SYNOPSYS®
Predictable Success

Design, Modeling, and Optimization of Silicon Solar Cells and Modules

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JTG @Semicon West 2011, San Francisco

Outlook

- Introduction
- Financial analysis
- Optical performance of PV cell
- PV cell optimization
- PV module analysis
- Summary

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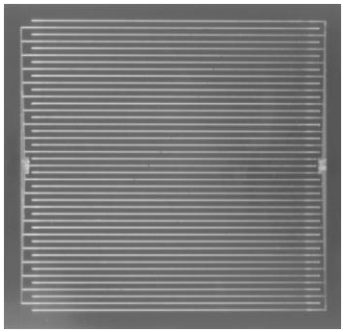
PV System Challenges

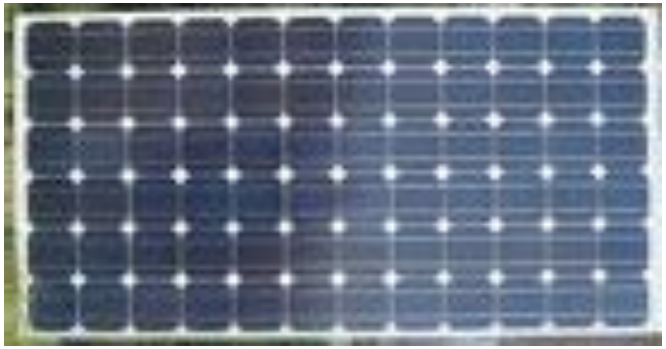
- Improving PV efficiency
- Optimizing for design performance and target reliability
- Reducing the effects of variation on system performance
- Predicting manufacturing yields
- Lowering production costs

Addressing Issues at All Stages

Cell



Module



System

Synopsys TCAD tools → *Synopsys Saber tools*

Design criteria – Cell Level

- Maximize efficiency
- Optimize cell: contact pitches, junctions, anti-reflective coatings, etc.

Design criteria – Module Level

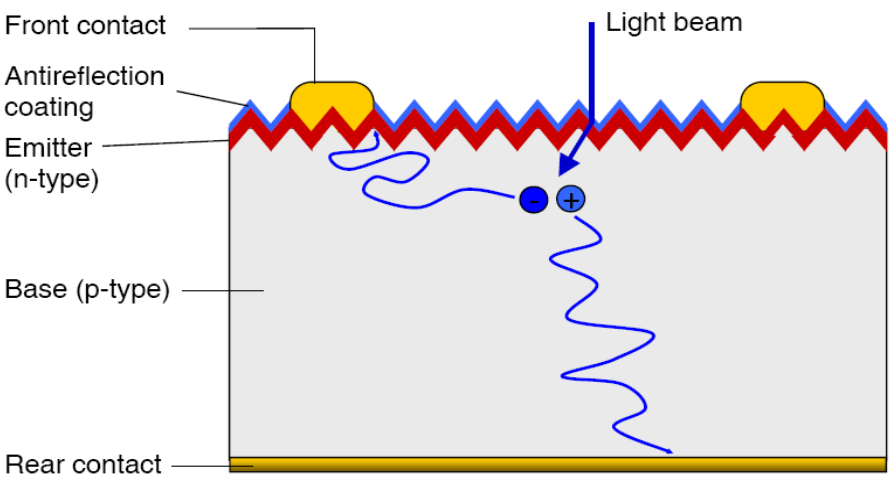
- Minimize effect of interconnects on performance
- Minimize impact of cell variation or degradation on module performance

Design Criteria – System Level

- Maximize system performance accounting for diurnal solar inclination
- Maximize system level efficiency delivered to the grid, including inverter system

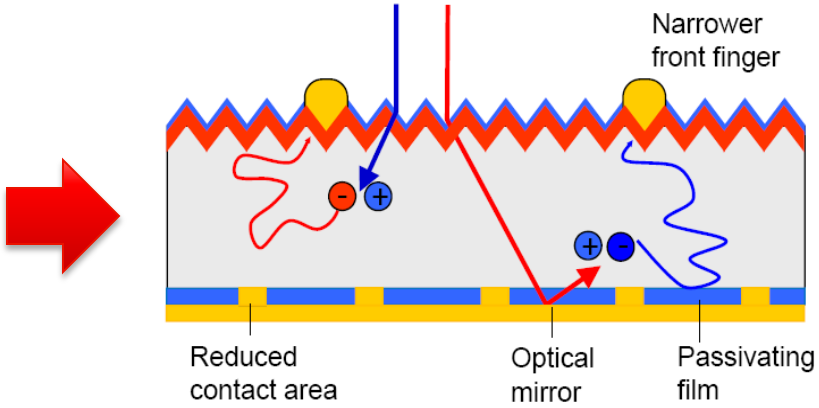
Why Simulate Solar Cells?

- **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**



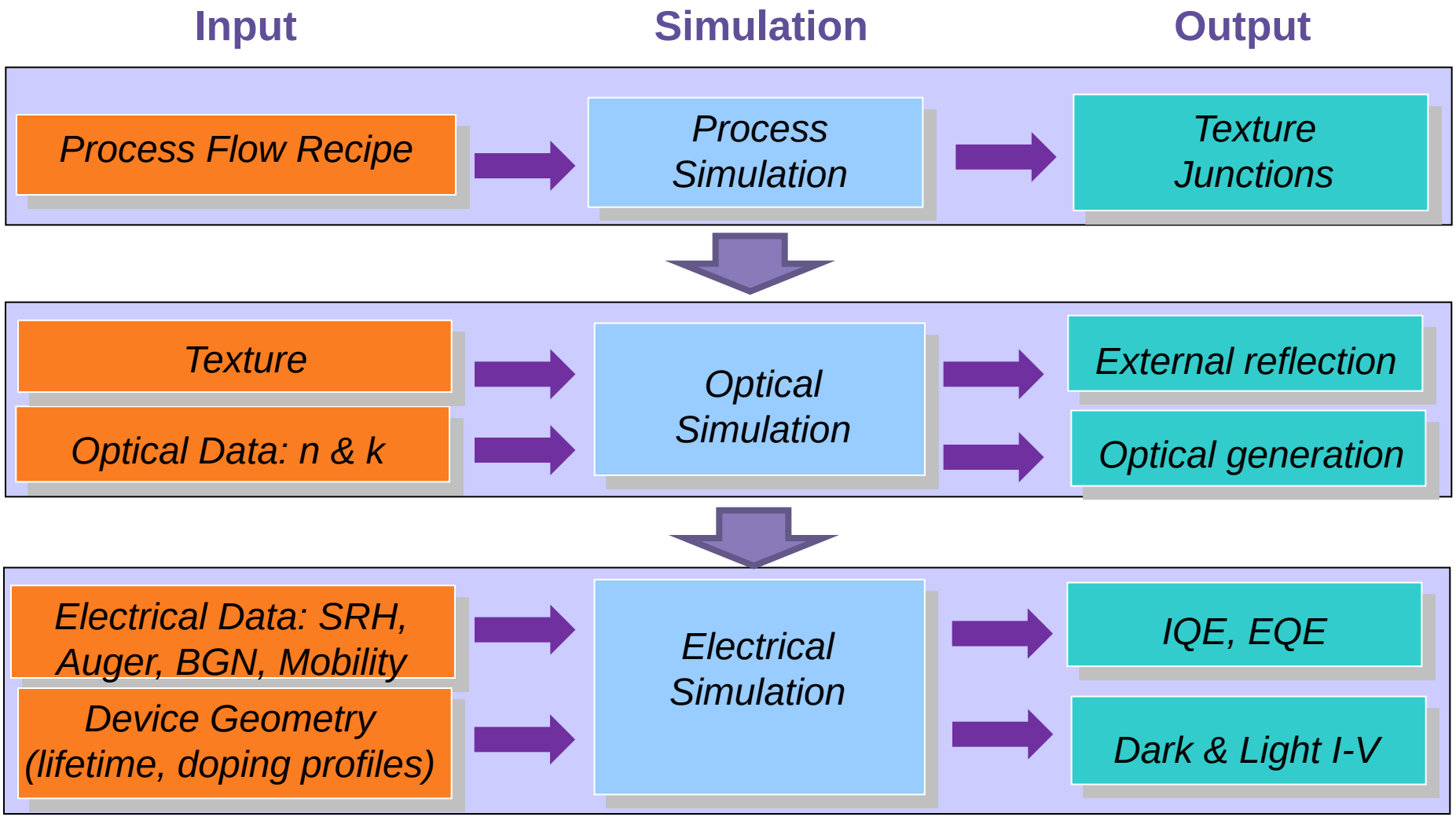
Source: SERIS

Early generation cell (Eff ~ 17%)



New generation cell (Eff > 20%)

