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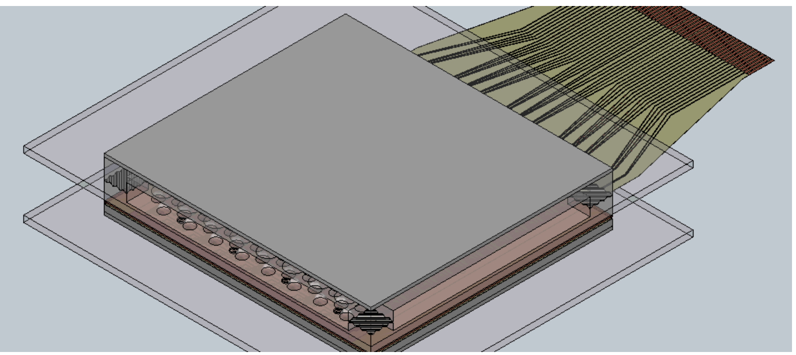

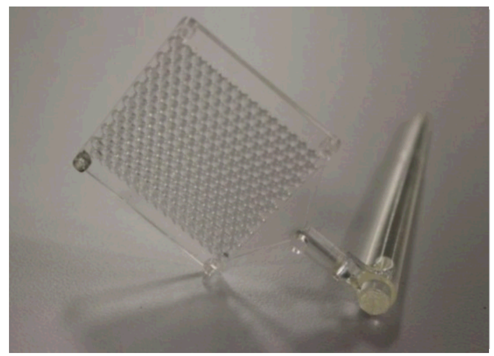

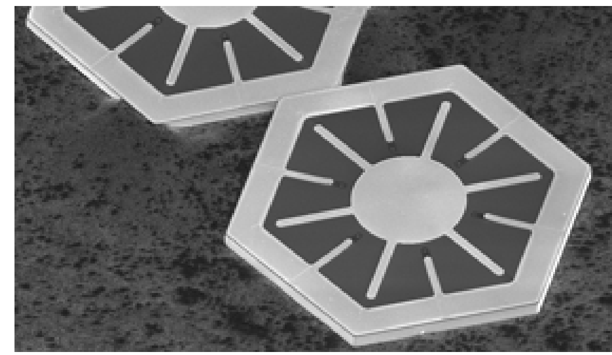

Micro-Optic Fabrication for Microsystems-Enabled Photovoltaics

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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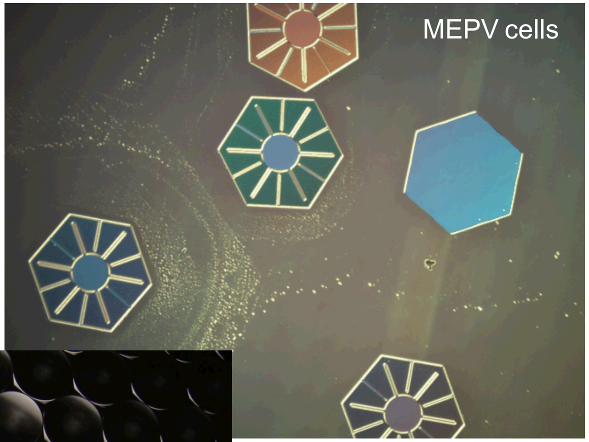
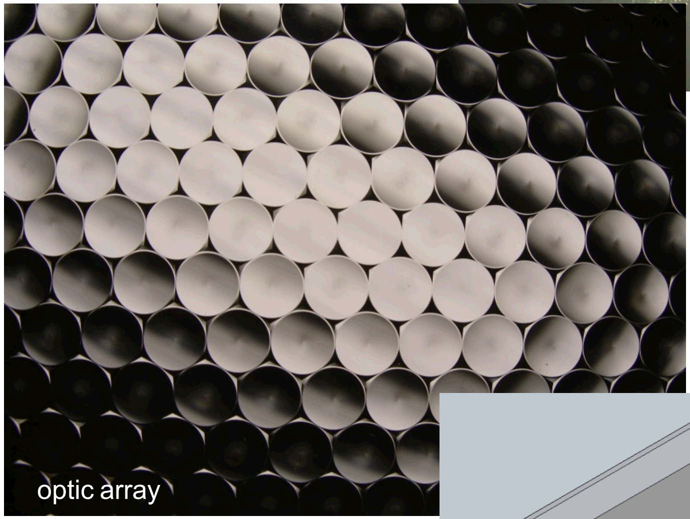
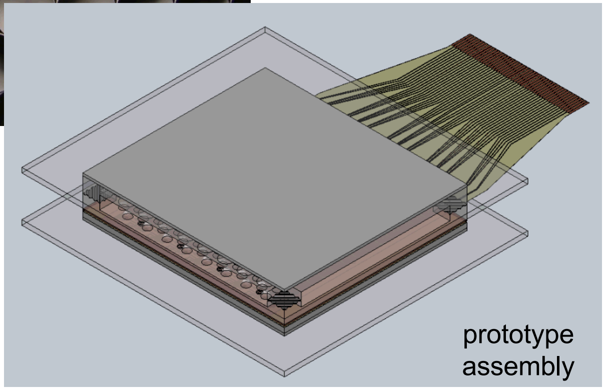
Introduction

- Microsystems-Enabled Photovoltaics (MEPV)
  - motivation
  - description
  - requirements
- Design
  - optical
  - opto-mechanical
- Fabrication
  - machining
  - molding
  - assembly
- Performance
- Conclusions

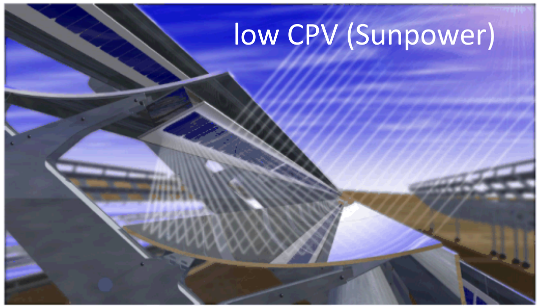


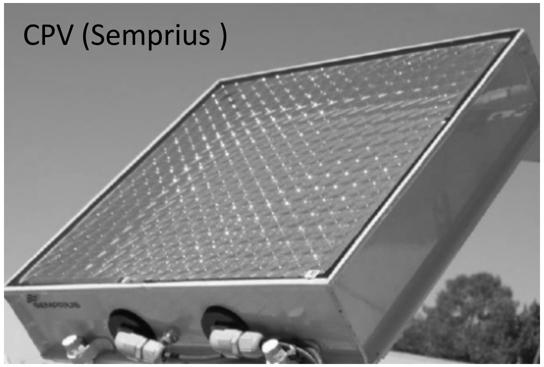




Motivation

- DOE SunShot = \$1.00 / W_{pk} utility scale power
  - "Make solar power the lowest cost energy source"
  - "Power for everyone everywhere"
- Commercial PV technologies
  - based on 1970s technology
  - flat panel
    - robust
    - efficiencies up to 20%
    - system cost = \$3.00/W_{pk}
    - material cost dominated
  - concentrating PV (CPV)
    - up to 1000x concentration
    - efficiencies up to 30%
    - system cost = \$3.00/W_{pk}
    - sensitive to disturbances
      - alignment, cloud cover, spectrum shifts, temperature

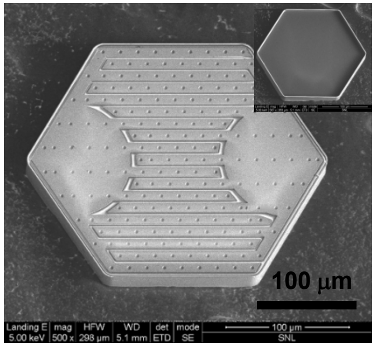




Microsystems-Enabled Photovoltaics

- New PV cell architecture
  - < 1 mm cell diameters
    - 10X+ reduction in cell material
  - multi-junction c-Si & III-V PV cells
    - 3D integration w/backside contacts
    - no lattice & current matching constraints
  - leverages IC, MEMS, LCD, & LED infrastructures

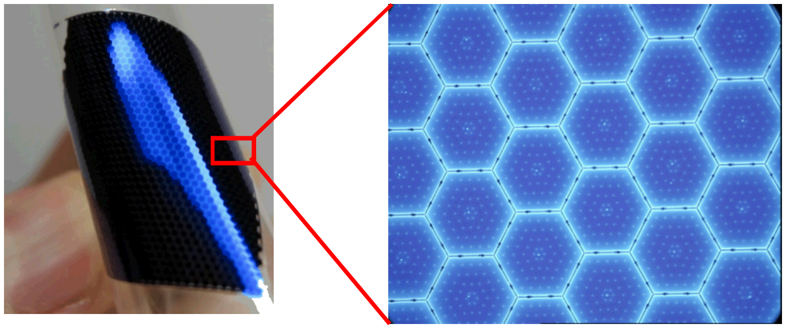
- Micro-concentrator systems
  - module thickness: ~ 1cm
  - concentration: up to 400x
    - molded micro-optics
    - acceptance angles: ±1-2°
  - compatible w/low cost flat panel infrastructure
  - large scale interconnection
    - improve performance w/cell shading or failure
  - paths targeted for
    - $0.50 / W_{pk} module
    - >40% module efficiency



250 µm crystalline Si cell


triple junction InGaP, GaAs, Si cell

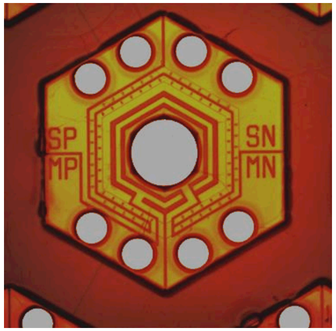

coarse 2-axis tracking


flexible array w/~2 mm bend radius

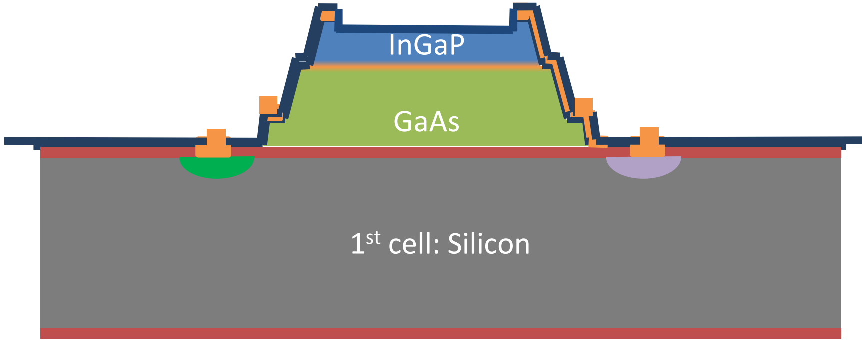
J. L. Cruz-Campa, et al, "Ultrathin flexible crystalline silicon: microsystems enabled photovoltaics," IEEE Journal of Photovoltaics.

