# Modeling and Optimization of Silicon Solar Cells

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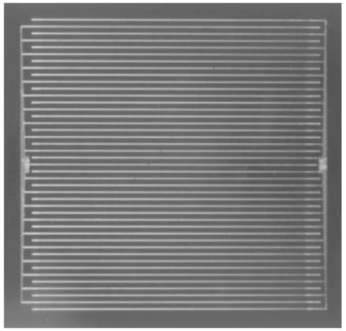
**NCCAVS Joint User Group**
**Topical Conference on "Photovoltaic Technology"**

# PV System Challenges

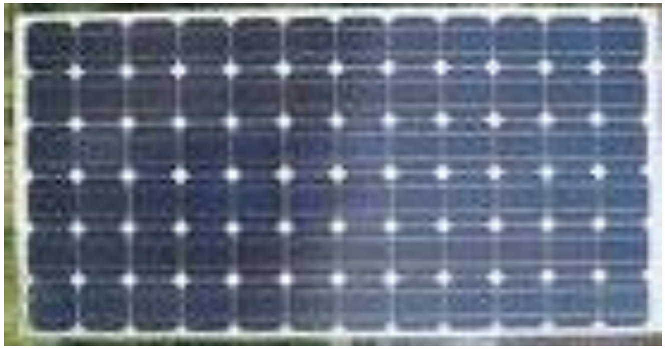
- Improving PV efficiency
- Optimizing for design performance and target reliability
- Reducing the effects of variation on system performance
- Predicting manufacturing yields
- Lowering production costs

# Addressing Issues at All Stages

**Cell**



**Module**



**System**

**Design criteria – Cell Level**

- Maximize efficiency
- Optimize geometric and process parameters

**Design criteria – Module Level**

- Minimize effect of interconnects on performance
- Minimize impact of cell variation or degradation on module performance

**Design Criteria – System Level**

- Maximize system performance accounting for diurnal solar inclination and tracking of solar path (some systems have 1- or 2-axis tracking of the sun)
- Maximize system level efficiency delivered to the grid, including inverter system

# Addressing Issues at All Stages

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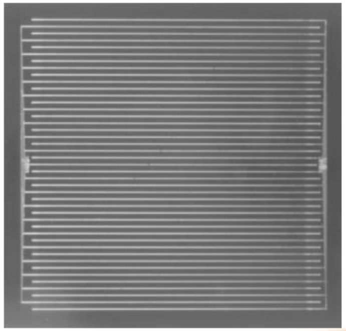

**Module**

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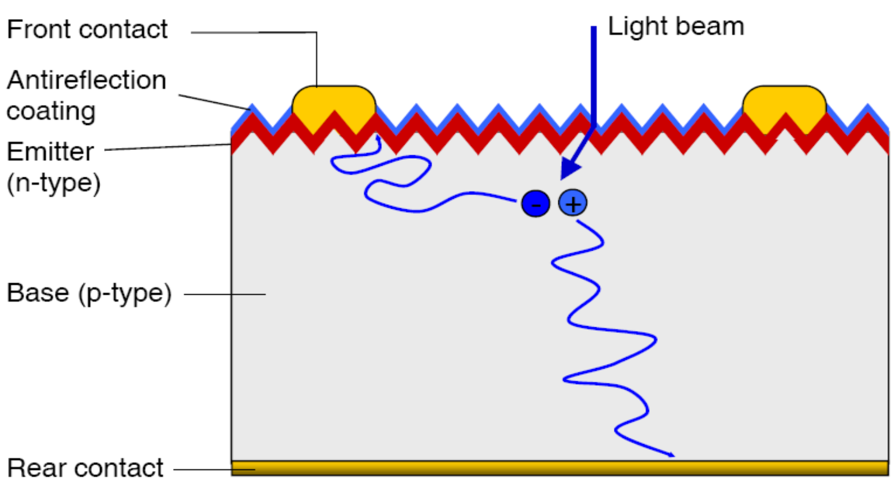
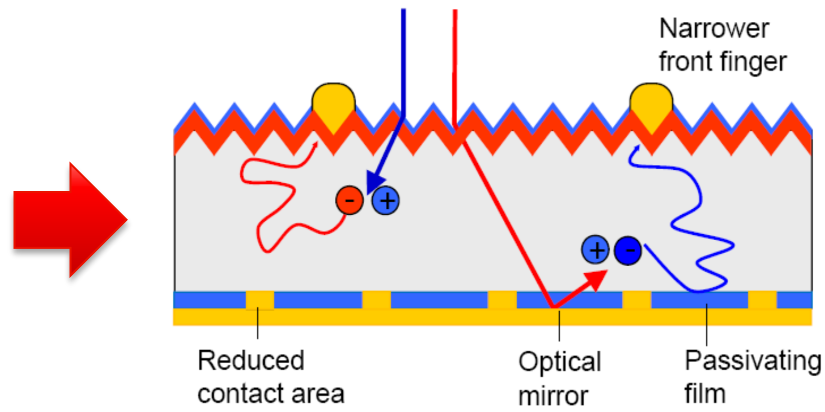
# Why Simulate Solar Cells?

- Continuous innovation makes cells more complex
  - More process and geometrical variables
  - 3D effects, complex light path, etc …
- It's impractical to design new cells without simulation
  - Too many experiments are needed to investigate design space
  - Risks missing optimum design and market window




Early generation cell (Eff ~ 17%)




New generation cell (Eff > 20%)

Source: SERIS



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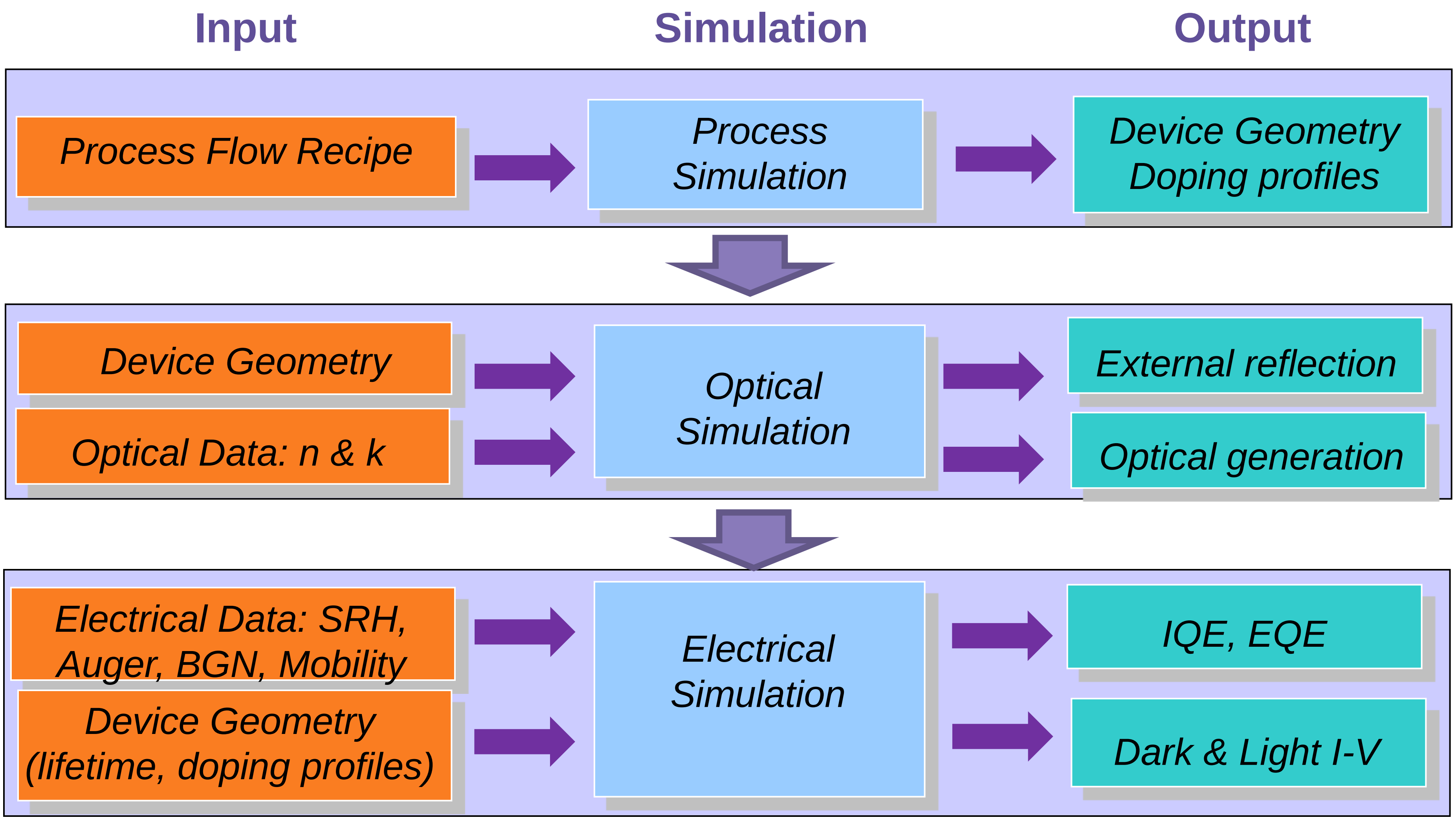
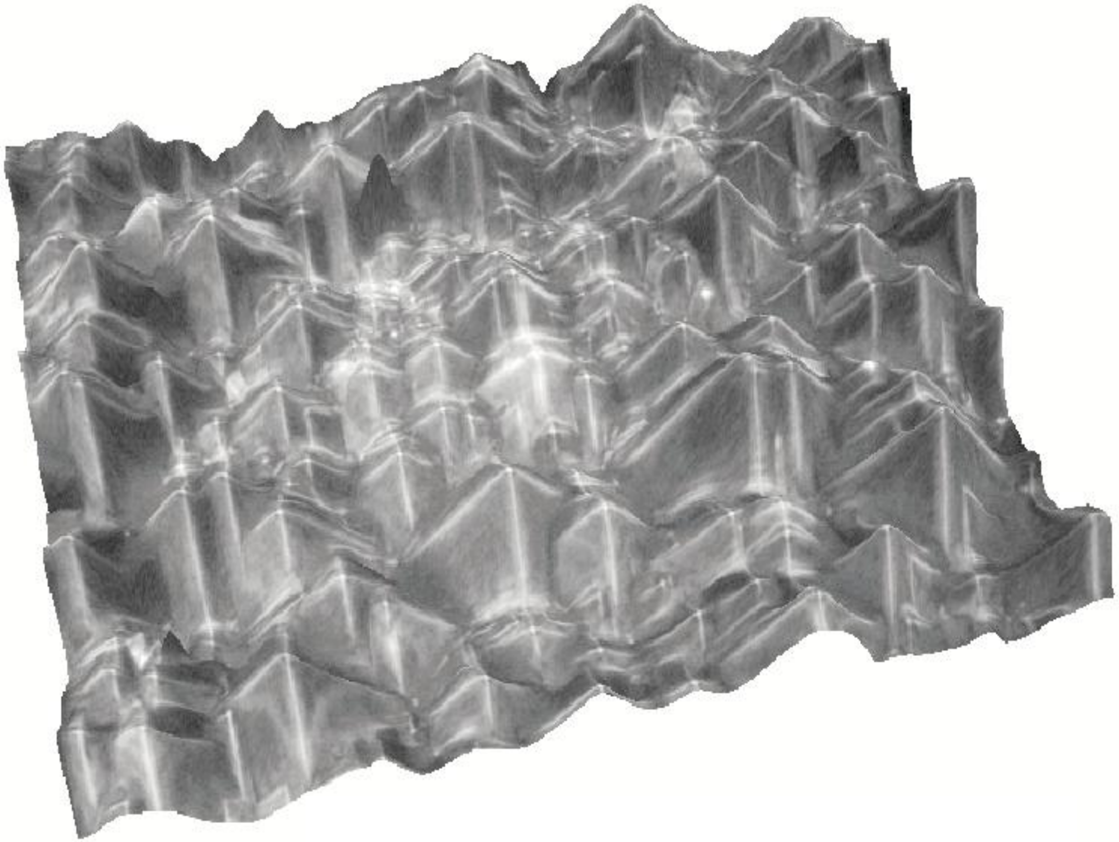
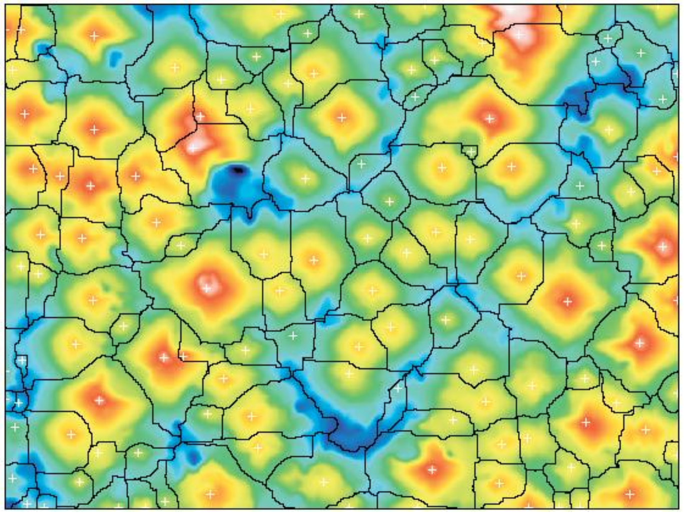
# Solar Cell Simulation Flow



