



U.S. Department of Energy
Energy Efficiency
and Renewable Energy

Bringing you a prosperous future where energy
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Expanding the Limits

NREL Subcontract ZXL-6-44205-07
First Solar US Manufacturing

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- **Overall objective – Develop an accurate assessment of the upper limit of power conversion efficiency for CdTe PV**
- **A specific objective is fabrication and analysis of champion cells and modules with world record efficiency**



- **First Year Milestone (30 June 2007) - Demonstrate 1 cm² 15% cells**
- **Summary of Phase I Tasks**
 - **Fabricate and analyze the performance of small area (1 cm²) cells with alternative frontside and backside device structures**
 - **Optimize device performance to produce champion cells**
 - **Analyze the device physics and underlying materials science to determine fundamental limits of CdTe PV performance**



- **Screening Activity**
 - 9 alternative structures screened
 - device performance model developed
- **Fabrication and evaluation of devices with alternative structures and materials**
- **Evaluation of device performance to reveal the underlying device physics**
- **Looking for suitable partner to assist with identification and elucidation of relevant materials science**



<u>Phase</u>	<u>Period</u>	<u>Budget*</u>	<u>Actual</u>
I	2/7/06 - 6/30/07	\$433,783	\$405,084**
II	7/1/07 - 6/30/08	\$440,065	
III	7/1/08 - 6/30/09	\$442,705	
Total		\$1,316,553	

- **A no-cost extension has been approved extending Phase I from February to June 2007**

* Subcontractor's Cost Share 6%

**As of 1/27/07

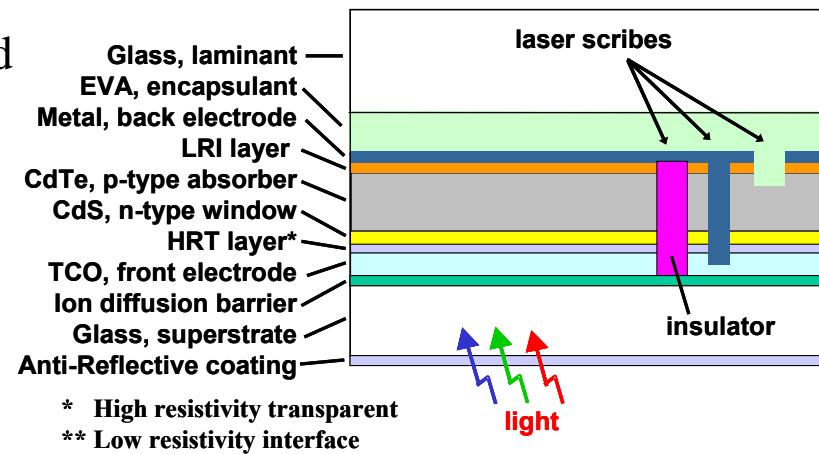


- Fabrication of device structures with potential to achieve enhanced performance
 - Preliminary evaluation of nine advanced cell structures
 - Several (~5) additional cell structures in the queue
- Analysis of device physics and identification of the physical, electrical and optical properties responsible for performance
 - IV, QE, CV LBIV for screening experiments
 - IVT purchased and in use; C-(f,T,t) in preparation for detailed analysis.
- Development of the fundamental materials science that underlies the practical realization of the required physical, chemical, electrical and optical properties required to achieve optimum device performance.
 - Limited progress in this area; original partner universities (U. Toledo, U. Delaware, CSM,..) have failed to reach agreement regarding protection of First Solar intellectual property
 - Proposed redirection involving commercial vendors for physical property measurements