Manufacturing Requirements

- System
  - low cost packaging & integration scalable to high volume production
  - ~30 yr reliability in environments
- Cells
  - lithography: ±1-2 µm
  - 3D cell integration: ±5 µm
  - cell to substrate transfer: ±25 µm
- Optics
  - "large", multi-element micro-optic arrays
  - aspheric prescriptions
  - form error: ±5-10 µm
  - surface finish: 5-20 nm
  - optic to cell alignment: ±10% of cell diameter
    - => ±25 µm for 250 µm cells
    - sensitivity in 6 DOF
  - $10/m² for materials & fabrication



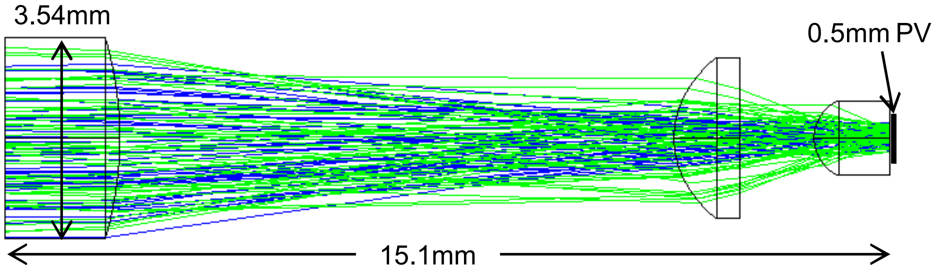
single cell



cells on substrate

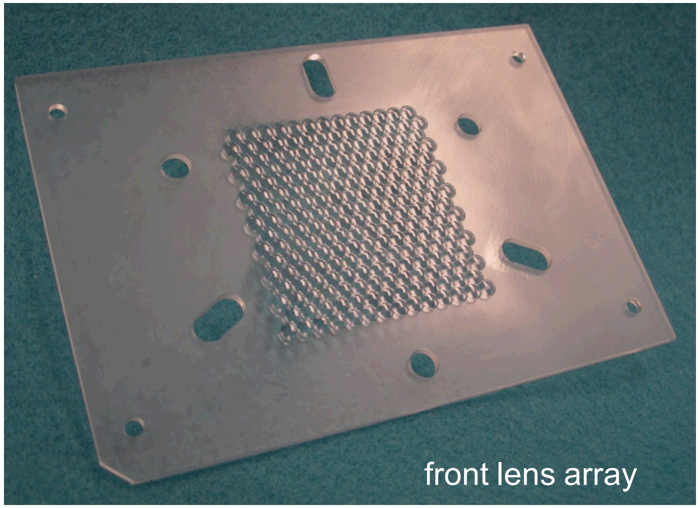
Optical Design (Gen I)

- Challenges
  - concentration: 100-400x
  - acceptance angle: ±1-2°
  - materials
    - minimal cost w/maximum robustness
    - AR coatings



Gen I optical design

- Gen I
  - MEPV feasibility demonstration
  - 500 µm diameter Si cell
  - PMMA plano convex lenses
    - 3.5 mm entrance aperture, 15.1 mm thickness
    - 36x concentration, ±4°FOV
  - 216 element hexagonal closed packed array
    - 50 mm x 50 mm array size
  - excessive design complexity & cost
    - directly machined

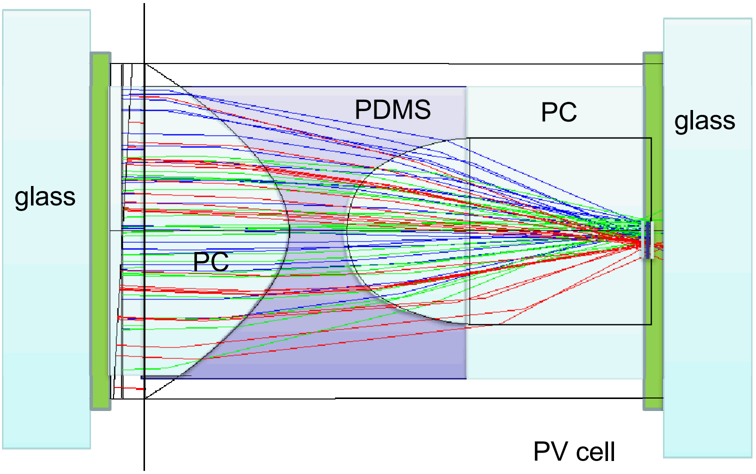


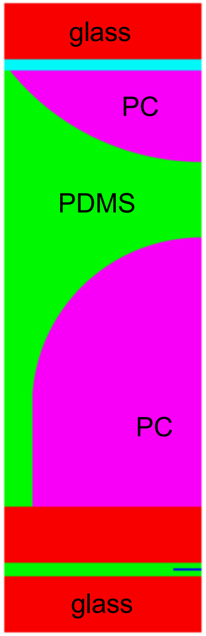
front lens array

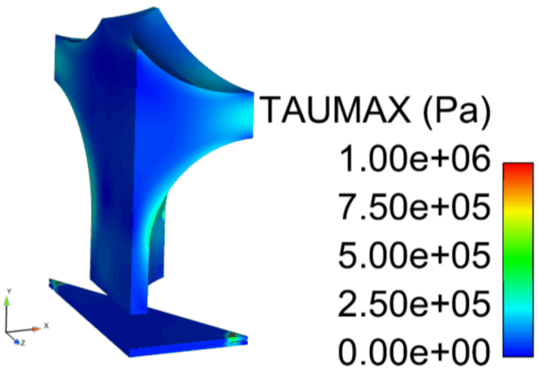
Optical Design (Gen II)

- Design
  - 250 µm diameter multi-junction cell
  - PC plano convex lenses w/PDMS fill
    - 2.5 mm entrance aperture
    - 4.5 mm thickness w/glass covers
    - 100x concentration, ±3°FOV
  - 240 element hexagonal closed packed array
    - 38 mm x 42 mm array size
  - reduced size, cost & complexity
  - robust
    - temperature range: -40°C to 80°C
    - 20 yr lifetime, robust to rain, dust & hail

- Materials
  - polycarbonate
    - low cost, moldable, better UV resistance than PMMA
  - PDMS
    - expensive, low modulus & moisture permeability, excellent transmission & UV resistance
  - Δn = 0.19 is smaller than desired, but workable
    - lower Fresnel surface loses reduce finish requirements



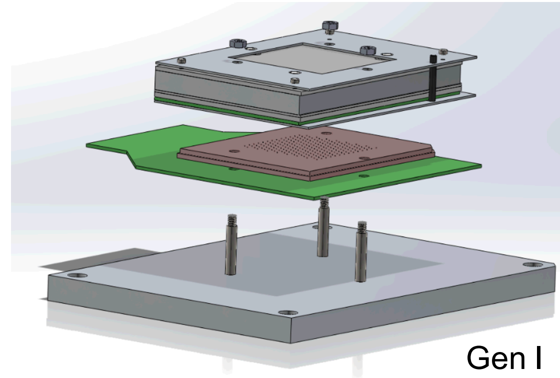


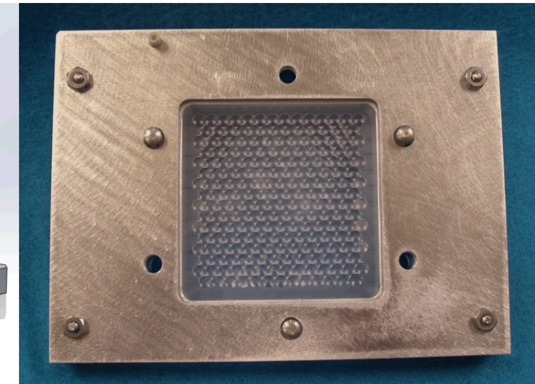


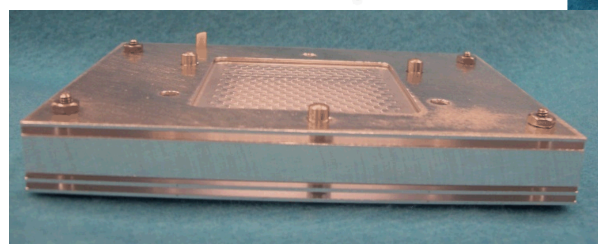
analysis w/40°C process temp reduced initial design stresses by increasing PDMS gap thickness 5x

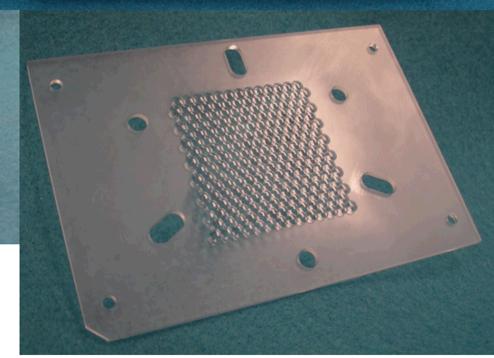
Opto-Mechanical Design

- Challenges
  - “modest” assembly tolerances
  - scalable
  - CTE mismatches
  - cost
- Design principles
  - passive alignment
    - dependent on machining accuracy
  - kinematic
  - athermal
- Gen I
  - sub-module for characterization
  - machined alignment features
  - footprint ~ 6 x 12 in



