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Micro-Optic Fabrication for Microsystems-Enabled Photovoltaics

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MOTIVATION

In response to the DOE SunShot initiative to achieve utility scale solar power generation at $1 per watt peak, Sandia National Laboratories is investigating a microsystems-enabled photovoltaics (MEPV) approach that combines the high conversion efficiencies of concentrated photovoltaics (CPV) with the form factor and low system costs of flat panel PV. MEPV combines fully integrated stacked multi-junction PV cells having lateral dimensions smaller than 1 mm with micro-optic concentrators to reduce the use of expensive semiconductor materials and to increase solar conversion efficiency [1]. While existing semiconductor infrastructure is being leveraged for MEPV cell research [2], a parallel effort is underway to develop design and fabrication techniques for MEPV micro-optics.

MICRO-OPTIC DESIGN

A cross-section of an MEPV design, Figure 1, shows that PV cells are mounted onto an electronic substrate that is aligned to lens elements which focus the incident sunlight onto the cell surface. Optical concentration, or magnification, and acceptance angle, or field of view, represent the primary optical requirements for the MEPV optics. While typical CPV systems utilize optical concentrations on the order of 500 to 1000x, MEPV designs are leveraging more moderate concentrations on the order of 50 to 100x based on desired cell designs, manufacturing tolerances and system costs.

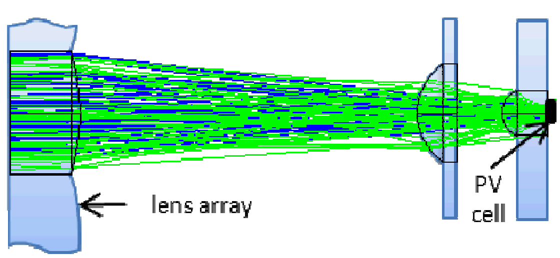

FIGURE 1. First generation MEPV optics.

Initial optical designs sought to maximize the system acceptance angle, but recent work has targeted a ±2° angle based on the performance of tracking systems fielded in current flat panel PV systems. Optical tolerances are roughly 25-50 µm for surface form accuracy and alignment to the PV cell; a common and readily achievable tolerance for single lens train assemblies. Maintaining lens to cell alignment across an array size on the order of tens of cm under temperature extremes approaching -40 to 80°C, however, introduces significant design, fabrication and assembly challenges for a MEPV module. Requirements for a 20 year service life under UV exposure, wind-blown debris, moisture and other environment extremes provide additional constraints to the optical design, predominantly around material selections.

Figure 1 represents the optical design for a first generation prototype that has been used to demonstrate the feasibility of MEPV systems using 720 µm single junction Si cells [2]. The design uses three aspheric PMMA lenses which have an entrance aperture of 3.5 mm, an assembly thickness of 15.1 mm, a magnification of 36x and an acceptance angle of ±4°. Polymer lenses have been primarily considered throughout design evaluations due to their low material costs and amenability to mass production via molding or other replication process. The collection area of the prototype module is approximately 5 cm on a side and includes 216 micro-lens elements in a hexagonal closed pack array to minimize sunlight losses at the entrance apertures. The lens arrays are passively aligned in a pseudo-kinematic manner using dowel pins and machined slots in the optic arrays, Figures 2 and 3. The slots are also positioned in an athermal manner to provide a point of zero thermal expansion at the geometric center of the optic arrays.

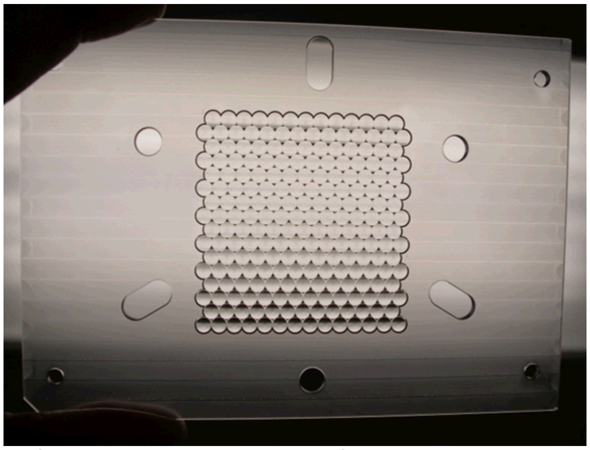

FIGURE 2. First generation front lens array.

