UiO : Department of Physics
University of Oslo

# Photonic crystals for light trapping in solar cells

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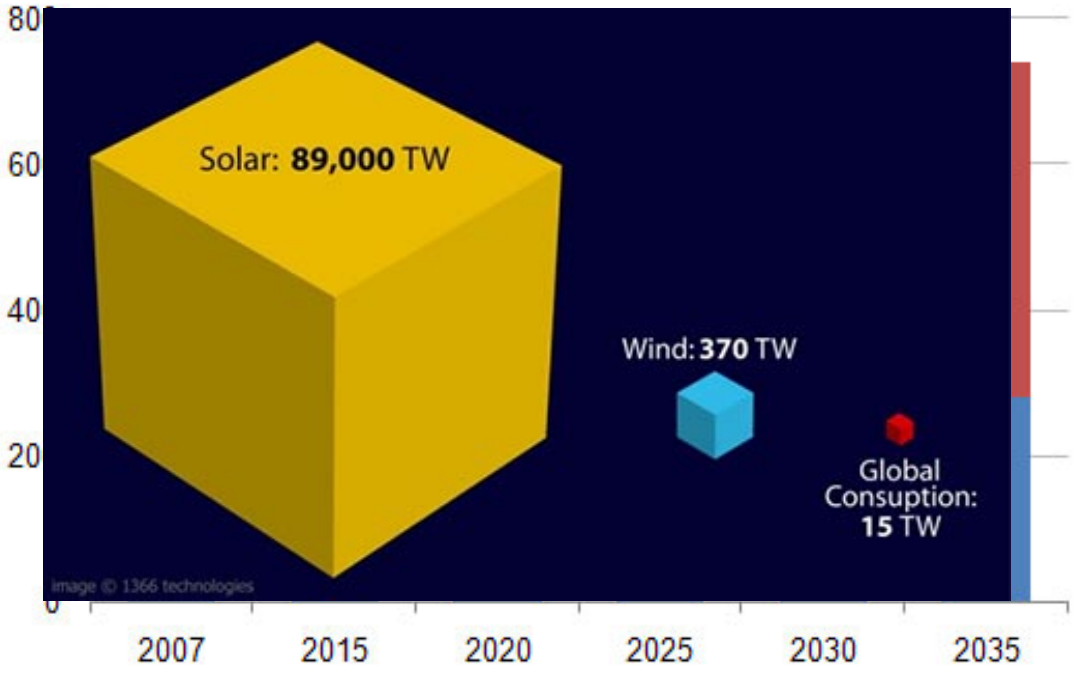
# Outline

- Introduction
- Light trapping in silicon solar cells
- 2D photonic crystals for light trapping
- Simulation results
  - Photogenerated current density
  - Diffraction efficiencies
  - Different unit cells structures
- Fabrication and characterization
  - First demonstration: Standard silicon fab
  - More cost-effective fabrication
- Conclusions

# Energy consumption and $CO_2$ emissions increase

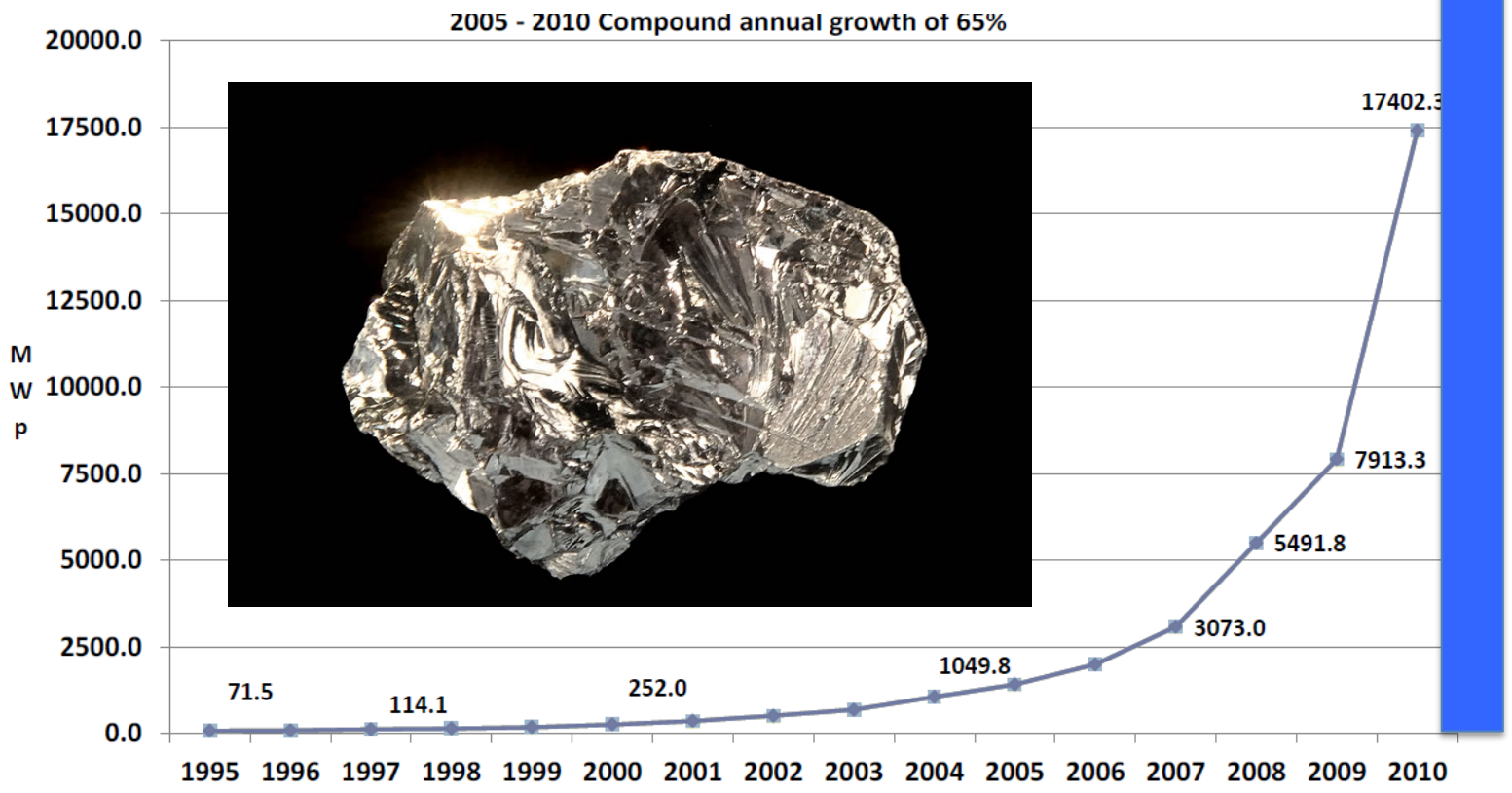
Figure 1. World marketed energy consumption




US Department of Energy, 2010

2011: 4 nuclear reactors

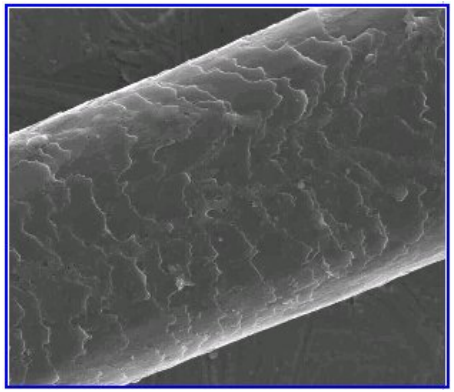
# Annual PV installations 1995-2010



# Cheaper PV with thinner solar cells

Solar cell today:
160-200 µm thick
+100-150 µm lost

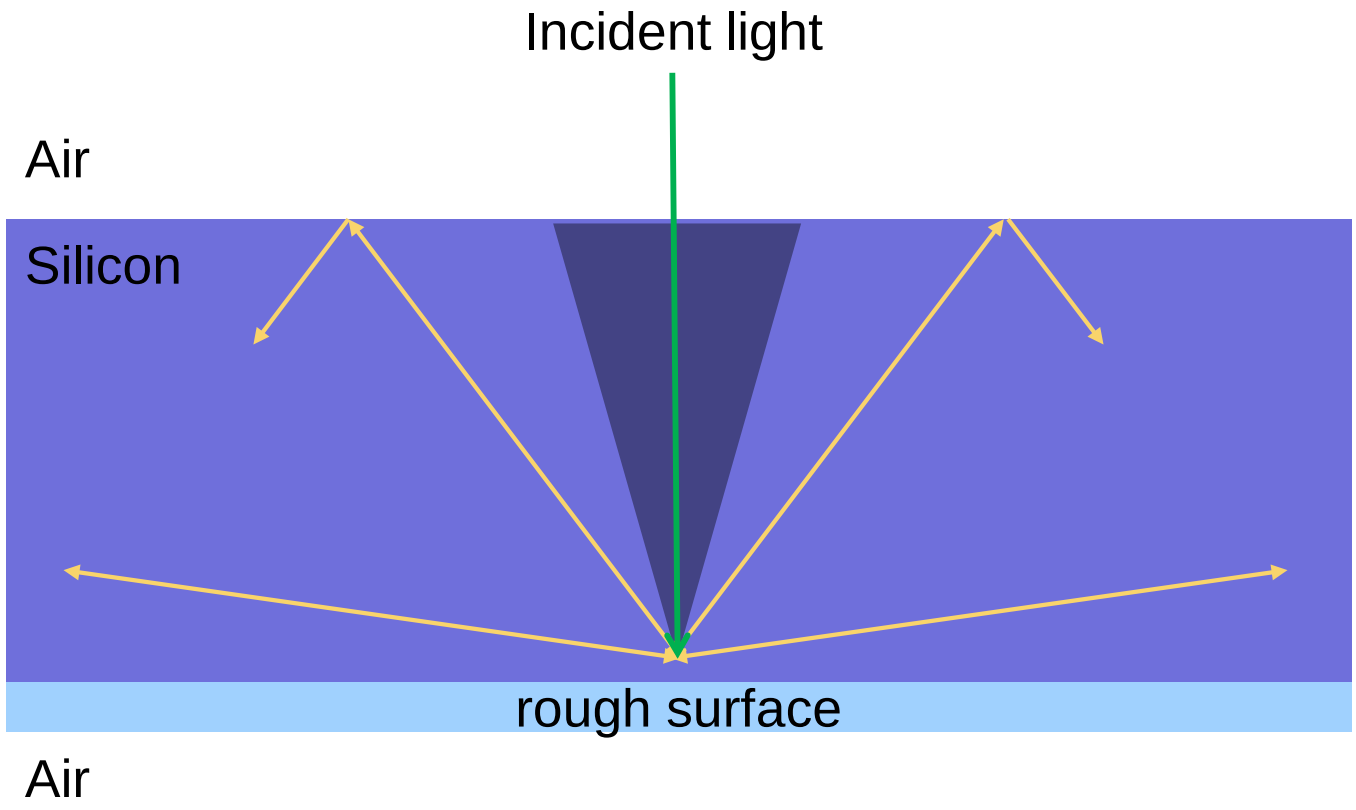
Human hair – 60 µm



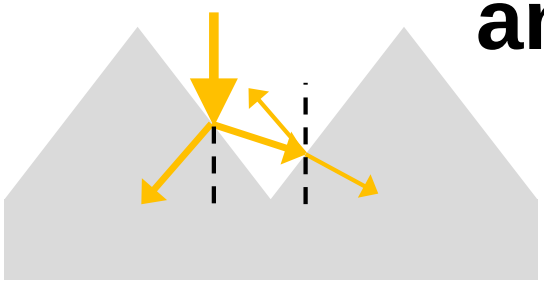
Future solar cells:
20 µm thin ?

