SAND2012-2106 C
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Next Generation Photovoltaic Cells and Systems through MEMS Technology

March 19, 2012

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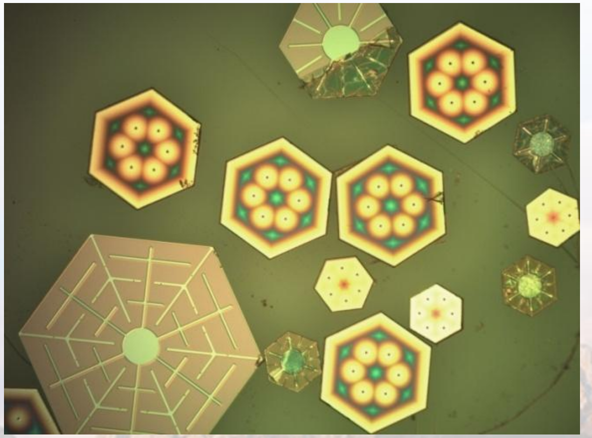
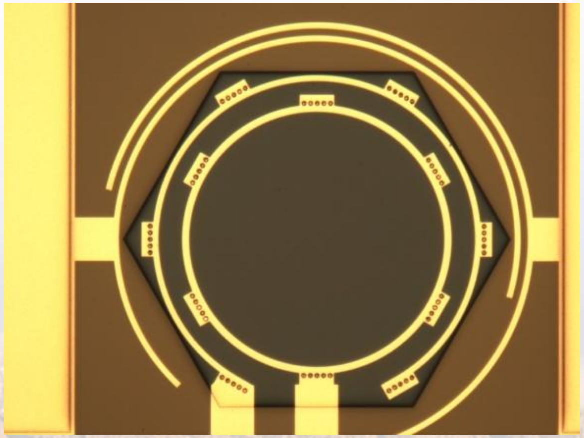


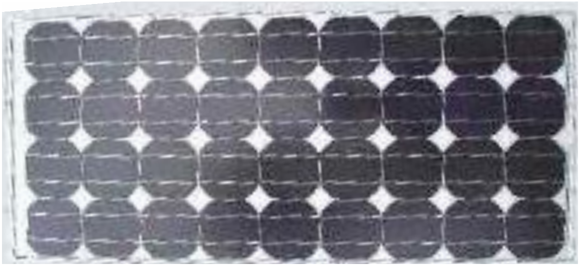


Commercial PV Technologies

Thin Film PV

- Efficiency: 5-11%
- Manufacturing Cost:
  - Module $0.75/W_p$
  - System ~$3.00/W_p$
- Pros: Small amount of semiconductor material, Flexible form factors
- Cons: Low efficiency, Toxic materials, rare elements (Te, In), materials cost dominated

C-Si PV



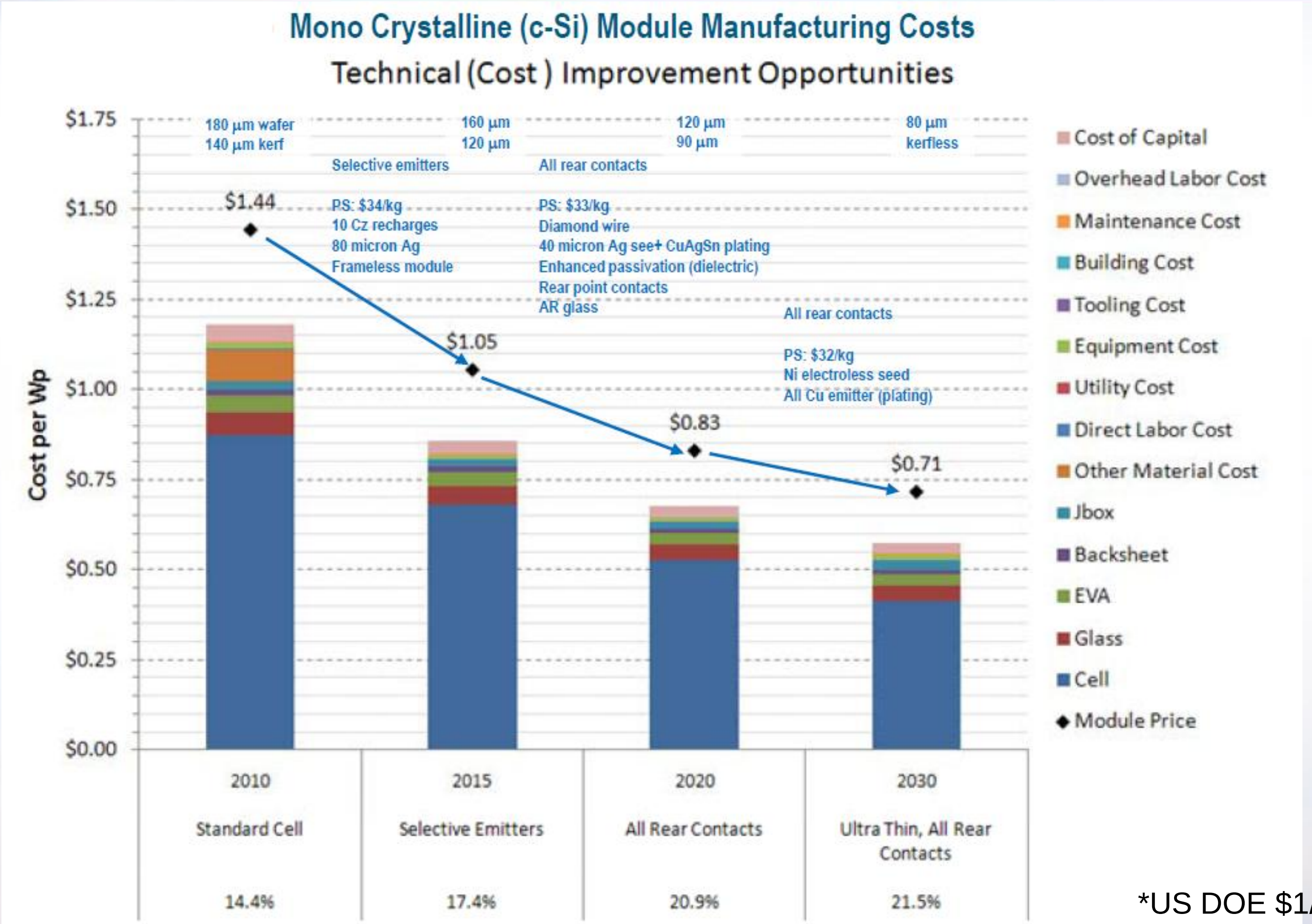
- Efficiency: 13-20%
- Manufacturing Cost:
  - Module $1.05/W_p$
  - System ~$3.00/W_p$
- Pros: Moderate efficiencies at moderate costs, Silicon based, Reliable and bankable
- Cons: Reaching efficiency boundaries, Materials cost dominated

Concentrated PV

- Efficiency: 18 - 27%
- Manufacturing Cost:
  - Module $?/W_p$
  - System ~$3.00/W_p$
- Pros: High efficiency
- Cons: Unproven technology, Very high BOS costs, Challenging thermal effects, Sensitive to spectrum shifts

These PV module/system technologies represent evolutionary developments of concepts proposed in the 1970's (or earlier). Our proposed system would be a disruptive development for PV systems that takes advantage of significant S&T developments of the last 5 to 20 years.

