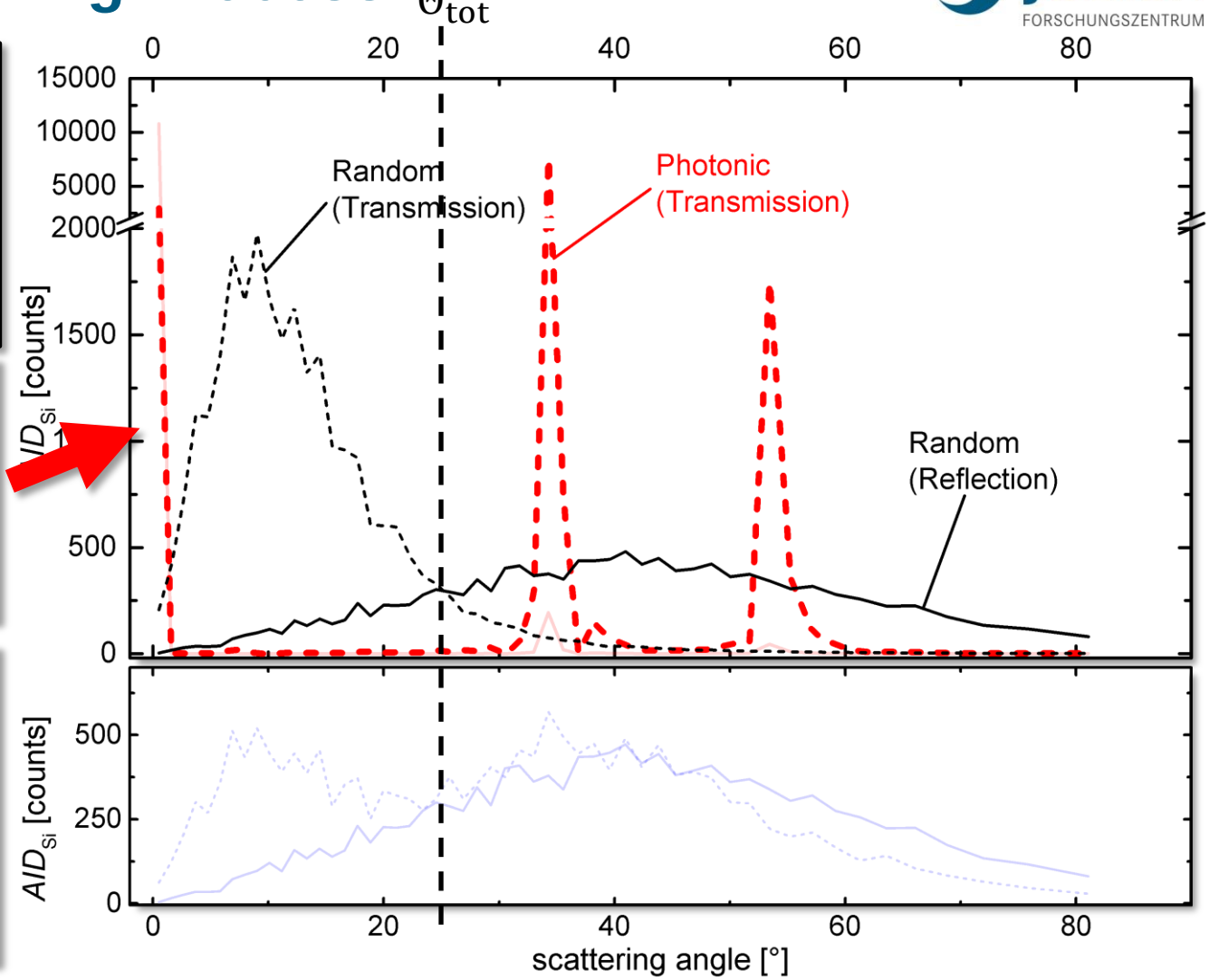

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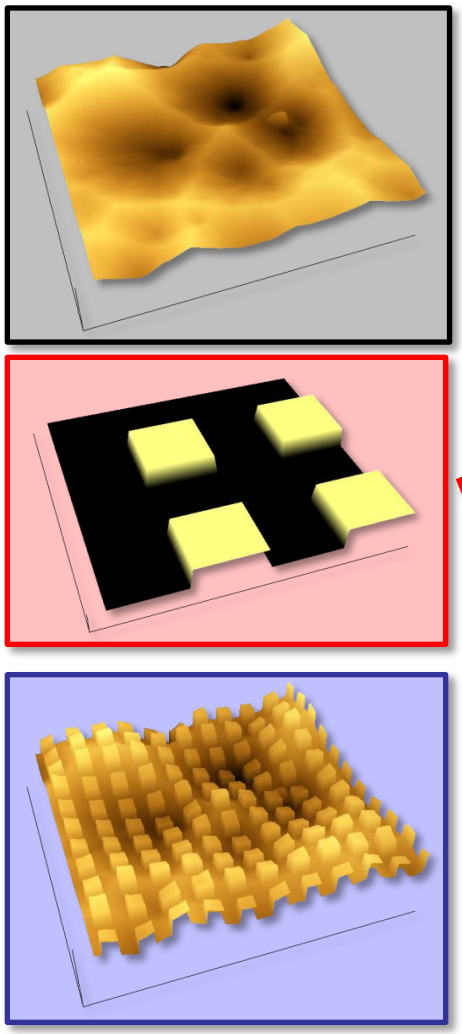

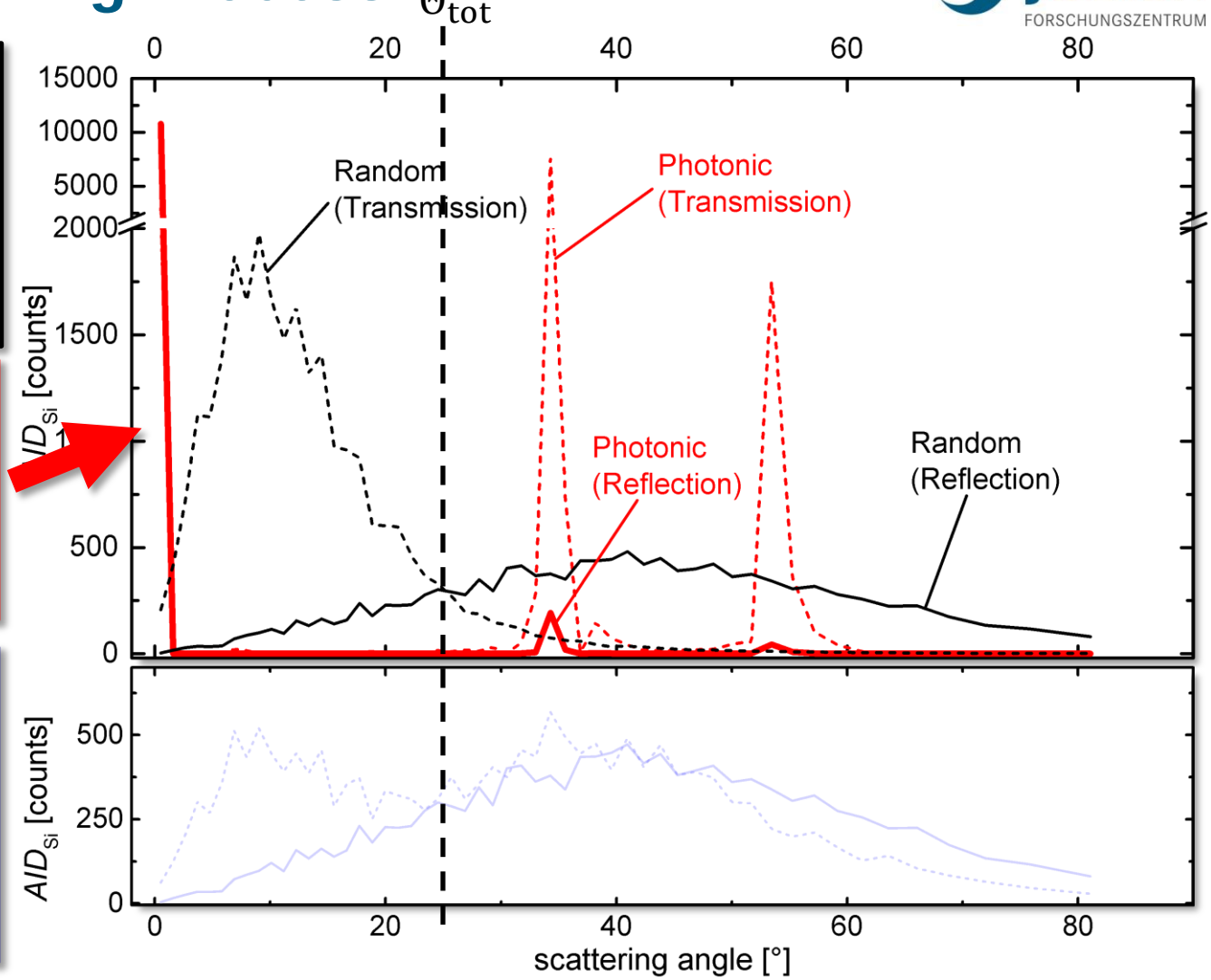

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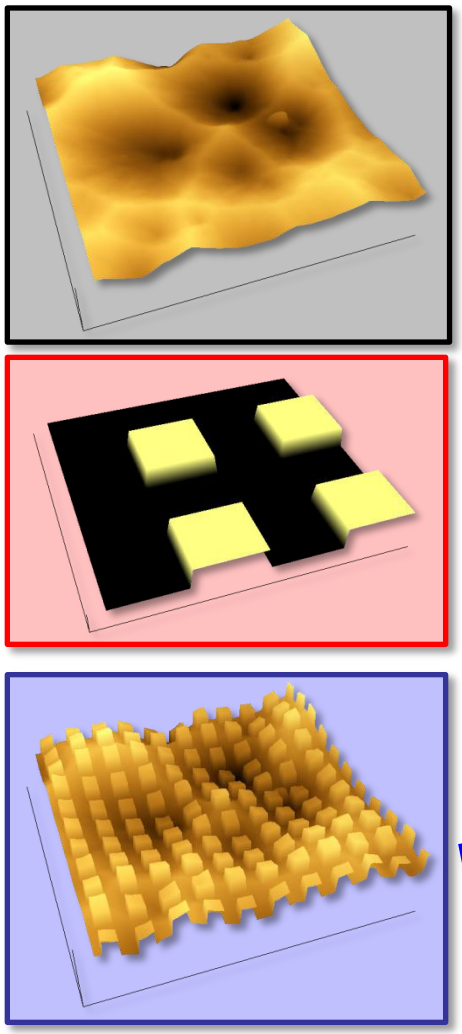