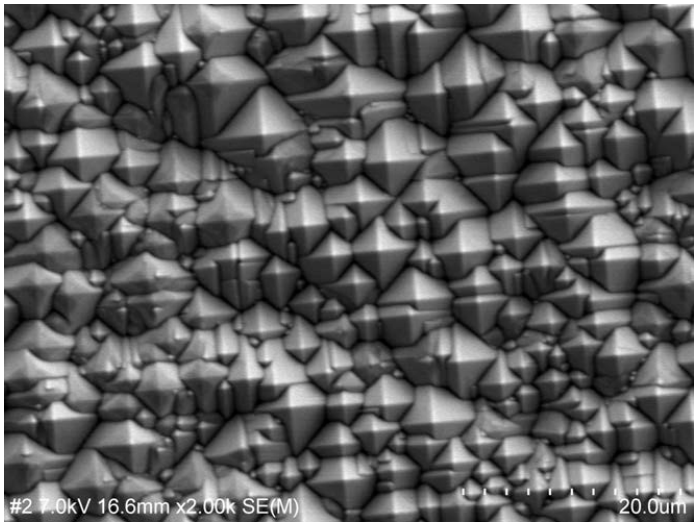
- Problem: Long-wavelength light is not collected in thin silicon cell
- Can we make thin silicon cell and collect light as before?

