ECE 695 Numerical Simulations Lecture 30: Finite-Difference Time Domain in MEEPPV

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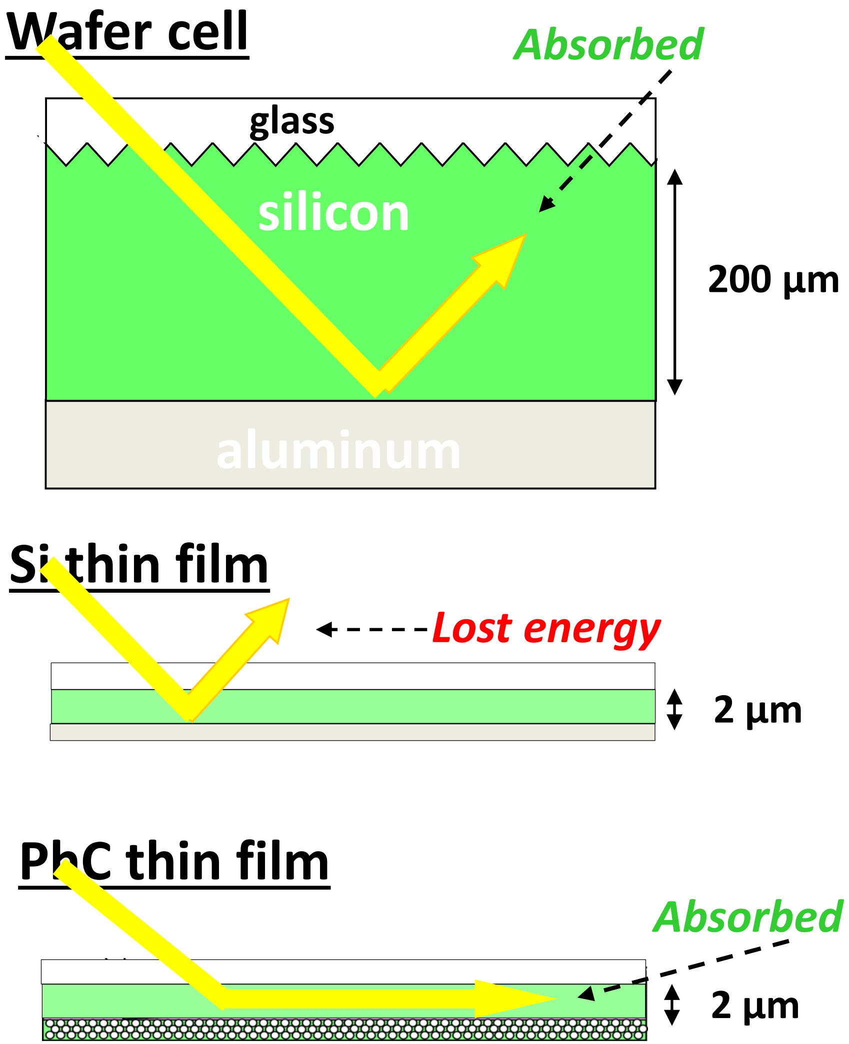
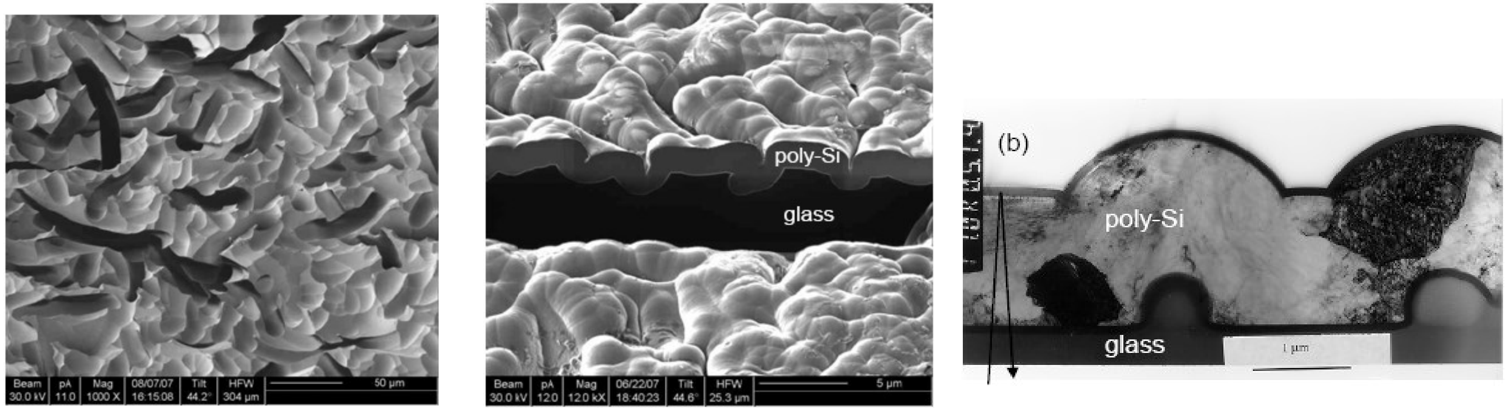
March 31, 2017

Example: Simulating Si PV Absorption



Different Geometric Light Trapping Approaches for Commercial μc-Si Cells



Treatment #1	Sand blast	Abrasion etch	Bead coat
Treatment #2	HF etch	HF etch	(used in our samples)
Feature depth	10-100 μm	500 nm	500 nm
Feature width	10 μm	1-5 μm	500 nm

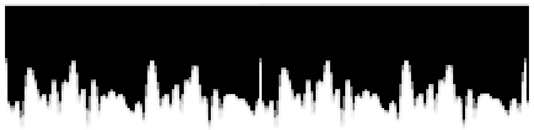
M.J. Keevers et al., "10% Efficient CSG Minimodules,"

Correlated Randomness

Combine gratings for each wavelength

Combine periodicity with texturing in systematic fashion

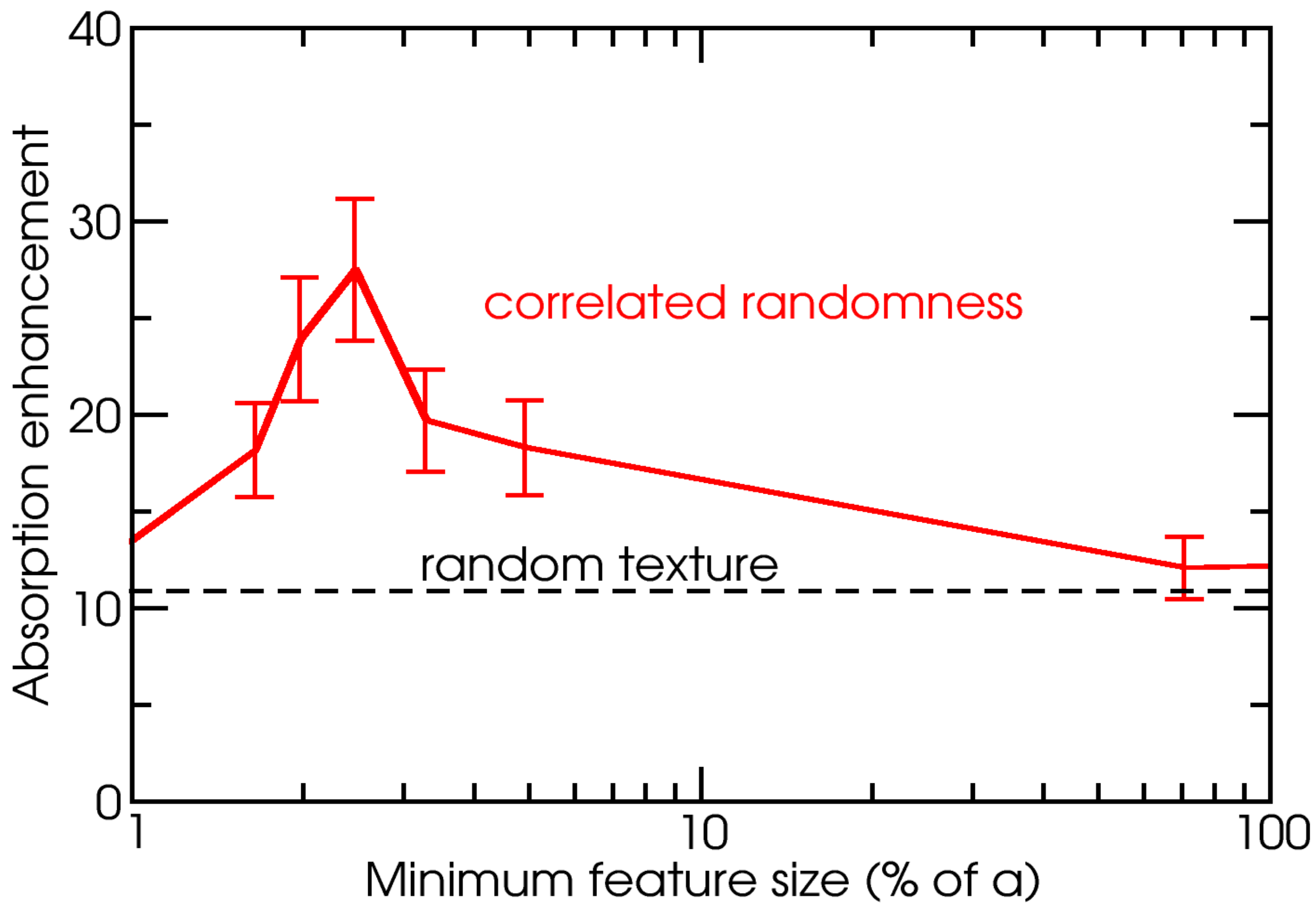
inhomogeneous



homogeneous

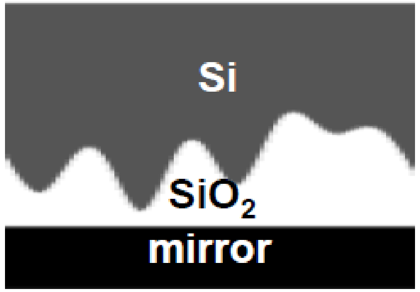
A.N. Bloch & P. Sheng, US Patent 4,683,160 (1987)
X. Sheng *et al*., *Opt. Express* **19**, A841 (2011)

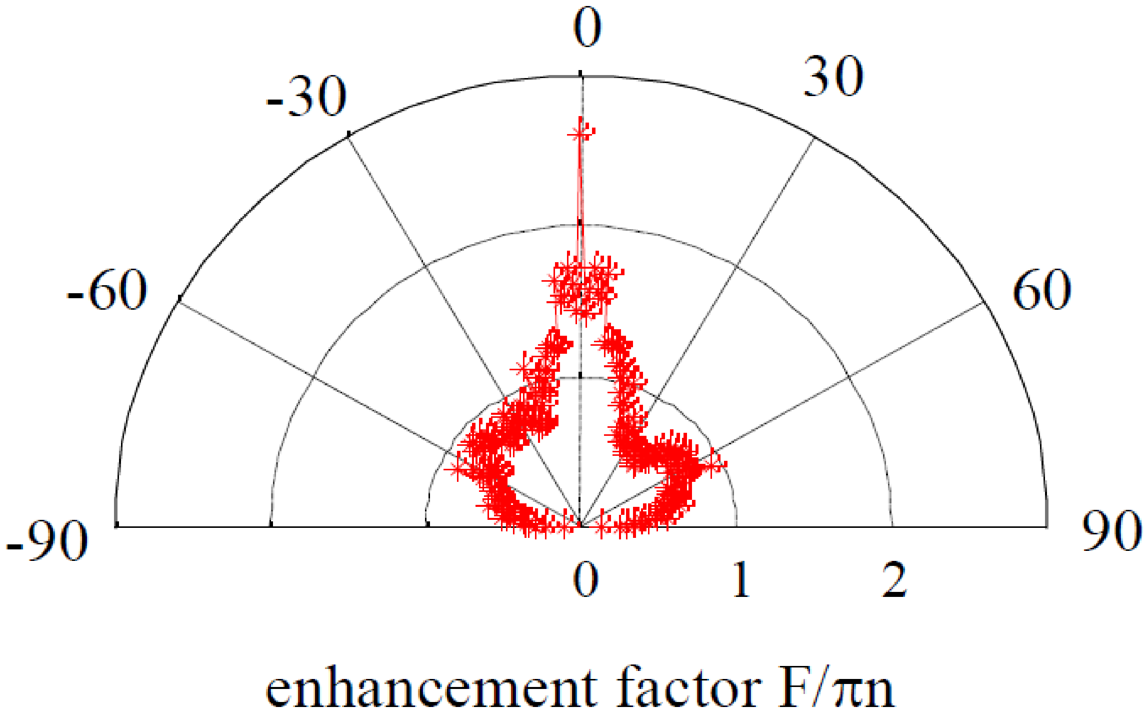
Correlated Randomness in 2D



For n=3.46 and 33% bandwidth (e.g., 500-700 nm)

