Development of Large High-Voltage PV Modules with Improved Reliability and Lower Cost

NREL Contract **ZAX-6-33628-11**

John Wohlgemuth – April, 2007

OUTLINE OF TALK

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- **Overall Program Objectives**
- **Program Tasks**
- **Technical Approach**
- **Summary of Activities (first year)**
- **Budget History**
- **Accomplishments**
- **Schedule and Future Direction**

OVERALL PROGRAM OBJECTIVES

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- Ultra-thin 16% efficient cast Si solar cells
- Large area module > 250 watts at STC
- Module designed for:
  - Operation at up to 1500 volts
  - Warranty of at least 30 years
  - Elimination of toxic and hazardous materials
- Achieve 30% reduction in manufacturing cost through the module level.

PROGRAM TASKS

- CASTING
- YIELD IMPROVEMENTS
- HIGH EFFICIENCY CELL DEVELOPMENT
- MODULE DEVELOPMENT
- HIGH VOLTAGE SYSTEMS INTEGRATION

Technical Approach
CASTING PROGRAM PLAN

- **Thermal modeling (UMBC & in-house)**
- **Materials Characterization**
  - **NCSU**
  - **SUNY – Stony Brook**
- **Crystal Growth**
  - **Improved material quality – Mono²™**
  - **Faster growth rates**
- **Goal of increasing minority carrier lifetime by 5% in Yr 1, 15% in Yr 2 and 25% in Yr 3.**
- **Eliminate material variability – reduce low efficiency cells from 4% to 1%.**

Technical Approach
YIELD IMPROVEMENTS

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- **Study wafer fracture strength and formation of micro-cracks**
- **Perform a statistical analysis of the breakage and correlate with previous process steps**
- **Survey methods for preventing wafer breakage**
- **Develop a technique to observe micro-cracks**
- **Establish methods of simulating conditions that cause breakage.**
- **Evaluate (non breakage) yield loss mechanisms and select several candidates to work on improving.**
- **Result in modifications to the production processes and/or equipment to achieve a 5% increase in mechanical yield of wafers and cells.**

Technical Approach
HIGH EFFICIENCY CELL DEVELOPMENT

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- **Use modeling to provide guidelines and a roadmap for further technology development.**
- **Model the sensitivity of key thin cell design parameters**
- **Optimize the design of advanced cell features (BSF, BSR)**
- **Prepare a roadmap for increasing cell and module efficiency.**
- **Eliminate heavy metals from the screen-print pastes**
- **Goal is to develop a process for large area (> 246 cm^2), high efficiency ($\geq$ 16%) with a cell line yield > 95%.**

Technical Approach
MODULE DEVELOPMENT

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- Evaluate the performance of modules in high-voltage systems to improve performance.
- Develop High Voltage
  - Plastic Frames
  - Connectors
  - Encapsulant
  - Termination Pottants and Adhesives
  - Back Sheet
- Evaluate fault-tolerant processes for attaching interconnects to each cell.
- Develop new approaches to increasing module efficiency, increasing productivity and reducing cost.
- Goal to develop a PV module that is rated and qualified for operation at 1500 volts and will carry a 30 year warranty.

Technical Approach
High-Voltage Systems Integration

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- **Establish a high voltage test bed for PV modules and BOS components.**
- **Test modules at > 1000 volts and identify failure mechanisms.**
- **Review requirements of standards and codes as they relate to PV systems voltage.**
- **Evaluate approaches to protecting high voltage PV systems.**
- **This task is expected to result in recommended safe practices for high-voltage PV systems**

Activities -CASTING

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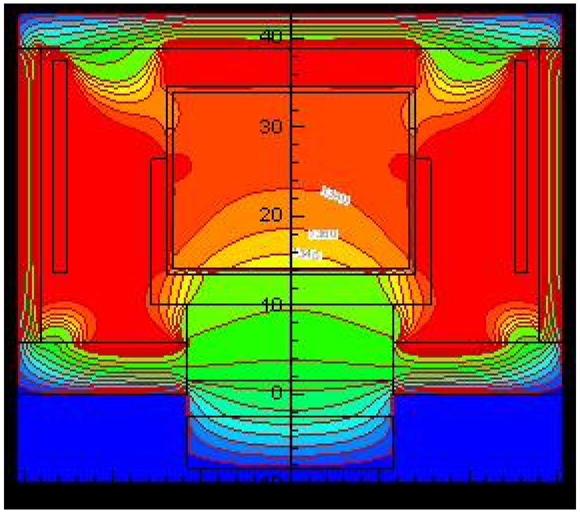
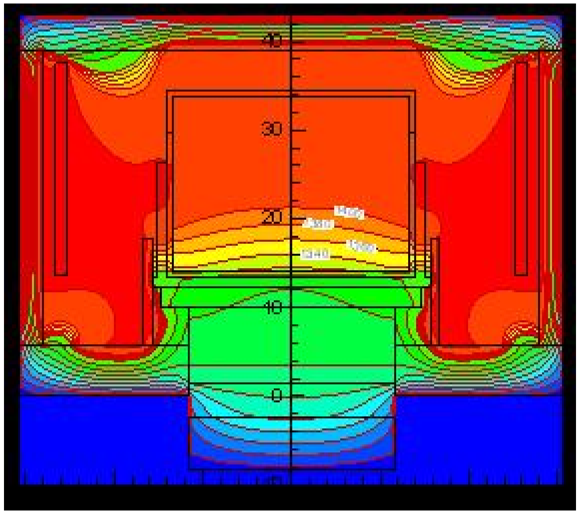
- Modeling (In-house and at UMBC): Fully functional
  - Providing improved understanding of the process
  - Guiding equipment redesign
  - Support for reducing process time
- Process Development
  - Mono²™ - Mono performance at multi cost
  - Process control and reproducibility
  - Reduced process time with equivalent or better performance
- Equipment development
  - Implementation of Mono²™