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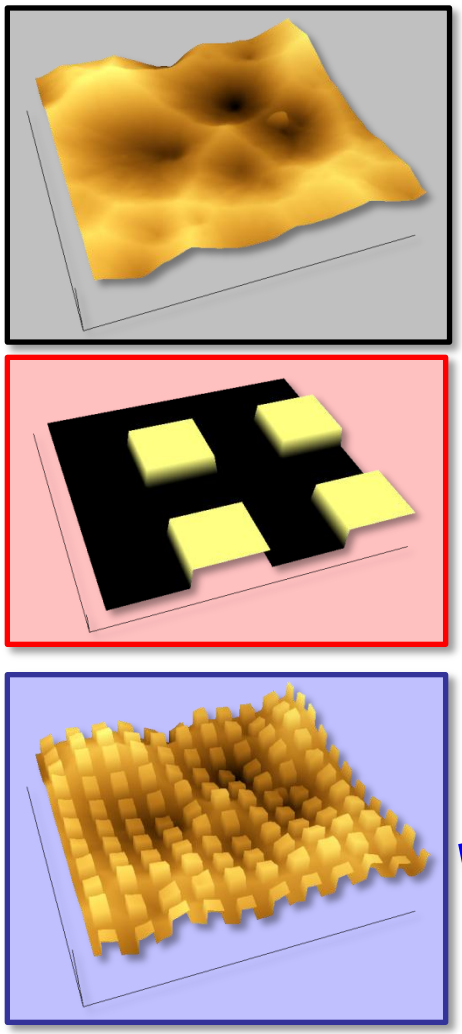

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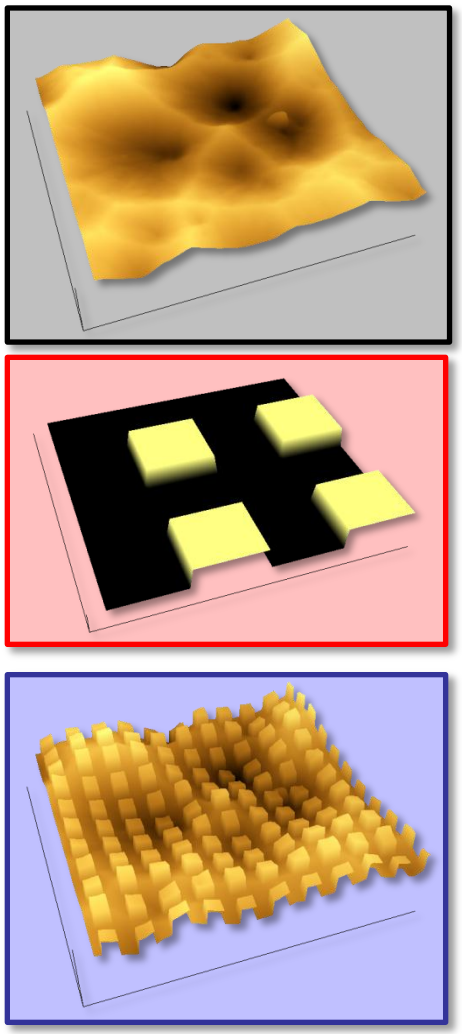
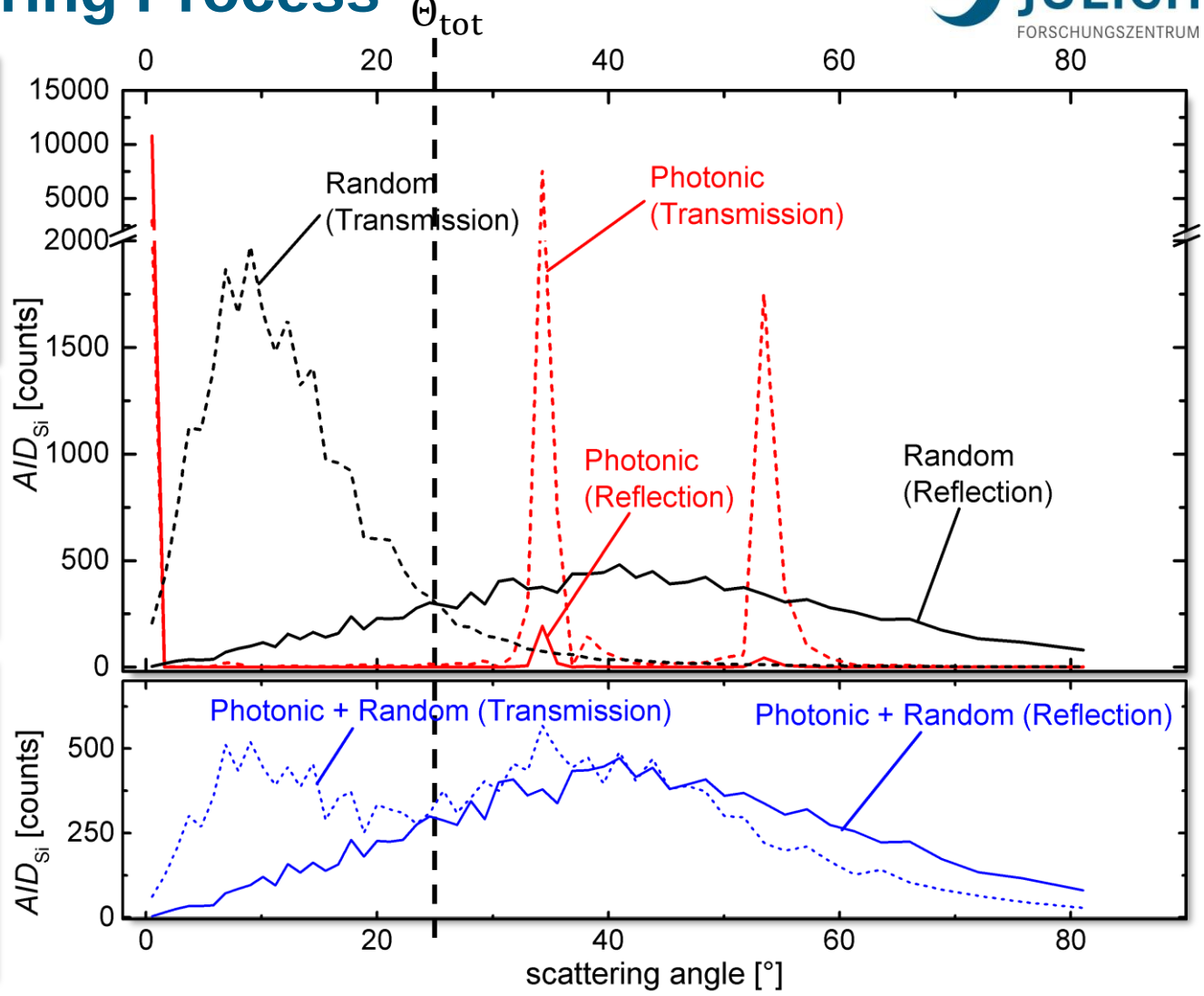




Photonic random texture combines best of both worlds

Conclusion

Predictive model for light scattering at rough interfaces

- Very fast due to scalar approach
- Topography and refractive indices as only input

Concept of photonic random textures

- Superposition of random texture and photonic grating structure

Combination of photonic and random outperforms its components

- Very promising light-trapping concept

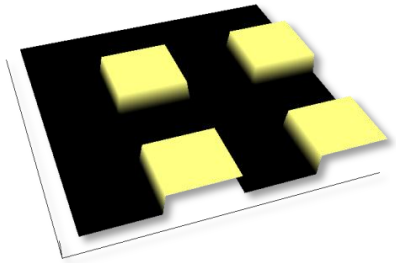
Investigation of light scattering process

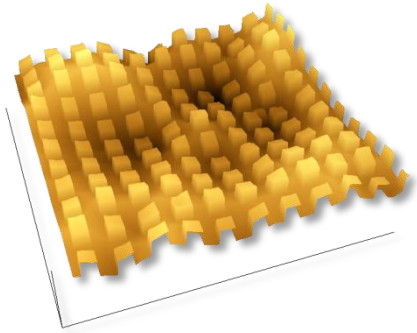
- Diffraction orders with distribution as broad as for the random texture
- Combines best of both worlds

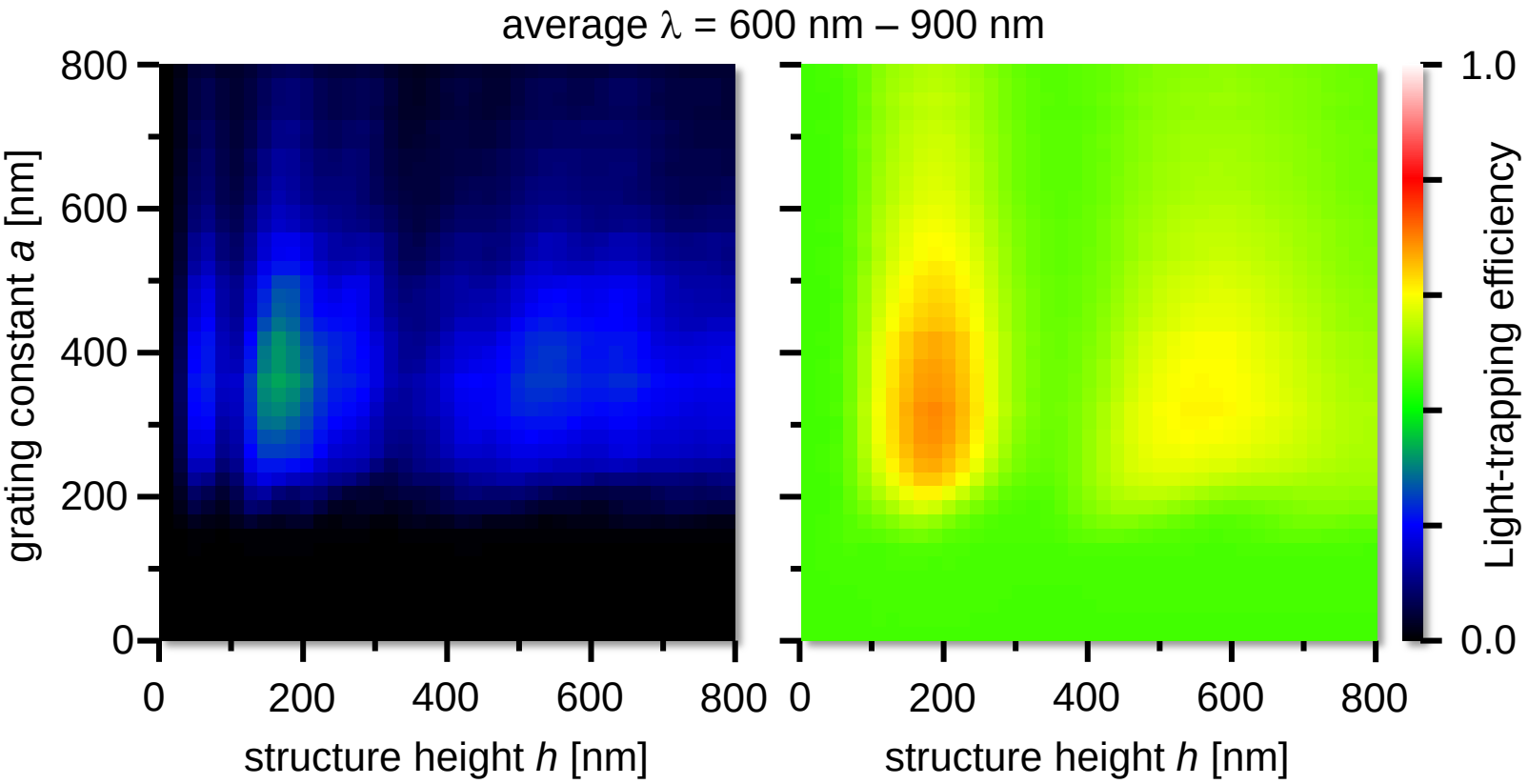
Thank you for your attention !

