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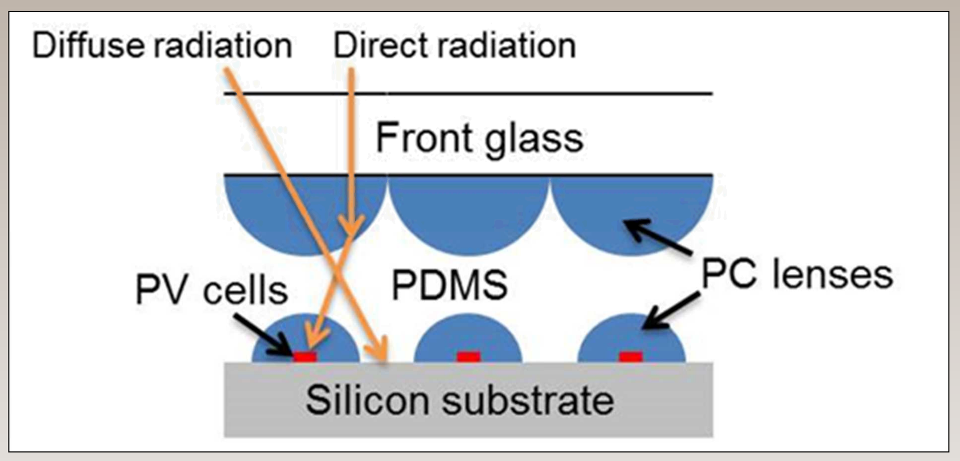
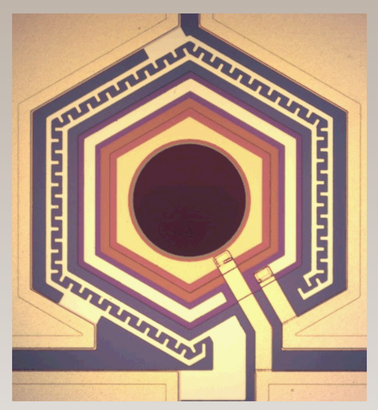
Cost Analysis of Flat-Plate Concentrators Employing Microscale Photovoltaic Cells for High Energy Per Unit Area Applications

Scott Paap, Vipin Gupta, Anna Tauke-Pedretti, Paul Resnick, Carlos Sanchez, Gregory N. Nielson, Jose Luis Cruz-Campa, Bradley Jared, Jeffrey Nelson, Murat Okandan, William Sweatt

Microscale photovoltaics (PV) basics

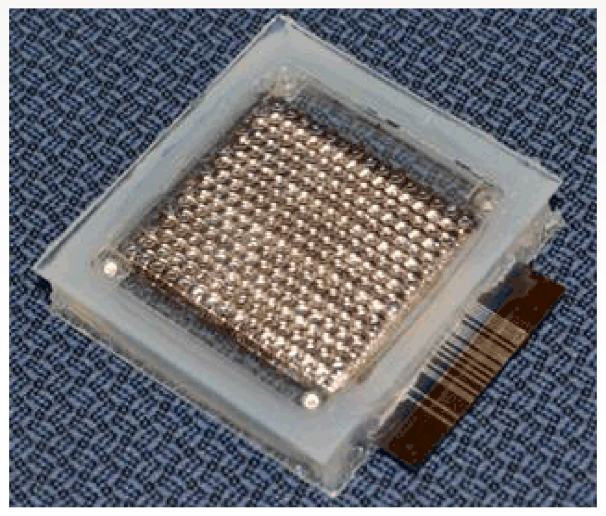




Microscale PV cell

Module architecture

- ***Silicon substrate:*** Conventional Si PV cells serve as mechanical substrate and collect diffuse light
- ***Microscale III-V PV cells:*** Hexagonal compound semiconductor photovoltaic cells with vertex-to-vertex diameters between 100 µm and 500 µm are placed in a sparse array on Si substrate



- ***Concentrating optics:*** A plastic lens stack concentrates direct sunlight on III-V PV cells. The lens stack consists of two polycarbonate (PC) lens arrays separated by poly-dimethylsiloxane (PDMS) to prevent ingress of moisture

← Microscale PV module prototype

Hybrid microscale PV module architecture leverages components and assembly methods used in conventional Si PV modules

