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

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***Abstract* — Microsystems Enabled Photovoltaics (MEPV) is a relatively new field that uses microsystems tools and manufacturing techniques familiar to the semiconductor industry to produce microscale photovoltaic cells. The miniaturization of these PV cells creates new possibilities in system designs that can be used to reduce costs, enhance functionality, improve reliability, or some combination of all three.**

In this article, we introduce analytical tools and techniques to estimate the costs associated with a hybrid concentrating photovoltaic system that uses multi-junction microscale photovoltaic cells and miniaturized concentrating optics for harnessing direct sunlight, and an active c-Si substrate for collecting diffuse sunlight. The overall model comprises components representing costs and profit margin associated with the PV cells, concentrating optics, balance of systems, installation, and operation. This article concludes with an analysis of the component costs with particular emphasis on the microscale PV cell costs and the associated tradeoffs between cost and performance for the hybrid CPV design.

***Index Terms* — hybrid photovoltaic systems, silicon, costs, modeling, photovoltaic cells.**

I. Introduction

While traditional concentrating photovoltaic (CPV) systems with III-V cells produce the highest photovoltaic energy generation by area, the transportability of the systems is limited due to bulk and fragile components. Microscale photovoltaics (PV) employs miniaturized multi-junction photovoltaic cells to maximize electricity generation per unit area worldwide while taking advantage of lower cell costs and robustness that accompany the use of miniaturized concentrating optics [1]. The hybrid microscale PV module design utilizes conventional silicon PV cells as the mechanical substrate to which high efficiency cells are attached, enabling the capture of diffuse light that conventional concentrating photovoltaics systems are unable to utilize [2]. This robust, easily transportable design provides high electricity output per unit area, which is particularly applicable 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).

We extend a previously introduced framework for cost analysis of microscale PV [3] to guide the design of systems for high energy per unit area applications. We present a discussion of significant cost and performance drivers, and explore important design trade-offs associated with this specific application.

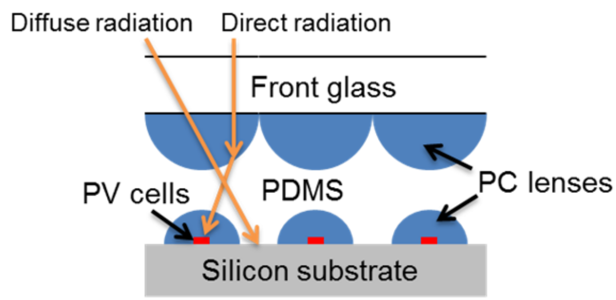

Fig. 1. Conceptual illustration of hybrid microscale PV concept. Polycarbonate (PC) lens arrays guide direct radiation to multi-junction PV cells. Poly-dimethylsiloxane (PDMS) fills the gap between the PC lens arrays, resulting in a solid lens design.

II. System Description and Cost Modeling Approach

The hybrid microscale PV module architecture is based on hexagonal compound semiconductor photovoltaic cells with vertex-to-vertex diameters between 100 µm and 500 µm placed in a sparse array on silicon substrates (conventional PV cells). The microscale PV cells feature one or more III-V semiconductor junctions with independent contacts for each junction. The junctions within a cell stack are placed in intimate contact in order to reduce optical losses; this architecture is possible due to the low resistance losses associated with microscale PV cells, which enable independent contacts without metal grids between junctions [4]. Independently contacted junctions free the design from current matching constraints and offer a path to thinner, more efficient cells.

The silicon substrates with attached III-V cells are bonded to an optical system comprising a plastic lens stack beneath a glass front sheet to form a complete module. The lens stack consists of two polycarbonate (PC) lens arrays separated by poly-dimethylsiloxane (PDMS) to prevent ingress of moisture (Figure 1). Small cell sizes and moderate concentration ratios of 200X to 500X result in modules of similar thickness to conventional non-concentrating PV. The cost modeling approach and inputs for microscale PV systems are similar to those described previously [3]; here we present an expanded model for estimation of fabrication costs for multi-junction III-V cells, and a discussion of the costs associated with parallel placement of high-efficiency cells in sparse arrays on silicon substrates.

A. Fabrication of Photovoltaic Cells

The compound semiconductor photovoltaic cells employed in microscale PV are produced using standard semiconductor processing techniques [5]. The primary stages in the cell fabrication process (Figure 2) are (1) diffusion or implantation of dopants to create cell junctions on silicon wafers, (2) deposition of III-V semiconductor junctions on GaAs substrates, (3) definition of individual III-V cells via etching, (4) release of cells from GaAs substrates and transfer to a sparse array on silicon substrates, and (5) deposition of metal contacts for each cell. The fabrication of additional junctions involves epitaxial deposition of the appropriate compound semiconductor material as well as additional processing steps to define contacts for each junction.