Solar Cell Simulation Flow



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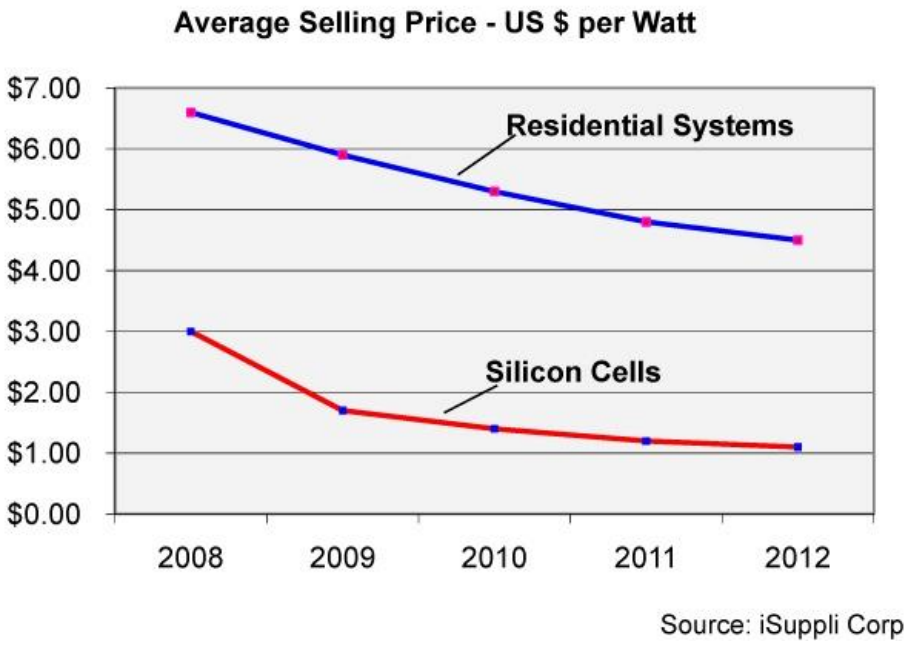
Solar PV Driving Force : $/W

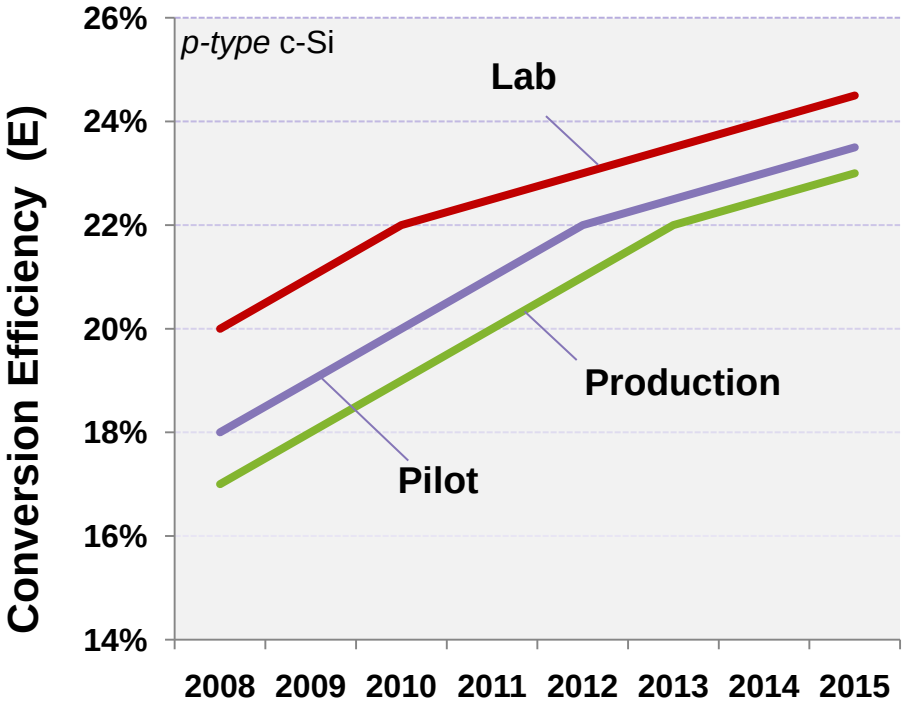


R&D cost ~ 1.5%

(about 1.2GW shipment)	(thousands)	
Net revenues	$2,000,000	
Cost of revenues	$1,320,000	66.0%
Gross profit	$680,000	34.0%
Operating expenses		
SG&A	$160,000	8.0%
R&D	$30,000	**1.5%**
Total operating expenses	$190,000	9.5%
Operating income	$490,000	24.5%

$$\frac{\text{Cost}}{\text{Watt}} = \frac{\text{Production cost (\$)}}{\text{Output power (W)}} \sim \frac{\textbf{Process Cost}}{\textbf{Conversion efficiency}}$$

Efficiency vs Profit



- Impact of $\Delta E = 0.5\%$
  - E_0=20% -> E=20.5%
  - $\Delta E/E_0$= 2.5%
    - 2.5% more power output
    - 2.4% less cost per Watt
    - 2.4% more gross profit

- 2.4% more gross profit = \$1.32B * 2.4% = \$32M[1]
- About the same as R&D budget (\$30M)

[1]Assume the same cost per unit module and wattage sales

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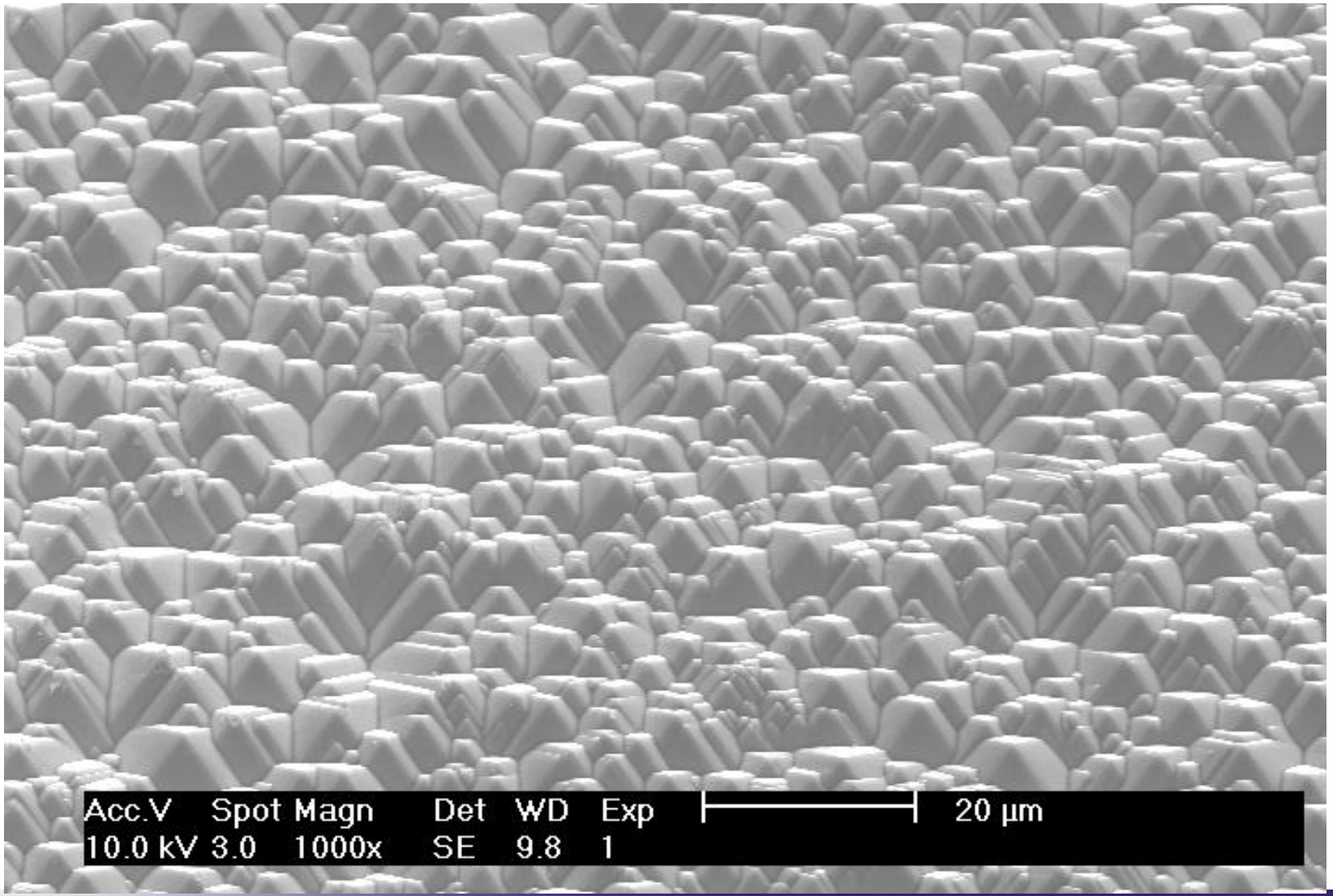
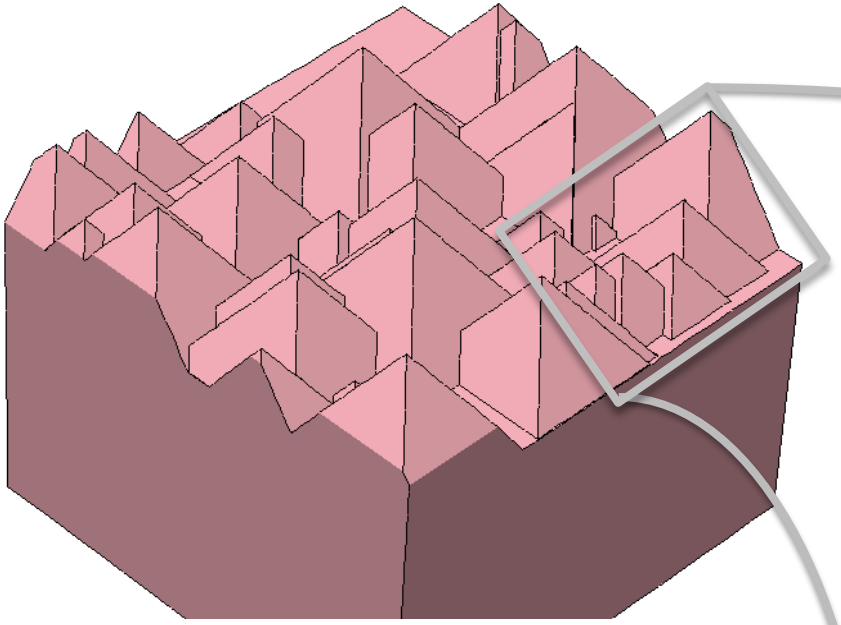
Measured Texture



