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Microsystem Enabled Photovoltaics

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MEPV Program Overview

- Initial ideas in 2005
- First funds in (EERE Solar Program) in 2007
- Total program funds to date: ~$20M
  - Sandia LDRD, EERE Solar Program, Army, ONR, NASA
- ~30 member diversified team at Sandia
- Many industry, university, and national laboratory partners
- ~45 patent applications filed
- ~60 technical publications
- Complete system-level R&D program
  - Cells: c-Si, GaAs, InGaP, InGaAs, InGaAsP, InGaN, CdTe
  - Optics: AR coatings, concentration, light trapping, etc.
  - Module design and manufacturing
  - Power electronics
  - Tracking
  - Cost modeling
  - Accelerated lifetime testing and failure analysis

Scaling Benefits of Micro-Scale PV

1. Enhanced Carrier Collection due to short diffusion lengths [2]
2. Statistical minimization of semiconductor defects per cell [2]
3. Reduced semiconductor material usage [1]
4. Fabrication possible with arbitrarily large wafers [1]
5. Reduced edge exclusion area for CPV cells [1 * †]
6. Back Contacts/no metal shading lines for c-Si *and* III-V [1,2]
7. Multi-junction cell architectures are possible that eliminate the need for lattice matched semiconductors or metamorphic epitaxial layers [1,2,3]
8. Multi-junction cell architectures are possible that eliminate the need for current matching between individual junctions [1,2,3]
9. Cells/modules utilize existing manufacturing facilities and supply chains in the Integrated Circuit, MEMS, LED, and Electronics Assembly industries [1]
10. Extremely flexible PV modules (1 mm bend radius) with high efficiency, single crystal semiconductor solar cells [2,3 † ‡ ♦]
11. 3D molding of the PV arrays is possible due to small, discrete cells making possible PV integration into products/systems in a way not possible with traditional PV [3 † ‡ ♦]
12. High optical concentration (up to 600X or more) within a thin (~1cm) module [1,3 * †]
13. High optically efficient optics (refractive optics instead of Fresnel optics) for concentrated systems [2 * †]
14. More sophisticated optical systems are possible which allow a larger acceptance angle than traditional CPV (reduces tracking portion of BOS costs) [1,2 *]

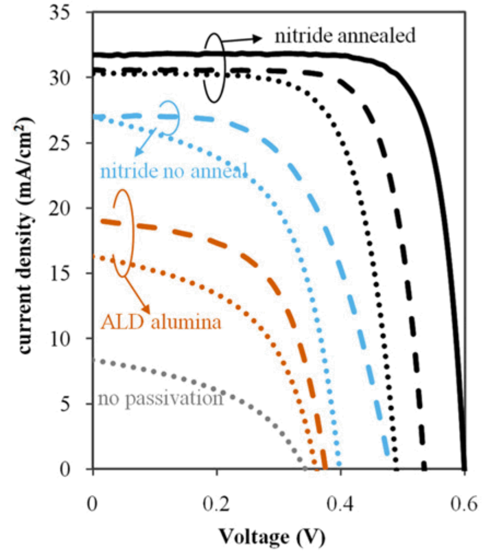
Category(s) of scaling benefits:
1 Cost reduction
2 Improved Performance
3 New Functionality

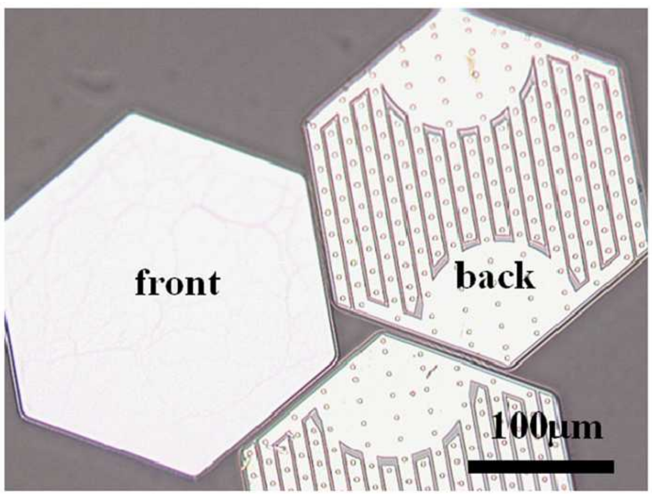
15. Heat rejection capacity significantly enhanced reducing or eliminating thermal management structures in CPV [1,3 * †]
16. Many small cells allows new interconnect networks (instead of simple series connections) between cells that provide optimal partial shade tolerance and robustness to damage, opens, shorts, failed cells, or variations in cell performance. [2,3]
17. Manipulation of optical coatings to create sophisticated images is possible due to the combination of manufacturing techniques, cell size, and interconnects [3 † ‡]
18. Interconnect designs are possible that allow elimination or significant reduction of bypass protection diodes. [1,3]
19. Interconnect designs for electrically independent cells allows for simple, passive voltage matching between different junctions within a module of different junction types [1,2,3]
20. Direct high voltage output (up to 1000V or higher) from a module is possible which reduces internal resistive losses and system wiring costs [1,3]
21. Active semiconductor devices can be placed within the module to allow "on-the-fly" switching of output voltages with high efficiency and low cost [1,3]
22. New, module-integrated inverter architectures are possible that eliminate or reduce large discrete components (inductors and capacitors) that current inverters require [1,2,3 * †]
23. Improvements in cell, optics, and inverter efficiencies reduces BOS cost components dependent on system efficiency (e.g., land and land prep, installation labor, racking/trackers, wiring, O&M, shipping, etc.) [1,2 *]

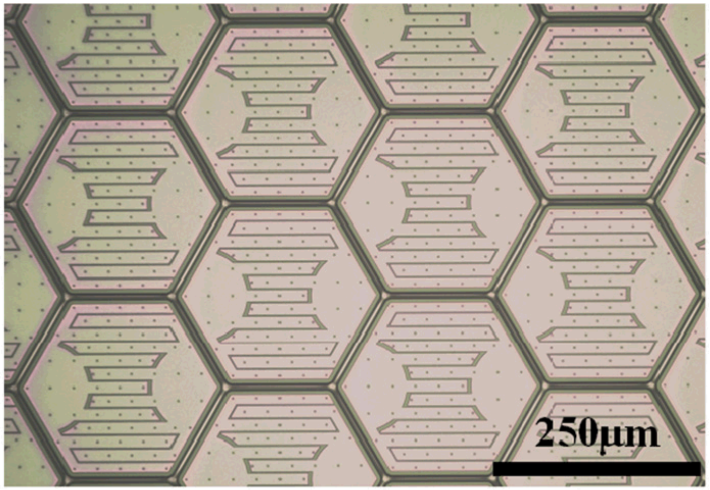
Application space benefiting from scaling effect (if all applications benefit no application is indicated):
* Grid-tied PV (Utility/Commercial)
† Grid-tied PV (BIPV)
‡ Flexible/Conformal PV (mobile)
♦ Flexible/Conformal (Space)

C-Si Cell Results

- C-Si interdigitated back contact (IBC) cells 14-20 mm thick, 200-700 mm across.
- Cell efficiencies up to 14.9%.
- Prototype modules created with up to approximately 500 interconnected cells.
- Module efficiencies up to 13.75%.
- Manufactured with methods allowing wafer reuse and/or conservation of c-Si material.







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J. L. Cruz-Campa, et al., “Ultrathin flexible crystalline silicon: microsystems enabled photovoltaics,” IEEE Journal of Photovoltaics, **1**, pp. 3-8, 2011.

Cell Results

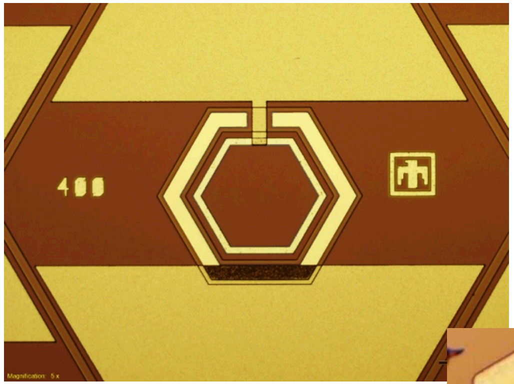
InGaP/GaAs:Si

- Developed GaAs and InGaP/GaAs single-side contacted cells
- Bonded GaAs and InGaP/GaAs cells to silicon and fully processed
- Demonstrated active (i.e., power producing Si cell as part of InGaP/GaAs:Si cell stack
- Achieved a 29.5% InGaP/GaAs cell efficiency bonded to an active silicon cell (not included in efficiency).

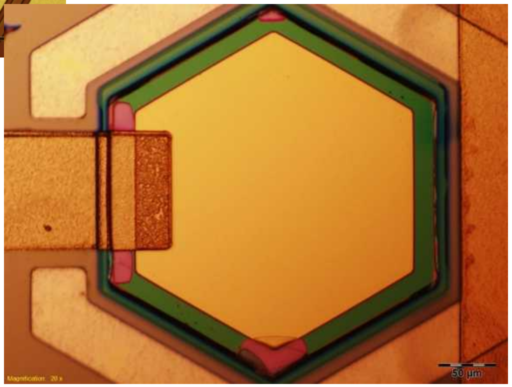
InGaP/GaAs cell on Si

Si:InGaAsP/InGaAs

- Developed both InGaAs and InGaAsP/InGaAs cells
- Bonded InGaAs and InGaAsP/InGaAs cells to silicon and fully processed
- InGaAs cell behind silicon achieved 3% conversion efficiency at one-sun



InGaAs solar cell on InP substrate

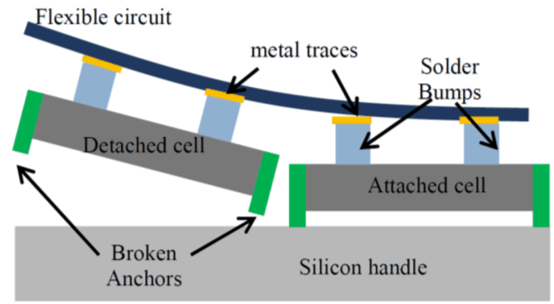


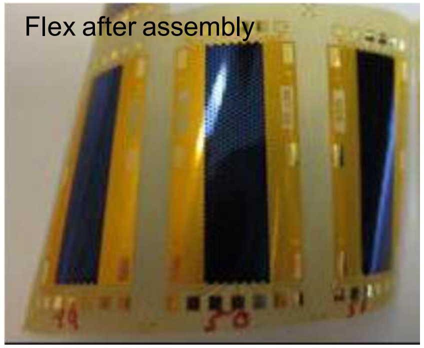
InGaAsP/InGaAs cell bonded to Si

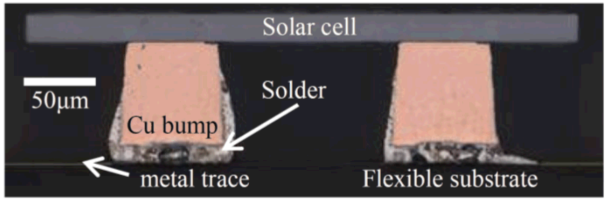
Tauke-Pedretti, et al., "Bonded InGaAs cells for microsystem enabled photovoltaics," IEEE PVSC, pp. 546-549, 2014.
J. L. Cruz-Campa, et al., "Back-contacted and small form factor GaAs solar cell," 35th IEEE PVSC, pp. 1248-1253, 2010