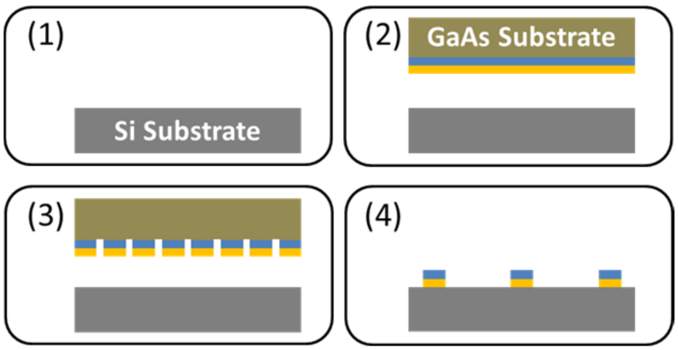

Fig. 2. Steps in cell fabrication process: (1) doping of silicon substrates, (2) deposition of III-V semiconductor junctions on GaAs substrate, (3) etching to define individual cells, and (4) sparse transfer of cells to silicon substrate. The final step, deposition of metal contacts, is not shown.

The proposed cell fabrication process offers the possibility of re-using epitaxy substrates such as GaAs, which represent a significant cost in the fabrication of traditional III-V photovoltaic cells. In the case of microscale PV cells, III-V semiconductor materials are released from the GaAs substrates after the initial epitaxial deposition, and transferred in a sparse array to silicon substrates. The GaAs substrates then undergo a minimum amount of processing to restore the surface in preparation for a subsequent cycle of epitaxial deposition, resulting in significant cost savings compared to the use of virgin GaAs. Processing of GaAs substrates for re-use is modeled as a chemical mechanical polishing step followed by wet bench processing to restore epitaxy-ready surface chemistry. Each substrate is assumed to undergo ten re-use cycles.

A representative cell fabrication process flow was developed, and the cost of each of the steps in the process was estimated based on contributions from raw materials, capital costs, labor, facilities overhead, and consumables. Model input parameters, including tool cost and performance parameters (e.g., throughput, capital costs, labor requirements, materials and energy consumption, and footprint) and materials costs were obtained through direct inquiries with tool vendors. A representative model output from a single step (epitaxial semiconductor deposition) is presented in Figure 2. Estimates of the total cell cost (on a per-wafer basis) were based on fabrication of III-V cells on 6” GaAs substrates, at an assumed process throughput of 60 wafers per hour. The cost of conventional PV cells to serve as large-area substrates was taken from a recent report by Goodrich *et al.* at the National Renewable Energy Laboratory (NREL) [6].

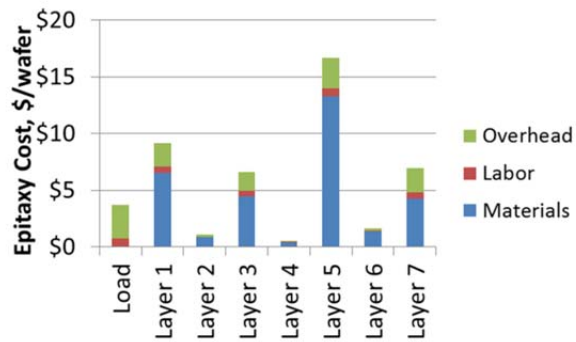

Fig. 3. Estimated epitaxy costs for a single III-V semiconductor junction consisting of seven semiconductor layers.

B. Parallel Placement of Cells in a Sparse Array

Following the fabrication of III-V cell stacks on GaAs substrates, it is necessary to transfer the closely packed cells to silicon substrates in a sparse array. The primary factors determining the cost of this step are the amount of time required for one transfer cycle (cycle time, *T*), the number of cells transferred per cycle, *P*, and the total capital and operating costs, *CT* over the lifetime, *L*, of the tool performing the transfer operation. These factors determine the cost to place a single cell, *CU*, according to the following relationship

Eqn. 1 $$CU = CT/(L \times P\ /\ T)$$

Pick-and-place tools are commonly used in the microelectronics industry to assemble microscale components; however, the use of these tools to place microscale PV cells would likely be cost prohibitive due to the large number of cell placements required per module at the concentration ratios of interest (best-case cost for placing 250 µm cells at 200X concentration ratio is approximately $0.40/W_p$). In order to reduce the cost per cell transferred, several concepts are under development for massively parallel transfer of cells to sparse arrays. These techniques have the potential to reduce the cost per part in Equation 1 by increasing the number of cells transferred per cycle, *P*.