# Light trapping in a silicon wafer

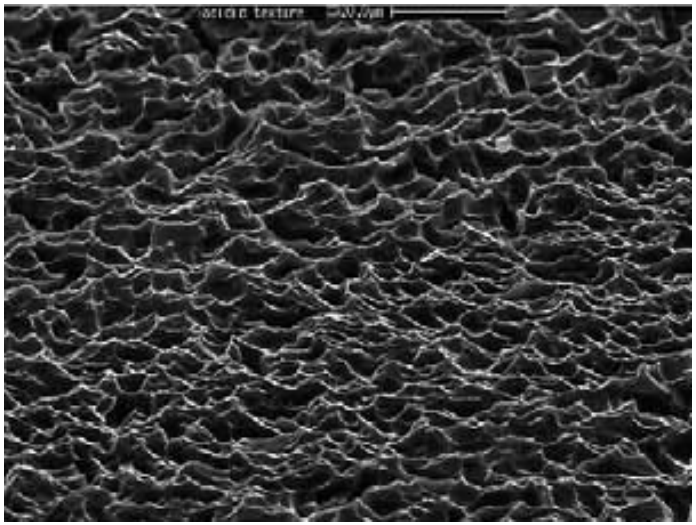


# Today: Dual-purpose surface treatment: anti-reflection going into silicon light trapping inside silicon



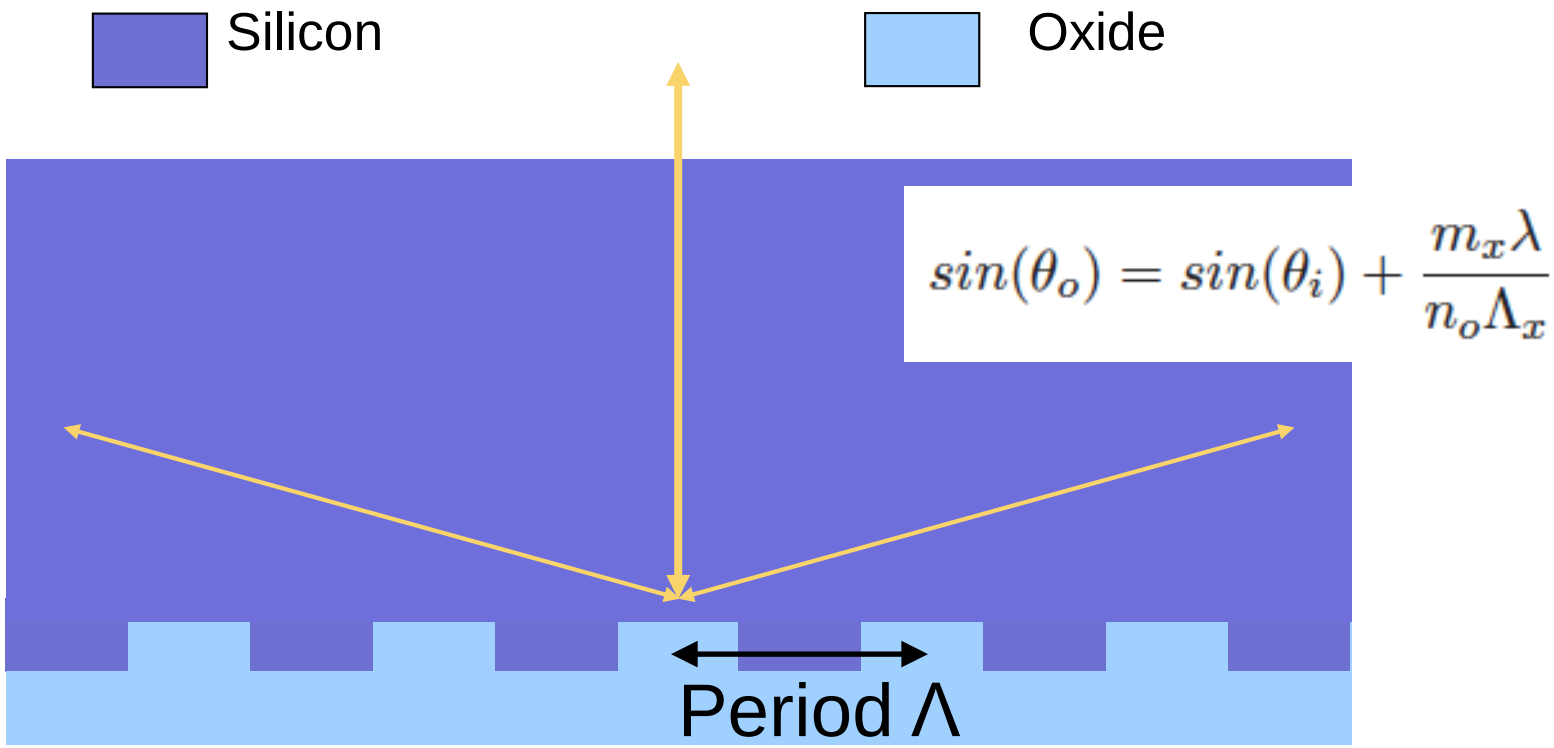



Pyramid structure

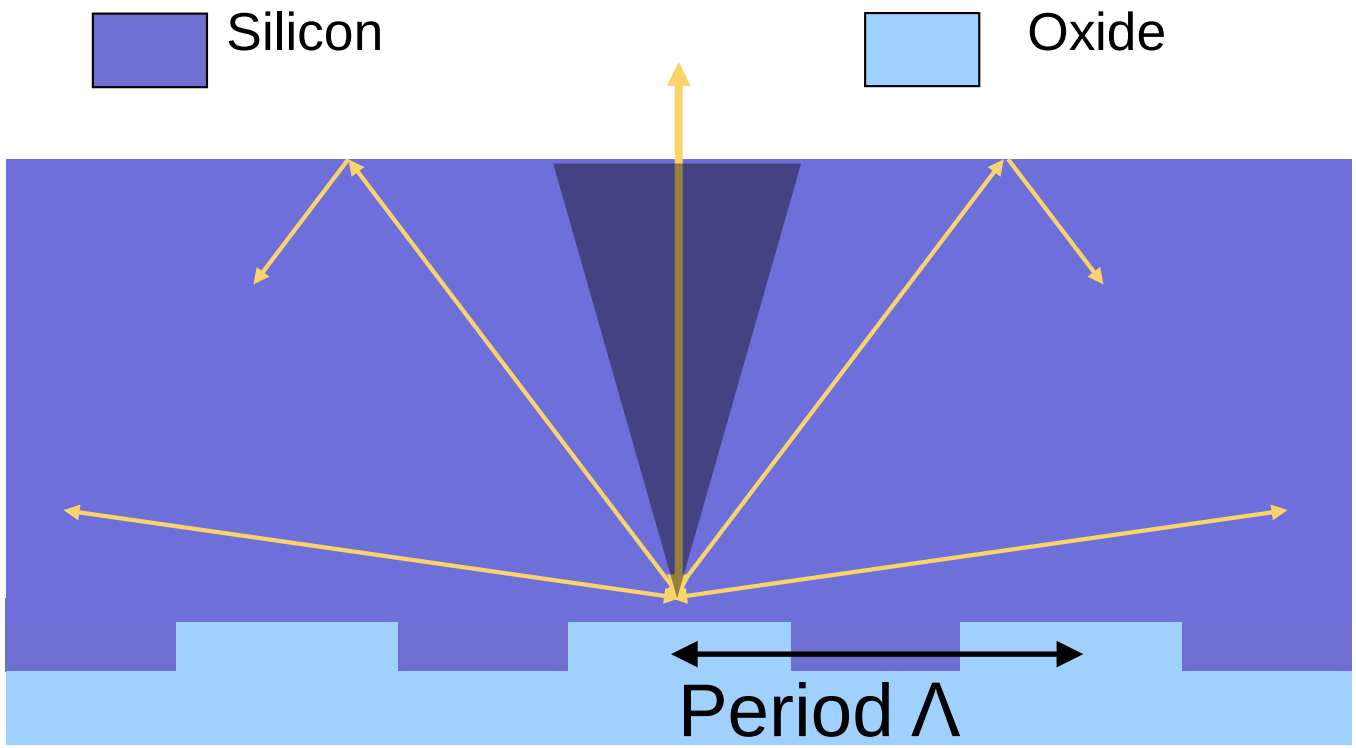


Isotropic structure

# Grating structures and diffraction

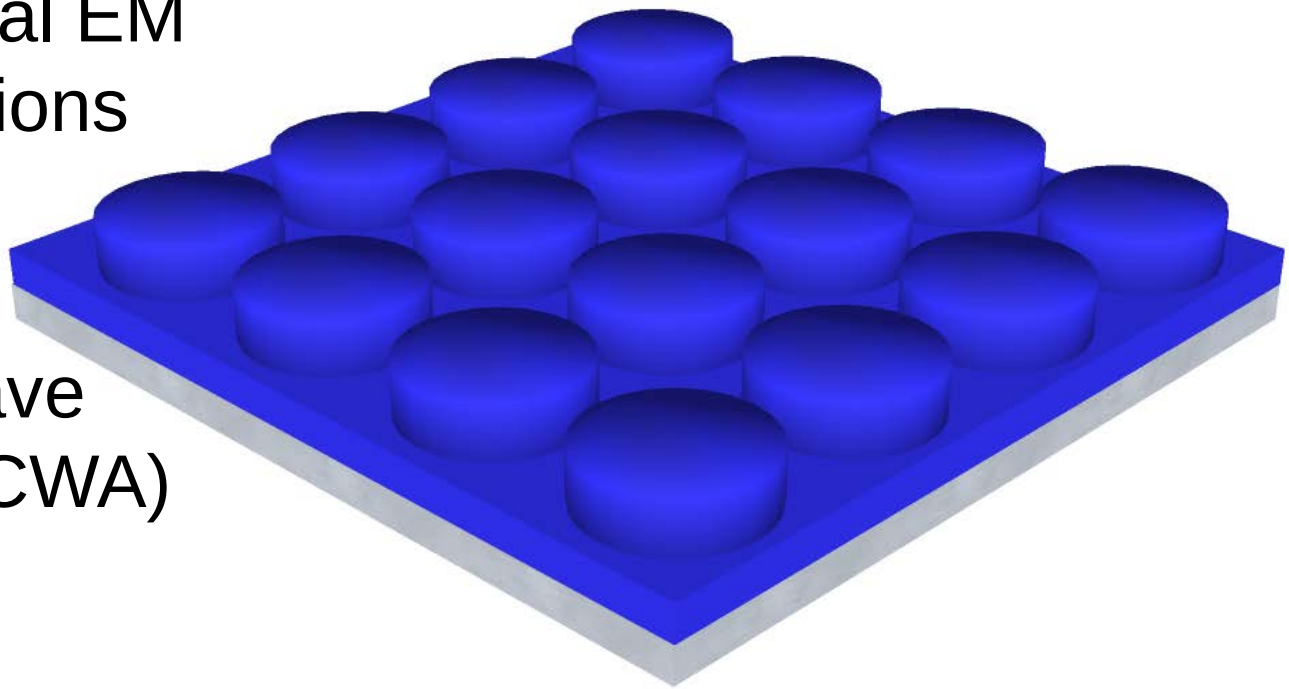


# Grating structures in solar cells

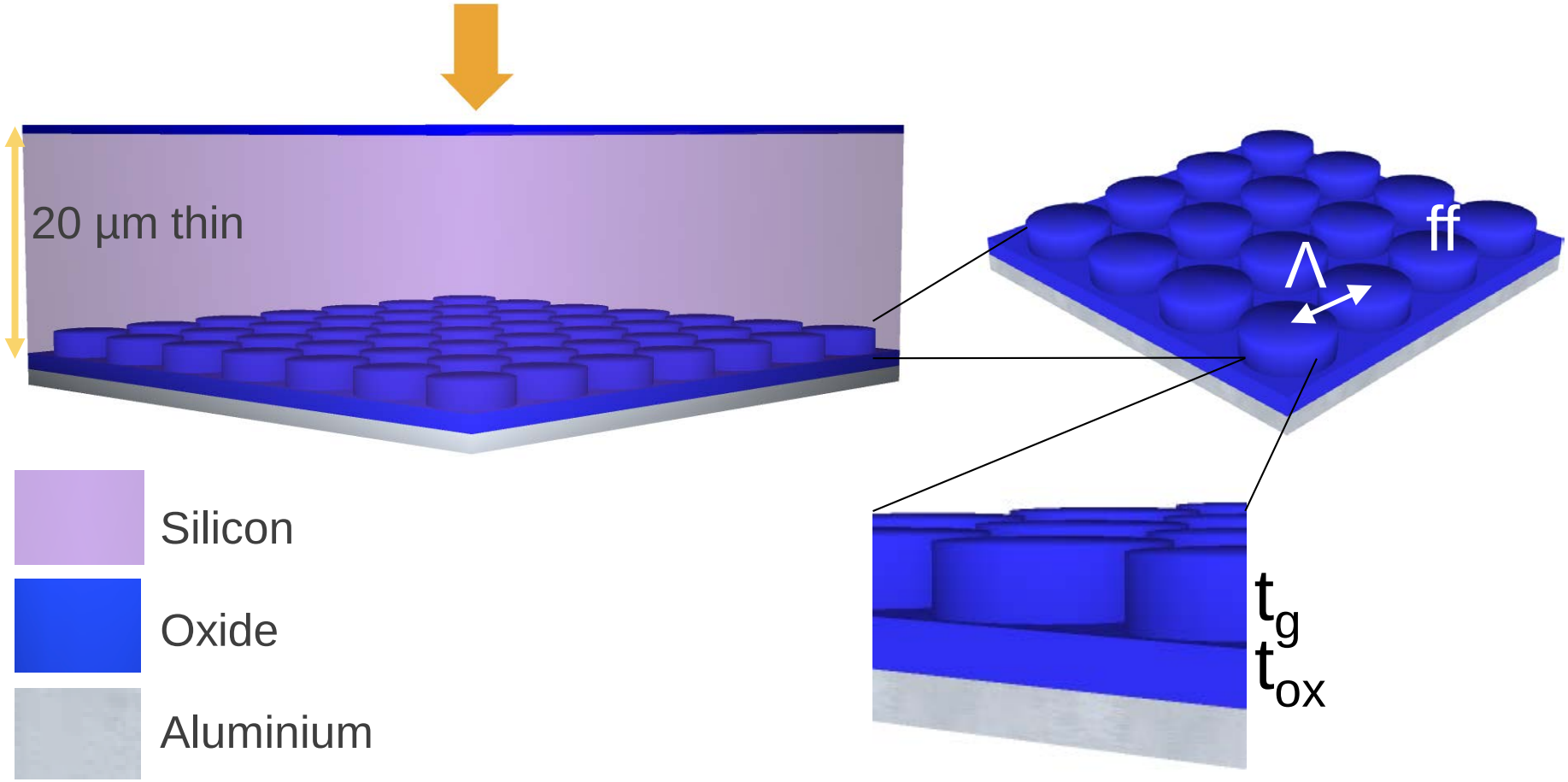


# 2D photonic crystal = 2D periodic grating

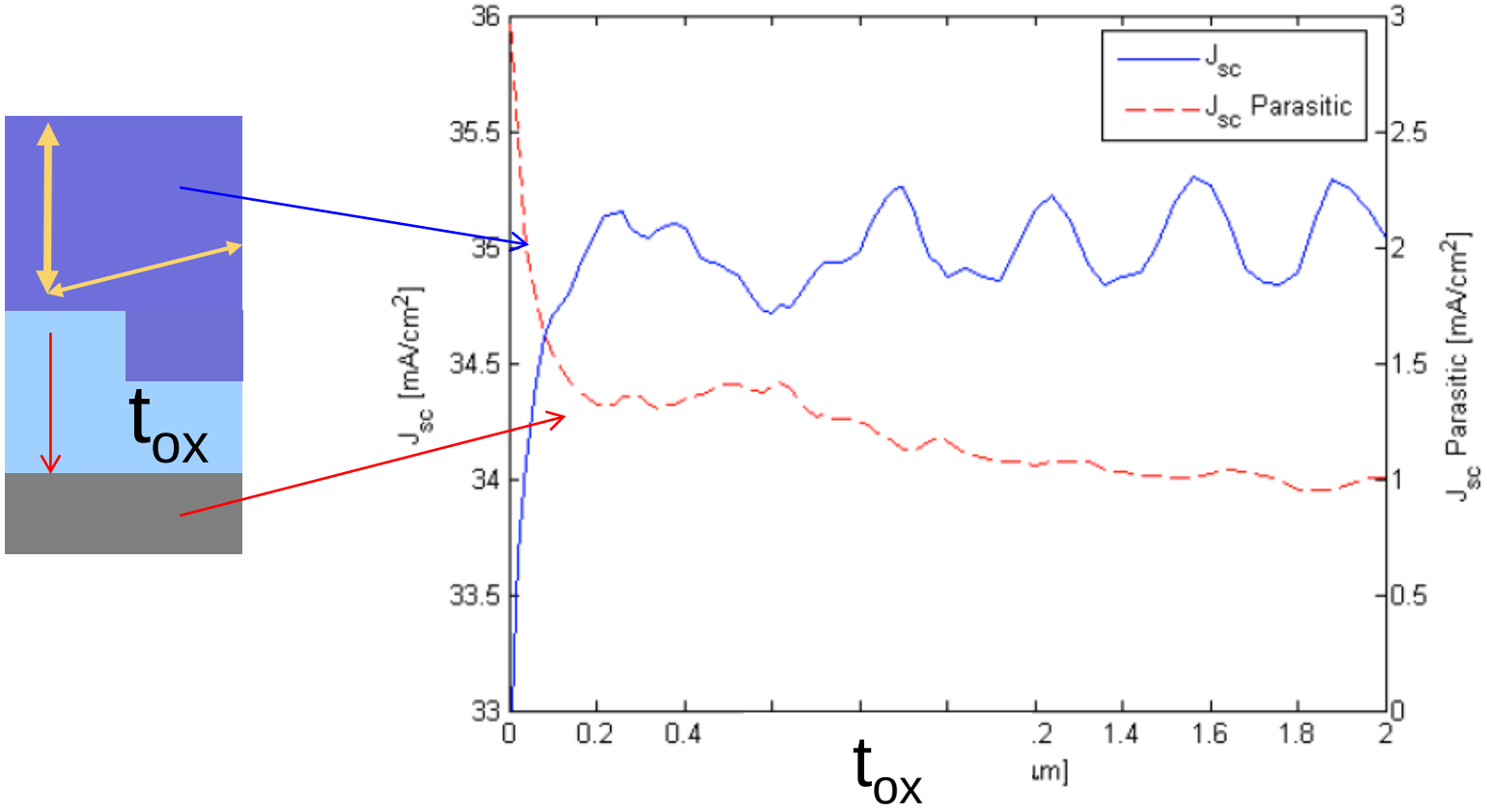
- Studied in numerical simulations
- Fully vectorial EM field simulations needed
- Rigorously Coupled Wave Analysis (RCWA)



