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Wafer Integrated Micro-scale Concentrating Photovoltaics

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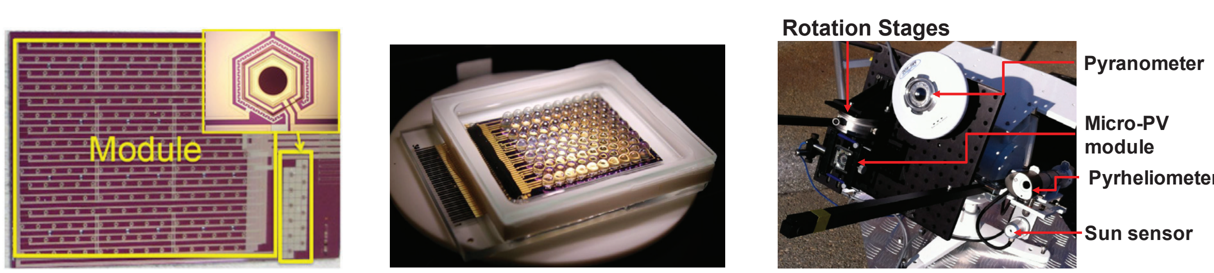
Abstract. Recent development of a novel micro-scale PV/CPV technology is presented. The Wafer Integrated Micro-scale PV approach (WPV) seamlessly integrates multijunction micro-cells with a multi-functional silicon platform that provides optical micro-concentration, hybrid photovoltaic, and mechanical micro-assembly. The wafer-embedded micro-concentrating elements is shown to considerably improve the concentration-acceptance-angle product, potentially leading to dramatically reduced module materials and fabrication costs, sufficient angular tolerance for low-cost trackers, and an ultra-compact optical architecture, which makes the WPV module compatible with commercial flat panel infrastructures. The PV/CPV hybrid architecture further allows the collection of both direct and diffuse sunlight, thus extending the geographic and market domains for cost-effective PV system deployment. The WPV approach can potentially benefits from both the high performance of multijunction cells and the low cost of flat plate Si PV systems.

INTRODUCTION

Solar energy has been growing fast in recent years with the rapid price falling of Si-wafer based photovoltaic (PV) technology, driven by technological advancements and scaling-up of deployment volume. As the efficiency of Si PV reaches its practical limit, balance-of-system (BOS) costs gradually become the dominant challenges for continued price reduction. High-efficiency, low-cost PV modules beyond Si are critical for further market penetration and can potentially enable new price learning curves of solar technology. By utilizing high performance multijunction cells and concentrator optics, concentrating photovoltaics (CPV) systems can in principle reduce energy production costs. However, while the cell performance has been advancing steadily recently, conventional CPV technologies are plagued by several issues that offset the potential cost effectiveness. Within the module level,



(a) (b) (c)

FIGURE 1. Prototype micro-scale CPV modules developed in the Microsystem-enabled Photovoltaic program: (a) prototypical module integrating molded micro- concentrating optics and micro-cell arrays; (b) fabricated micro-cell array and interconnects; (c) on-sun characterization setup.

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trade-offs exist among the cell, optic, and module manufacturing costs; within the system level, trade-offs exist between the module performance and system installation/operation costs. Finally, the inability of conventional CPV to collect diffuse light further limits its geographic and market penetration.

Micro-scale CPV integrate arrays of micro-cells and micro-optics within a compact module similar to flat plate Si PV using advanced cell fabrication approaches [1-4], introducing new benefits of such as enhanced cell performance, reduced semiconductor and optic materials costs, interconnect flexibility, improved heat dissipation and a compact physical profile. Through the Microsystems Enabled Photovoltaics (MEPV) program led by Sandia, we previously demonstrated several prototypical micro-CPV modules (Fig. 1) integrating a variety of advanced micro-cell and micro-optic arrays [1-3]. An integrated PV/CPV hybrid approach is also introduced [5].