supported by national projects: InfraVolt and PhoNa

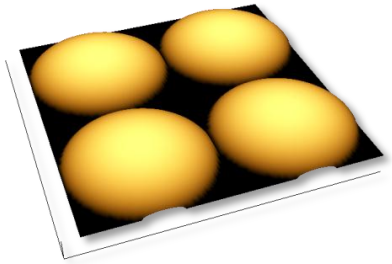
Rectangular Structure

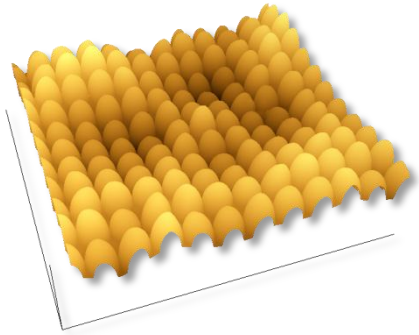


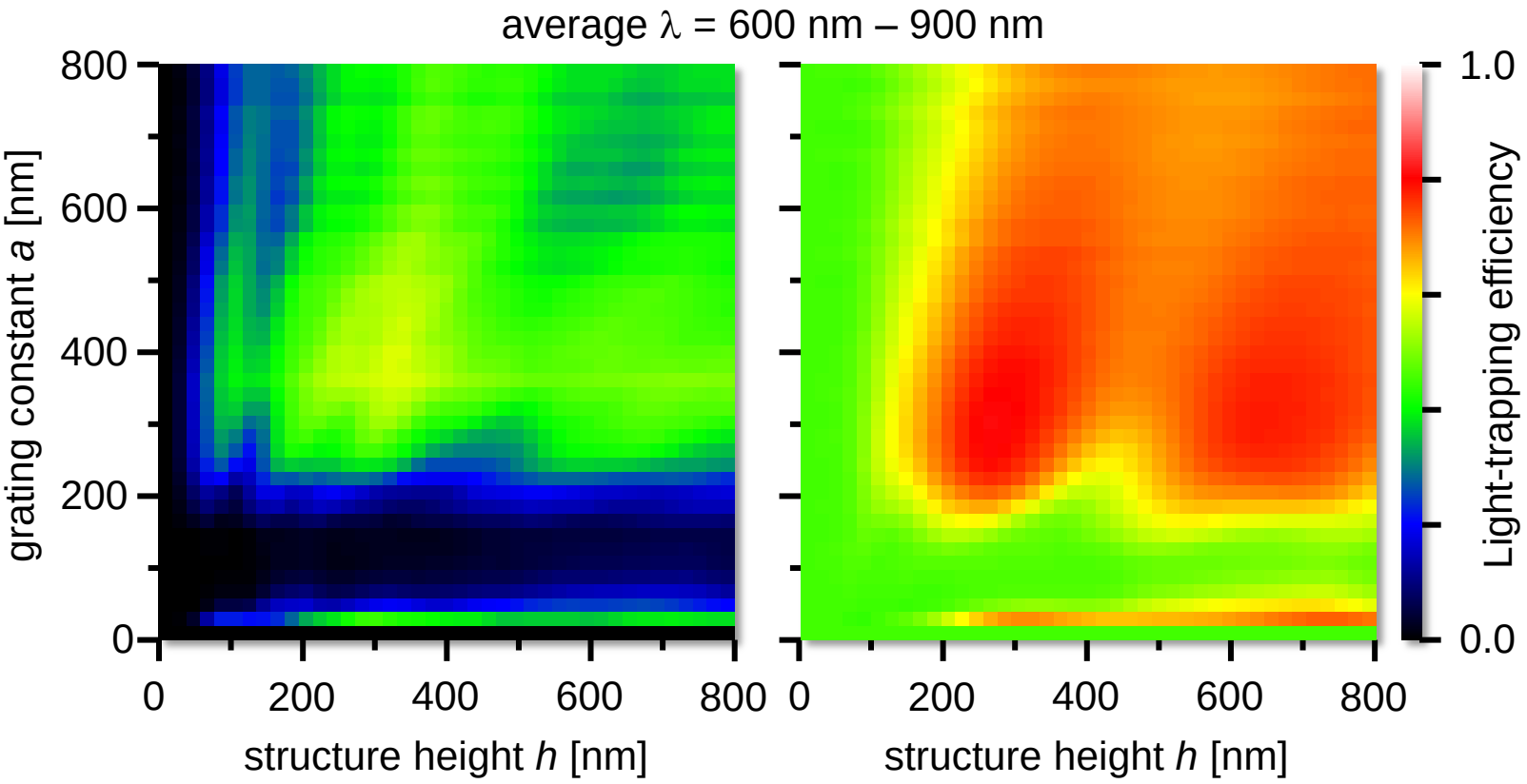




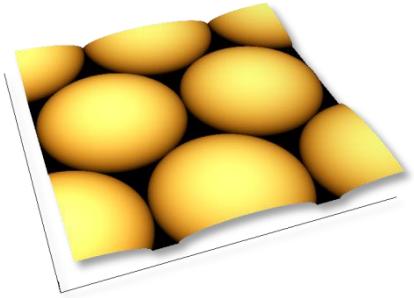
Spherical Structure (rectangular)

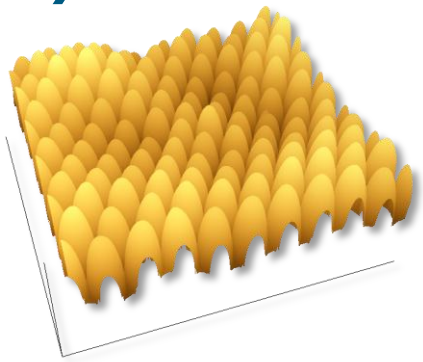


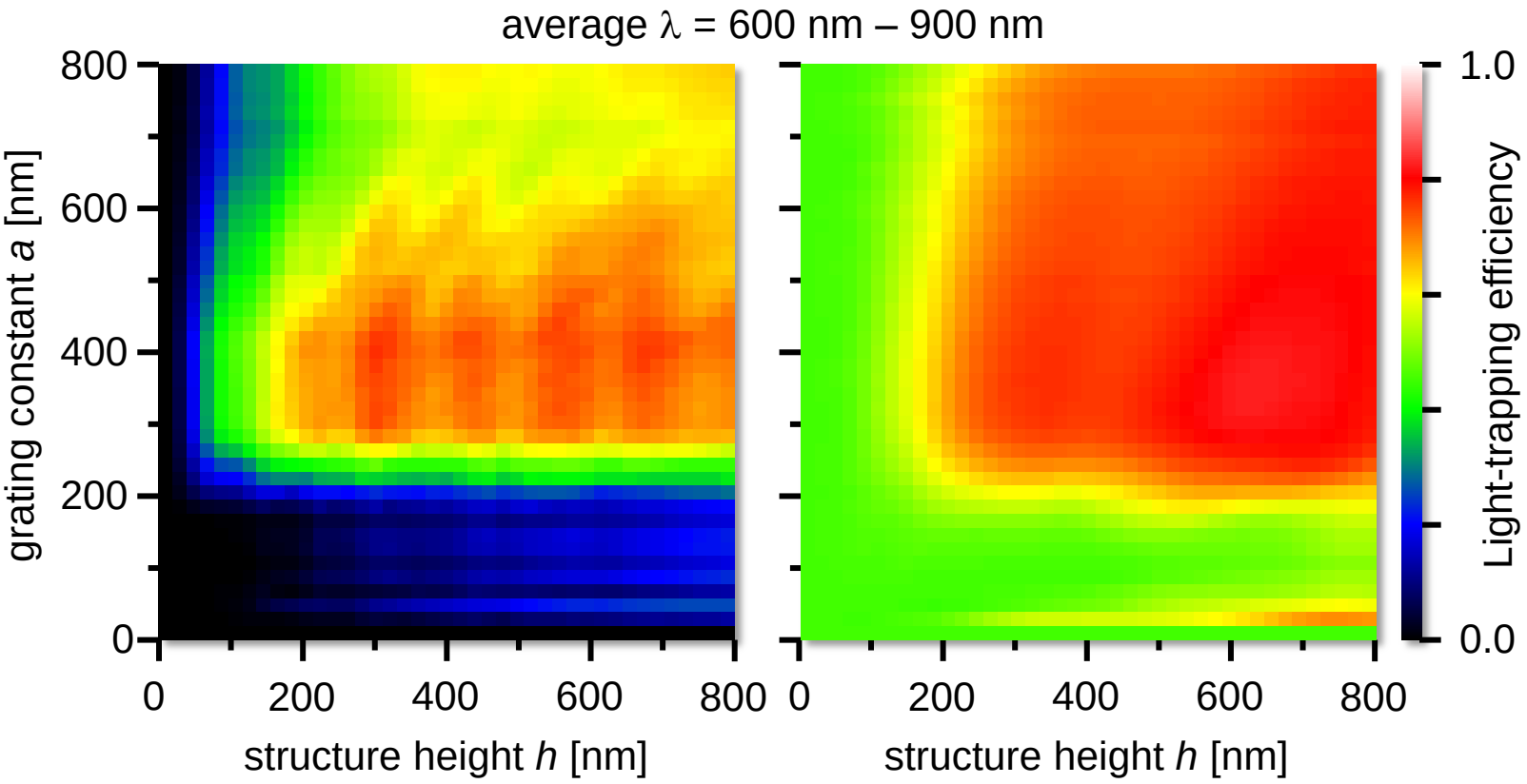




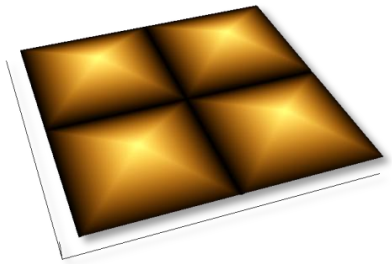
Spherical Structure (hexagonal)