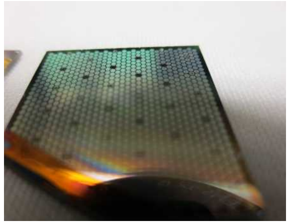
Cell Assembly

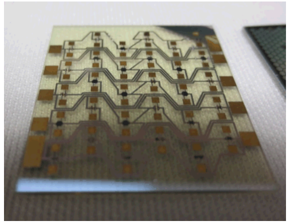
- **Pick-and-Place**
  - Industry standard
  - Serial assembly
  - Not compatible with thin III-V cells
- **Bump-Bond and Peel**
  - Parallel assembly
  - Limited to wafer size
  - Sparse and dense cell arrays
- **Activated Bond/ELO release**
  - Parallel assembly
  - Limited to wafer size
- **Self-Assembly**
  - Unlimited assembly area
  - Allows dissimilar wafer sizes
  - Challenging technical issues







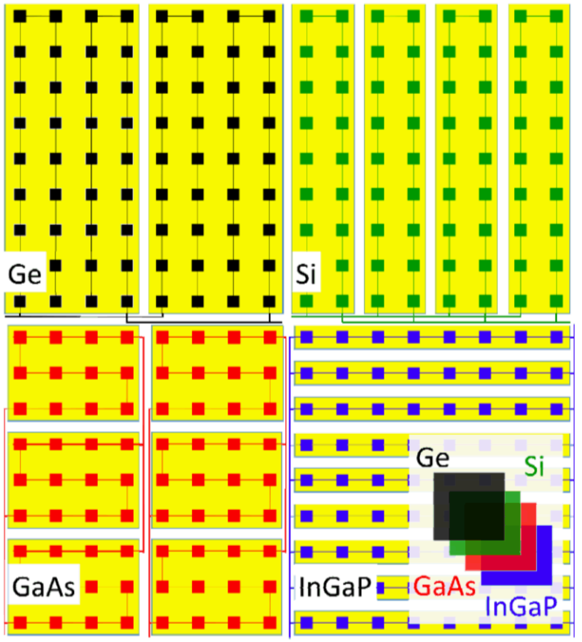


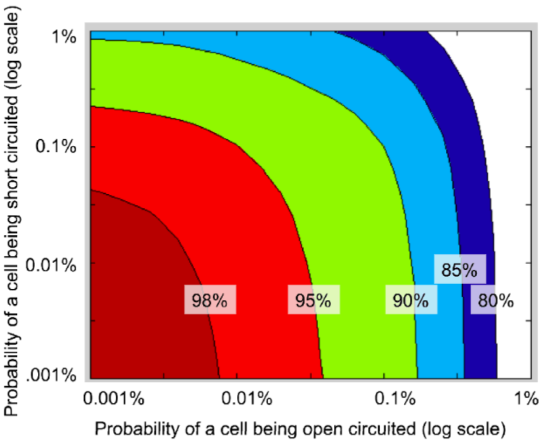


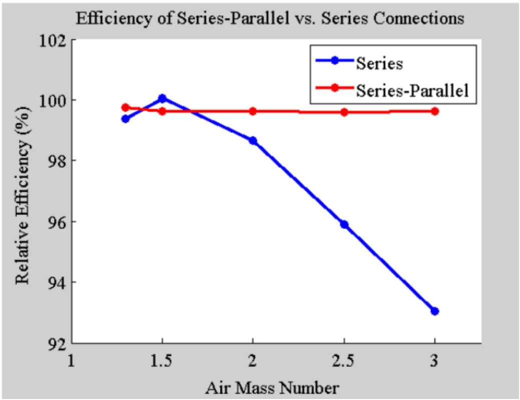
G. N. Nielson, et al., "216 cell microconcentrator module with moderate condentration, +/- 4° acceptance angle, and 13.3 mm focal length," IEEE PVSC, pp. 465-469, 2013.
J. L. Cruz-Campa, et al., "Ultra-thin single crystal silicon modules capable of 450 W/kg and bending radii < 1 mm: fabrication and characterization," 39th IEEE PVSC, pp. 1218-1223, 2013.
N. B. Crane, et al., "Self-assembly in additive manufacturing: opportunities and obstacles," Rapid Prototyping Journal, pp. 211-217, 2011.
J. L. Cruz-Campa, et al., "Self Assembly of Micro Photovoltaic Devices for Inexpensive Solar Energy," Self-Assembly of Materials Workshop, 2011.

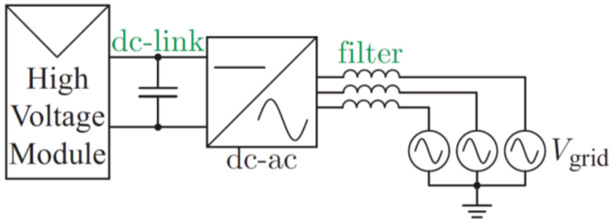
Cell Interconnects

- **Series/Parallel Connections**
  - Improves damage tolerance
  - Improves performance in partial shade
- **Independently connected multi-junction cells**
  - Improves performance under spectral variations
  - Allows greater flexibility in PV cell bandgaps
- **Parallel, Interleaved 3-phase Inverter**
  - Simplified AC module architecture with improve efficiency and reliability at lower cost







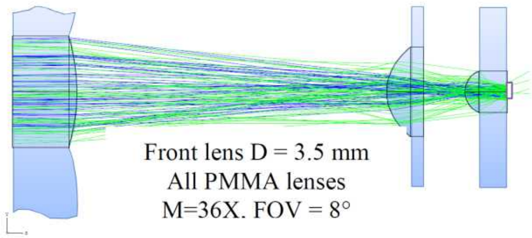


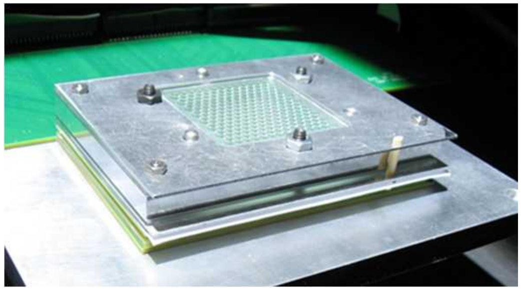
A. L. Lentine, et al., "Optimal cell connections for improved shading, reliability, and spectral performance of microsystem enabled photovoltaic (MEPV) modules," 35th IEEE PVSC, pp. 3048-3054, 2010.
B. Johnson, et al., "A single-stage three-phase AC module for high-voltage photovoltaics," 27th IEEE APEC, pp. 885-891, 2012.
A. L. Lentine, et al., "Enhanced efficiency for voltage matched stacked multi-junction cells: Optimization with yearly temperature and spectra variations," 39th IEEE PVSC, pp. 788-791, 2013.

Optics/Prototypes

Prototype I

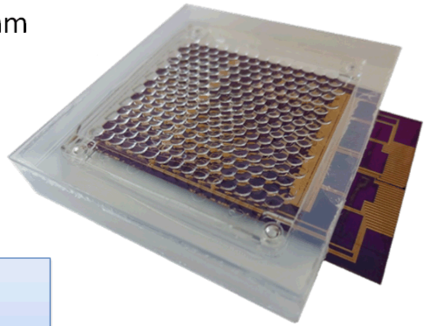
- 50X concentration
- 8° acceptance angle
- 60% optical transmission
- 3 lens optical system
- 13 mm focal length
- Module thickness ~20 mm
- Module efficiency: 6%

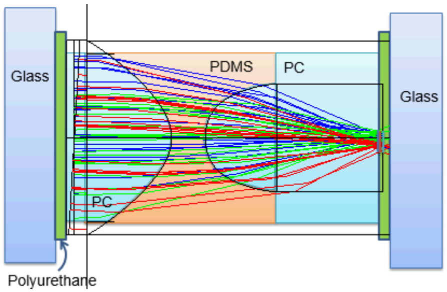




Prototype II

- 100X concentration
- 4.5 degree acceptance angle
- 90% optical transmission
- Immersion lens system (no air gap)
- Short focal length (~5 mm)
- Demonstrated parallel manufacturing of cells in sparse array
- Hybrid architecture (diffuse and direct collection)
- Module efficiency: 20%
- Module thickness of ~10 mm





B. H. Jared, et al., "Micro-concentrators for a microsystems-enabled photovoltaic system," Optics Express, **22**, pp. A521-A527, 2014.
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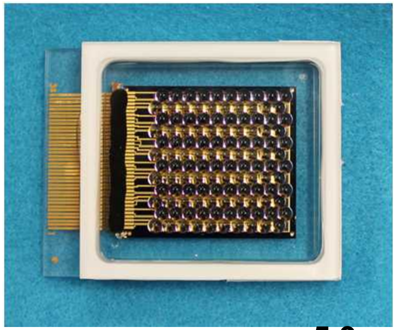
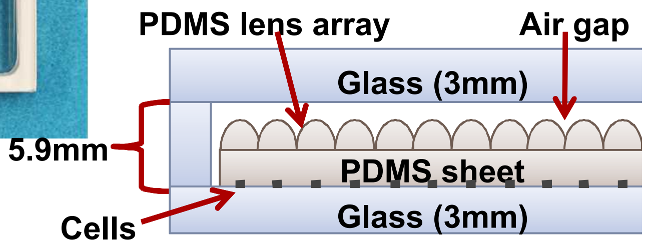
W. C. Sweatt, "Micro-optics for high-efficiency optical performance and simplified tracking for concentrated photovoltaics (CPV)," International Optical Design Conference, pp. ITuC4, 2010.
W. C. Sweatt, et al., "Photo-voltaic system using micro-optics," Optics for Solar energy, pp. SM2A, 2012.