# Simulations: Model structure

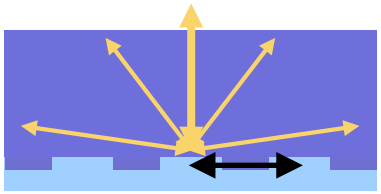


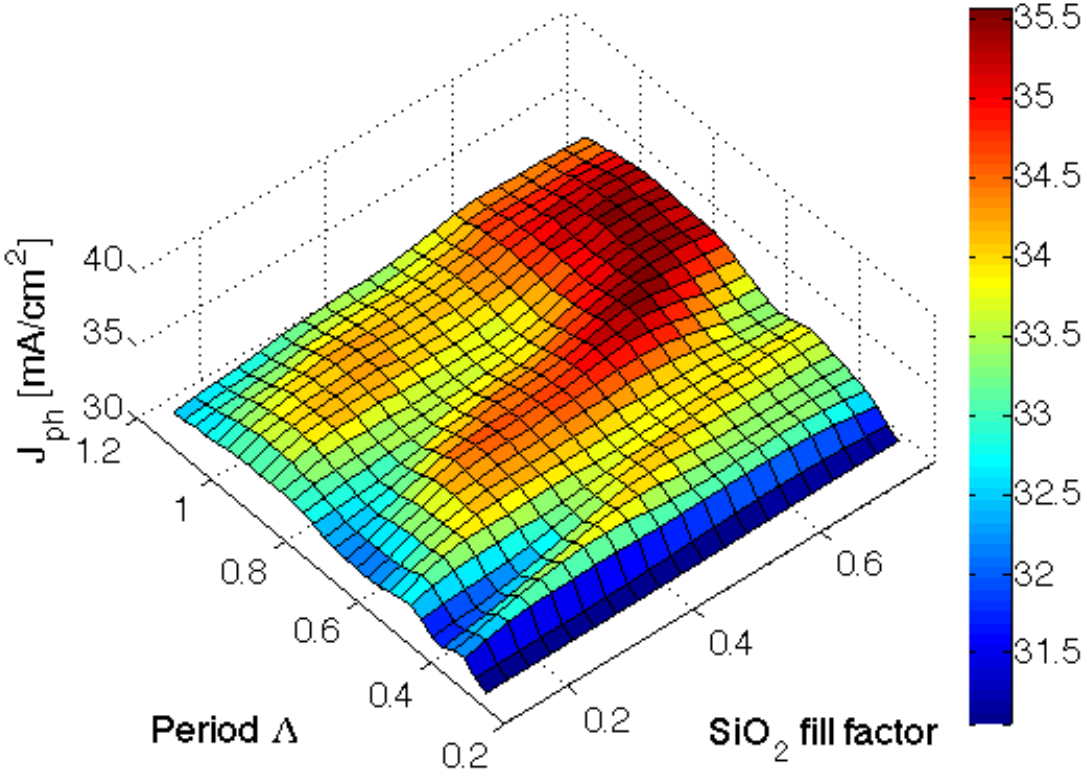
# Simulation results, photogenerated current: Influence of oxide thickness

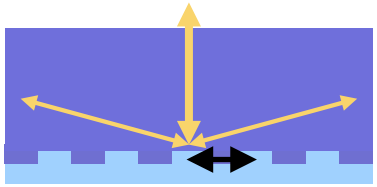



*Gjessing et al., OpEx 2010*

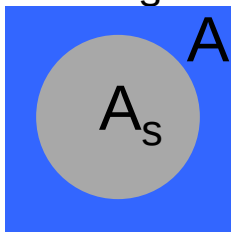
# Simulation results, photogenerated current: Influence of period and fill factor