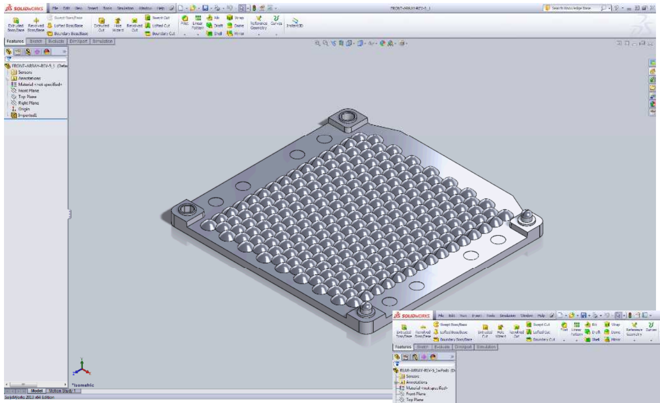


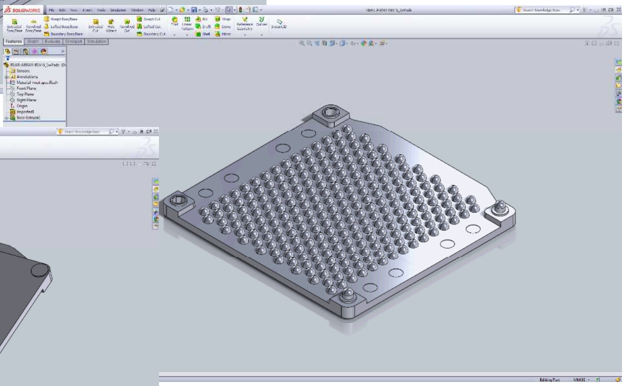


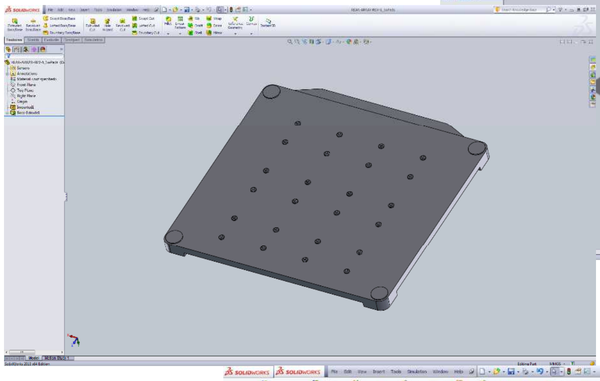


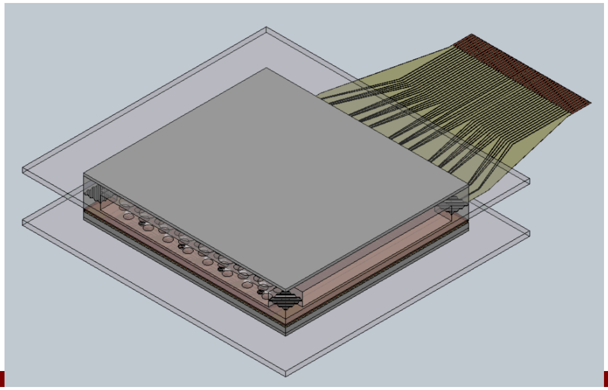
Gen II Design

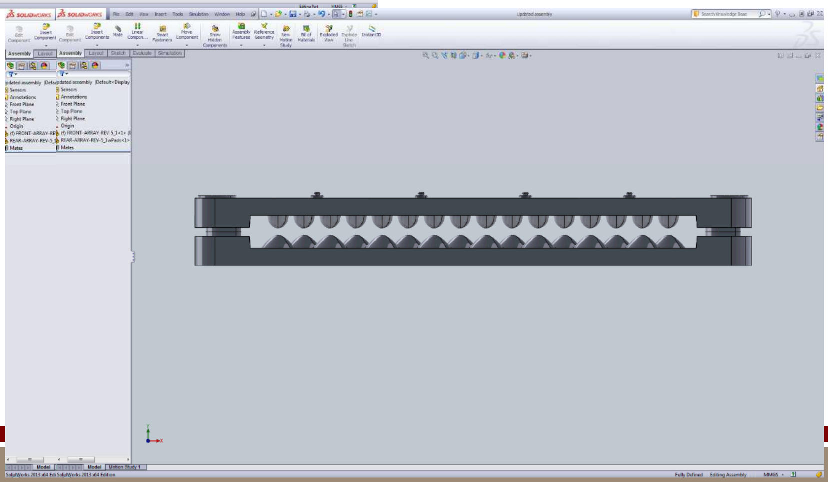
- Smaller, simpler package
  - footprint ~ 2 x 2 in
- Molded alignment features
  - bosses set axial position
  - pins in slots
  - oriented for accuracy
- Sealing



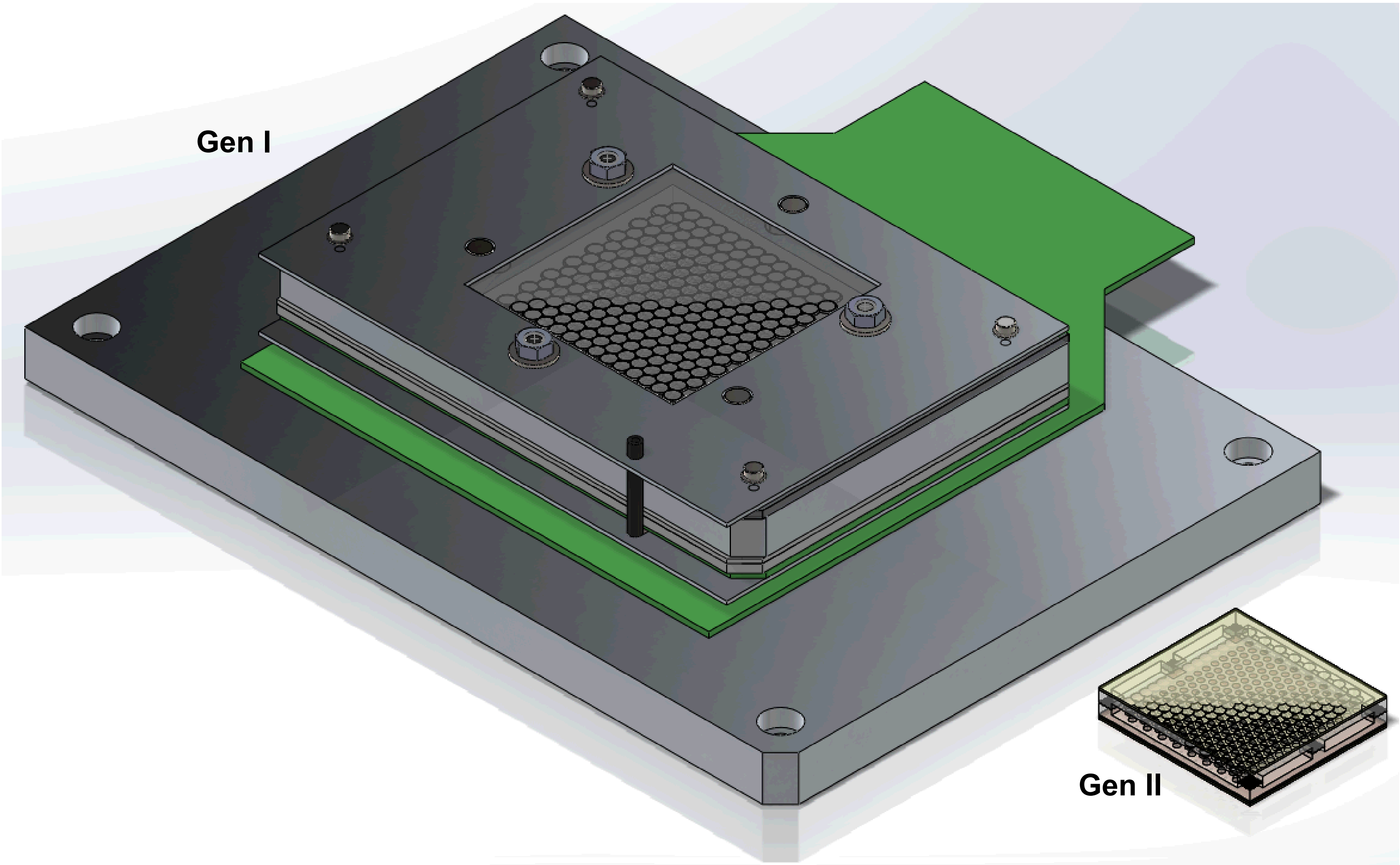








Gen I vs. Gen II Size Comparison

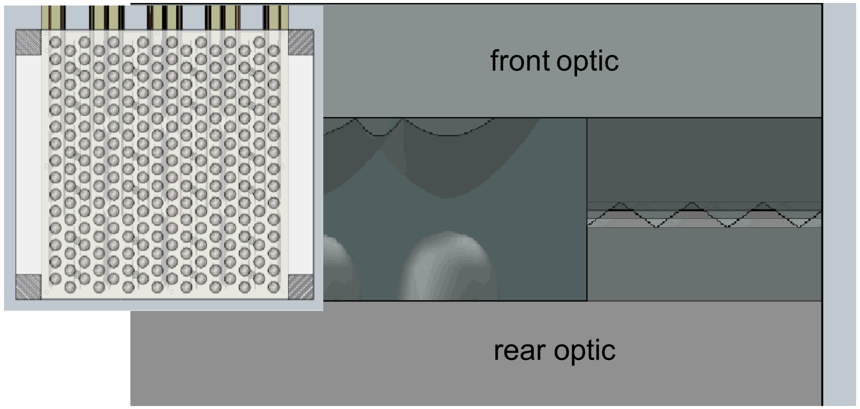


Alignment

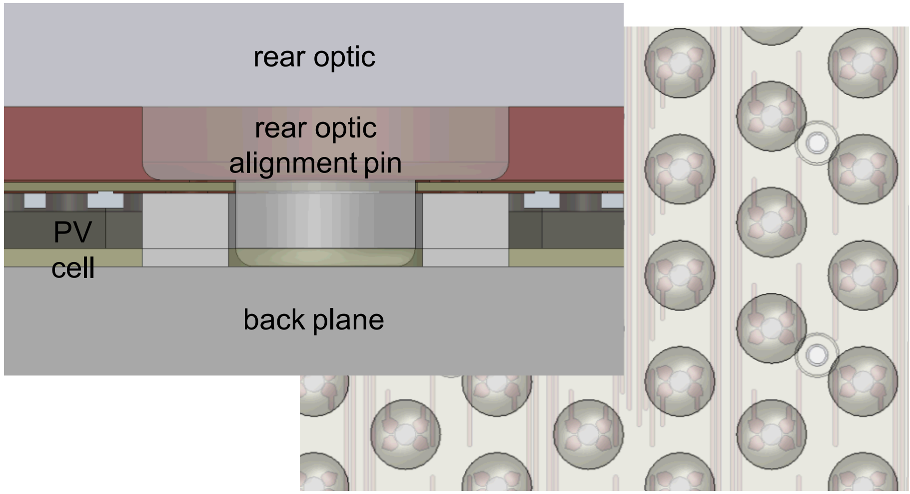
Lens/MEPV/Backplane Assembly

- Challenges
  - precision alignment
  - fabrication of passive features
  - minimal restriction to adhesive flow
  - CTE mismatches during processing
- Solution
  - Molded lens alignment structures
  - rear optic pin & spacer
  - alignment holes
  - backplane spacer