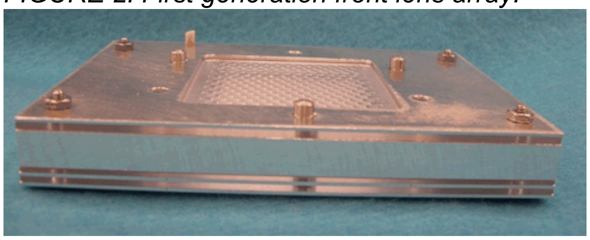

FIGURE 3. First generation optic module.

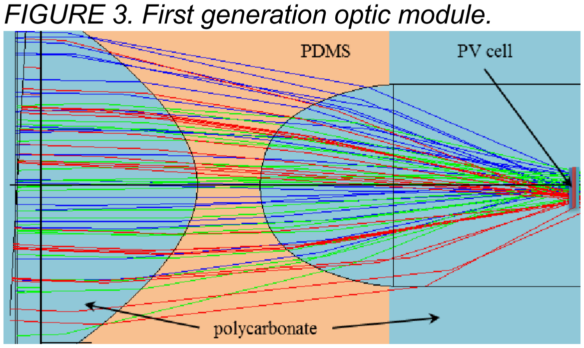

FIGURE 4. Second generation MEPV optical design.

A second generation optical design is in development to improve device performance and to examine the viability of mass producing MEPV at competitive costs. The design provides a 100X magnification with a ±3° field of view, a 2.75 mm entrance aperture, and an exit aperture onto a 250 μm diameter multi-junction PV cell. The lens train incorporates two polycarbonate aspheric lenses with a low index fill of Sylgard®184 PDMS. The thickness of the lens is only 5.30 mm, a 65% reduction from the first generation prototype, and an even greater reduction from traditional CPV systems. The module array arranges 240 elements in a hexagonal closed form across a roughly 40 mm square collection area. The front and rear micro-optic arrays are passively aligned in assembly using pin-in-slot features that are molded into each part, Figure 5. The symmetric geometry of

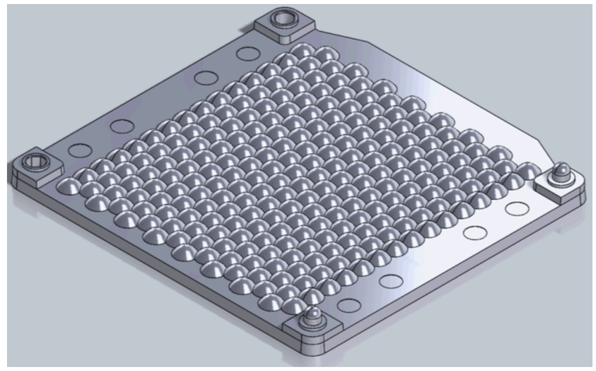

FIGURE 5. Second generation lens array model.

the mating features provides a semi-kinematic, athermal mounting configuration with expected alignment tolerances better than 25 μm. Alignment and assembly of the cell array is also performed passively using monolithic "wedding cake" features in the rear optic array.

FABRICATION

Diamond milling on a 4-axis Moore 350FG was originally planned for fabrication of the first generation prototype. Cost and schedule constraints, however, prompted the evaluation of a faster process based on a 5-axis Yasda YMC-430 micro-machining center. The YMC-430 provides adequate machining accuracy, on the order of 0.5 μm, as optical elements, reference features and mounting holes were all fabricated in a single machining setup, Figure 2. Rough machining with standard carbide micro tools allowed the use of a diamond milling tool for only the final finish pass. As a result, cutting with the diamond was minimized such that appreciable tool wear was not observed after machining in excess of 20,000 individual lens surfaces. The combination of micro-milling with diamond milling also enabled a 2-3x reduction in total machining time which proved critical in meeting project milestones. As expected, excessive surface finish, roughly 100 nm S_a in Figure 6, proved to be the primary drawback of the process producing estimated optical losses of 3% per surface due to scattering.