Device Structure Evaluation Strategy

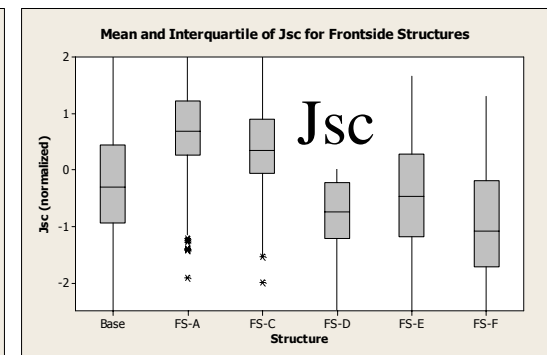
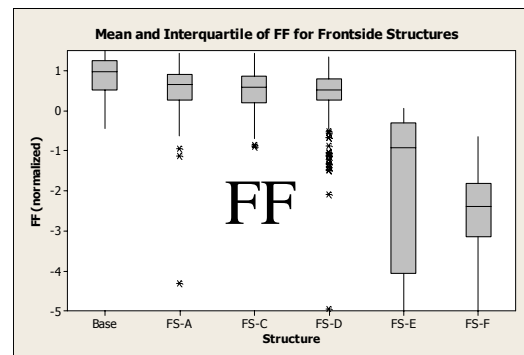
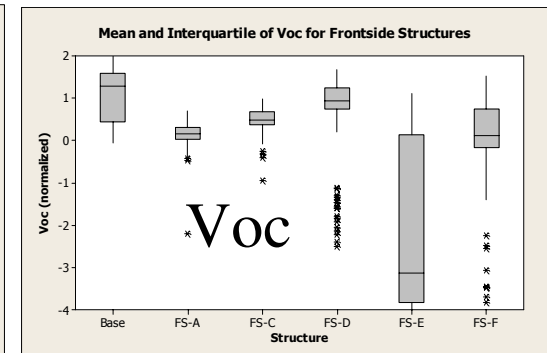
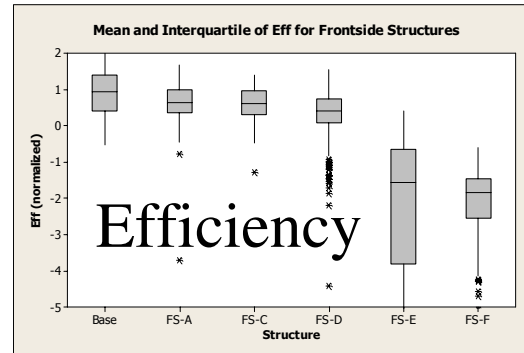
- Focus on improved baseline field performance – takes into account initial stabilization
- Evaluation of “Frontside” and “Backside” structures
 - Front Side structures
 - Anti-reflective coating, glass superstrate, ion diffusion barrier, transparent conducting oxide electrode, high resistivity transparent layer and CdS
 - Objective is increase J_{sc} and FF without reducing V_{oc}
 - Back Side Structures
 - Low resistance interface layer and metal electrode
 - Objective is increase V_{oc} and FF
- Experimental device structures are proprietary





Initial Performance - Frontside (FS) structures

- “Base” is current structure
- Experimentation within each “structure” includes a wide variety of process variations and some structural variations
- Five FS structures have undergone preliminary evaluation
- Initial Efficiency and 2LM are displayed on mean and interquartile plots
- Selected process variations were stress tested to obtain an initial indication of baseline field performance