Angle-Sensitive Solar Absorbers

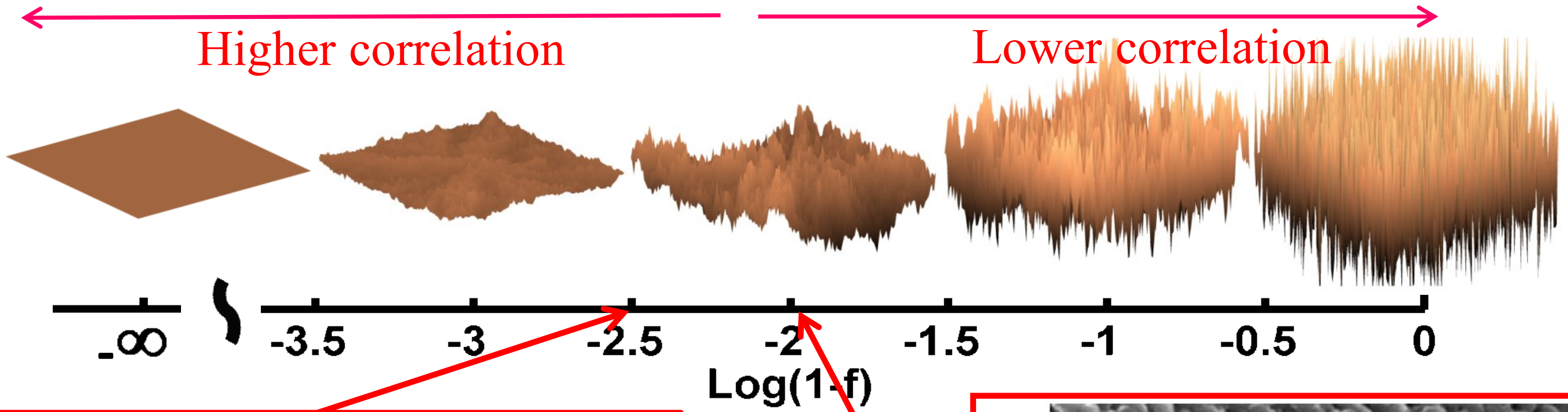


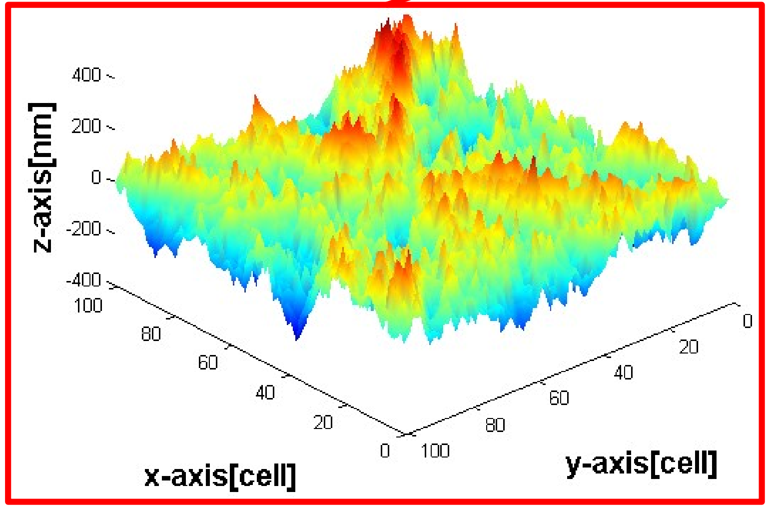


X. Sheng *et al.*, *Opt. Express* **19**, A841 (2011)

X. Wang et al., "Approaching the Shockley-Queisser Limit in GaAs Solar Cells", IEEE J. Photovolt. (2013).

From flat to totally random structures via correlated random textures





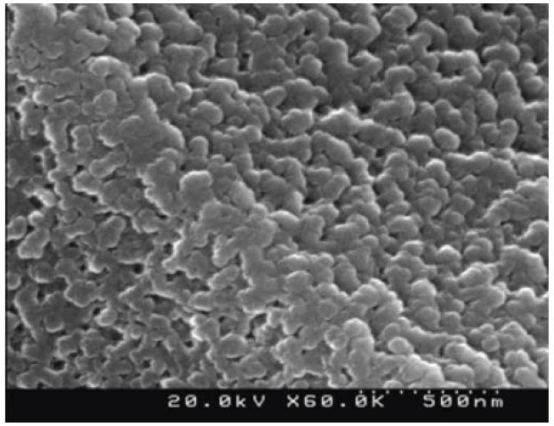
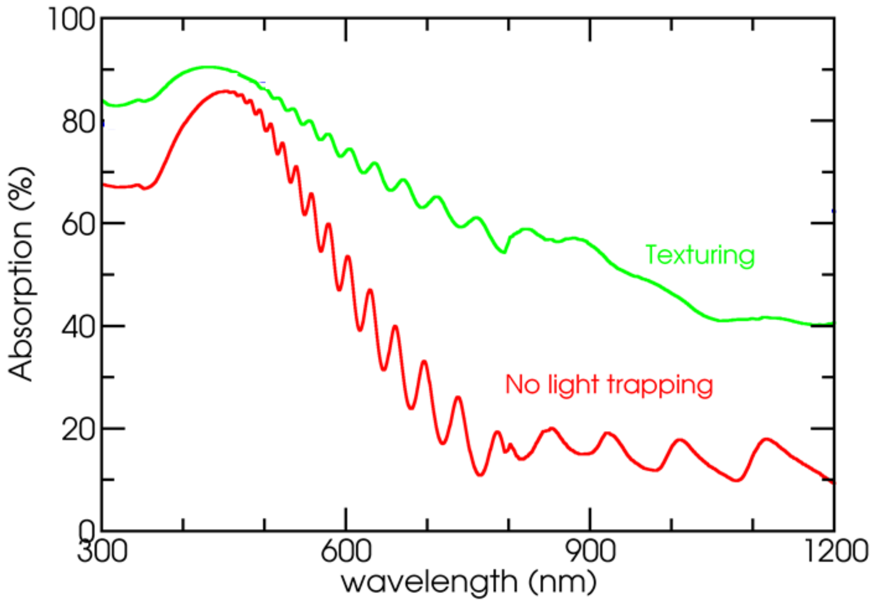


Fig. 4.7. Plan view SEM image of porous silica AR layer formed by vapour-etch method [56].

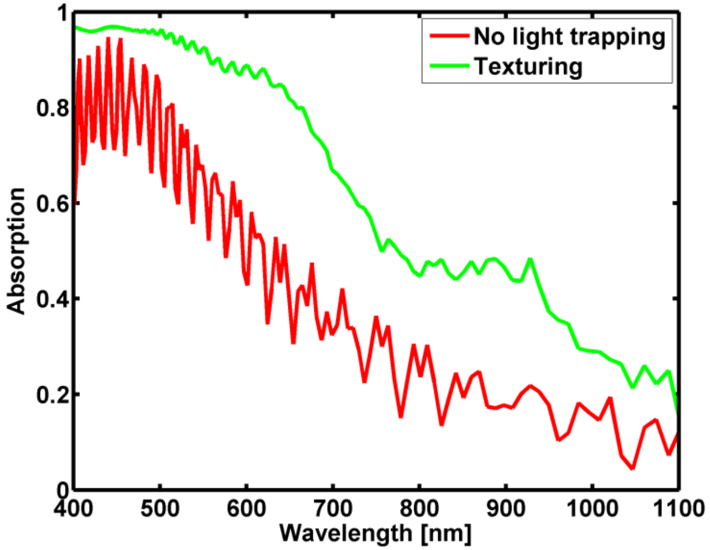
Keevers, M. J., et al. "10% efficiency CSG minimodules." *Proceedings of the 22nd European Photovoltaic Solar Energy Conference.* (2007).

Experimental absorption versus simulated absorption

Experiment



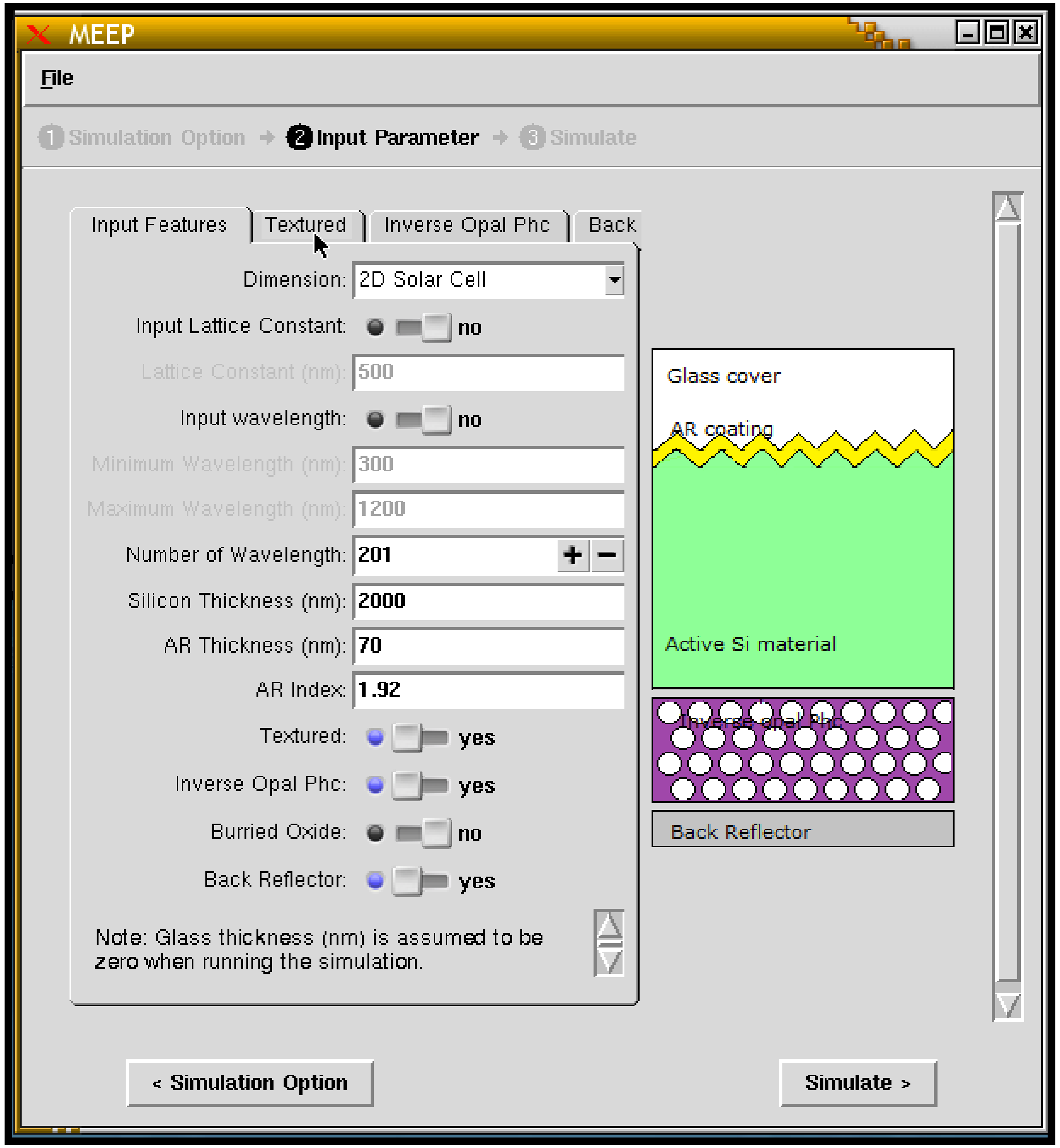
Simulation (3D QCRF-FDTD)



L. T. Varghese, Y. Xuan, B. Niu, L. Fan, P. Bermel, and M. Qi, "Enhanced photon management of thin-film silicon solar cells using inverse opal photonic crystals with 3d photonic bandgaps," *Advanced Optical Materials* **1**, 692–698 (2013).