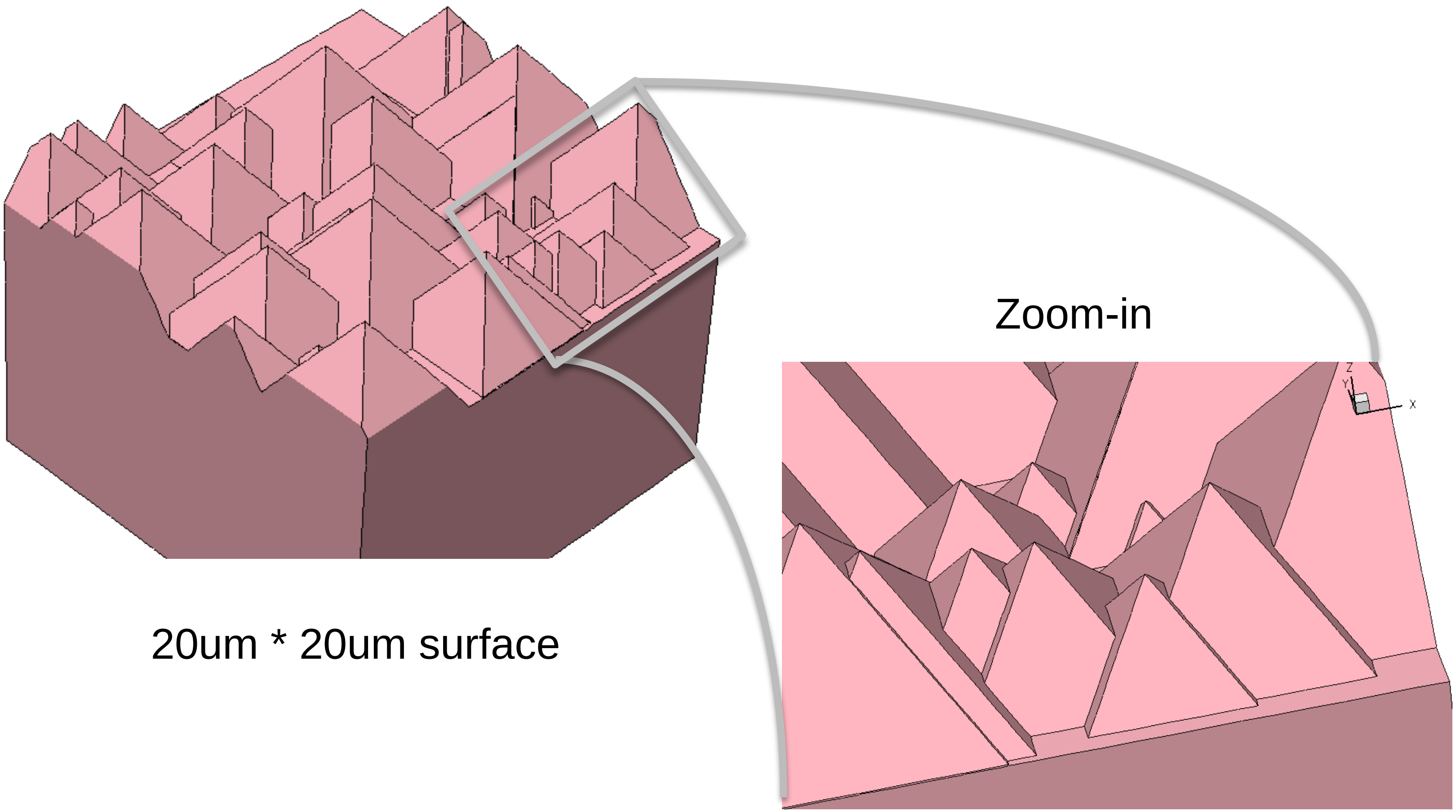
# Measured Texture





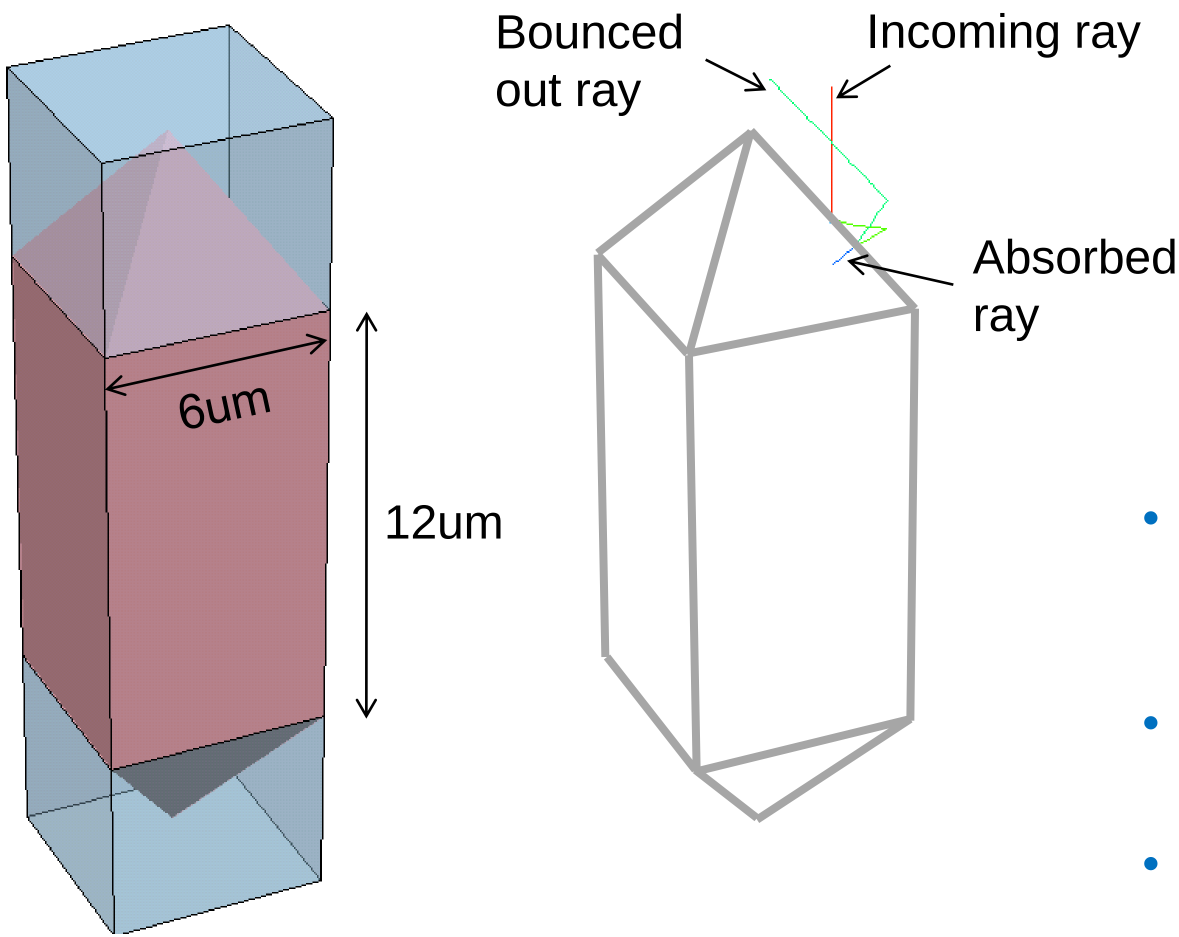
**Data from www.sensofar.com**

# Simulated Surface Texture



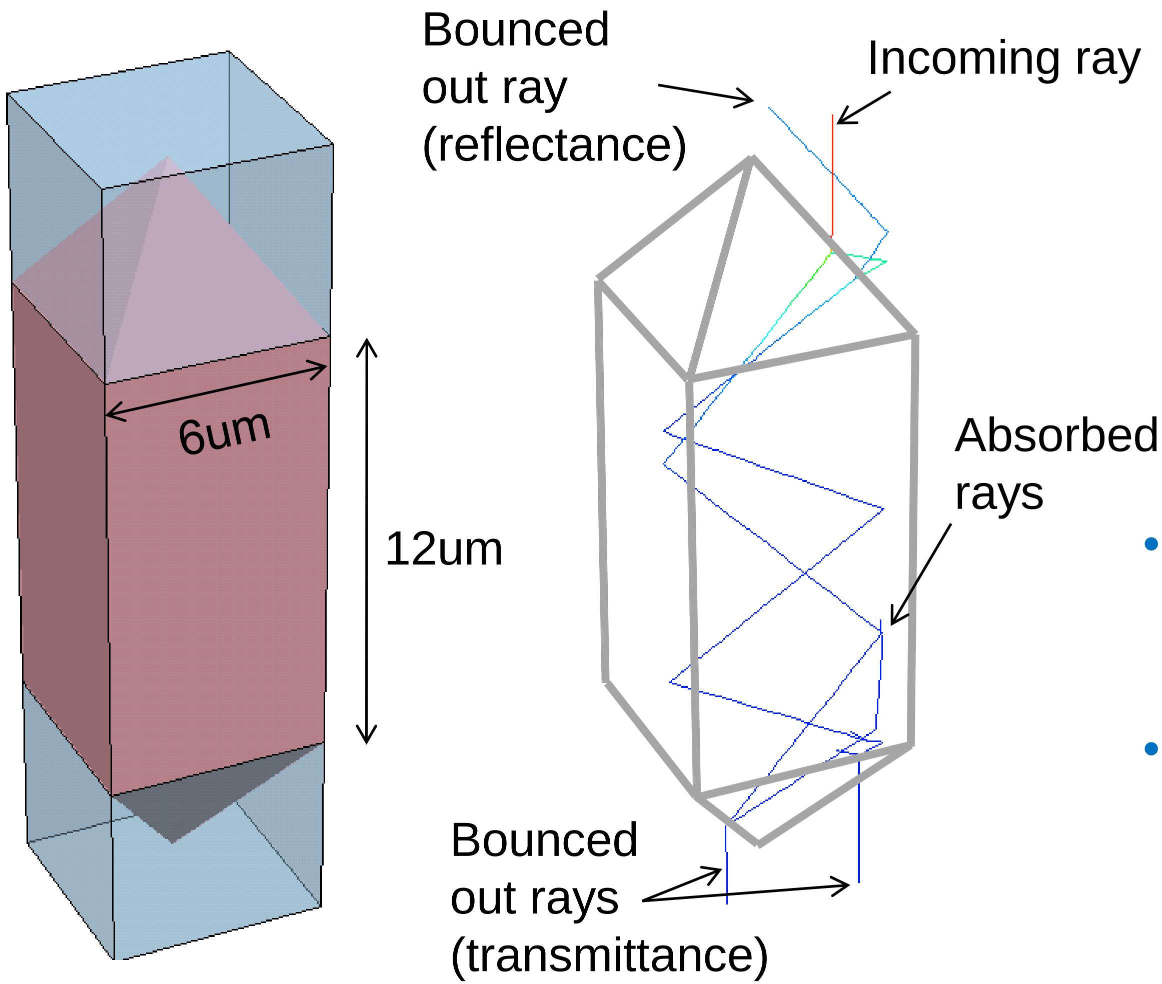

- **Robust mesh and geometry handling makes it possible to model!**

# Behavior of UV light (0.3um Wavelength)



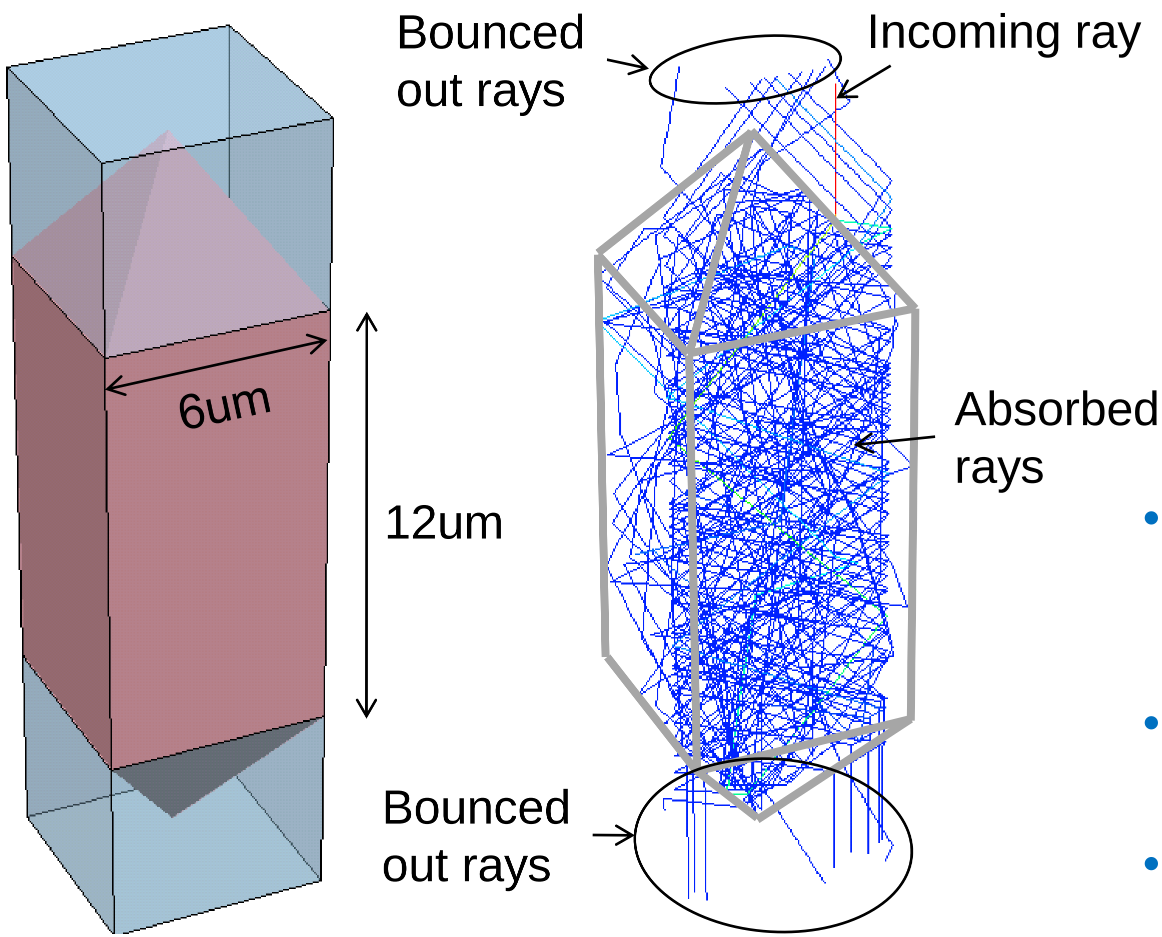

- Absorption in Si happens within one micron from surface
- Typically one or two reflection events
