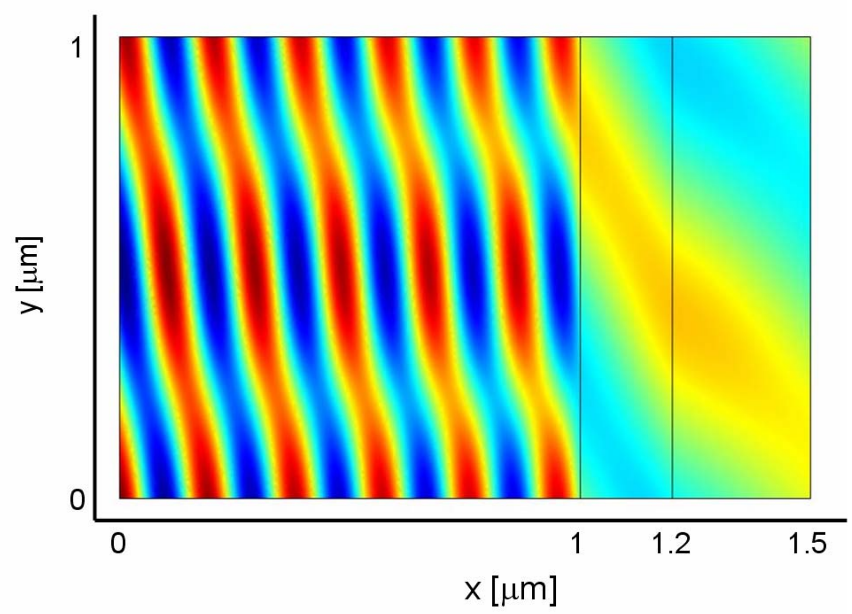

Simulation of Optical Properties of the $Si/SiO_2/Al$ Interface at the Rear of Industrially Fabricated Si Solar Cells

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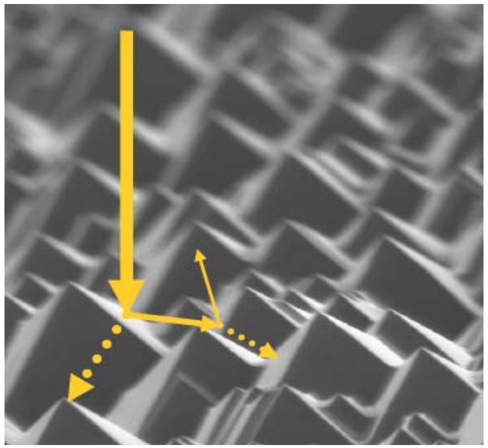
Motivation

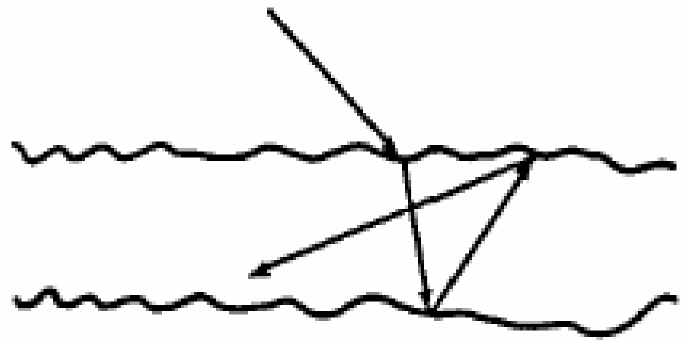
Why do we develop “flat” texturing schemes?

- ✓ Industrially fabricated solar cells have pyramids at the front surface to enhance the optical path length of weakly absorbed rays (light trapping, confinement).
- ✓ Pyramid texture cannot be easily applied to thin (< 30 μm) Si cells.
- ✓ Scattering at rear (and front) are efficient for light trapping as well.

pyramids



rough surfaces



E. Yablonovitch, J. Opt. Soc. Am. 72, 899 (1982)

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Task and Outline

1. Simulation model for reflection at planar and rough interfaces

✓ Definition of random surfaces, boundary conditions

2. Reflection near the critical incident angle in the $Si/SiO_2/Al$ system

✓ Evanescent waves under frustrated total internal reflection (FTIR)

3. What kind of roughed schemes will foster scattering at the rear the most?

✓ Computation of angularly resolved reflection for various interfaces and materials.

✓ Nanoscale metal dots.