In this paper, the recent development of a new micro-scale PV approach under *ARPA-E's Micro-scale Optimized Solar-Cell Arrays with Integrated Concentration* (MOSAIC) program is presented, aiming to radically improve PV system's cost effectiveness by further exploiting the cell/optic scaling effects. A novel Wafer Integrated Micro-scale Photovoltaic (WPV) concept is proposed [6], which utilizes III-V micro-cells integrated with a multifunctional Si platform to fully leverage the high performance of multijunction cells and module- and system-level benefits of Si flat-plate PV. The PV system designs are guided by a detailed cost model based on industrial-scale fabrication processes that analyzes and predicts energy production costs [7].

WAFER-INTEGRATED MICRO-SCALE CONCENTRATING PHOTOVOLTAICS

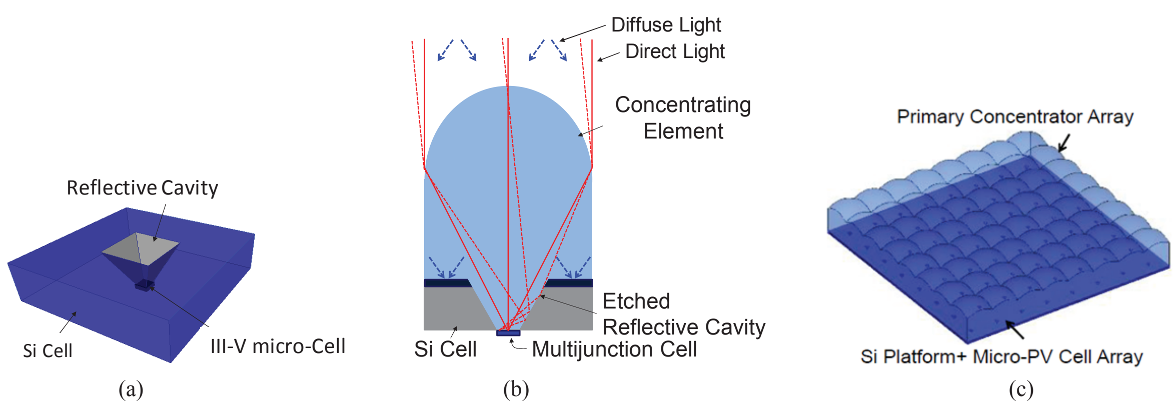


FIGURE 2. (a) A novel multi-functional Si cell platform that integrates an array of concentrated multijunction micro-cells; (b)&(c) a baseline structure consists of a molded lens array layer, a multi-functional Si cell, and an integrated array of high concentration multijunction micro-cells.

The recent development and characterization results of a prototypical module based on the WPV concept is described in this paper. The key notion is a multi-functional silicon cell platform that provides optical micro-concentration, hybrid photovoltaic, and mechanical micro-assembly functionalities for high concentration multijunction micro-cell arrays hybridly integrated on the 1X or low-concentration Si cell, as schematically illustrated in Fig. 2 (a). The Si cell contains etched V-shaped reflective cavities that serve as efficient non-imaging micro-optical concentrators and/or alignment features embedded at the wafer level. By anisotropic-etching conventional (100) oriented silicon substrates to expose the (111) crystal planes, inverted-pyramid-shaped rectangular cavities are formed with facets of a 35.3° slanting angle and precisely-defined optical apertures matching the micro-scale cells. The Si cell is also designed to capture diffuse sunlight which usually cannot be collected by conventional CPV systems.

A baseline WPV structure is illustrated in Fig. 2 (b) and (c), which consists of: 1) a Si cell platform embedding the reflective cavities and cell interconnections, 2) a multi-junction micro-scale PV cell array integrated on the Si platform, and 3) a primary concentrating optic array. The Si platform with wafer level alignment features can be further integrated into a variety of single- or multi-stage optical concentrators with a compact form factor.

Optical Micro-concentration

A key figure of merit for evaluating CPV systems is the concentration-acceptance product [8],

$$CAP = \sqrt{C_g} sin\theta_{in} \qquad (1)$$

where C_g and θ_{in} are the geometric concentration ratio and acceptance angle, respectively. Note that *CAP* is nearly an invariant for a given optical architecture due to the conservation of étendue. Hence Equation (1) reveals the trade-offs between concentration ratio and acceptance angles and accordingly the balance among materials, module, and system level costs. With limited *CAP* values close or below 0.5, state-of-the-art CPV technologies are typically designed for high concentration to reduce cell costs, at the expenses of complex module designs and tight tolerances to assembly and operation misalignments.