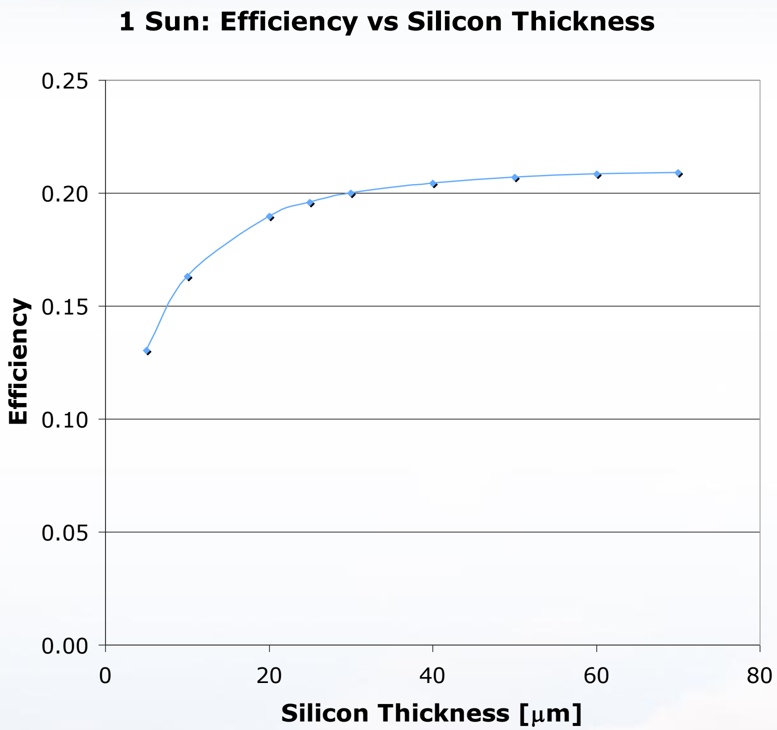
C-Si PV Solar Power System Costs

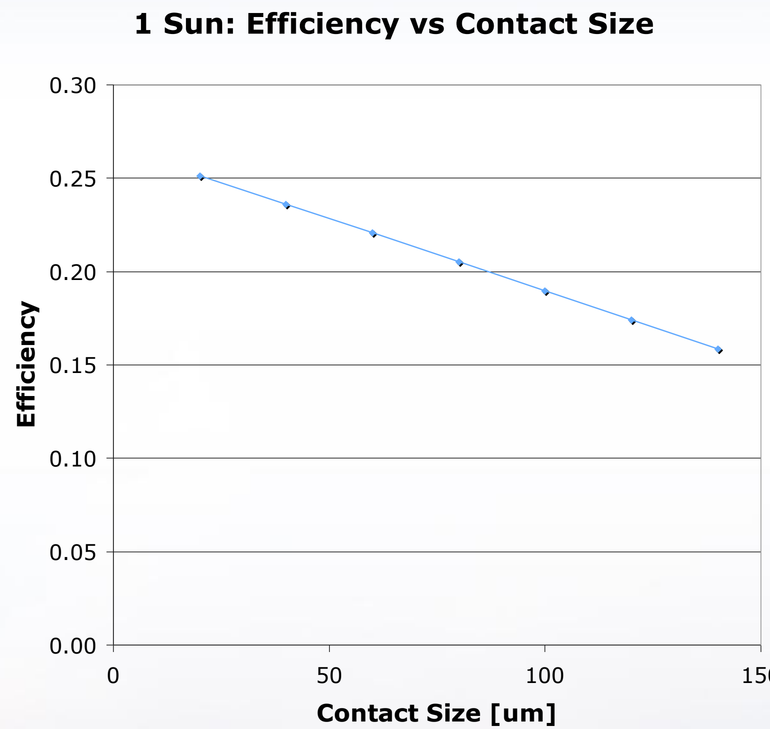


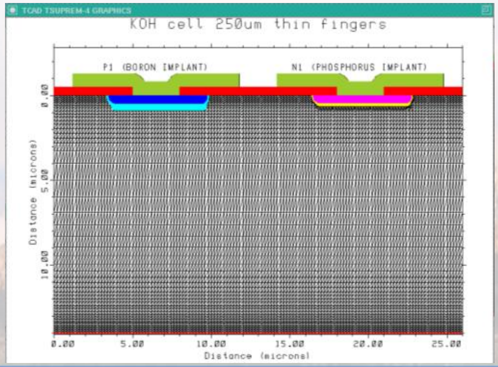
*US DOE $1/W workshop

Cost reductions must come from virtually all components of a PV system to achieve necessary cost reductions

2D Simulations of c-Si Cells







Simulated performance of c-Si cells with varying geometric parameters

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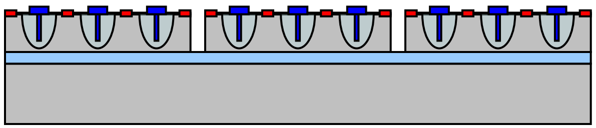
Thin c-Si PV Cells

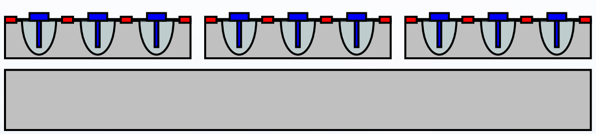
Micro-PV cells follow typical PV process with back contacts. Release achieved with either SOI/HF or using a Si wafer with a (111) face and a KOH (or equivalent) etch.

SOI wafer

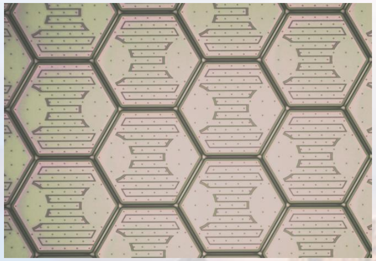
Create p-n junction then anisotropically etch between cells to buried oxide layer.



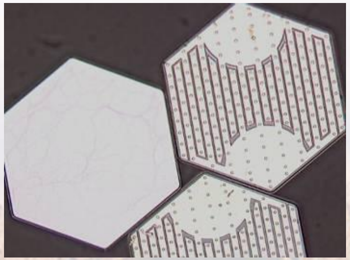
Release from handle wafer using an HF based release etch.



After release, the handle wafer can be reused to create a new SOI wafer.



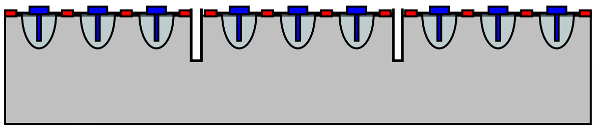
Cells on wafer



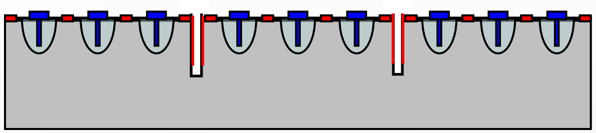
Released cells

(111) Si wafer

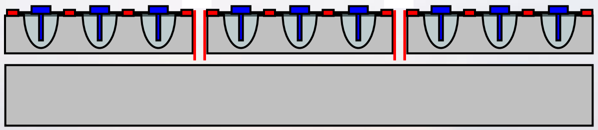
Create p-n junction then anisotropically etch between cells to desired cell thickness.



Coat etch sidewall and extend etch further into Si for KOH undercut

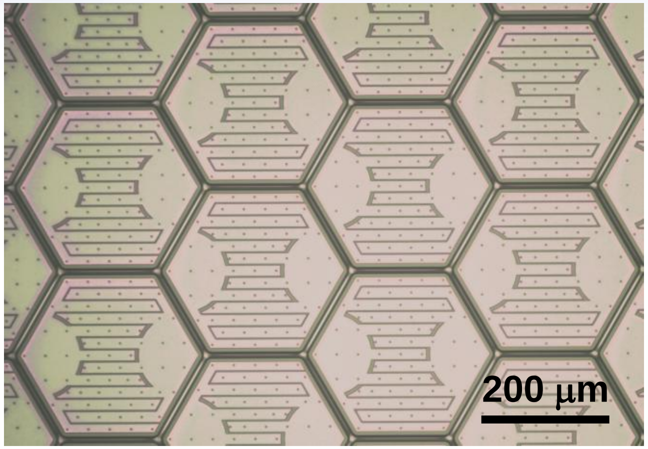


Due to convex corners, KOH (or EDP, TMAH, etc.) will completely undercut and release micro-PV cells.

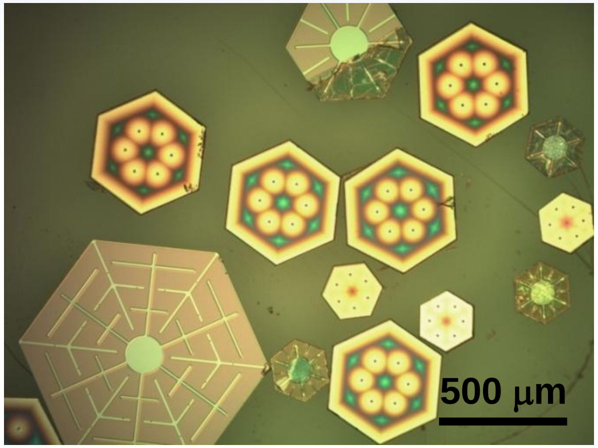


After chip release, remaining wafer portion can be reused for fabrication until Si completely used up (at some point a handle wafer will be necessary).