Optics/Prototypes

Prototype III

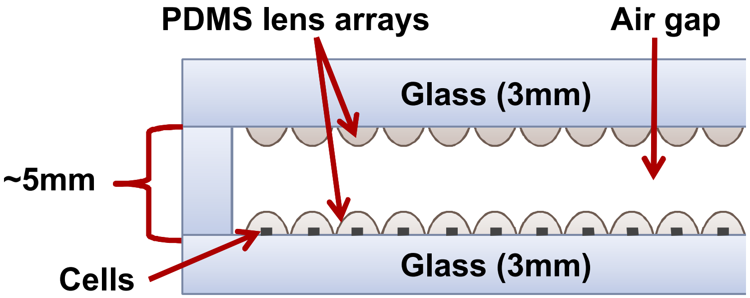
- 200X concentration
- 3 degree acceptance angle
- Simple single lens element
- Short focal length (~5 mm)
- 90% optical efficiency (not demonstrated)
- Hybrid architecture (direct/diffuse collection)
- Potential module efficiency of up to 30% with project cells (up to 40% with optimized cells)
- Module thickness of ~12 mm





Prototype IV (not built)

- 200X Concentration
- > 3° acceptance angle
- 2 lens element
- 5 mm focal length
- 90% optical efficiency
- Hybrid architecture possible
- Potential module efficiency up to 40%
- Module thickness ~12 mm
- Reduced optics materials costs
- Reduced module complexity
- Reduced cell manufacturing complexity



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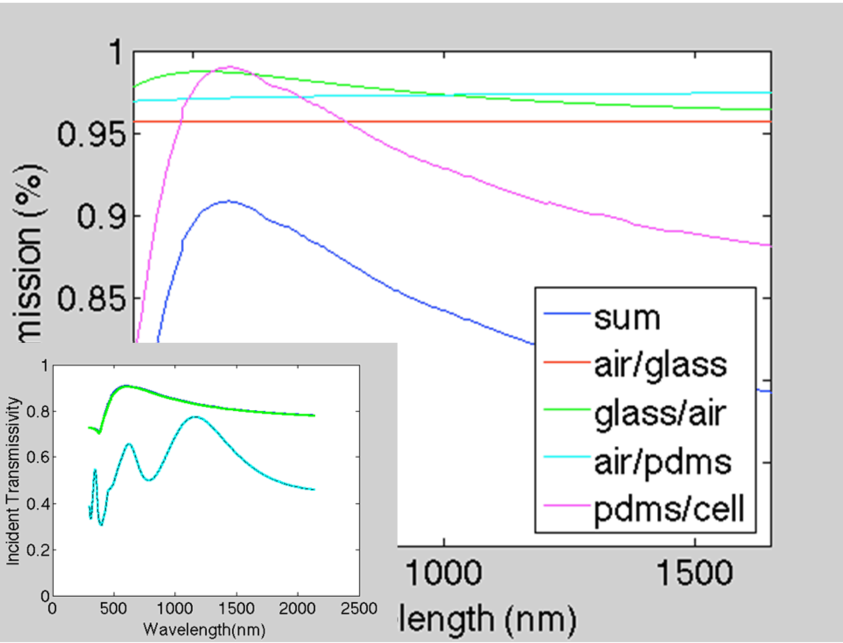
W. C. Sweatt, "Micro-optics for high-efficiency optical performance and simplified tracking for concentrated photovoltaics (CPV)," International Optical Design Conference, pp. ITuC4, 2010.
W. C. Sweatt, et al., "Photo-voltaic system using micro-optics," Optics for Solar energy, pp. SM2A, 2012.

Expected Module Efficiency: Prototype 3

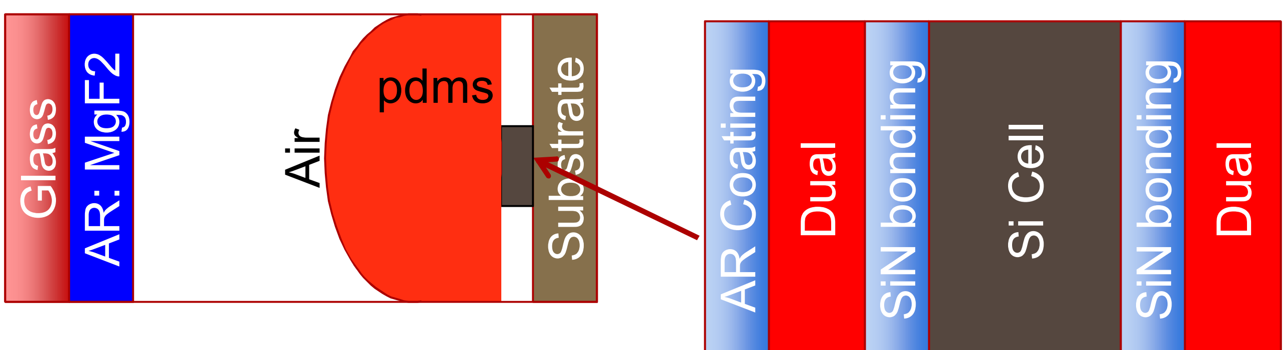


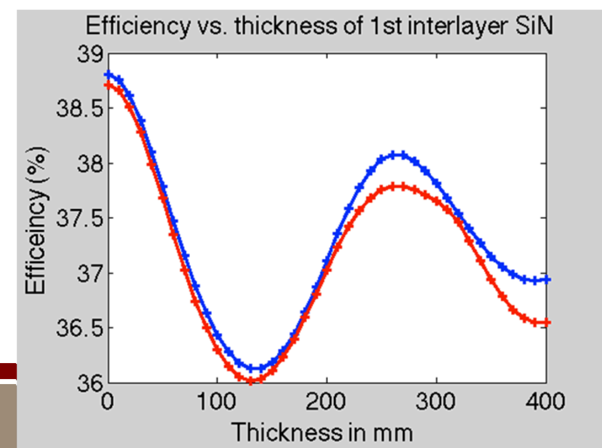
- One sun efficiency fit estimates:
  - Measured InGaP/GaAs > 29% at 100X
  - Good Si ~ 20%, C=1
  - Measured InGaAs ~ 2.9% after Si
- Optical Loss = 13.8% (380-1127 nm, incl. AR)
  - Improved 2% excess loss!
  - 380nm wavelength cutoff
- P3 (100X) expected efficiency: 37.8%

  (AM1.5D, 200X/100X cell)
  - Top Dual Contribution: 27.7%
  - Si Contribution: 4.6%
  - InGaAs Contribution: 3.5%
  - Diffuse Light ~2.0%

Glass/AR/Air

GOAL: 40%





Cost Rationale for MEPV R&D

$$LCOE = \frac{NPV[\text{Module Cost} + \text{BOS Cost} + \text{Tracker Cost} + \text{Installation Cost} + \text{O\&M Cost}]}{NPV[\text{Energy generation}]}$$

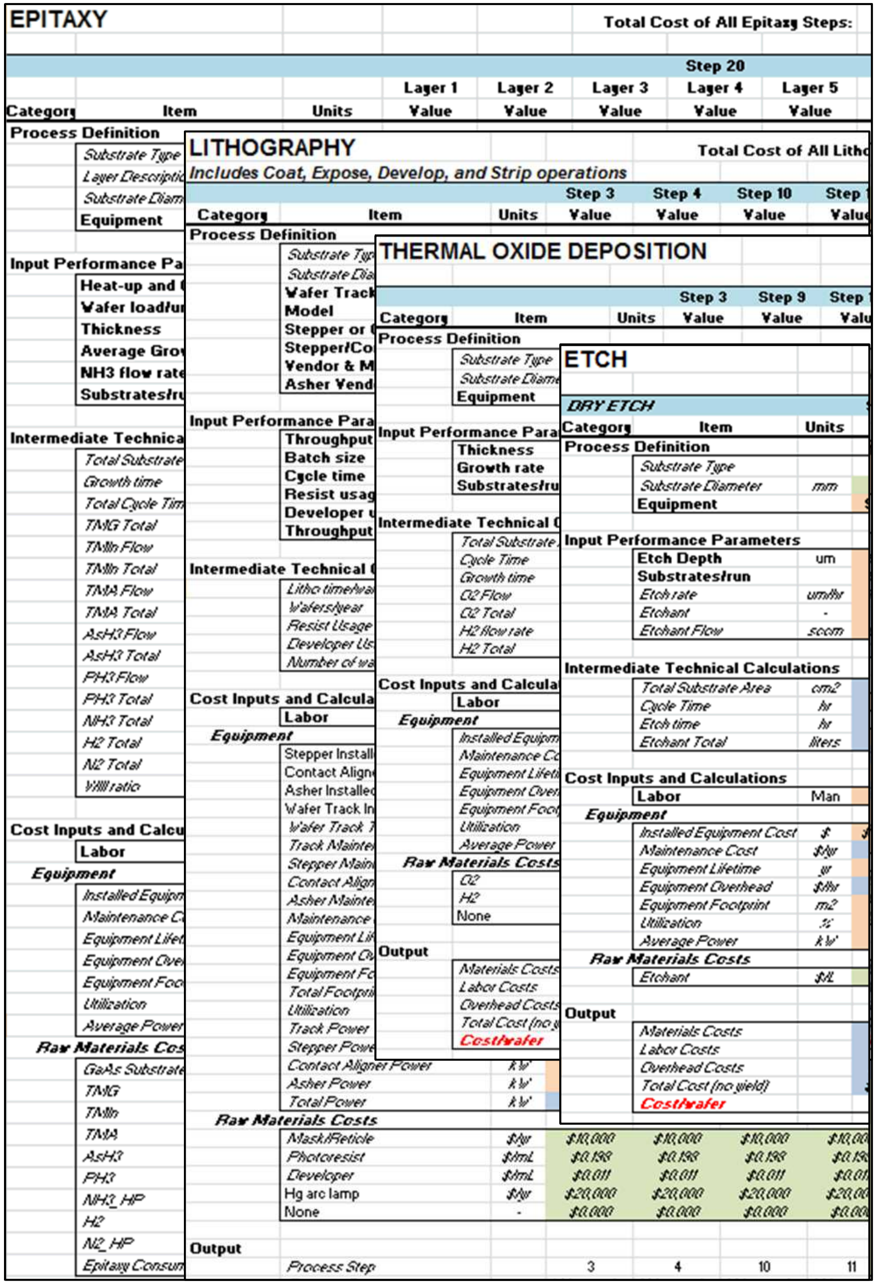
Lower costs

Increase energy generation

LCOE Component	PV	CPV	MEPV
Module Cost	Low	High	TBD
Tracker Cost	Low	High	Low
Installation Cost	Low	High	Low
O&M Cost	Low	High	Low
BOS Cost	High	High	TBD
Energy Generation	Low	High	High

Cost Modeling Effort

- Completed multi-junction cell cost model
- Employed cost model in cost-benefit analysis of additional junctions
- Investigated cost implications of alternative module architectures
- Leveraged previous modeling efforts to arrive at a “final” MEPV cost
- Identified potential pathways for future MEPV cost reductions