4. Conclusions

Equations to solve numerically

1. Maxwell equations

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

$$\frac{\partial \vec{D}}{\partial t} = \nabla \times \vec{H} - \vec{J} \qquad \nabla \cdot \vec{B} = 0,$$

2. Coupled with materials equations

$$\vec{D} = \epsilon \vec{E} \qquad \vec{B} = \mu \vec{H} \qquad \vec{J} = \sigma \vec{E}$$

3. Harmonic formulation: $\vec{E}(\vec{r},t) = \vec{E}(\vec{r})e^{i\omega t} \qquad \vec{H}(\vec{r},t) = \vec{H}(\vec{r})e^{i\omega t}$

$$\nabla \times (\mu^{-1} \nabla \times \vec{E}) - \omega^2 \epsilon_c \vec{E} = 0$$

$$\nabla \times (\epsilon_c^{-1} \nabla \times \vec{H}) - \omega^2 \mu \vec{H} = 0$$

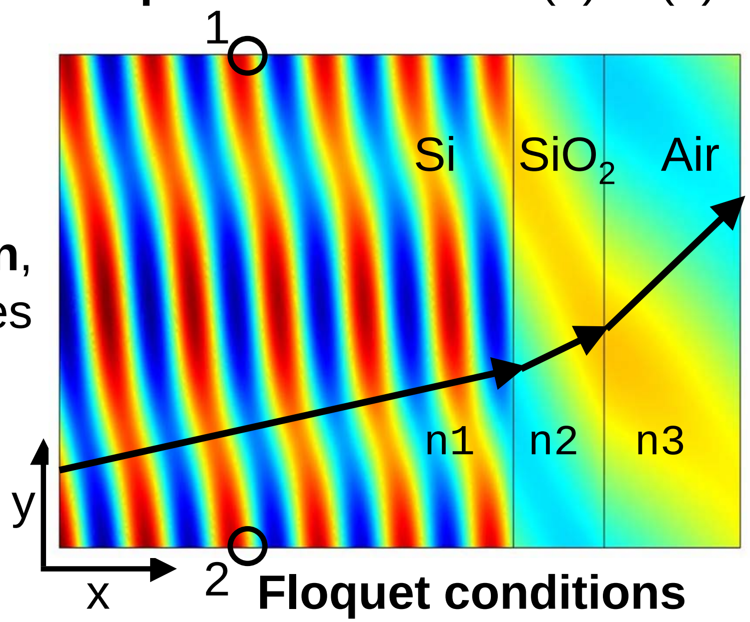
Boundary conditions for planar interfaces

Floquet conditions: E(1)=E(2)e^{-ikd}

Port condition,
excitation of TE or TM waves

E_{oz}(or H_{oz}) = exp(-i*k1y*y)