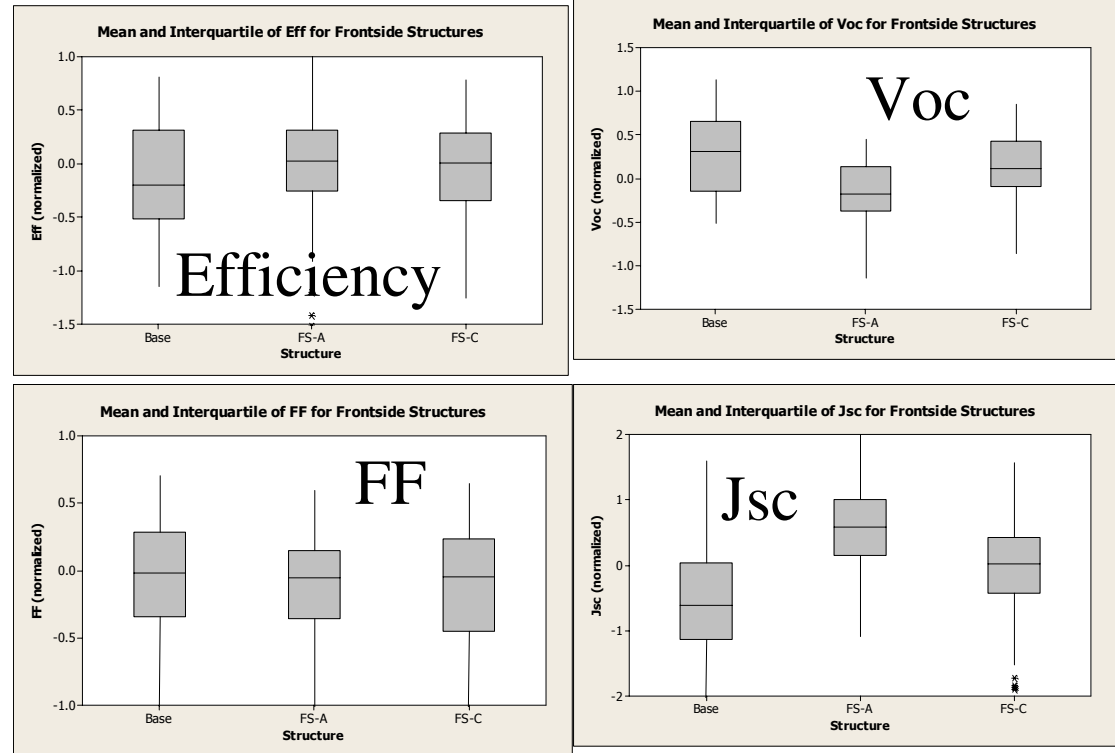


Mean and Interquartile plots for five frontside structures; “Base” structure is on left



Baseline Performance – Frontside Structures

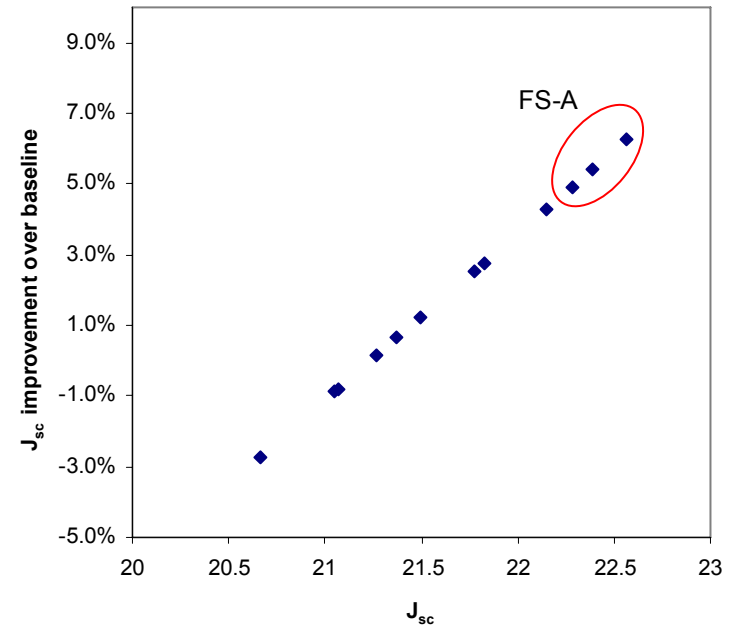
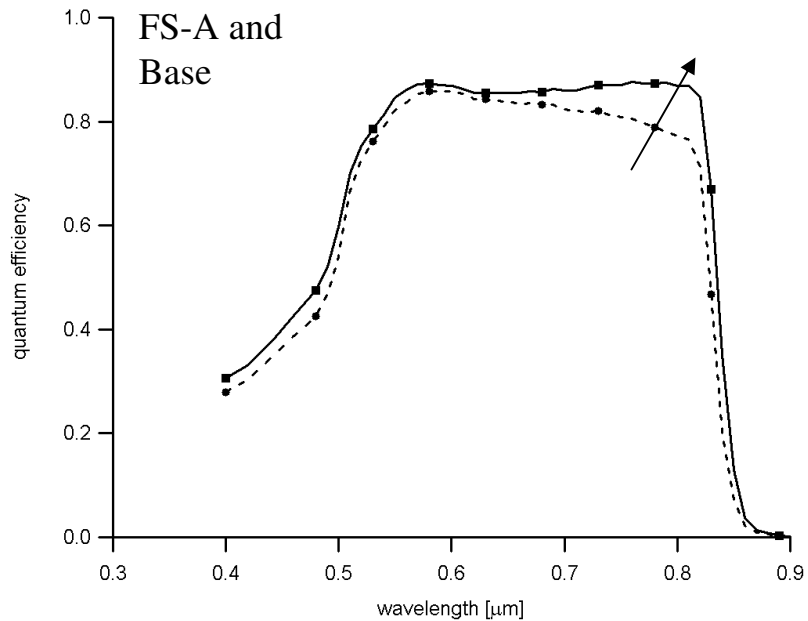
- Frontside structures FS-A and FS-B both display enhanced current but not enhanced efficiency
- No fundamental limits on FS-A or FS-B and have been identified that limit further improvement in FF and Voc