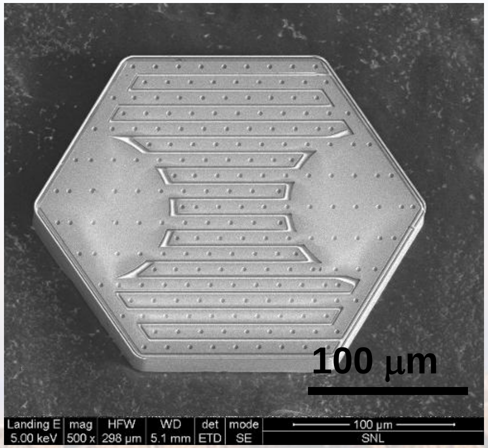
Thin Crystalline Silicon PV Cells

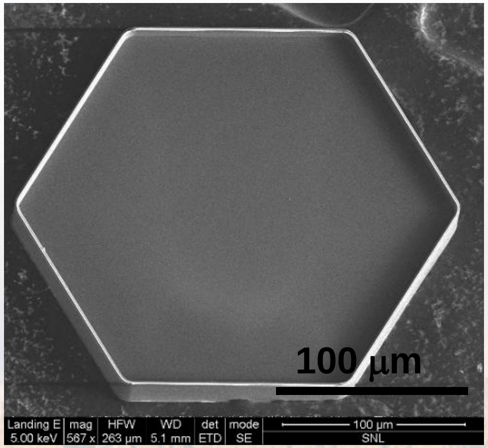


PV cells prior to release from substrate



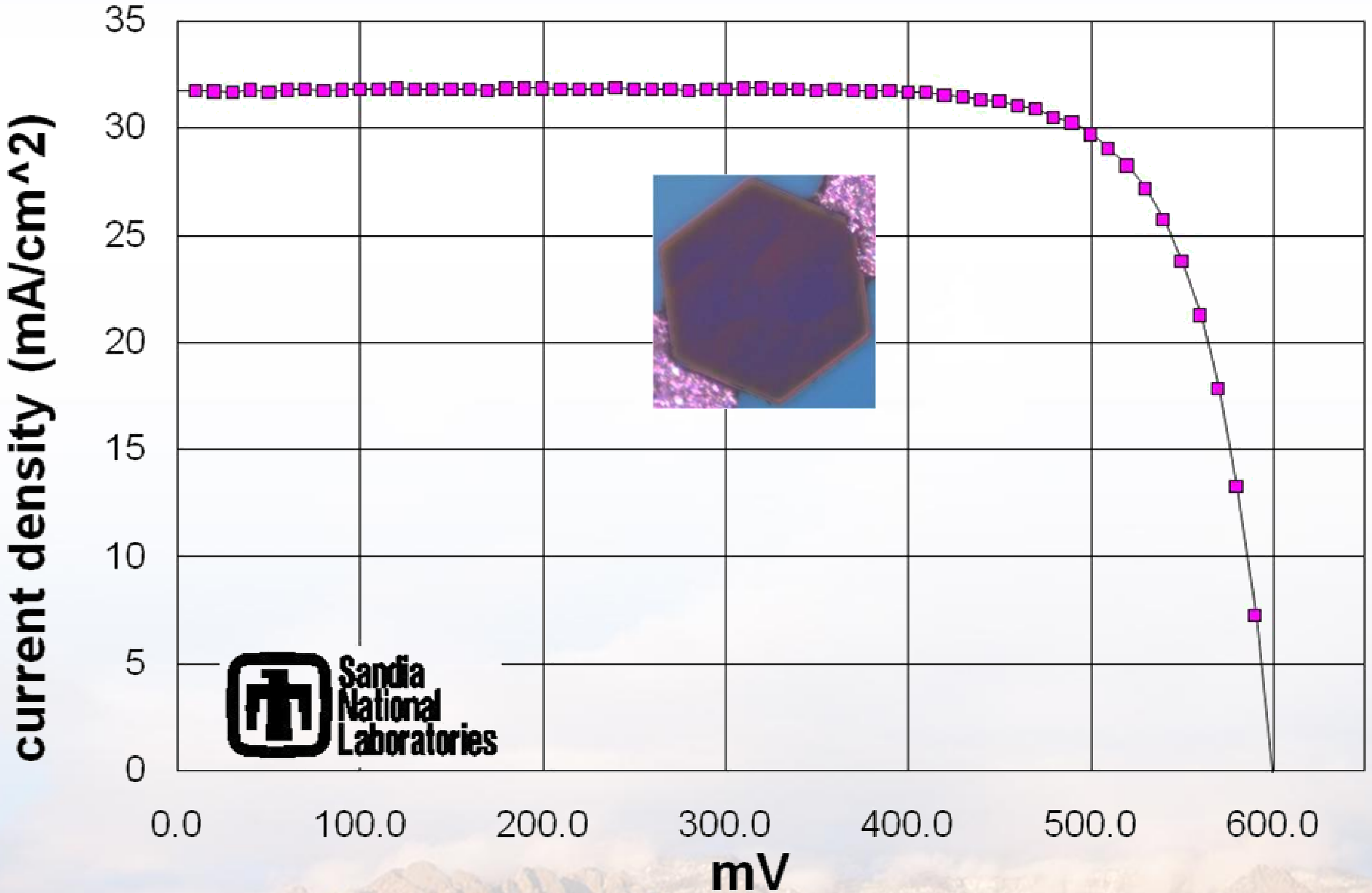
Variety of solar cell sizes and designs





Fully backside contacted solar cell showing contacts on back and unshaded front ("Sunny") side of the cell

Thin c-Si PV Cell Performance



08/20/09 2:18 PM
LN3_2_250k

25.0 °C	0.0003763 cm^2	31.75 J_{sc}(mA/cm^2)	0.784 FF	AM1.5G
1.0000 M'	597.3 V_{oc}(mV)	11.946 I_{sc}(uA)	14.86 % Eff	1.00 Suns
1.0000 S'	501. V_{mp}(mV)	11.161 I_{mp}(uA)		

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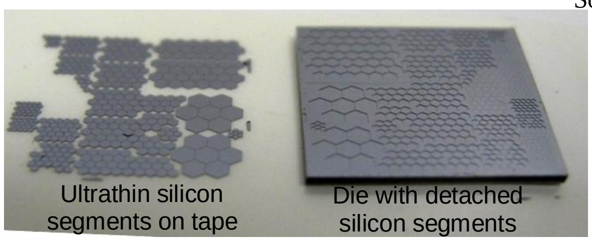
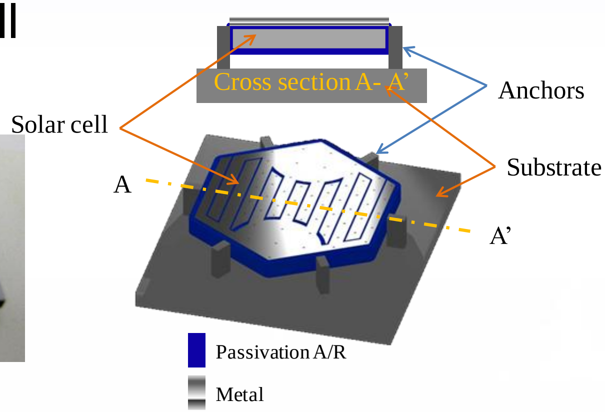
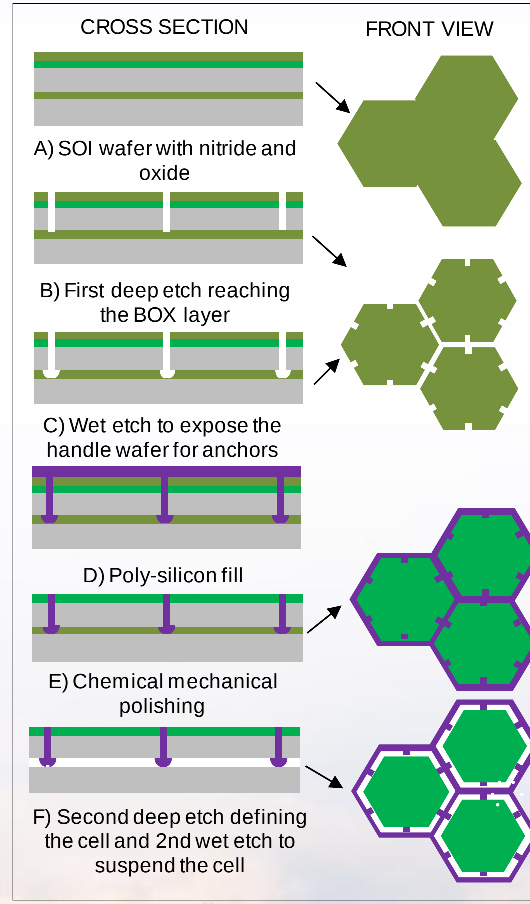
Unique Process: Ultrathin Film of Silicon Cell

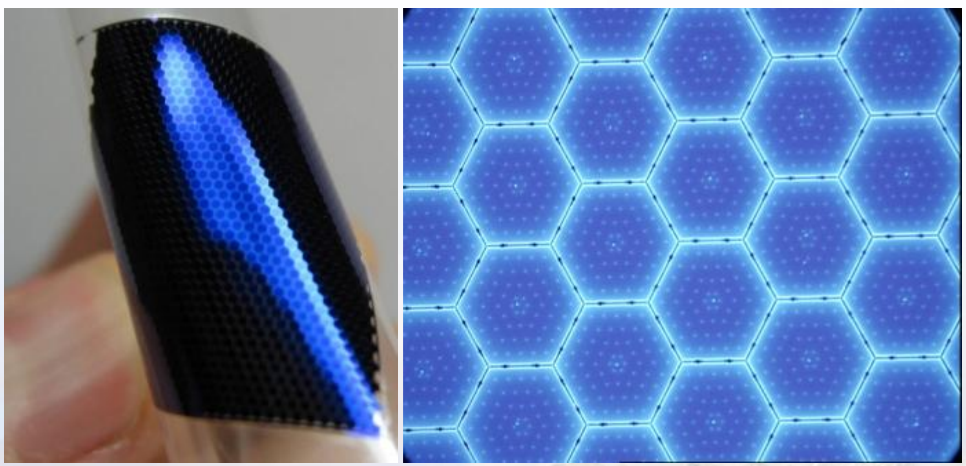
Concept of Suspended Cell



Released die on tape







Highly flexible and ultrathin sheets of passivated silicon segments

Jose L. Cruz-Campa, Gregory N. Nielson, Paul J. Resnick, Carlos A. Sanchez, Peggy J. Clews, Tom Friedmann, Murat Okandan, Vipin Gupta, *Ultrathin Flexible Crystalline Silicon: Microsystems Enabled Photovoltaics*, Invited talk to be presented at Photovoltaic Specialist Conference in Seattle, WA on June 23th, 2011