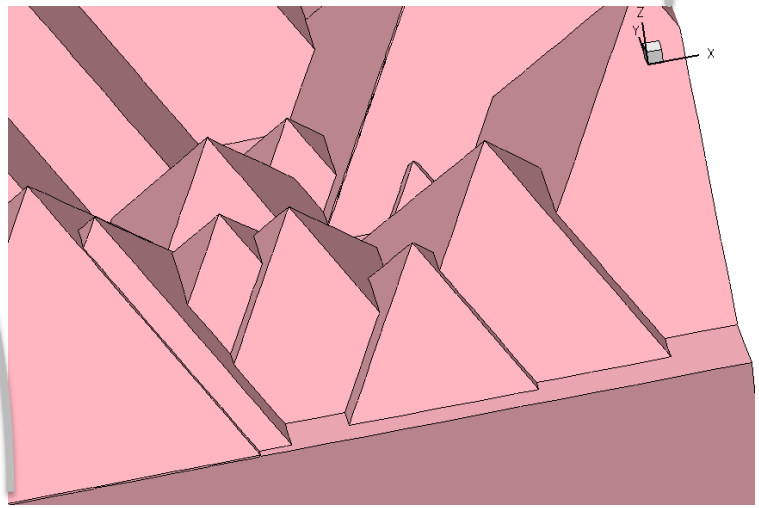
Source: AMAT

Simulated Surface Texture



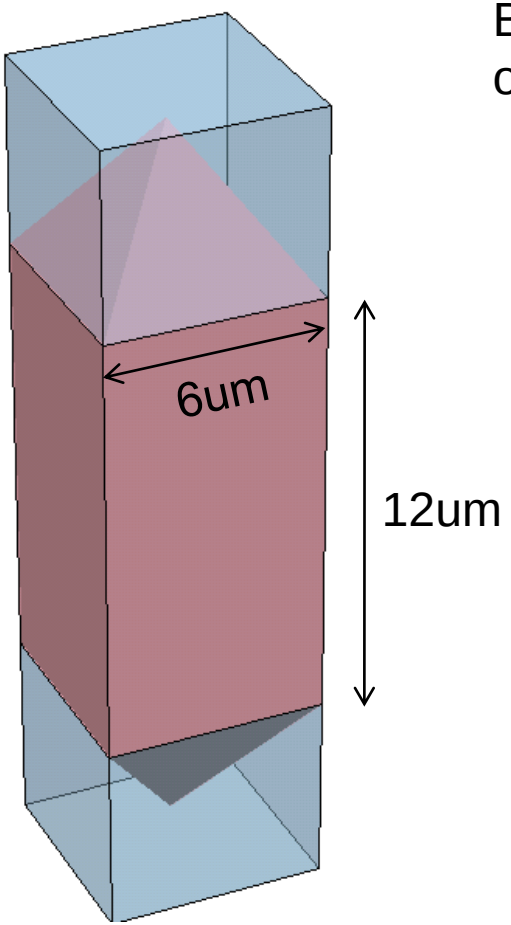
20um * 20um surface

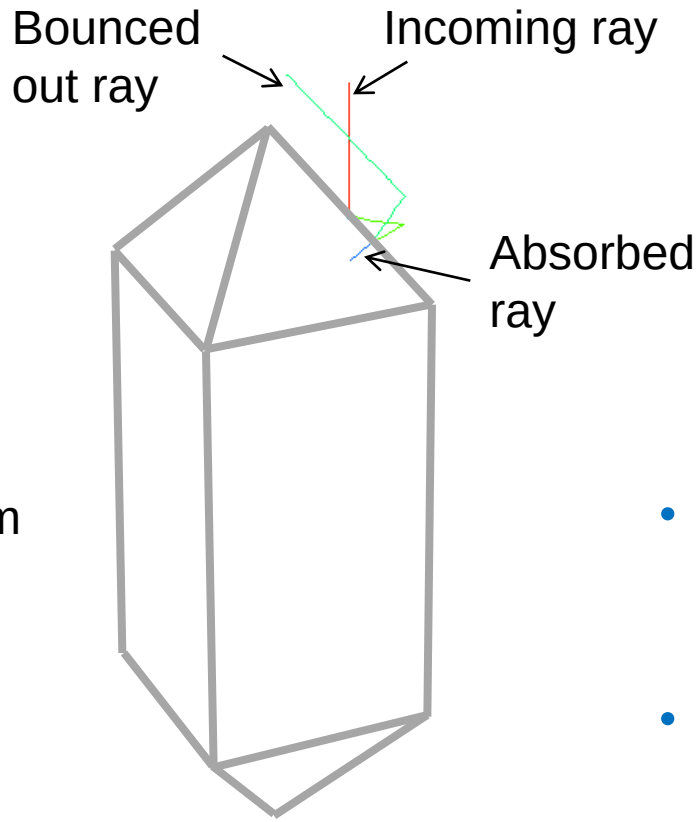
Zoom-in



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

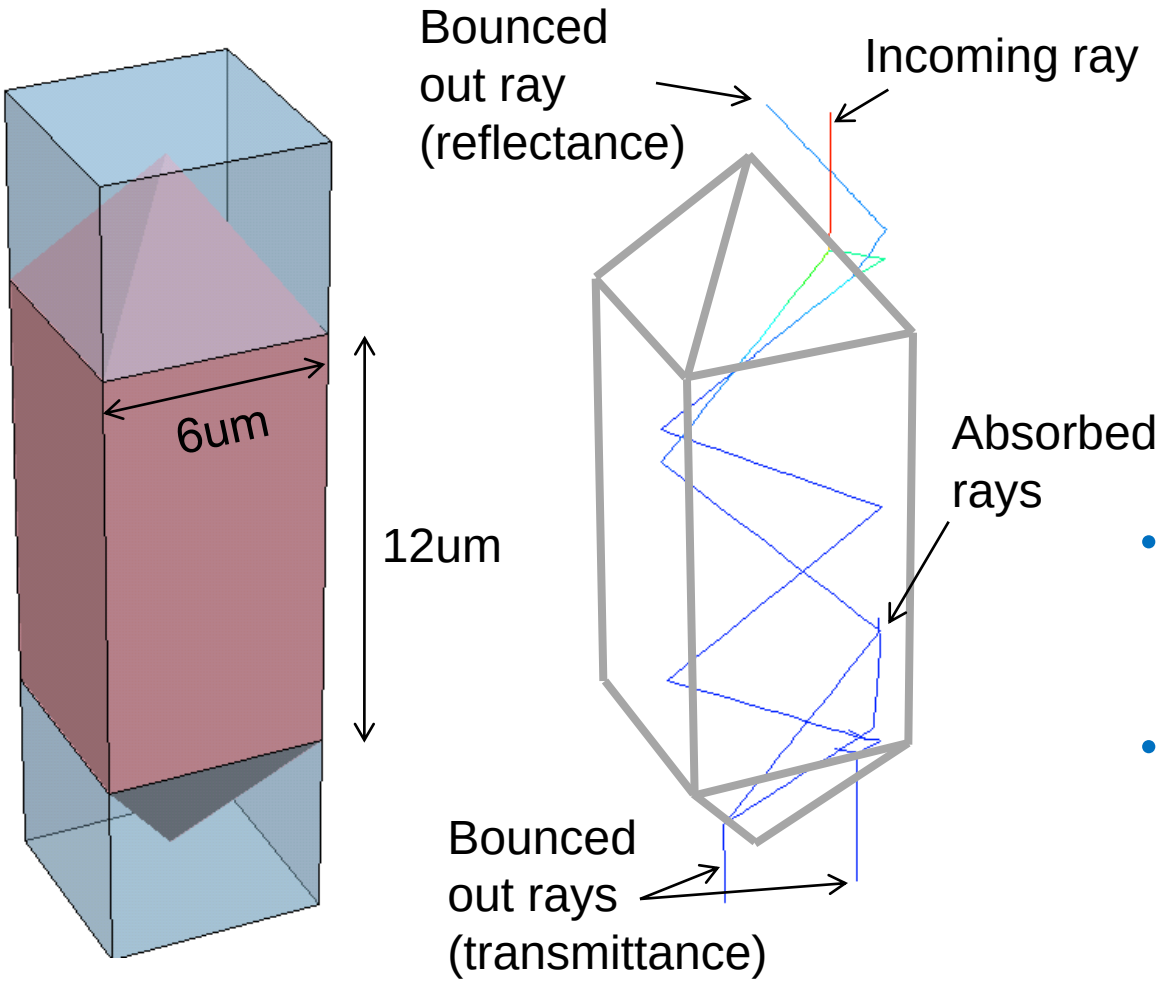
Behavior of UV light (0.3um Wavelength)