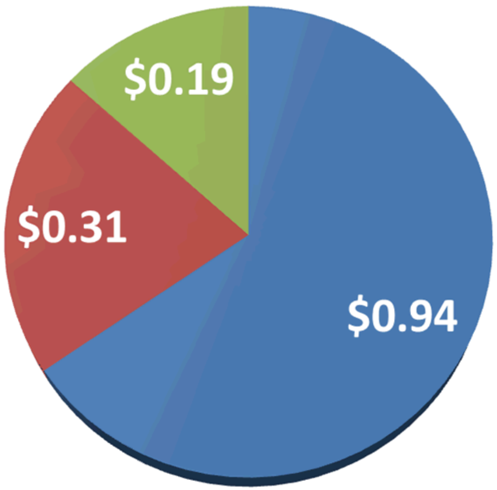
Overview of MEPV module costs

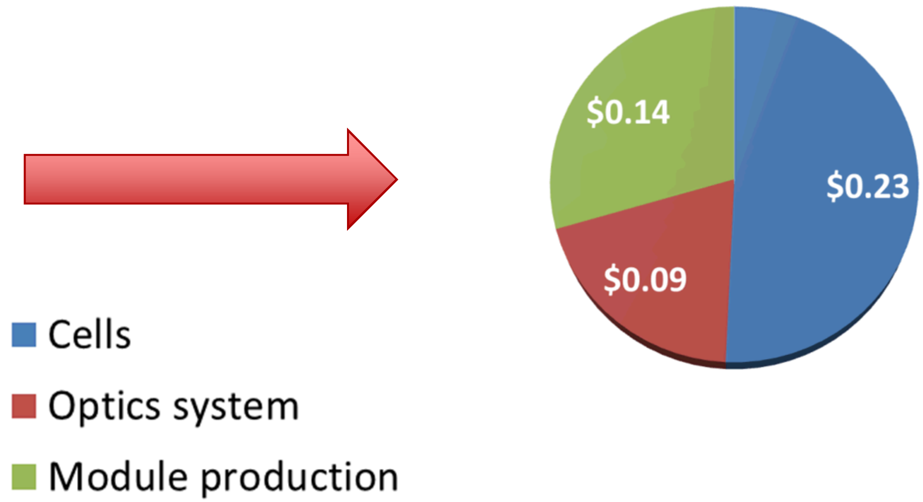
Prototype 3

Current estimate: **$1.44/W$_p$**

Prototype 4

2020 estimate: **$0.46/W$_p$**

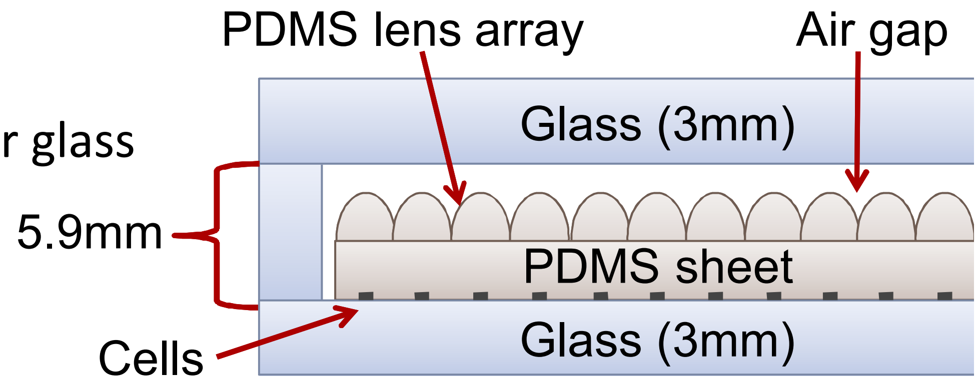




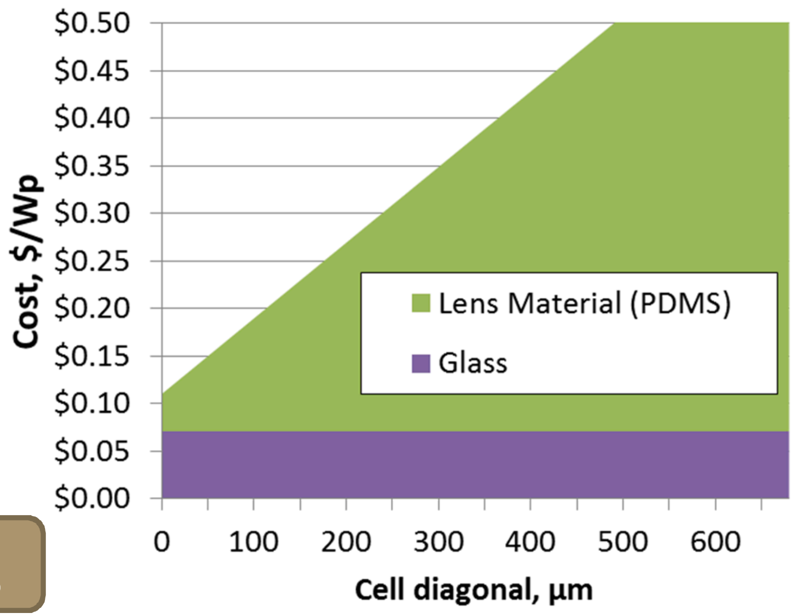
- Fabrication of cells represents largest cost
  → Also the largest potential near-term cost reductions

Prototype 3 optics cost

- Prototype 3 architecture
  - PDMS sheet & lens array on rear glass
  - Front glass protects lenses
  - Concentration ratio (CR) = 200X



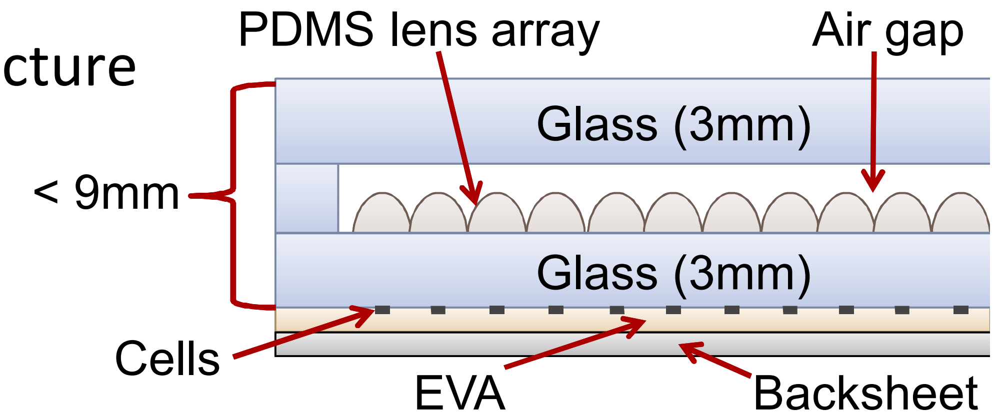
- Prototype 3 advantages
  - Lower materials costs
    - Air gap → Eliminate fill material
    - 250µm cell size → Thinner lenses
  - Simple design: PDMS cast on glass
- Key trade-off: Optics vs cell costs



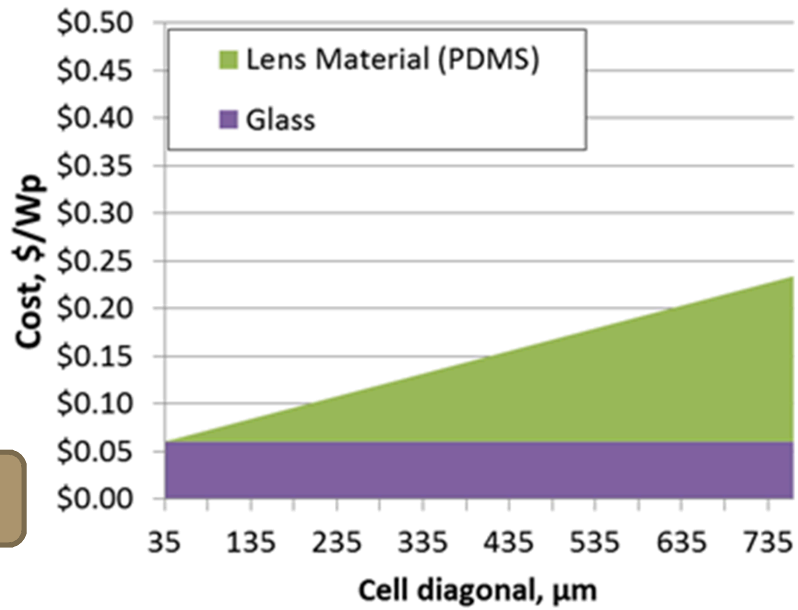
Estimate of current optics costs: $0.31/W_p$

"Modified Prototype 3" optics cost

- Modified Prototype 3 architecture
  - PDMS sheet replaced by glass
  - Front glass protects lenses
  - Concentration ratio = 200X
  - EVA encapsulant and Tedlar backsheet



- Modified Prototype 3 advantages
  - Lower materials costs
    - Replace PDMS sheet with glass
  - Thinner PDMS reduces casting time



Estimate of 2020 optics costs: $0.11/W_p$

"Prototype 4" optics cost

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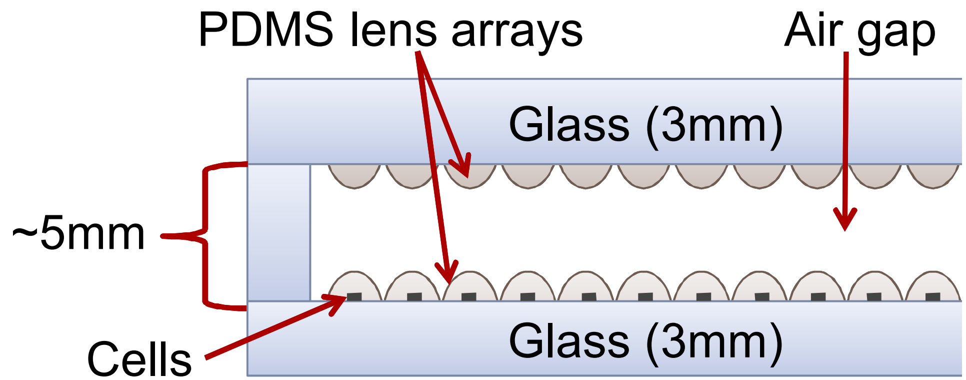
- Prototype 4 architecture
  - PDMS lens arrays on front and rear glass
  - Cells on top of rear glass → no EVA, Tedlar, or frame
  - Concentration ratio = 200X



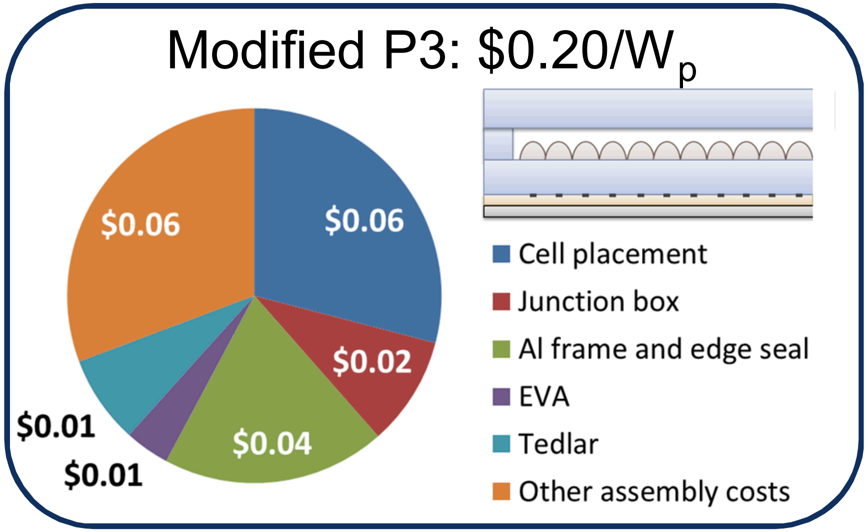
- Prototype 4 advantages
  - Lower materials costs
    - Reduced PDMS usage → $0.04/W_p$
    - No EVA or Tedlar
  - Potential for higher concentration ratio