- Only top surface matters

# Behavior of Visible Light (λ=0.6um)




- Absorption in Si happens within tens of microns
- Several reflection events

# Behavior of Infrared Light (λ=0.9um)




- Absorption in Si happens within hundreds of microns
- Dozens of reflection events
- Both the top and the rear surfaces matter



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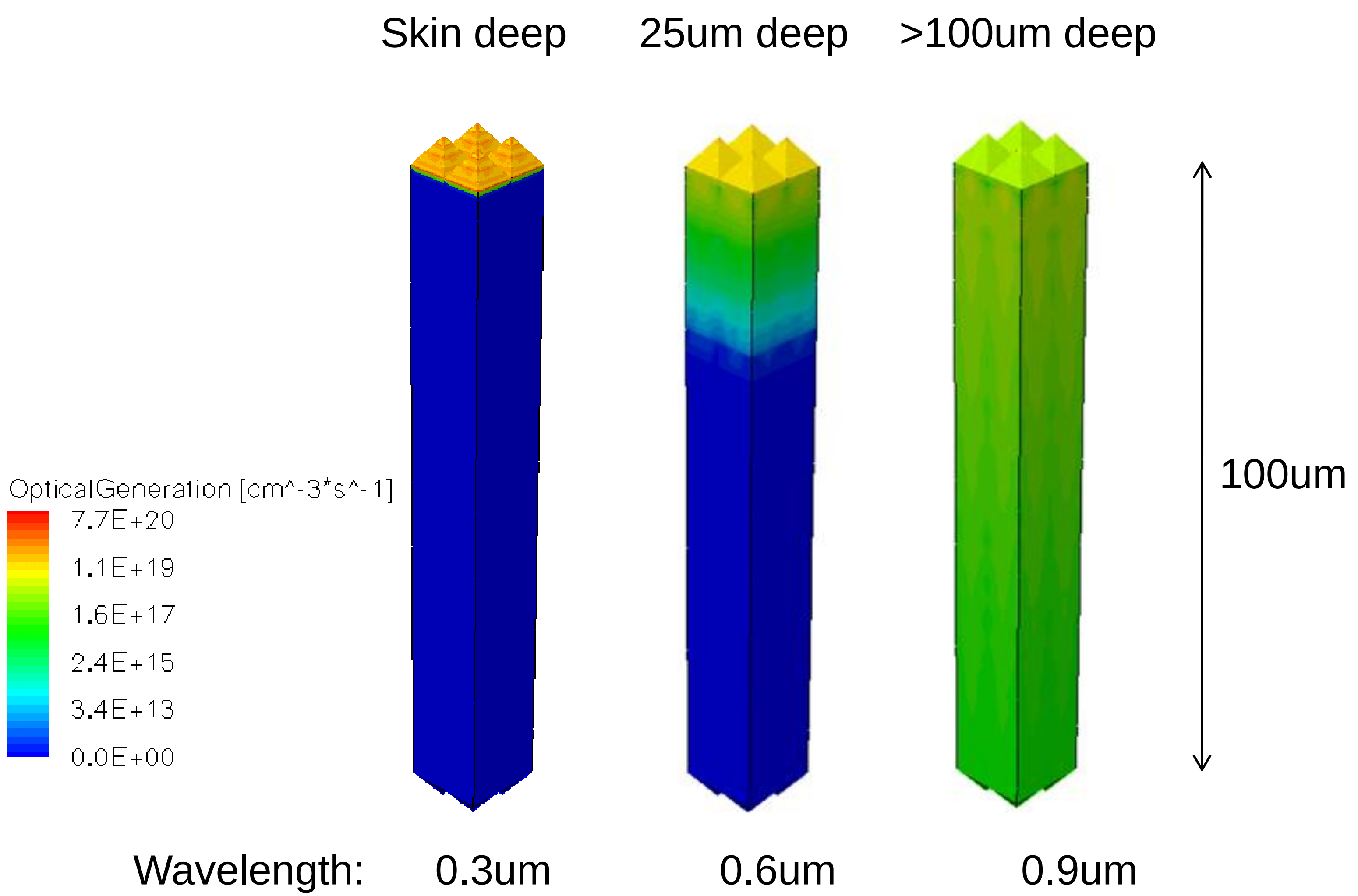
# Optical Generation @Different Wavelength