β = k1x

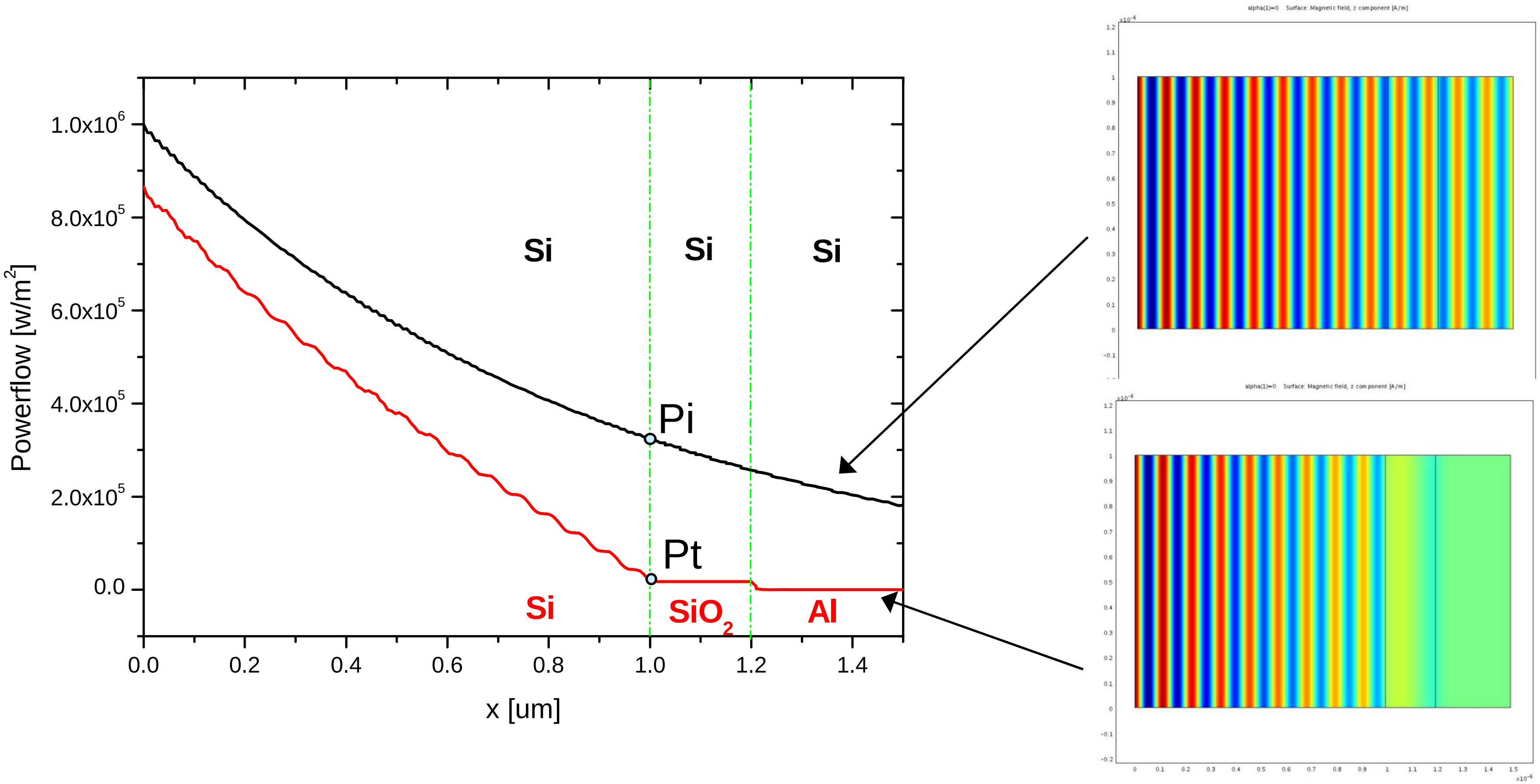


Floquet conditions

Port condition,
no excitation

alpha1	alpha2= asin(sin(alpha1)*Re(n1)/n2)	alpha3 = asin(sin(alpha2)*n2/Re(n3))
k1x= k0_emwh*Re(n1)*cos(alpha1)	k2x= k0_emwh*n2*cos(alpha2)	k3x= k0_emwh*Re(n3)*cos(alpha3)
k1y =k0_emwh*Re(n1)*sin(alpha1)	k2y= k0_emwh*n2*sin(alpha2)	k3y= k0_emwh*Re(n3)*sin(alpha3)

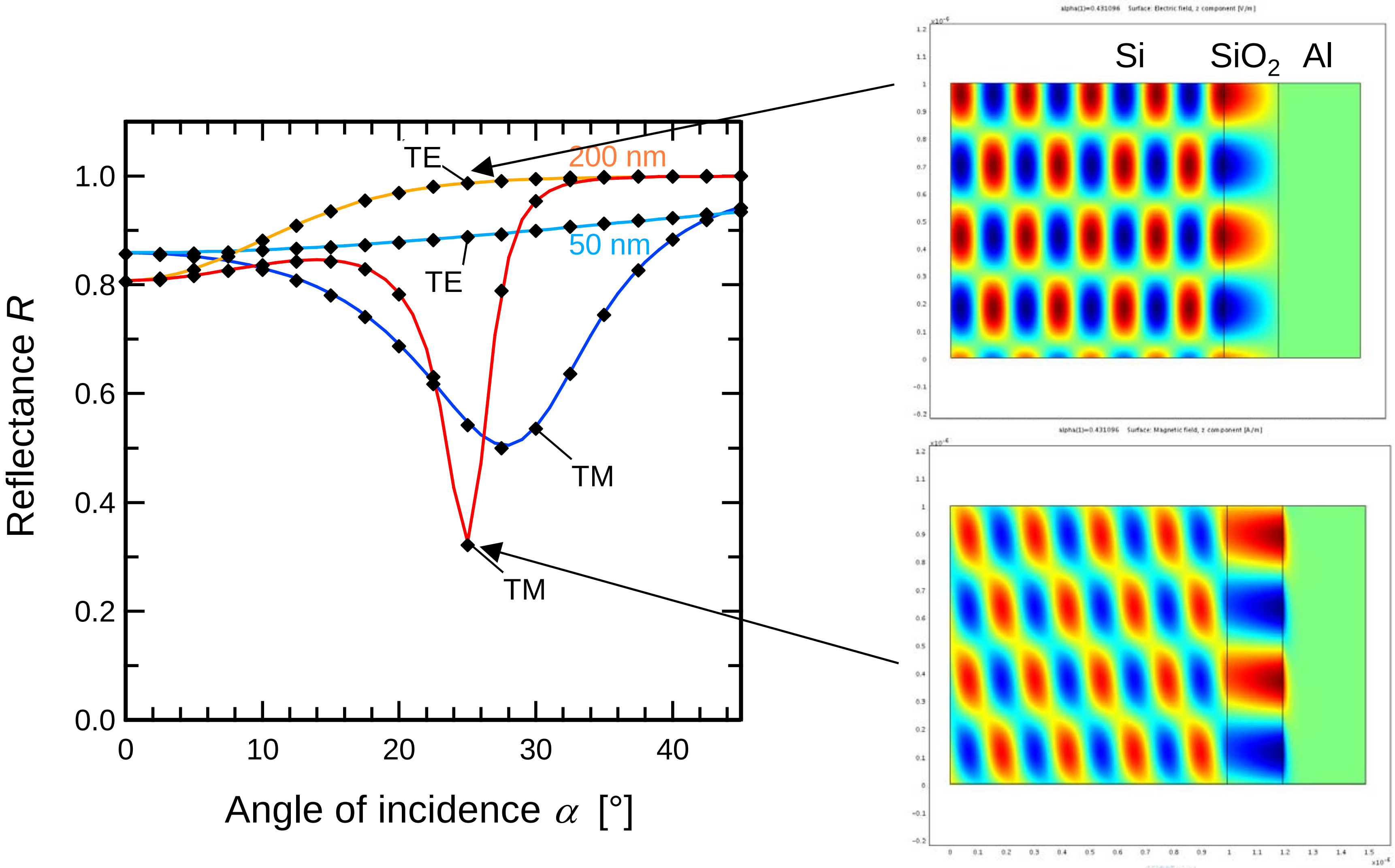
Extraction of R



First, in background field (Si/Si/Si), the power outflow at the interface is taken as incident power $\boldsymbol{P_i}$. Then, the power outflow in the Si/SiO2/Al model is taken as transmitted power $\boldsymbol{P_t}$. The reflectance $\boldsymbol{R}$ at the interface is calculated by:

$$R = 1 - P_t/P_i$$

Simulated (lines) and analytical *R* (dots)