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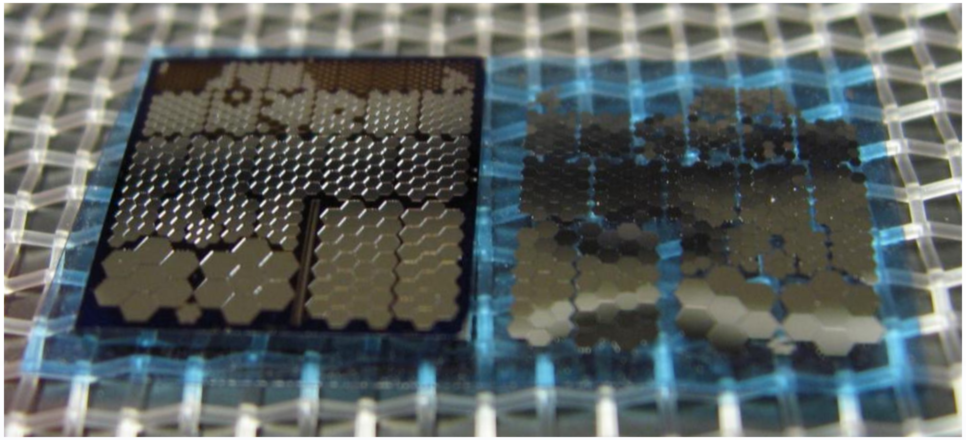
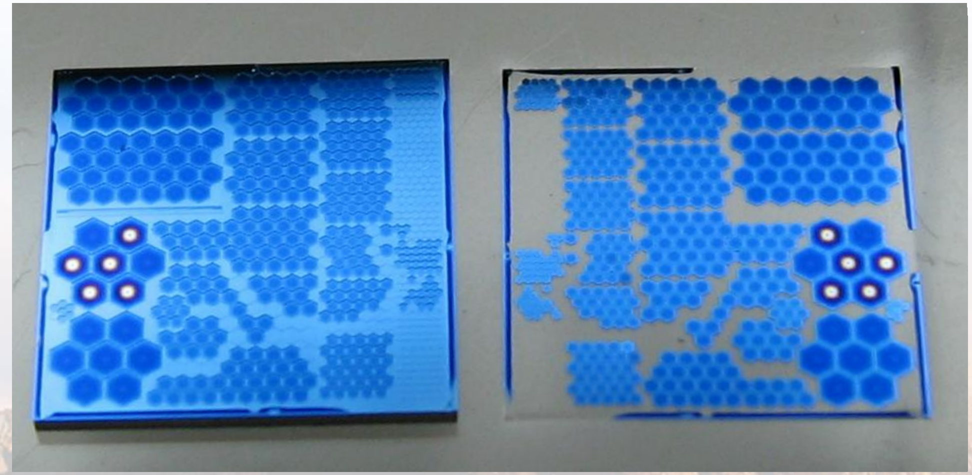
Nitride deposition in suspended cell

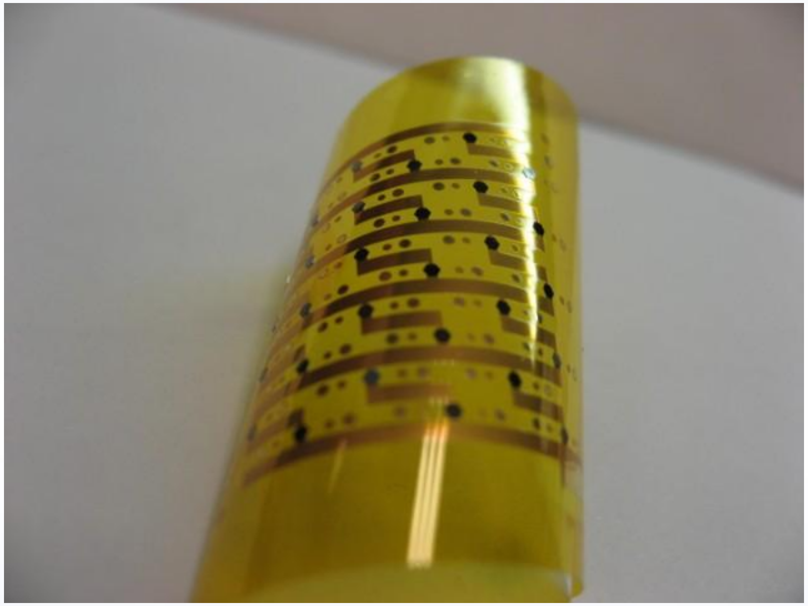


Cells in tape w/o nitride

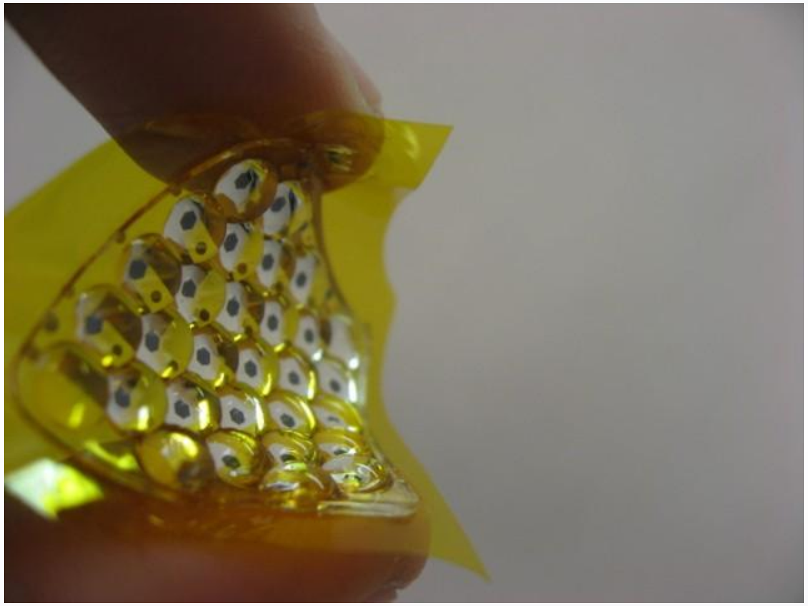


Cells in tape with oxide and nitride

Pick-and-Place assembly of 20 μm thick c-Si cells



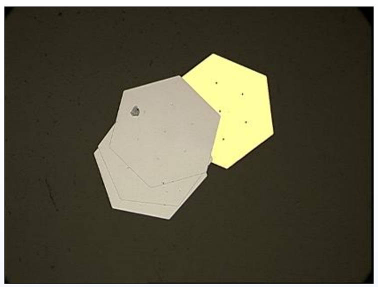
Electrically connected sparse array of 20 μm thick c-Si cells on 12 mm thick flex-circuit substrate.

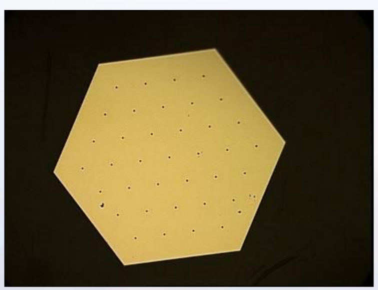


Sparse array with molded PDMS microlens array. Cell spacing corresponds to a 49X system. (Note: mechanical demo only – optical system is not accurate.)

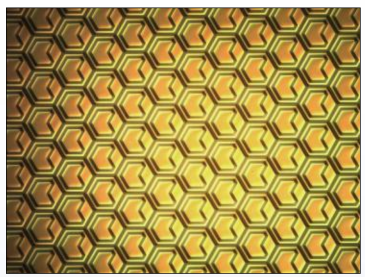
Thin III-V PV Cells Evolution

- **Using small area ELO**
  - Release time is relatively rapid.
  - Handling of released chips can be done with self-assembly.
  - Backside contacting possible with small PV cells.
  - Small cells lend themselves to micro-concentrator structures.