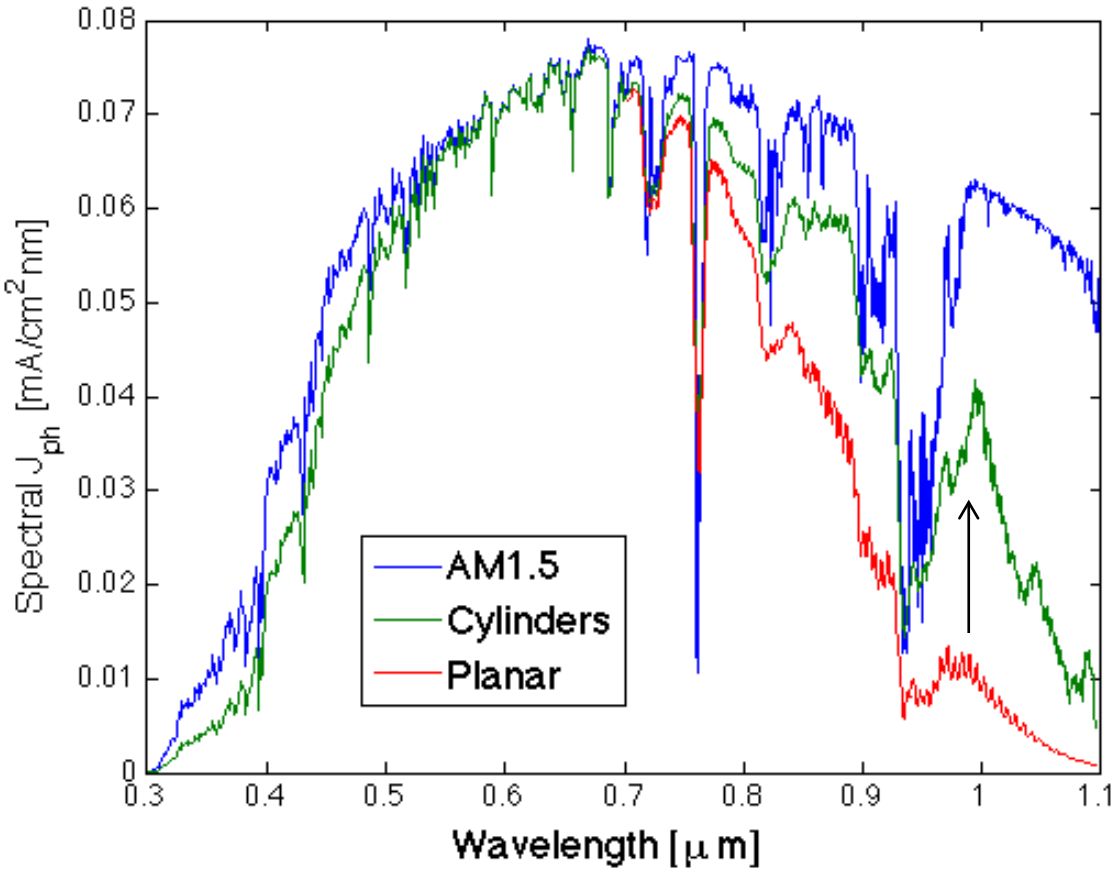



ff=$A_s$/A

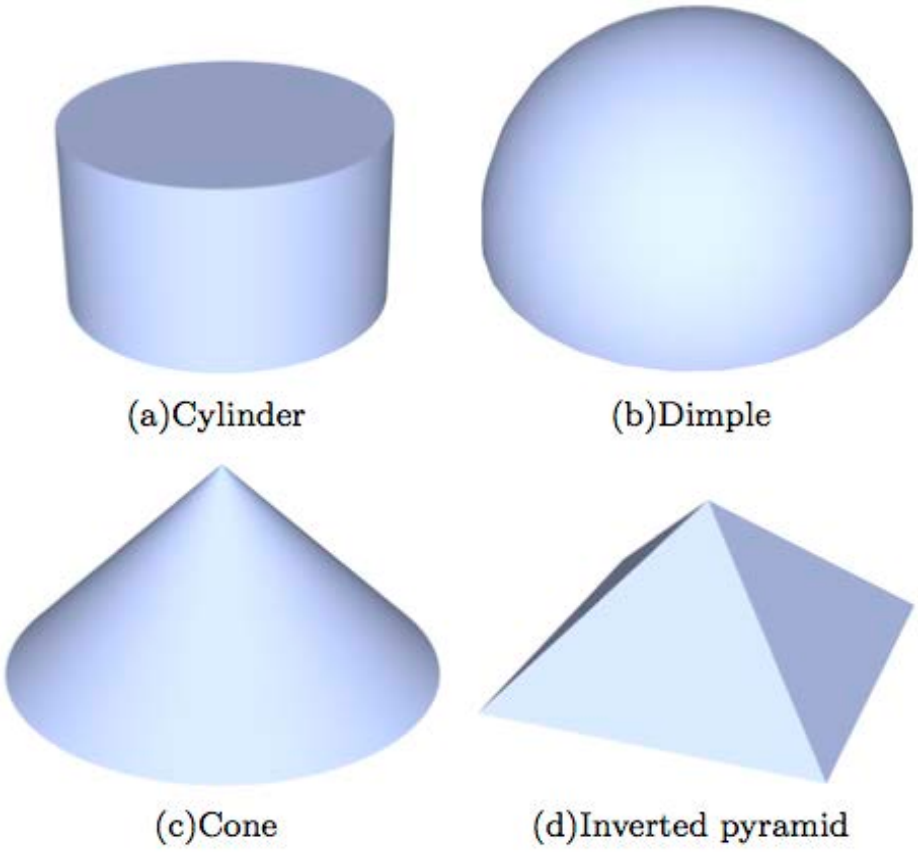



*Gjessing et al., OpEx 2010*

# Simulated spectral absorption

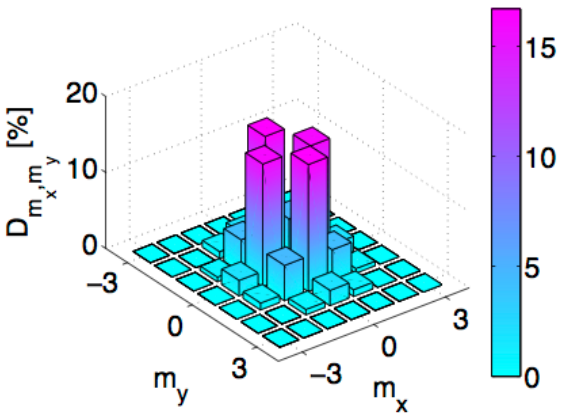


# What about other shapes?

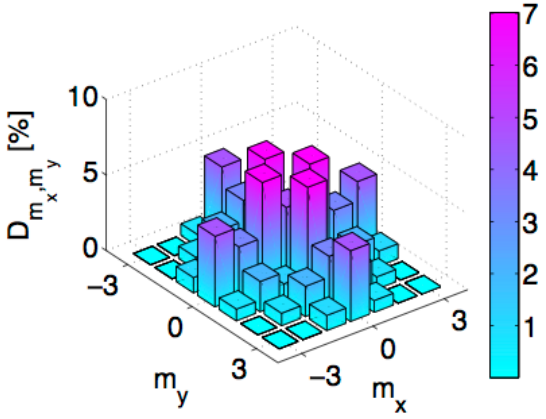



*Gjessing et al., J. Appl. Phys. 2011*

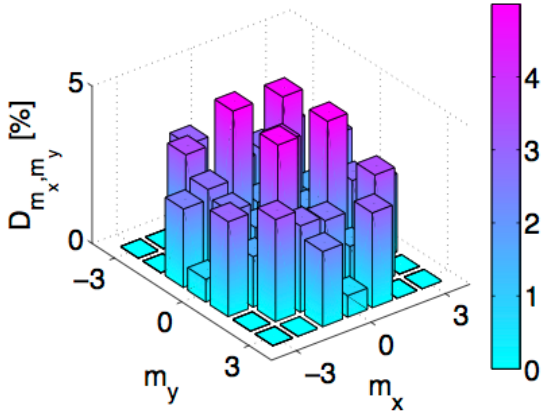
# Simulated 2D diffraction patterns




(a) Cylinder



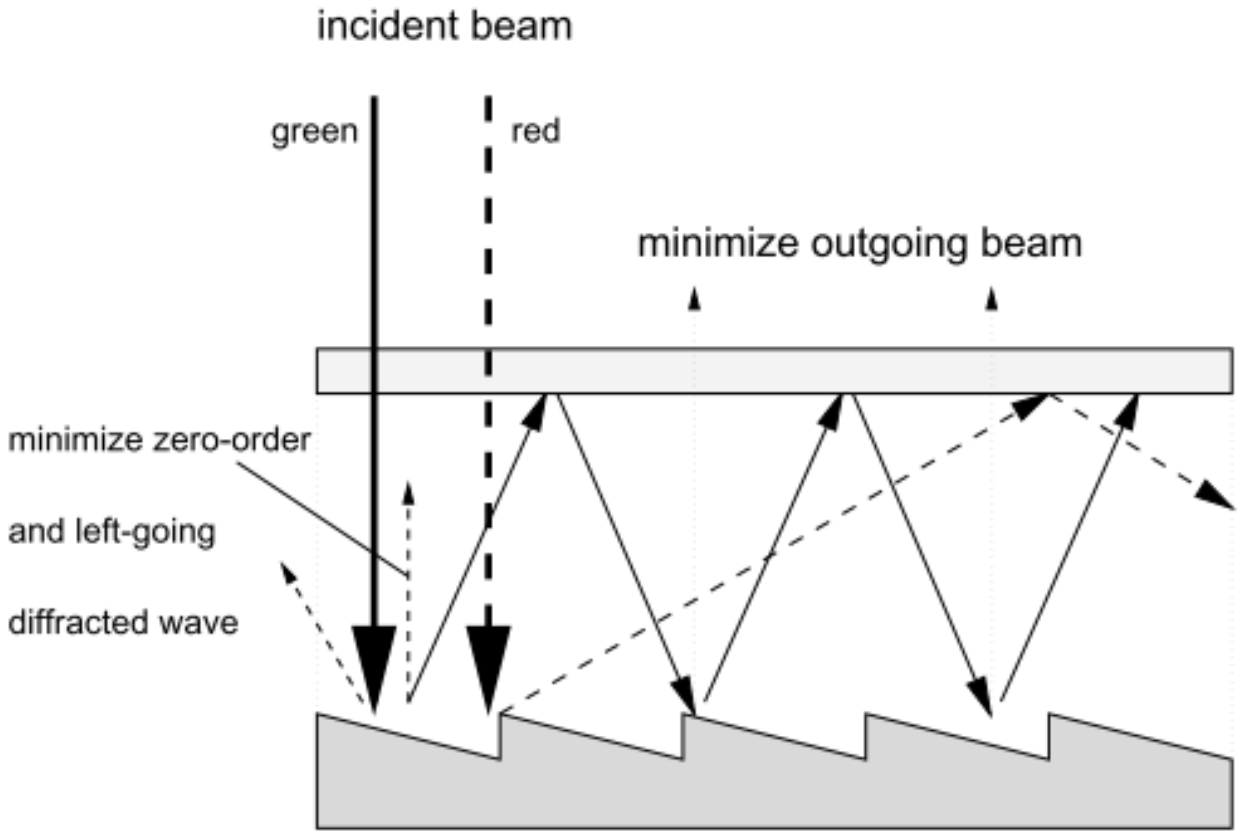

(c) Inverted pyramid




(e) Dimple

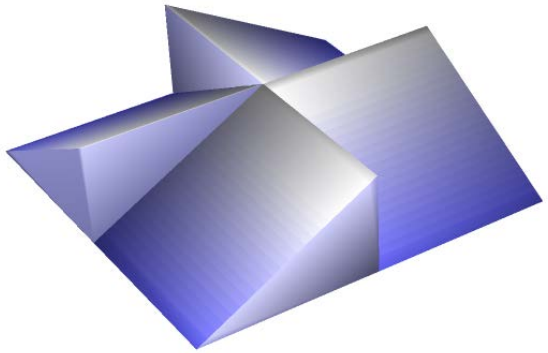