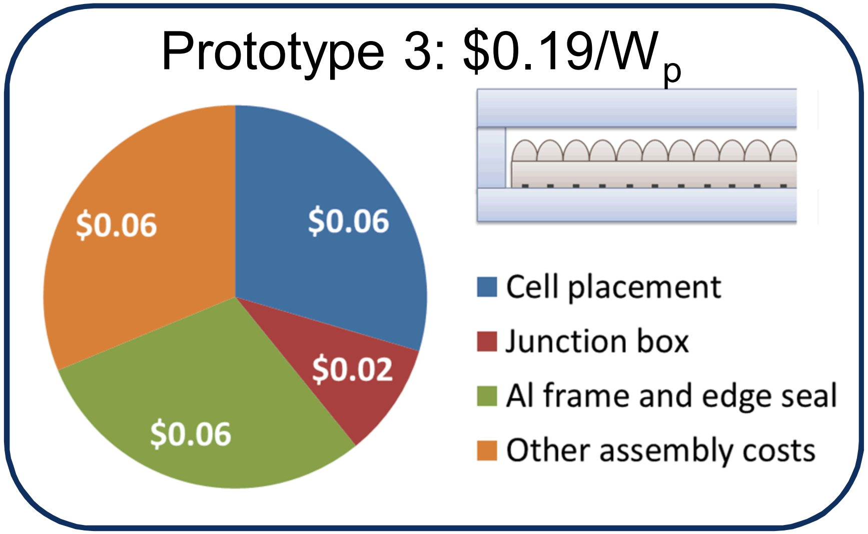
Prototype 4 architecture assumed for 2020 module cost estimates

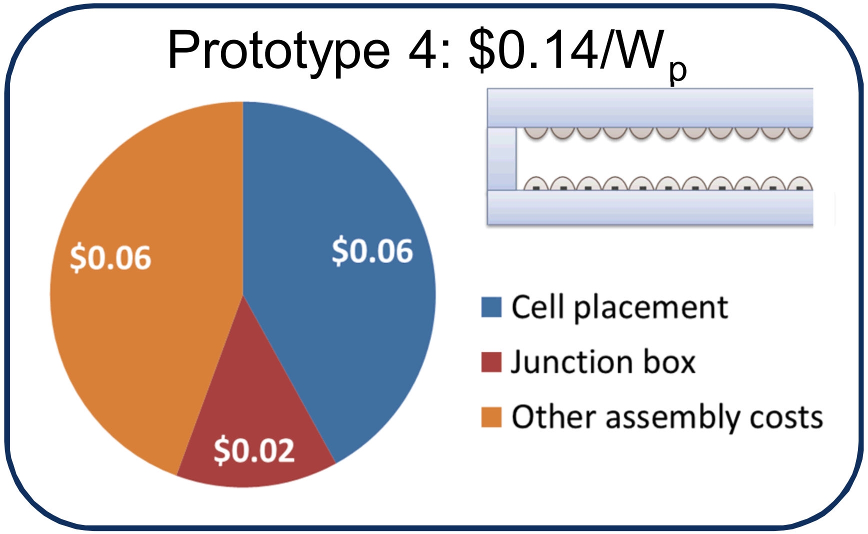
Estimate of 2020 Prototype 4 optics costs: $0.09/W_p$

MEPV module assembly leverages Si PV materials and processes

- Main module assembly steps
  - Screen print interconnects on glass
  - Transfer cells to glass in sparse array
  - Cast PDMS lens array (optics cost)
  - Align and assemble glass sheets
  - Laminate EVA & Tedlar (Modified P3)
  - Install frame (P3) & junction box







MEPV BOS, installation, and O&M costs will not exceed one-sun Si PV costs

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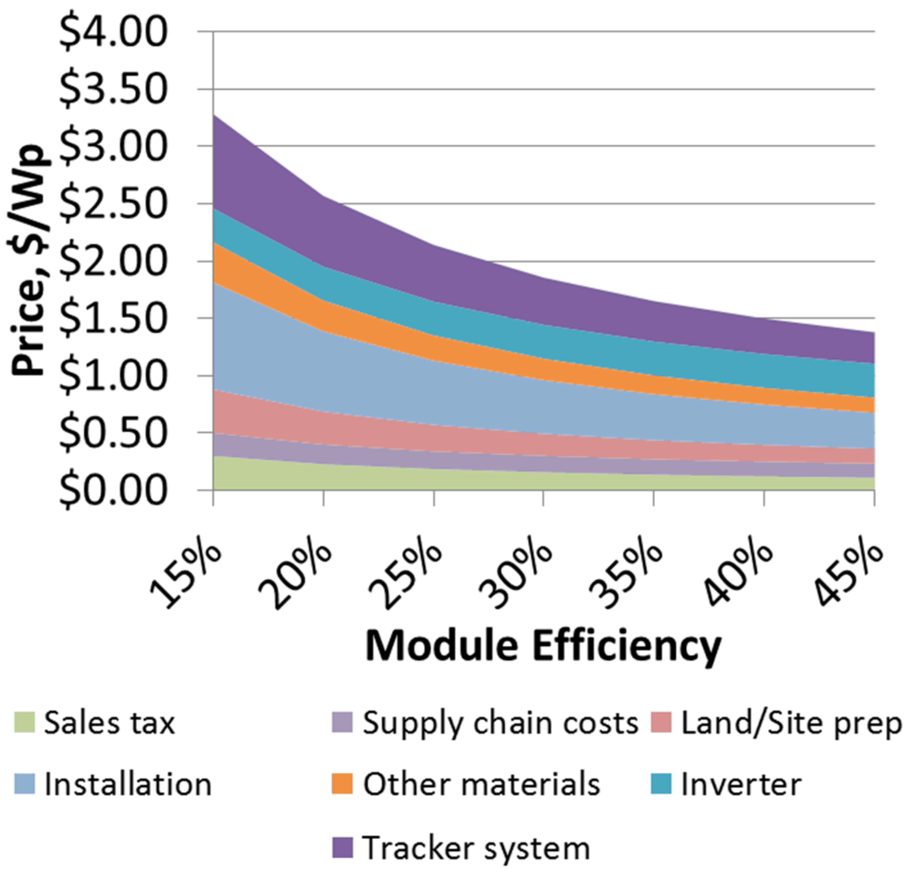
- MEPV form factor and weight is similar to conventional PV
  - No unique installation or O&M requirements
- Higher MEPV module efficiency effectively reduces system costs
- MEPV may reduce BOS costs by
  - Connecting cells in parallel to produce high voltage output, eliminating DC-to-DC converters and thicker, more expensive wiring
  - Enabling module-integrated inverters



The optimal number of junctions depends on assumptions about BOS costs & efficiency

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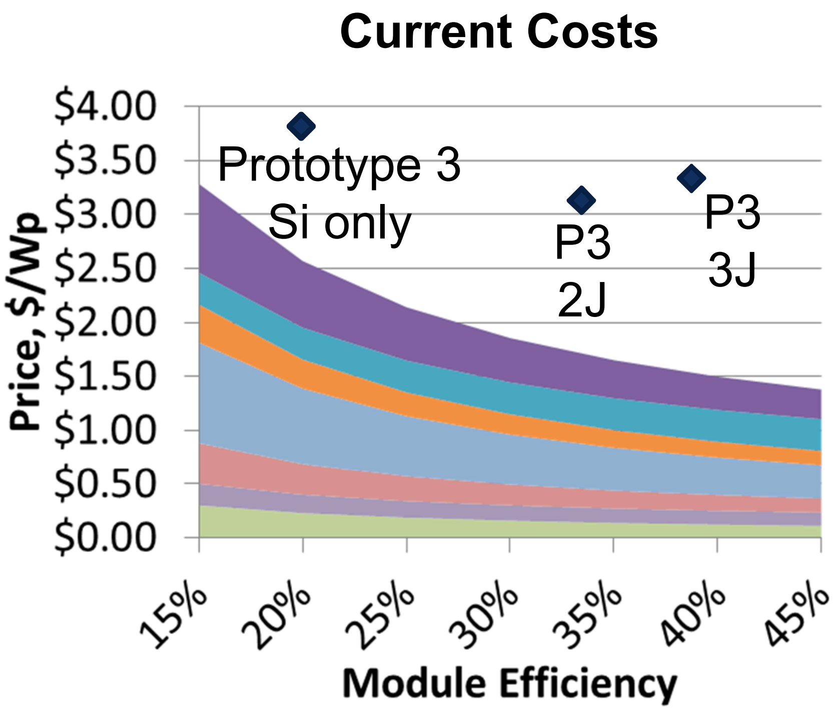
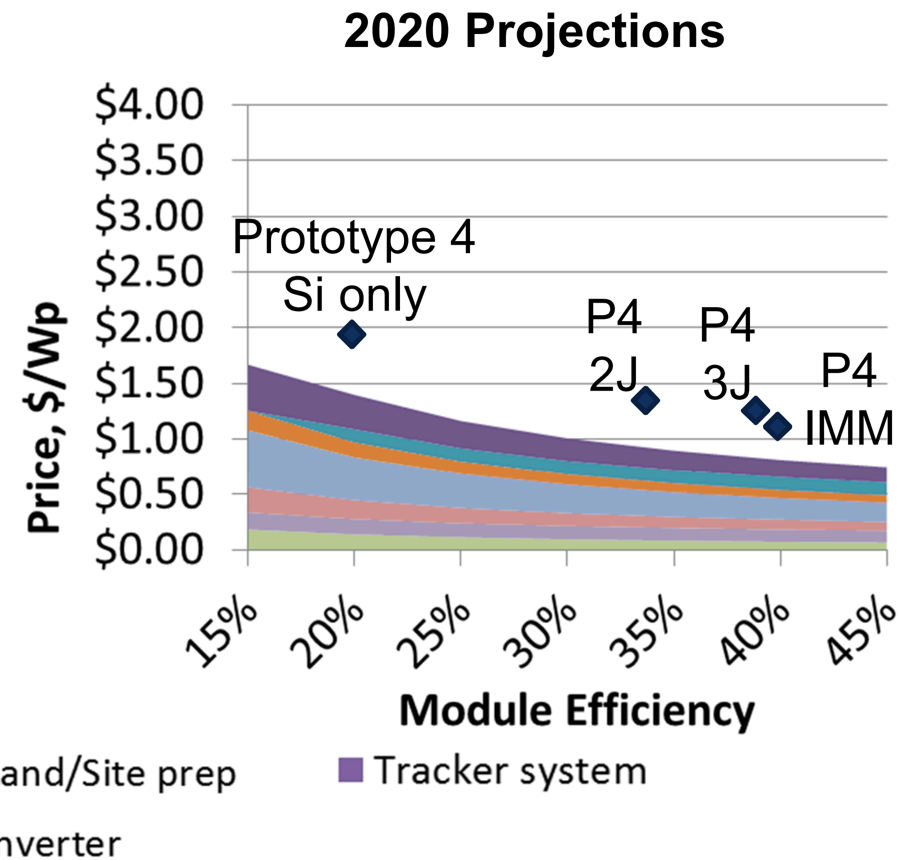




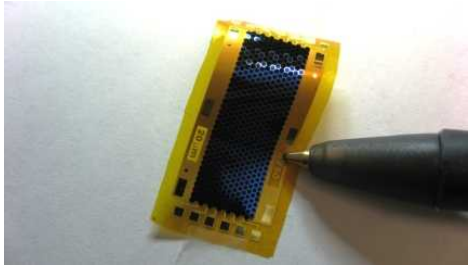
Modules with 3 junctions have the lowest 2020 system cost

Commercialization

- Target cost and performance at product launch date
- Efficiency impact on system cost
  - System cost breakdown
- What is price/performance limit of c-Si?
- Rapid cost reductions create opportunities for module start-ups
- Usage/space constrained rooftops
  - Community Solar (Yeloha)
- Rooftop (distributed) vs. utility solar
- Policy driven industry
- Product test and code requirements
  - UL, IEC, NFPA, etc.