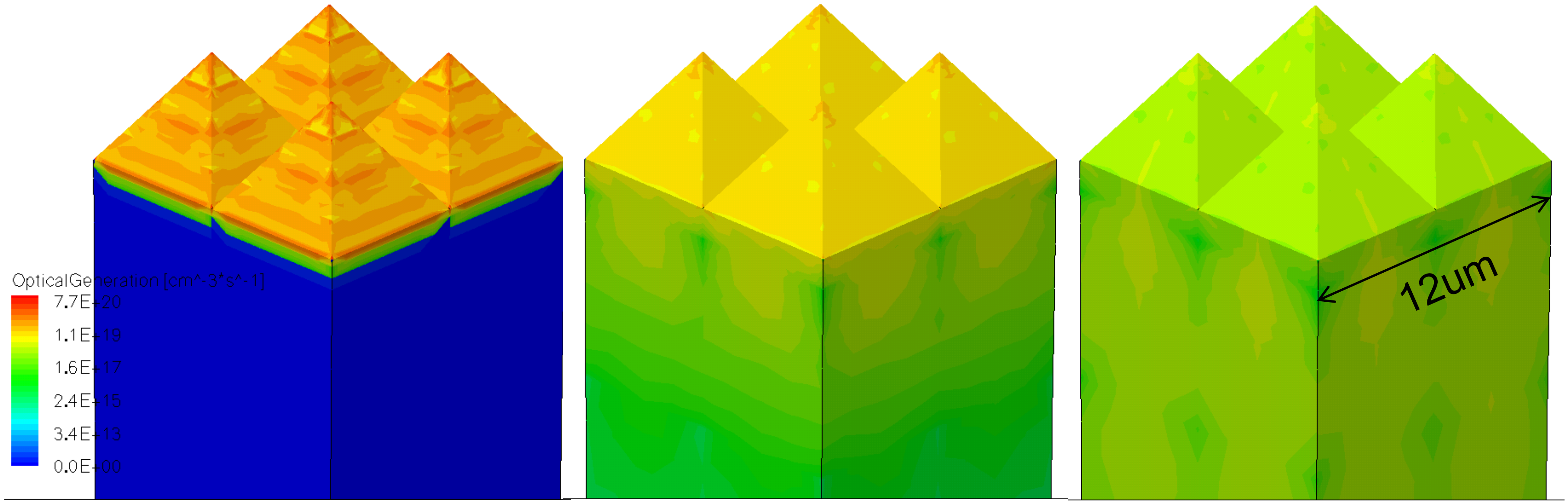


# Optical Generation Patterns (Zoom-in)

High carrier density
Standing waves

Medium carrier density

Low carrier density

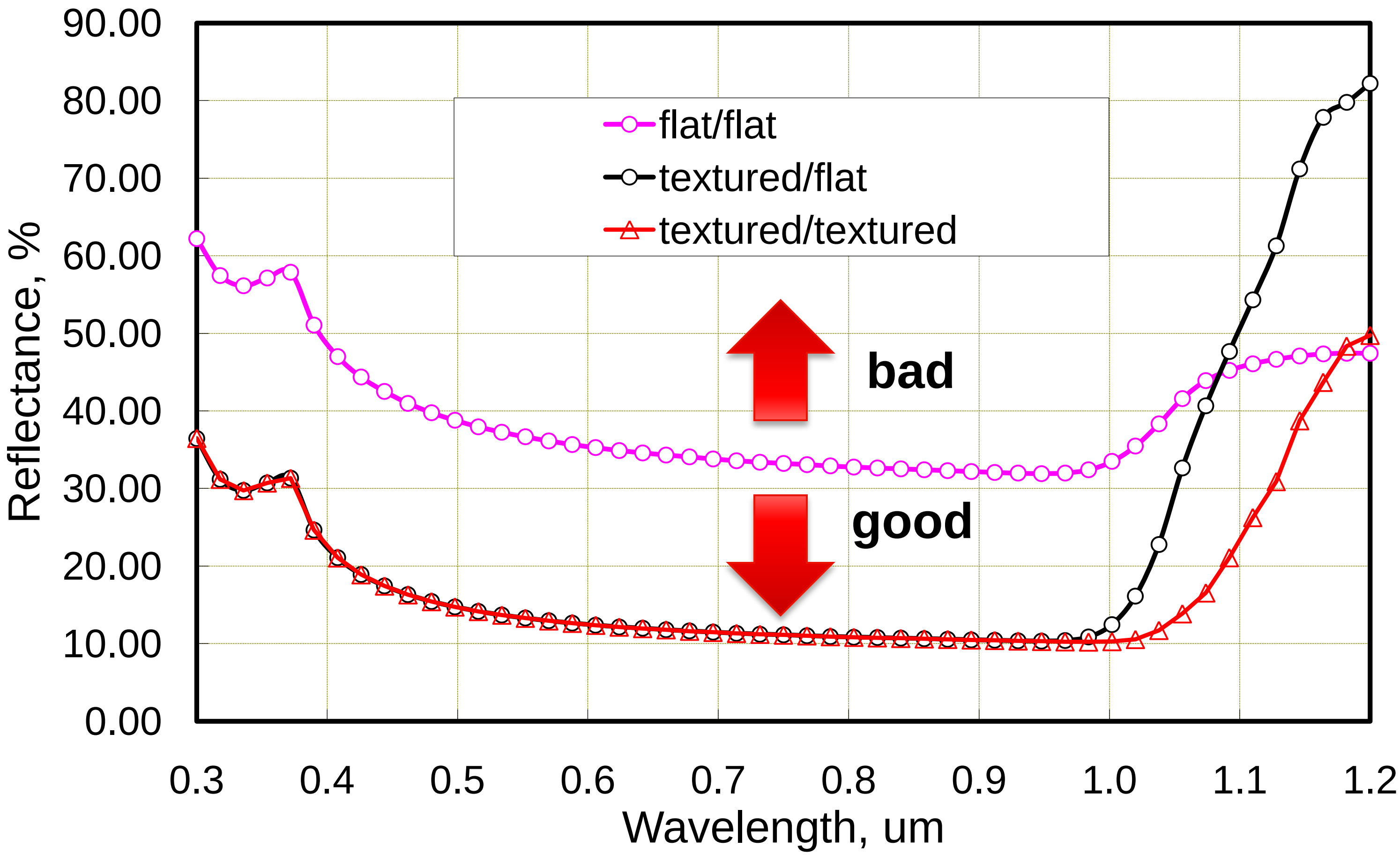



Wavelength: 0.3um

0.6um

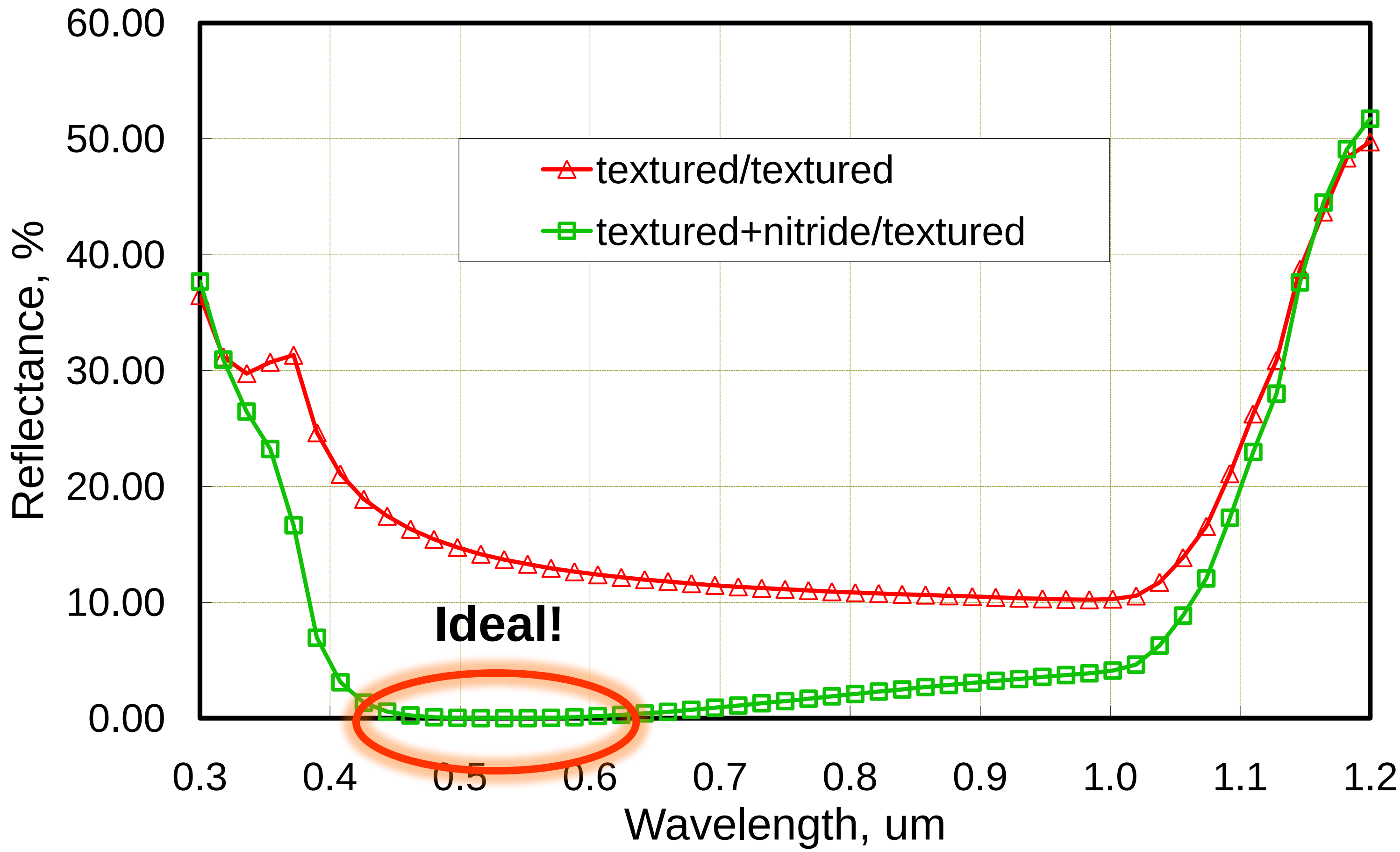
0.9um

# Reflectance Curves: Texture is Good



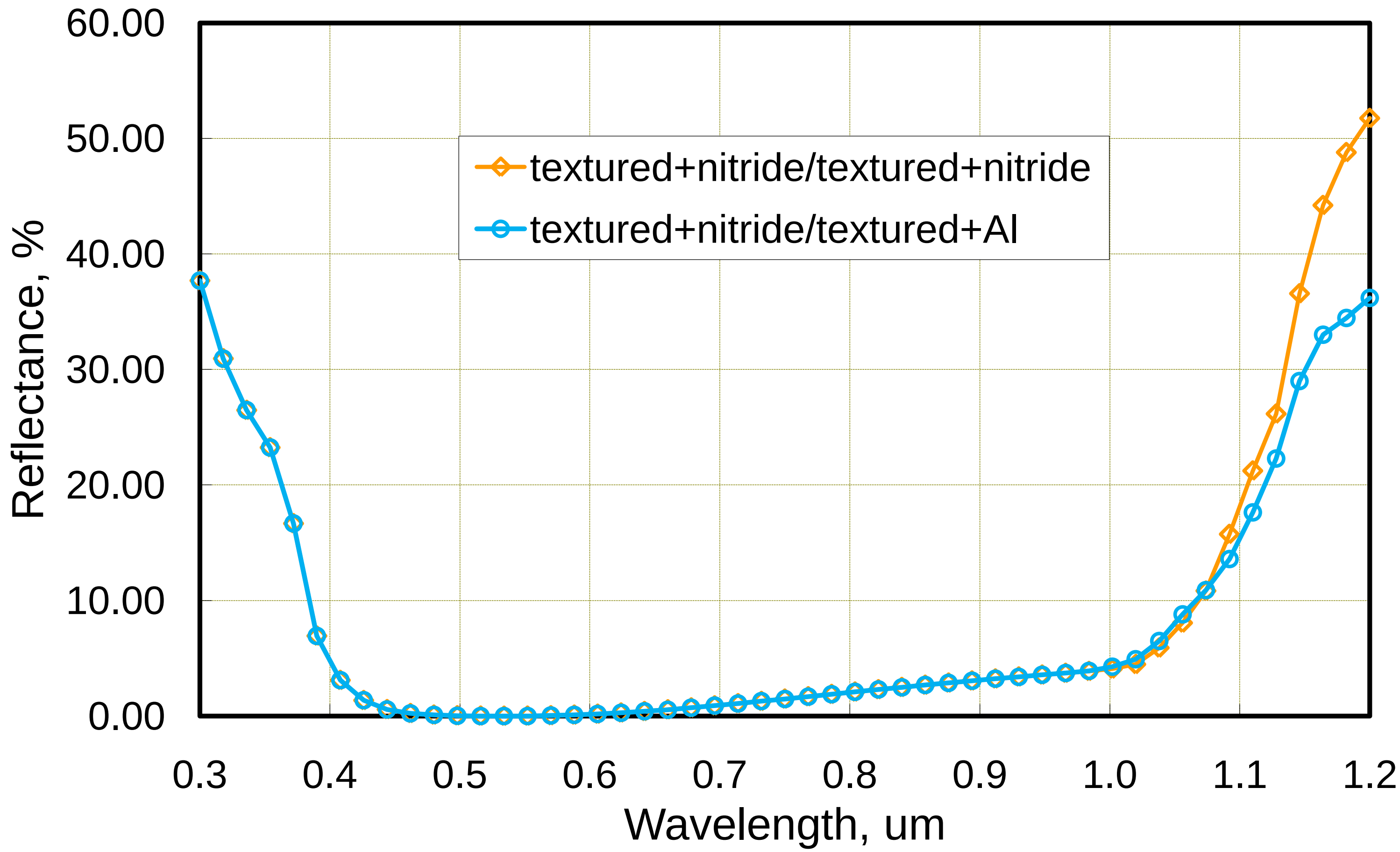

- **Texture reduces reflectance by 3x**