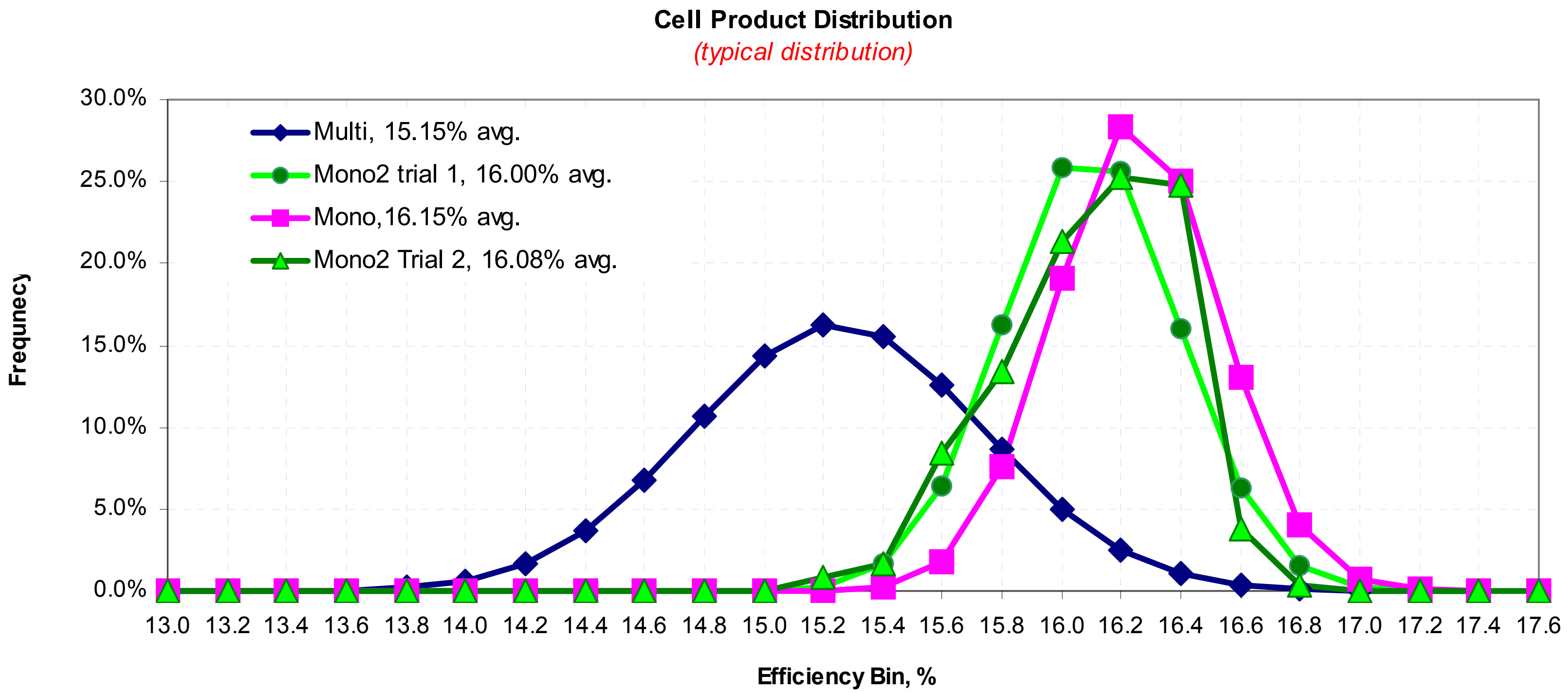
Modeling of Casting Process

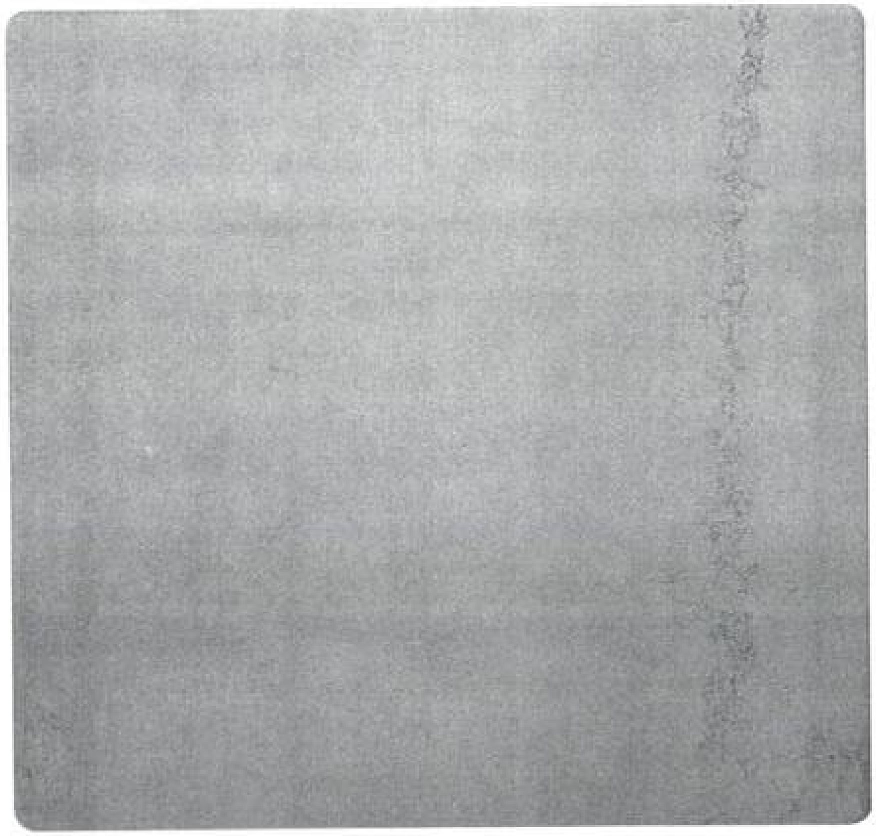
- Modeling indicates that in present configuration isotherms are quite rounded.
- Thermal gradients stress the Si.
- The corners solidify and cool much slower than the center extending the growth process.
- Modeling guided change to station insulation geometry to flatted the isotherms.
- Simulation suggests that curvature of the growth interface can be decreased allowing for a faster growth cycle.
- Process implemented with following benefits
  - 14% reduction in casting run time.
  - 18% reduction in energy consumption in casting process.
  - 15% reduction in sizing cycle time.
  - Increase in average ingot lifetime
  - 50% reduction in defects from station





Mono^2 ™ Cell Distribution





Preferential etching delineating dislocations and grain boundaries. Left: standard multicrystalline wafer. Right: Mono^2 wafer (thin line of defects on the right side). Even bad wafers have ~10x fewer dislocations than multi.

