Microsystems-Enabled Photovoltaics: A Path to the Widespread Harnessing of Solar Energy

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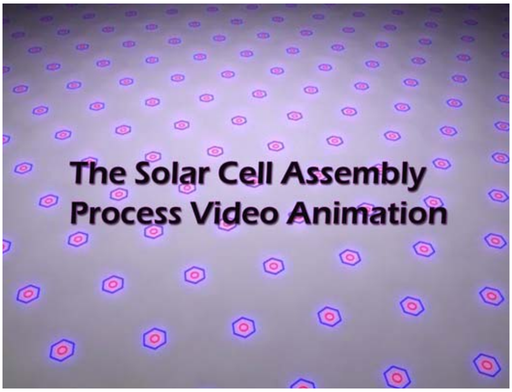
Abstract

If solar energy is ever going to become a mainstream power source, the technologies for harnessing sunlight have to become cheaper than all other forms of energy, be easy and quick to install, and work more safely, reliably and durably than present-day grid power. Our research team is striving to make this happen by utilizing microdesign and microfabrication techniques used in the semiconductor, LCD and microsystem industries. In this article, we describe microsystems-enabled photovoltaic (MEPV) concepts that consist of the fabrication of micro-scale crystalline silicon and GaAs solar cells, the release of these cells into a photovoltaic (PV) "ink" solution, and the printing of these cells onto a substrate using fluidic self-assembly approaches. So far, we have produced 10 percent efficient crystalline GaAs cells that are 3 µm thick and 14.9 percent efficient crystalline silicon cells that are 14 µm thick. The costs associated with this module assembly approach in conjunction with optical concentration can be well below $\$1/\text{Watt}_{peak}$ while retaining the superior conversion efficiency and durability of crystalline silicon and III-V materials.



Our Vision

With the emerging electrification of personal transportation, decentralization of energy generation in places that lack a reliable electricity grid, growing concerns about atmospheric emissions from fossil fuel use, and ever-increasing global demand for electricity, there is an insatiable need for point-of-use technologies that generate electricity in a clean way.

Our group is striving to make microsystems-enabled photovoltaics (MEPV) the most efficient, versatile and inexpensive way to provide that electricity. We envision high-concentration, sun-tracking MEPV for power utilities; low-concentration, flat-plate MEPV for horizontal rooftops; and flexible, integrated MEPV for sloped rooftops, vehicles, gadgets and the human body.

Many things have to be accomplished before photovoltaics become a ubiquitous technology: reducing the amount of necessary high-cost semiconductor material, developing highly efficient cells, achieving long-term durability and reliability, using low-cost packaging substrates, creating scalable high-speed assembly processes, and establishing fast methods to install and wire the grid-connected circuitry.

Several groups across the world,[1-4] including ours, have developed prototype small and ultrathin photovoltaic cells that reduce PV material use dramatically. These ultrathin cells perform nearly as well as thick ones[4-6] that are much thicker than what is necessary for photoelectric conversion simply to minimize breakage during cell processing, handling and assembly.

Figure 1a depicts the normalized cell efficiency (efficiency/potential efficiency) vs. the cell thickness. It shows that ultrathin cells can substantially decrease the cost associated with the use of silicon material while retaining 90 percent of the potential conversion efficiency. This graph assumes a single light pass through