Microlens Array Alignment



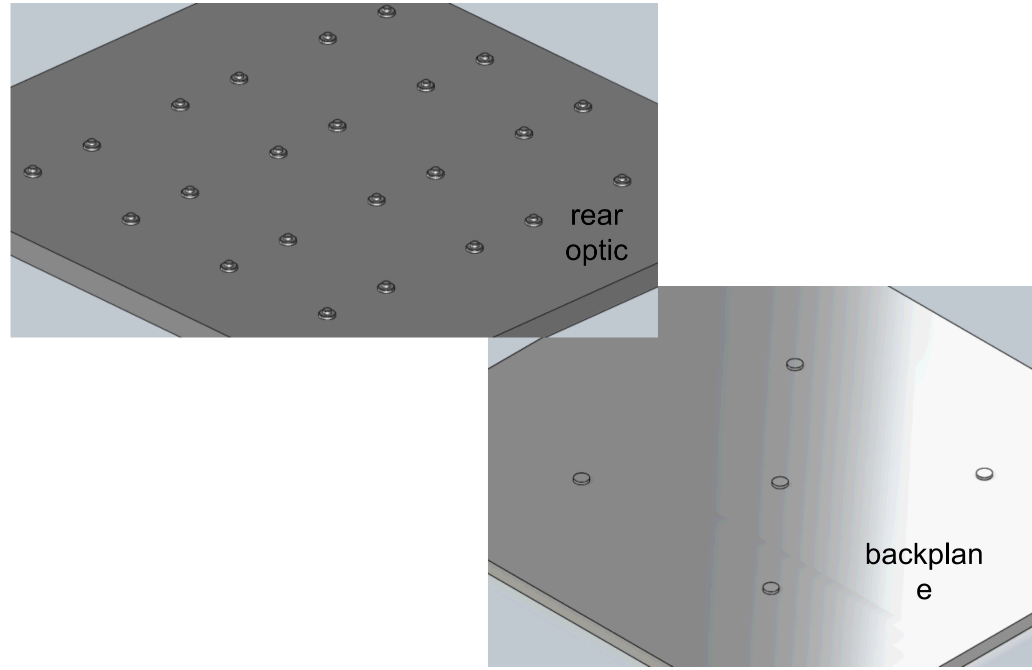
PV Cell to Optic Alignment

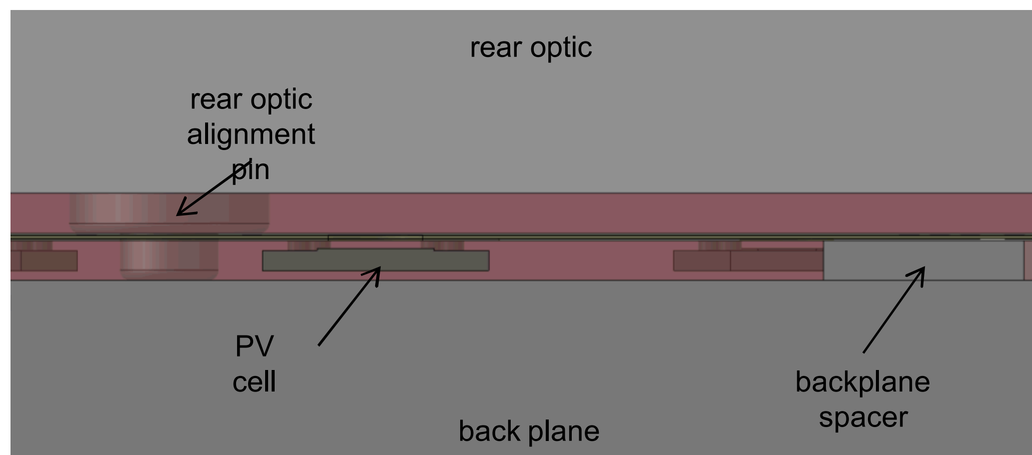


Lens/Flex Alignment

Lens/Flex/Backplane Assembly

- Challenges
  - precision alignment
  - fabrication of passive features
  - minimal restriction to adhesive flow
  - CTE mismatches during processing
- Solution
  - rear optic pin & spacer
  - flex holes
  - backplane spacer





Direct Lens Array Fabrication

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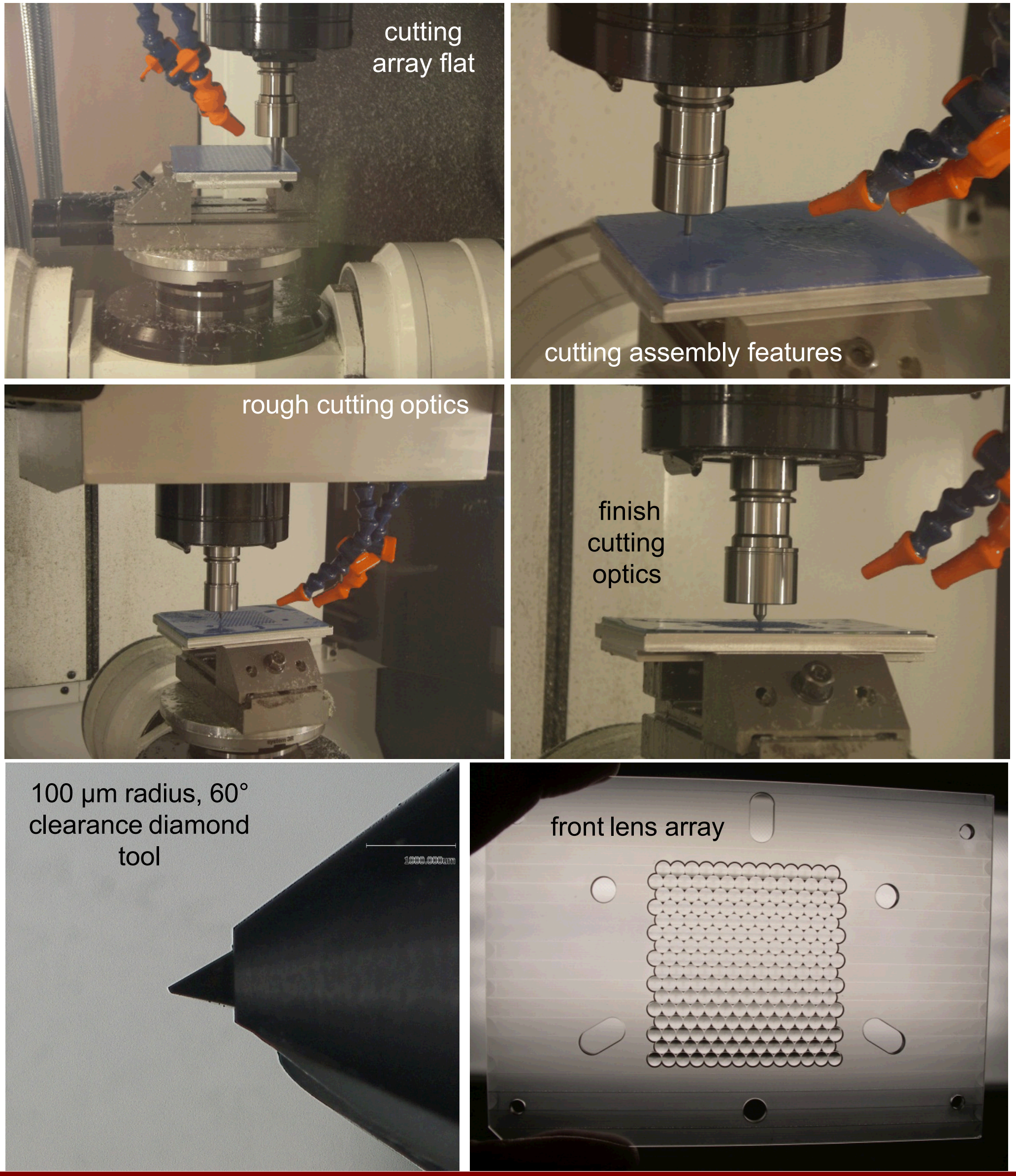
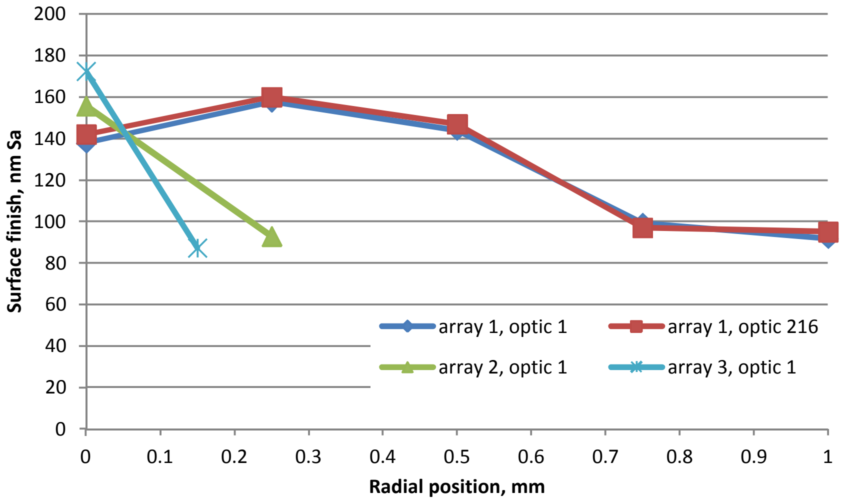
- Diamond-milling planned for Gen I
  - milling required for large array format
  - ~15 min / lens (~60 hr / array)
  - 3 arrays / set, multiple sets requested
  - schedule prohibitive