Boundary conditions for scattering (A)

Comsol "scattering" boundary conditions

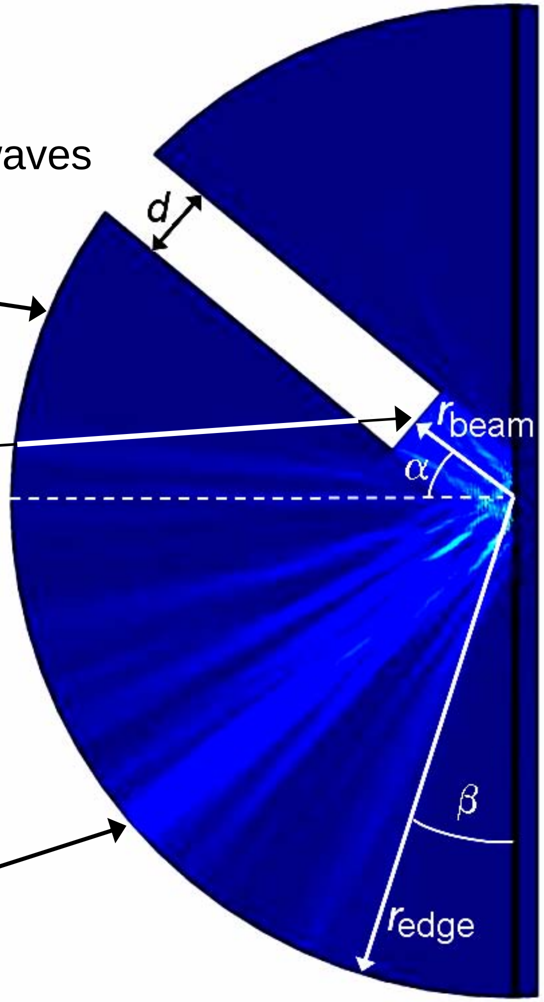
Transparent to outgoing plane waves and scattered waves

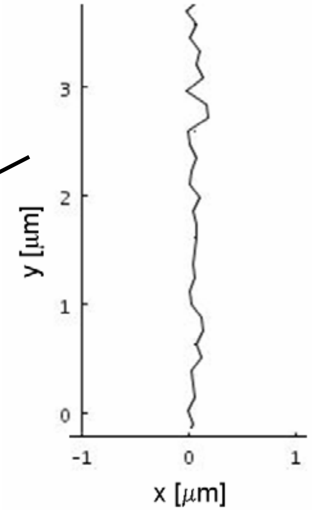
$$E_{tot} = E_0 e^{ik(\vec{k}\vec{r})} + E_{0,sc} e^{ik(\vec{n}\vec{r})}$$

Generation of incoming plane wave

$$E_{gen} = E_{0,gen} e^{ik(\vec{k}\vec{r})}$$

Detection of time-averaged
energy in segments of 5º

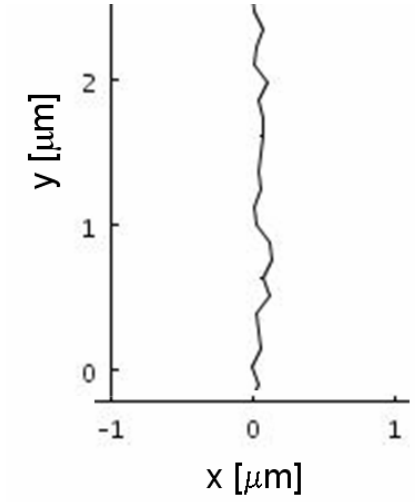




Random surfaces and statistical angular distributions

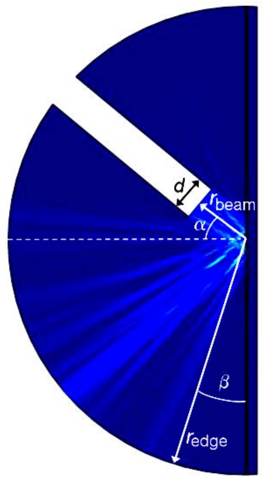
Definition of Roughed surfaces

- ✓ Equidistant set of points in the y-direction with distance Δy
- ✓ Random set of x-values defined with normal (Gaussian) distribution with standard deviation σ
- ✓ Connect these points with straight lines to define the rough surface



Method to get statistical angular distributions

- ✓ Any random number created by computer is pseudo random number
- ✓ 10 simulations with different random surfaces with same standard deviation
- ✓ Average boundary integration values of these 10 simulations