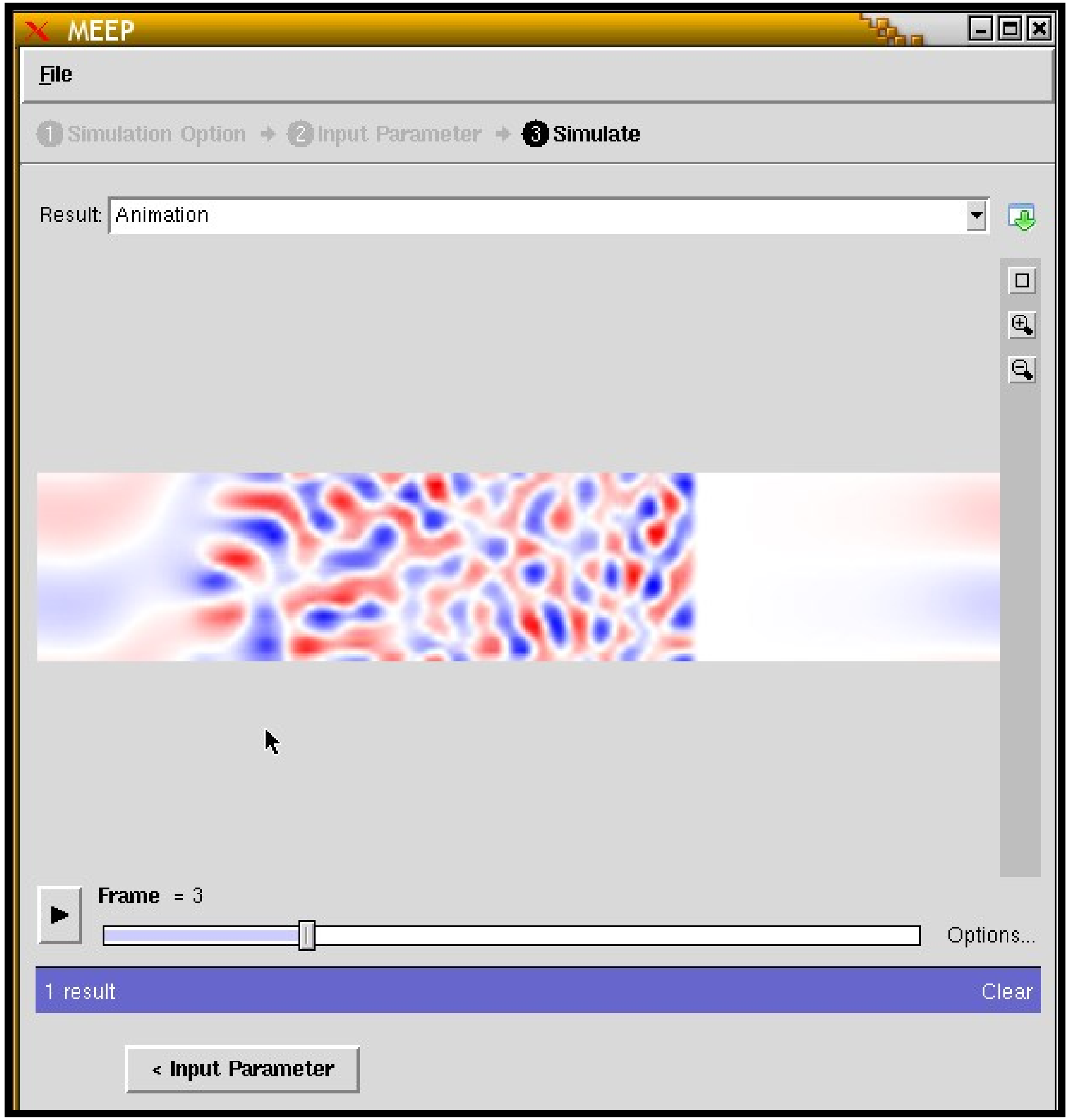
H. Chung, K-Y. Jung, X. T. Tee, and P. Bermel, "Time domain simulation of tandem silicon solar cells with optimal textured light trapping enabled by the quadratic complex rational function," *Opt. Express* **22**, A818-A832 (2014).

MEEPPV: https://nanohub.org/tools/meeppv



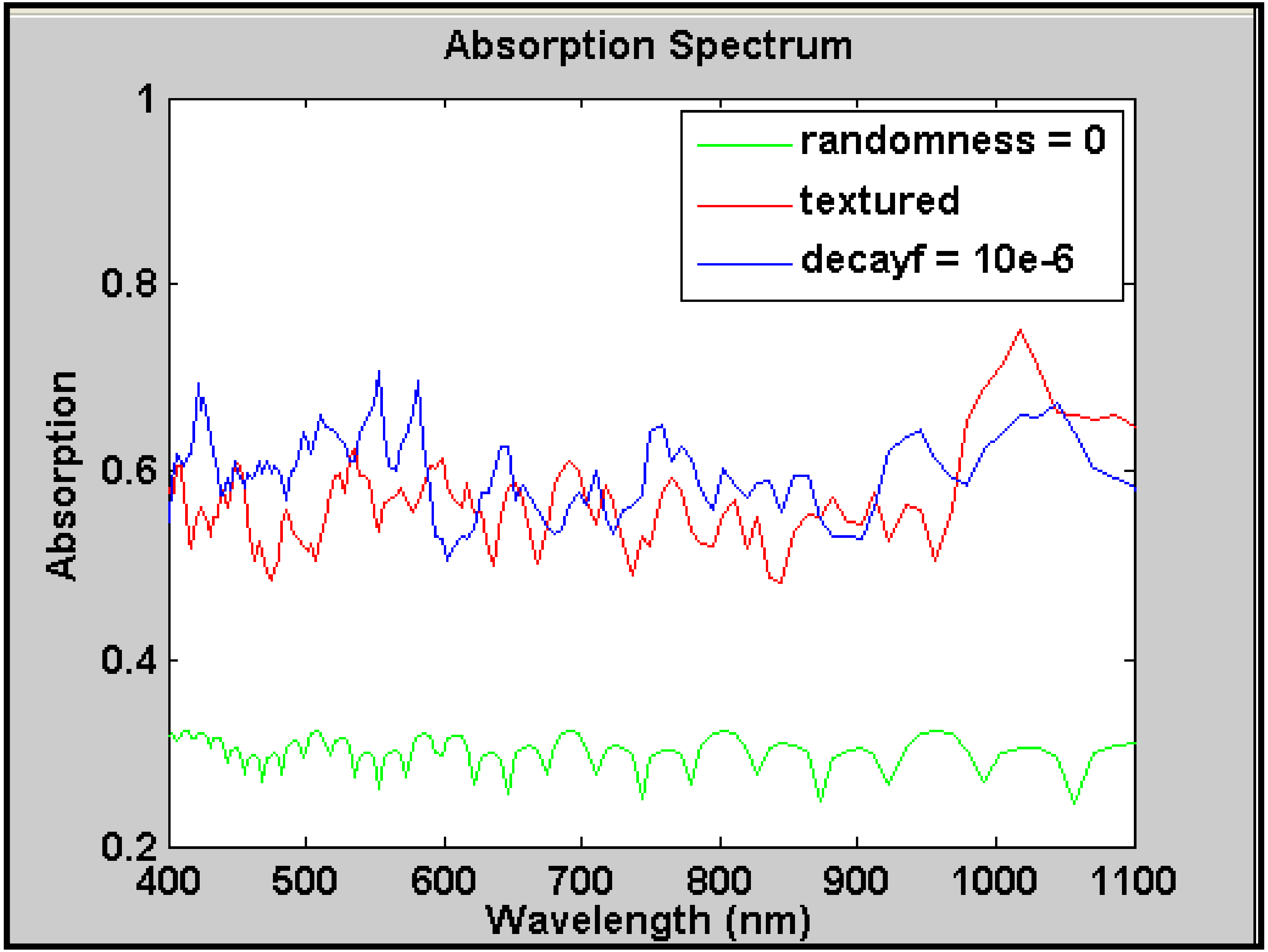
Solar cell schematic

MEEPPV: https://nanohub.org/tools/meeppv

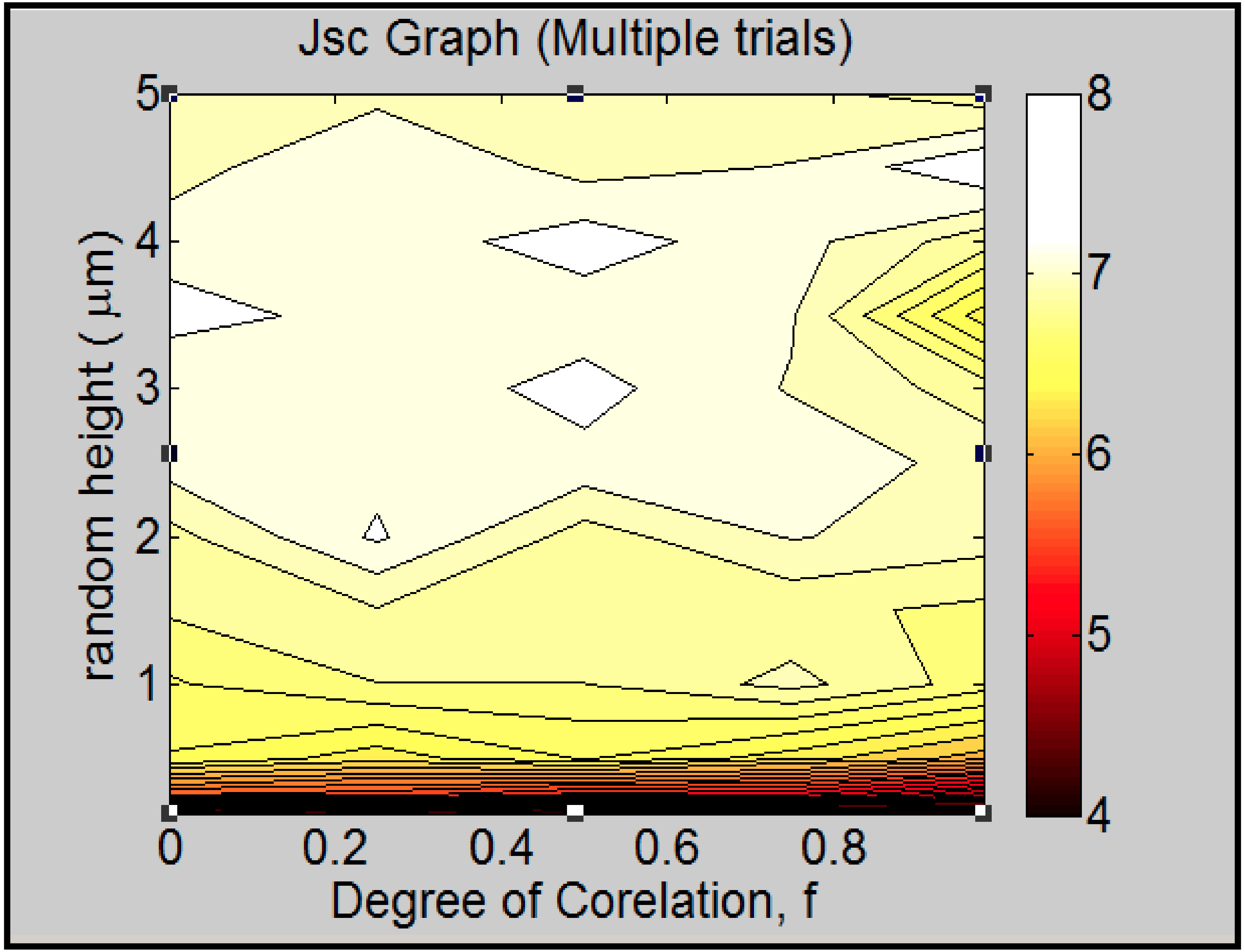


Output animations

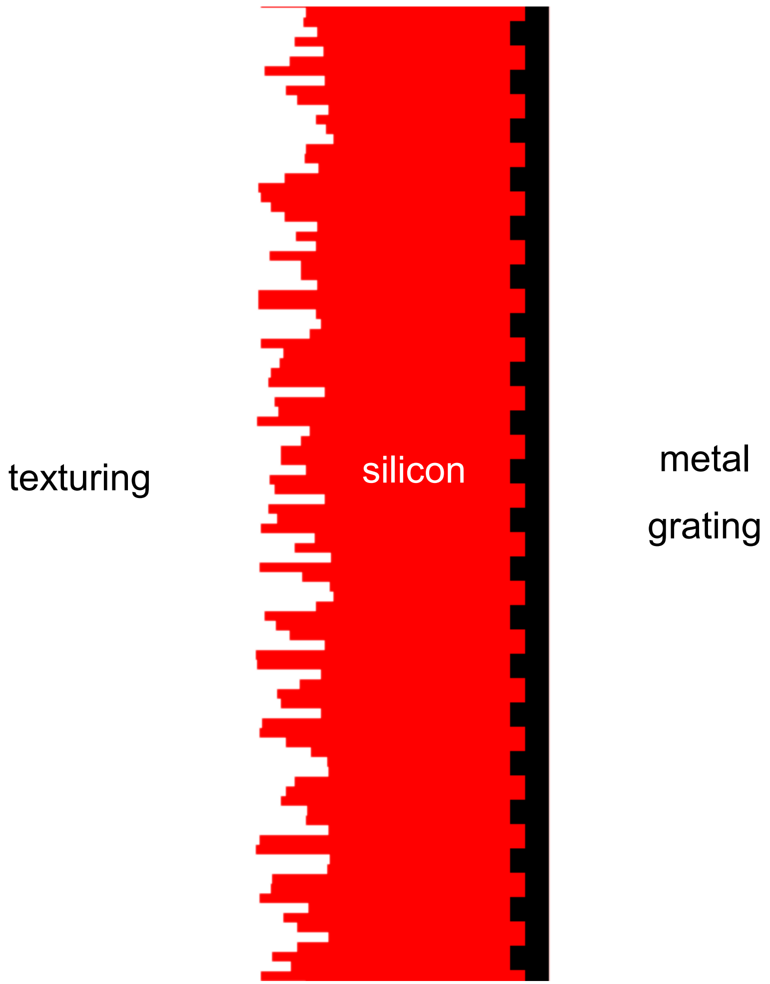
MEEPPV: https://nanohub.org/tools/meeppv