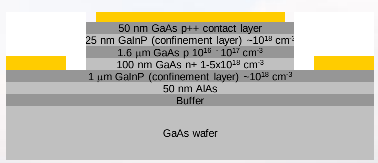




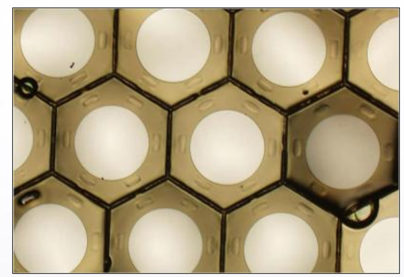
Single junction with front-back contacts



Back



Single junction with all back contacts at different levels



Front

Cross section

Double junction with all back contacts at the same level

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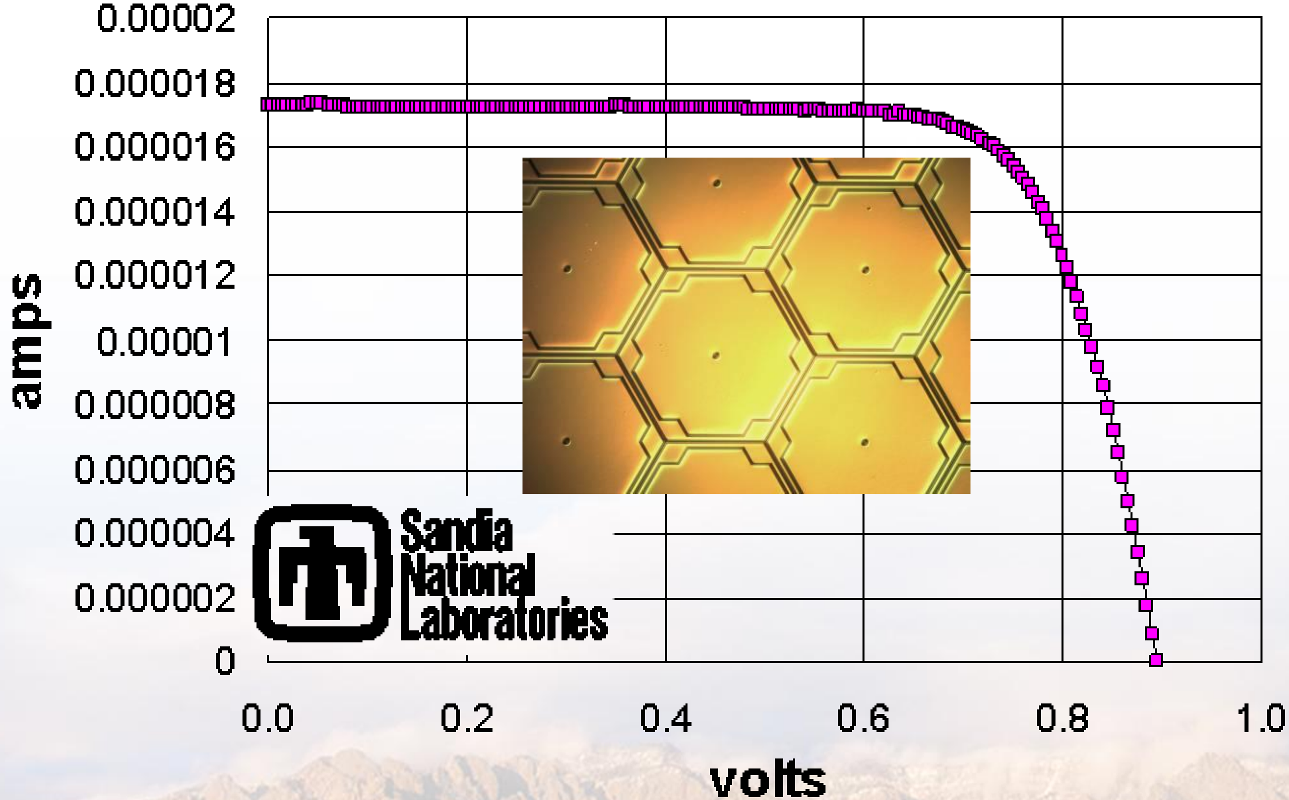
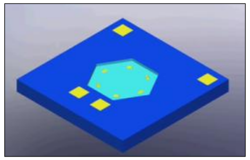
Thin III-V Cell Performance

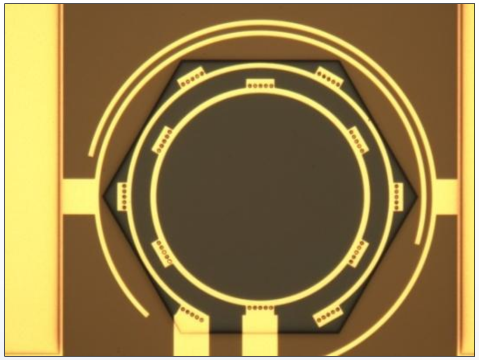
Best GaAs back contact solar cell (1sun) Efficiency 10.03% +/-0.4%



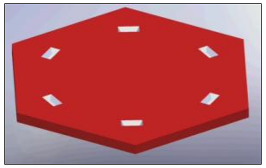
10/06/09 1:54 PM	24.9 °C	0.001164 cm^2	14.86 J_{sc}(mA/cm^2)	0.754 FF	AM1.5G
GaAs slide 2 500um AR coat cell2	1.0000 M*	894.8 V_{oc}(mV)	17.300 I_{sc}(uA)	**10.03 % Eff**	1.00 Suns
	1.0000 S*	723.6 V_{mp}(mV)	16.127 I_{mp}(uA)		

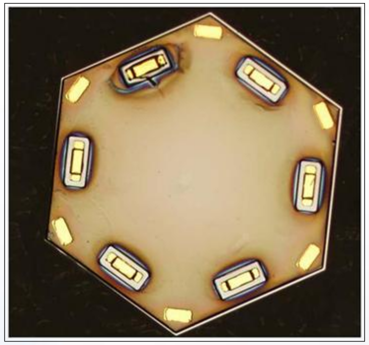
3D Integration of Triple Junction Micro Cell (InGaP, GaAs, Si)