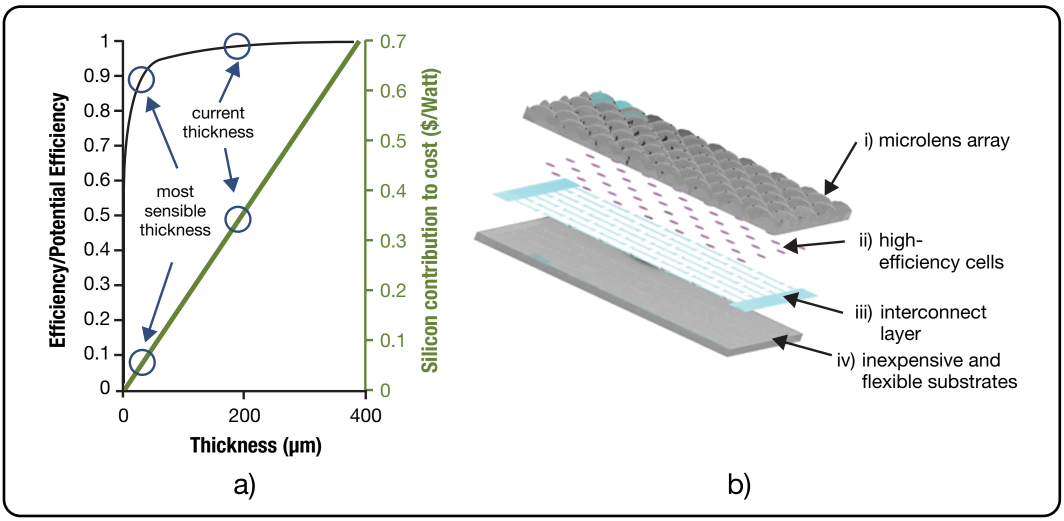
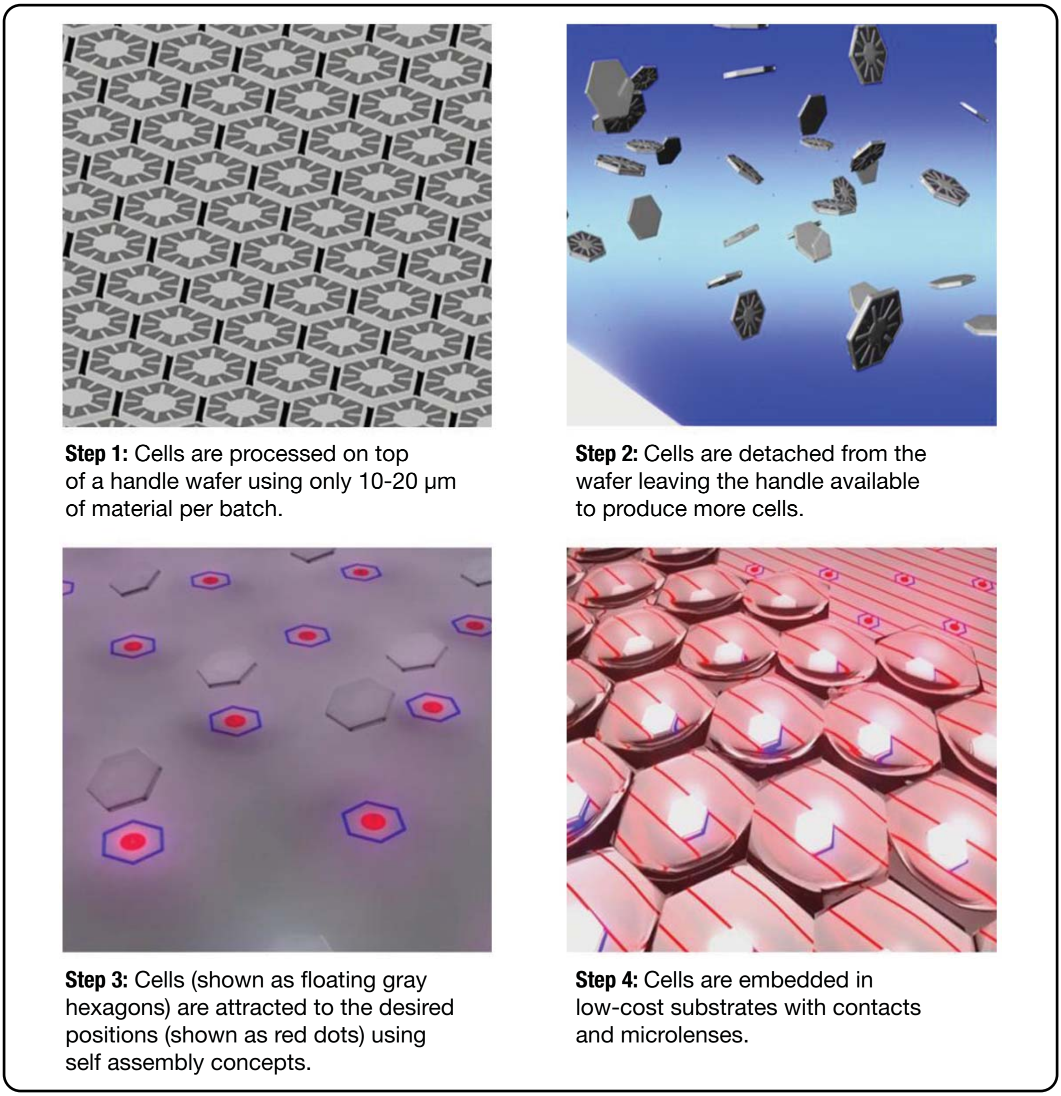


Figure 1 – a) Cost and potential conversion efficiency in silicon solar cells as a function of thickness; b) the microsystems-enabled photovoltaic module concept showing the four distinct layered components

the cell; adding back reflectors and light trapping structures would further enhance the conversion efficiency and make the knee of this curve move to thicknesses below 10 µm.[6]

Our method integrates multiple technologies in an effort to produce an inexpensive module. Figure 1b shows the four



Step 1: Cells are processed on top of a handle wafer using only 10-20 µm of material per batch.