MEEPPV: https://nanohub.org/tools/meeppv



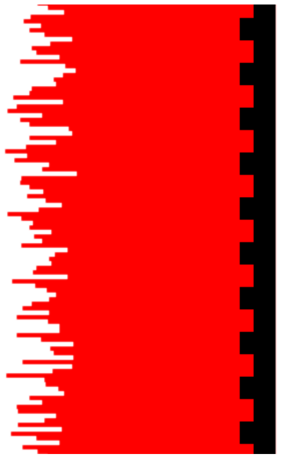
Computational Set-up



- Thickness of film = our experimental samples (1.47 μm)
- Four geometries tested
- Random texturing:
  - Uniform height distribution over 500 nm
  - Distance between features varies
- Photonic crystal:
  - Reflection captured by metal
  - Diffraction captured by grating (optimized for this thickness)

Varying spacing between features

5 periods

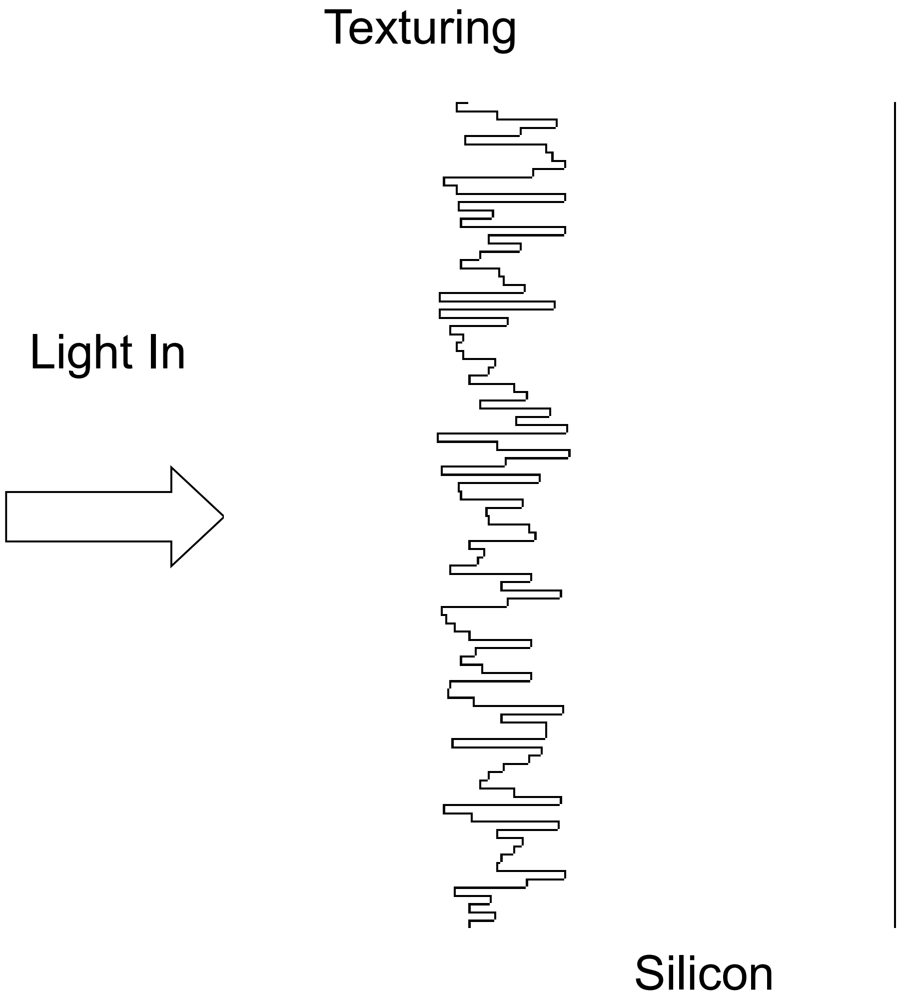


10 periods

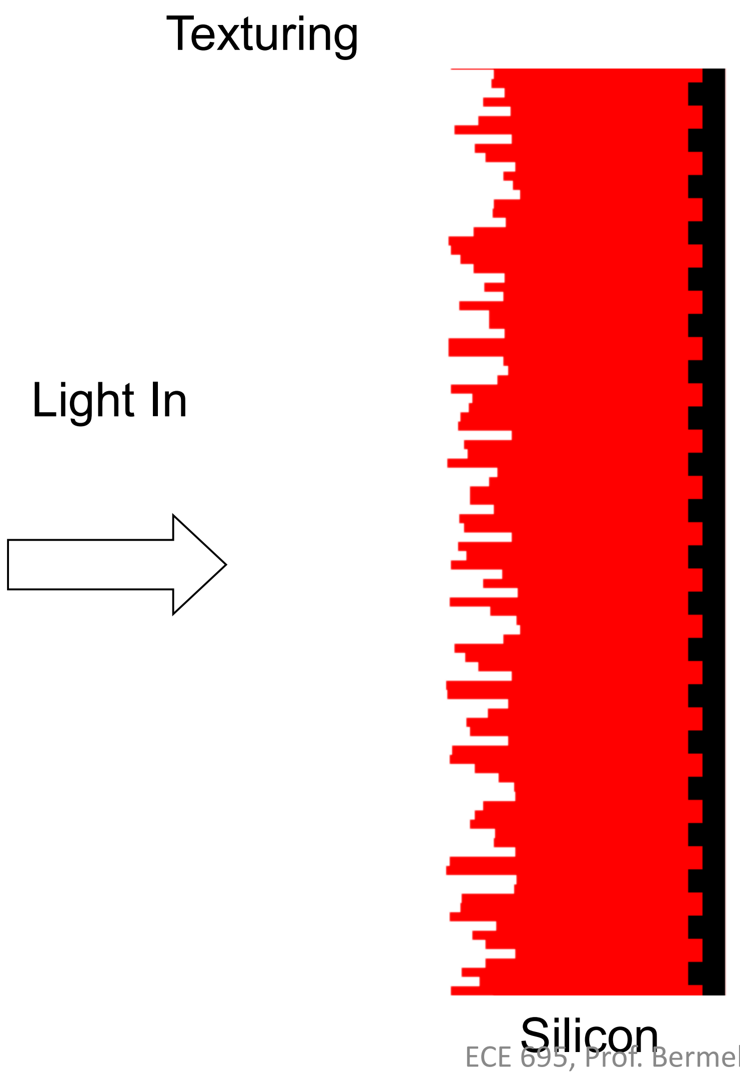
20 periods

Propagation of Light in Planar Geometry

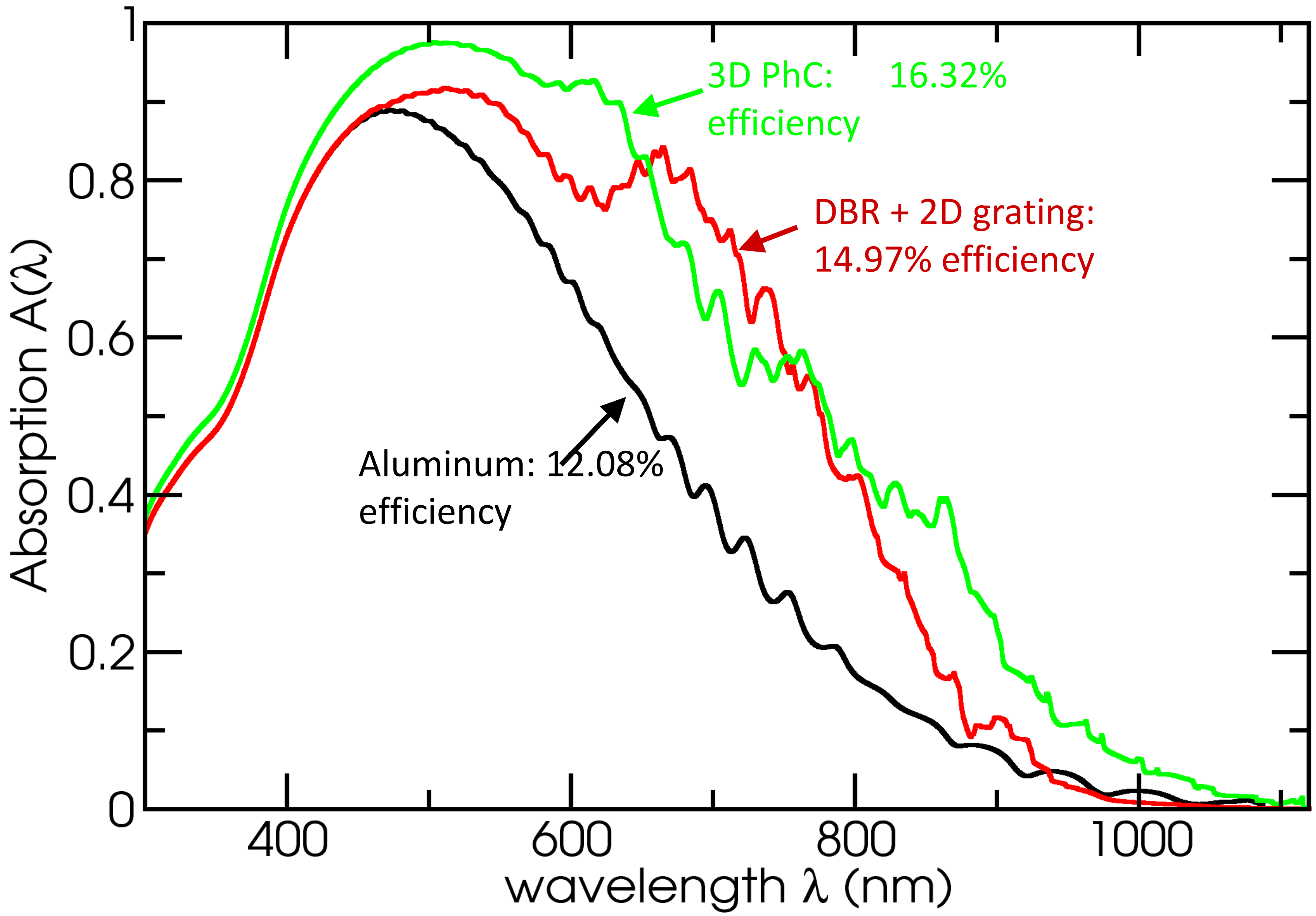
Propagation of Light in Textured Geometry (no backing)