Multiple Power Markets: PV to fit the system

MEPV solar cells can be integrated into flexible and/or moldable polymer substrates for high-efficiency and flexible or 3D conformal applications



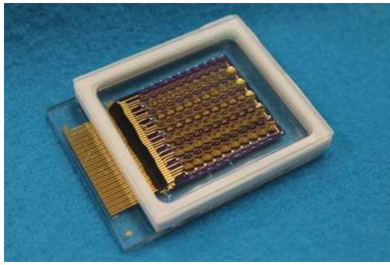
Space (500 kW/yr)
$500 – 1000/$W_{peak}$

Defense (~100 MW/yr)
$15 - 50/$W_{peak}$

Consumer-Logistic (>100 MW/yr)
$15 - 50/$W_{peak}$

Consumer-Mobile (~1 GW/yr)
$5 – 10/$W_{peak}$

MEPV solar cells can be built into a thin concentrator module and sold for solar power applications



Residential Solar Power (>100 GW/year)
$0.10 – 0.20/kWh = ~$2/W_{peak}

Commercial (>100 GW/yr)
$0.10 – 0.20/kWh = ~$2/W_{peak}

Utility (>100 GW/yr)
$0.05 – 0.10/kWh = ~$1/W_{peak}

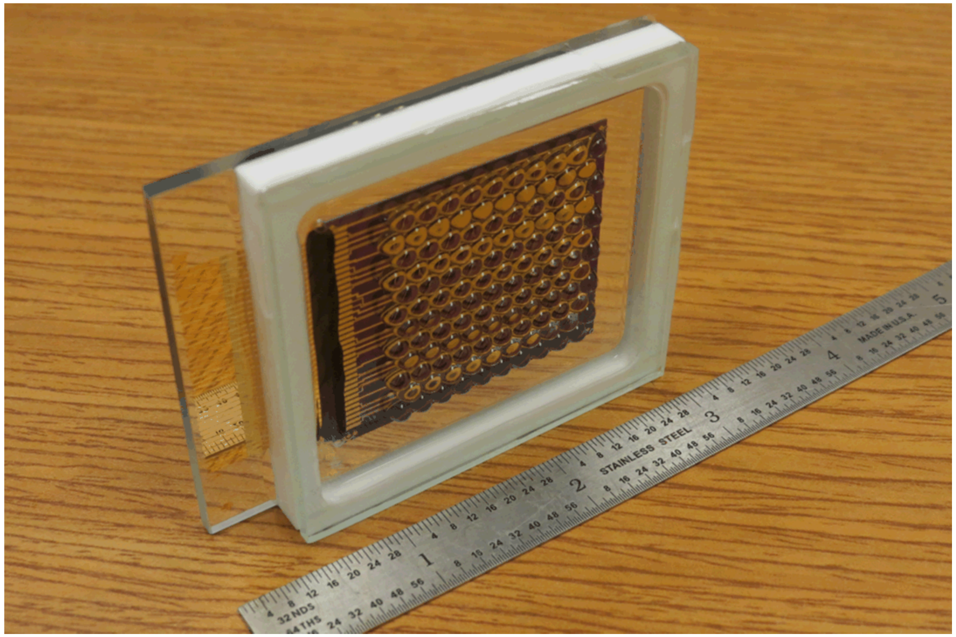
Value of Power

Market Size

Conclusion

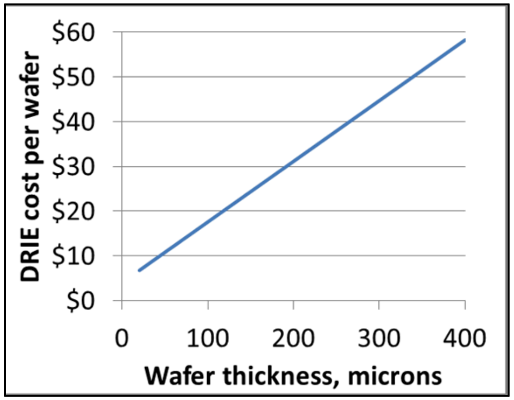
Cost Model

- Costs as low as ~$0.50/Wp are possible with module efficiencies of up to 35-40%
- Further cost reductions are potentially possible with further refinements of overall process flows, process steps, and module designs
- Cell processing, module components, and BOS are based on wafer Si PV where possible so cost reductions achieved by wafer Si PV may also benefit MEPV

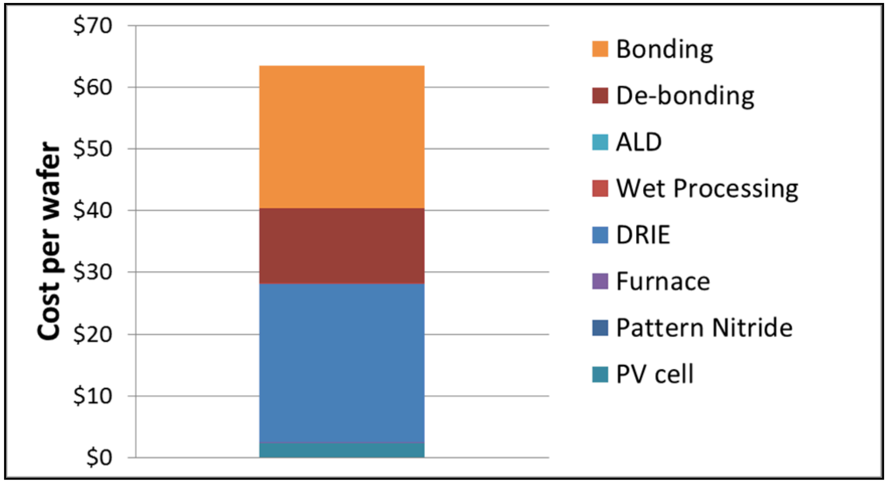


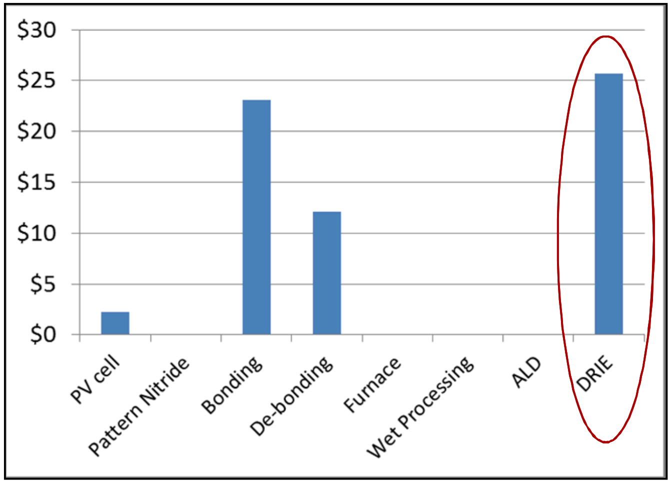
Costs of III-V cell transfer and Si singulation

- Primary costs are temporary bonding/ de-bonding and deep etch to define cells
- Etch (DRIE) cost increases with thickness
  - → Explore options to thin wafer before etch



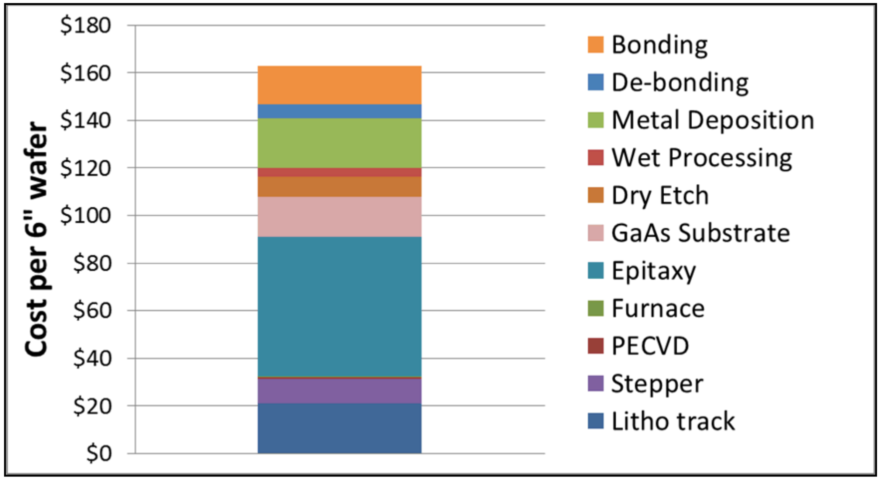
Total cost: $64/wafer

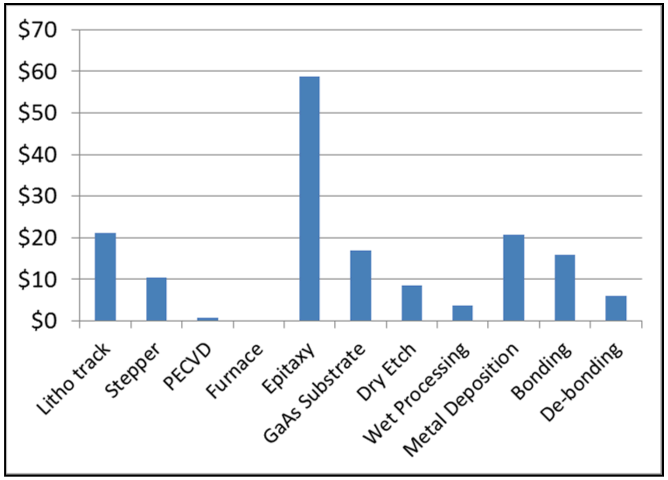




Current III-V processing costs

Total cost: $163/wafer

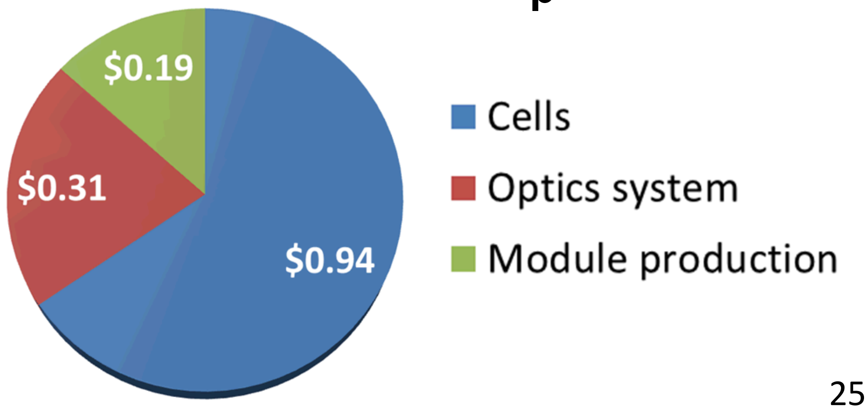




- Epitaxy and GaAs substrates are the largest costs
- Other major costs:
  - Lithography
  - Metal deposition
  - Bonding/de-bonding