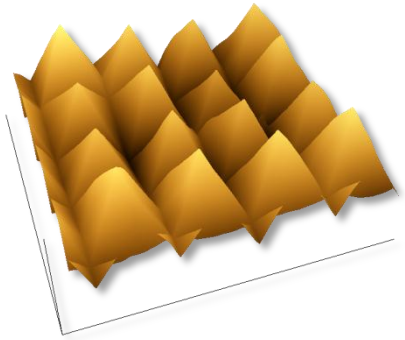


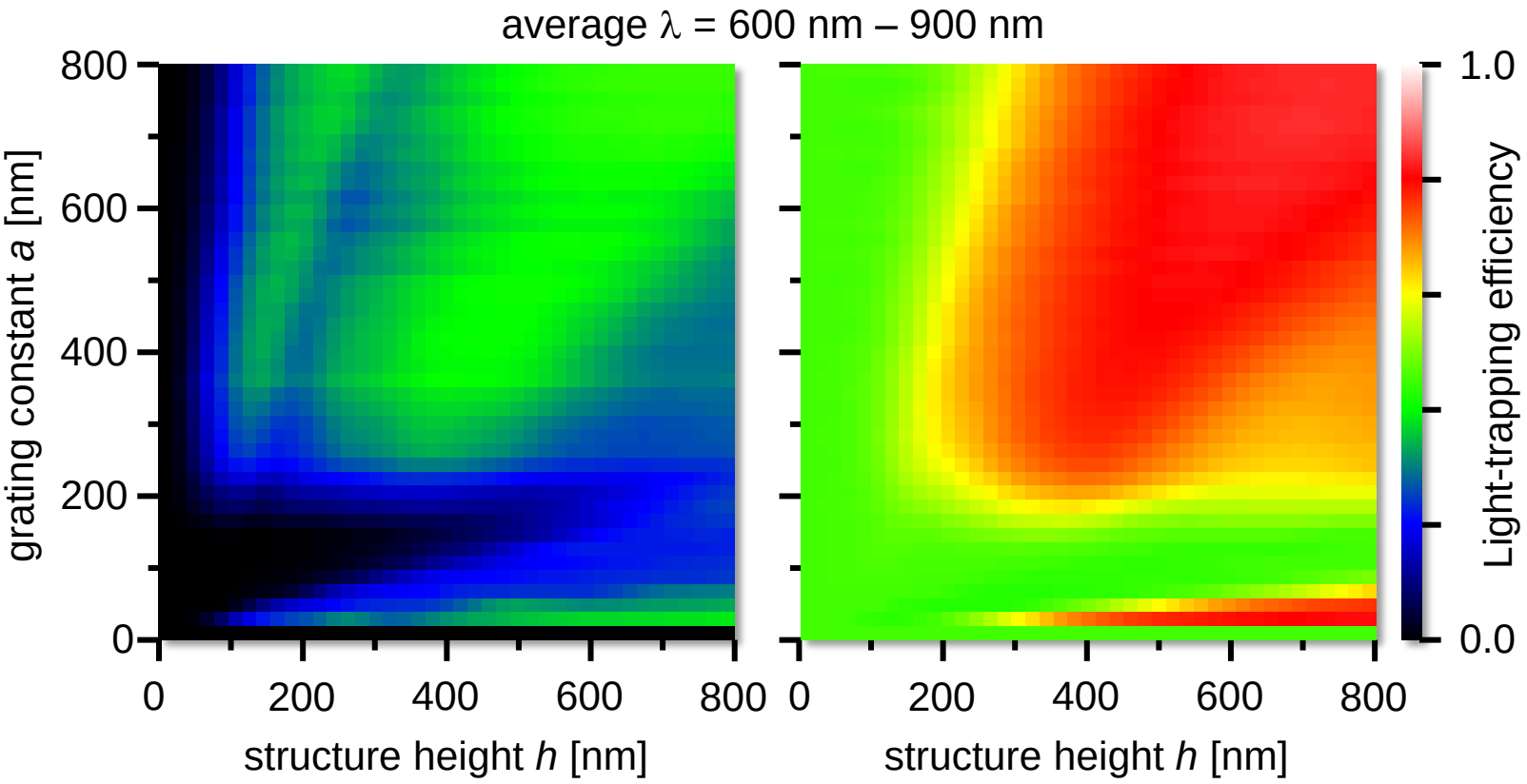




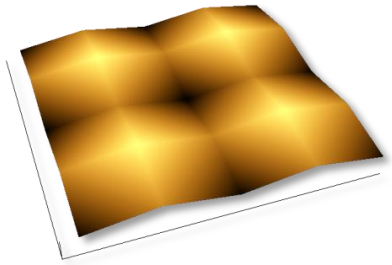
Pyramidal Structure

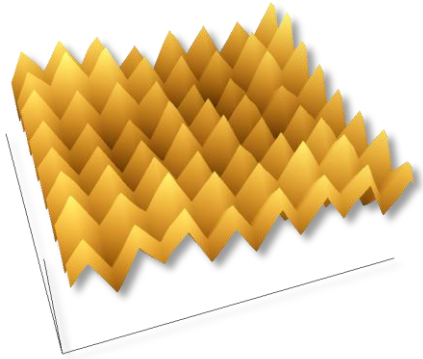


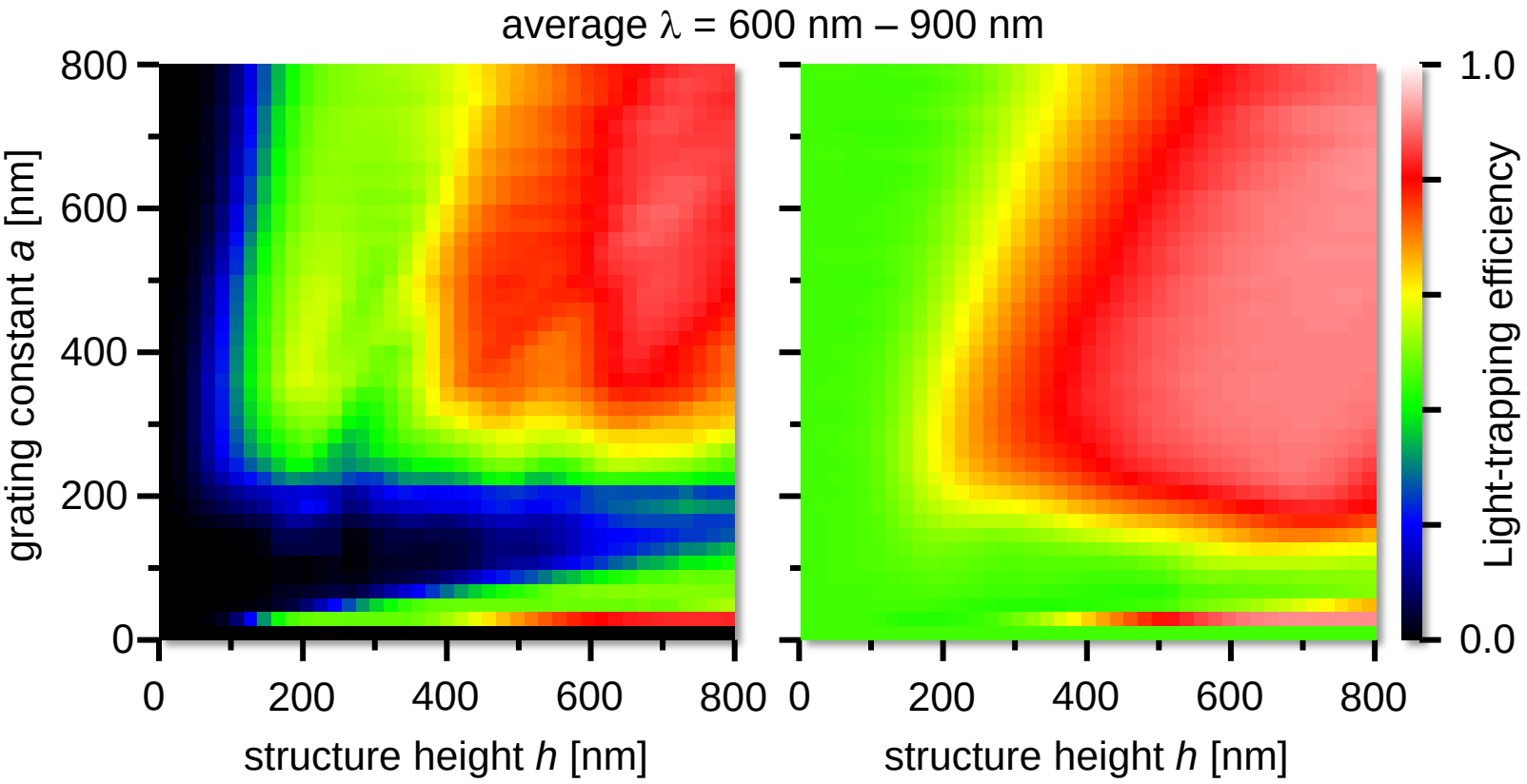




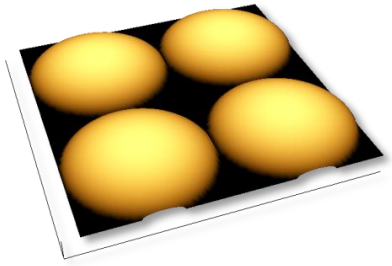
Triangular Structure

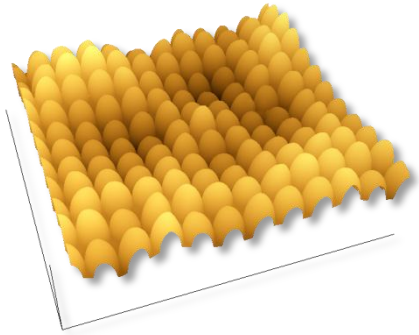


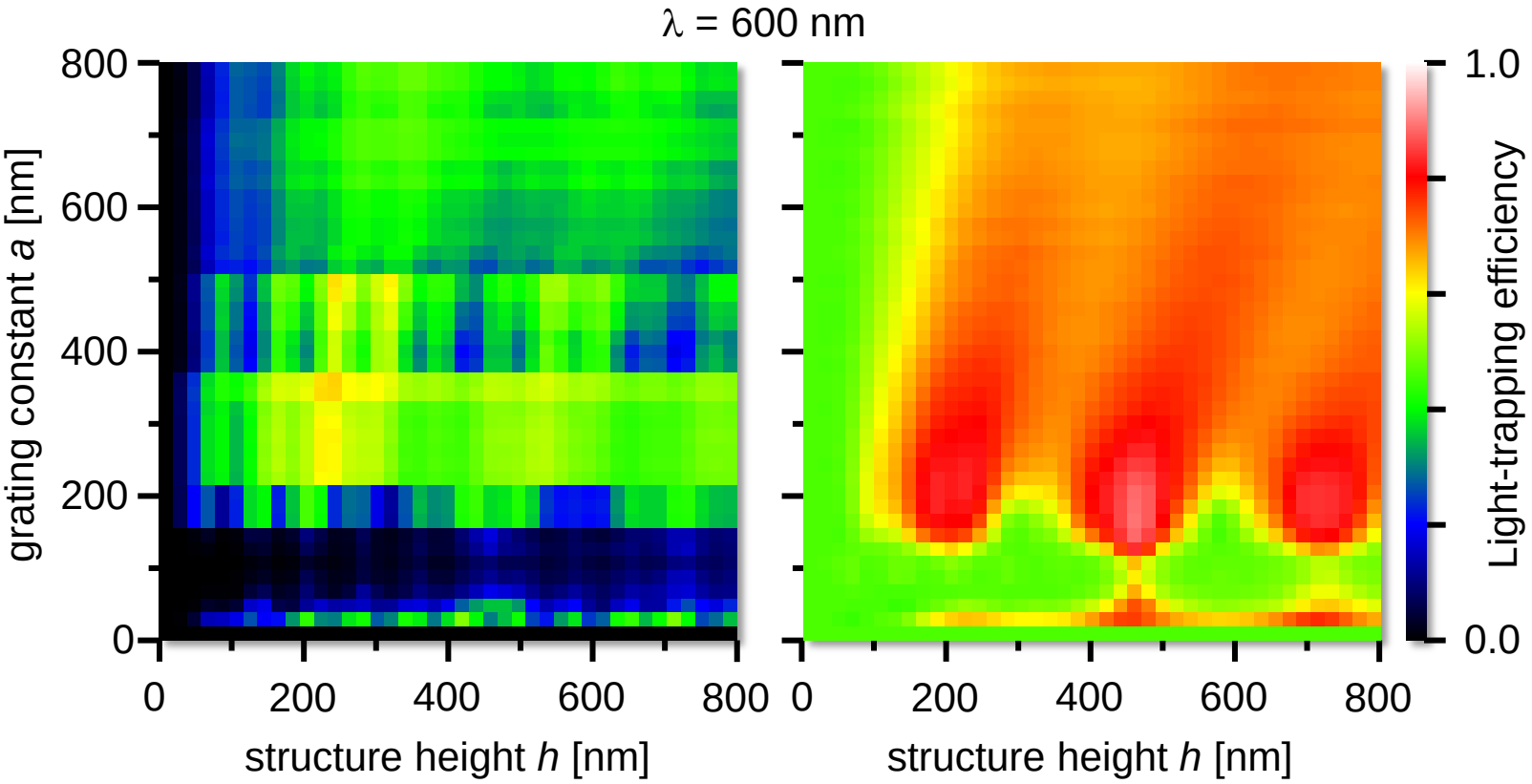




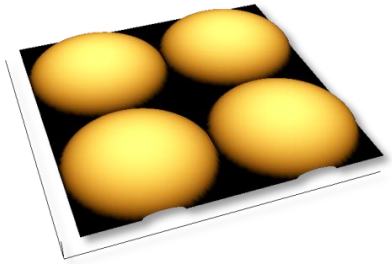
Wavelength Dependence

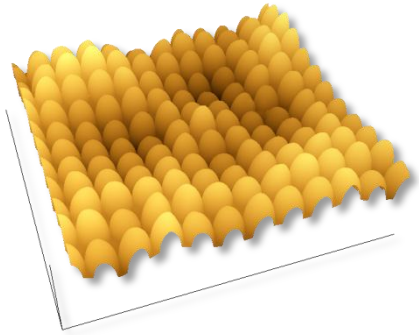


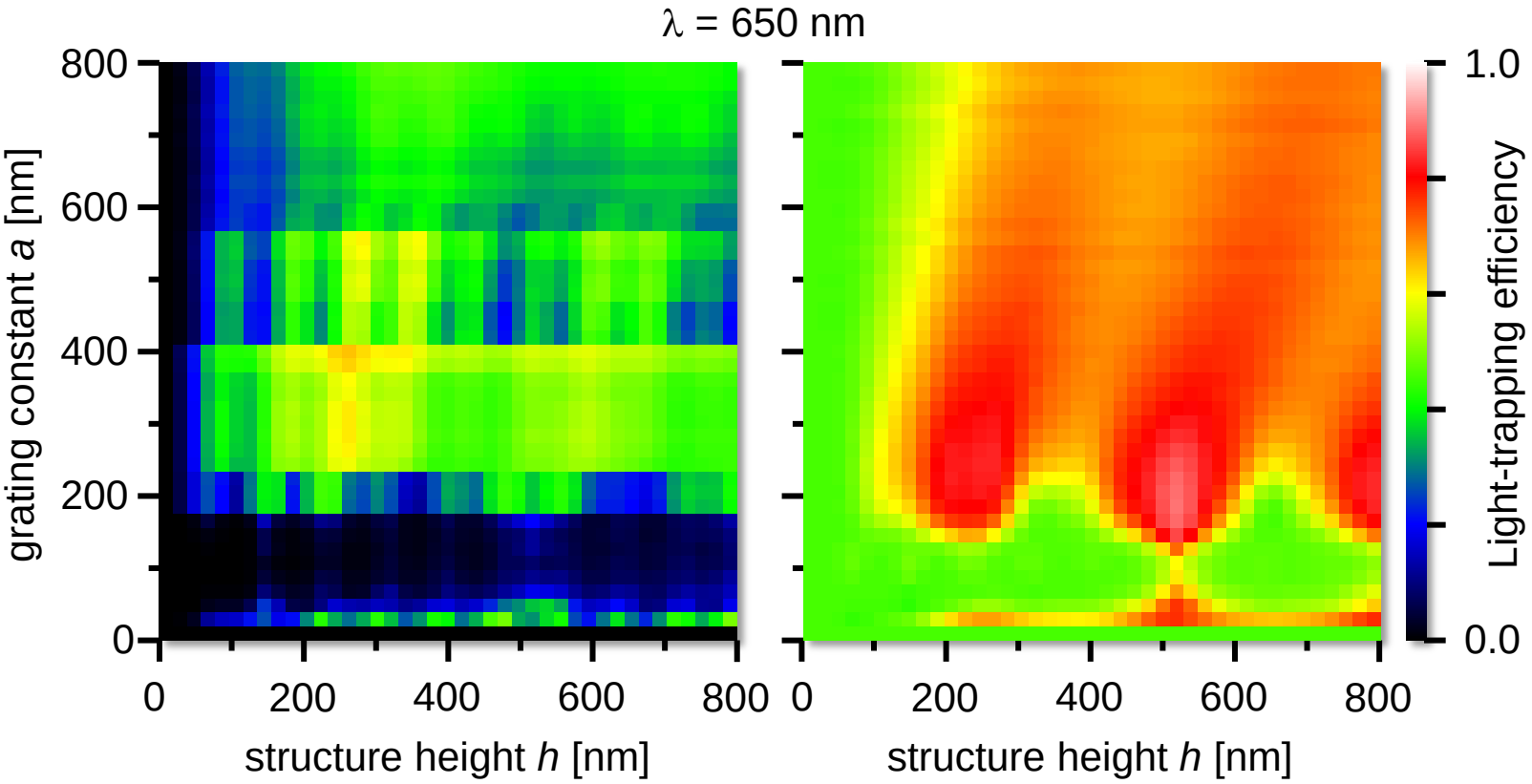




Wavelength Dependence







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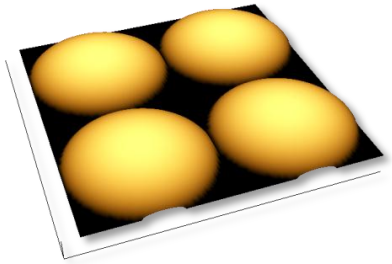