Activities - Yield Improvements

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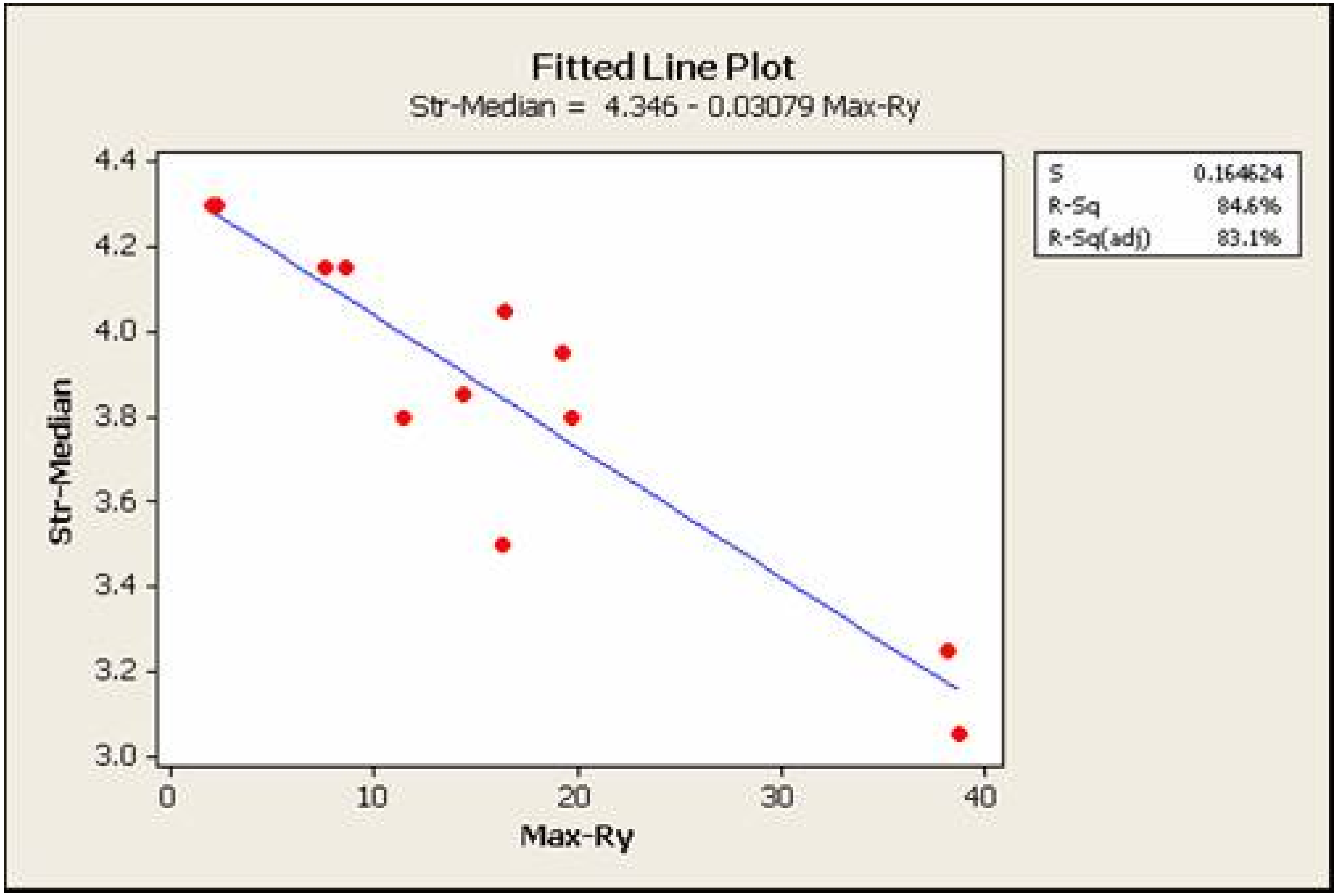
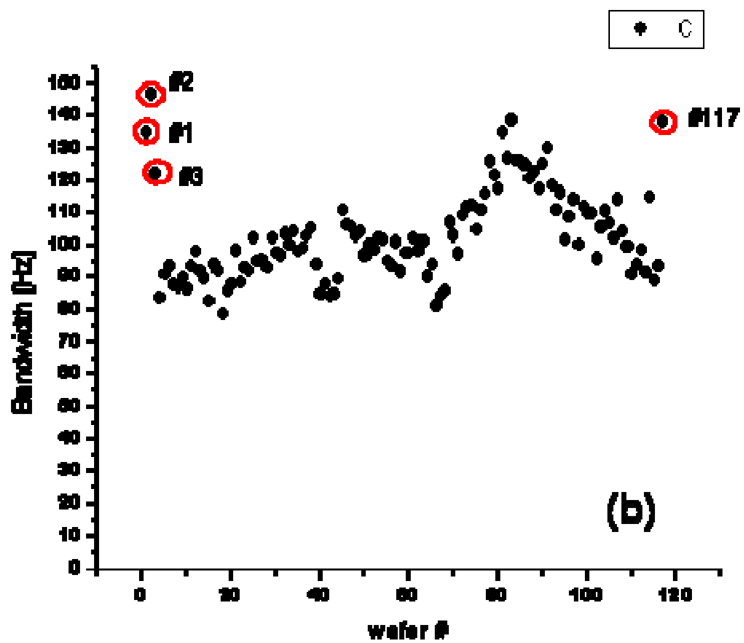
- **Proved performance of ATI equipment for cassetting wet wafers after demounting from wire saw.**
- **Switched production from 225 micron wafers to 200 micron wafers.**
- **Ran 175 micron wafers in production line and demonstrated reasonable yields but result are sensitive to equipment and process. Need modifications before 175 microns can become the standard.**
- **Demonstrated that the surface roughness of the brick has an impact on subsequent mechanical yield.**
- **Evaluated USF RUV equipment for its ability to detect cracks and micro-cracks.**

Plot of median wafer strength versus maximum distance between the deepest groove and the highest ridge of a brick face



USF RUV Equipment

- **Equipment uses ultrasonic vibrations to detect wafers with micro-cracks**
- **We monitored amplitude, peak position and bandwidth of detected resonance.**
- **Bandwidth change was best for evaluation.**
- **See figure for bandwidth for 120 wafers.**
- **Wafers circled were broken and equipment detected them.**
- **However, samples from 80 to 100 with different grain structure had similar signal bandwidth to those with cracks. These wafers were not cracked.**
- **Conclusion: System could be used to identify cracked wafers, but required human intervention to correctly use the results.**



Activities - High Efficiency Cell Development

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- **Modeling**
  - **Determined material and cell parameters for baseline model of today's cells.**
  - **Performed a sensitivity analysis to determine how changing the material and device parameters will impact performance.**
- **Process Development**
  - **Iso-Chemical Texturing (ICT) - experimental**
  - **Selective Emitter - experimental**
  - **Edge Isolation via back etch - experimental**
  - **Low bow Al pastes for thinner cells –qualified and implementing**
  - **Lead free pastes – qualified but still loss in efficiency**
- **Production Implementation**
  - **Hot melt**
  - **200 micron thick cells**