*Gjessing et al., J. Appl. Phys. 2011*

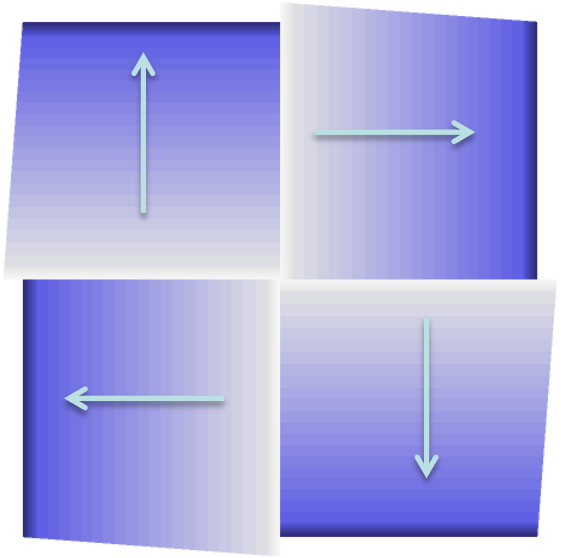
# Loss mechanism: Out-coupling




*Heine et al., Appl. Optics 1995*

# Blazed grating in 2D

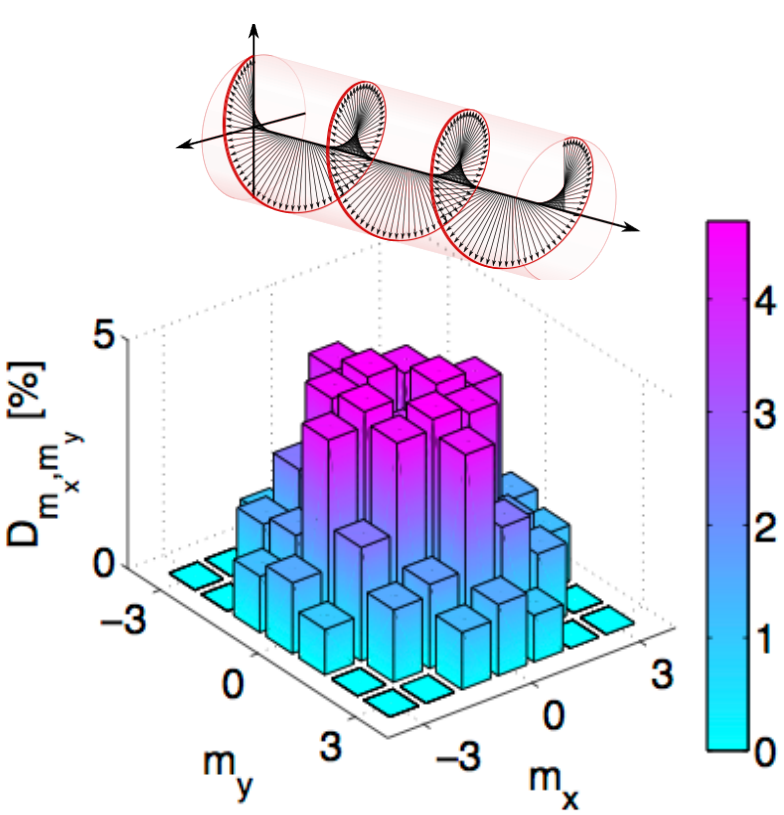




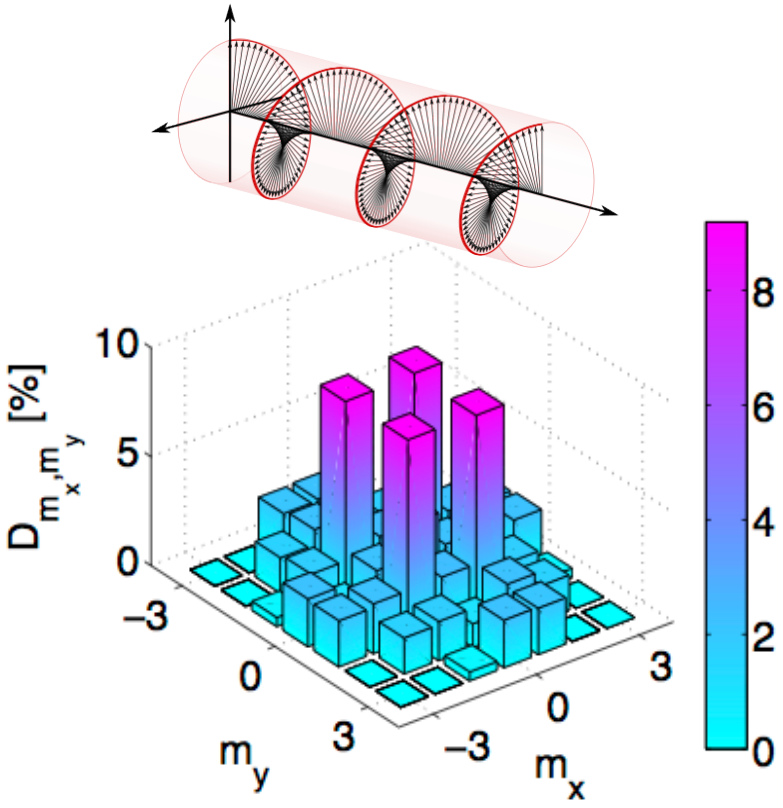
Rose structure

*Gjessing et al., Optics for SOLAR, Tucson 2010*

# Simulated diffraction pattern, rose structure

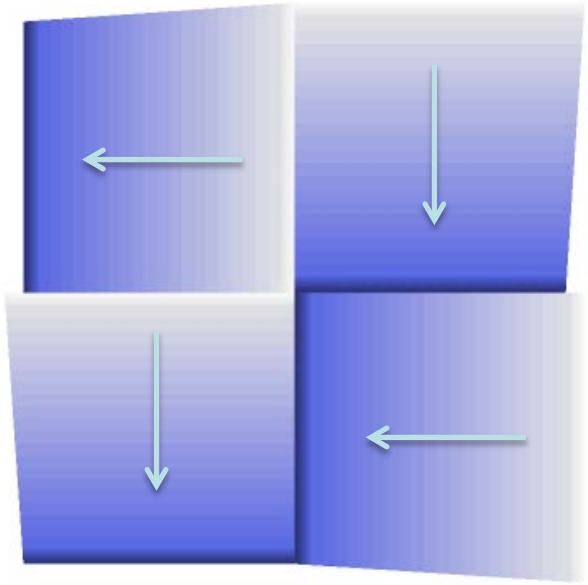


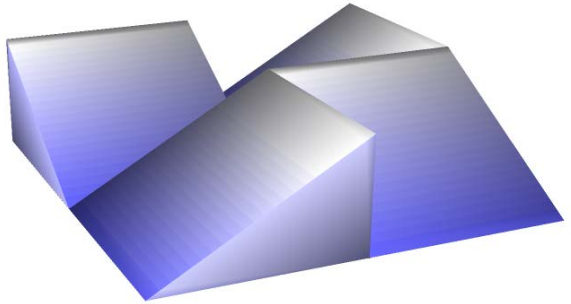

(g) Rose right hand




(h) Rose left hand

# Further reduction of symmetry

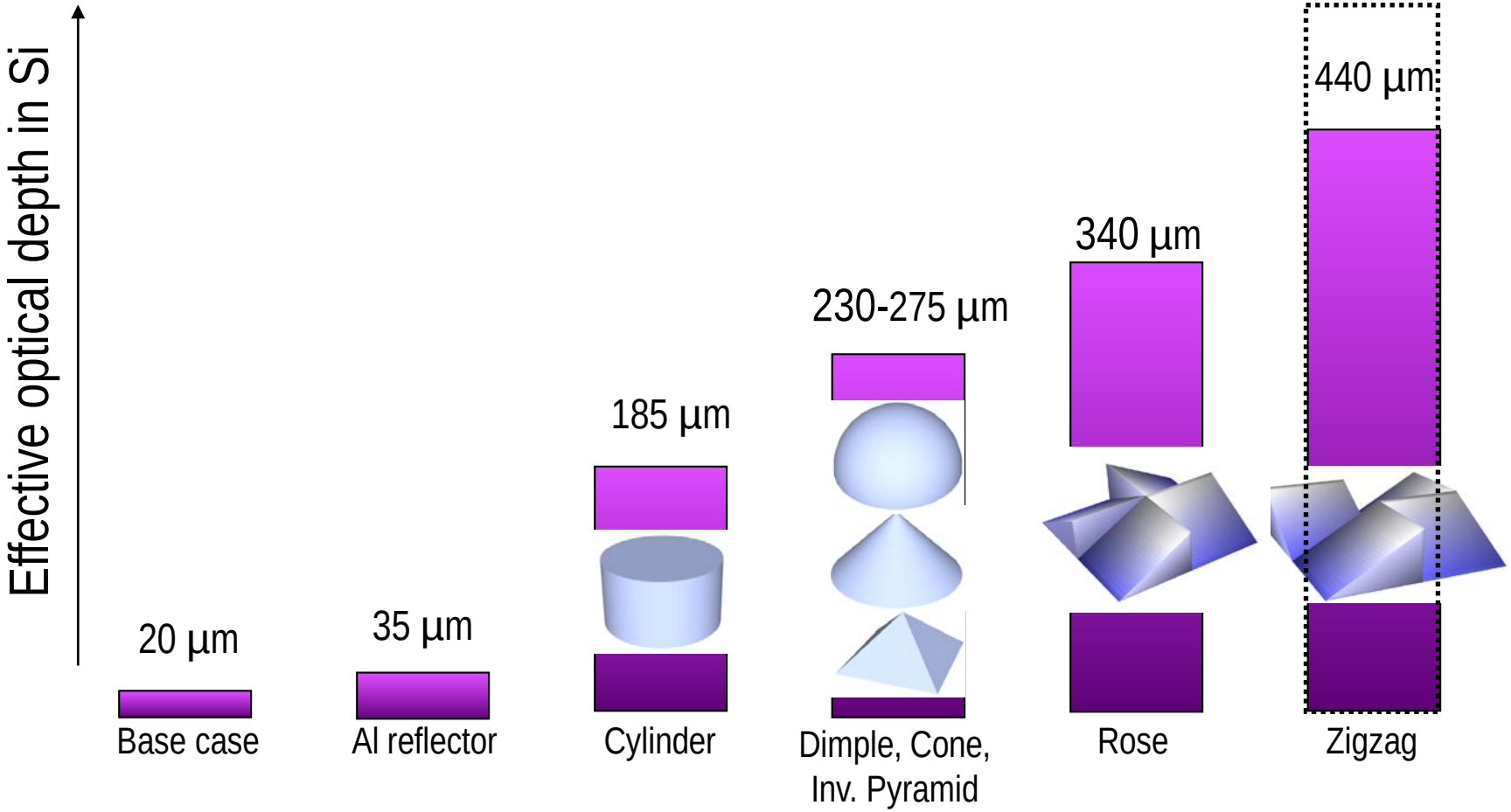