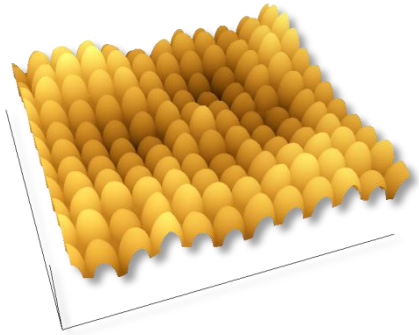

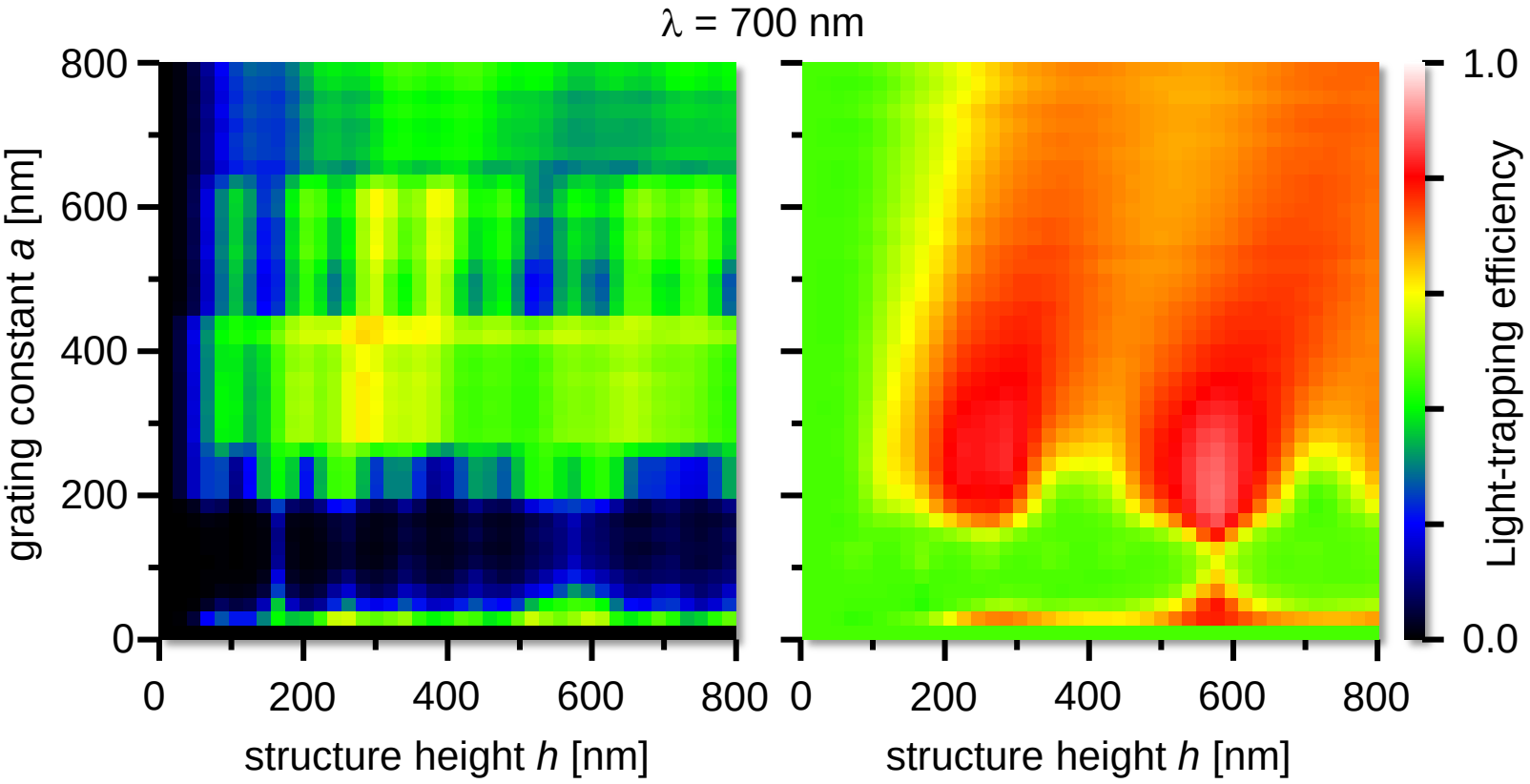

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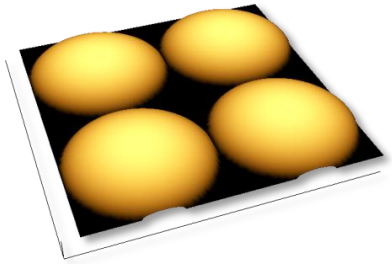
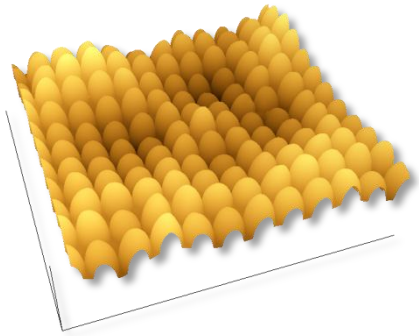
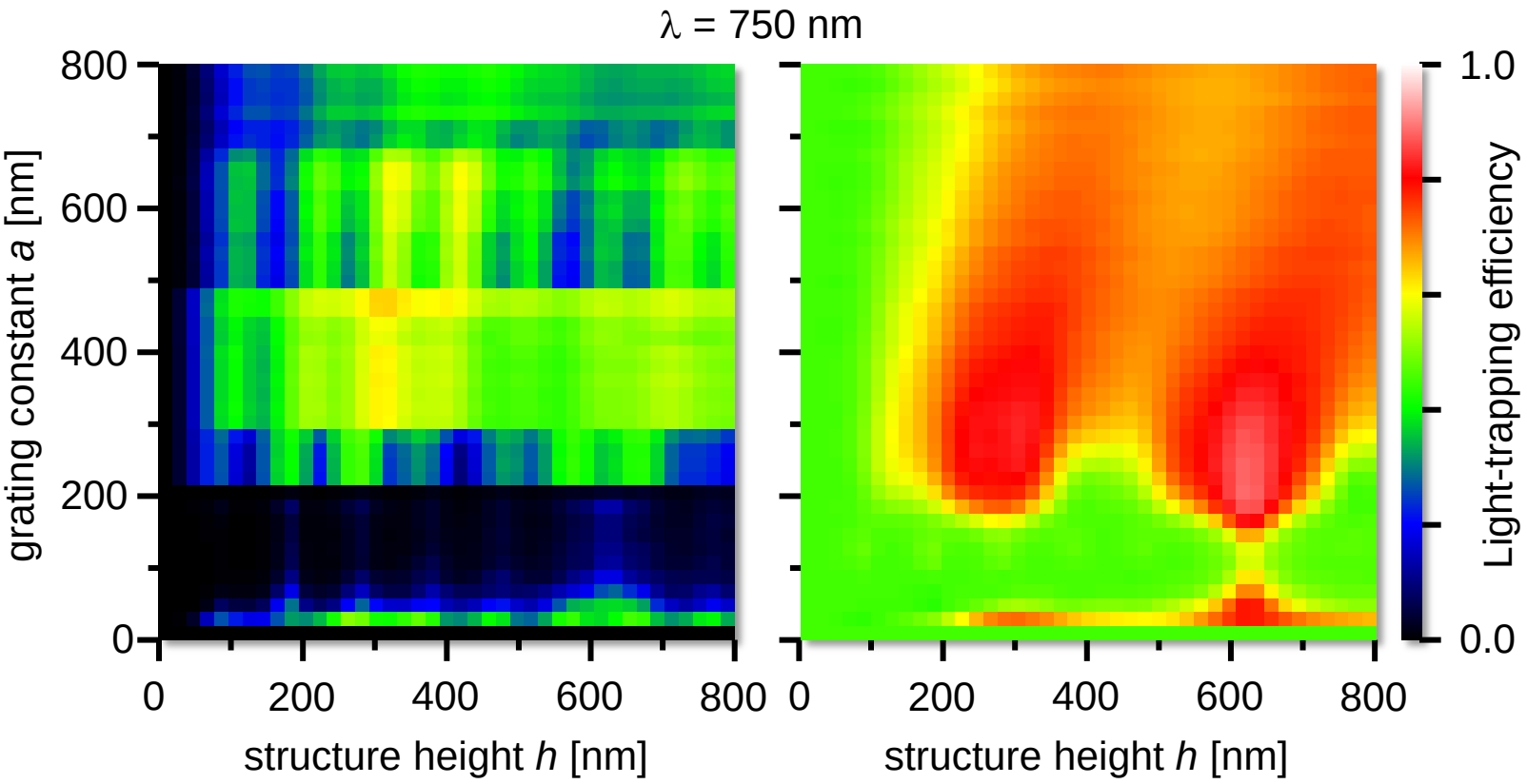
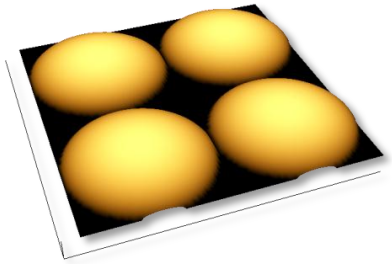
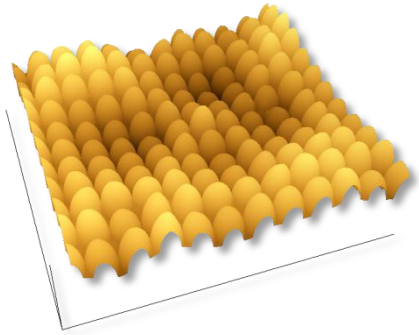