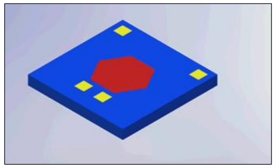


Silicon Substrate/Cell



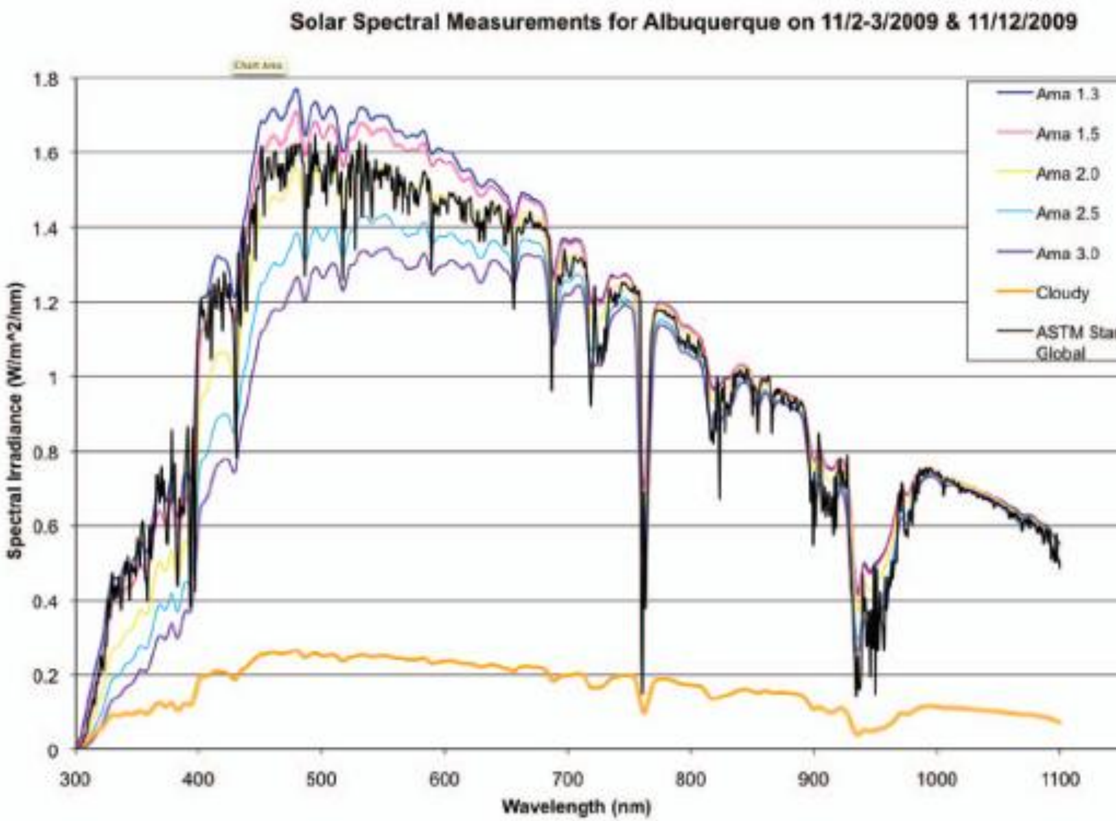


Double junction InGaP GaAs



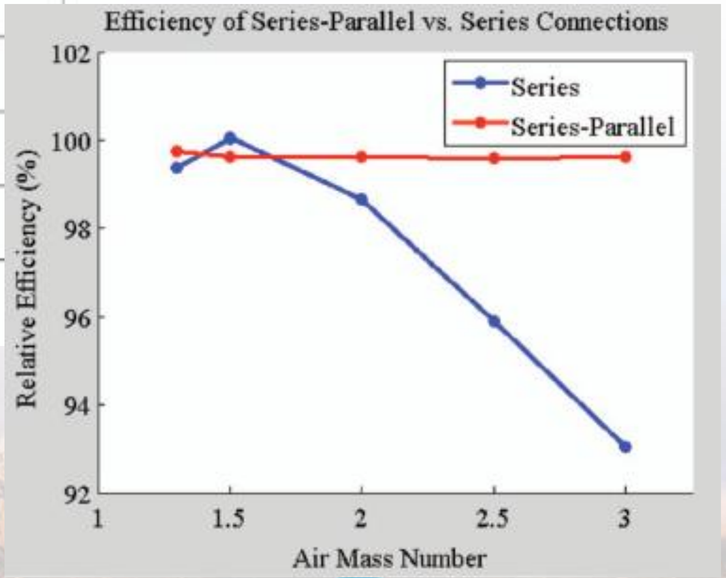
Assembled triple junction microsolar cell with decoupled connections

Microsystem-Enabled PV Cells for High Solar Conversion Efficiency



Solar spectrum change with variation in air mass (i.e. time of day).

Series connected multi-junction PV cells are constrained to one peak efficiency spectrum



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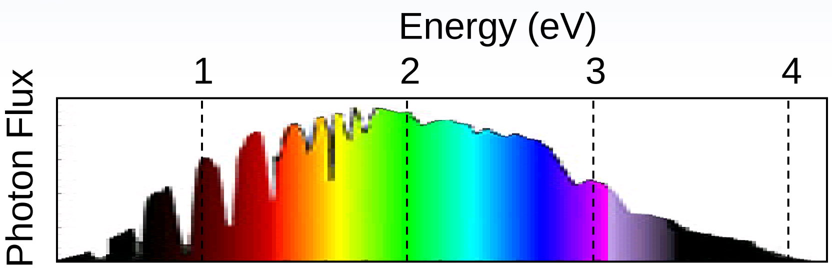
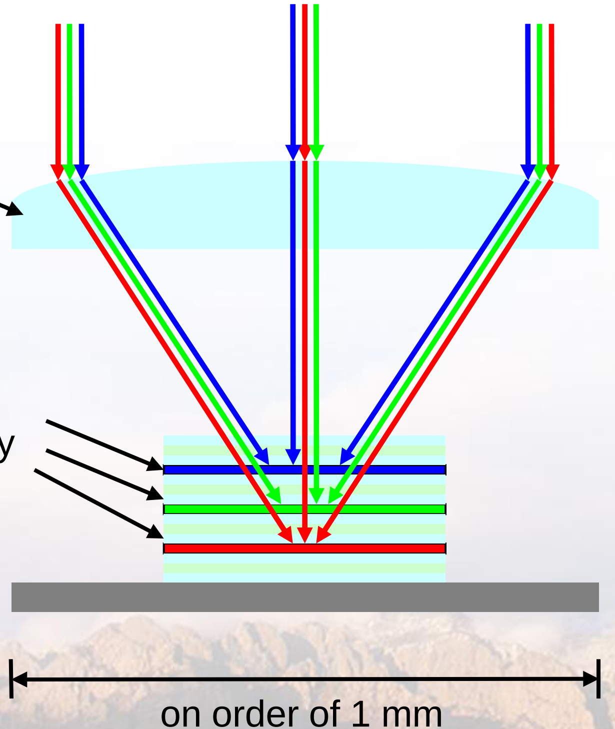
Microsystem-Enabled PV Cells for High Solar Conversion Efficiency

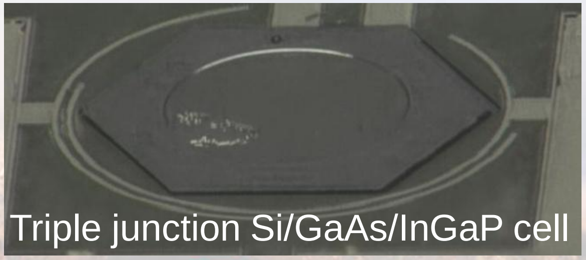


Small dimensions allow high-quality, molded refractive optics

PV junctions created from ideal materials at ideal thicknesses and electrically independent



Material	Bandgap
InGaN	*2.5*
InGaP	*1.85*
GaAs	*1.4*
Si	*1.1*
InGaAsP	0.9
InGaAs	0.6


Triple junction Si/GaAs/InGaP cell

Concentrated Photovoltaic Systems (CPV)

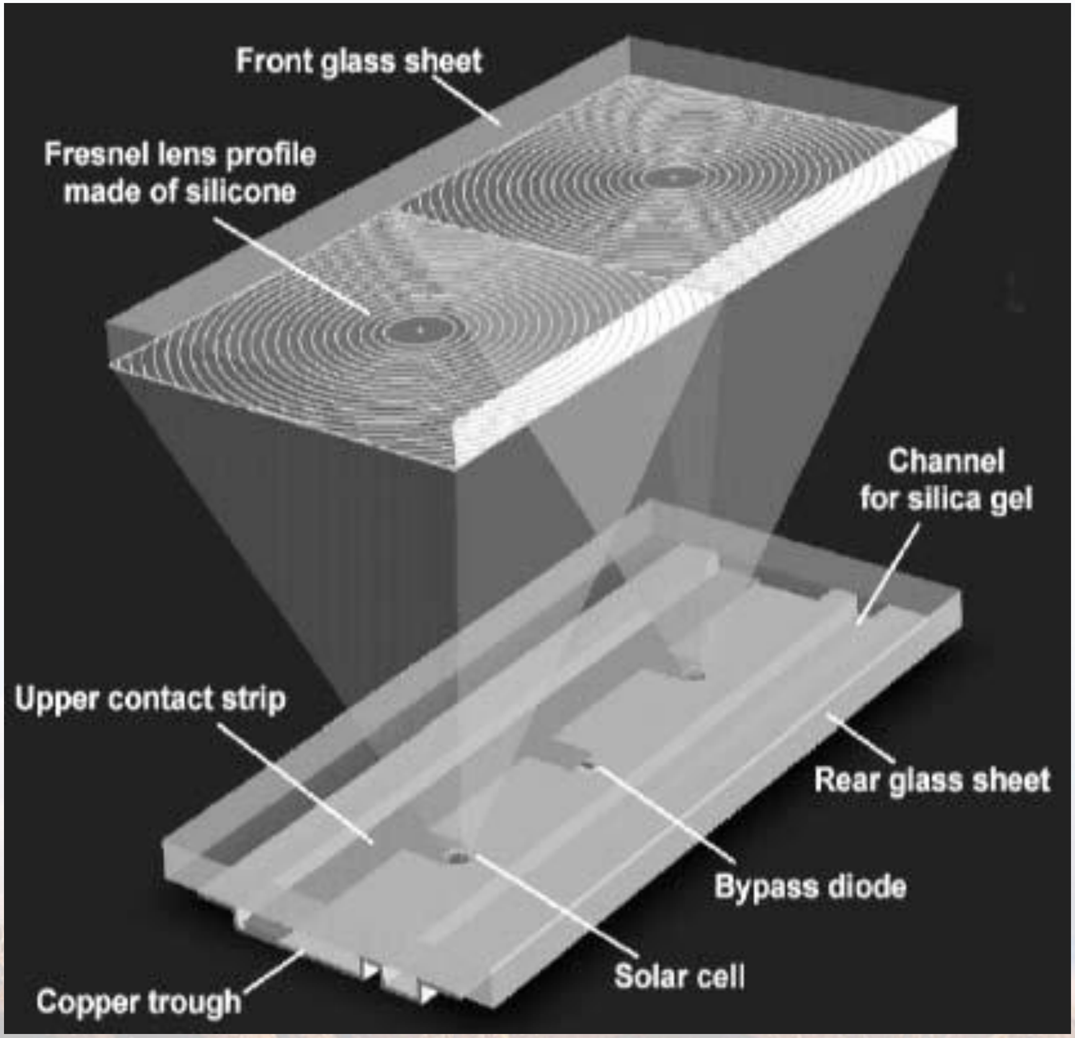
•CPV systems use optics to concentrate (focus) light onto PV cells.