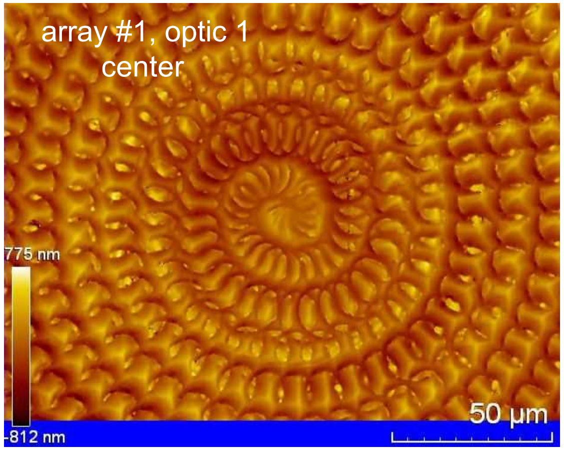
- Actual parts micro-milled
  - Yasda YMC 430 micro-machining center
    - ~0.5 µm machine accuracy
    - milling tools for roughing & assembly features
    - final pass w/diamond tool
  - ~4 min / lens (~25 hr / array)

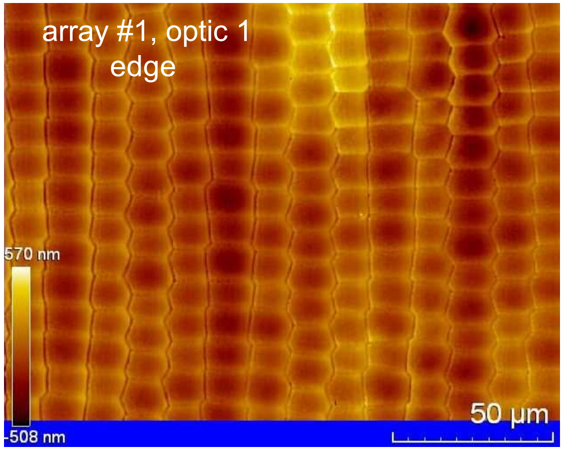


Micro-Milling Surface Finish

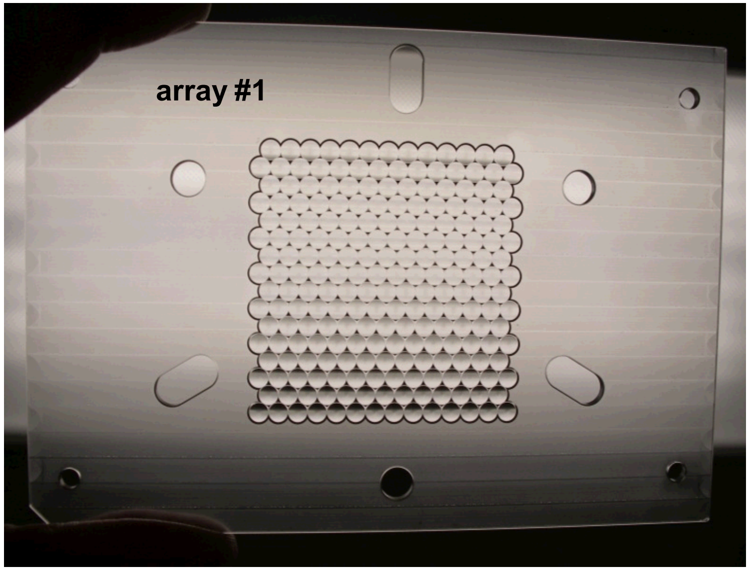
- Excessive finish
  - increases near center
  - machine limit ~ 90 nm S_a
- 3% scatter / machined surface
  - acceptable for Gen I
  - Gen II requires diamond milling
    - longer fabrication cycles
- Minimal tool wear observed over 10+ parts

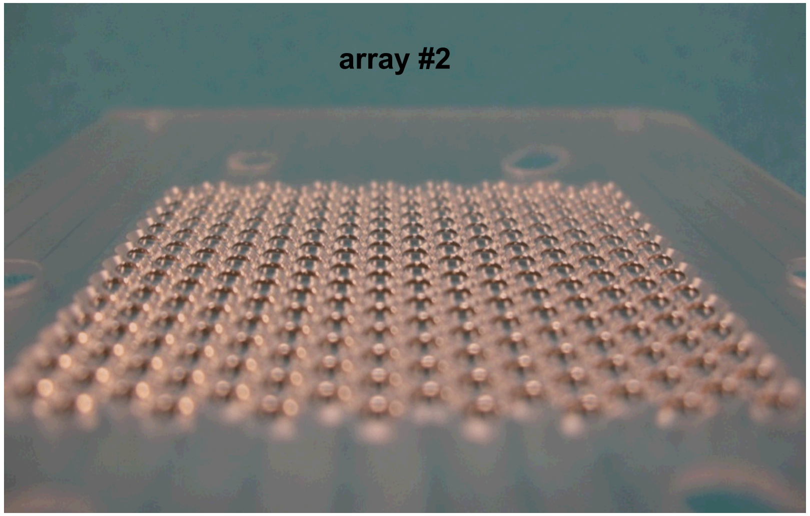


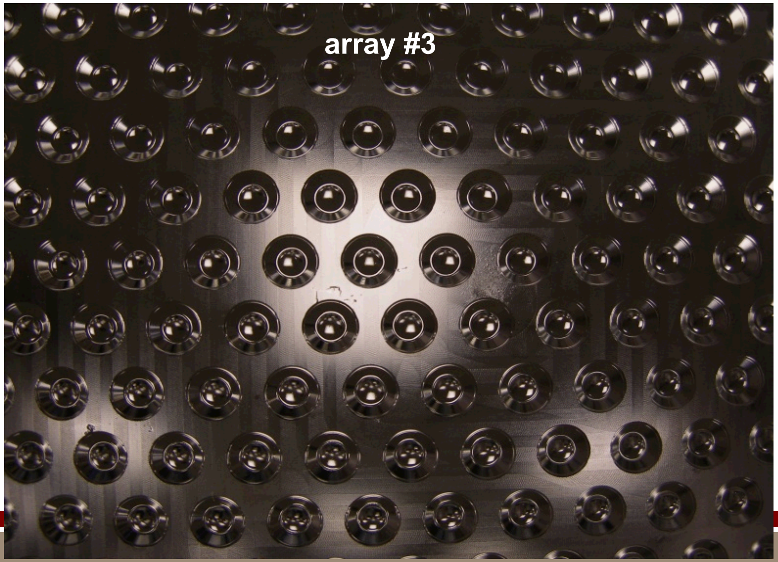




Completed Lens Array

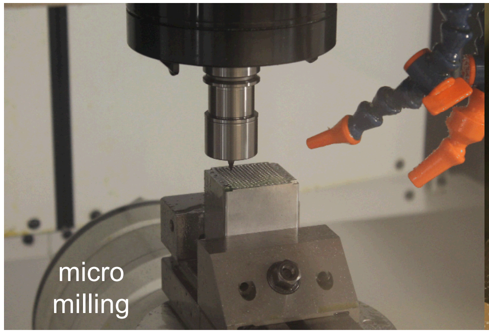


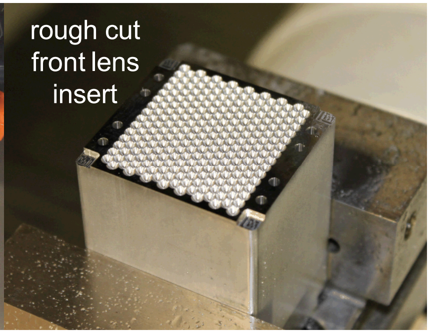


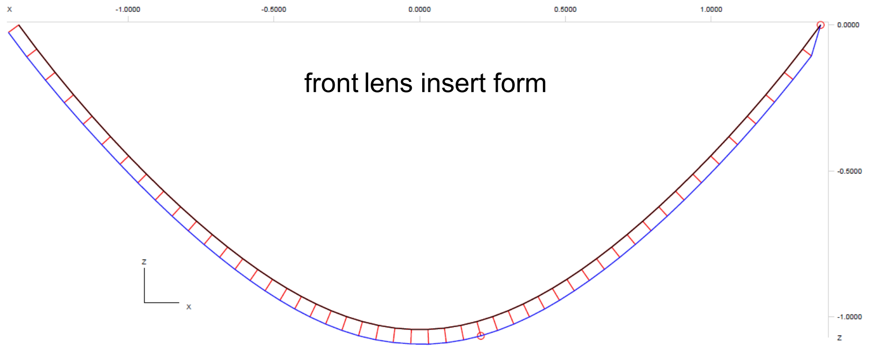


Mold Insert Fabrication

- Gen II utilizes molded optics
  - ~300 parts requested
  - 6061-T6 inserts
- Inserts fabrication combined micro & diamond milling
- Micro-milling
  - mold & optic alignment features
  - rough lens arrays
    - 3-4 hr / insert
    - ~20 µm of material left on part
    - form error: 5 µm