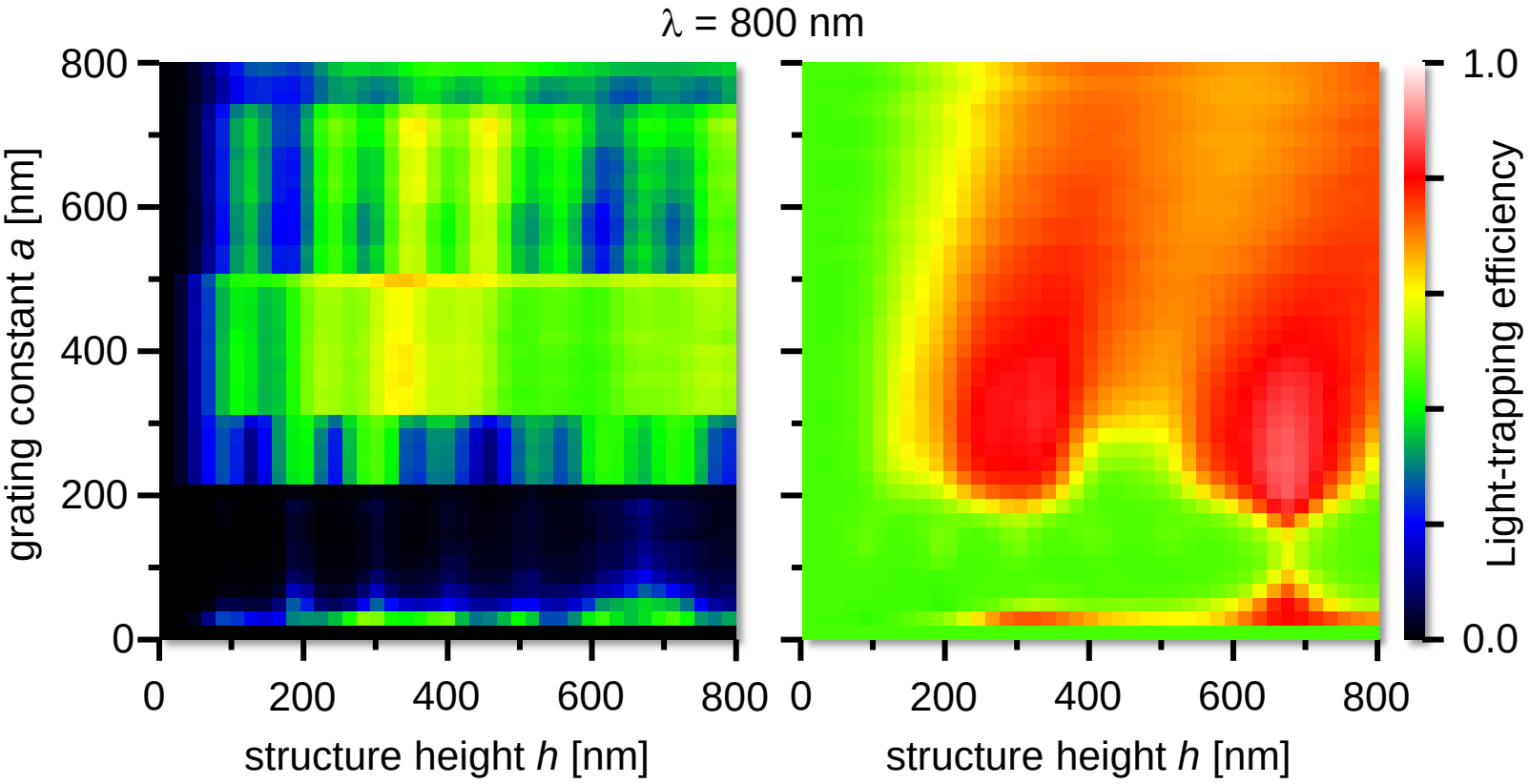




Wavelength Dependence







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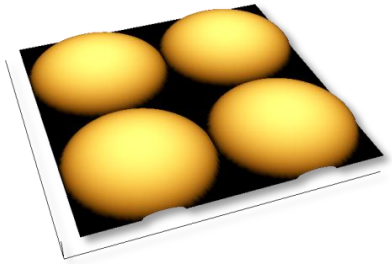
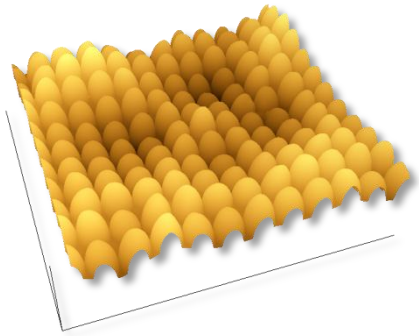
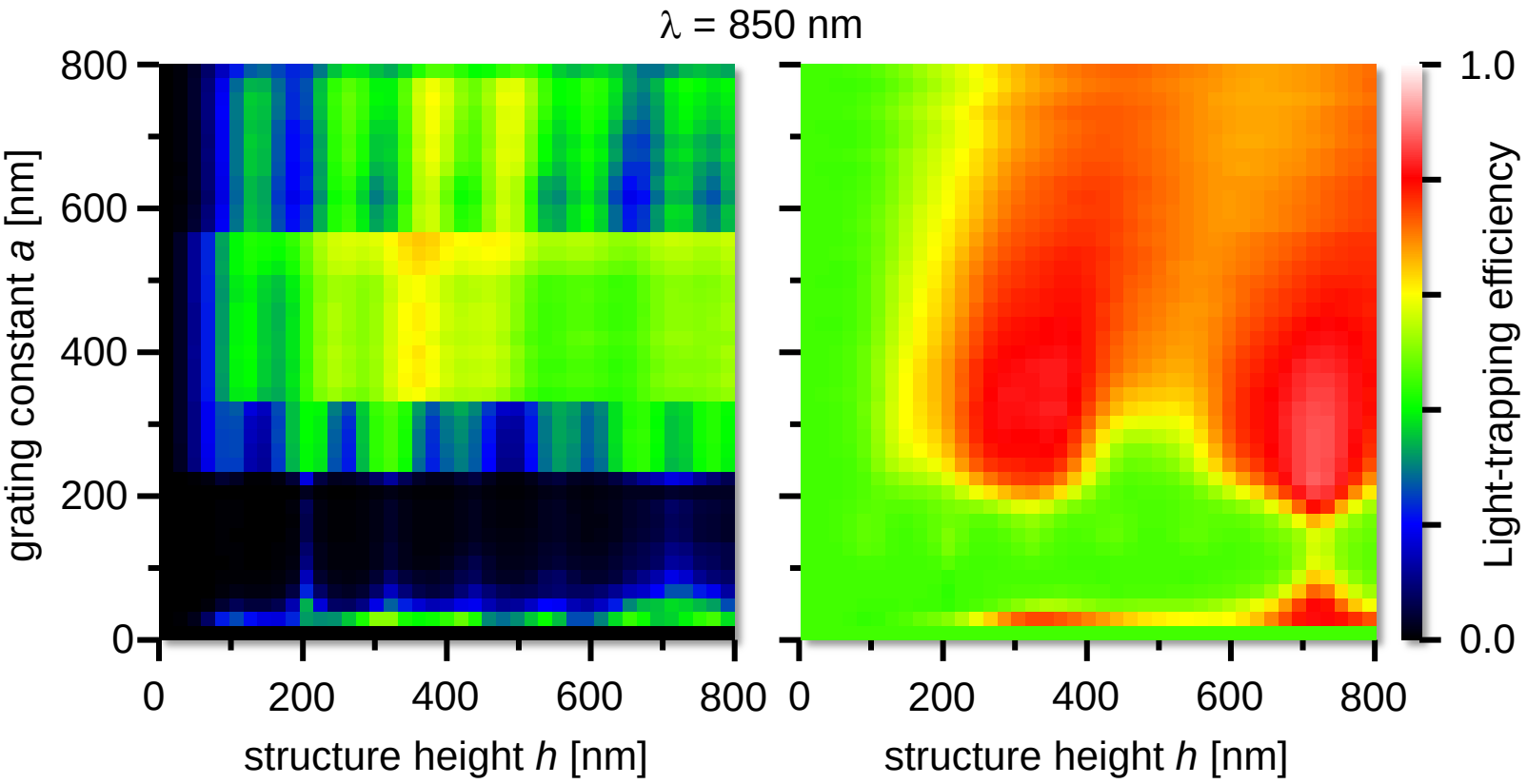
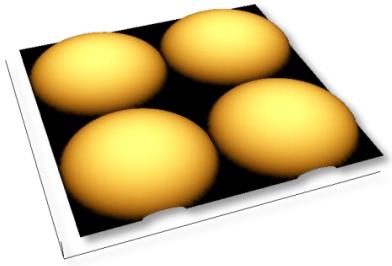
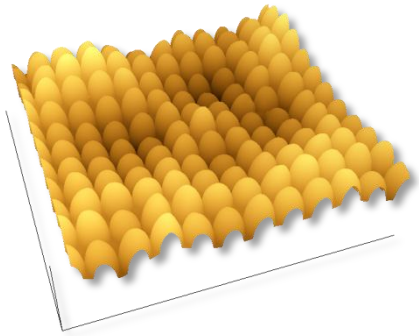