Mean and Interquartile plots for two stressed frontside structures; “Base” structure is on left



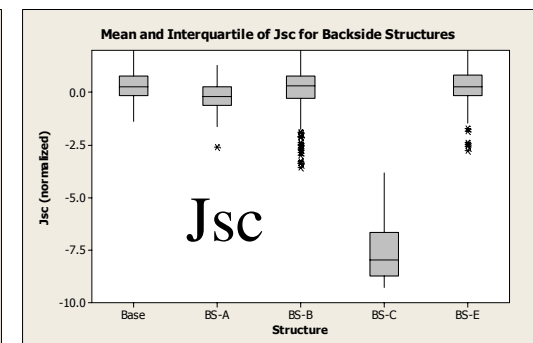
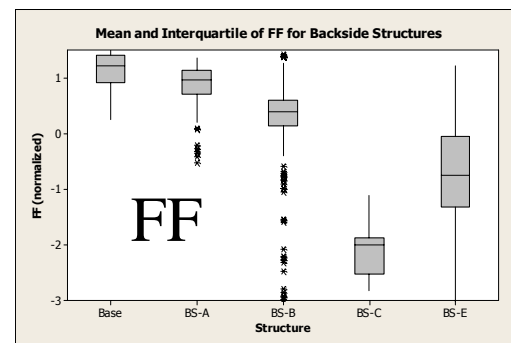
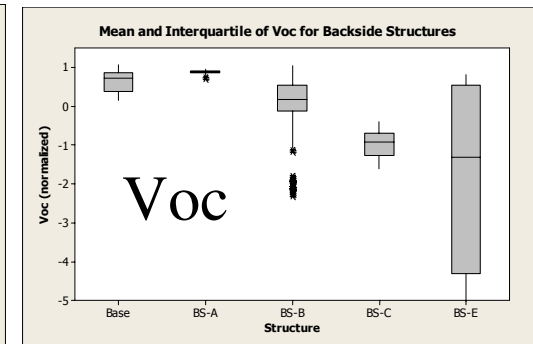
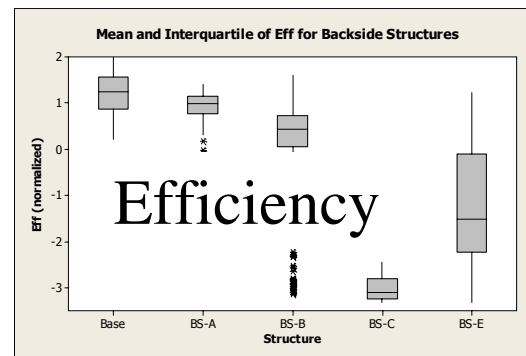
- Device analysis confirms that increase in J_{sc} is due to fundamental difference between the device structure FS-A and Base structures





Initial Performance – Backside Structures

- Backside structures were selected for their potential to display enhanced Voc and FF
- Four backside structures have undergone preliminary evaluation
- Initial efficiency and 2LM are compared to Base structure
- Selected process variations were stress tested to obtain an initial indication of baseline field performance