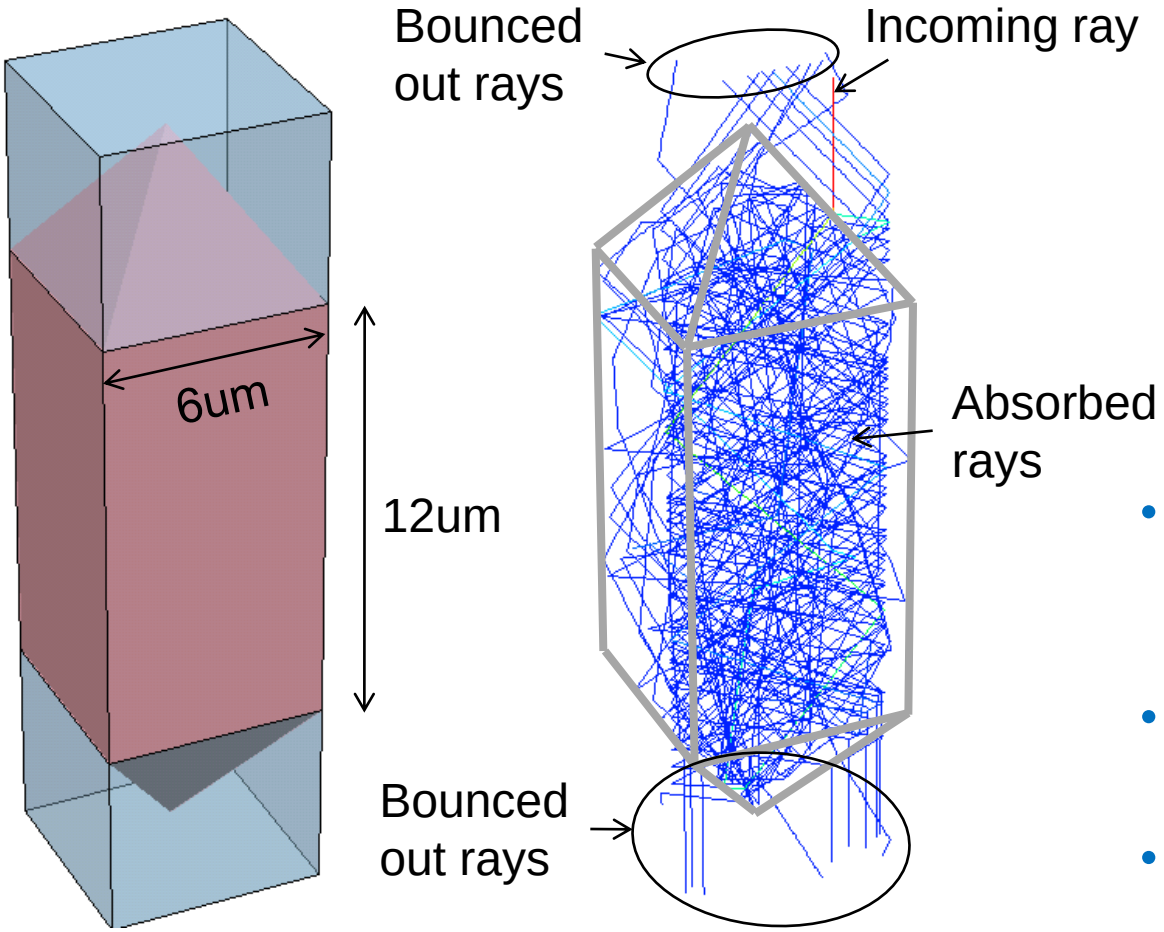
- Absorption in Si happens within one micron from surface
- Typically one or two reflection events
- Only top surface matters

Behavior of Visible Light (λ=0.6um)



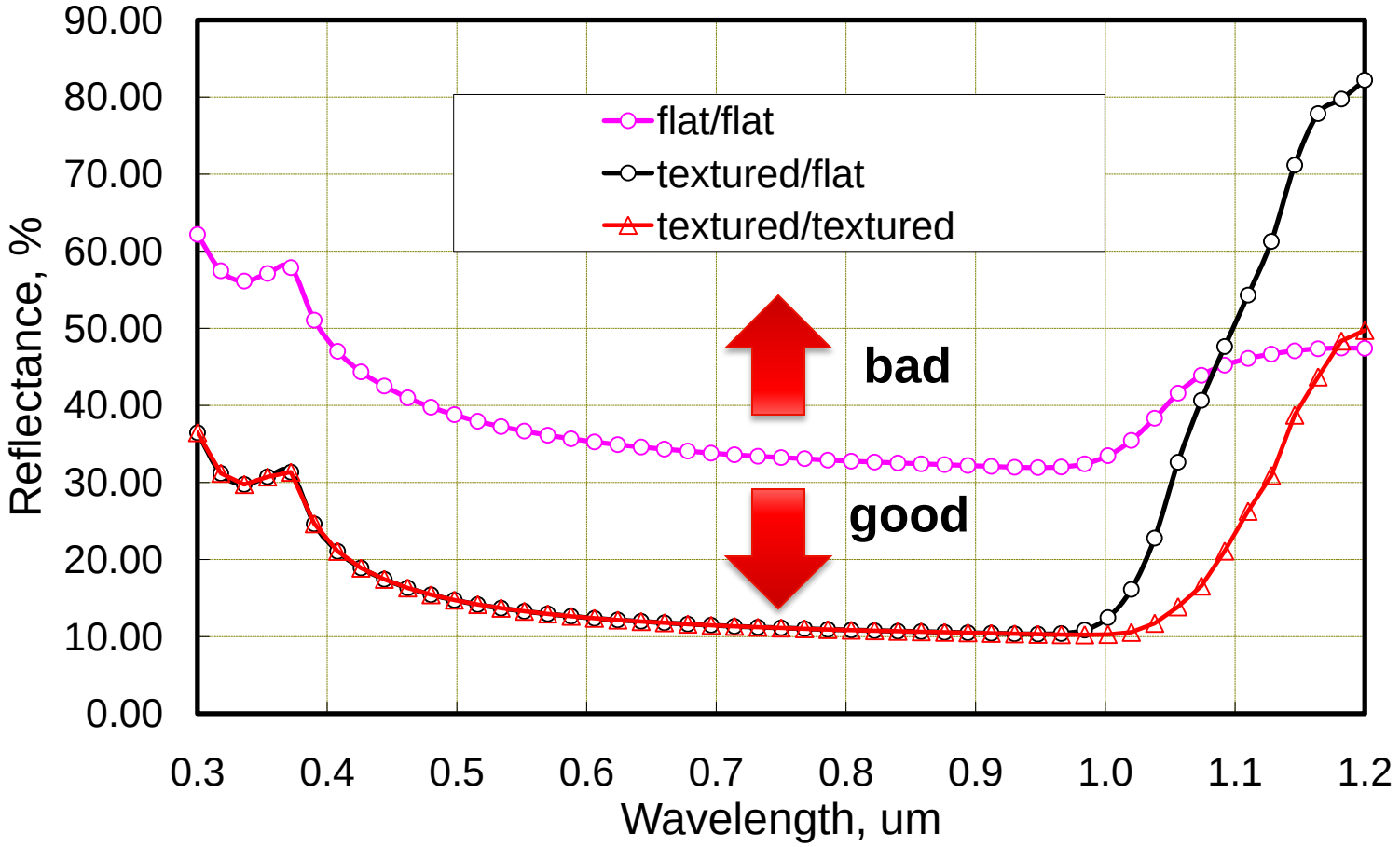
- Absorption in Si happens within tens of microns
- Several reflection events

Behavior of Infrared Light (λ=0.9um)