Step 2: Cells are detached from the wafer leaving the handle available to produce more cells.

Step 3: Cells (shown as floating gray hexagons) are attracted to the desired positions (shown as red dots) using self assembly concepts.

Step 4: Cells are embedded in low-cost substrates with contacts and microlenses.

Figure 2 – Process to Create Photovoltaic Sheets of Micro Cells From Cell Liftoff to Final Assembly

main parts of our approach: i) a microlens array that concentrates the light onto the cells; ii) the ultrathin, small and highly efficient solar cells; iii) an interconnection layer; and iv) the entire system encapsulated in flexible substrates.

Benefits of our Approach

Our approach uses tiny solar cells that are 14-20 µm thick and 250 µm to 1 mm in lateral dimensions. This method enables three main ways of reducing the PV module costs[7]: by making the cells with a small lateral dimension, by creating ultrathin cells and by using micro-concentrators. The small lateral size enables better use of the available wafer area (i.e., reduction in edge die loss), increases area usage through the production of hexagonal cells, and gives semiconductor manufacturers the flexibility to use any wafer size. Thinning the cells reduces semiconductor material costs, improves carrier collection and potentially achieves higher open circuit voltages. The small size also enables the cells to be processed with IC fabrication tools, allowing near-ideal cell performance (>20 percent for c-Si, >40 percent for III-V multijunction cells). Finally, micro-optical elements concentrate sunlight onto each cell, further reducing the need for high-cost semiconductor materials. All together, this three-pronged approach decreases the need for high-cost materials, reduces overall system cost and increases conversion efficiency per gram of utilized PV material.

Another advantage of our method is that it utilizes mature technology, tools and techniques used in the production of microelectronics and microsystems. This enables the production of micro solar cells with consistent IV parameters, high efficiencies and superior robustness compared to conventional large-area thin cells. All of the manufacturing steps (patterning, diffusion, passivation and metalization) are done while the micro cells are still attached to the substrate wafer to facilitate handling. Then, thousands of ultrathin micro cells are detached from the wafer by means of a sacrificial layer or an anisotropic etch (liftoff technique) and released into a solution. Only 15-25 µm of the handle wafer is consumed in each batch and the rest is left available to be reused and produce another lot of micro cells. Each substrate wafer (e.g., c-Si, GaAs, Ge) thus has the possibility of being reused many times rather than being consumed in a single fabrication run.

The micro size subsequently requires novel and workable parallel self-assembly methods[8] to place the cells onto designated spots. These assembly concepts use energy minimization approaches to make arrays of the cells on inexpensive substrates. The cells can be embedded in low-cost flexible materials that produce virtually flat modules. Figure 2 shows the procedure used to create PV sheets using this technology.

In addition to the benefits obtained at the cell level, there are multiple advantages at the module and system level due to the scale of the cells. Small cell size allows the use of inexpensive refractive optics[2] instead of Fresnel optics, giving better optical efficiencies; reduced thickness and small lateral cell size simplifies the management of thermal loads on the PV modules (which is particularly important for optical concentrating designs); the microscale PV concentrator makes high-accuracy and high-bandwidth tracking possible, thereby reducing tracking cost and complexity as well as providing pointing accuracy during windy conditions (due to the high-speed response of the tracker)[7,10]; and finally, small form factor (i.e., thin) con-