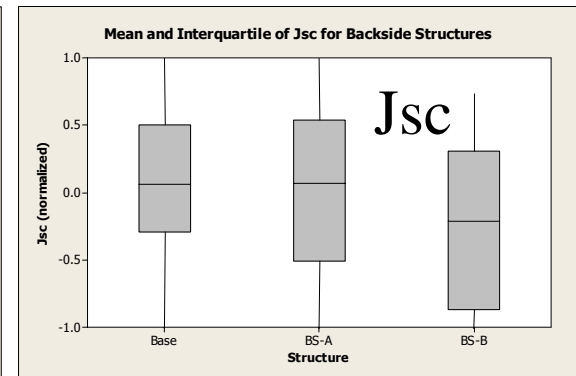
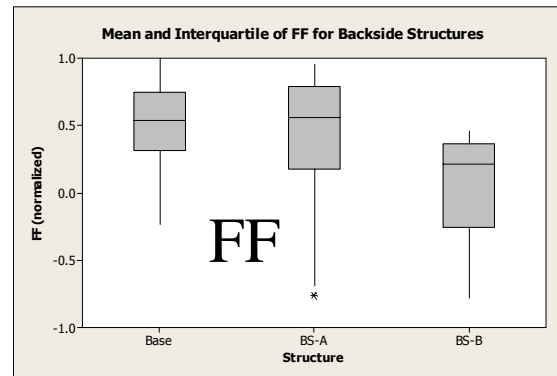
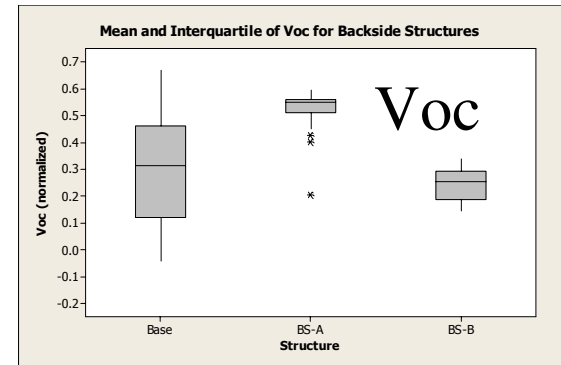
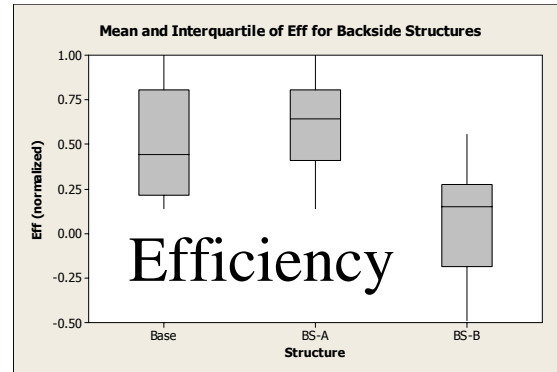


Mean and Interquartile plots for four backside structures; “Base” structure is on left



Baseline Performance – Backside Structures

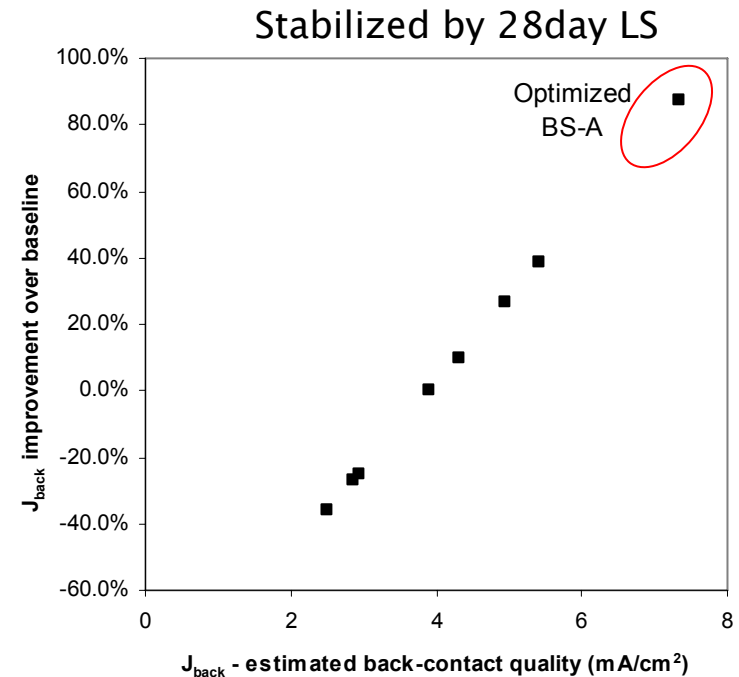
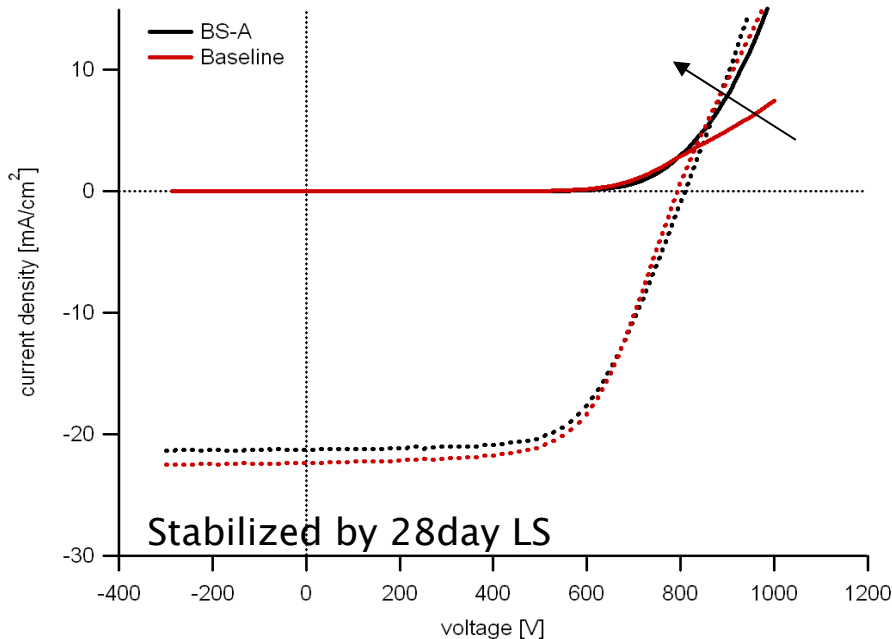
- BS-A shows promise for Voc and FF
- No fundamental limits have been identified