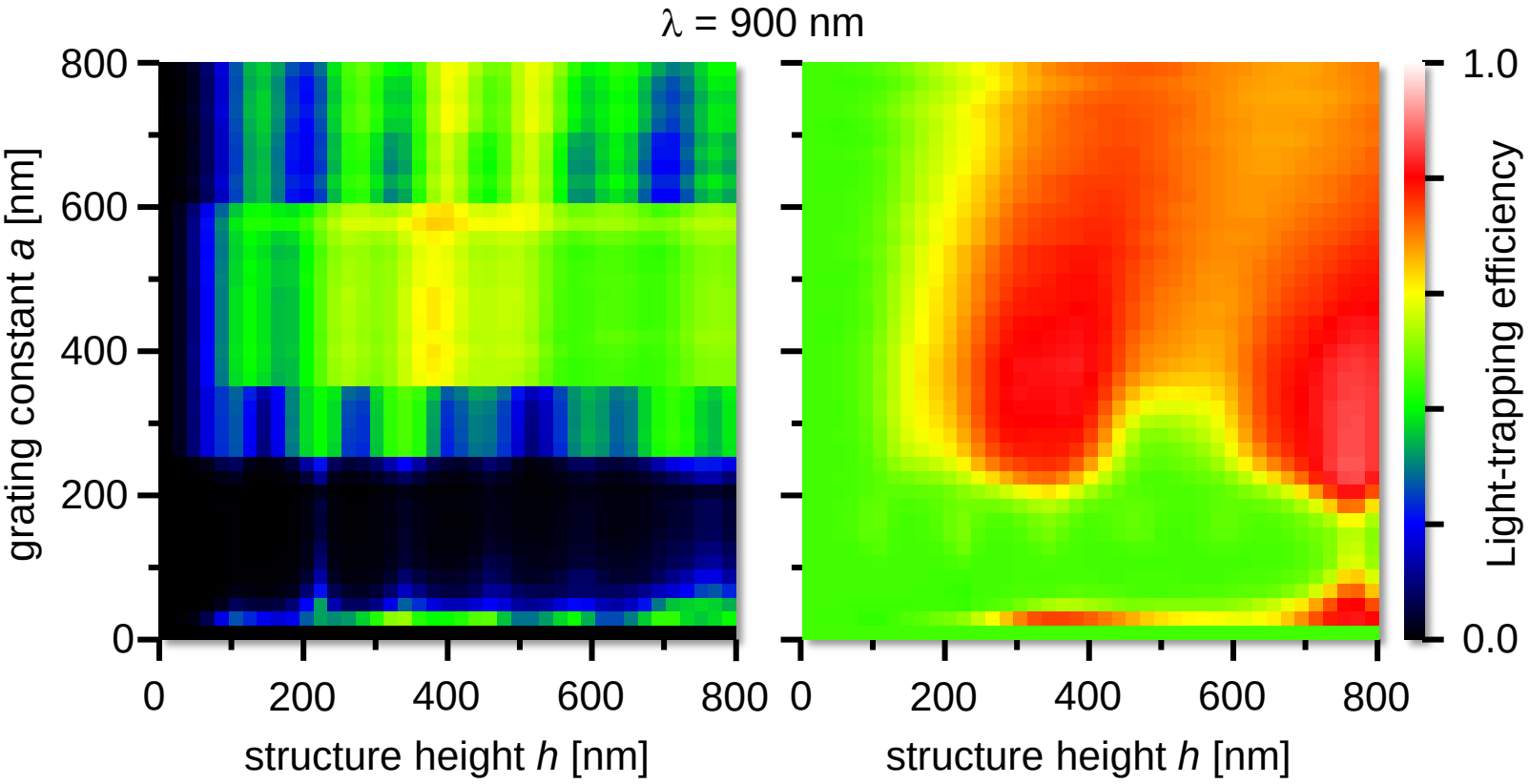




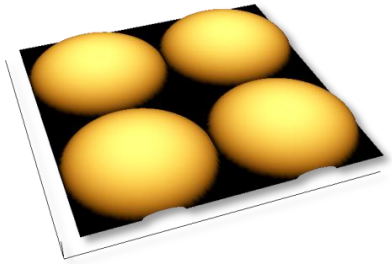
Wavelength Dependence

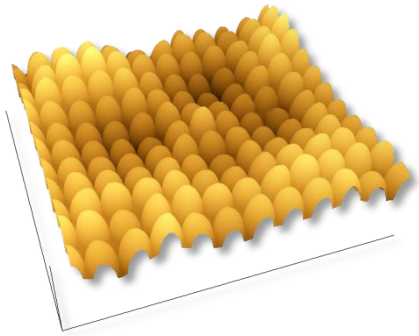


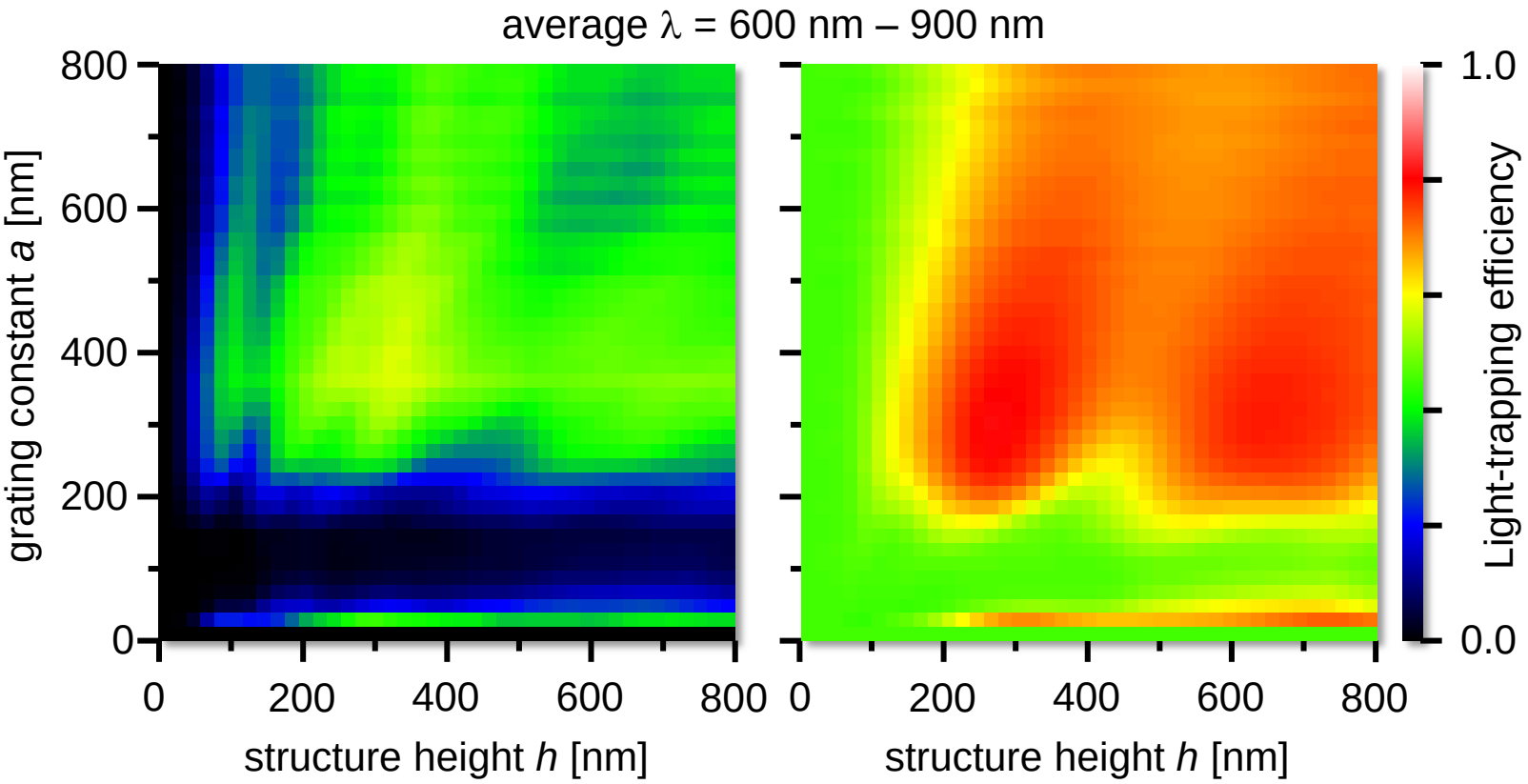




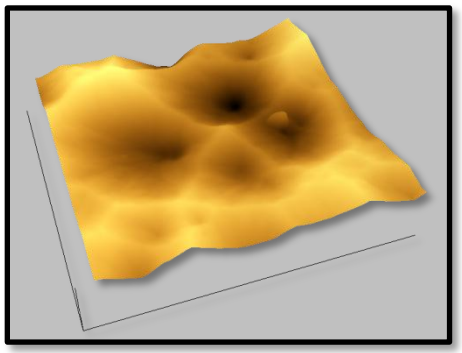
Wavelength Dependence

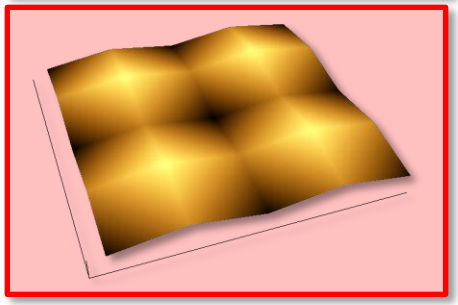


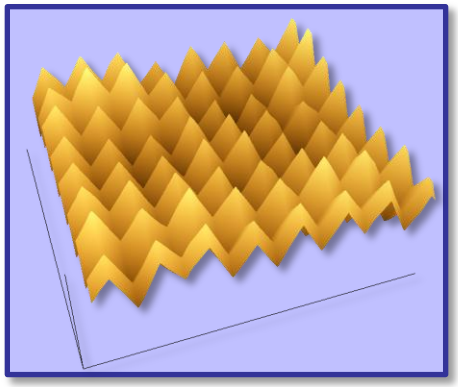


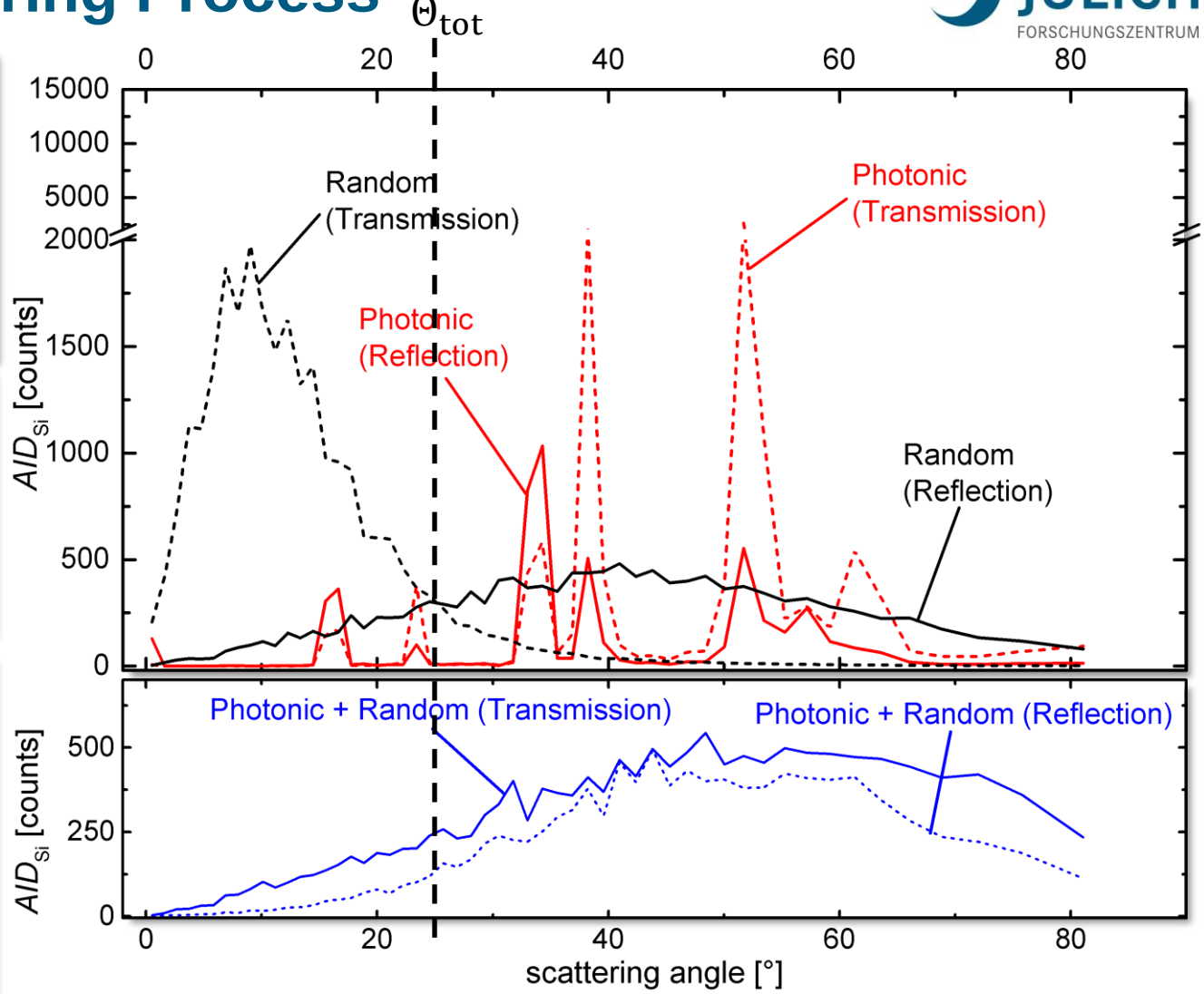