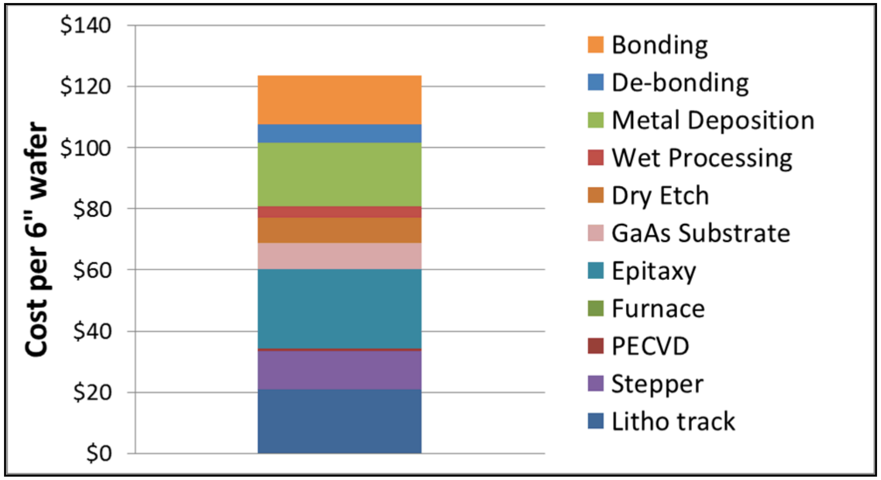
Prototype 3

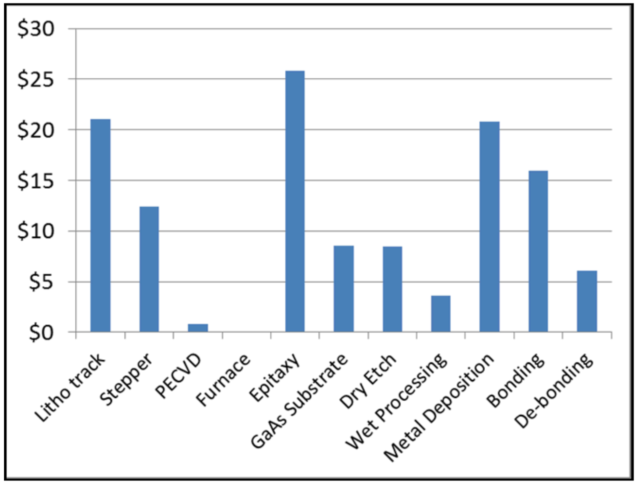
Current estimate: **$1.44/W$_p$**



Projected 2020 III-V processing costs

Total cost: $124/wafer

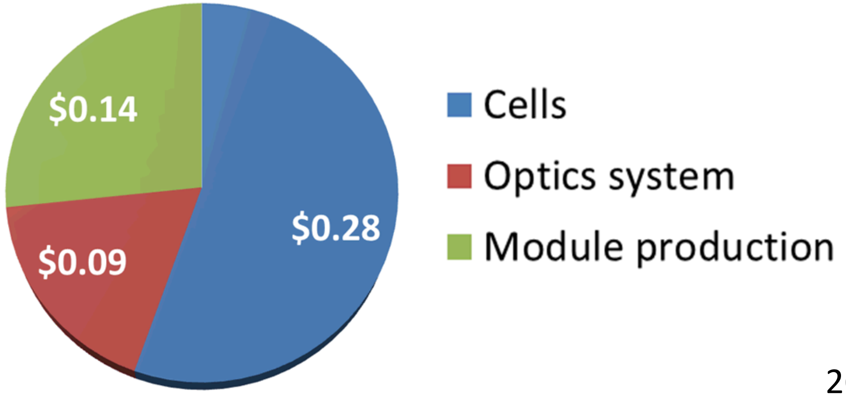




Prototype 4

2020 estimate: **$0.51/W$_p$**

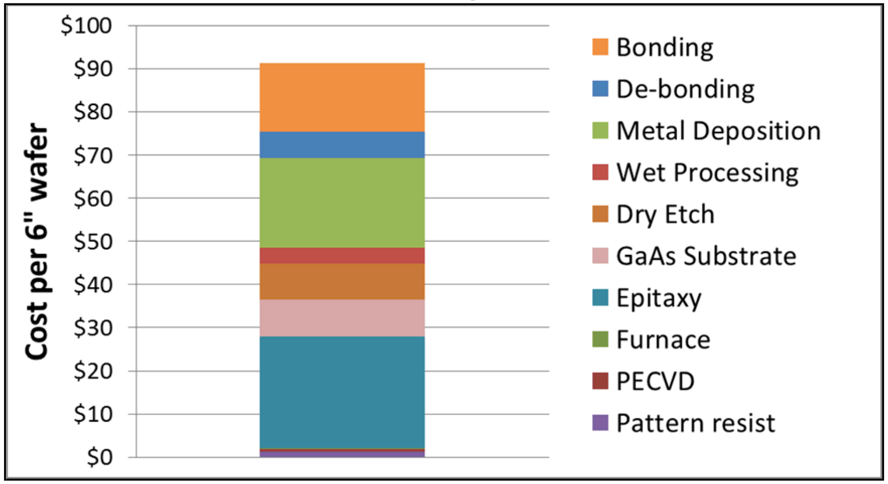
- Epitaxy process improvements specified by tool vendor
- Assume optimization of GaAs substrate re-use
- Also assume a thinner non-illuminated cell border

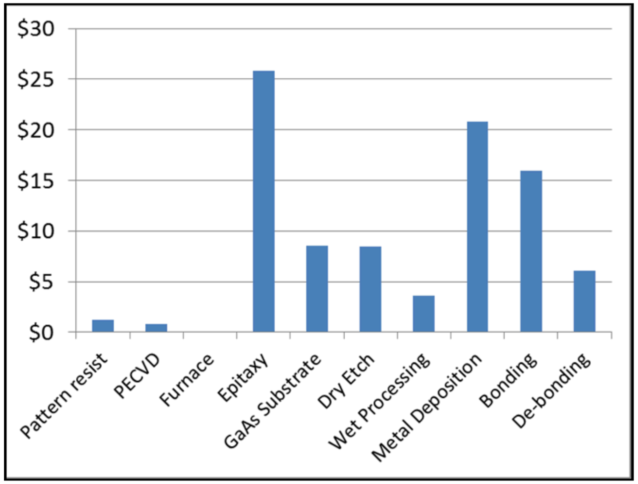


Lithography-free III-V processing costs

Sandia National Laboratories

Total cost: $91/wafer

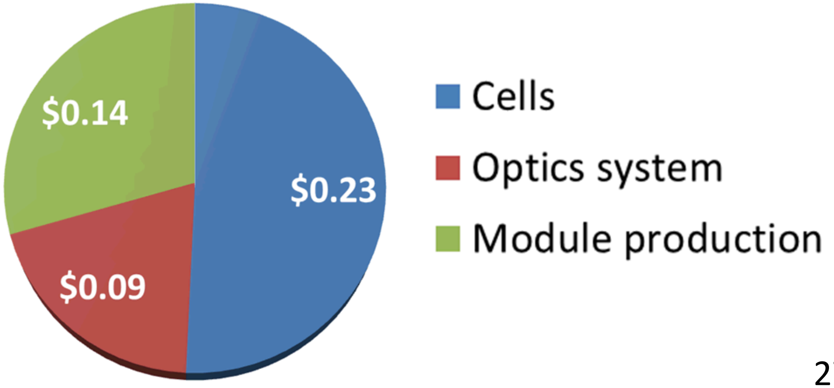




- Alternatives to lithography :
  - Ink-jet printed resists
  - Aerosol printing
  - Laser ablation of nitride
- Each technology is significantly cheaper than lithography
  →lower resolution is acceptable

Prototype 4

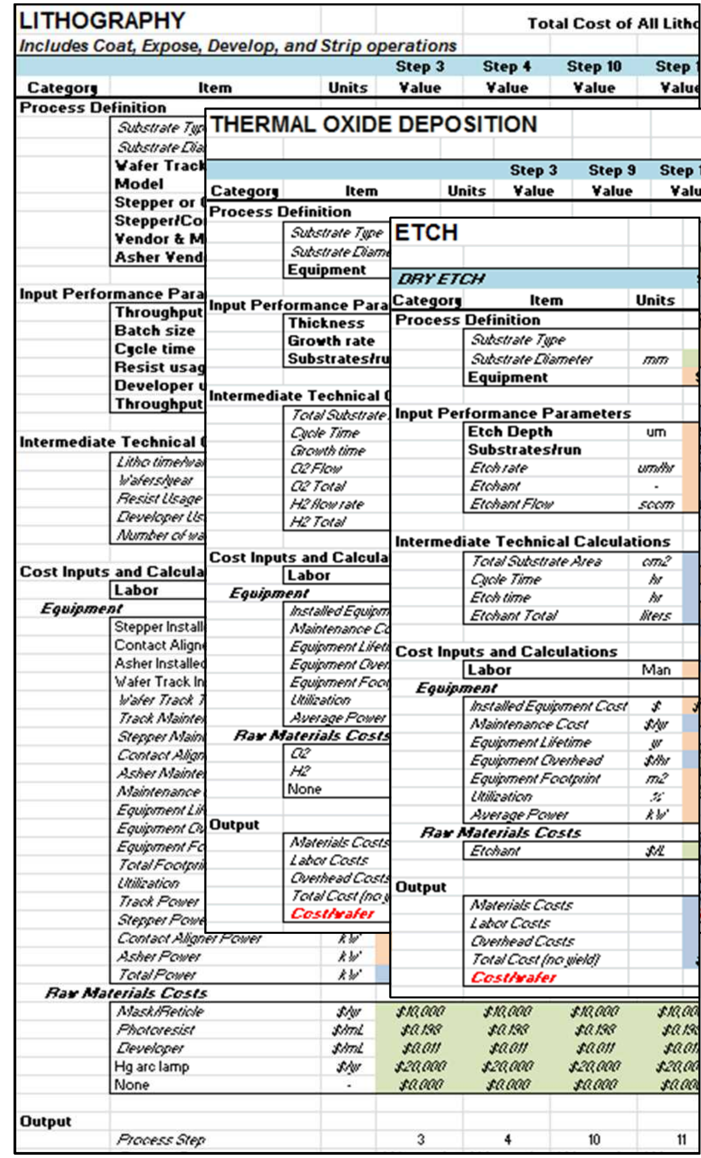
2020 estimate: **$0.46/W$_p$**



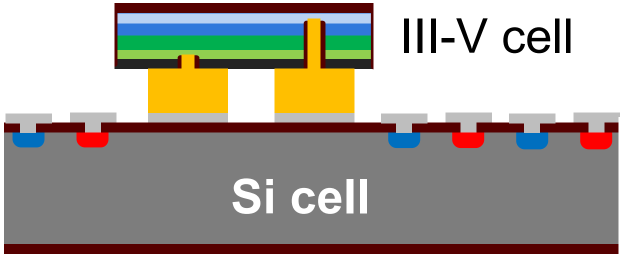
MEPV cell production cost model

- Cell production cost is estimated on a per-wafer basis
  - Assume 6" GaAs substrates for III-V semiconductor processing
    - Final cell size: 250 µm (200X concentration)
  - 8" silicon substrates