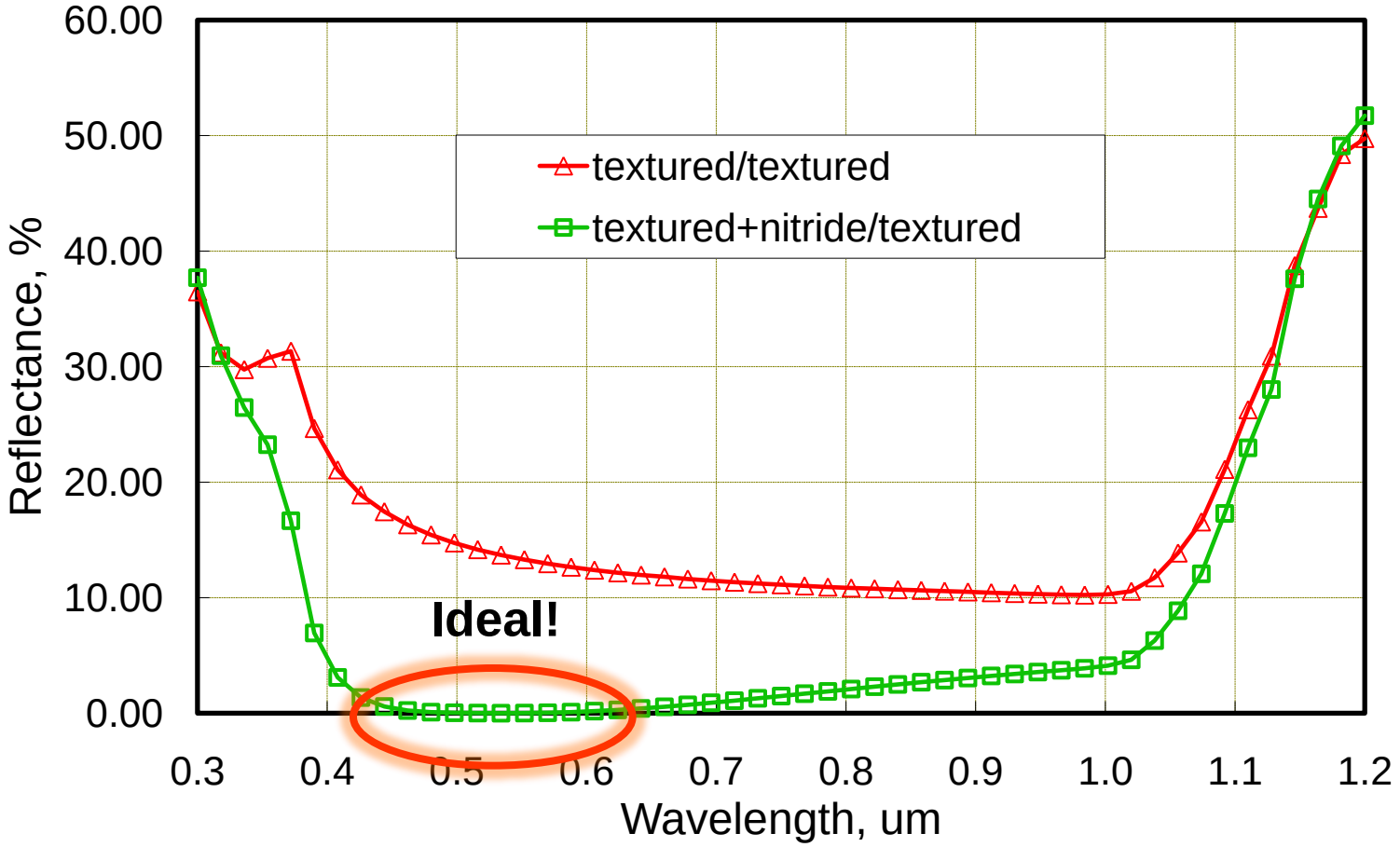
- Absorption in Si happens within hundreds of microns
- Dozens of reflection events
- Both the top and the rear surfaces matter

Reflectance Curves: Texture is Good



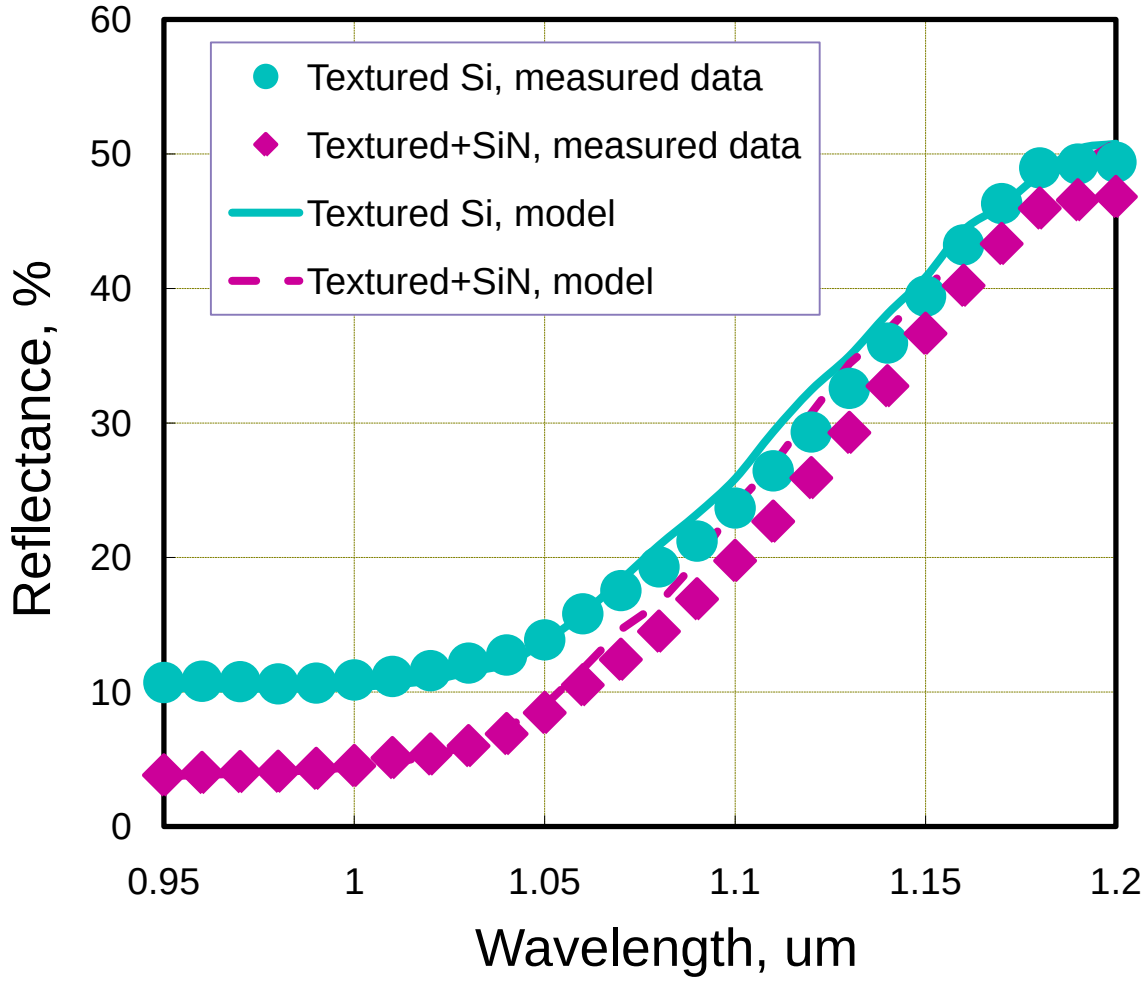
- **Texture reduces reflectance by 3x**

Reflectance Curves: Nitride is Good



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

Model Accuracy



- Calibrated model captures Si texture and nitride ARC film

Si data from AMAT

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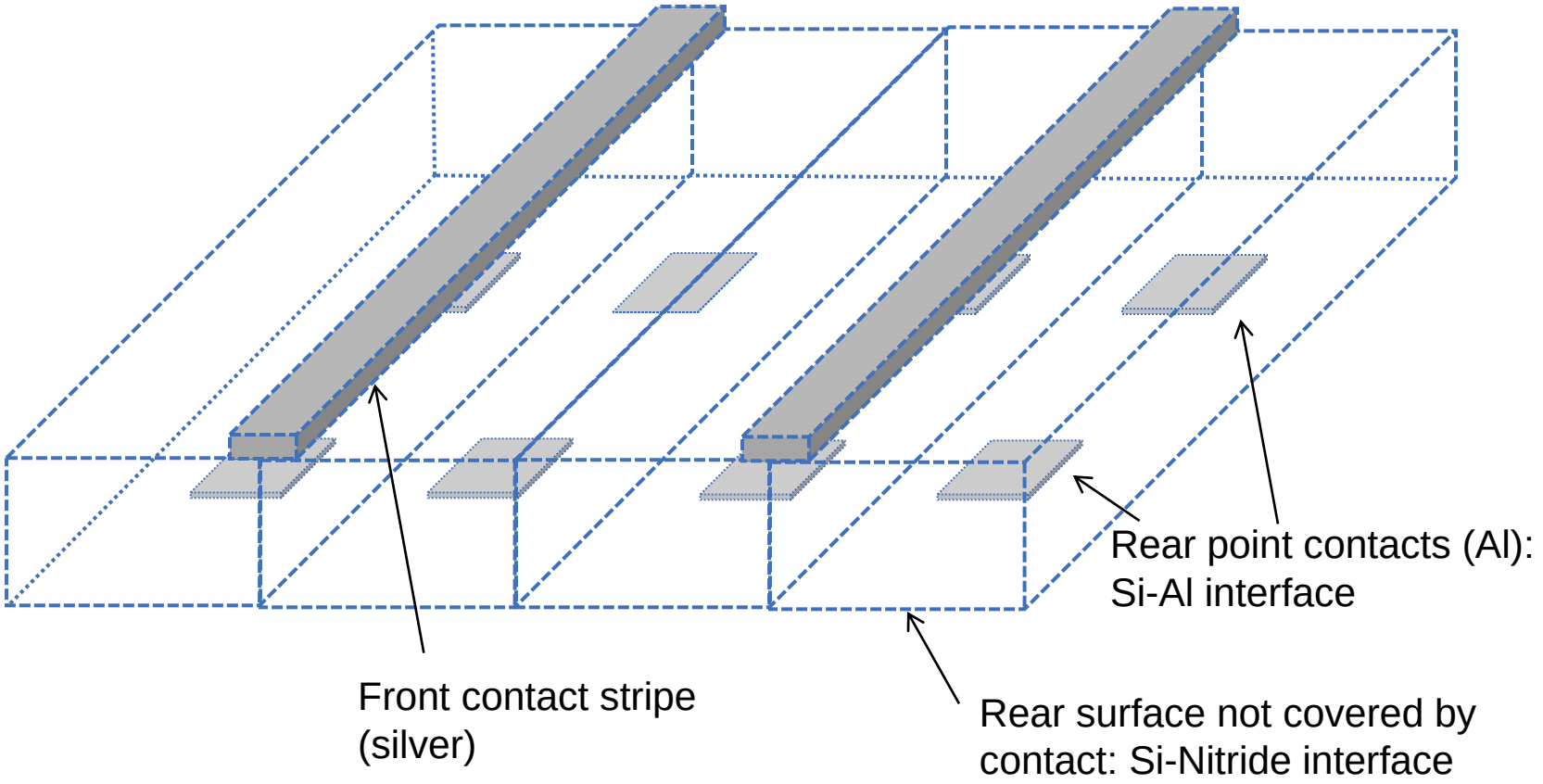
c-Si Solar Cell with Rear Point Contacts