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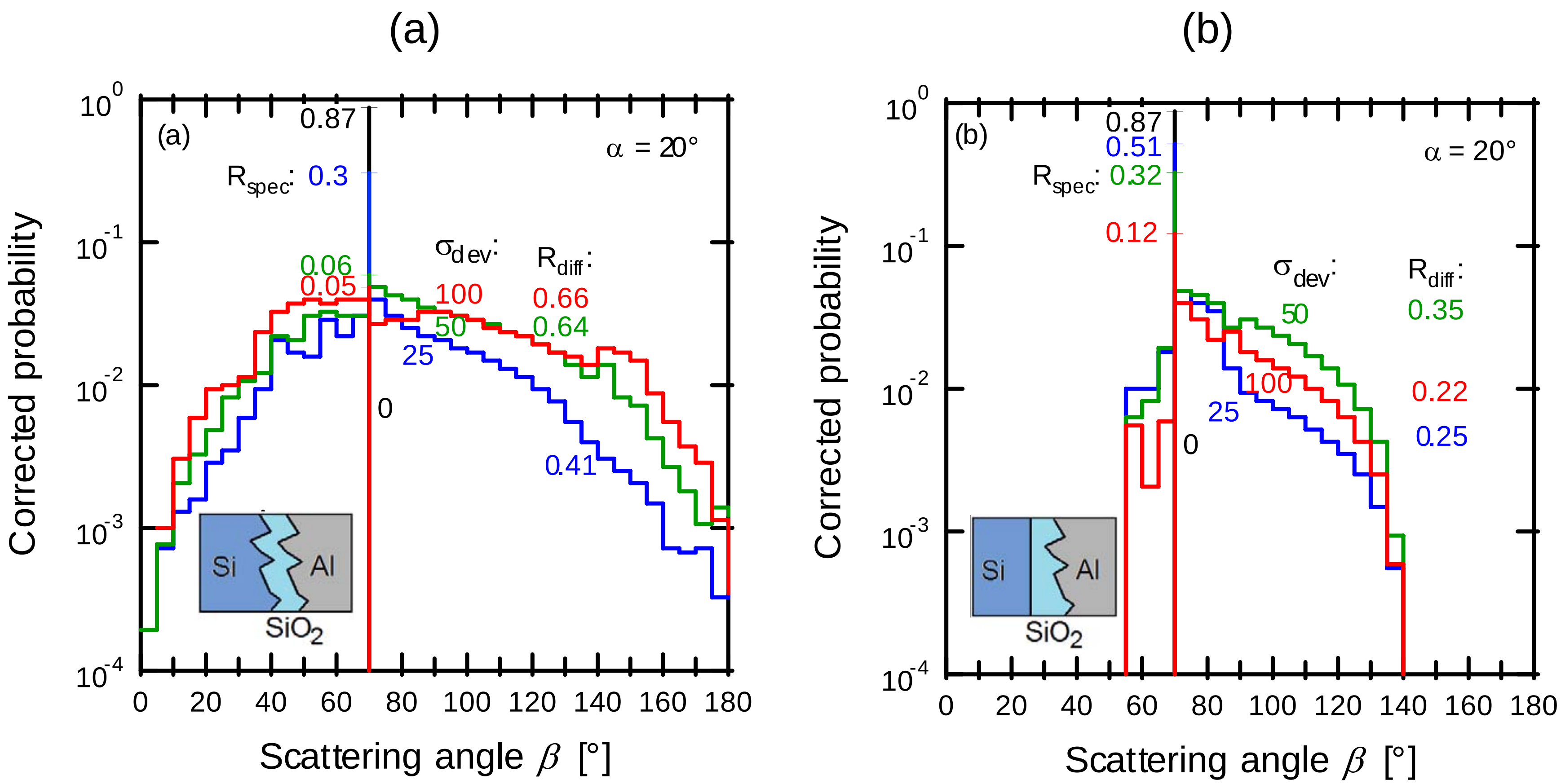
Example of simulated reflectance



Boundary conditions for scattering (B)

Comsol " scattered field " solve mode

Global plane wave instead of generated at boundary:

$$E_{gen} = E_{0,gen} e^{ik(\vec{k}\vec{r})} \in \text{Volume}$$

```
Eoiz (or Hoiz) = exp(-i*k0_rfweh*n1*(cos(alpha)*x+sin(alpha)*y))
```