Cell Modeling – How to achieve 16% with 100 micron thick cells

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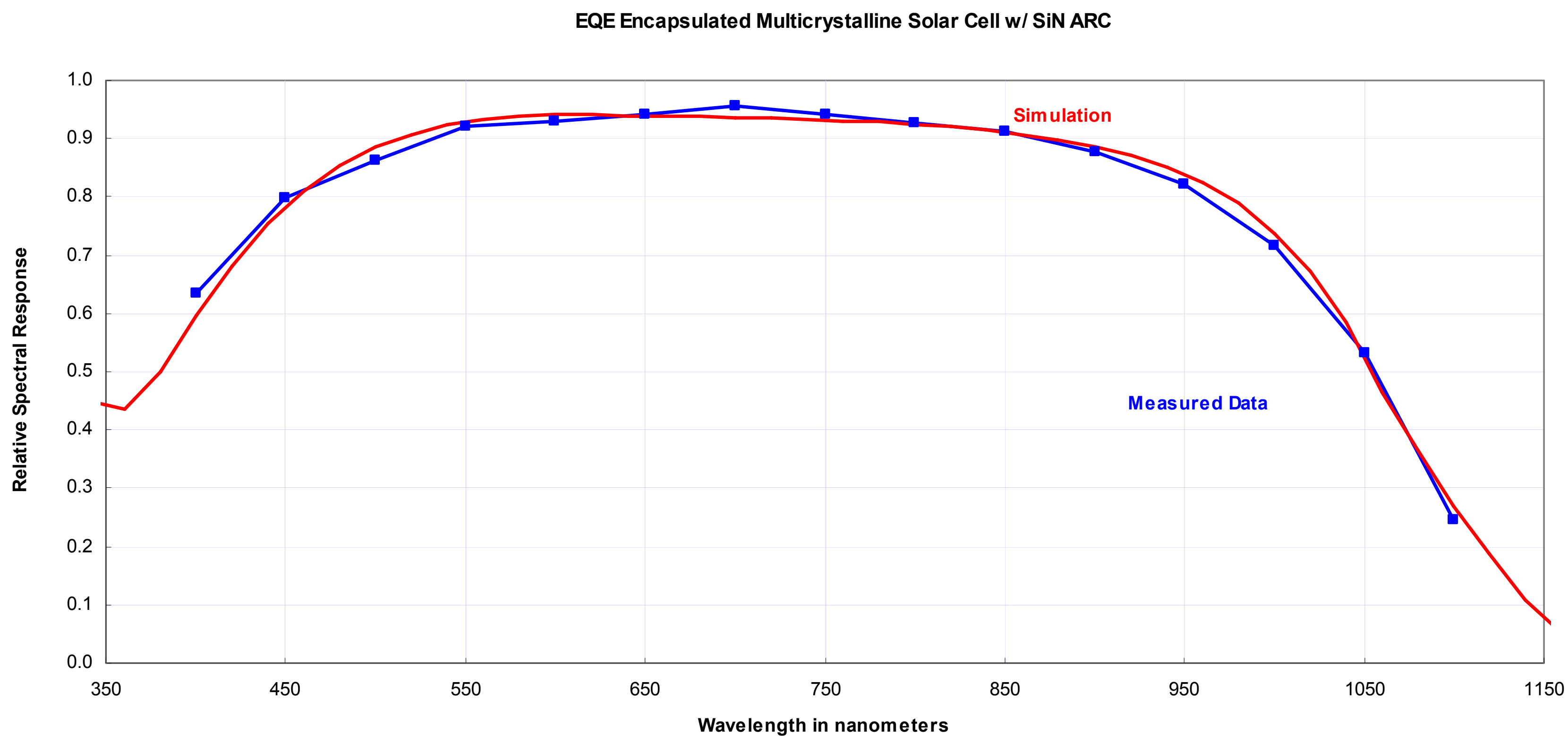
Improvement required - for 100 micron multicrystalline cells - as per simulation