Rear Point Contact Optimization

Doping
Silicon quality
Cell size
Contact pitch
…

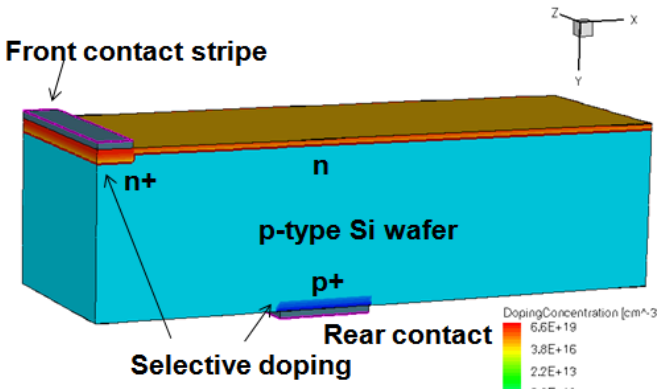
Increasing Rear Point Contact Area is GOOD!

Current Crowding
Contact Resistance
Bulk Recombination

Increasing Rear Point Contact Area is BAD!

Optical Reflectivity
Surface Recombination Rates

Rear Point Contact Design



Junction Optimization

Junction depth
…

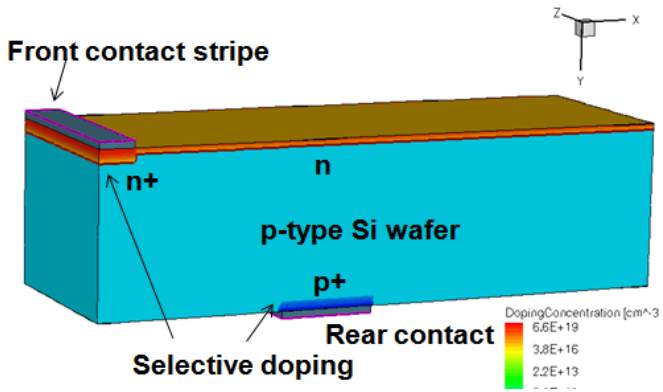
Higher doping in n layer is BAD!

Higher doping increases recombination

Higher doping in n layer is GOOD!