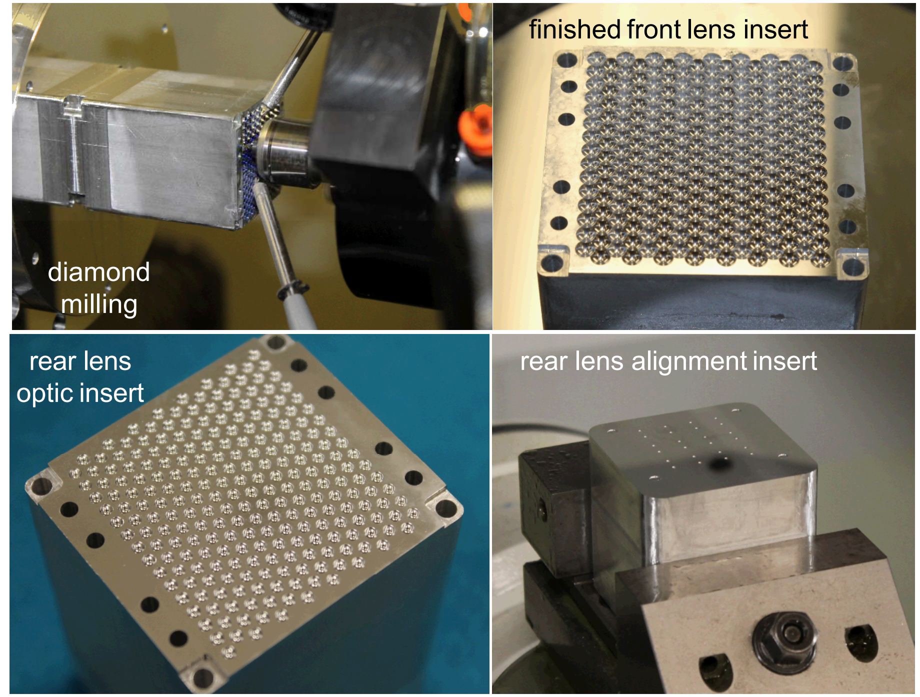


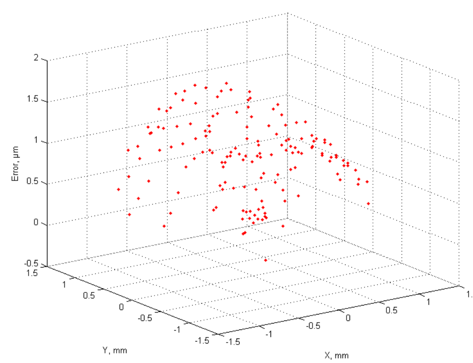




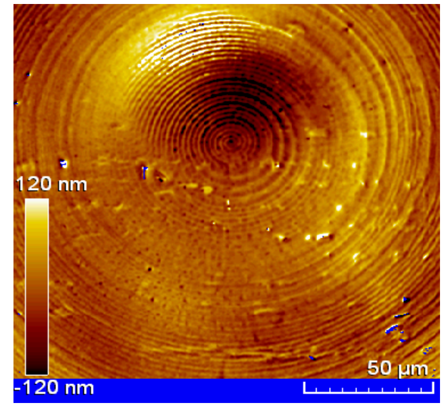
Diamond Milling

- Single lens array finish pass
  - Moore 350FG
  - 60 min / lens for front, 30 min for rear
- 200 µm radius tool
  - 55°clearance angle
  - limits optical design
- 30 krpm, 3 µm crossfeed, 50 to 10 mm/min
  - form accuracy ~ 1.5 µm
  - surface finish ~ 30 nm S_a





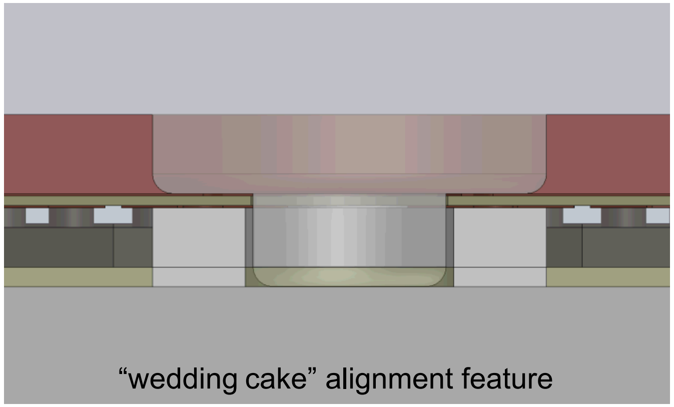
insert form error

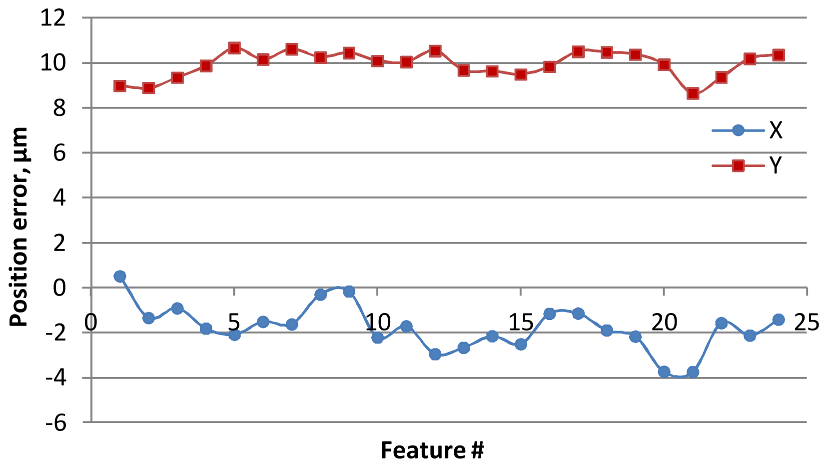


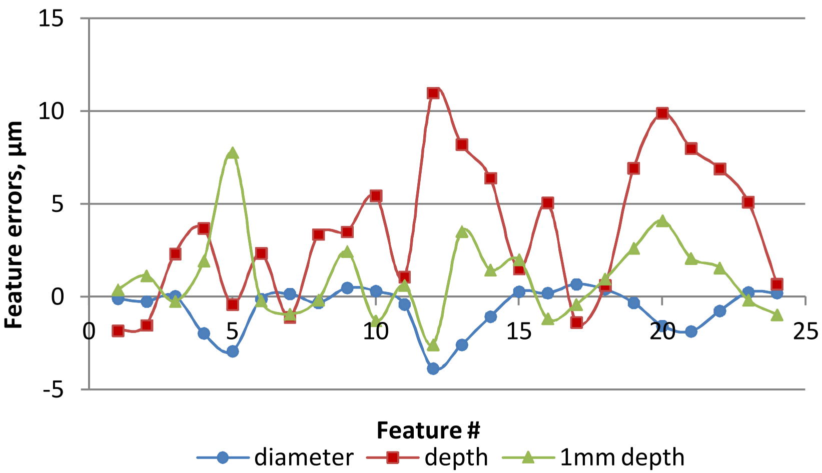
insert surface finish

"Wedding Cake" Fabrication

- Features align & constrain flex to optical assembly
- Process development
  - test mold pin machined
  - position accuracy ~ 10 µm
  - dimensional accuracy
    - diameter ~ 2 µm
    - depth ~ 10 µm

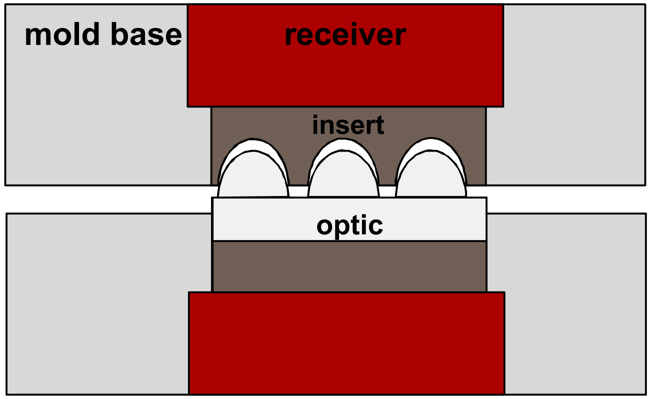






Molding

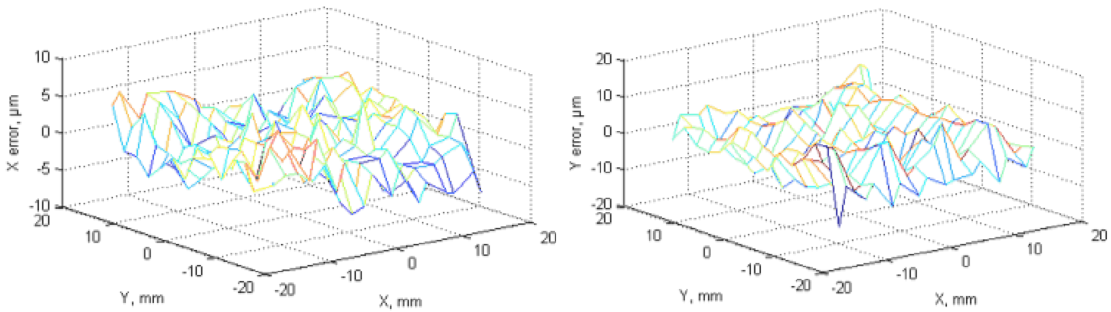
- Molding challenges
  - accuracy is critical for optics & alignment features
  - material shrinkage
    - in-plane will dominate, not worried about optic surfaces
    - test mold & parts will quantify
      - final mold will require changing optic inserts
    - compensate in mold fabrication
- Partnering w/Greenlight Optics
  - feedback for optic design & cost modeling
  - molding simulations
  - mold design, fabrication & assembly
  - molding of optic arrays

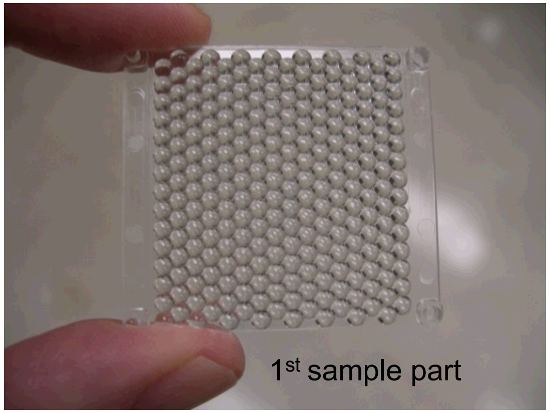


simplified mold schematic

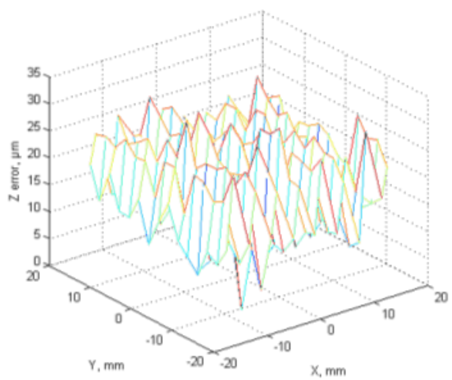
First Sample Molded Parts

- Ball milled “optics” w/pin-in-slot assembly
- In-plane material shrinkage < 0.2%
  - XY position accuracy of optics within ±5 μm

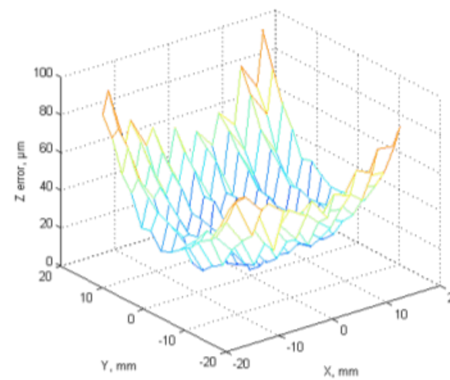




- Difficulty balancing part flatness & corner filling
  - design changes incorporated into Gen 2
  - flatness
    - mold ~ 30 μm
    - part ~ 100 μm