PC1D input values	Base Cell 250 micron	Modeled Cell 100 micron	Remarks
Metal coverage factor	8.20%	8.20%	No improvement considered
Reflectance	Measured Reflectance data	Measured Reflectance data	No improvement considered
Cell thickness	250µ	100µ	
Within band absoprtion	Free carrier absorption	Free carrier absorption	
Int. optical reflectance	75/92 Front and 75/80 rear	90/95 Front and 90/95 rear	; **20% improvement considered for Internal Reflection**
Lifetime	28µS	100µS	**; ~ 3 to 4 fold carrier life time improvement considered**
Bulk Resistivity/doping	0.99 ohm (1.513 x 10^{16} cm^3)	0.99 ohm (1.513 x 10^{16} cm^3)	No improvement considered
Front Doping	Measured _SIMS data	Measured _SIMS data	No improvement considered
J_{01} & J_{02}	1.1e-10A J01 & 5.62e-6A J02	1.1e-10A J01 & 5.62e-6A J03	No improvement considered
AL BSF	5e18 conc. and 10µ depth, uniform	5e18 conc. and 10µ depth, uniform	No improvement considered
FSRV	100000cm/sec	10000cm/sec	**; One order magnitude improvement considered**
BSRV	800cm/sec	500cm/sec	**; 37.5% improvement considered for Internal Reflection**
Shunt	20 Ohm	20 Ohm	No improvement considered
Resistive series	2.5 & 11 mOhm front & rear	2.5 & 11 mOhm front & rear	No improvement considered

Results

Voc	**0.6103**	**0.629**	**; 3% improvement achievable**
Isc	**5.188**	**5.300**	**; 2% improvement achievable**
Pmax	**2.291**	**2.429**	**; 6% improvement achievable**
Eff	**14.66%**	**15.55%**	**; 6% improvement achievable**

Spectral Response Match

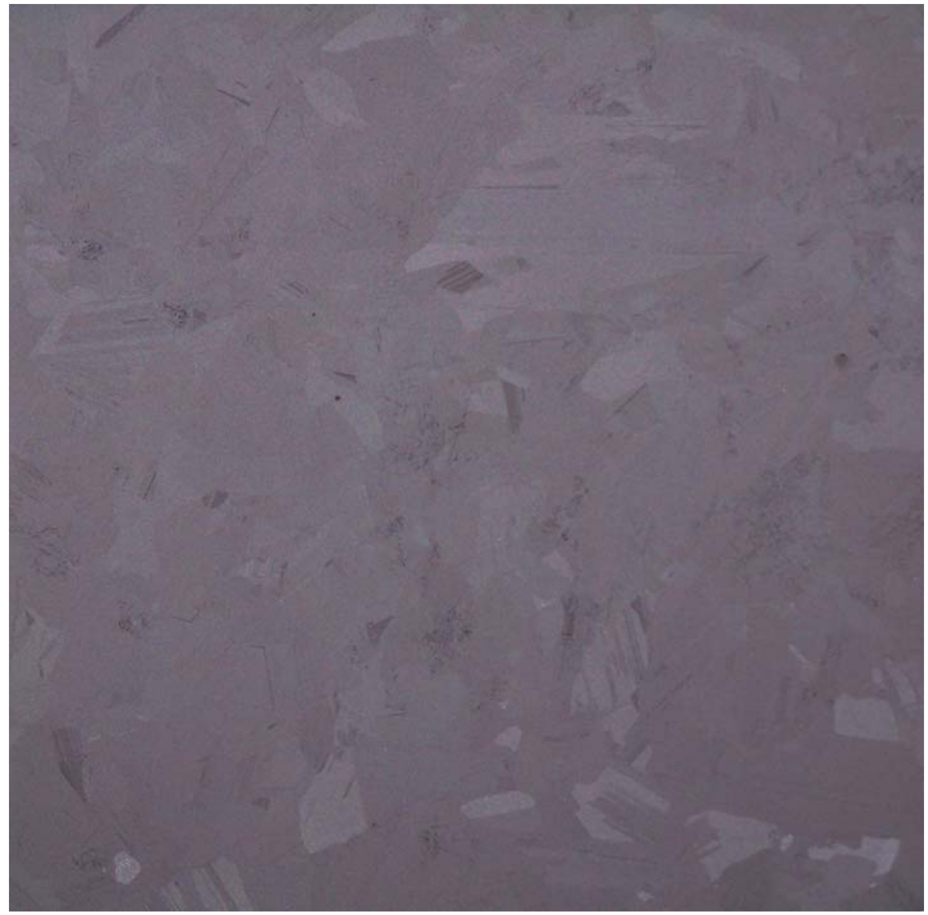


ICT Trial

- **Trial of 2000 matched wafers through production line. 1000 NaOH & 1000 ICT**
- **Thicknesses:**
  - **As cut 195 to 200 microns**
  - **NaOH 175 to 180 microns**
  - **ICT 185 to 190 microns**
- **Yields**
  - **NaOH 98.54%**
  - **ICT 98.99%**