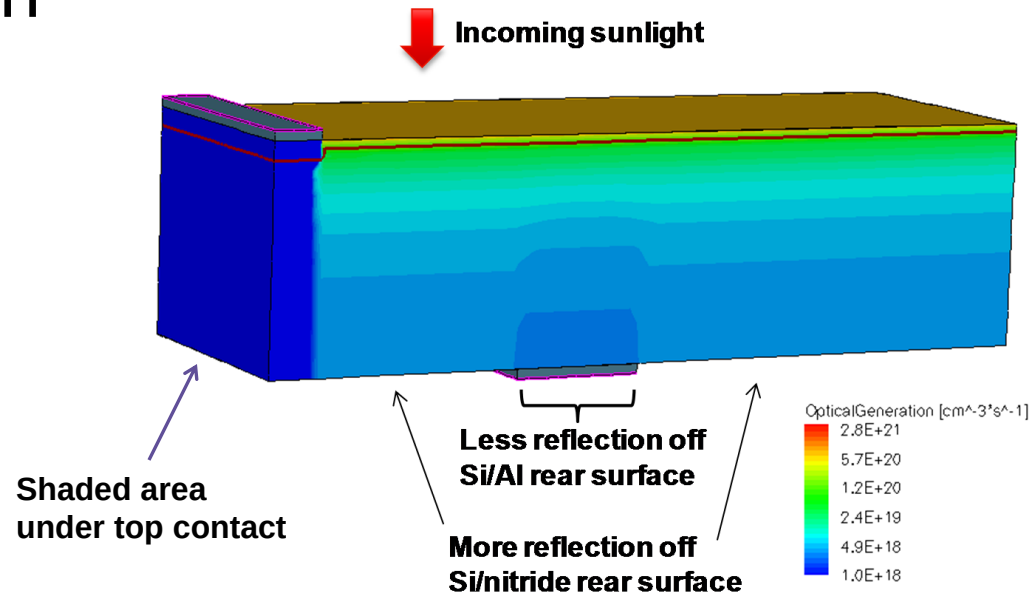
Higher doping increases conduction

Top Surface p-n Junction Design

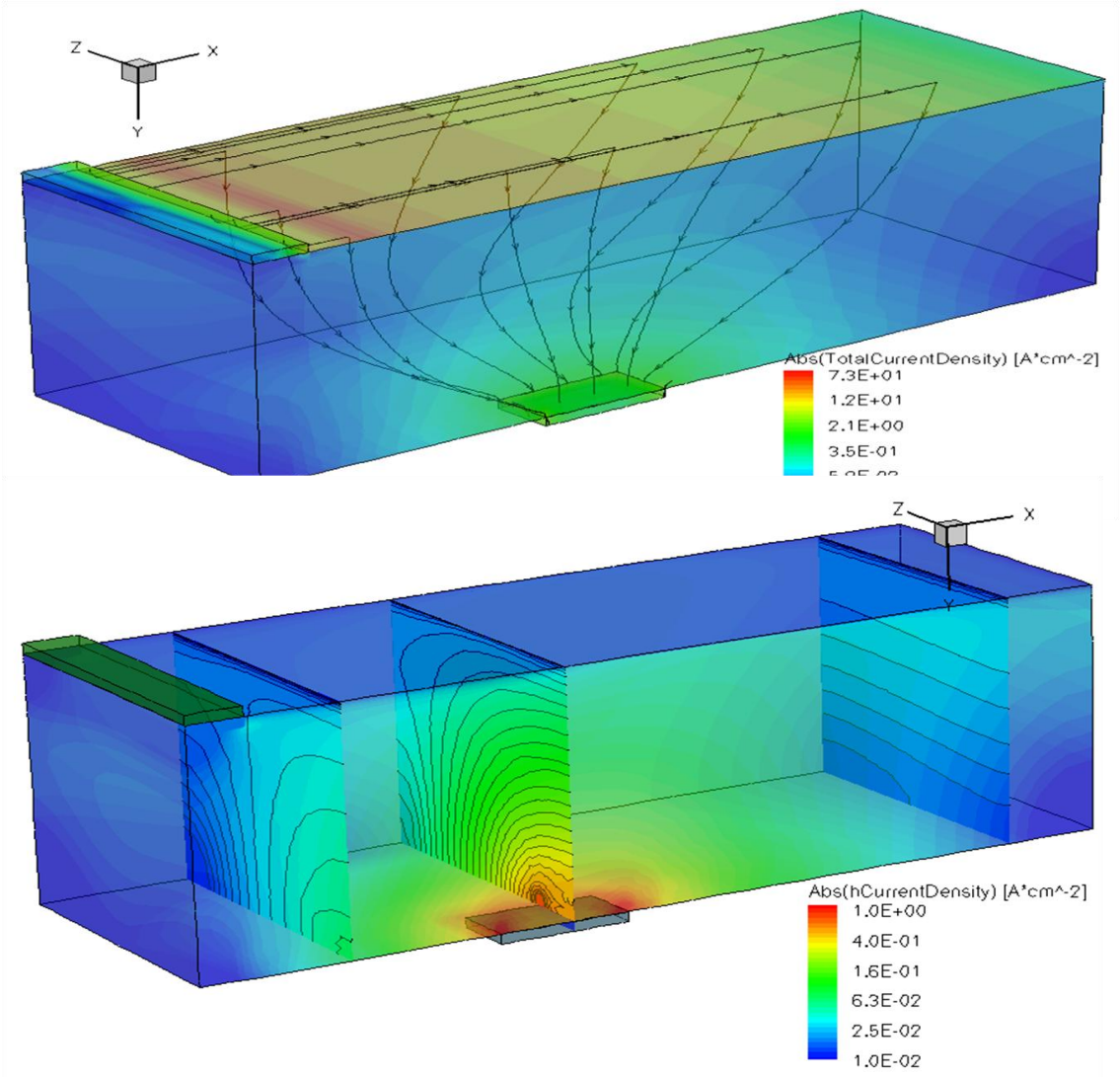


Modeling Major Effects

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

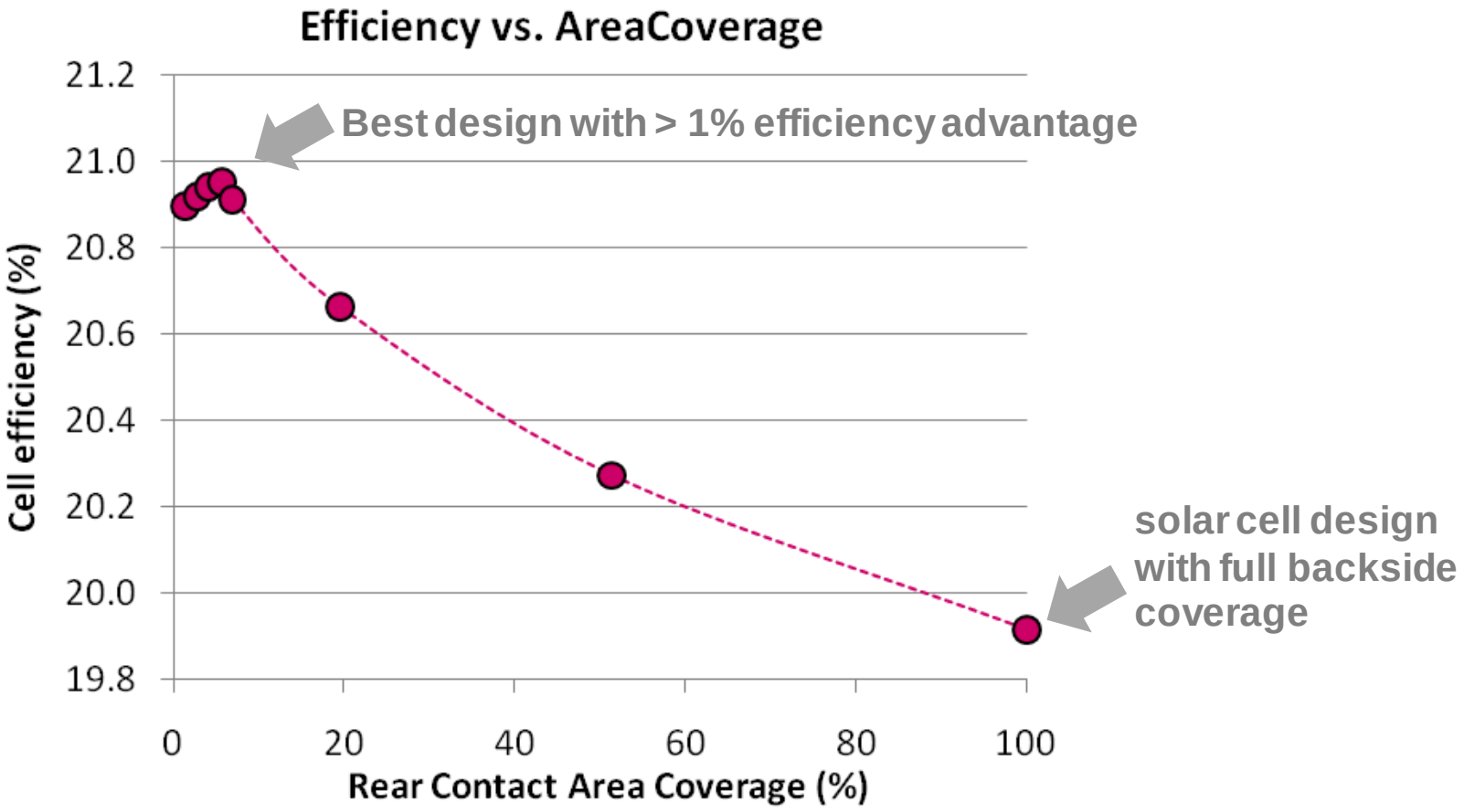


Current Crowding Pattern

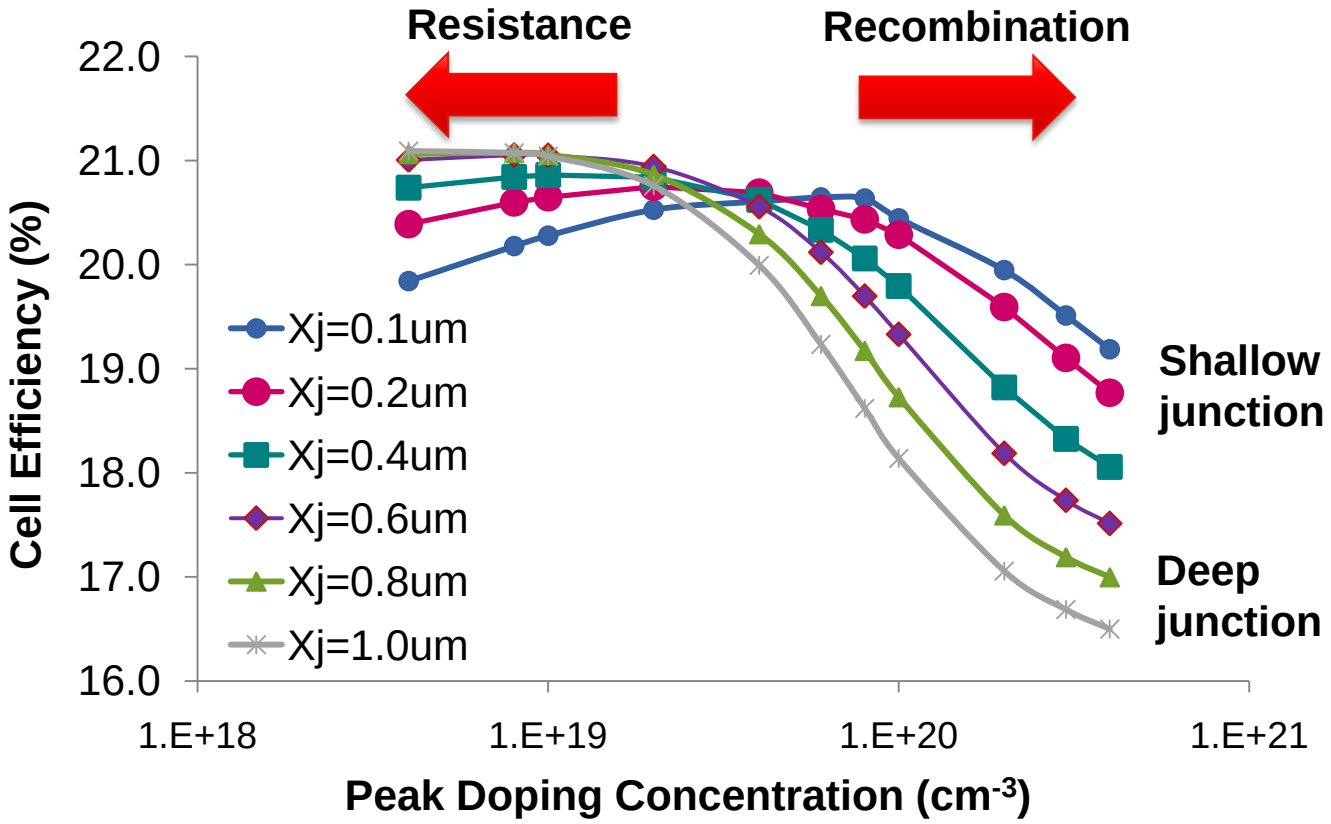


Current crowding is observed in both lateral directions, which makes it a 3D effect