•Replaces expensive PV cells with less-expensive optics to allow.

•Allows the use of high-efficiency PV cells that would otherwise be cost prohibitive.

•Requires the use of tracking with the accuracy of tracking dependent on the concentration level.

•High efficiency power production can lead to balance of system cost reductions.



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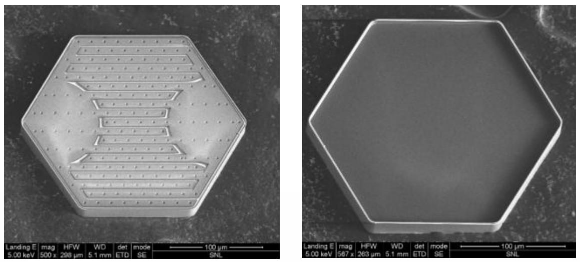
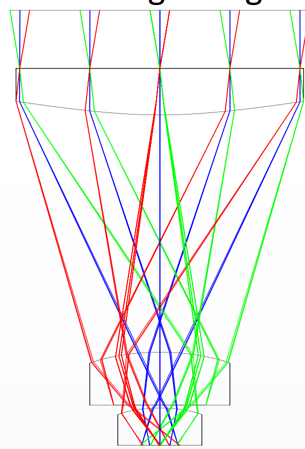
Microlens Concentrator System (Dual Axis Tracker)

Very small cell sizes allows high-quality refractive optics to be molded inexpensively in microlens arrays, opening up a broad new design space of solar concentrators.



250 micron across, 14 micron thick crystalline silicon cells

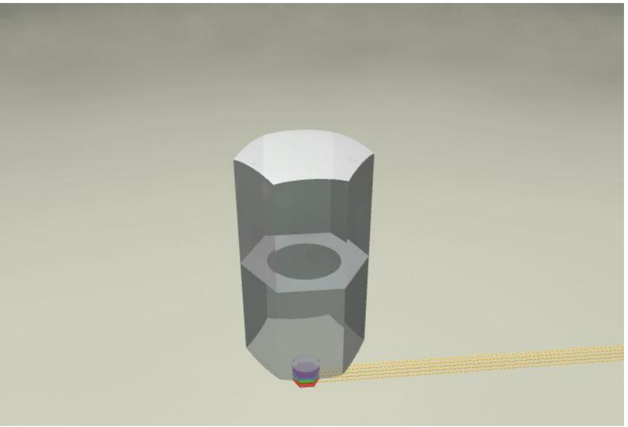


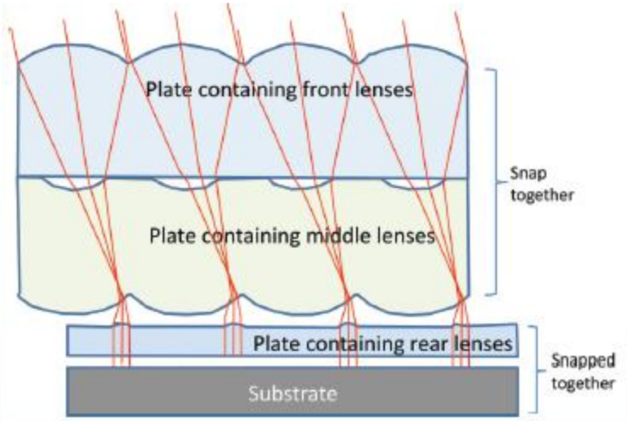
Optical ray trace model of optical concentrater made possible by microscale solar cells.

- Provides 100X concentration
- $\pm$ 4° tracking in both axes
- Flat external surface
- ~ 1 cm module thickness

Microlens Concentrator System (Single Axis Tracker)

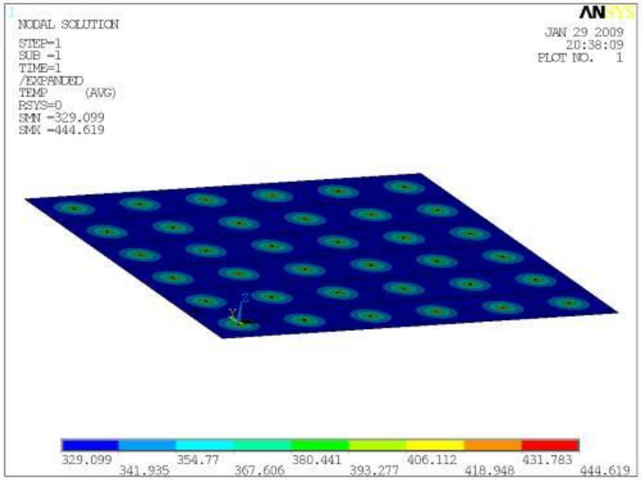
By moving a microlens array relative to a PV cell array, tracking over a fairly broad range is possible.

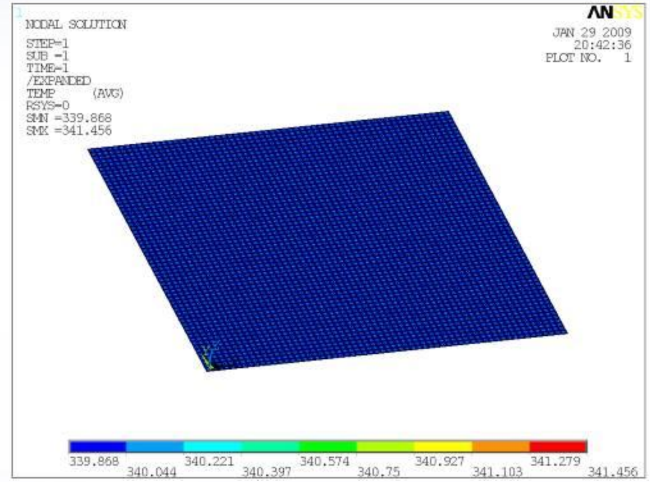




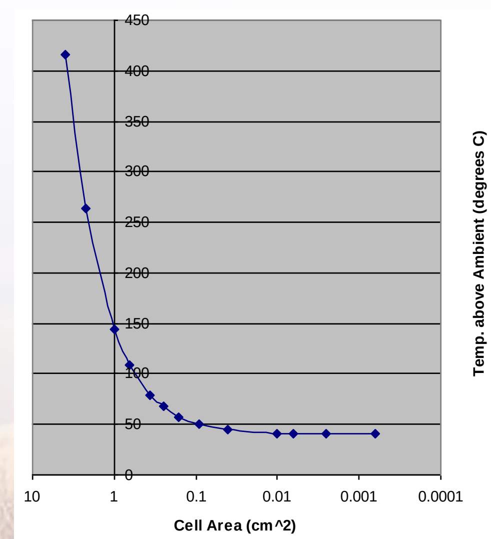
- Provides 49X concentration
- ± 20° acceptance angle in both axes (± 23.5° desired)
- Presents light as a normal plane wave to PV cells (optimal for AR coating performance)
- Requires order 1 mm motion between lens elements and PV cells.

Thermal Performance of Small PV Cells



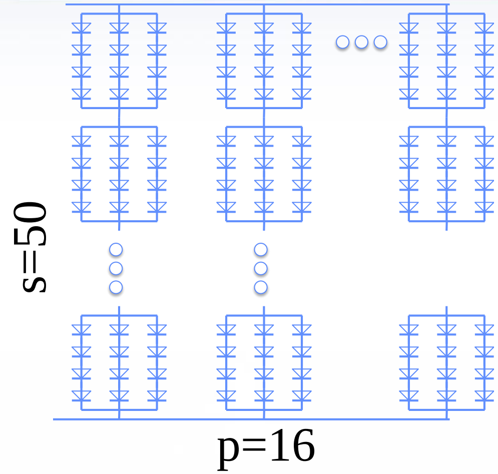


FEA analysis of a simplified 500X concentrator system using a .7 mm aluminum sheet as the substrate with cooling provided only by convection. The contour plots are of cells of 1 cm^2 (left) and 1 mm^2 (right) on the same collection area. The difference in cell operating temperature between the two cases is more than 100°C.