NaOH Planar vs. ICT Surface

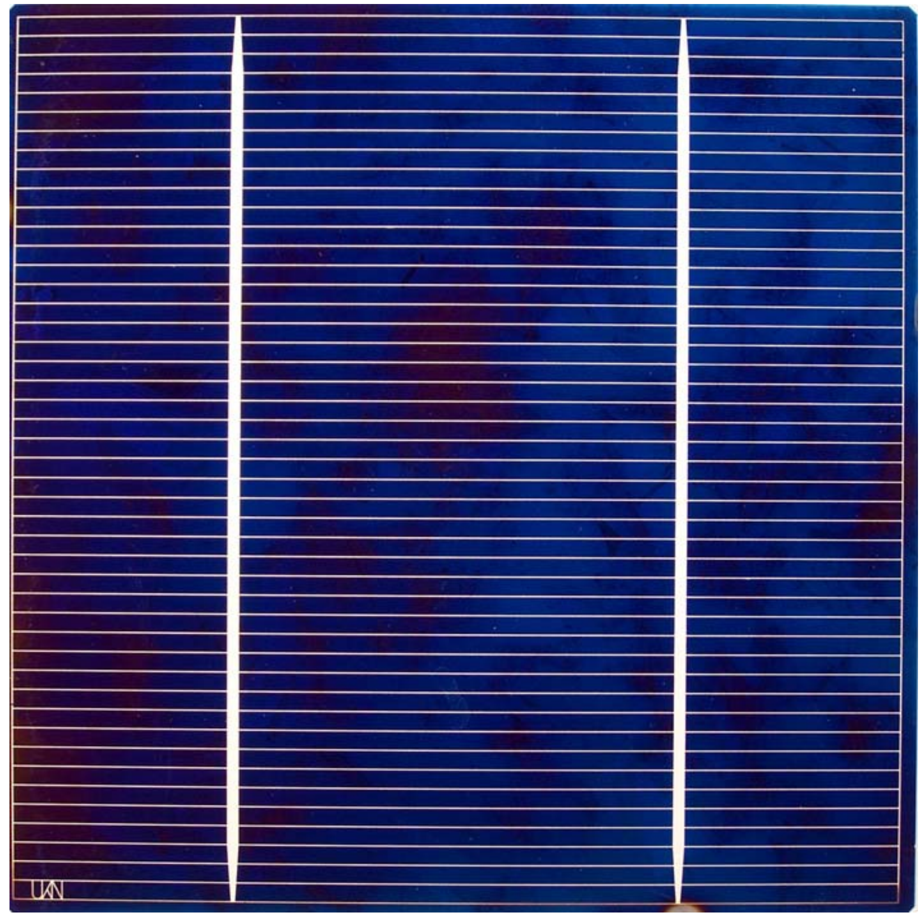
Standard NaOH Etched Surface



IsoChemical Texturing

Finished Cell – *Planar vs. ICT Surface*

Standard NaOH Etched Surface



IsoChemically Textured

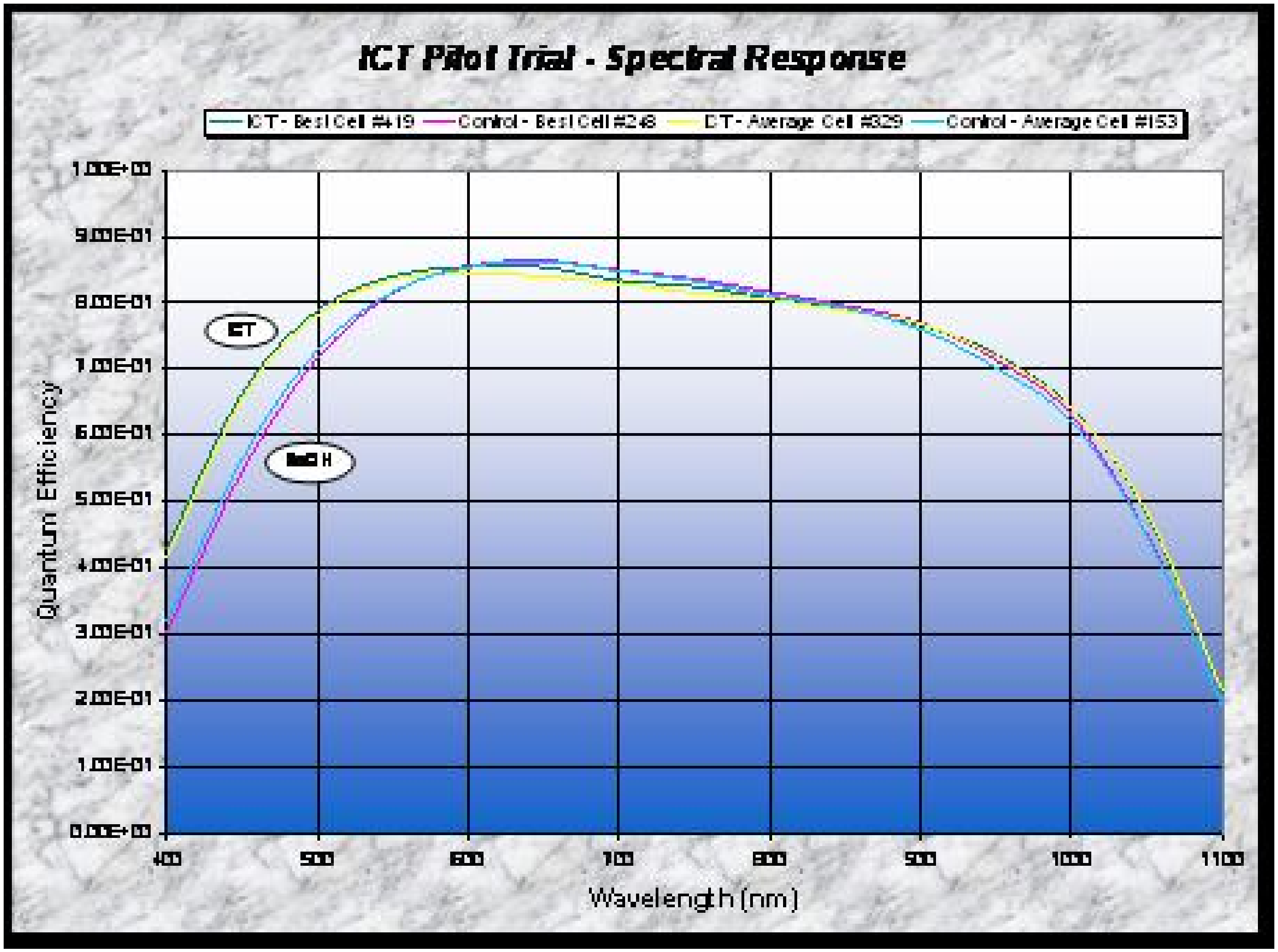
Results of ICT Trial

- **Cells from ICT had 2.3% higher power driven by higher current, but limited by lower voltage and fill factor.**
- **Spectral response shows current gain is in short wavelengths.**
- **Measurements on 7 modules of each type on simulator indicated no power increase.**
- **However, module measurement all made using NaOH reference module.**
- **Outdoor measurements yielded**
  - **+1.1% in power**
  - **+2.8% in Isc**

Cells	Pmax (W)	Isc (A)	Voc (mV)	FF (%)
NaOH	2.38	5.056	607.2	77.1
ICT	2.44	5.232	605.6	76.4
Delta (%)	+2.3	+3.5	-0.3	-0.9

Mods	Pmax (W)	Isc (A)	Voc (V)	FF (%)
NaOH	173.86	5.35	43.88	74.1
ICT	173.86	5.44	43.75	73.0
Delta (%)	0	+1.7	-0.3	-1.4

Spectral response of ICT versus NaOH



Activities - Module Development

- Designed of new 60 cell (15.6 cm by 15.6 cm) modules
- Molded polymer frame development and test
- AR Coated Glass
  - Demonstrated 2.4% power gain at STC and 4% energy gain
  - Qualified an additional vendor.
- Diodes and Cabling – To improve reliability
- Developing advanced cell interconnection with standard and back contact cells.

Polymer Frame

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- **Eliminate conductive frame for high voltage systems.**
- **Flexibility in design**
- **Design frame to serve as integral part of the mounting system.**
- **Minimize time on the roof.**
- **Look to design products for specific applications.**

Polymer frame module on concrete tile roof

Activities - High voltage systems integration

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- **FSEC has developed safety procedures for and is building a High Voltage Test Bed**
- **Studying issues of safety in high voltage PV systems**