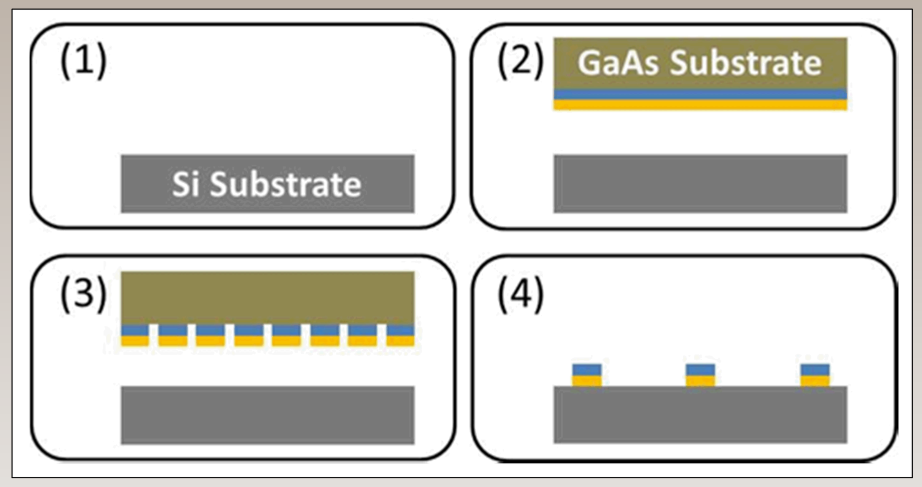
Benefits of microscale PV for high energy per unit area applications

- ***Collection of direct and diffuse light:*** Hybrid microscale PV module design maximizes energy generation per unit area in all conditions
- ***High module efficiency:*** Multijunction III-V cells enable high light conversion efficiency; efficient lenses minimize optical losses
- ***Robust, transportable modules:*** Solid lens design is mechanically robust and prevents moisture ingress, for systems that need to be deployed almost anywhere on short notice to provide off-grid or micro-grid power (e.g., disaster areas, temporary logistic sites, village power)
- ***Compatibility with non-concentrating Si PV infrastructure:*** Small cell sizes and moderate concentration ratios of 200X to 500X result in modules of similar thickness to conventional non-concentrating PV; also enables the use of less accurate (= less expensive) tracking systems

Fabrication of microscale PV cells

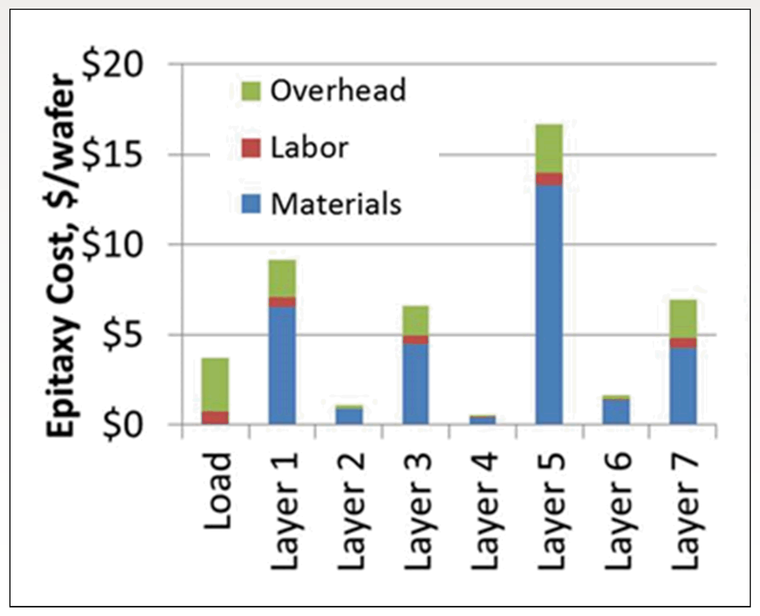
Cell fabrication process

(1) Create cell junctions on Si
(2) Deposit III-V semiconductor junctions on GaAs substrates
(3) Define III-V cells via etching
(4) Release cells from GaAs and transfer to sparse array on Si
(5) Deposit metal cell contacts



Benefits of microscale PV cells

- Leverages high-volume semiconductor processing tools
- Enables re-use of GaAs substrates for III-V semiconductor epitaxy