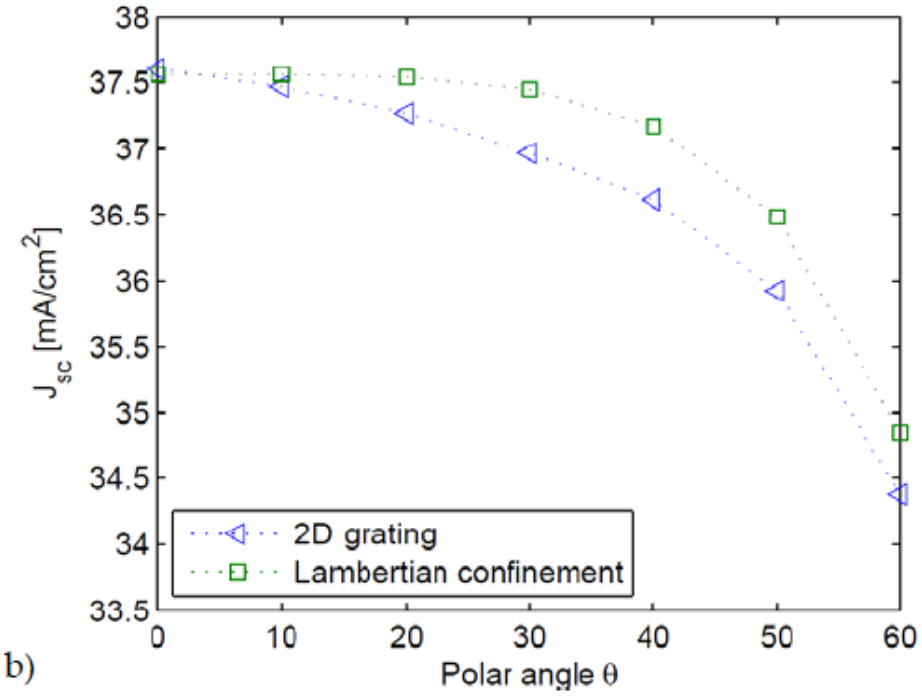
Zigzag structure

*Gjessing et al., J. Eur. Opt. Soc. – Rap. Publ. 2011*

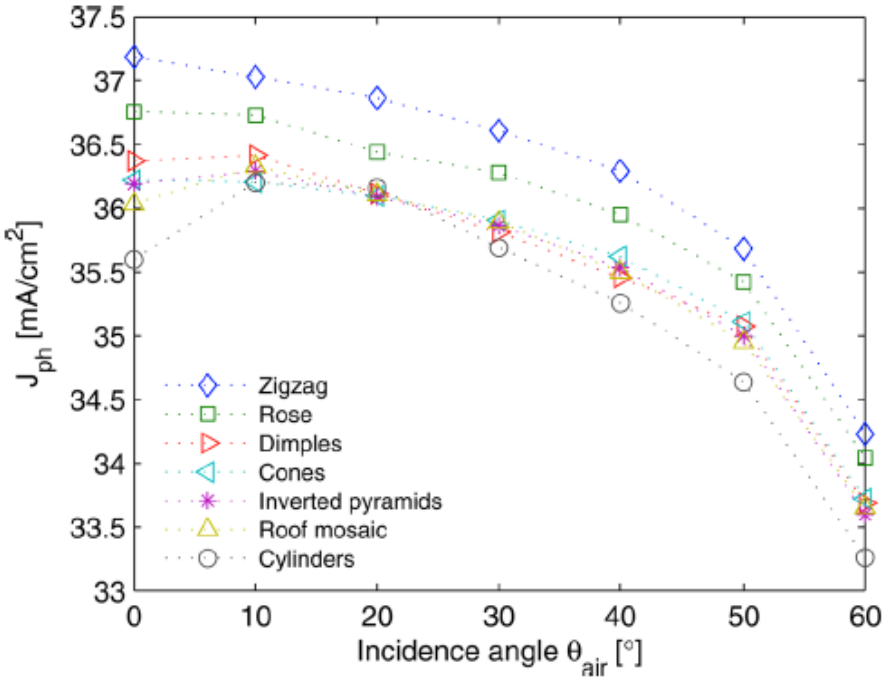
# Equivalent Si thickness



# Photogenerated current density: Oblique incidence (simulations)

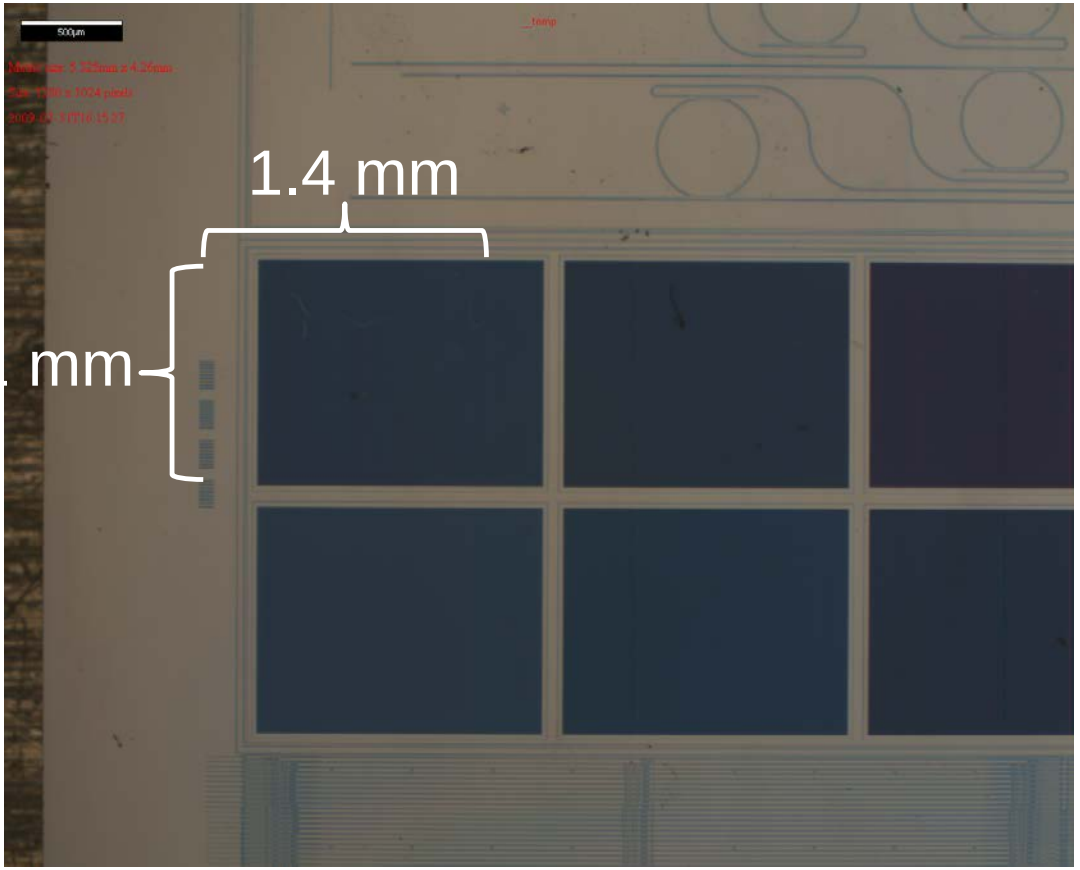



*Gjessing et al., JEOS-RP, 2011*

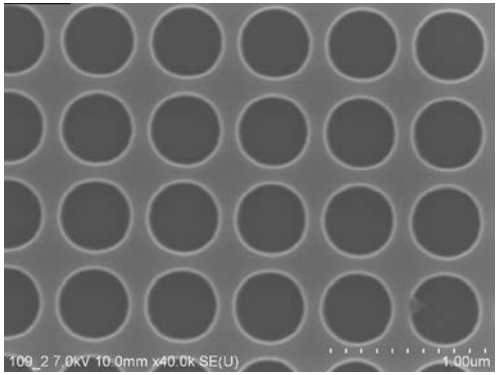


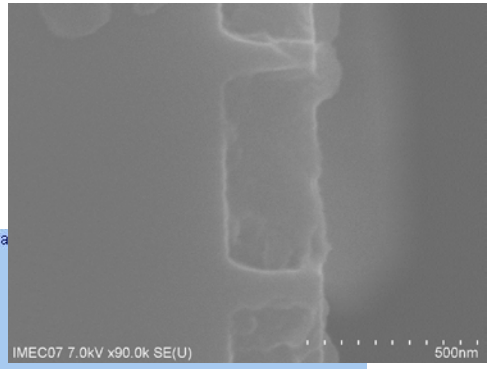

*Gjessing et al., J. Appl. Phys., 2011*

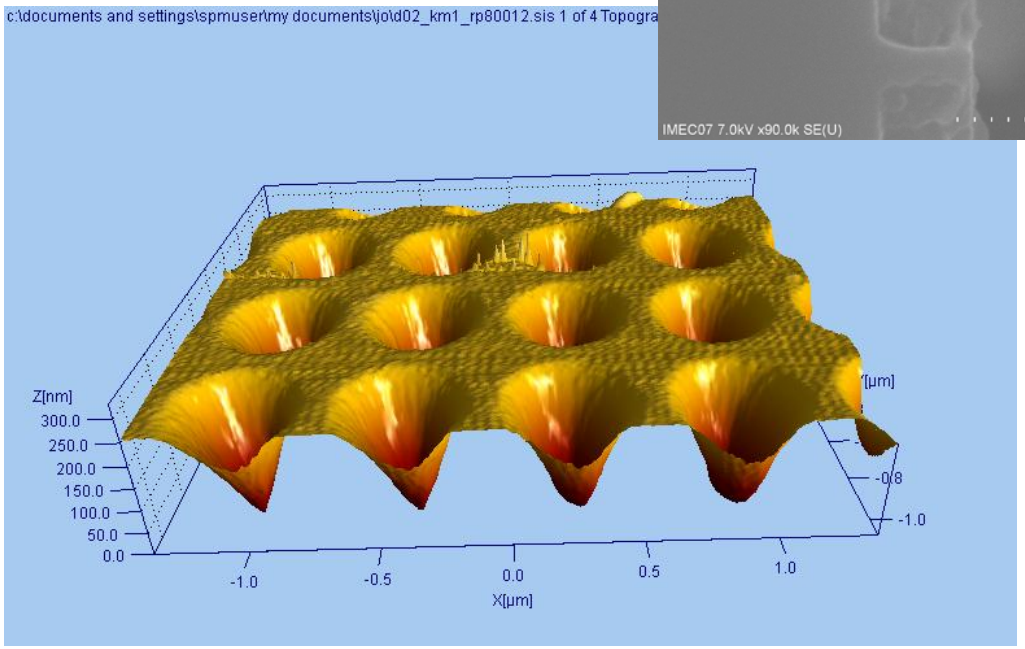
# What about reality?