Fabrication of the second generation prototype optics has investigated techniques amenable to low cost, volume manufacturing. The polycarbonate lens arrays are being injection molded using 6061-T6 aluminum mold inserts that are micro-milled on the YMC-430 using carbide tools for rough figuring. 20 μm of material remains after rough machining which is removed in a single final finishing cut on the

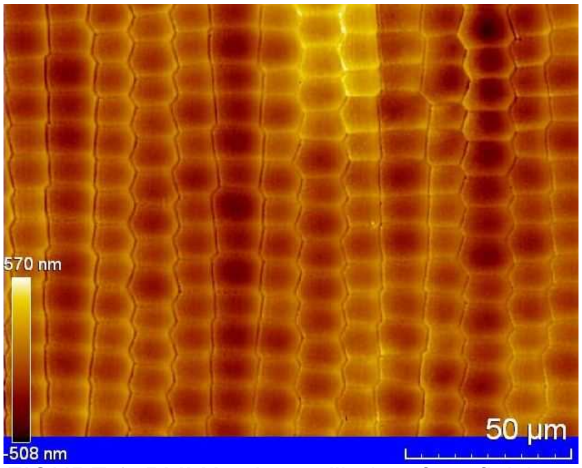

FIGURE 6. PMMA micro-milled surface finish.

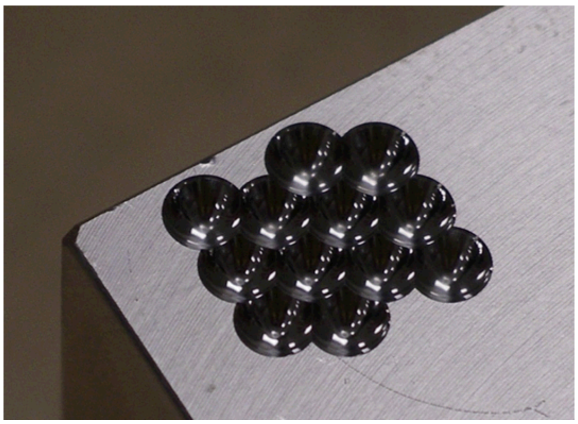
FIGURE 7. 4x4 array test cut in 6061-T6 Al.

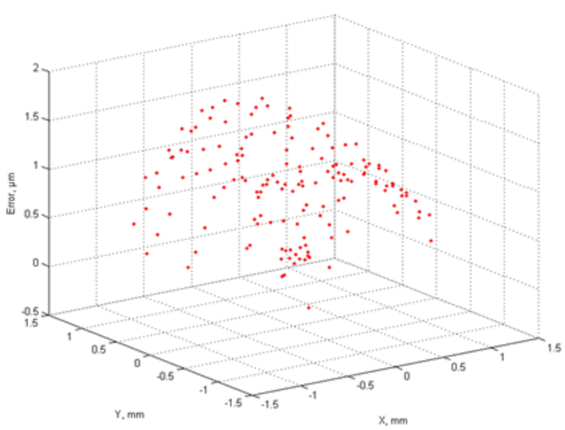

FIGURE 8. Representative test cut 1.5 µm form accuracy.