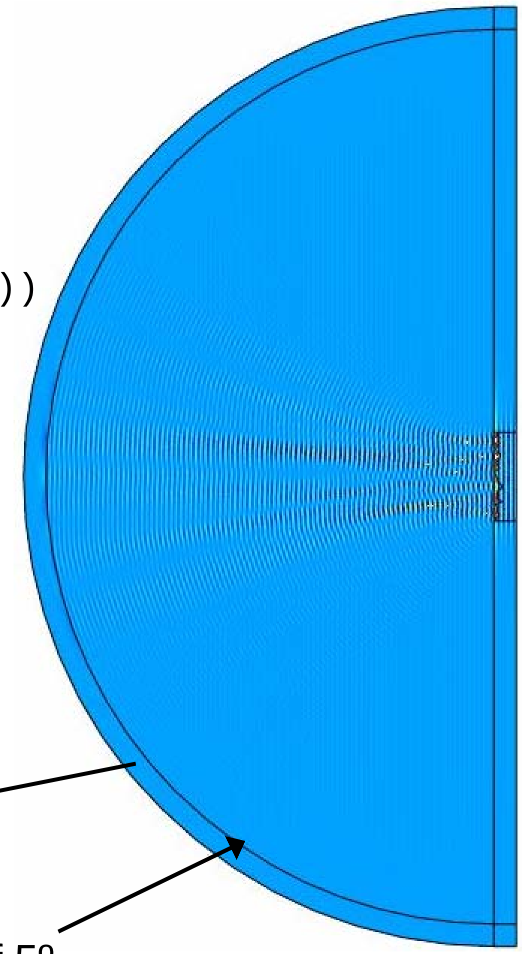
Comsol solves only for the scattered waves instead of all waves:

$$E_{sc} = E_{0,sc} e^{ik(\vec{n}\vec{r})}$$

Total field is sum of both:

$$E_{tot} = E_{0,sc} e^{ik(\vec{n}\vec{r})} + E_{gen}$$

"Boundary" condition: perfectly matched layer (PML)

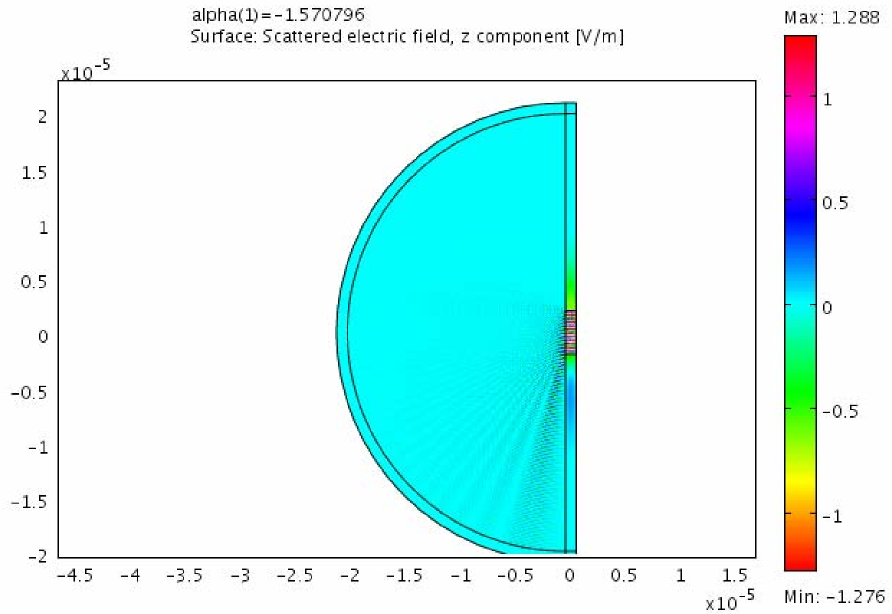


Detection of time-averaged energy in segments of 5º

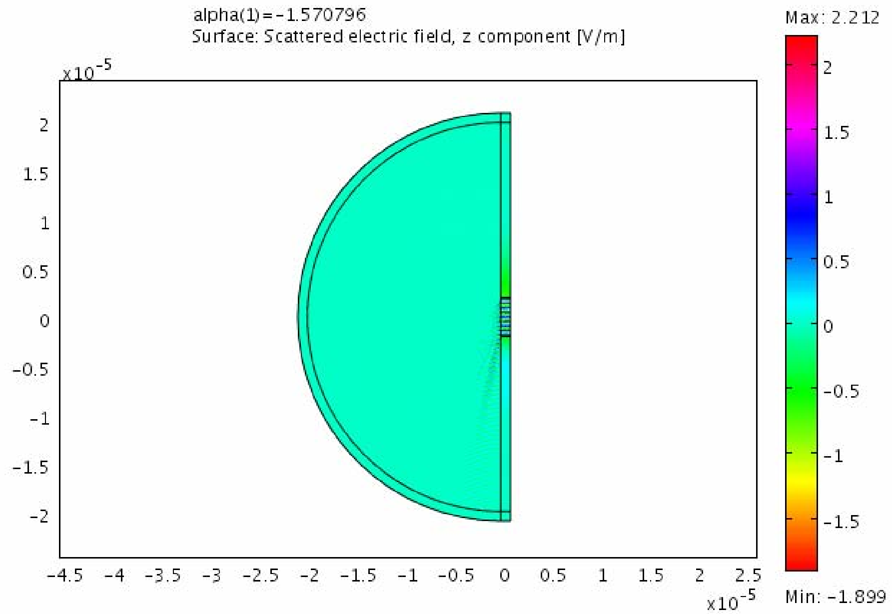
Scattering from Planar and roughed(sd50nm) surfaces