The proposed parallel placement concepts are at an early stage of development, and thus significant uncertainty is associated with the specific cost and performance factors that would determine cell placement cost according to Equation 1. Rather than estimate cell placement cost for a specific concept, a generalized analysis was conducted in order to understand the parameter space that would yield cost reductions due to parallel placement compared to conventional pick-and-place techniques. A cell size of 250 µm was selected based on previous analysis results [3], and tool life, *L*, was assumed to be five years; the number of cells per placement, *P*, was set at 500, which is a conservative estimate based on the lowest value of *P* among the parallel placement concepts under consideration. The total cost, *CT*, and placement time, *T*, are subject to the greatest uncertainty, and were varied in order to provide insight into their impact on cell placement cost in terms of $\$/W_p$; the results are plotted in Figure 4, with total costs given in terms of costs for a pick-and-place process.

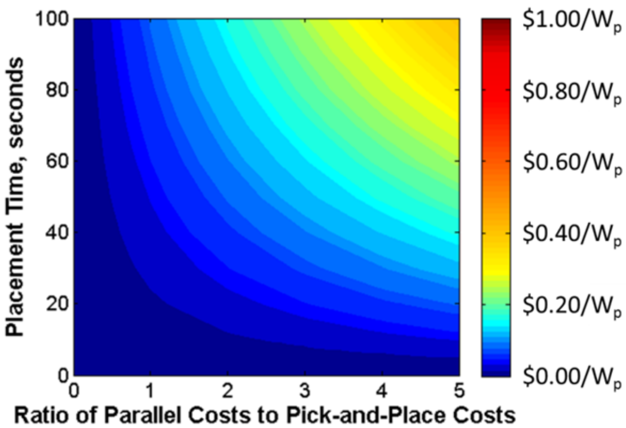

Fig. 4. Contour plot of cell placement costs, based on 250 µm cells, 200X concentration ratio, 5-year tool life, and 500 cells per placement cycle. Colors represent total cost of placing cells in units of $\$/W_p$.

The expected cycle time (placement time) for the parallel techniques under consideration is on the order of seconds to tens of seconds. This is substantially longer than placement times for conventional pick-and-place tools, which are able to place several cells per second. However, the large numbers of cells placed per cycle more than compensate for this difference, and translate to significant improvements in the throughput of parallel placement approaches. Although no estimates of capital or operating costs have been developed for parallel placement processes, the proposed concepts were developed with an eye toward simplicity and inexpensive tool designs. An order of magnitude reduction in cell placement cost compared to pick-and-place operations would be achievable even for cycle times in the tens of seconds and total costs that exceed those for pick-and-place by several times.

III. Cost and Performance Trade-offs

In the design of hybrid microscale PV modules for high electricity output per unit area, several key design factors must be carefully selected in order to balance cost and performance. As one example, we must examine the trade-offs between cost and module efficiency as additional junctions are added to the compound semiconductor stack. It is useful to consider the benefit of adding additional junctions in terms of the LCOE equation, represented conceptually in Figure 5. The cost of adding a junction must be offset by the benefits of increased efficiency; it is important to note that the cost reduction due to increased efficiency depends on the total cost of the system, including installation and maintenance throughout the system lifetime.

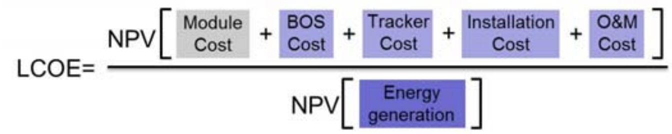

Fig. 5. Conceptual representation of the calculation of LCOE. NPV refers to the net present value of the quantities in parentheses.

The cell cost model described above yields estimates of cell fabrication cost on a per-wafer basis; the dependence of cell cost per peak Watt on cell fabrication cost (per wafer) and module efficiency is depicted in Figure 6 for a fixed concentration ratio. The cell cost per peak 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 Figure 6 and together with estimates of the other cost elements identified in Figure 5, this information can be used to determine the optimum number of junctions in terms of cost. It is important to note that in discussions with semiconductor epitaxy tool vendors, clear pathways to cost reduction in the semiconductor deposition step of the cell fabrication process were identified based on increased materials usage efficiency and enhanced throughput. The incentives to incorporate additional cell junctions are thus likely to increase as epitaxy costs continue on a downward trajectory.

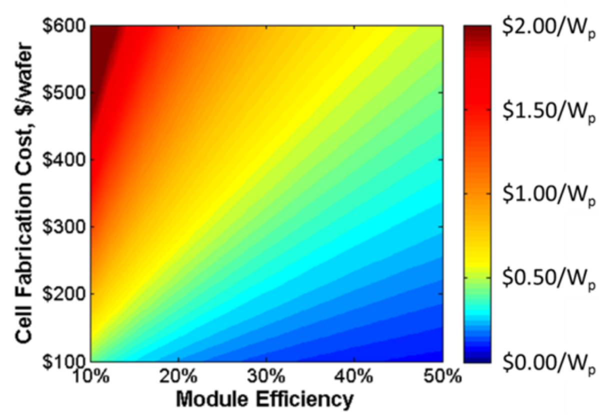

Fig. 6. Contour plot of cell costs ($\$/W_p$) as a function of cell fabrication cost ($/wafer) and module efficiency at a concentration ratio of 200X.