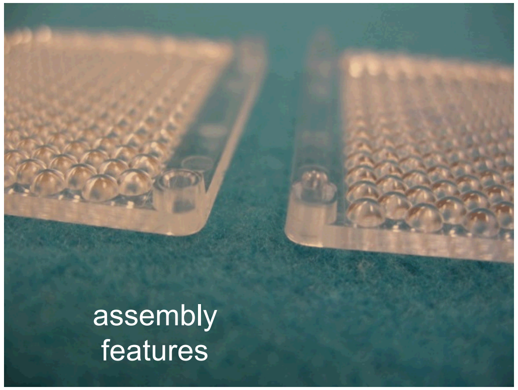


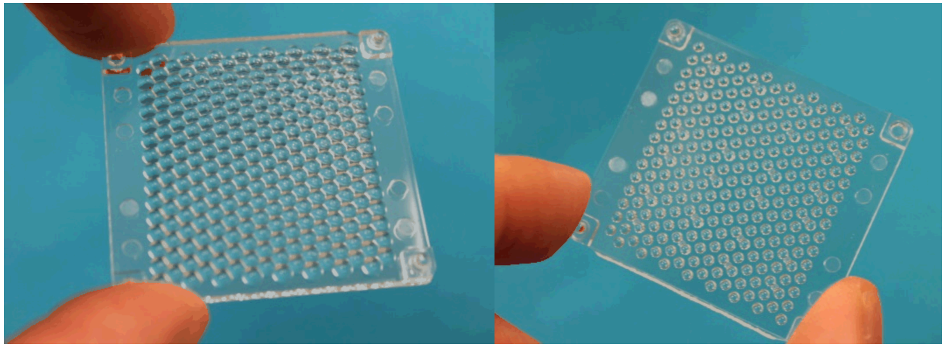
mold



part

Recent Results



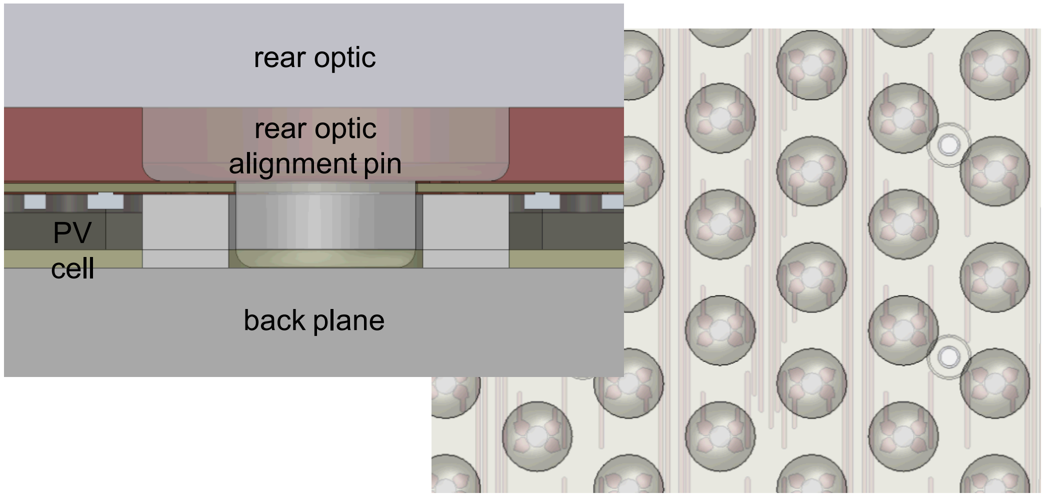


molded front & rear arrays

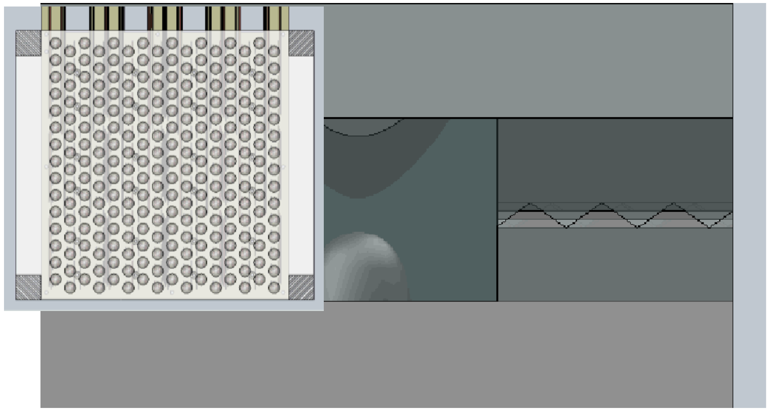
Assembly

Prototype 2

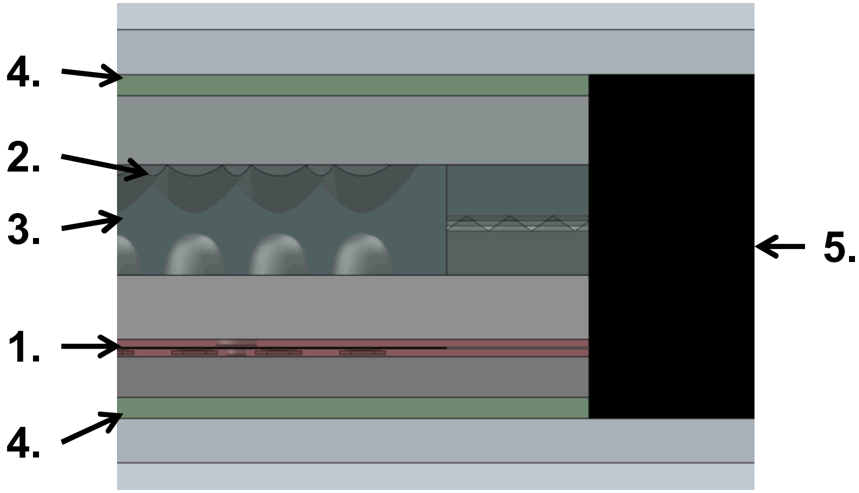
PV Cell to Optic Alignment

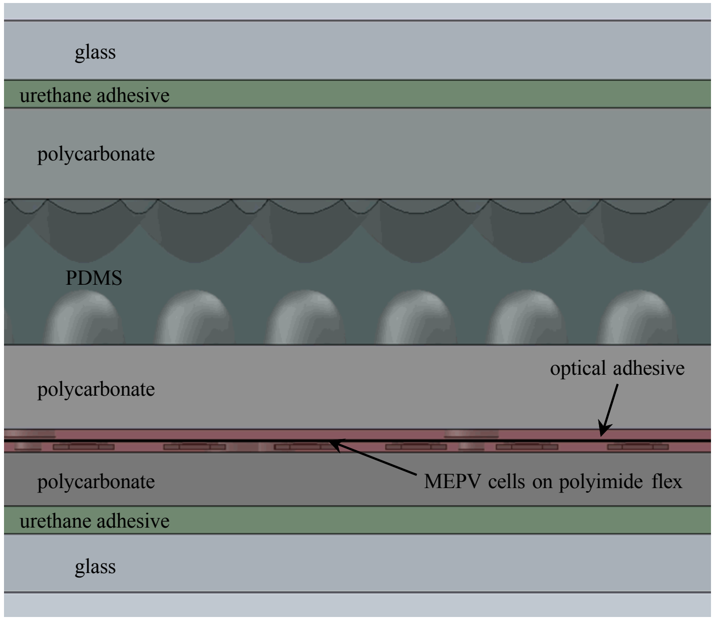


Microlens Array Alignment



1. Optical adhesive bond of flex circuit to PC secondary lens and base plate
2. Adhesion primer application to PC surface
3. PDMS Encapsulation
4. Vacuum lamination process elastomeric adhesive
5. Hot melt butyl sealant application



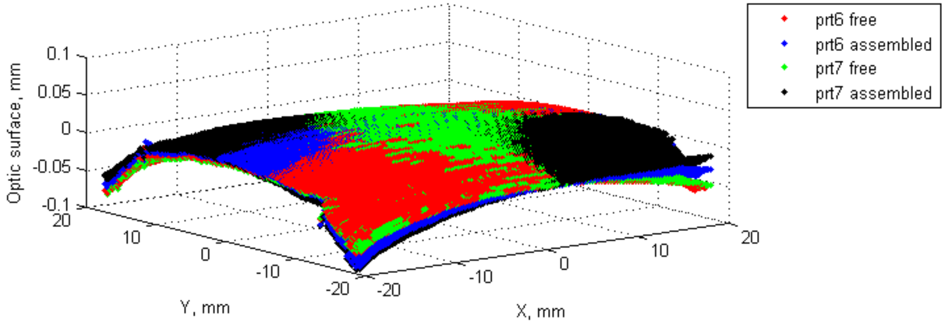

glass
urethane adhesive
polycarbonate
PDMS
polycarbonate
optical adhesive
polycarbonate
MEPV cells on polyimide flex
urethane adhesive
glass