- Cost for each major process step is calculated based on estimates of equipment, materials, labor, and overhead costs
  - 200+ individual process steps
  - Each step corresponds with a single operation carried out by one piece of equipment
  - Equipment performance parameters obtained directly from vendors when possible



MEPV cell fabrication



- Cell architecture: III-V cell bonded to a silicon cell
- III-V processing on 6" GaAs substrates
- Si processing on PV wafers → Assume a structure similar to interdigitated back contact cells (IBC)

GaAs

Deposit III-V layers, define metal contacts, singulate cells

III-V cells: 200X CR

Si

Fabricate "IBC-like" Si substrate → Transfer III-V cells to Si → Singulate Si cells

~$2.30/wafer

Si cells: 1X-80X CR

Module efficiency estimates: 33.2% for 2J, 38.7% for 3J

Additional III-V junctions

Si Processing → III-V epitaxy, shape “mesa”, metal contacts, transfer to Si → Singulate Si cells

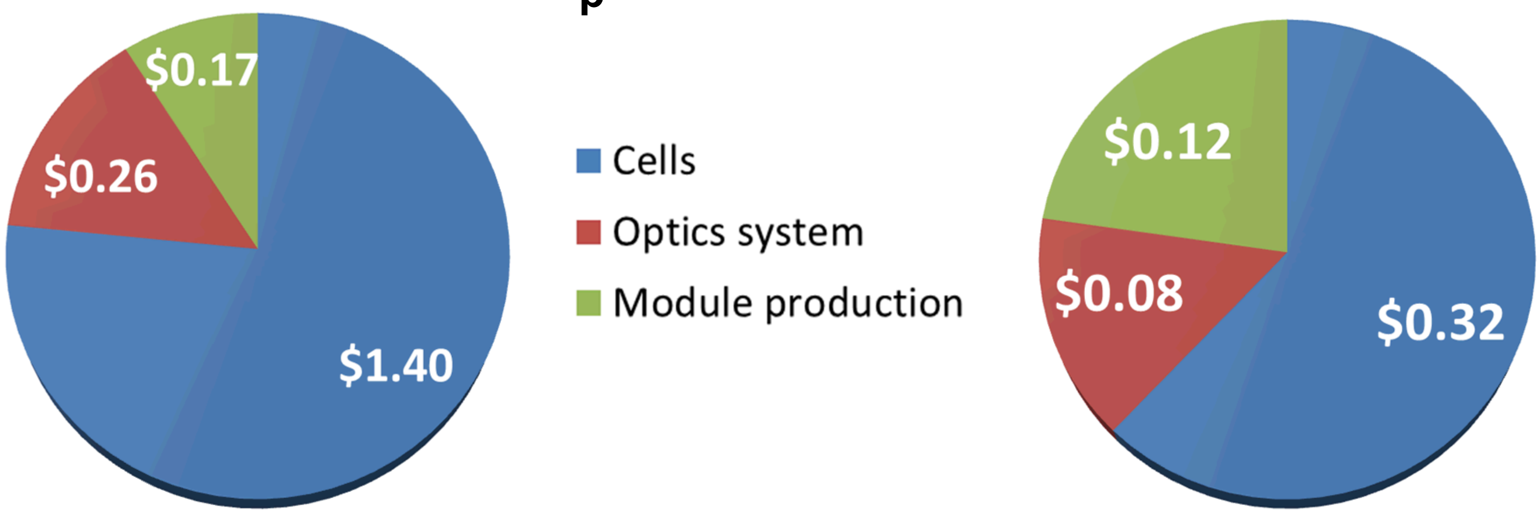
These steps are repeated for additional junctions

Prototype 3

Current estimate: **$1.83/W_p$**

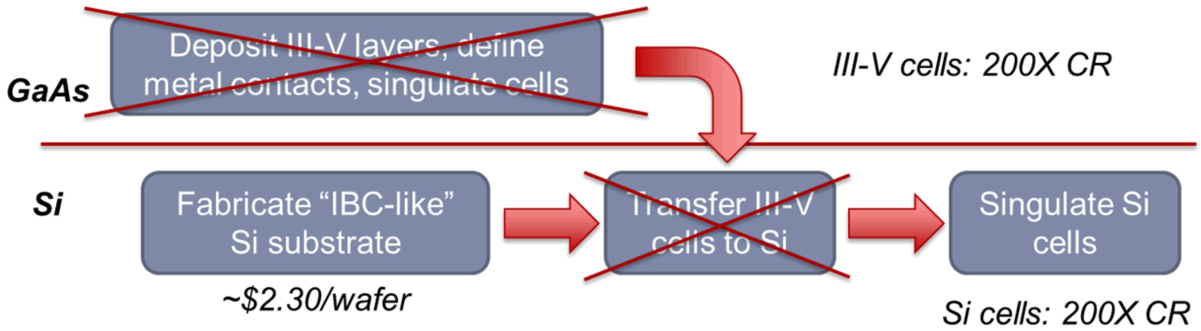
Prototype 4

2020 estimate: **$0.51/W_p$**



Addition of III-V junctions: Cell costs ↑ but efficiency ↑

Single junction Si cells for MEPV

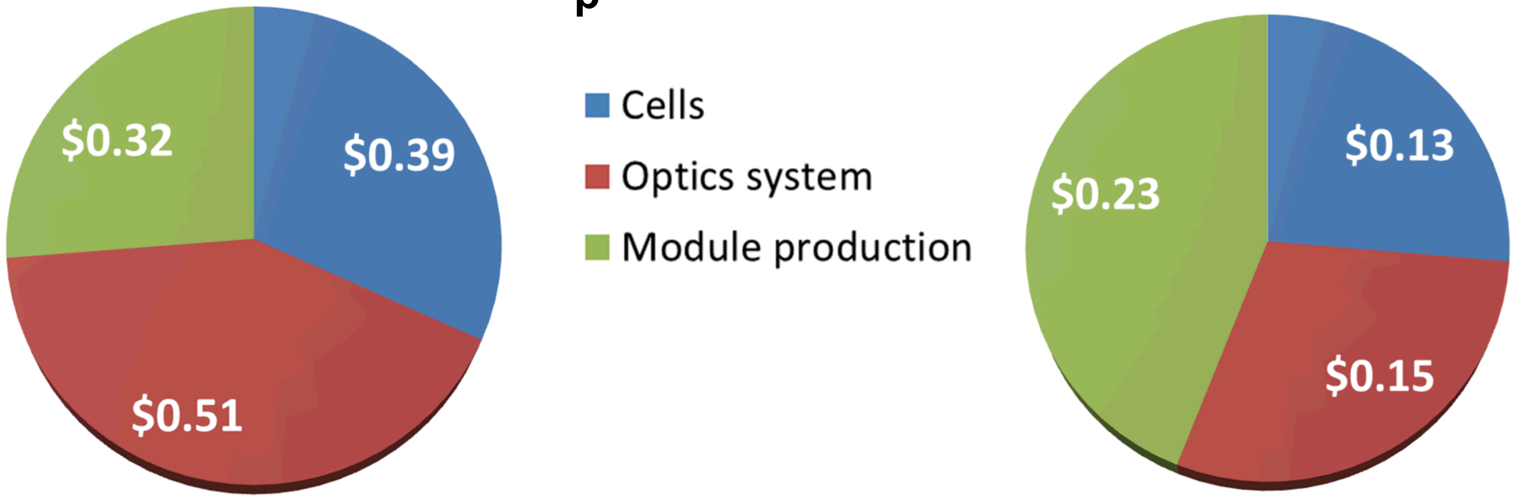


Prototype 3

Current estimate: **$1.22/W$_p$**

Prototype 4

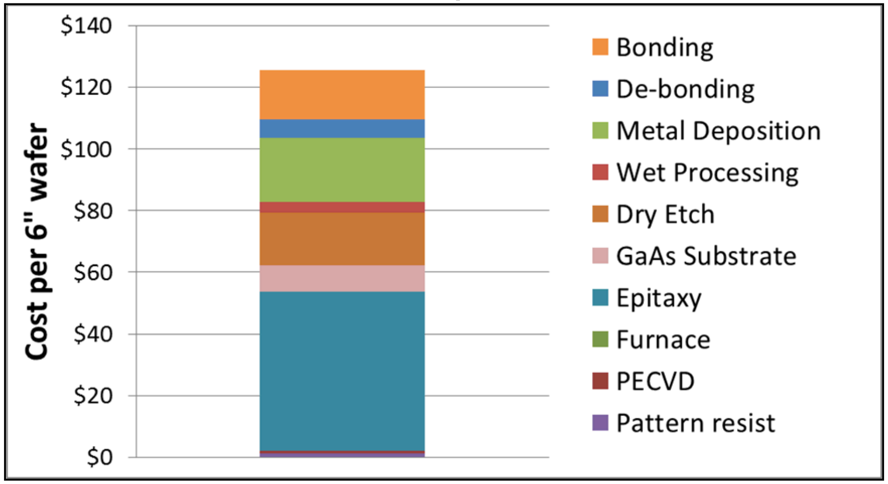
2020 estimate: **$0.51/W$_p$**

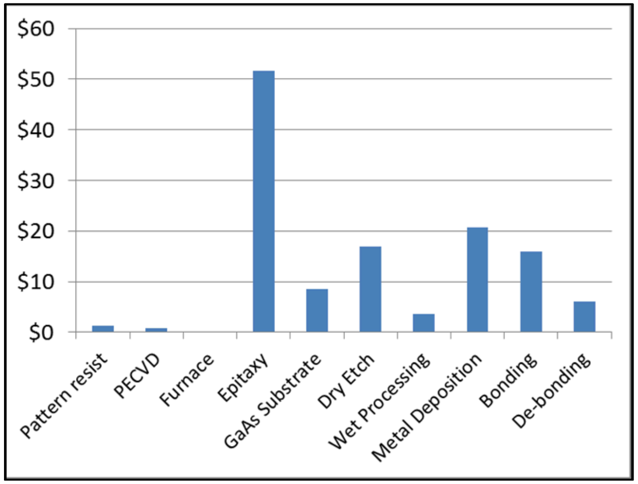


Elimination of III-V cells: Cell costs ↓ but efficiency ↓

Inverted Metamorphic Multi-junction (IMM) cells

Total cost: $126/wafer





- Grow 3-junction cells on one GaAs substrate
  - No silicon cells → Transfer directly to modules
- III-V processing costs ↑ slightly, but Si costs are eliminated
  - Estimated module efficiency: 40%

Prototype 4

2020 estimate: **$0.36/W$_p$**