The etched Si cavity plays a critical role in simultaneously improving the concentration ratio and acceptance angle of a micro-CPV module with minimally induced module complexity and costs. As shown in Fig. 3 (a) and (b), reflective V-groove cavity arrays with 100 µm × 100 µm output apertures designed to match micro-cell arrays are fabricated on a 280-µm thick Si wafer using KOH etching and metallization. The optical performance is characterized by coupling the reflective cavity to an off-the-shelf primary concentrator. As shown in Fig. 3 (c), experimental results indicate that a >100% improvement on the concentration-acceptance-product is achieved, when compared to the concentrator-only case. Enabled by such wafer-level integrated micro-concentrators, the simple baseline WPV architecture yields prototype designs with concentration ratio ranging between 400X and 2400X while maintaining sufficient angular tolerances (±1°~ ±2°) that are fully compatible with commercial low-cost trackers (1°~1.5° tracking accuracy).

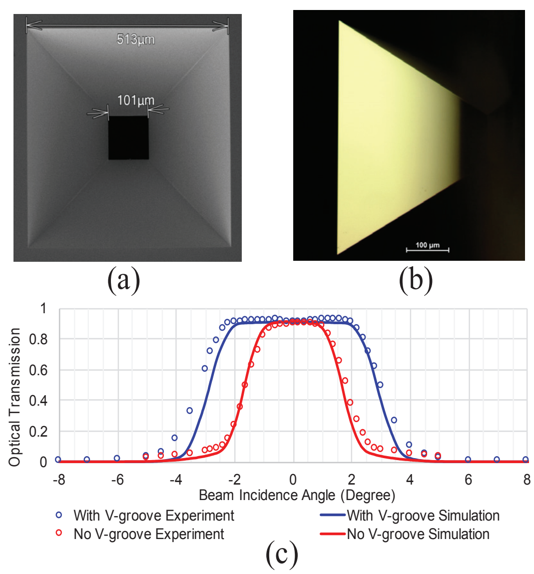
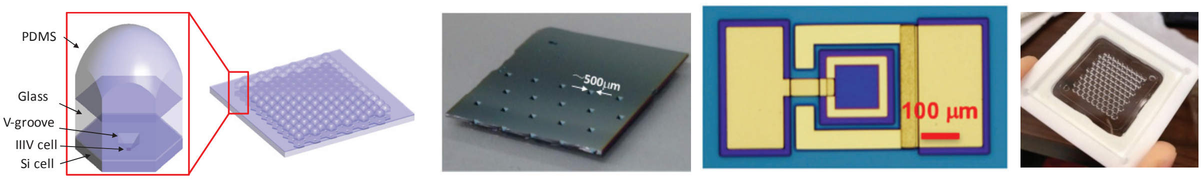


FIGURE 3. (a) Top view and (b) side view of an etched Si V-shaped cavity; (c) experimental vs. simulation results indicate >100% improvement on acceptance angle and *CAP* by incorporating the low-profile Si cavity into a traditional optical concentrator system.

Hybrid Photovoltaics

The multi-functional Si platform also enables a highly-integrated hybrid PV/CPV architecture at low cost. The diffuse radiation component of the sunlight (i.e., light scattered by atmospheric aerosols and clouds) constitutes a considerable portion of the total incident power, depending on location, but usually cannot be captured by conventional CPV systems. A hybrid PV/CPV architecture integrating high-concentration, high-performance micro-cells and non- or low-concentration, low-cost flat plate PV would significantly improve overall power conversion efficiency. According to standard solar radiation data from different regions across the USA which spans a wide range of solar insolation [9], the contribution from diffuse radiation is approximately 2-2.5 kWh/m^2-day for most locations, representing 20-40% of the global radiation. Assuming 18% efficient Si PV and 30% efficient CPV systems are used, analysis indicates that the hybrid approach is able to provide 40-50% and 15-40% more energy production per unit area across the USA than conventional flat plate PV and CPV, respectively.