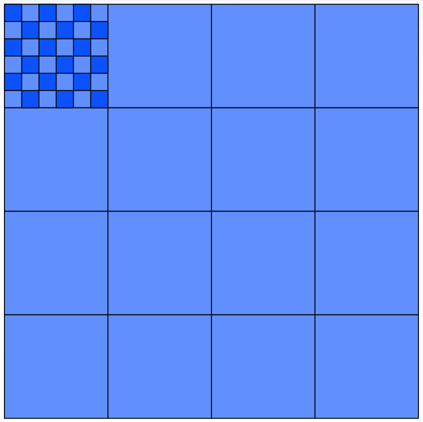


High Voltage MEPV Modules

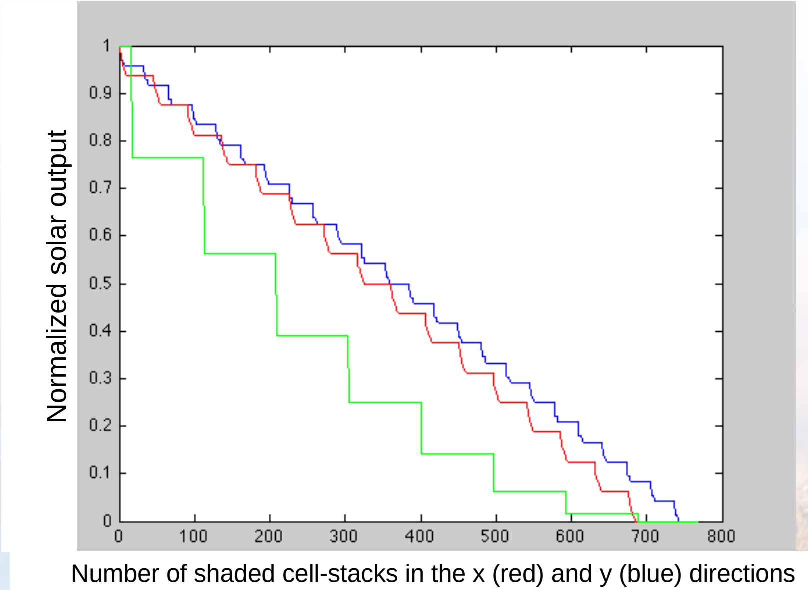
- 10k-40k cells per sq. meter!
- 100s of Volt operation
- Better shading performance
- Tolerance to cell failures and variations (depends on config.)

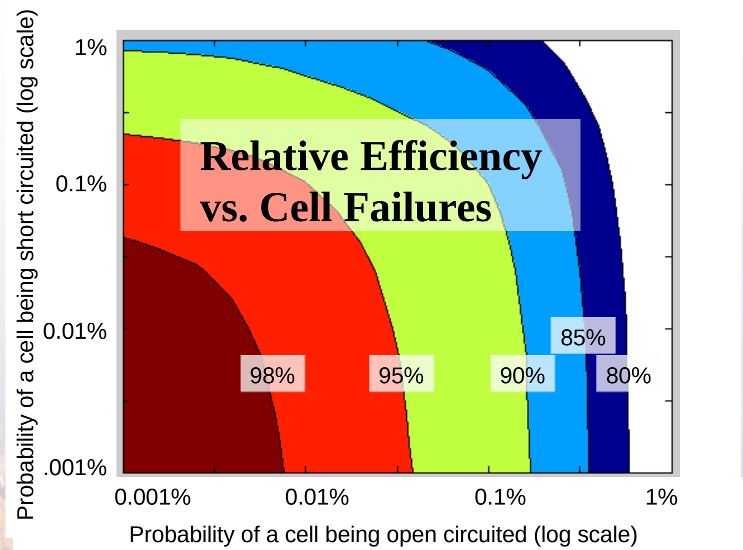


Logical Connections



Physical Layout





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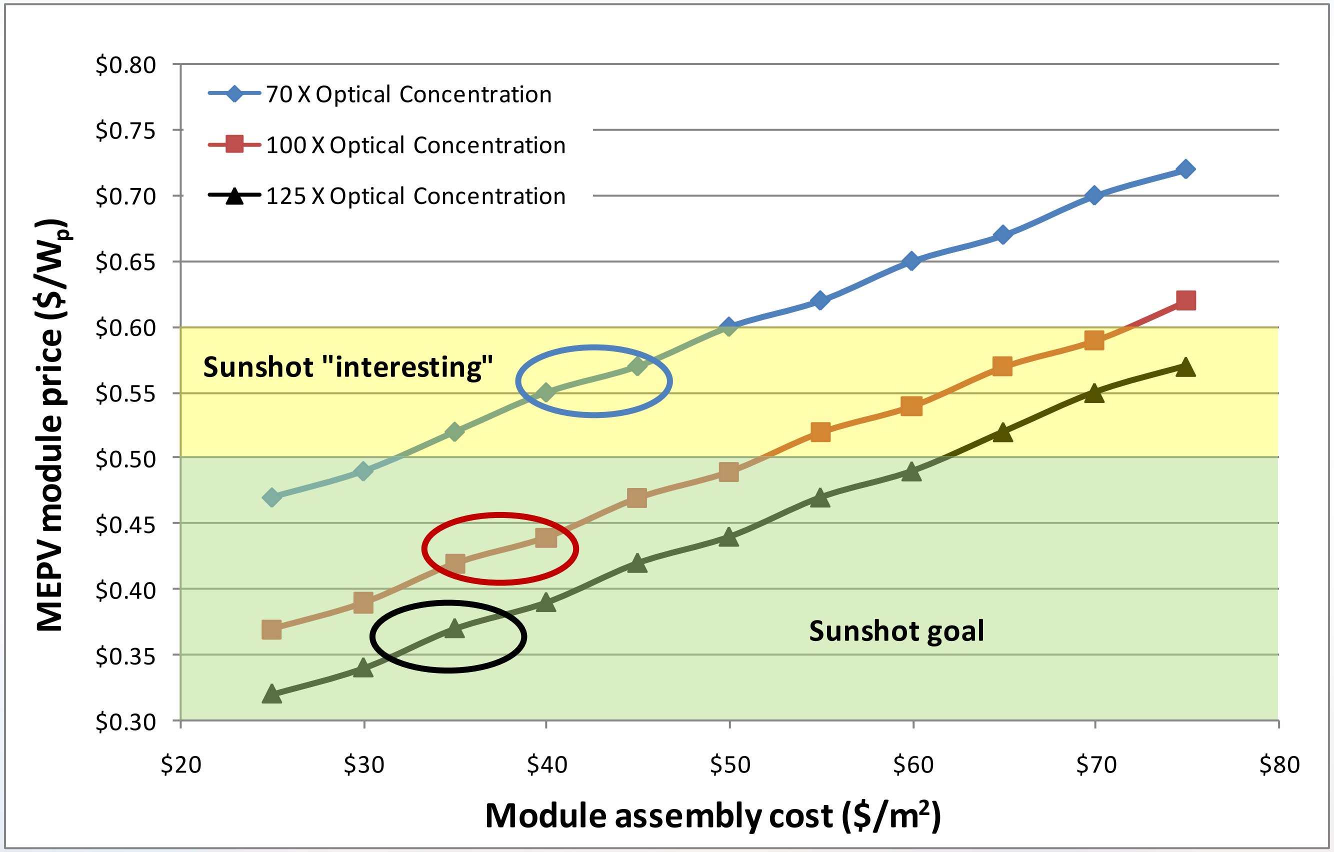
MEPV Module Assembly Costs & SunShot Targets

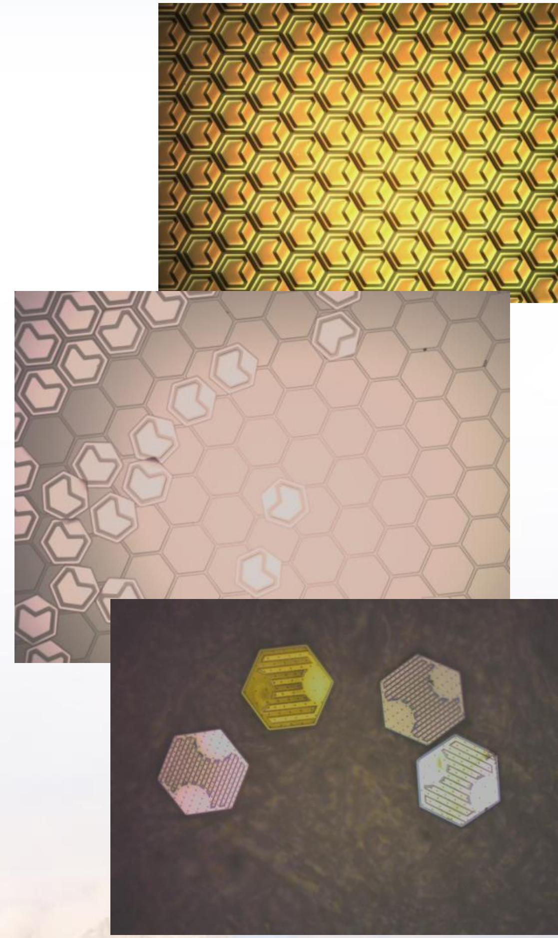


Inputs:
- $150/wafer (8 inch)
- 24% cell efficiency
- 1 mm^2 cell area

Calculation:
- NREL PV Price Model (incl. 18% profit margin)

	70X	100X	125X
Assembly cost	$40-45/m^2	$35-40/m^2	$33-38/m^2

Conclusion and Acknowledgements



Conclusions

- Micro-scale solar cells allow improved performance, reduced cost, and new functionality
- High-efficiency flexible PV
- Low-cost utility and commercial scale PV systems

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