350 FG using ultra-precision diamond milling. Process development has focused on reducing optic surface finish to improve system efficiency; increasing process throughput to reduce manufacturing costs, and reducing diamond tool wear to minimize performance variations across the lens arrays. Constraints implicit from both machining and molding processes were

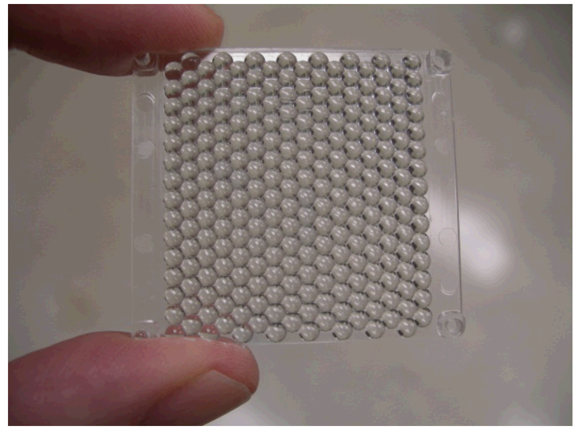
FIGURE 9. Second generation test molded lens array.

incorporated into the opto-mechanical design process. While final insert fabrication remains in process, a 4 x 4 hexagonal test array was produced in 6061-T6 to demonstrate the integrated machining process. Figure 7 shows the machined test part as the form accuracy of the optical elements is roughly 1.5 µm, Figure 8, with a surface finish of 30 nm Sa near the optic apex. Similarly, fabrication of the mold insert for the “wedding cake” features on the rear optic has demonstrated feature dimensional and position accuracies of ±5 µm or better.

Initial optic molding has also been examined by molding a simplified test part, Figure 9. Conventional ball milling was utilized to fabricate the mold insert “optic” array since process development, material shrinkage and array distortion were the metrics of interest; not optic surface finish or form. In-plane material shrinkage across the part was less than 0.2% as the optics were located in X and Y with an accuracy of ±5 µm, Figure 10. Out-of-plane distortion of the entire part, Figure 11, however, approached 100 µm as proper part filling at the corners with minimal distortion has proven difficult. As a result, design changes have been incorporated into the mounting features and part geometry to improve filling and reduce distortion.

FUTURE WORK

Continued work on prototype MEPV systems is focused on increasing collection efficiencies, reducing module size, improving module integration and packaging, and demonstrating cost effective manufacturing strategies. The second generation MEPV system is currently being fabricated and assembled, while a third generation device is being designed.

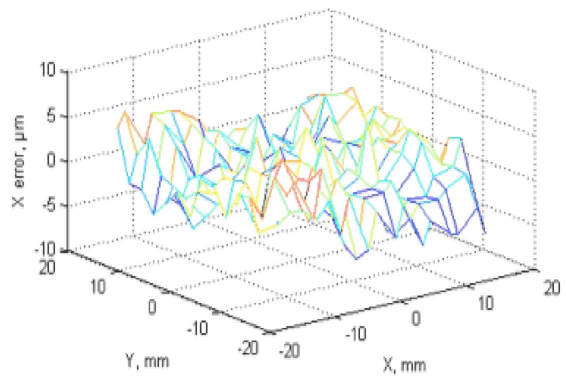

FIGURE 10. Molded test sample in-plane X position errors.

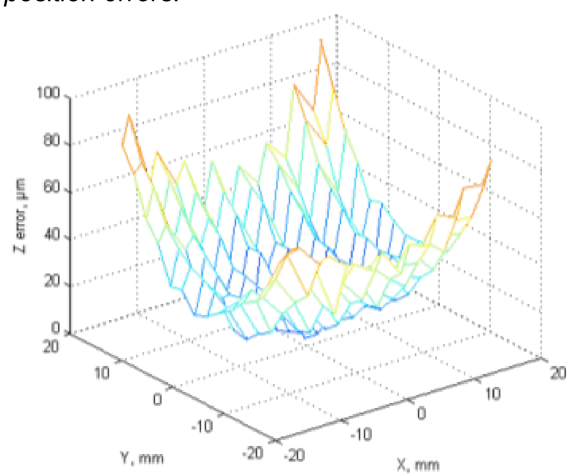

FIGURE 11. Molded test sample out-of-plane Z distortion.

ACKNOWLEDGEMENTS

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