(a) (b) (c) (d)

FIGURE 4. (a) Baseline prototype module design; (b) etched cavity arrays on a Si substrate; (c) optical image of a fabricated InGaP/GaAs micro-cell; (d) packaged PDMS lens array molded on glass.

PROTOTYPING

A first prototypical module is under development based on the baseline design, as shown in Fig. 4 (a). It consists of a Si platform, an array of 100-µm-wide InGaP/GaAs micro-cells hybrid-integrated on the output apertures of the V-groove cavities, and a 400X-concentration molded PDMS primary lens array assembled on the Si platform via a middle glass plate, as shown in Fig. 4 (b) – (d).

The Si platform and III-V micro-cell arrays are processed in parallel before the hybrid integration. Reflective cavity arrays are first formed on a 280-µm thick Si wafer using KOH etching, followed by metallization. The cavity side walls achieve an RMS surface roughness of (9 ± 1) nm, ensuring high optical reflection. The Si wafer is subsequently processed into an interdigitated back contact (IBC) solar cell with interconnects and contacts formed on its backside for the Si and III-V cells. The III-V multijunction micro-cell arrays are then bonded onto the Si platform matching the apertures. InGaP/GaAs micro-cells bonded on Si have demonstrated cell efficiencies of 29.5% under 200 suns, while other multijunction cells with higher efficiencies can be readily integrated onto the same Si platform. The Si platform is subsequently assembled onto the backside of a glass plate with the V-groove cavities filled with PDMS. A high-quality PDMS aspherical primary concentrator array is directly cast on the front side of the glass. Including a front cover glass and a backing sheet, the total thickness of the fully-packaged module is less than 1 cm.

For advanced multi-stage optic designs, the etched cavity can simultaneously serve as an optical micro-concentrator and a micro-mechanical bench. Fig. 5 shows a 2-mm diameter ball lens concentrator positioned and self-aligned on the Si platform via the V-shaped cavity.

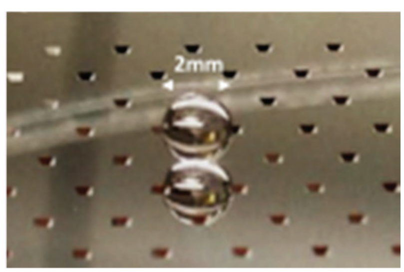


FIGURE 5. Self-aligned ball-lens concentrator positioned on a Si cavity.

COST MODEL

Cost models were developed for both cell and module production. The cell cost model yields an estimate of the cost ($/wafer or $/cm^2) to fabricate cells based on an industrial-scale cell fabrication process flow. The cost of each step in the process was estimated based on contributions from raw materials, capital costs, labor, facilities overhead, and consumables and obtained through direct inquiries with tool vendors. The cell fabrication cost serves as an input to the module cost model, which calculates the expected module cost for a given optical concentration ratio and cell size. Many of the module-level costs are similar to those for conventional non-concentrating silicon-based PV, obtained through direct inquiries to vendors or from [10]. The estimated costs for each of the system elements project that the WPV approach can achieve a module cost of less than $150/m^2. It should be noted that the Si platform replaces an additional non-imaging secondary optical element array, which eliminates the fabrication and assembly costs of such micro-optics arrays as a discrete module component.

SUMMARY

The development of a novel micro-scale integrated PV/CPV concept is described. The multi-functional Si platform integrated with IIIV micro-cell arrays provides micro-optical concentration, hybrid photovoltaics, and micro-mechanical assembly. We experimentally demonstrated that the wafer-embedded Si cavity concentrator can provide over 100% improvement on the concentration-acceptance-angle product, leading to considerably reduced module costs, sufficient angular tolerance to low-cost trackers, and an ultra-compact flat-plate form factor. The current development of a baseline prototype module is presented. The micro-scale PV/CPV approach can potentially combine the high performance of multijunction cells and the low costs of flat-plate Si PV systems.

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