The Role of Simulation in Photovoltaics: From Solar Cells To Arrays

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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**
- Maximize efficiency
- Optimize geometric and process parameters

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

**System**
- 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

*Synopsys TCAD tools ➔ Synopsys Saber tools*
What is TCAD?

**Process Simulation**
- LDMOS: doping, mesh
- 1D doping profile simulation
- PVD (Physical Vapor Deposition)
- Photogeneration in CIS
- Mechanical stress in intermetal dielectric

**Device Simulation**
- Current in Drift-Diffusion Model
  \[ J_n = -nq\mu_n \nabla \Phi_n \]
- Potential distribution in flash memory
- Inductance Simulation
- Snapback of a UMOS
- AlGaAs VCSEL
- Full Chip H-Bridge
- EM Wave
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 ~ 15-16%)
New generation cell (Eff ~ 20%)

Source: SERIS
Solar Cell Simulation Flow

**Input**
- Process Flow Recipe
- Device Geometry
- Optical Data: n & k

**Simulation**
- Process Simulation
- Optical Simulation
- Electrical Simulation

**Output**
- Device Geometry (doping profiles)
- External reflection
- Optical generation
- IQE, EQE
- Dark & Light I-V
Example: 2D Cell Optimization

- Select parameters to be investigated
- Parameterize the TCAD model
- Run simulations
- Visualize the influence of each parameter
Example: Unit Cell Optimization Results

- Each array of points represents a separate simulated condition.
- Unit cell pitch, base layer thickness, doping, and lifetime, and surface recombination velocity show major influence on cell response.
- Design trade-offs can be investigated quantitatively.
Application: Back-contact Silicon Cells

• Design problem: optimization of metal finger pitch to achieve good performance with low cost screen printing manufacturing

• Simulation correctly captures the measured behavior across a range of contact pitch and bulk resistivity

• Optimization of the structure results in 21.3% efficiency

Application: Multi-Junction Solar Cells

- GaAs/GaInP Dual-Junction Cell
- Excellent match between Sentaurus simulation and measurements in MJ cells
- Calibrated model allows researchers to explore more advanced structures: Bragg reflectors, additional junctions, etc

Cells to Systems: Why simulate?

- Cells alone are physically interesting;
- Modules and Systems bring the power of the sun to the end user
- Once cell behavior is understood, need model capable of system-level simulation to:
  - Minimize interconnect losses
  - Evaluate effects of environmental variation:
    - Light intensity and incidence angle
    - Temperature variation
    - Electrical environment
- Optimize power conversion
What is Saber?

Multi-domain circuit simulation… enabling full system “Virtual Prototyping”

Multiple Domains

Power Electronics

Behavioral Models

Optimizing System Performance and Reliability
Cells to Modules

- Design problem: active width optimization
- Given TCAD device design, physical parameters contributing to interconnect resistances can be extracted and a system-level model developed
Module Optimization

• From system cell level model, sweeps can be done to determine the effect of different cell widths on module performance

• Allows for optimization of Maximum Power Point at a module level as a function of luminance and cell width
Module Validation

- Accurate, physics-based models take TCAD results to system simulation for validating real-world measurements
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
System Integration & Optimization

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

Environment

Power Electronics

Control System & Algorithms
Battery Charging System Simulation

System highlights:

• Maximum Power Point Tracking through impedance matching using controlled DC/DC converter

• Dynamic thermal capable array model
Unit Cells to Systems Simulation

• 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
Predictable Success