# Reflectance Curves: Nitride is Good




- **Nitride anti-reflective layer reduces reflectance almost to zero at mid-range**

# Reflectance Curves: Aluminum vs Nitride




- **Rear-side nitride reflects infra-red light better than rear side Al contact**



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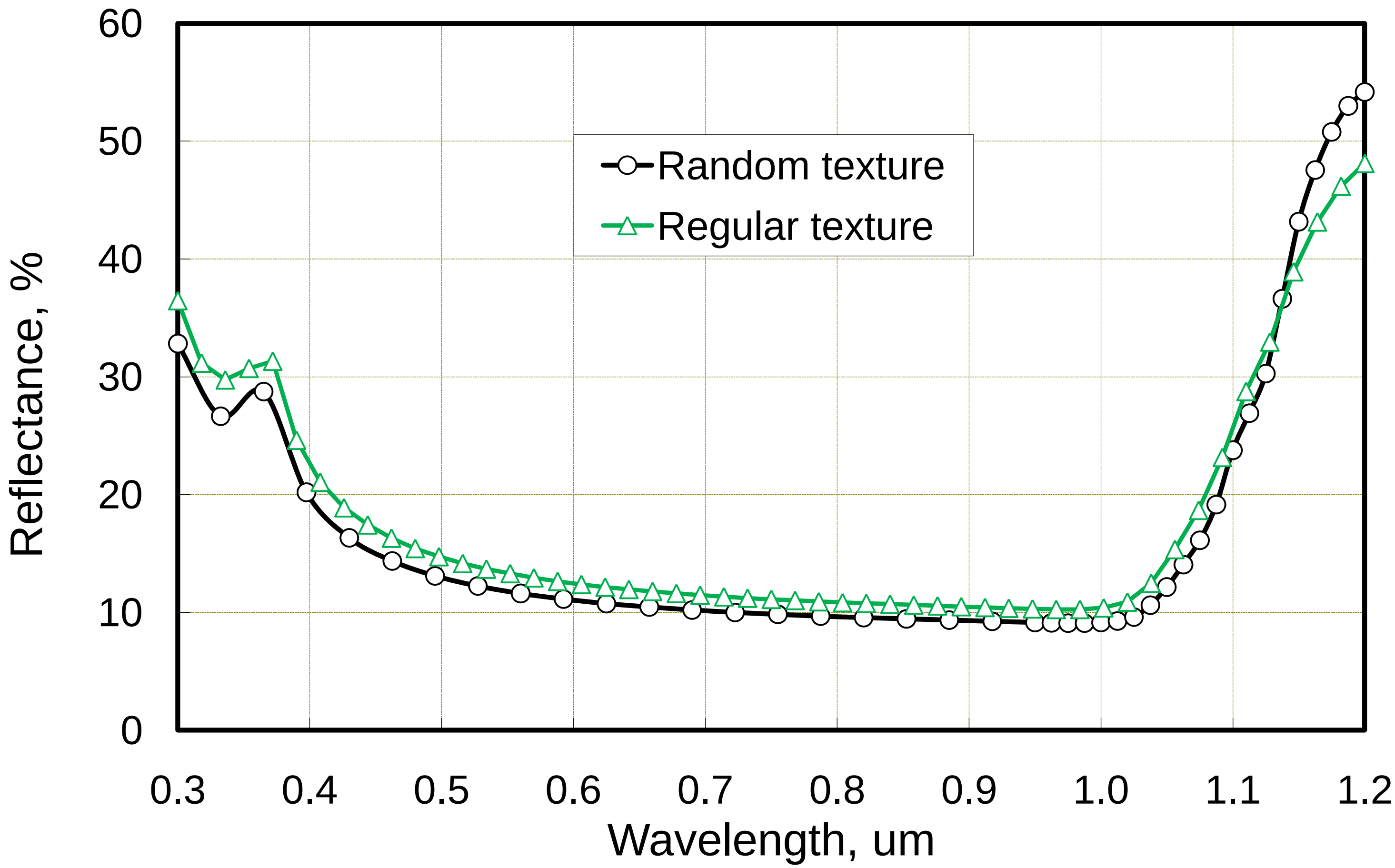
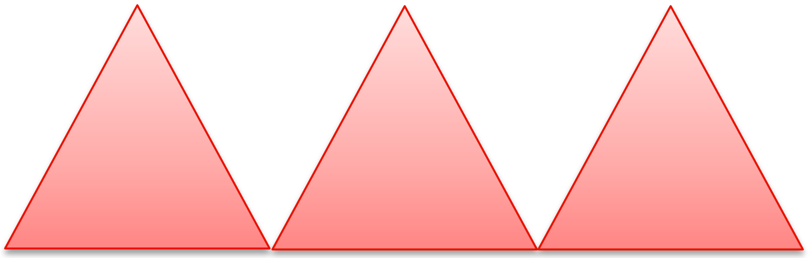
# Reflectance Curves: Random vs Regular