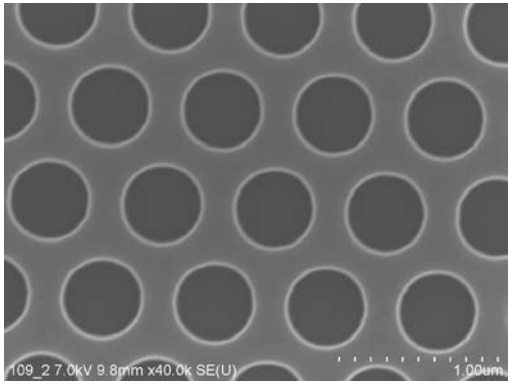


# Fabricated 2D photonic crystals
# SEM and AFM characterization

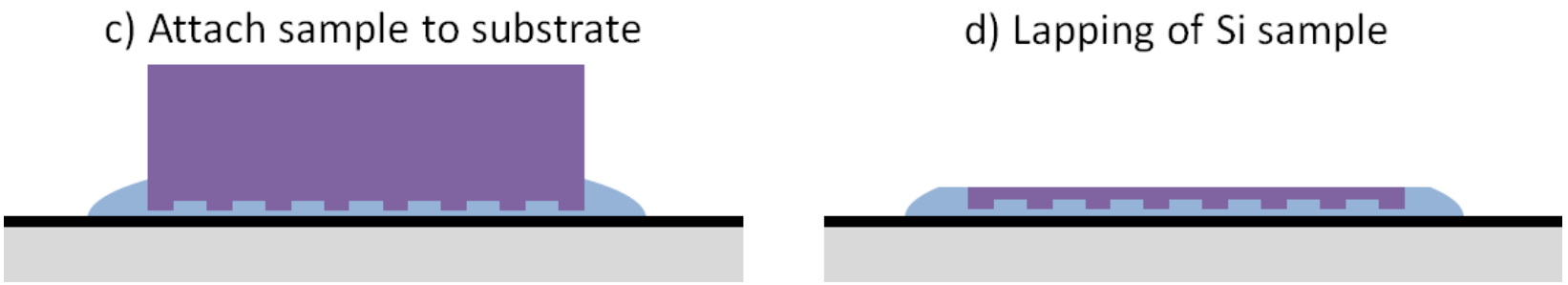


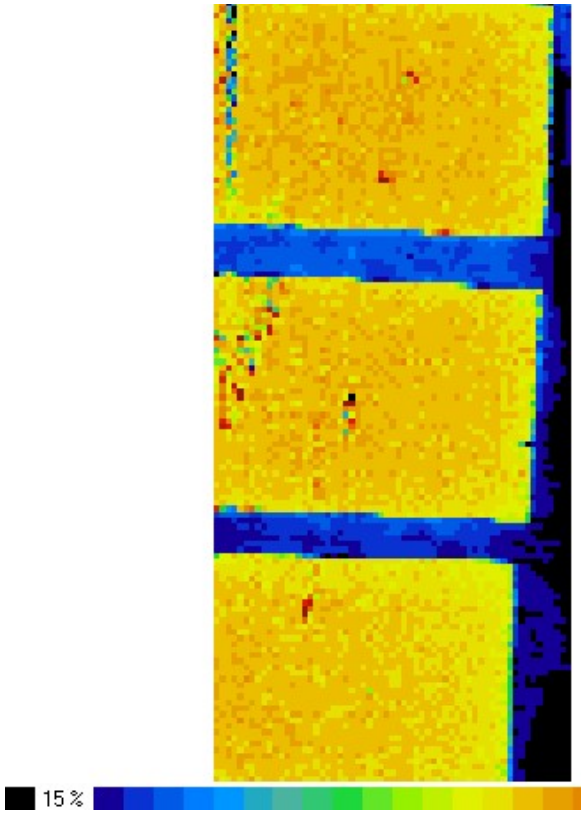
# Sample preparation

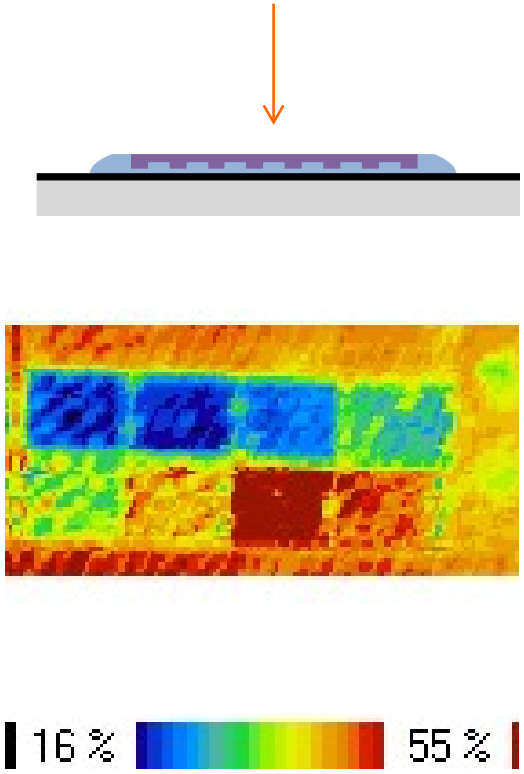



300 µm => ~20 µm

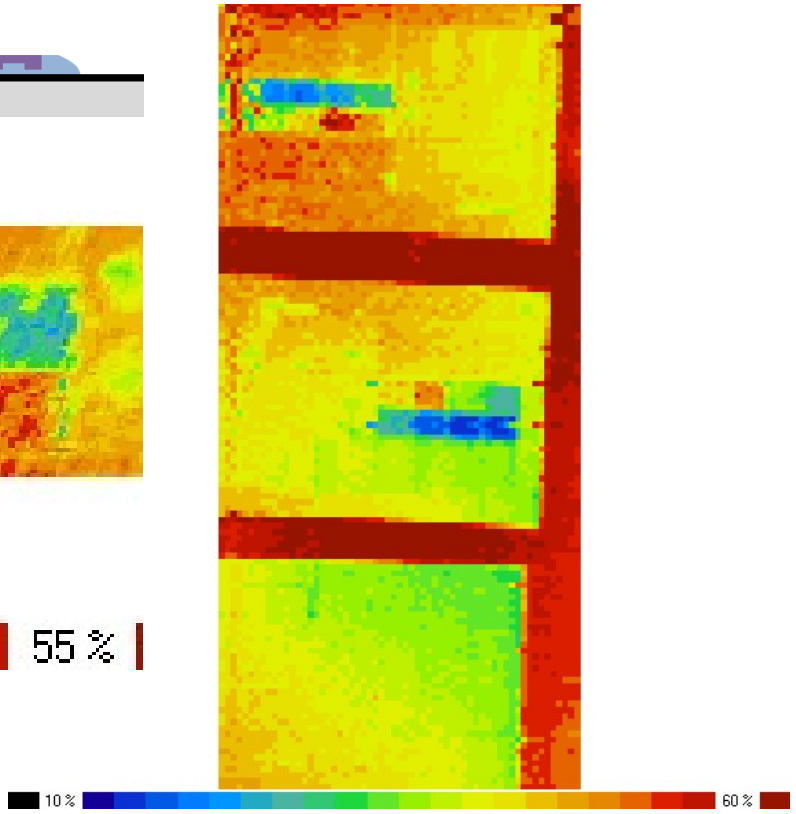
# Spatial reflection mapping

406 nm



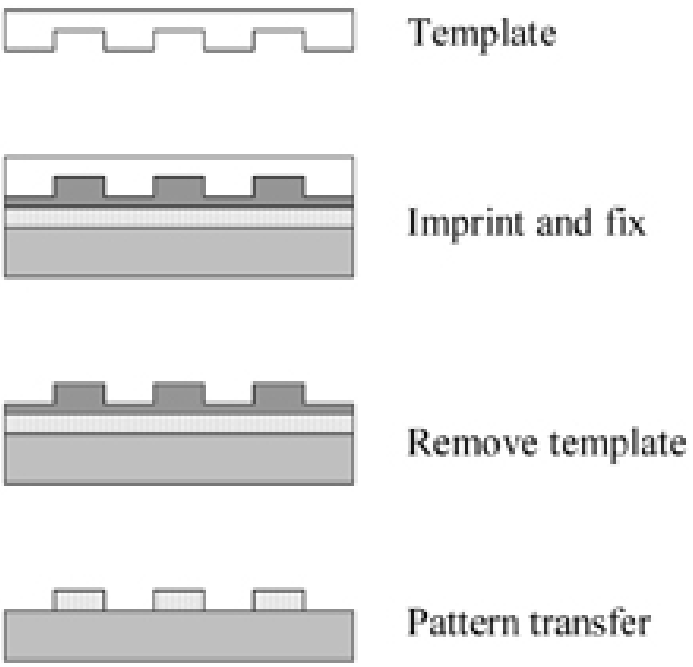




968 nm



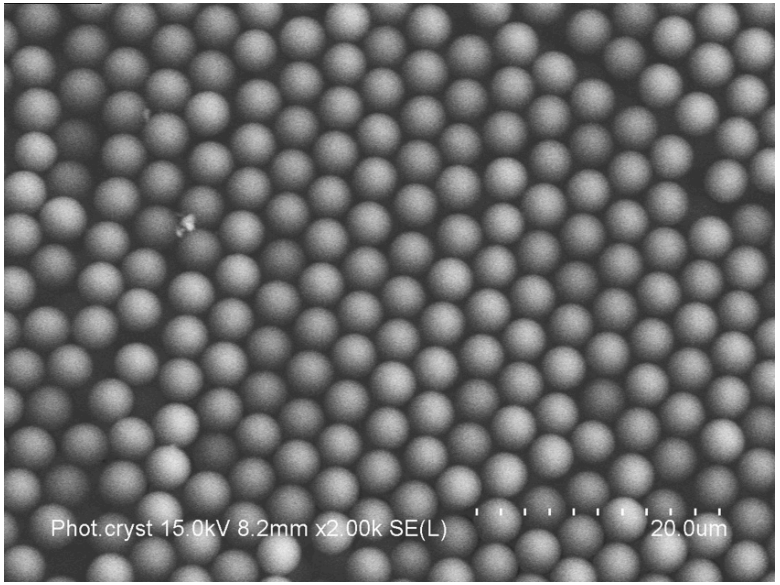
# Large scale fabrication?

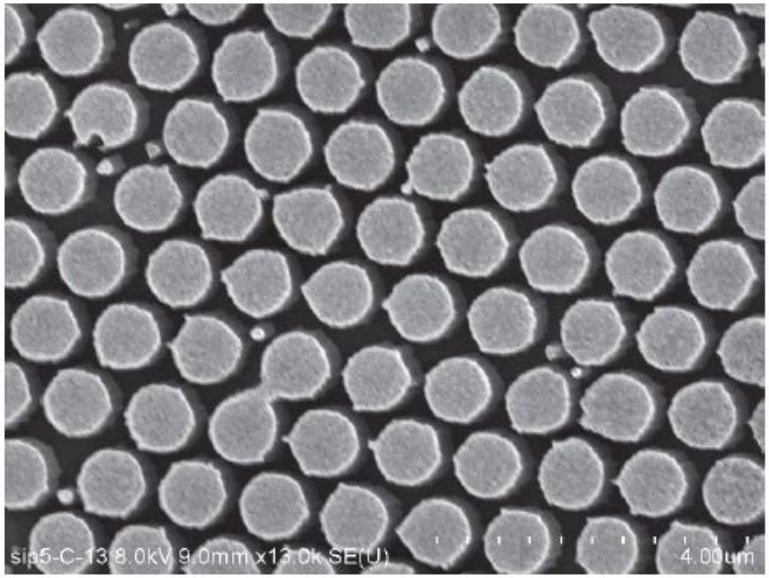
## Nanoimprint lithography




# Large scale fabrication?

## Self assembly




*Haugan et al., MRS 2011*

# Summary

- Light trapping may be achieved with small periodic structures
- Oblique structures slightly superior to binary
  - Optimal period almost the same for different structures
- Symmetry more important than shape
- Breaking symmetry is key to approach light trapping limit
  - Affect how we design light trapping structures in the future
- More work needed on experimental characterization, and on design and fabrication of low-symmetry structures

# Thank you for your attention

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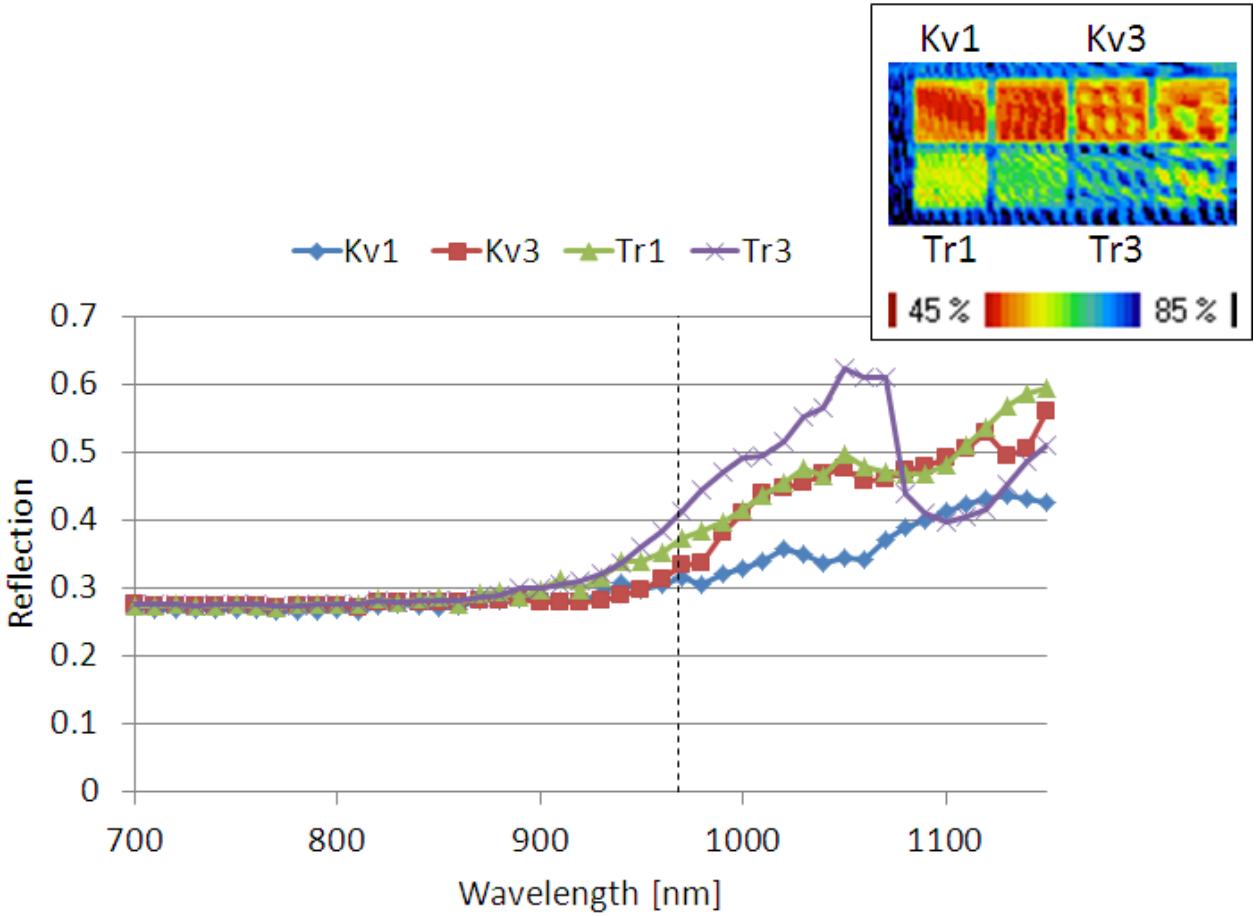
www.ife.no → Solenergi

Thanks to IFE and UNIK for funding

# Measurements with ellipsometry



# Higher order diffraction

$$D_{HO} = \sum_{n,m} D_{nm} = 1 - D_0 - A$$