Model output: III-V semiconductor deposition

Cell fabrication cost modeling

- Model was constructed to represent each step in cell fabrication process
- Contributions from raw materials, capital costs, labor, overhead, and consumables
- Model inputs: Materials costs, tool cost, and performance parameters

Tool cost and performance data provided by : Applied Materials, SPTS, Plasma-Therm, Temescal, and SAMCO

Parallel cell placement

The hybrid design requires transfer of closely packed cells to a sparse array

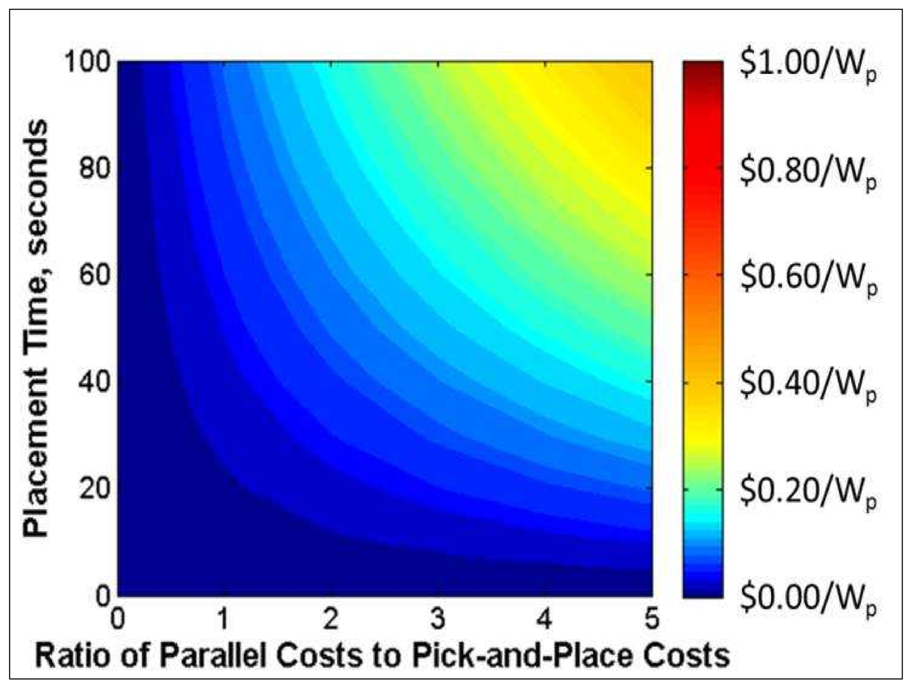
- Conventional "pick-and-place" tools used in microelectronics industry transfer one part per operation at high speed → several parts per second
- Large number of placements per module for microscale PV would result in significant pick-and-place costs → ~$0.40/W$_P$
- Several concepts are under development for massively parallel cell transfer

Cost to place one cell, CU:

$$CU = CT/(L \times P\ /\ T)$$

CT: Total capital and operating cost over lifetime of tool, *L*
P: Number of cells transferred per operation
T: Time for one operation

Parallel placement methods increase *P*, but *CT* and *T* are not yet known → parameterize



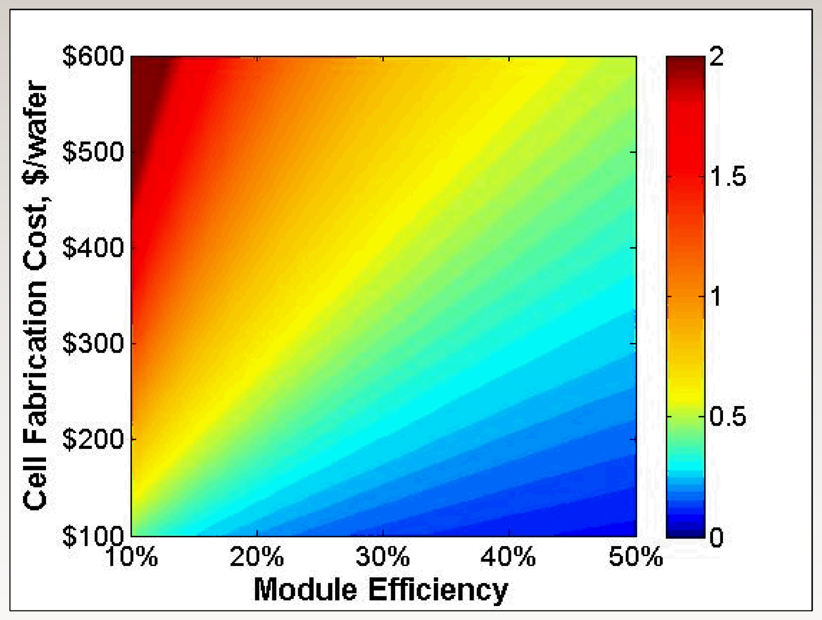
Conclusion: Massively parallel placement techniques have the potential to reduce placement cost by an order of magnitude vs. pick-and-place tools, even for cycle times in the tens of seconds and higher total costs