  - **In higher voltage systems, ground faults are likely to occur more frequently and to lead to more severe consequences. Therefore use of non-conductive framing and support structures is recommended.**
  - **Any open circuit in a high voltage DC system can lead to an arc. Therefore need to minimize open circuits throughout the system, including at end of life and minimize possible consequences of arcing by using less flammable materials in contact with current carrying components.**
  - **Higher voltages can drive electro-corrosion of components that would normally be stable at lower voltages. Once again the use of non-conductive framing and support structures is recommended along with testing of components, particularly modules under humid conditions with applied "systems" voltage.**

Budget and Spending for 11 months

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Tasks	Budget ($ x 1000)	Actual ($ x 1000)
1 – Casting	238	203
2 – Yields	121	213
3 – Cells	622	492
4- Modules	229	303
5- HV Systems	202	18
6 – Project Management	38	43
TOTAL	1,450	1,272

Accomplishments

- Developed and demonstrated Mono²™
- Developed method to reduce casting cycle time while improving material quality.
- Found correlation between brick roughness and mechanical yield.
- Implemented Hot Melt Front metallization in production
- Performed pilot demonstration of ICT.
- Transferred production to 200 micron thick cells.
- Qualified second vendor of AR coated glass.
- Developed design and process to minimize open circuits at the module/interconnect interface.
- Increased understanding of high voltage system requirements and module requirements within those systems.
- Demonstrated the flexibility of polymer frames.

Schedule and Future Direction

- **Anticipate our PV Manufacturing Program to end at the end of Phase 1 – mid 2007.**
- **We expect to meet all of the Phase 1 milestones and objectives.**
- **All major technical areas will be transferred to SAI TPP Program.**
- **SAI will accelerate efforts and add 16 new partners to the effort.**