Propagation of Light in Textured Geometry + Metal Grating

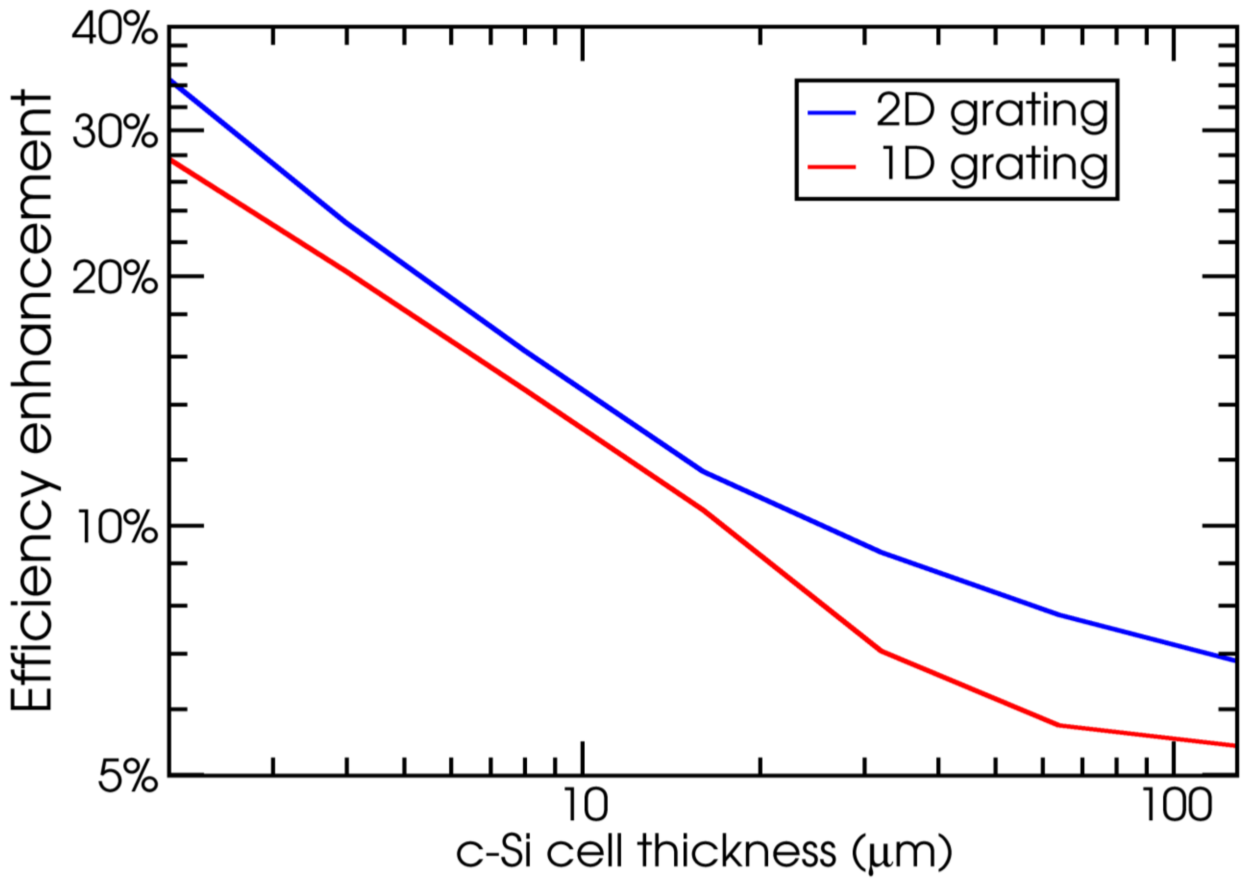


Calculated Absorption Spectrum for 2 μm μc-Si



P. Bermel *et al*., *Opt. Express* **15**, 16986 (2007)

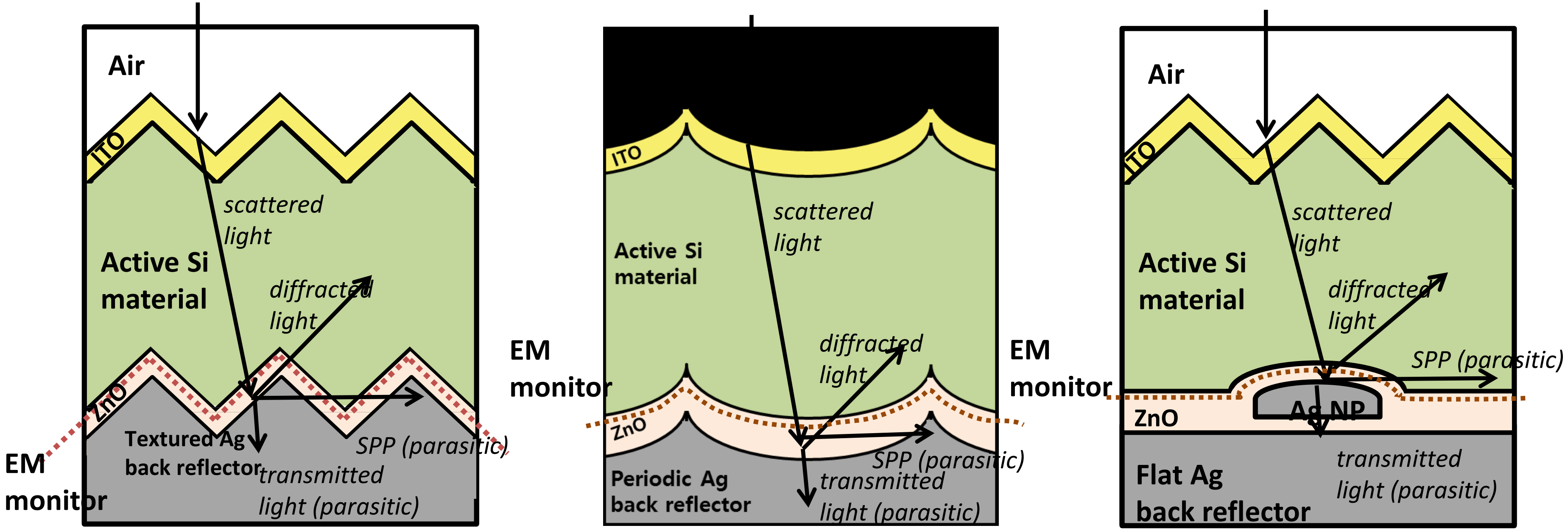
Efficiency Enhancement of Period Structures



For optimized parameters, 2D grating efficiency enhancement ranges from 7% at 128 μm up to 35% at 2 μm

Thin c-Si Solar Cell Designs Incorporating Plasmonics

Plasmonics can <u>double</u> path length from ideal light trapping
K. Catchpole & A. Polman, *Appl. Phys. Lett.* 2008, *93*, 191113.

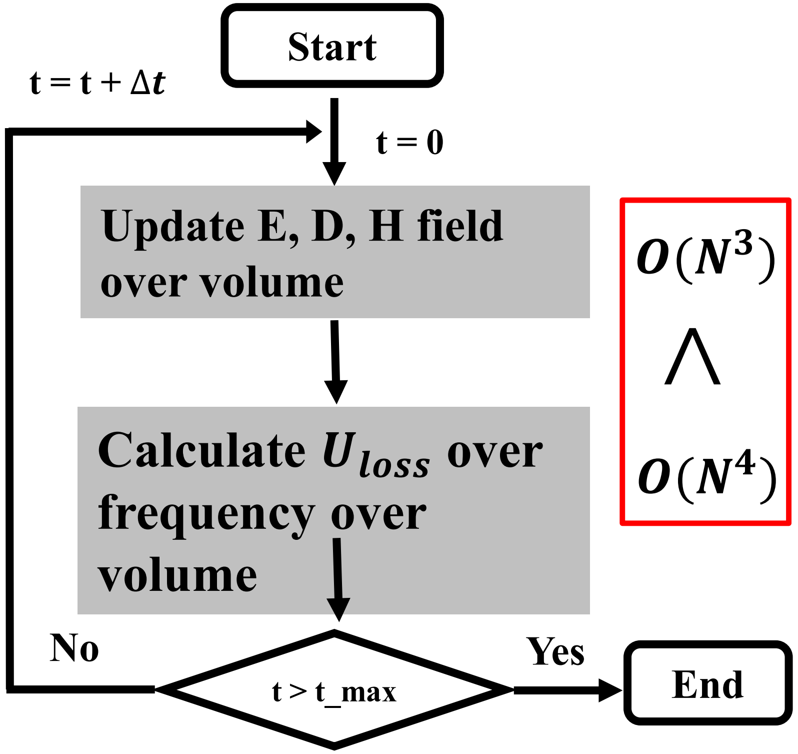


Random texturing on the front and back surfaces, deposited conformally

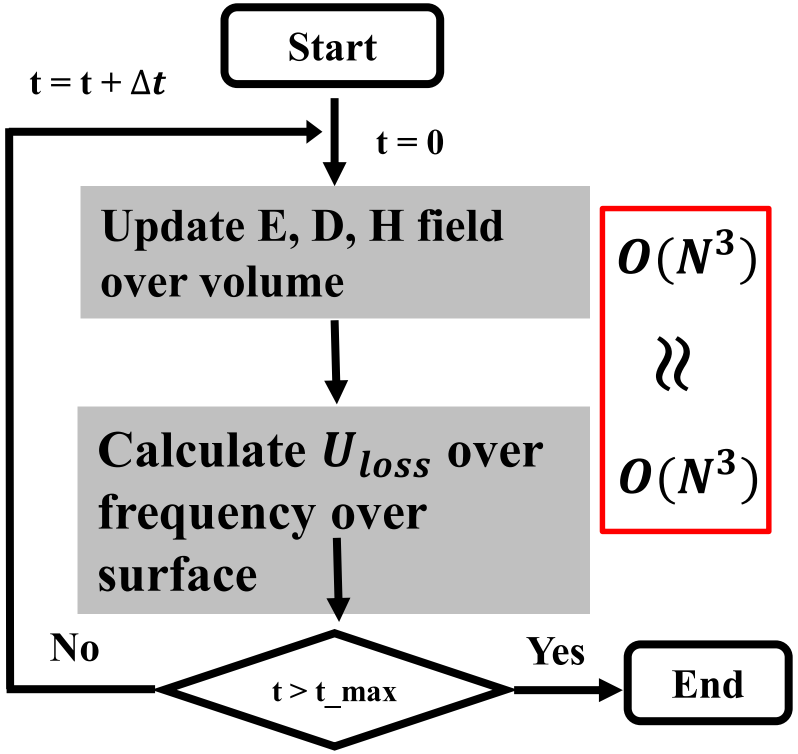
Periodic (grating-like) texturing on the front and back surfaces, deposited conformally

Random texturing on the front surface combined with a back plasmonic nanoparticle

Simulation Methodology



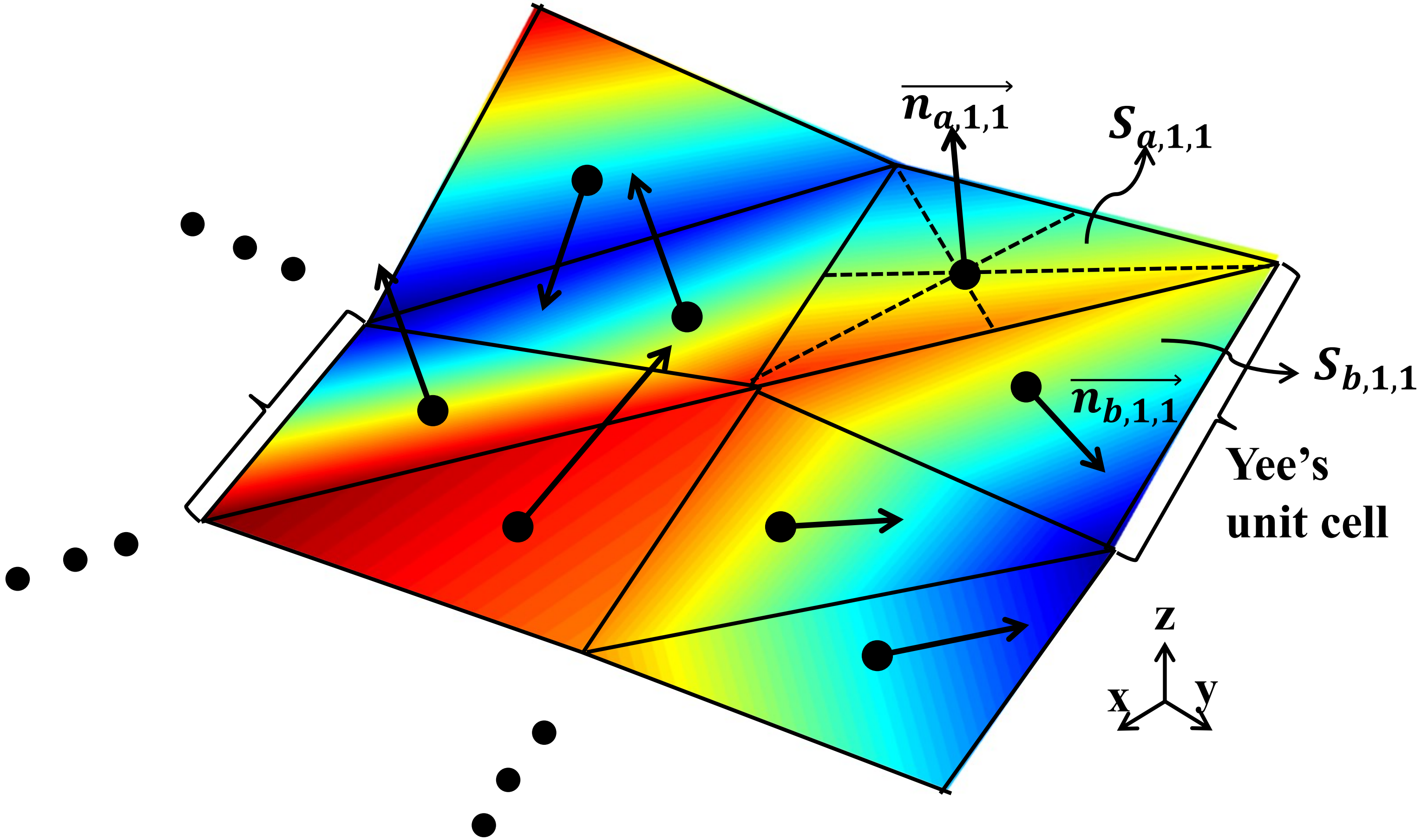
Volume-Integrated Finite-Difference Time Domain Method