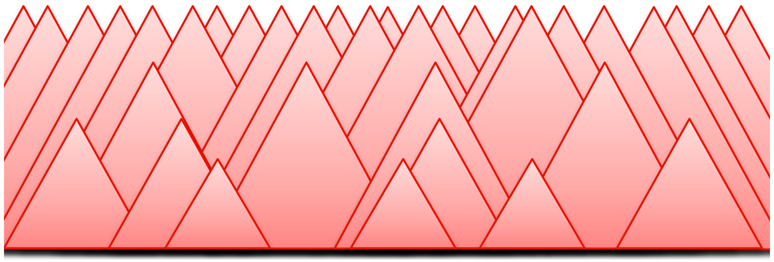

- **Random texture performs ~15% better than regular texture**

# Skyline of the Wafer Texture (Side View)

## Regular pyramids



## Random Pyramids

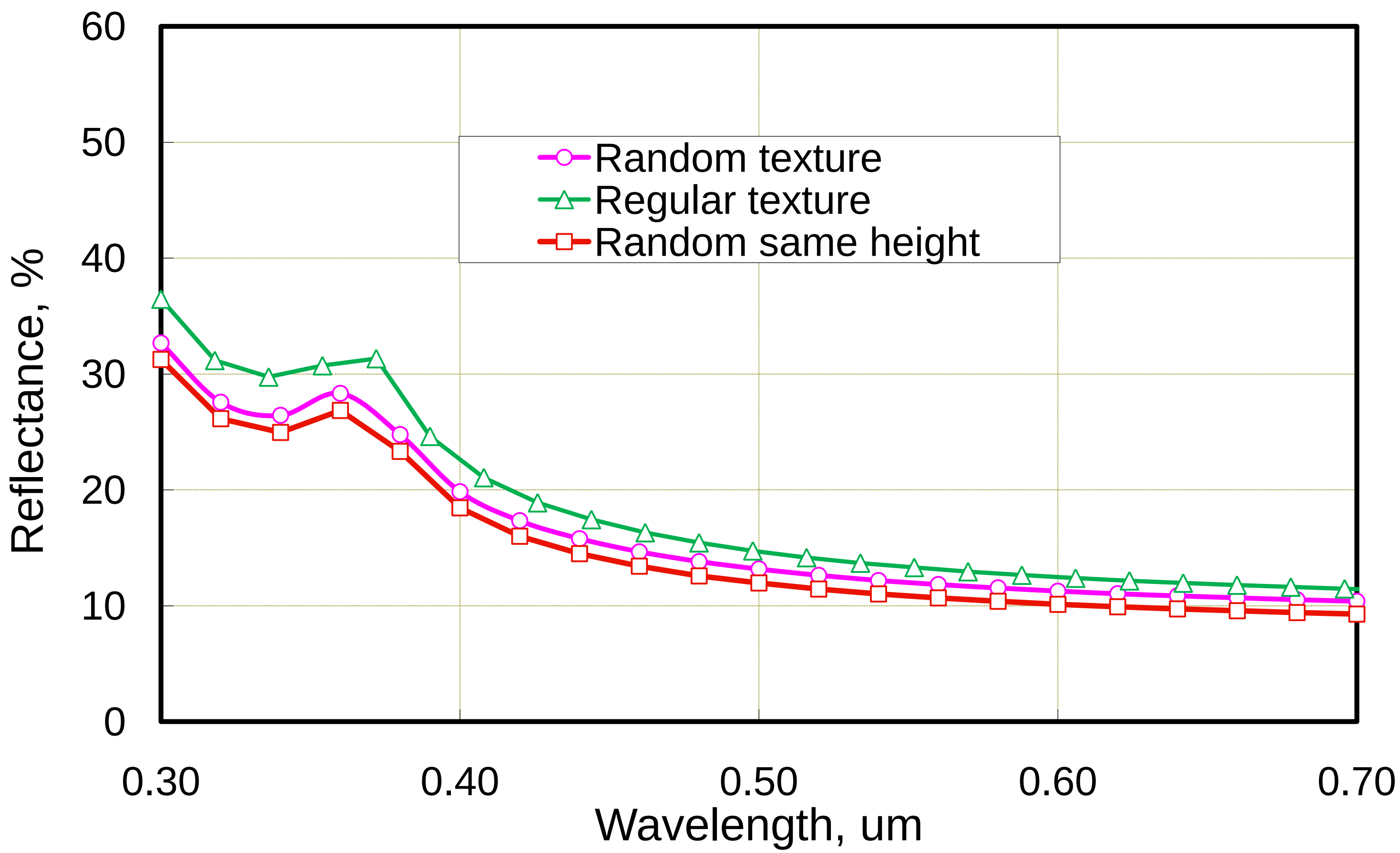


- **Random pyramids cover more area for the rays that are bounced at low angles to the wafer**

# Controlled Randomness Test

- Let's look at reflectance of an artificial structure:
  - With all pyramids of the same height (same as the regular pyramids), but
  - With random placement of the pyramids (same "random" locations as in true random texture)
  - This changes one variable at a time and makes the results cleaner and easy to interpret

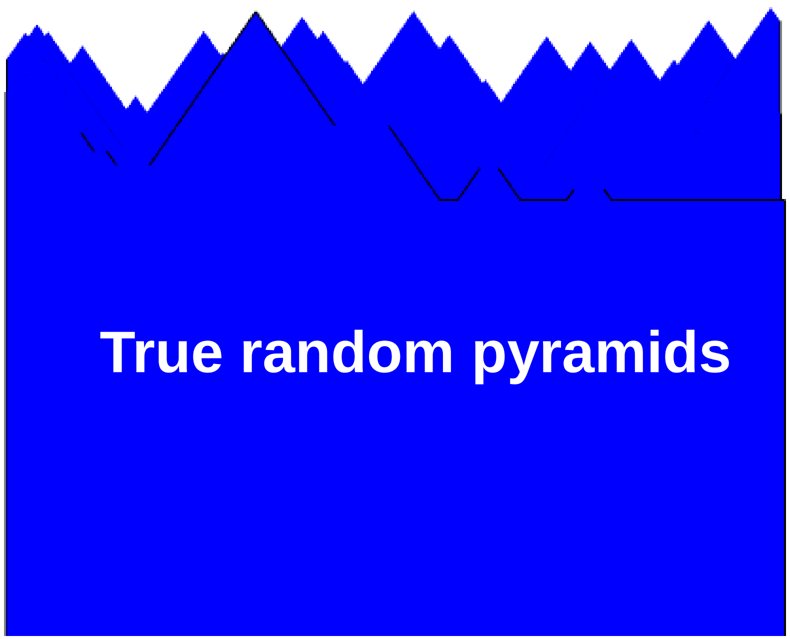
# Controlled Randomness Components



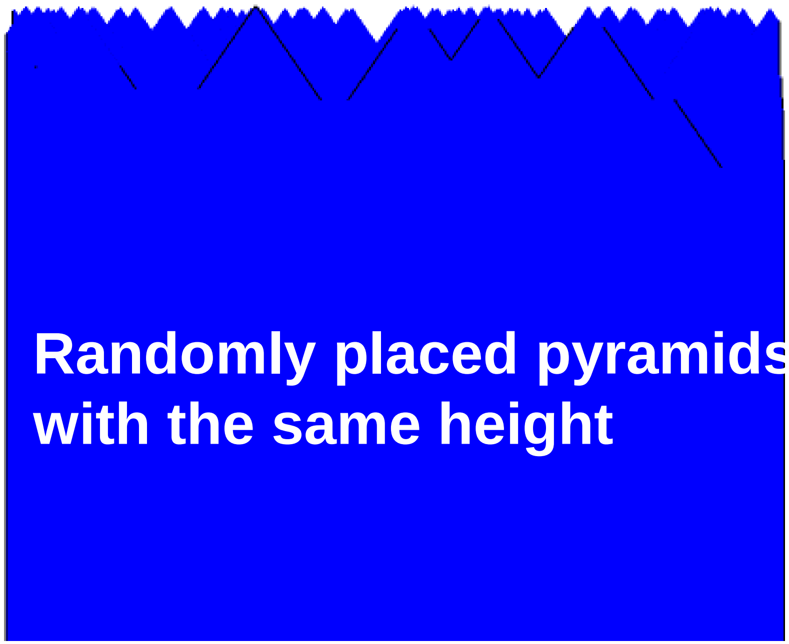

- **The same height random texture is even better than true random texture**

# Actual Texture Skylines

There are some holes in the skyline due to limited 20um by 20um size

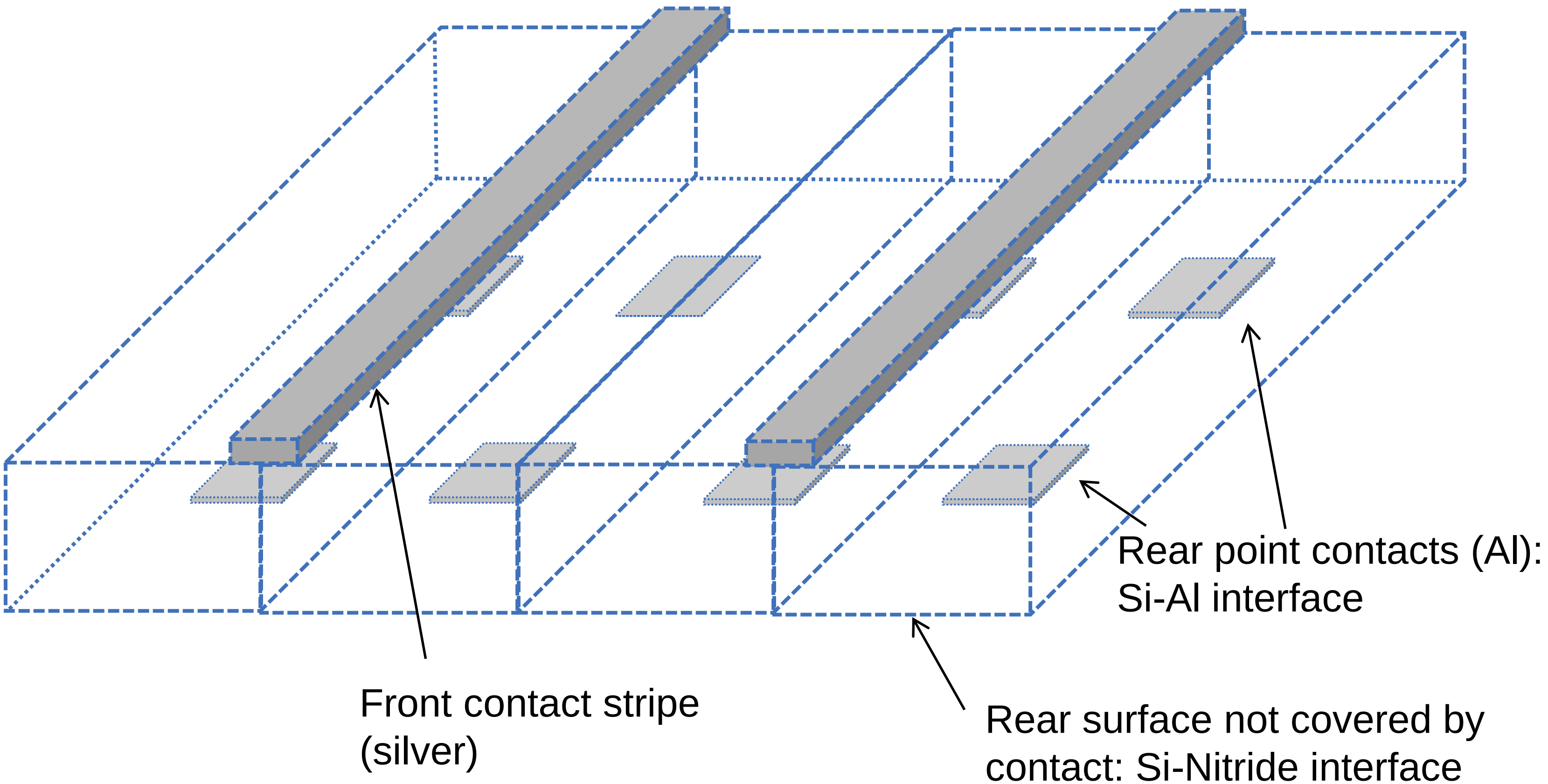



The skyline covers most of the space




- **It is not random pyramid height that helps, but the random pyramid placement**