Si/Al system

Incident angle varies from 0º to 180º

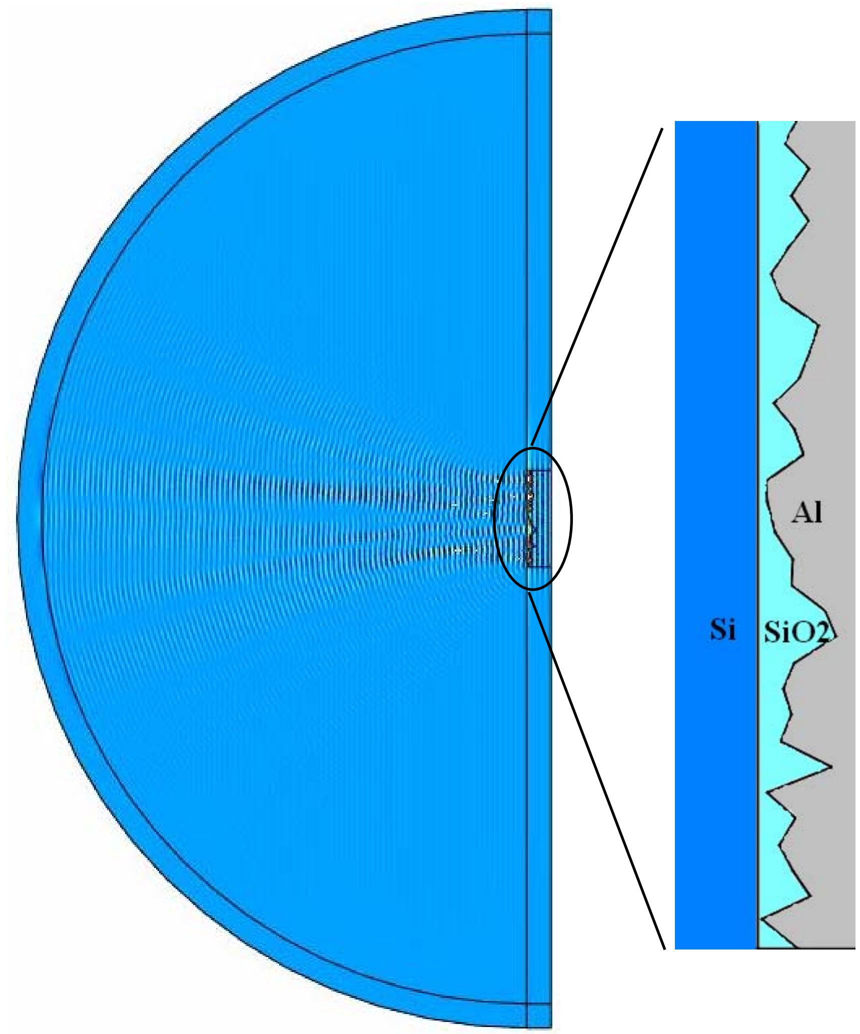


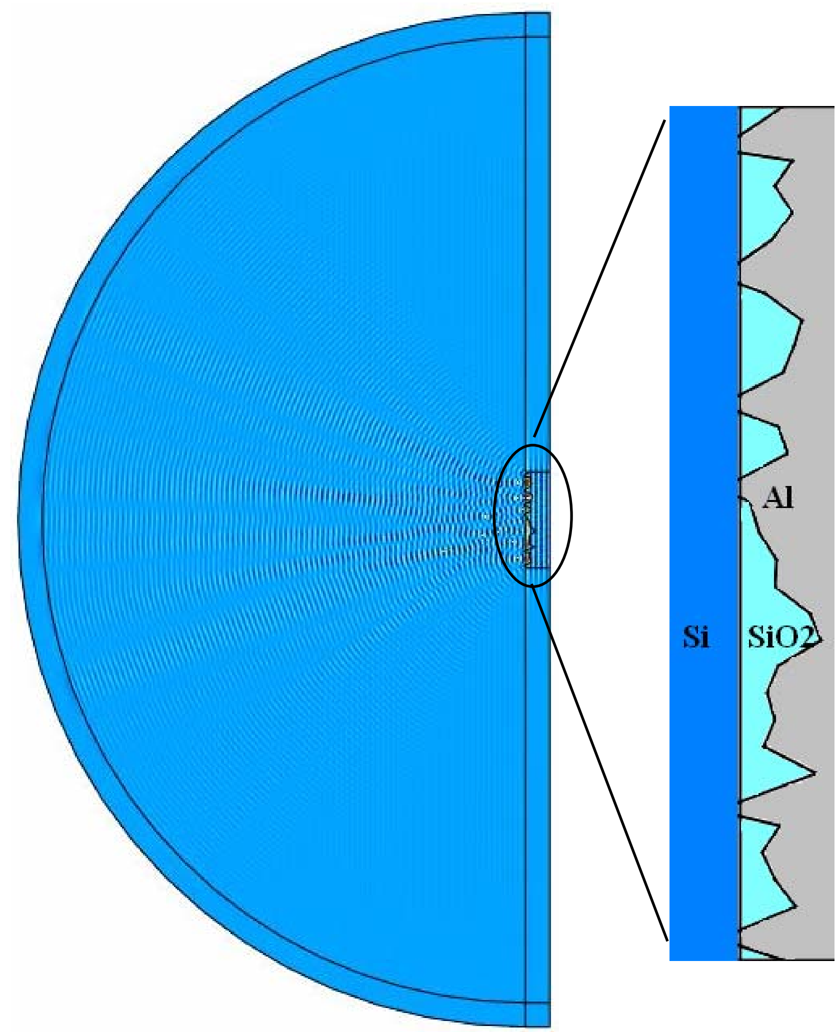
Planar surface



Roughed surface

Scattering properties with and without metal dots





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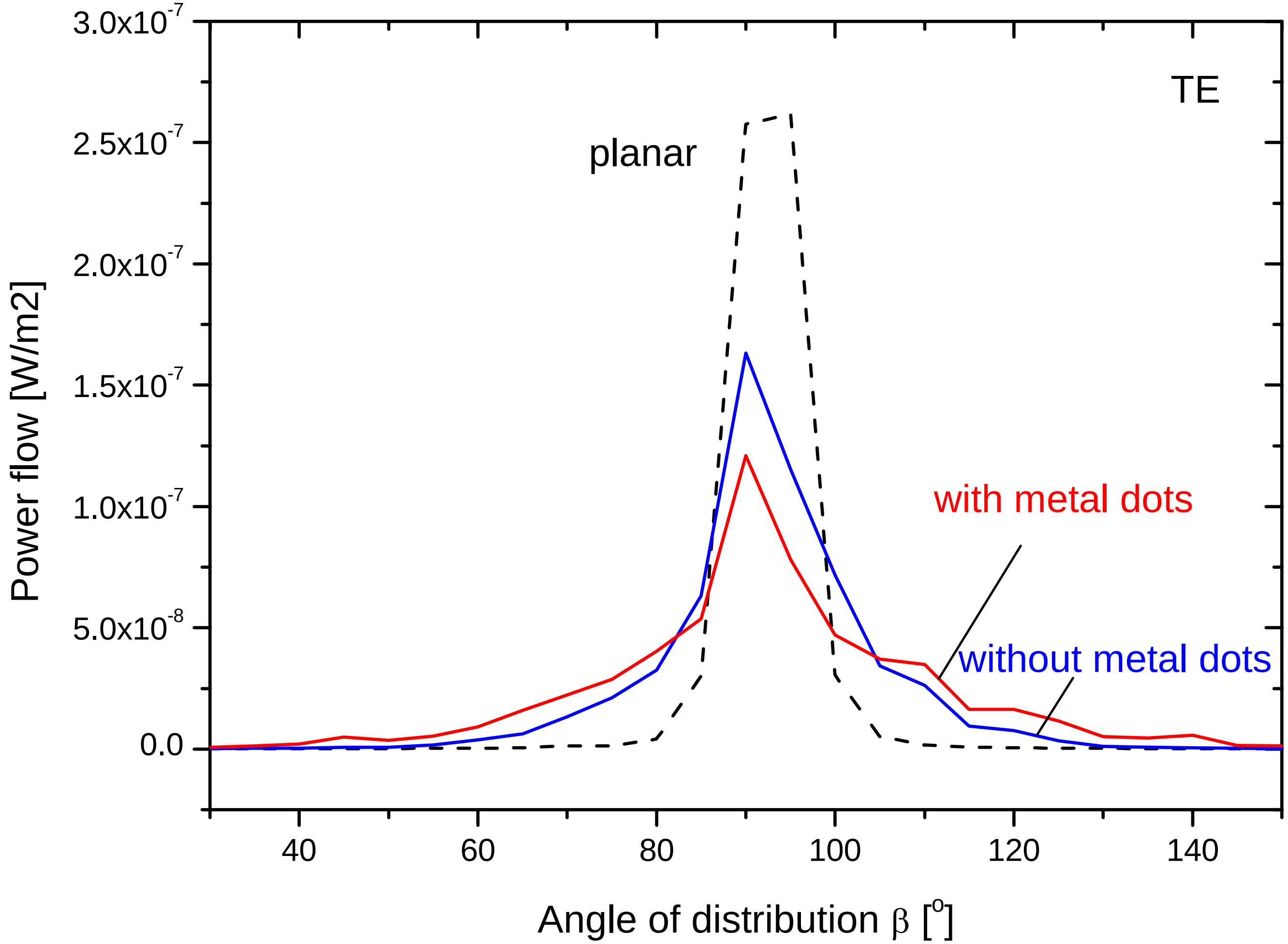
Scattering properties with and without metal dots



Conclusions

1. Simulation of planar surfaces by means of Floquet boundary condition gives perfect agreement with Fresnel theory.
2. Simulation of rough surfaces yield angular distribution of reflection at Si/Al or Si/SiO_2/Al interface.
3. An optimally diffuse reflection is achieved with a standard deviation for roughness of about 50nm.
4. Random distributed metal dots on Si/SiO_2 interface enhance scattering

Thank you!