Flexible Flux Plane Finite-Difference Time Domain Method

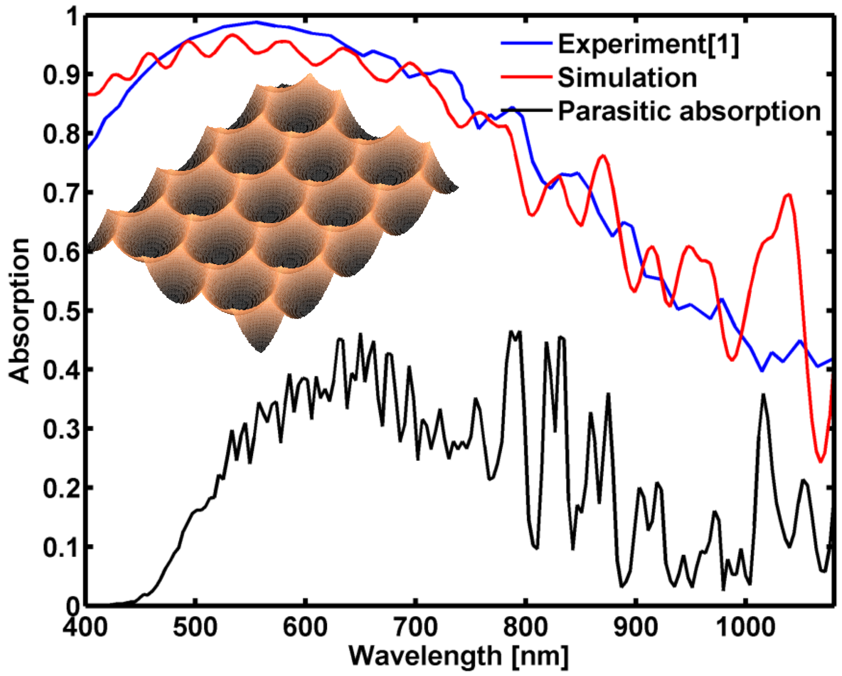
Haejun Chung, K.Y. Jung, and Peter Bermel, “Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach” *Opt. Express* (2015, submitted)

Simulation Methodology

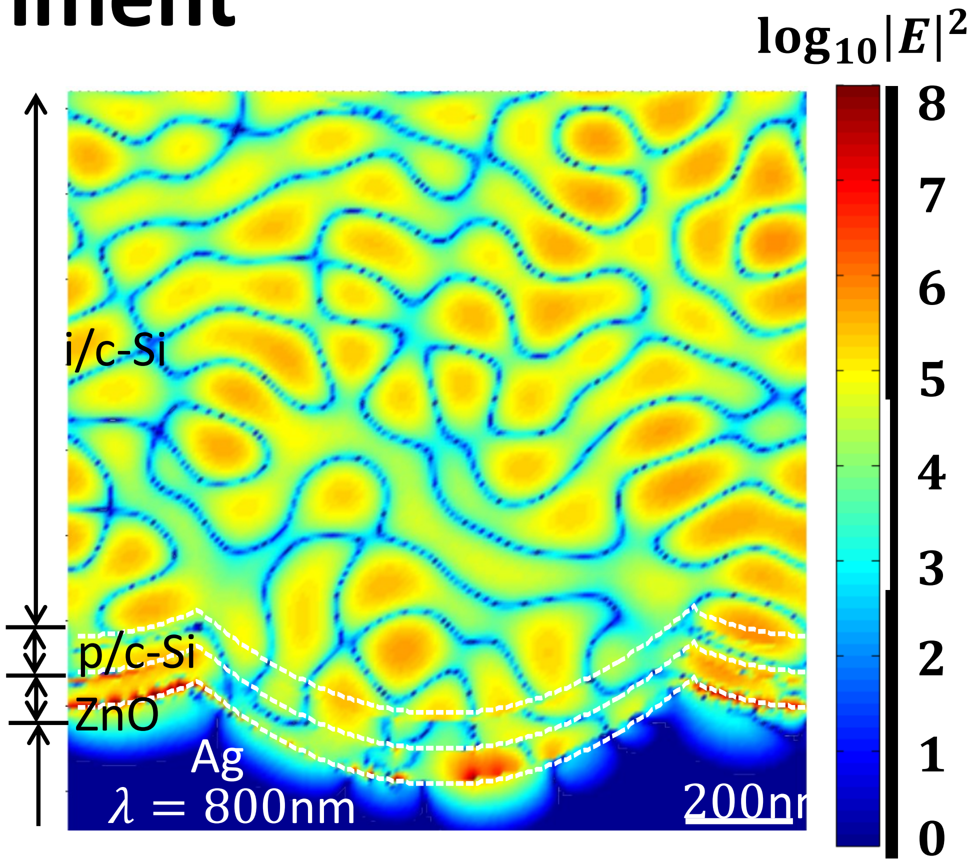


Flexible flux planes offer rapid frequency-sensitive integration of parasitic losses.

Periodically Textured Cells: Theory and Experiment



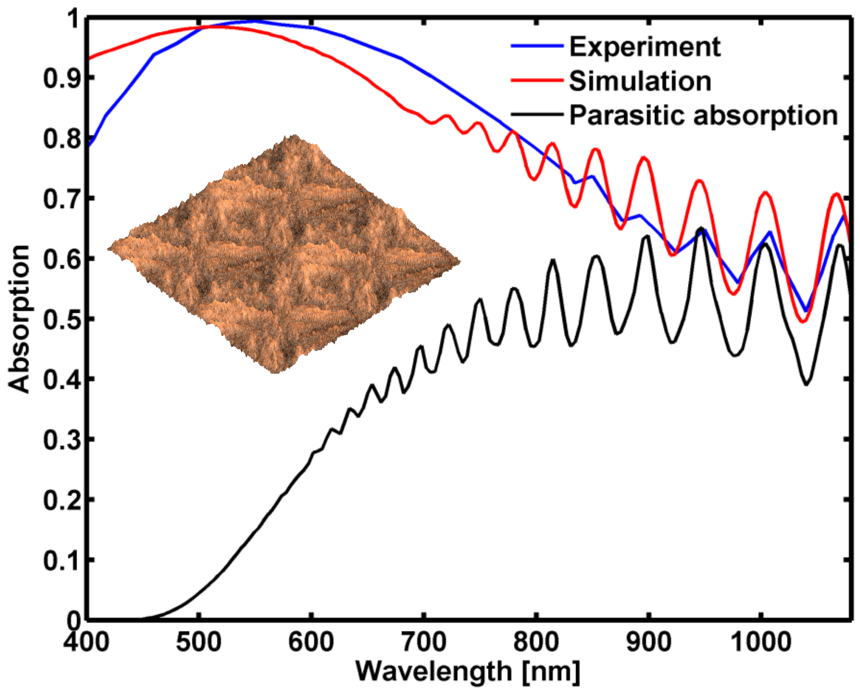
Detailed comparison of experimental and simulated total absorption, and the parasitic component



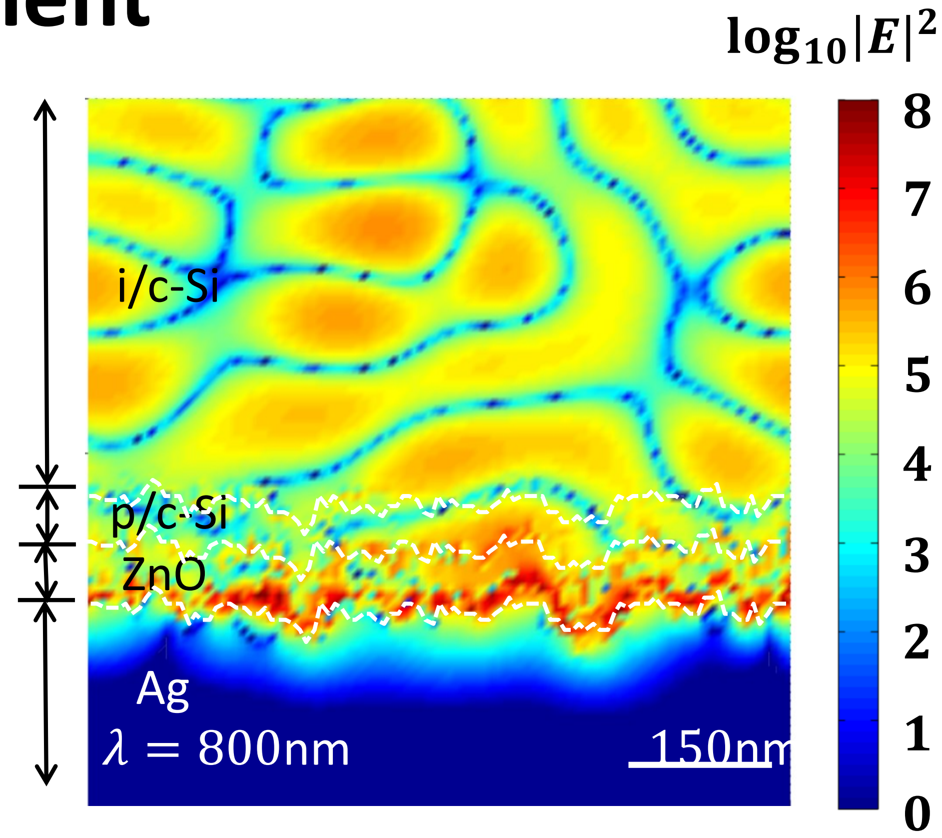
Electric field energy distribution, with enhancement observed near the Ag/ZnO interface

Haejun Chung, K.Y. Jung, and Peter Bermel, "Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach" *Opt. Express* (2015, submitted)

Randomly Textured Cells: Theory and Experiment



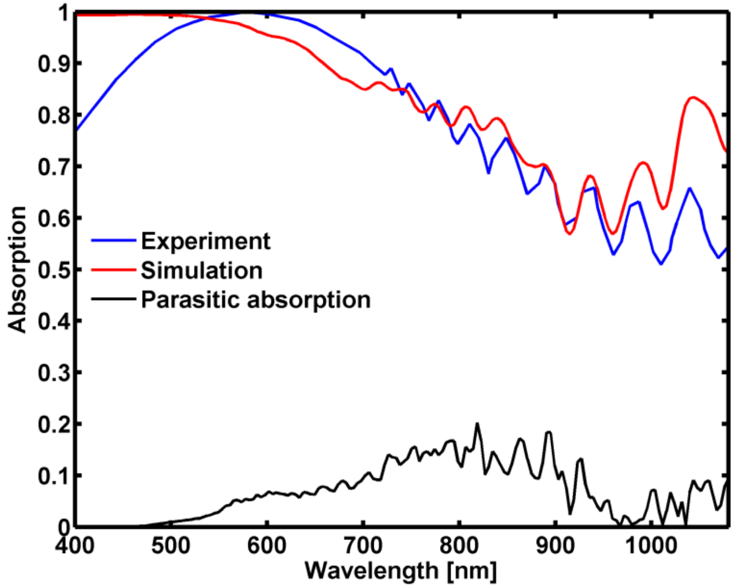
Comparison of experimental and simulated total absorption, and the parasitic component



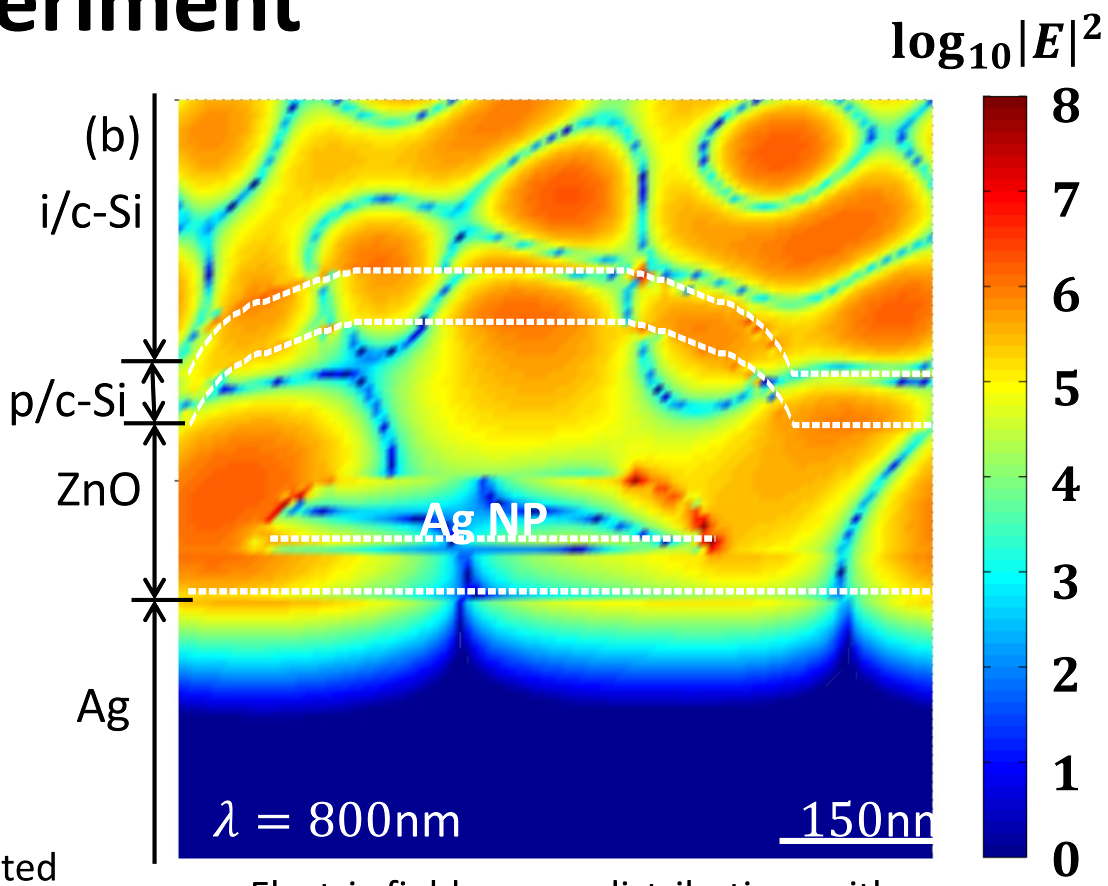
Electric field energy distribution, with enhancement observed near the Ag/ZnO and c-Si/ZnO interfaces