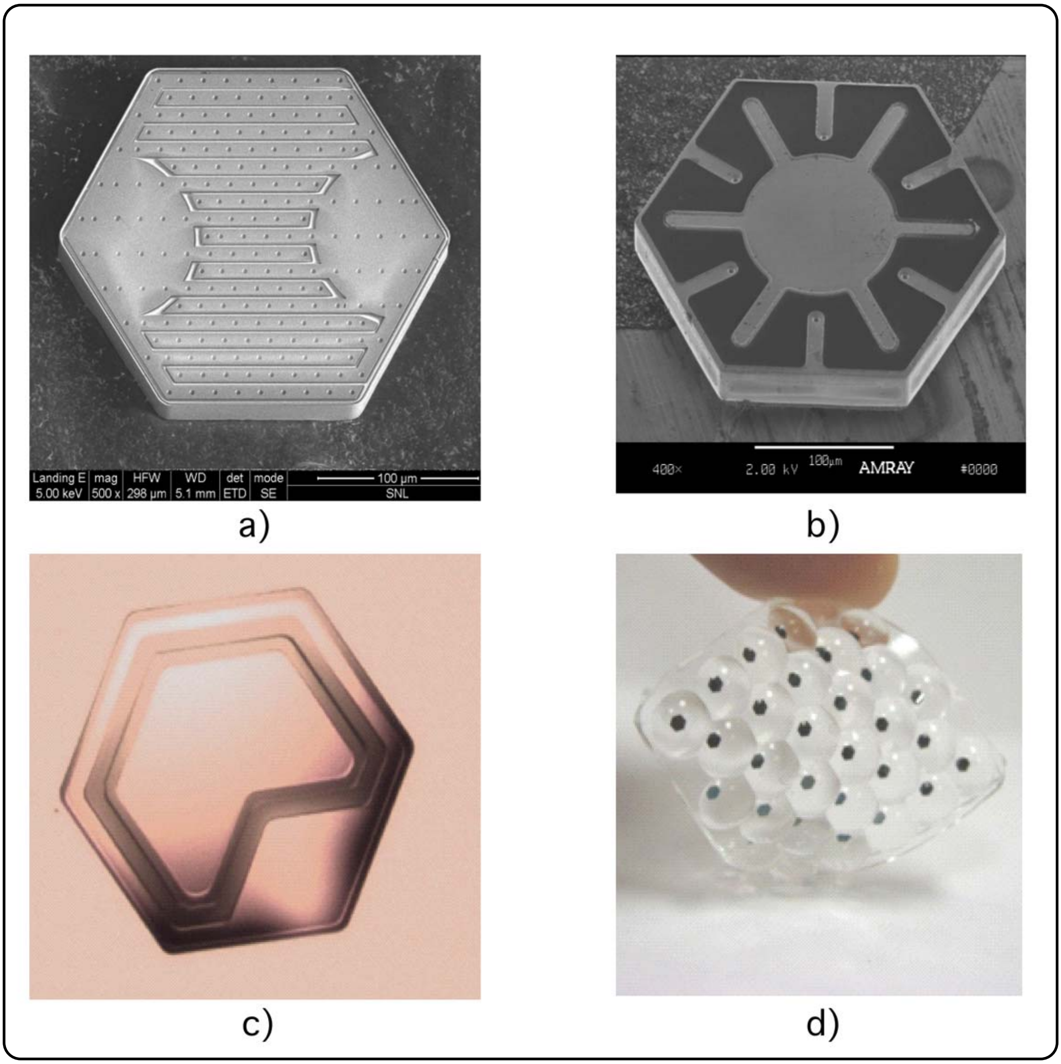


Figure 3 – Pictures of our released solar photovoltaic cells: a) Scanning electron microscope (SEM) image of a 250 µm wide silicon solar cell released through an anisotropic KOH under-etch with lateral interdigitated fingers; b) SEM of 250 µm wide silicon solar cell released using a buried silicon dioxide layer with radial contacts; c) 250 µm GaAs solar cell released using a buried AlAs layer; d) flexible mechanical model with embedded cells and micro optics

centrator modules with integrated in-plane trackers can be flat mounted at the point of use for the generated electricity.

Our Results to Date

Our technique produced ultrathin solar cells with lateral dimensions ranging from 250 µm to 1 mm. We have utilized a variety of materials, approaches and designs, including single crystal silicon in (111) or (100) crystallographic orientations and single-crystal GaAs. The approaches differ in the chemistry and technique used to detach the wafers from the cell: (111) oriented silicon wafers require a potassium hydroxide (KOH) anisotropic etch that undercuts the cell, while (100) oriented silicon wafers make use of a buried silicon dioxide sacrificial layer. In the case of GaAs cells, the release sacrificial layer used is AlAs.

The designs of our solar cells include: i) a silicon back-contacted radial pattern; ii) a silicon back-contacted interdigitated format; and iii) an ultrathin, single-junction GaAs cell with back contacts. Figure 3 shows optical and scanning electron microscope (SEM) images from the finished cells using the different materials, approaches and designs as well as a mechanical model with the cells embedded in an inexpensive, flexible substrate with an integrated microlens array.