Light Scattering Process



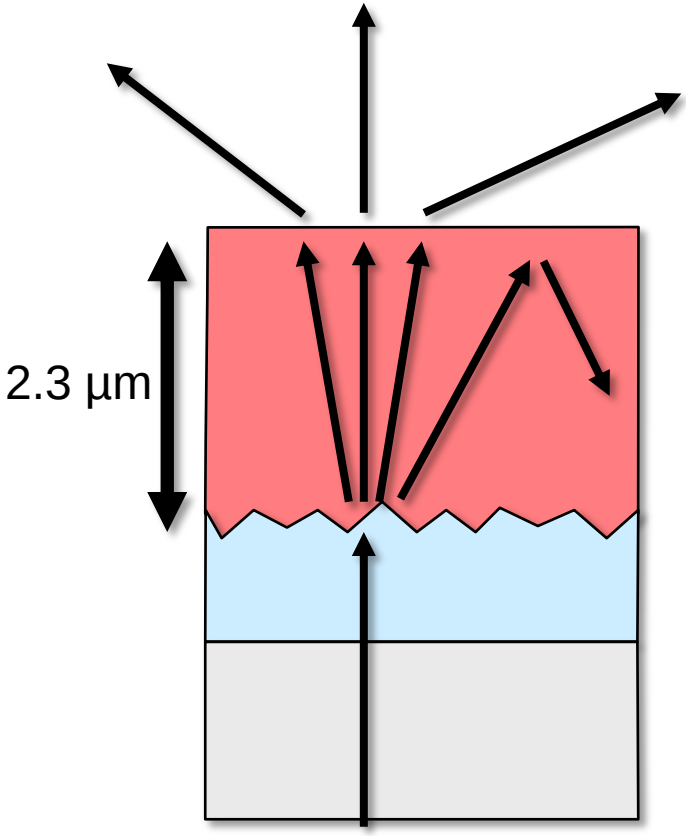


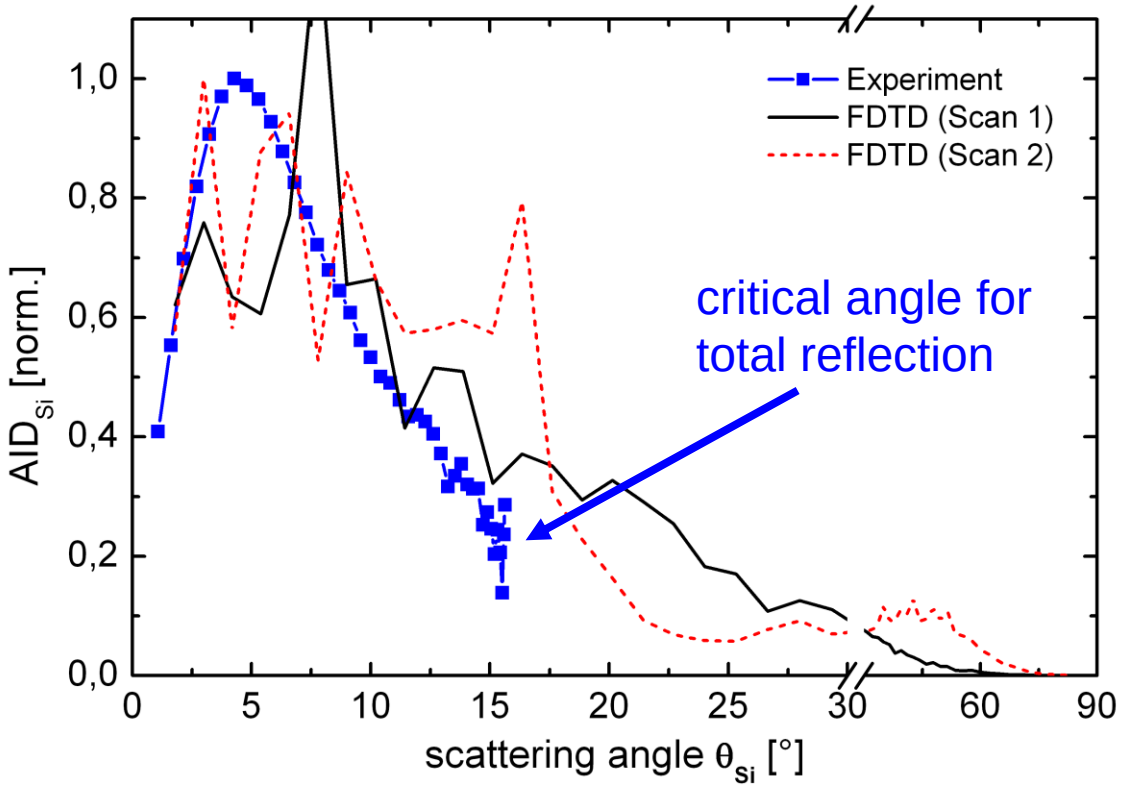




Photonic random texture combines best of both worlds

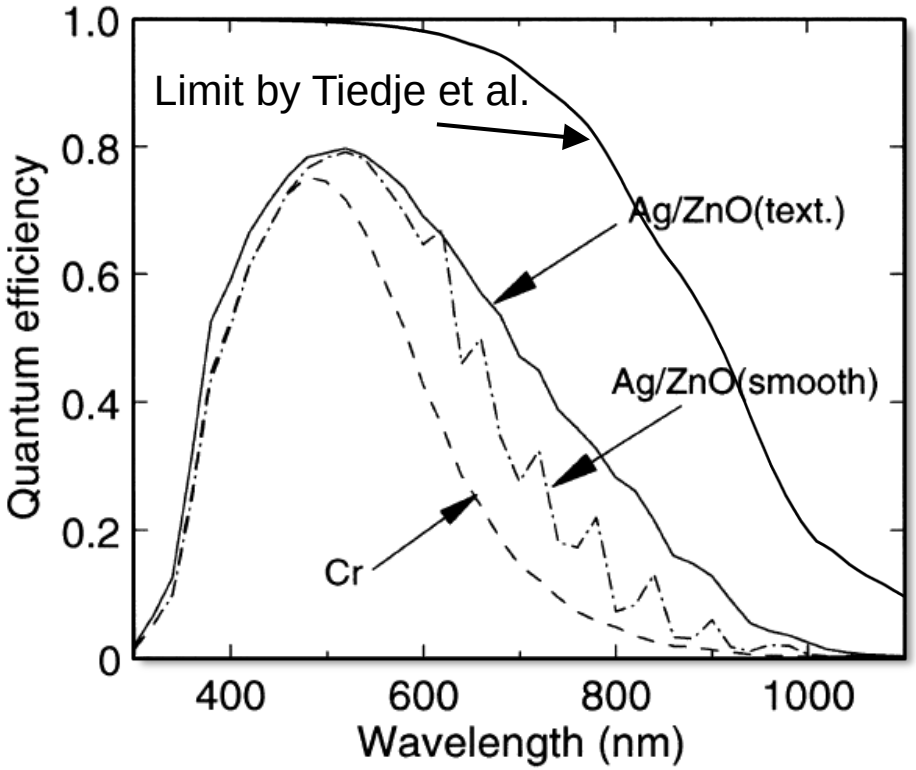
Light Scattering into Silicon





M. Schulte et al., Appl. Phys. Lett. 99, 111107 (2011)

Light Trapping – Upper Limit



O. Vetterl et al., Solar Energy Materials & Solar Cells **62**, 97 (2000)