Haejun Chung, K.Y. Jung, and Peter Bermel, "Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach" *Opt. Express* (2015, submitted)

Ag Nanoparticle Cells: Theory and Experiment



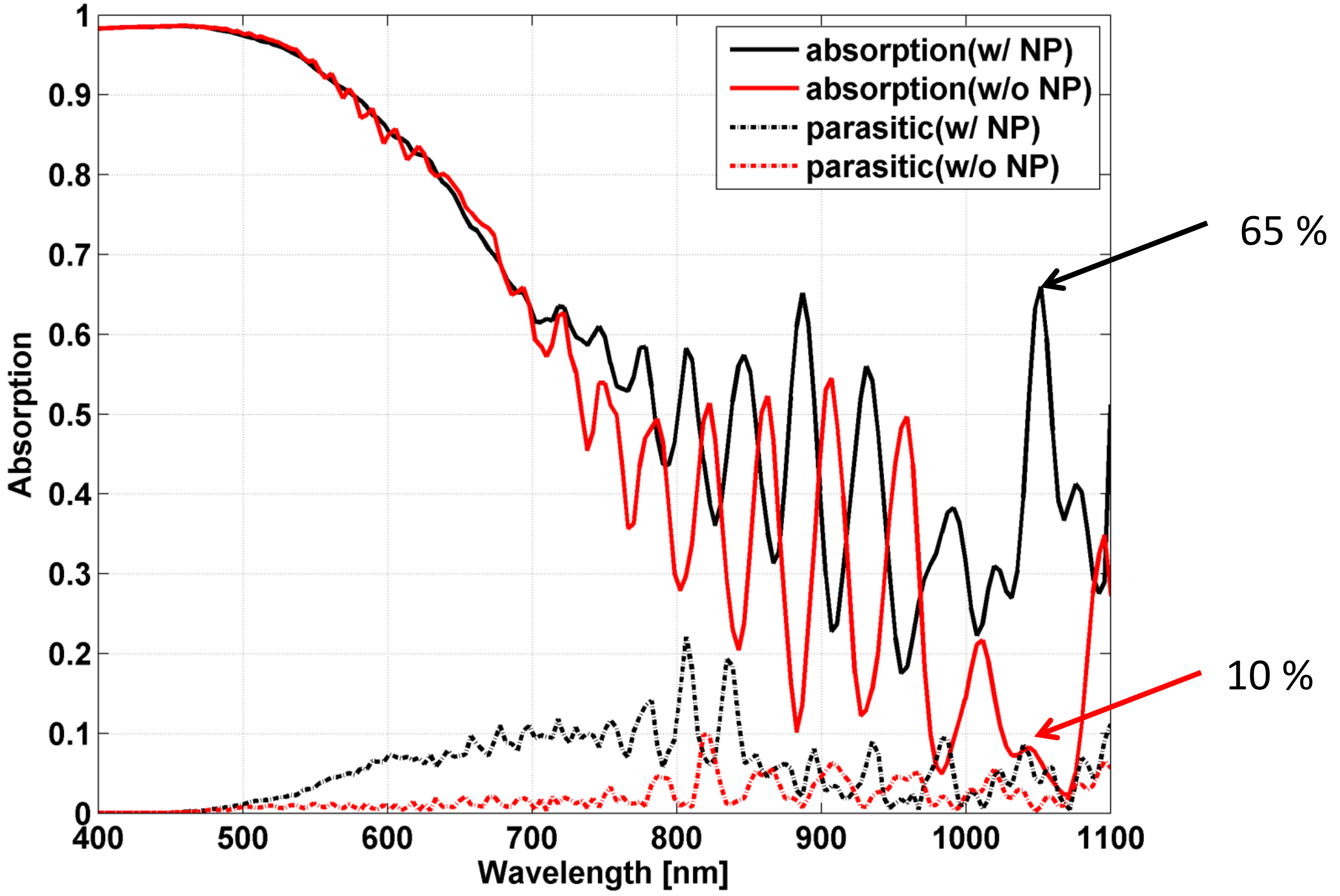
Comparison of experimental and simulated total absorption, and the parasitic component



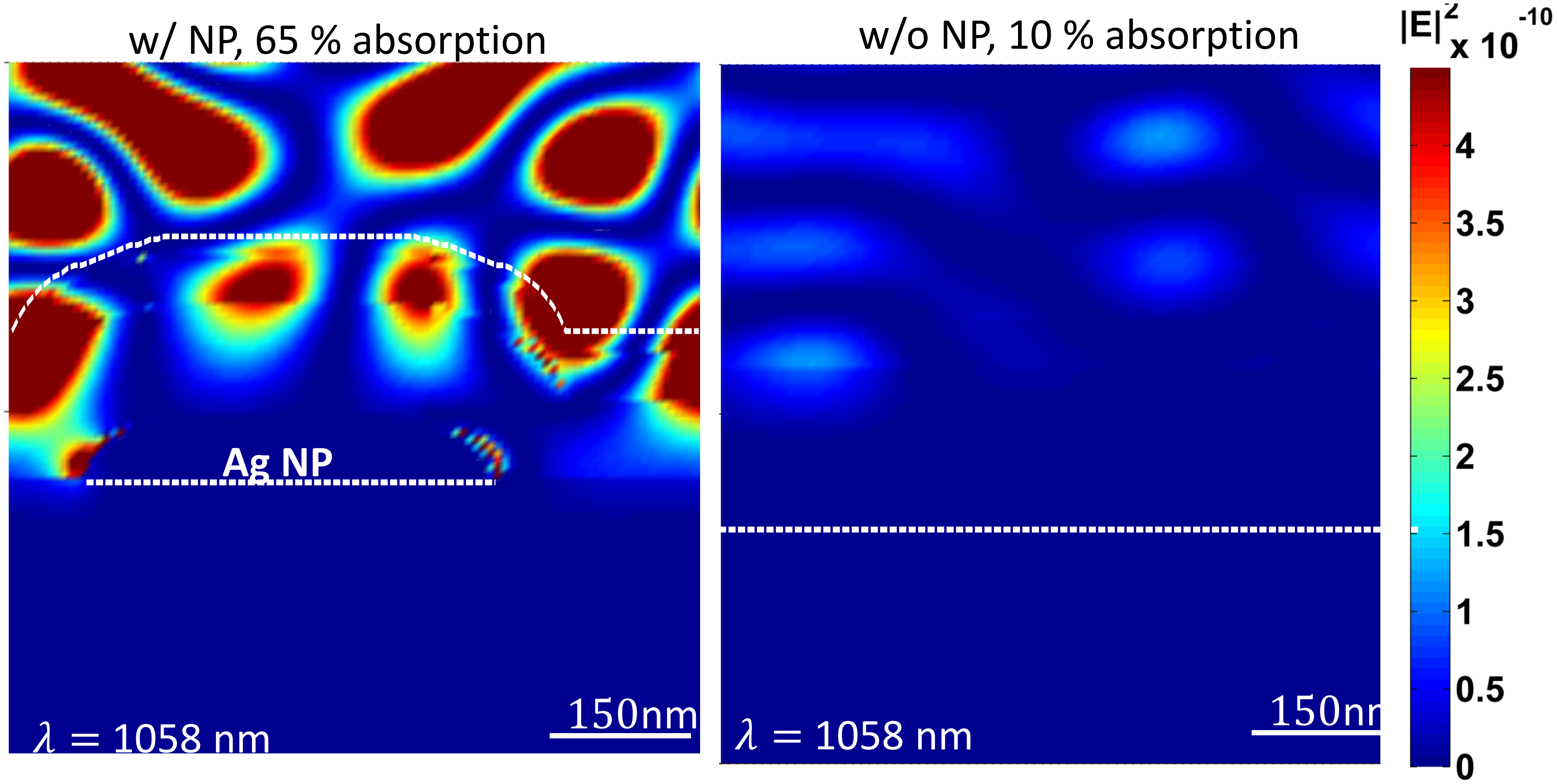
Electric field energy distribution, with enhancement observed throughout the structure, except Ag

Haejun Chung, K.Y. Jung, and Peter Bermel, "Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach" *Opt. Express* (2015, submitted)

Ag Nanoparticle Cell Absorption Enhancement



Ag Nanoparticle Cell Absorption Enhancement

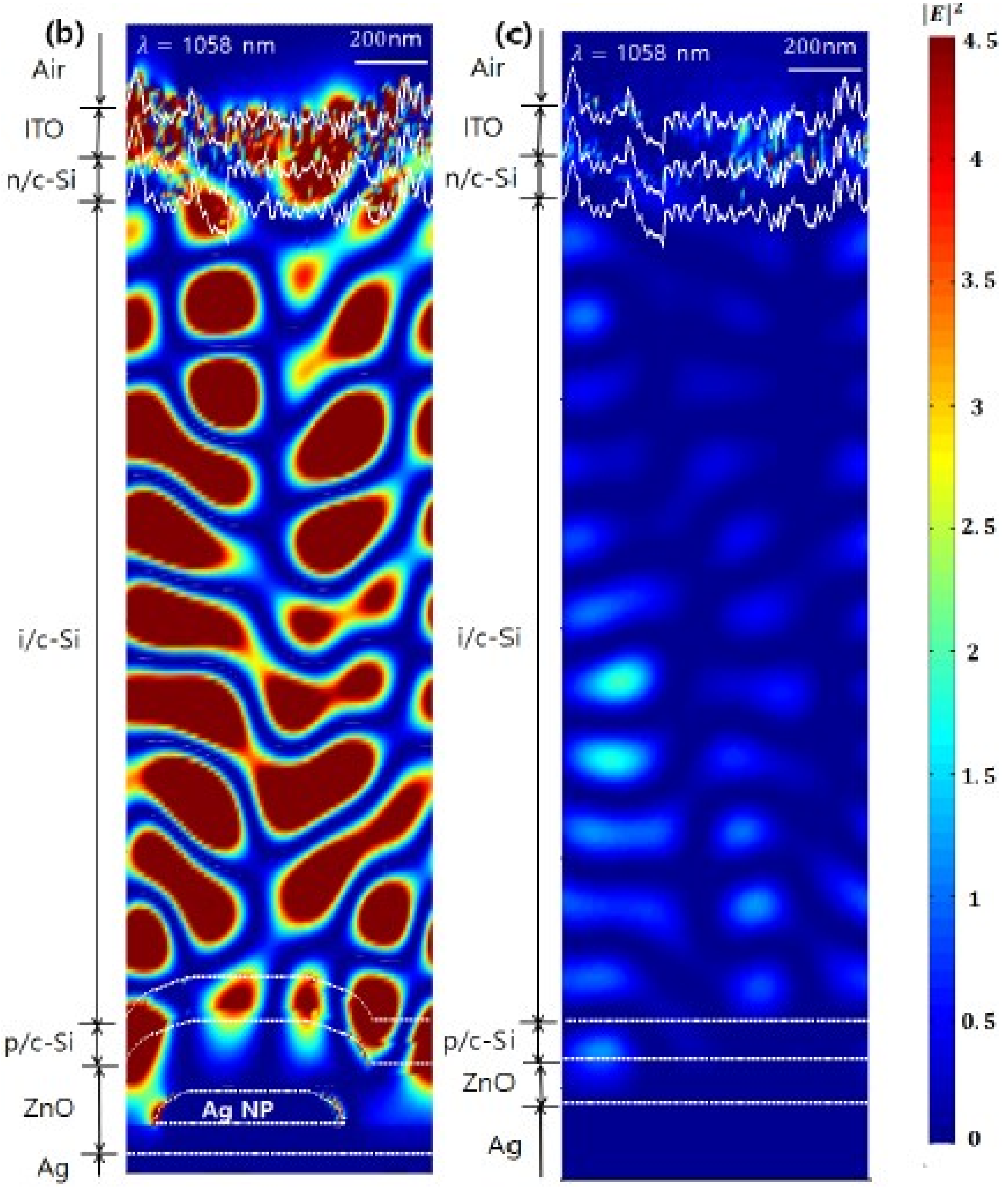


Haejun Chung, K.Y. Jung, and Peter Bermel, "Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach" *Opt. Express* (2015, submitted)