The balance of system (BOS), tracker, installation, and operations and maintenance (O&M) costs are not expected to be significantly affected by changes to the cell architecture (e.g., incorporation of additional junctions); however, module cost and performance may be optimized for each cell design, primarily through adjustments to the cell size and the concentration ratio of the optical system. While a cell size of 250 μm was selected for the current study based on the quantitative results from our earlier cost analysis work [2], the concentration ratio must be optimized based on estimates of cell cost and efficiency. As the concentration ratio is increased, the total cost of cells decreases due a reduction in total cell area. At the same time, for constant cell size the thickness of the concentrating optics increases with concentration ratio, leading to concomitant increases in weight and cost (Figure 7). In terms of overall module performance, lower concentration ratios are preferred, as they lead to thinner, lighter modules, and also widen the acceptance angle of the optics. Thus, the concentration ratio that minimizes cost may not be the preferred option if a premium is placed on any of these performance attributes.

V. 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.

Building on a previously introduced framework for analyzing the costs of microscale PV technology, trade-offs between cost and performance have been identified and explored. A detailed cost model of the cell fabrication process is currently being employed in an optimization of the cell architecture, specifically focused on the number of junctions in the multi-junction cell stack. For each potential cell architecture, the costs of the cells and the optics must be balanced by adjusting the concentration ratio, taking into account the desired performance of the module in terms of thickness, weight, and acceptance angle.

Although the discussion presented here has focused on utilization of the microscale PV concept for applications requiring high energy output per unit area, the methodology and general conclusions are relevant to other implementations of the technology. Similar cost analyses will be carried out as the microscale PV approach is applied in other areas – particularly utility-scale solar farms in high annual average solar radiation areas (kWh/m^2-day).

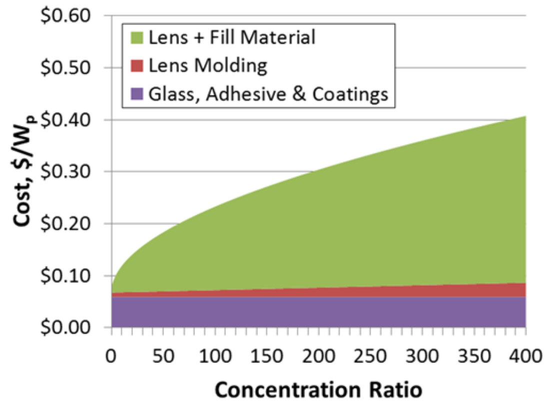

Fig. 7. Cost of microscale PV optical system as a function of concentration ratio. Cell size (vertex-to-vertex distance) is 250 μm.

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REFERENCES

[1] G. Nielson, M. Okandan, P. Resnick, J. Cruz-Campa, T. Pluym, P. Clews, E. Steenbergen, V. Gupta, "Microscale c-Si (C) PV cells for low-cost power," in *34th IEEE PVSC*, 2009, pp. 1816-1821.

[2] S. Paap, V. Gupta, J. Cruz-Campa, M. Okandan, W. Sweatt, B. Jared, B. Anderson, G. Nielson, A. Tauke-Pedretti, J. Nelson, "Cost analysis for flat-plate concentrators employing microscale photovoltaic cells," in *39th IEEE PVSC*, 2013.

[3] M.W. Haney, T. Gu, and G. Agrawal, "Hybrid Microscale CPV/PV Architecture," Submitted to *40th IEEE PVSC*, 2014.

[4] A. Tauke-Pedretti, J. Cederberg, G. Nielson, J. Cruz-Campa, C. Sanchez, C. Alford, M. Okandan, E. Skogen, A. Lentine, "Resistance considerations for stacked small multi-junction photovoltaic cells," in *39th IEEE PVSC*, 2013.

[5] G. Nielson, M. Okandan, J. Cruz-Campa, V. Gupta., P. Resnick, C. Sanchez, S. Paap, B. Kim, W. Sweatt, A. Lentine, J. Cederberg, A. Tauke-Pedretti, B. Jared, B. Anderson, R. Biefeld, J. Nelson, "Advanced compound semiconductor and silicon fabrication techniques for next-generation solar power systems," *ECS Transactions*, vol. 50, 2012, pp. 351-359.

[6] A. Goodrich, P. Hacke, Q. Wang, B. Sopori, R. Margolis, T. James, M. Woodhouse, "A wafer-based monocrystalline silicon photovoltaics roadmap: Utilizing known technology improvement opportunities for further reductions in manufacturing costs," *Solar Energy Materials & Solar Cells*, vol. 114, 2013, pp. 110-135.