# c-Si Solar Cell with Rear Point Contacts



# Rear Point Contact Optimization

Doping
Silicon quality
Cell size
Contact pitch
…

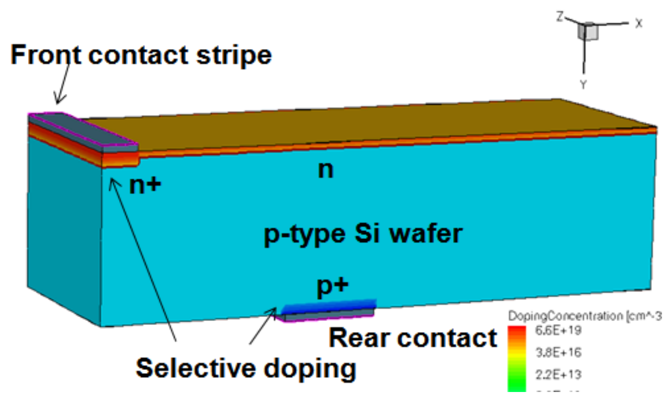
**Increasing Rear Point Contact Area is BAD!**

Optical Reflectivity
Surface Recombination Rates

**Increasing Rear Point Contact Area is GOOD!**

Current Crowding
Contact Resistance
Bulk Recombination

Rear Point Contact Design



# Junction Optimization

Junction depth

…

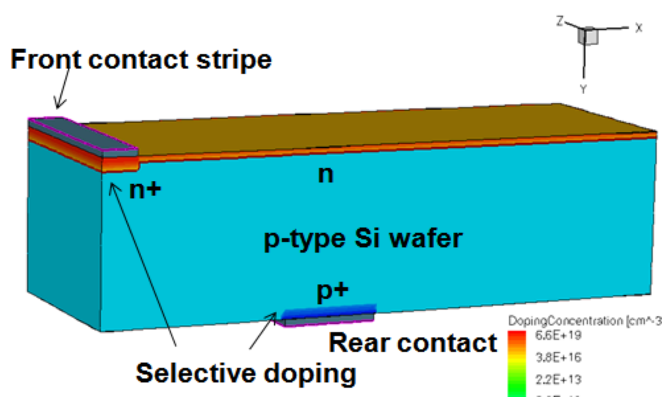
**Higher doping in n layer is BAD!**

Higher doping increases recombination

**Higher doping in n layer is GOOD!**

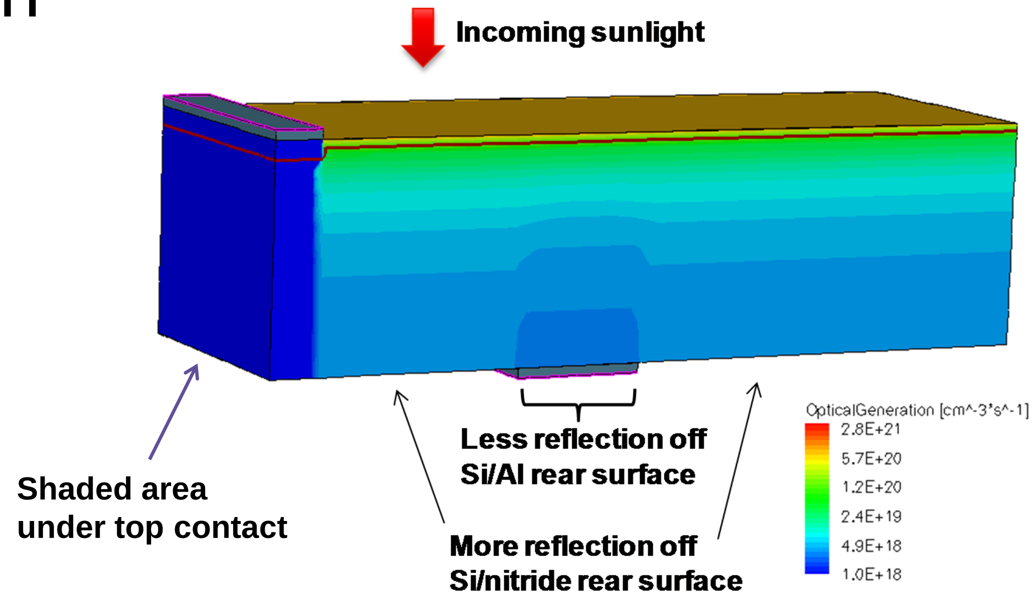
Higher doping increases conduction

Top Surface p-n Junction Design



# Modeling Major Effects

- Optical Reflectivity
- Surface Recombination
- Contact Resistance
- Bulk Recombination
- Current Crowding



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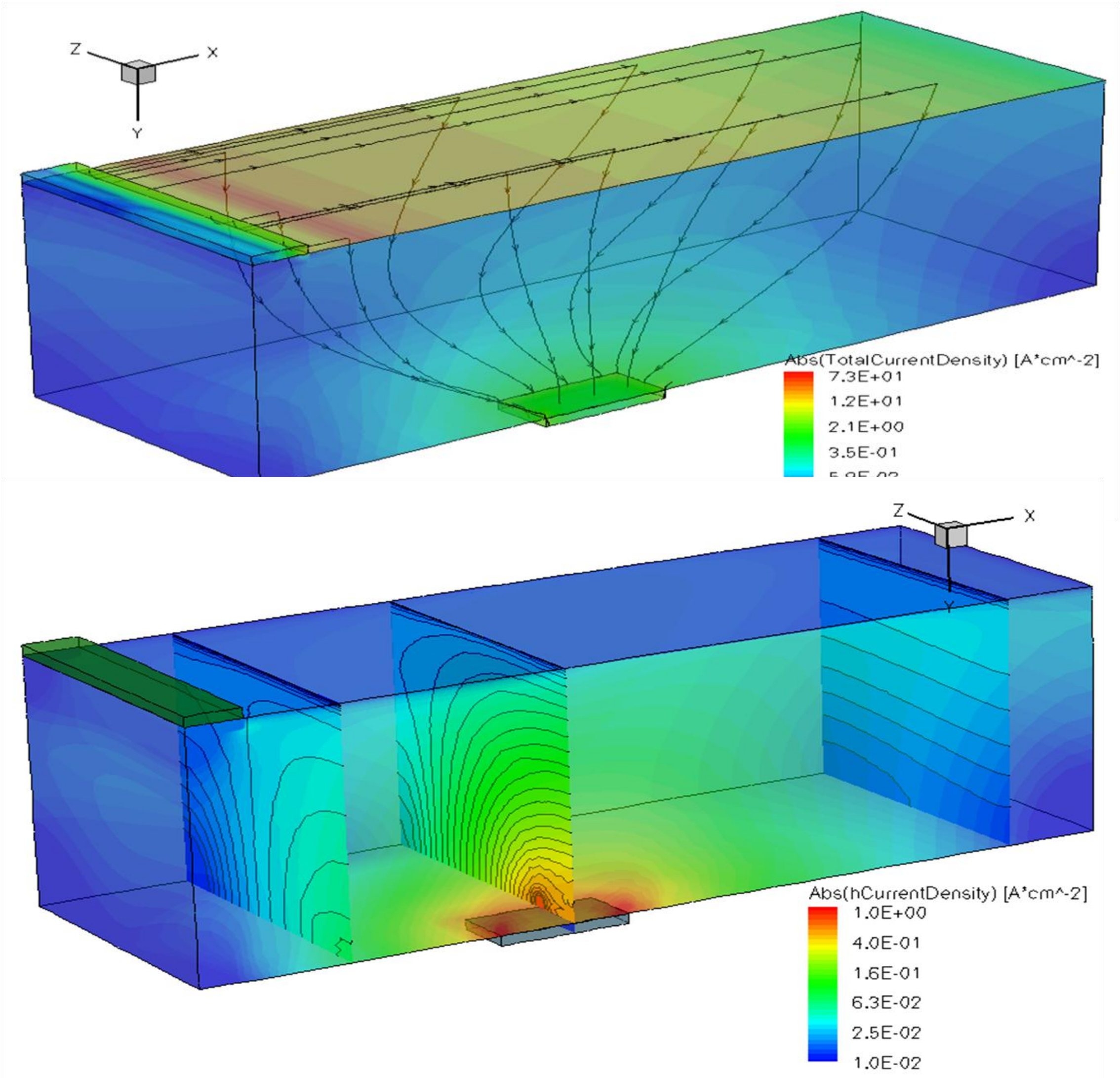
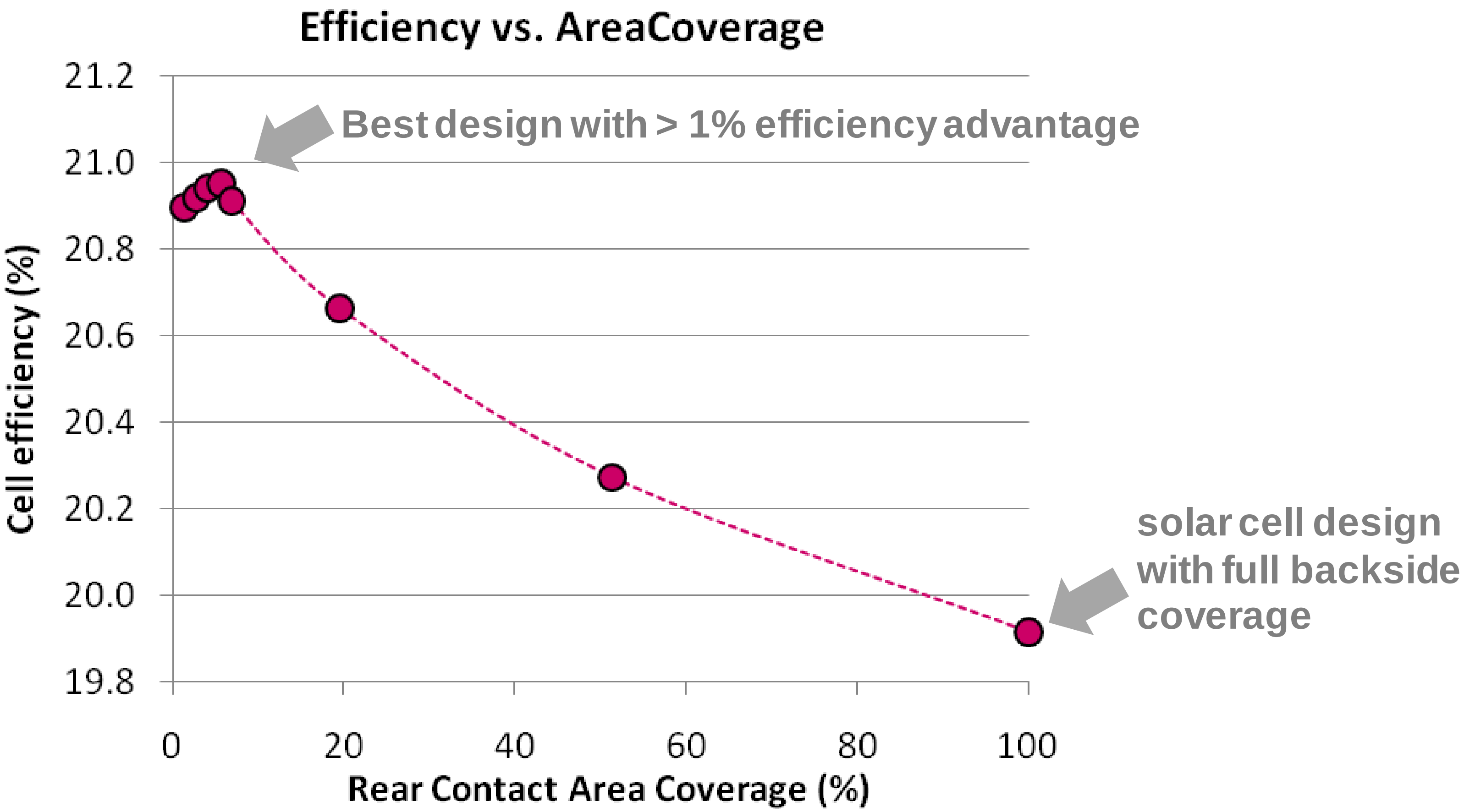
# Current Crowding Pattern