Cost and performance trade-offs

Optimal number of microscale PV cell junctions

The cost of adding a junction to the compound semiconductor stack must be offset by the benefits of increased efficiency; cost reduction due to increased efficiency depends on the total cost of the system, including installation and maintenance throughout the system lifetime.

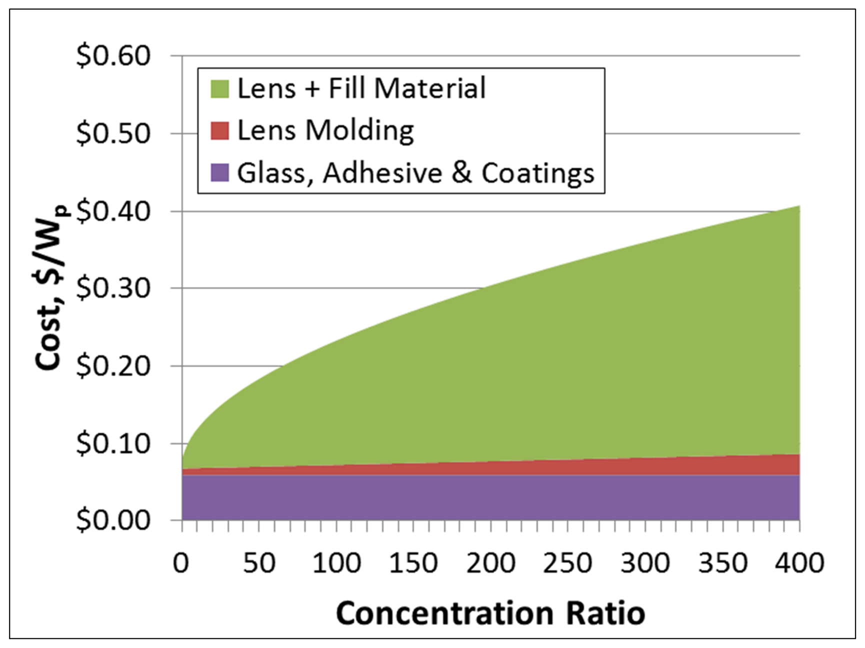
The cell fabrication cost model yields cost estimates on a per-wafer basis. Cell cost per Watt for various cell architectures – spanning the range of potential numbers of junctions – may be represented as points on a plot such as shown in the figure at right.



Cell costs as a function of cell fabrication cost ($/wafer) and module efficiency at a concentration ratio of 200X.

Selecting cell size and concentration ratio (CR)

For each potential cell architecture, the costs of the cells and the optics must be balanced by adjusting the concentration ratio and cell size, taking into account the desired performance of the module in terms of thickness, weight, and acceptance angle.



Cost of microscale PV optical system as a function of concentration ratio. Cell size is 250 µm.

As concentration is increased

- The total cost of cells decreases due a reduction in total cell area
- The thickness of the concentrating optics increases, leading to increases in weight and cost (see figure at left)
- The acceptance angle of the concentrating optics is reduced

The concentration ratio that minimizes cost may not be the preferred option if a premium is placed on size/weight or optics acceptance angle

Conclusions

Hybrid microscale PV represents a new PV architecture that is well-suited to applications requiring high energy production per unit area. The miniaturization of PV cells enables highly efficient conversion of direct solar radiation in modules featuring a size and profile similar to conventional silicon PV. Further, the incorporation of conventional PV cells as active substrates yields additional energy production from diffuse radiation, and provides a certain level of electricity production even on cloudy days.

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NNSA National Nuclear Security Administration

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