In order to explore the commercial potential of MEPV technology, a cost analysis was carried out assuming a solar flux of

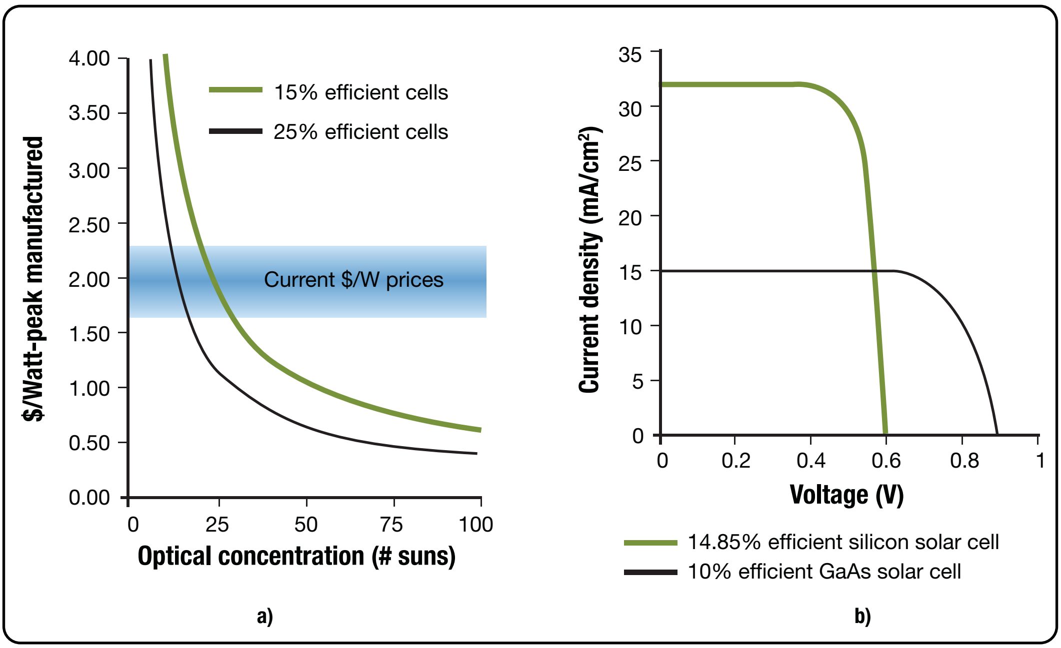


Figure 4 – a) Cost analysis of our technology: $/Watt vs. concentration for different cell efficiencies assuming a $25/m^2 assembly cost; b) experimental J-V measurement curves of our micro cells

100mW/cm^2, a process cost of \$150/wafer, a wafer diameter of 200 mm, a \$25/m^2 assembly cost, and 95 percent overall cell process yield. This analysis revealed that the costs of our technology approach could be well below \$1/Watt$_{peak}$ by using moderate concentration (below 50x) and massive parallel assembly. Figure 4a graphically shows the results of these calculations.

So far, our technology has produced 14.9 percent conversion efficiency for 14 μm (13.7 +/- 0.38 μm) thick cells made from crystalline silicon and 10 percent conversion efficiency for 3 μm thick cells made of GaAs.[11] This level of performance is comparable to the conversion efficiency in available commercial silicon-based modules with PV cells that are 10-15x thicker. Figure 4b shows the current density-voltage curves (J-V) for two of our cells. Both cells were tested with a solar simulator normalized to 1000W/m^2 using a silicon reference solar cell.

Conclusions

In the United States, solar energy generation, including photovoltaics, presently produces 0.1 percent of the energy used for electricity, heating and transportation. If PV adoption is to grow at a compounded annual growth rate of 40 percent per year and thereby become a 40 percent contributor to the U.S. and global energy portfolio within one human generation,[12] a series of technology breakthroughs are needed in PV cell development, assembly, installation, operation and end-of-life retirement.

The microsystems-enabled photovoltaic concepts described in this article show one technology pathway to realizing this vision. The 10 percent efficient, 3 μm thick crystalline GaAs cells along with the 14.9 percent efficient, 14 μm thick crystalline silicon cells developed by our team suggest that there are breakthrough possibilities along this pathway. Combining these experimental results plotted in Figure 4b with the parallel self-assembly approach illustrated in Figure 2 as well as the cost analysis shown in Figure 4a, there appears to be a reasonable probability of developing a MEPV manufacturing approach that is as low or perhaps lower in U.S. dollar per Watt-peak cost than all other forms of energy, including PV thin film technologies.