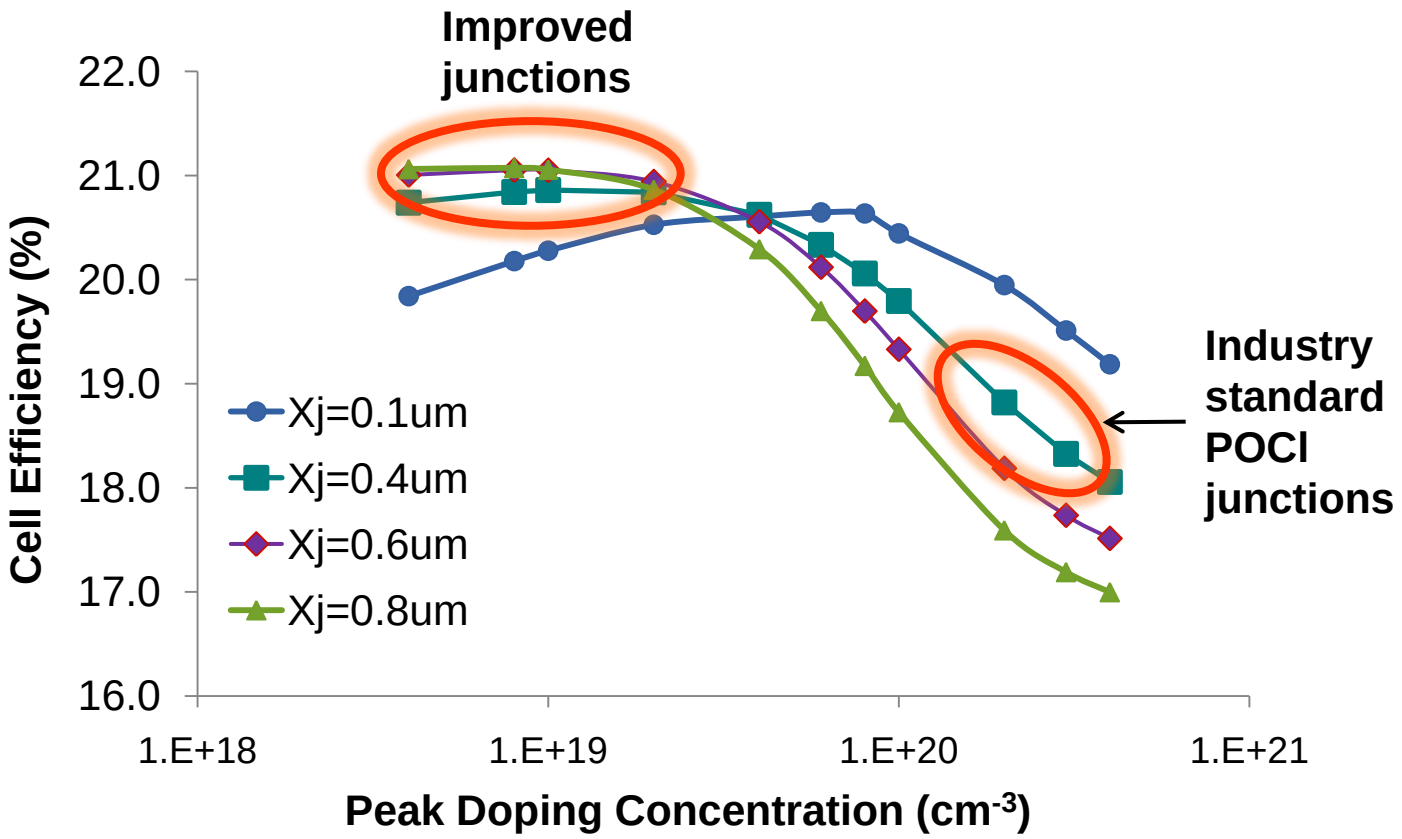
Rear Contact Optimization



Junction Optimization



Junction Optimization



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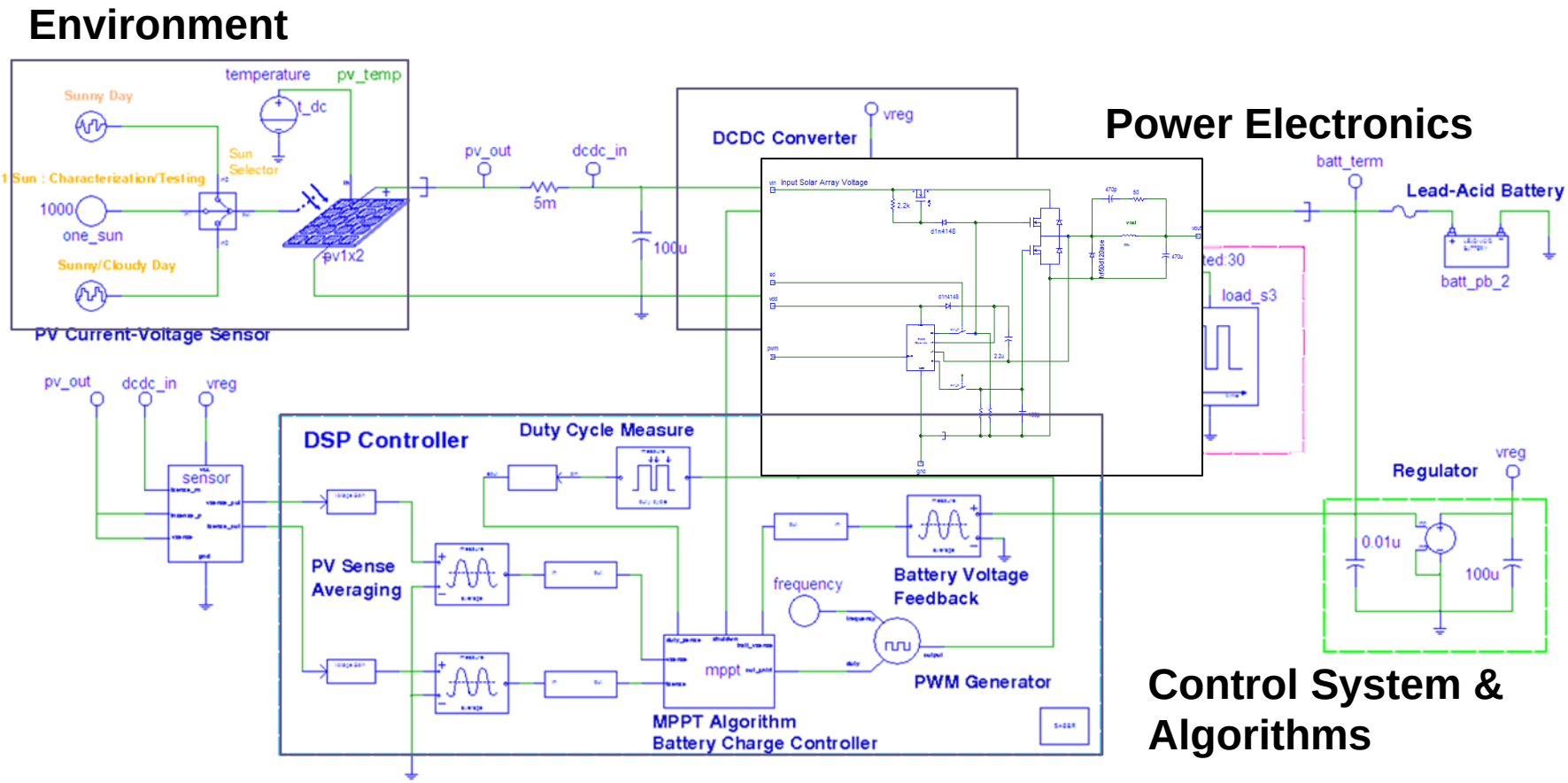
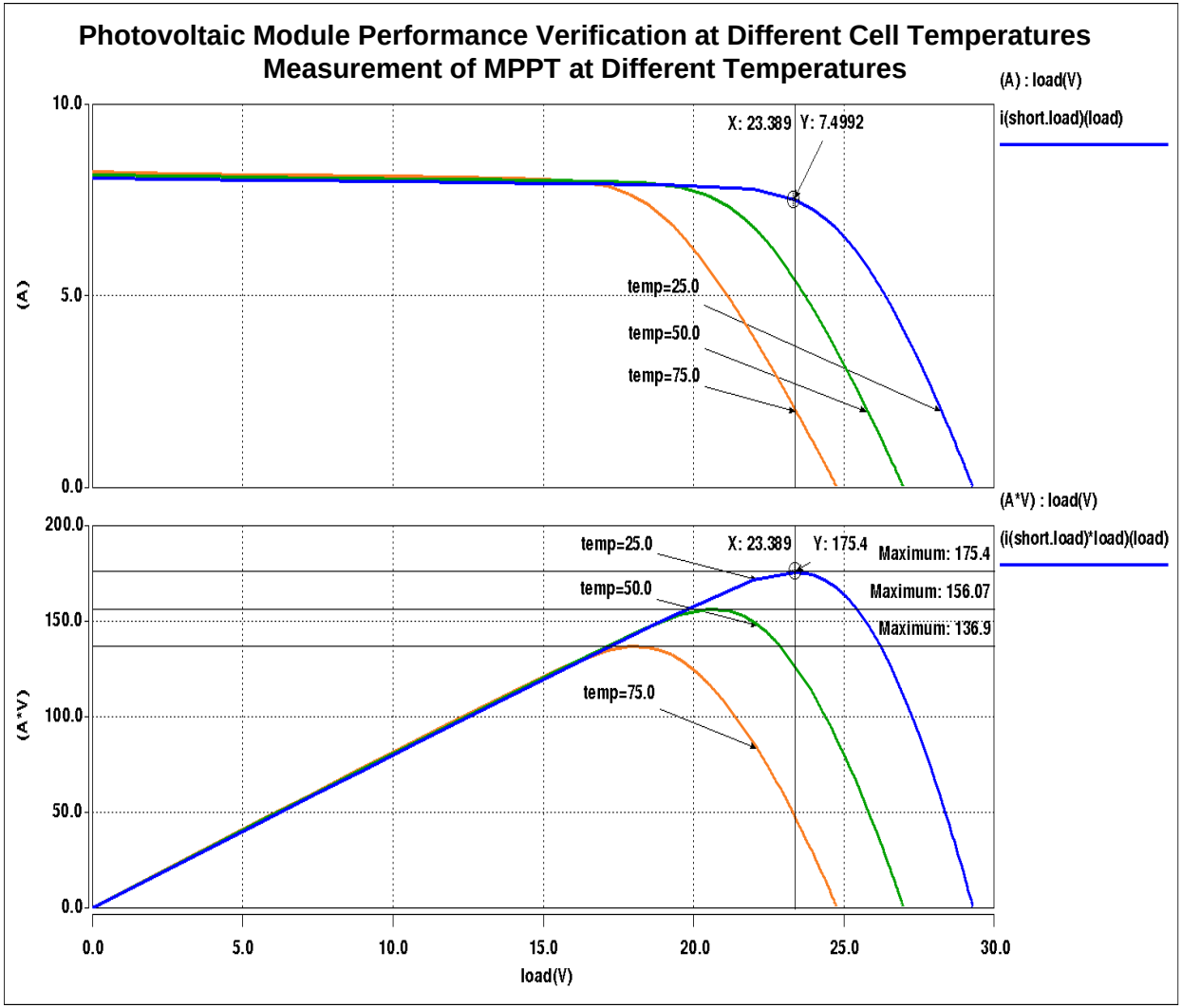
System Integration & Optimization

- Simulation provides integrated test, validation and optimization environment for all aspects of the system:



Modules to Arrays and Systems

- Design problem: Thermal Effects on Module/Array performance and Maximum Power Point
- Analysis of faults on strings within the array



Summary

- 3D cell simulation can optimize:
  - Light absorption
  - Rear point contact placement
  - Junction design
- Optimal contact & junction design can boost cell efficiency by more than 3%
- Early validation of novel cell design
- Development of application-optimized cells, modules and arrays
- System level virtual prototyping for test & validation before anything physical is built