Assembly Impact

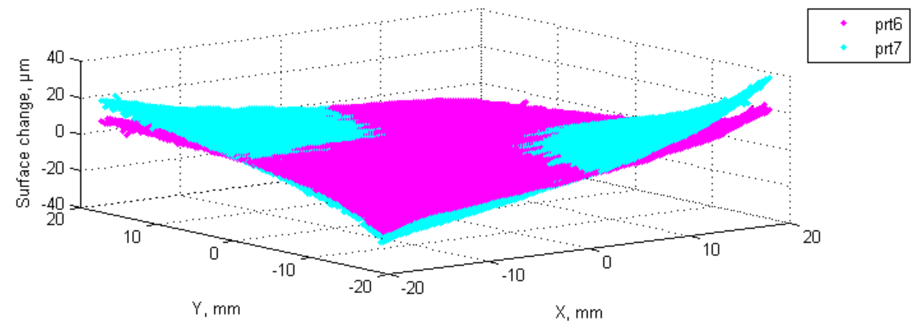
Sandia National Laboratories

Prototype 2

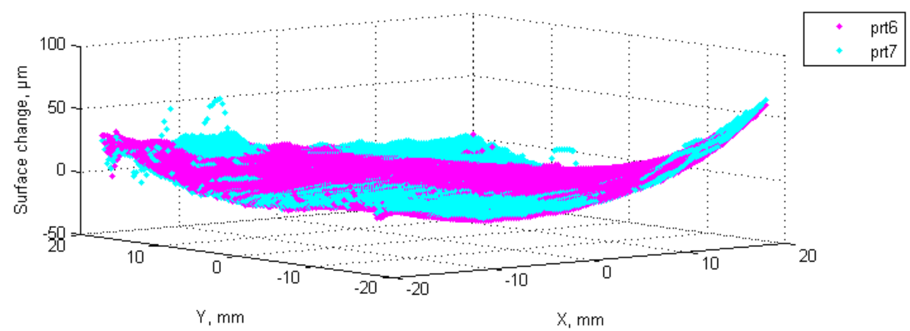
- What is the impact of assembly on the optics?
- Part deformation during
  - assembly ~ 30-40 µm at corners
  - bonding ~ 20-30 µm at corners
  - current deformation is advantageous



free state rear surface profiles



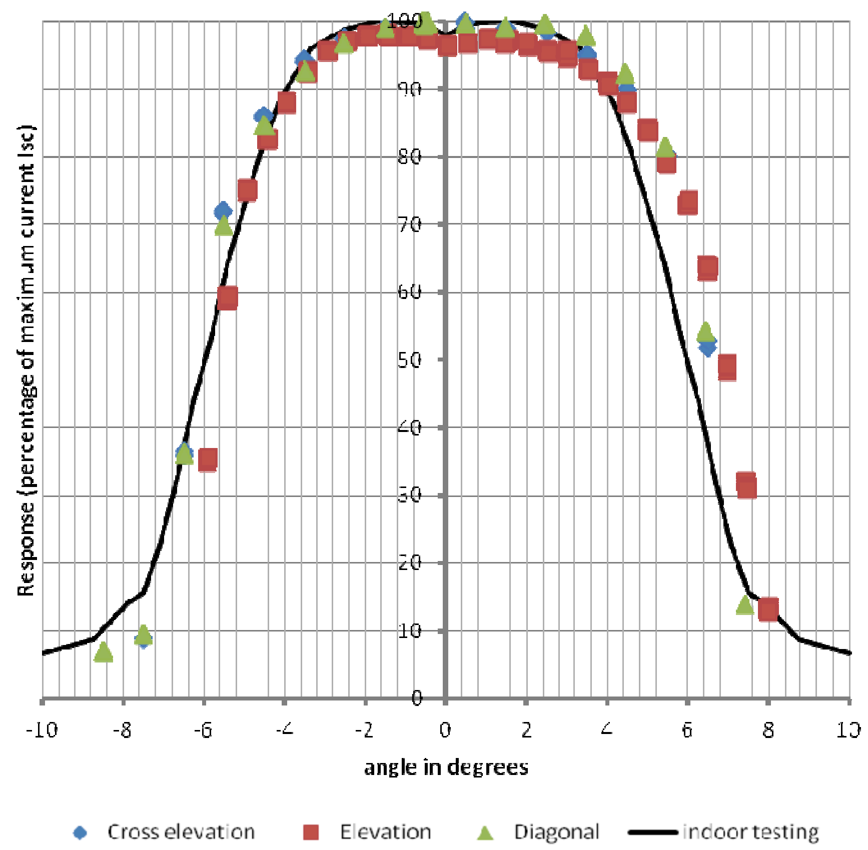
surface change from free state to assembly



surface change from free state to bonded

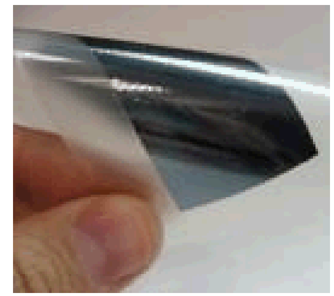
Performance

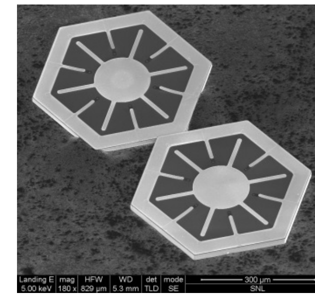
- Gen I
  - design
    - concentration: 36x
    - FOV: ±4°
  - experiments
    - cell performance consistent w/Si cells
    - concentration: 21x
    - FOV ~ ±4°
    - efficiency: 14.5%
    - no AR coatings & rough surfaces: ~40% expected scatter loses
- Gen II
  - hardware in assembly
  - expected module efficiency: 28%

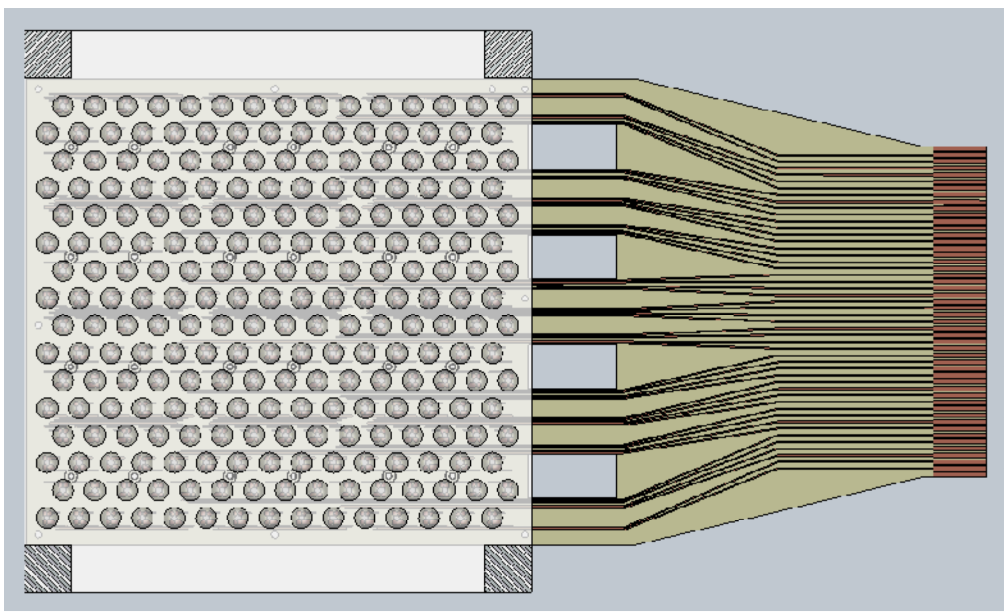


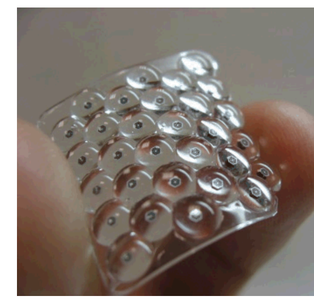
Conclusions

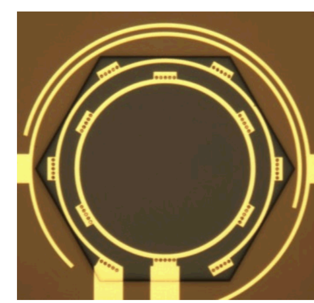
- Summary
- Future Work











Questions??

Photovoltaics that fit

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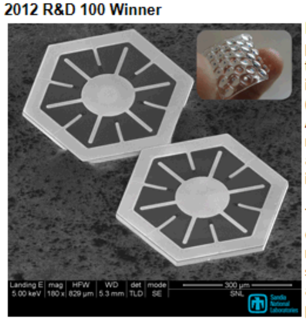


Email Print

Picture a solar cell and chances it will look like a flat panel. The demand for photovoltaics that can conform to a certain size, shape, or structure, however, is increasing. **Microsystems Enabled Photovoltaics (MEPV)** from **Sandia National Laboratories**, Albuquerque, N.M., represent a move toward miniaturized crystalline silicon and crystalline gallium-arsenide (GaAs) solar cells that can fit within the intricate shapes and contours of various objects.

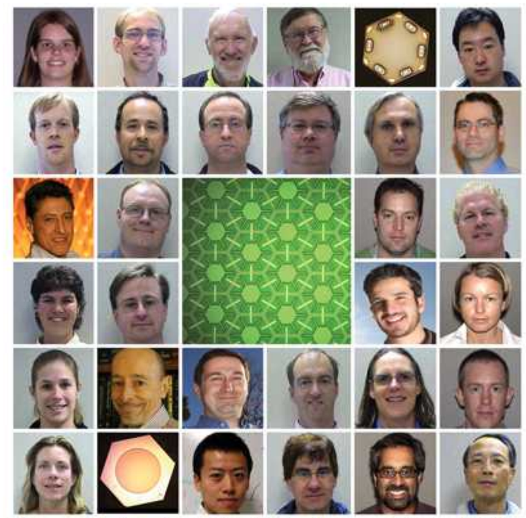
To fabricate these cells, Sandia's MEPV team have combined microfabrication techniques from several microsystem technologies. The process flow uses standard equipment and standard wafer thicknesses and allows all high-temperature processing to be performed prior to cell release. This means that for both silicon and GaAs cells are backside contacted, which enables the fabrication of uniform, aesthetically pleasing front sides without electrical lines. In addition, the remaining post-release wafer can be reprocessed and reused, resulting in a substantial increase in the number of watts generated per gram of semiconductor material.

With dimensions as small as 100-μm wide and 1-μm thick, these PV building blocks can be installed in flexible, moldable, or flat-plate formats in sizes that conform to the shapes and contours of natural terrain, large structures, vehicles, and mobile electronics.

Technology
Photovoltaic cells

Developers
Sandia National Laboratories

Development Team



(Top row, l-r): Anna Tauke-Pedretti, Ben Anderson, Bill Sweatt, Bob Biefeld, Bongsang Kim (Second row): Bradley Jared, Carlos Sanchez, Craig Carmignani, Dan Koleske, Gerry Girard, Greg Nielson (Third row): Igal Brener, Jeff Cederberg, Jeff Koplow, Jeff Nelson (Fourth row): Jennifer Granata, Jonathan Wierer, Jose Luis Cruz-Campa, Judi Lavin (Fifth row): Kira Fishgrab, Mike Haney, Murat Okandan, Paul Resnick, Peggy Clews, Scott Paap (Bottom row): Tammy Pluym, Tian Gu, Tony Lentine, Vipin Gupta, Willie Luk

Solar Spectrum