Mean and Interquartile plots for two stressed backside structures; “Base” structure is on left



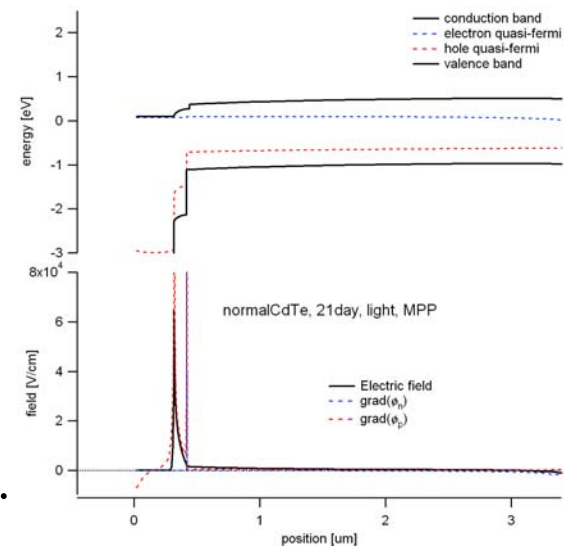
- Proprietary method used to estimate back-contact quality; this method has been confirmed by fully consistent device models.
- Comparison of BS-A with Base structure indicates that after 28 day light soak BS-A has an electrically superior contact to the back electrode





Development of fundamental materials science underlying baseline field performance

- Materials and defect chemistry establish physical limits of device performance
- CdTe has relatively low defect formation energy and thus the key to stable field performance is development of device designs in which the electrical potential values and gradients necessary for high power conversion efficiency are consistent with stable steady state electrochemical potential across the various materials, interfaces and structural defects of the device.
- Stable electrochemical values are those obtained with electron and hole quasi-Fermi levels that exist at V_{mp}
- Currently looking for partner who can evaluate proprietary device structures





Summary of Accomplishments

- Completed evaluation of five distinct frontside and four distinct backside device structures
- Obtained improved Voc for one backside structure
- Obtained significantly improved Jsc for two frontside structures



- Evaluate additional frontside and backside structures
- Downselect at least one frontside and backside structure combination for overall optimization
- Optimize downselected structure for baseline performance
- Demonstrate 1 cm² cells with predicted baseline field performance of 15% efficiency (Phase I objective) and ultimately 17% (Phase III)
- Utilize analytical techniques and device simulation capable of predicting baseline field performance
- Identify key elements of materials science that limit device performance