Contrary to the popular belief espoused by futurist thinker Tom Friedman, the world is not flat.[13] It is filled with the various shapes and curved contours of natural terrain, large manmade structures, portable electronics, vehicles and the human body. All of these prospective PV hosts are becoming ever more ready to adopt efficient, versatile and inexpensive photovoltaic devices for powering important things. Microsystems-enabled PV can provide those devices, and our research team is committed to doing our part to develop the technological means of making it so.

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References

1. W.P. Mulligan, A. Terao, D.D. Smith, P.J. Verlinden, R.M. Swanson, "Development of chip-size silicon solar cells," Conference record on the 28th IEEE Photovoltaic Specialist Conference (2000) 158-163.
2. J. Yoon, A.J. Baca, S.I. Park, P.S. Elvikis, J.B. Geddes III, L. Li, R.H. Kim, J. Xiao, S. Wang, T.-H. Kim, M.J. Motala, B.Y. Ahn, E.B. Duoss, J.A. Lewis, R.G. Nuzzo, P.M. Ferreira, Y. Huang, A. Rockett, J.A. Rogers, "Ultrathin silicon solar micro cells for semitransparent, mechanically flexible, and microconcentrator module designs," Nature Materials 7 (2008) 907-915.
3. K.J. Weber, A.W. Blakers, M.J. Stocks, J.H. Babaei, V.A. Everett, A.J. Neuendorf, P.J. Verlinden, "A Novel Low-Cost, High-Efficiency Micromachined Silicon Solar Cell," IEEE Electron Device Letters 25 (2004) 37-39.
4. G.N. Nielson, M. Okandan, P. Resnick, J.L. Cruz-Campa, T. Pluym, P. Clews, E. Steenbergen, V. Gupta, "Microscale c-Si (c)PV cells for low-cost power," Conference record on the 34th IEEE Photovoltaic Specialists Conference (2009) 1816-1821.
5. T.H. Wang, T.F. Ciszek, C.R. Schwerdtfeger, H. Moutinho, R. Matson, "Growth of silicon thin layers on cast MGSi from metal solutions for solar cells," Solar Energy Materials and Solar Cells 41-42 (1996) 19-30.
6. M.A. Green, "Limiting Efficiency of Bulk and Thin-Film Silicon Solar Cells in the Presence of Surface Recombination," Progress in Photovoltaics: Research And Applications 7 (1999) 327-330.
7. G.N. Nielson, M. Okandan, P. Resnick, J.L. Cruz-Campa, P. Clews, M. Wanlass, W. Sweatt, E. Steenbergen, V. Gupta, "Microscale PV cells for concentrated PV applications," Conference record of the 24th EU PVSEC (2009) 170-173.
8. S. Shet, R.D. Revero, M.R. Booty, A.T. Fiory, M.P. Lepselter, N.M. Ravindra, "Microassembly Techniques: A Review," Conference record on the Materials Science and Technology 1 (2006) 451-470.
9. J.L. Cruz-Campa, M. Okandan, M. Busse, G.N. Nielson, "Microlens rapid prototyping technique with capability for wide variation in lens diameter and focal length," Microelectronic Engineering (2010) in press.
10. W.C. Sweatt, B.H. Jared, G.N. Nielson, M. Okandan, M.B. Sinclair, A. Filatov, A. L. Lentine, "Micro-Optics for High-Efficiency Optical Performance and Simplified Tracking for Concentrated Photovoltaics (CPV)," OSA International Optical Design Conference (IODC), in press.
11. J.L. Cruz-Campa, G.N. Nielson, M. Okandan, M. Wanlass, C. Sanchez, P. Resnick, P. Clews, T. Pluym, V. Gupta,

"Back contacted and small form factor GaAs solar cell," Conference record of the IEEE 35th Photovoltaic Specialists Conference (2010) in press.

12. S. Dwyer, "Solar Growth Rate Projections to Make Solar Mainstream in the United States," DOE Tiger Team Technical Memorandum, August 3, 2009, 1-3.
13. Friedman, Thomas L., "The World Is Flat: A Brief History of the Twenty-First Century," Farrar, Straus and Giroux (2005). ■

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