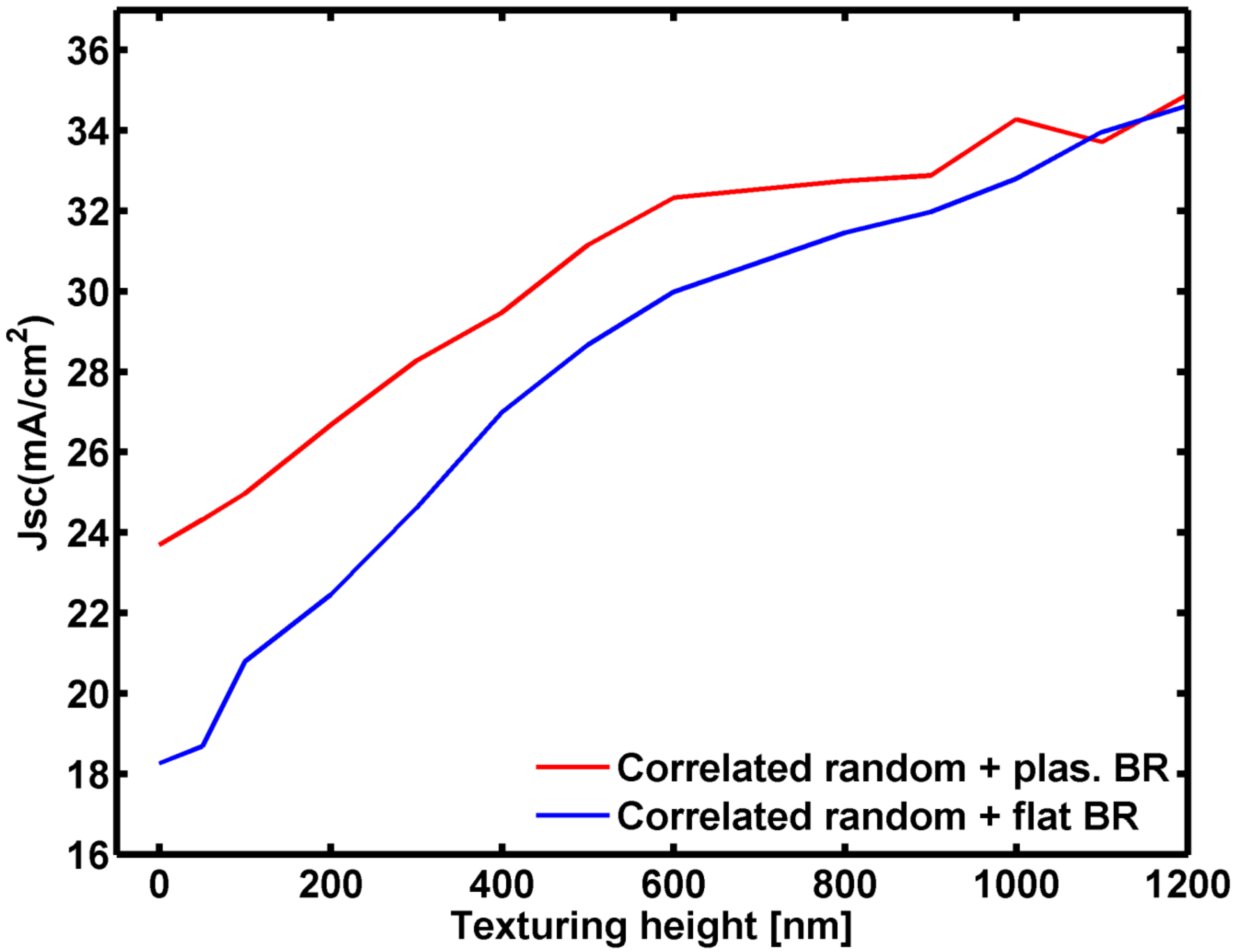
Ag NP Cell Absorption Enhancement

Again, the Ag nanoparticle increases field power throughout most of the structure, except the Ag itself; **removing NPs cancels out most of this effect**

Haejun Chung, K.Y. Jung, and Peter Bermel, “Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach” *Opt. Express* (2015, submitted)

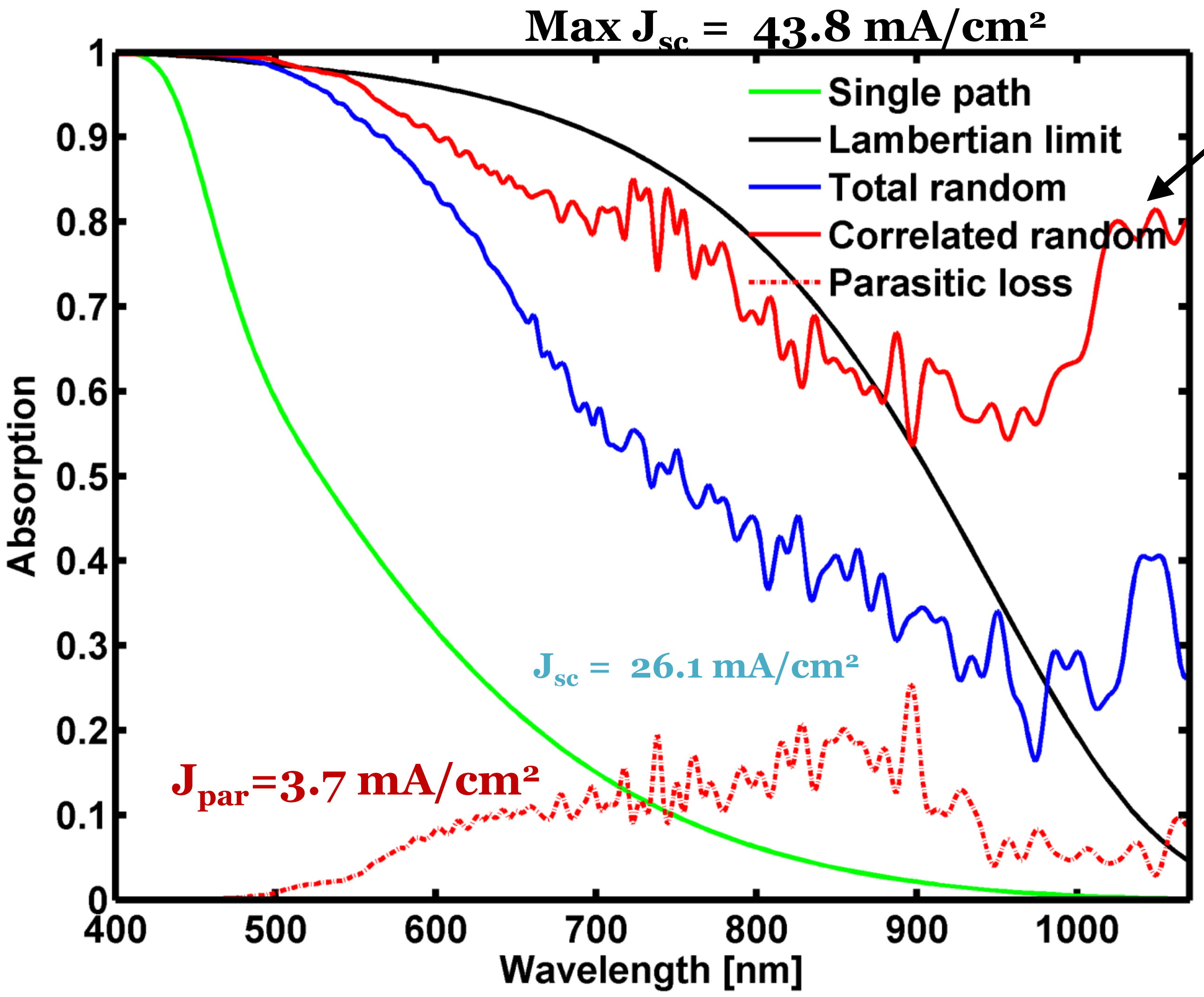


Ag Nanoparticle Cell Absorption Enhancement



Haejun Chung, K.Y. Jung, and Peter Bermel, "Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach" *Opt. Express* (2015, submitted)

Optimizing Ag Nanoparticle Cell Absorption



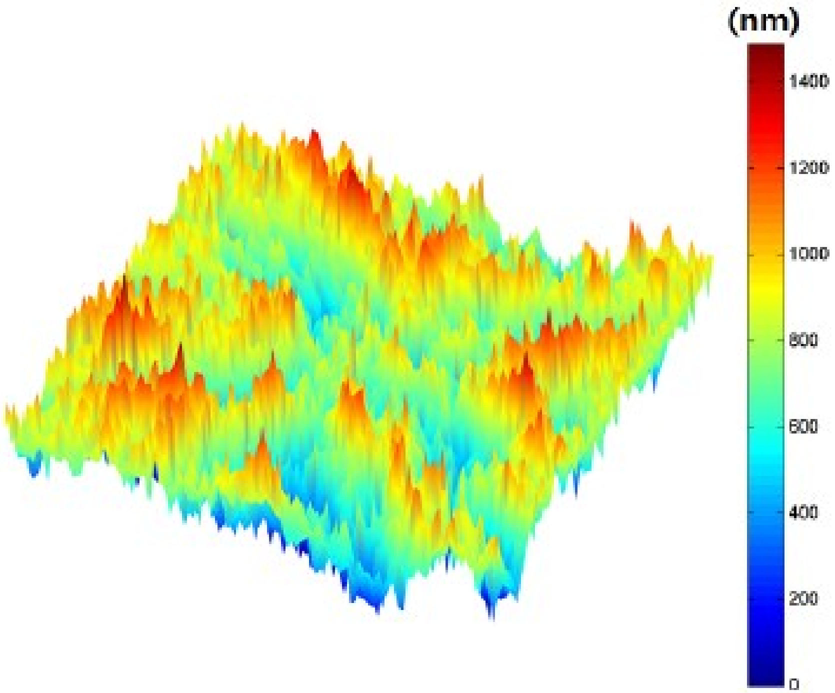
Effective path length: 700x enhancement

J_{sc} = 36. 6 mA/cm²

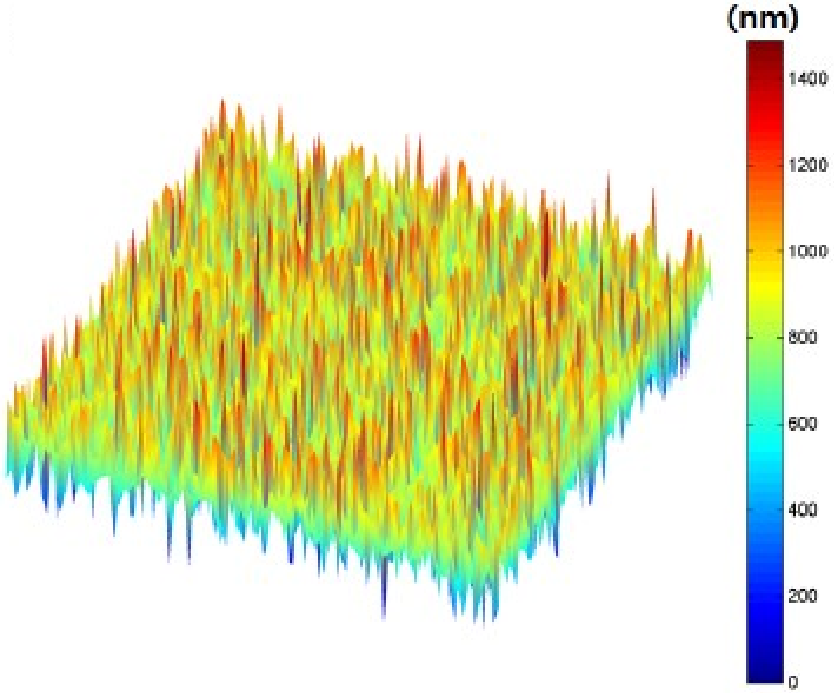
J_{refl}= 5.0 mA/cm²

Haejun Chung, K.Y. Jung, and Peter Bermel, "Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach" *Opt. Express* (2015, submitted)

Optimizing Ag NP Cell Front Texture



Optimal correlated random front surface texture



Completely random front surface texture

Haejun Chung, K.Y. Jung, and Peter Bermel, "Understanding light trapping in nano-textured silicon thin-film solar cells by a novel simulation approach" *Opt. Express* (2015, submitted)

Next Class

- Next time: we will continue finite-difference time domain techniques
- Suggested reference: S. Obayya’s book, Chapter 5, Sections 4-6