**Current crowding is observed in both lateral directions, which makes it a 3D effect**

# Rear Contact Optimization



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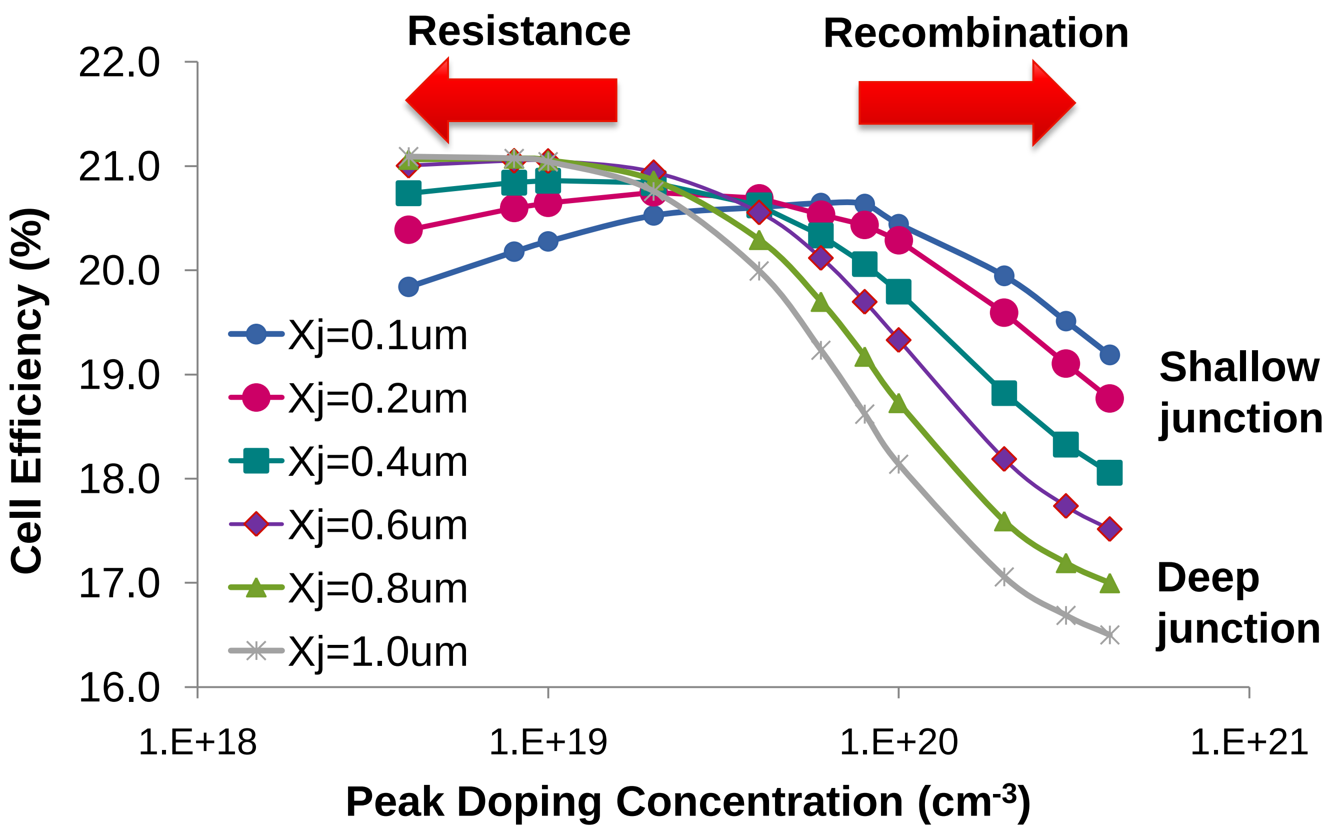

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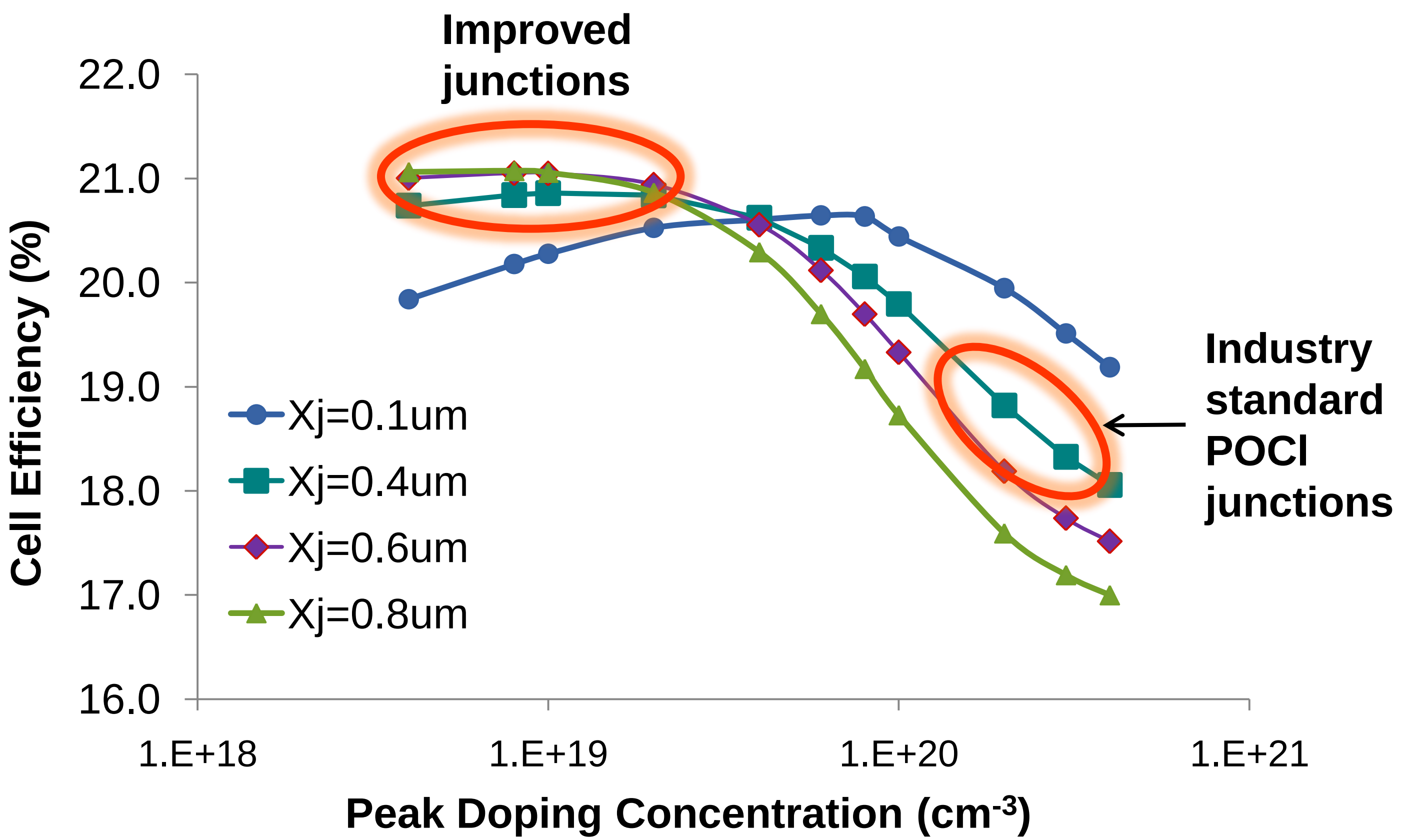

# Summary

- 3D simulation can optimize:
  - Light absorption
  - Rear point contact placement
  - Junction design
- Optimal design with rear point contacts can boost cell efficiency by more than 1%
- Optimal design of optics and junctions can increase efficiency by more than 4%
- Each new cell design requires re-optimization of its components