Compact monocrystalline silicon solar modules with high voltage outputs and mechanically flexible designs

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Broader Context

Silicon continues to represent one of the most compelling materials for solar energy conversion; it remains the dominant choice for commercial photovoltaic applications. Research in this area focuses mainly on enhancing the conversion efficiency of non-crystalline Si, reducing the materials usage per unit power output and relaxing the requirements on purity. Thin films of amorphous or microcrystalline Si and thin sheets of single crystalline Si enable efficient materials utilization. Recently, we reported an alternative strategy that involves production of ultrathin and small Si solar cells (i.e. μ-cells) from bulk, commodity wafers by use of lateral anisotropic etching techniques, followed by assembly of these μ-cells into interconnected arrays by use of soft, transfer printing methods. Here we describe modules that exploit large collections of such μ-cells printed to allow series electrical interconnection for compact modules (0.95 cm × 0.63 cm) that are capable of producing high voltage outputs. When formed on thin sheets of plastic in optimized neutral mechanical plane designs, these modules can bend to radius of curvature as small as ~ 2 mm without any measureable changes in the mechanical or electrical properties. These devices provide a relatively simple route to low-cost, high-voltage flexible photovoltaic device, suitable for portable and wearable electronic applications.

A type of compact (~cm^2) high voltage photovoltaic module that utilizes large collections of ultrathin (~15 μm), small (~45 μm wide, ~1 mm long) silicon solar cells was fabricated and characterized. Integration on thin sheets of plastic yielded small, flexible modules with per-cell efficiencies of ~8%, voltage outputs >200 V and maximum power outputs >1.5 mW.

In the past several years the photovoltaic (PV) market has experienced rapid growth, with Si (in various crystalline forms) constituting ~90% of the market.[1] Enhancing the conversion efficiency of non-crystalline Si,[2] reducing the usage of Si per unit power output[3] and relaxing purity[4] requirements on Si feedstock represent some priorities for research. Routes for reducing silicon usage and facilitating large area processing, both with the potential to lower costs, include use of ultrathin layers of either amorphous or microcrystalline Si.[5] The main disadvantage of these approaches is the diminished performance of the associated solar cells compared to similar devices formed with monocrystalline Si. One alternative strategy to large area, materials efficient cells relies on anisotropic etching procedures to create thin 'slivers' of silicon from bulk wafers, followed by mechanical manipulation to form modules.[6] Recently, we reported a complementary approach that first creates ultrathin bars, membranes or ribbons of silicon from the near surface of a wafer. This uses procedures originally developed for thin silicon electronic devices,[7,8] and assembles the elements, each configured as a separate, functional solar cell (i.e. a microcell, or μ-cell), in ordered arrays on a target substrate by use of a soft printing process.[3] These techniques allow for the fabrication of compact modules out of hundreds or thousands of such μ-cells, with good efficiencies and the capacity to exploit Si in unconventional module designs. These offer, for example, mechanically flexible and even stretchable formats, semitransparent layouts, and ultralow profile microconcentrator designs.

An important additional feature of the μ-cell module construction introduced here is the relative ease with which the outputs can be configured for high voltage. Such layouts can be important for driving devices that require high (e.g. microelectromechanical systems and certain classes of electronic paper technologies) or even moderate voltage (logic circuits), and they can also be exploited to reduce series resistance losses. Recent reports describe small scale modules with high voltage outputs based on thin films of polymer[9] and crystalline Si[10] as active materials. The former case employs a structured design that offers the possibility for cost effective, mechanically flexible modules, but with efficiency and long term reliability limited by the polymers. The latter example involves the use of a rigid, silicon-on-insulator wafer whose cost is unlikely to be compatible with most applications. Neither system offers the combination of small scale design, robust high performance operation and mechanical properties required of some of the most demanding (i.e. mechanically) or otherwise interesting applications.

The fabrication for the μ-cells reported here use processes whose details are described elsewhere.[3] Briefly, the process begins with a p-type (111) Czochralski Si wafer (3 inch diameter, 1-10 Ω cm, 450 μm thickness, Virginia Semiconductor) coated with a layer of SiO_2 (600 nm) formed by plasma-enhanced chemical vapour deposition (PlasmaTherm SLR). The SiO_2 was lithographically patterned with stripe openings. Inductively coupled plasma reactive-ion etching (STS ICP-RIE)[8] formed trench structures in the silicon, with typical depths of 15–20 μm and widths of 45 μm. Selective doping of emitter and bottom contact areas used solid-state sources of boron (BN-1250, Saint

Gobain) and phosphorus (PH-1000N, Saint Gobain) at 1000 °C under N_2 atmosphere for 30 min (boron) and 10 min (phosphorus). Protecting the top surfaces and sidewalls with a bilayer SiO_2/Si_3N_4 mask followed by immersion in a KOH bath resulted in undercut etching of the μ-cells, leaving them tethered to the underlying wafer only at their end points and ready for printing and integrating into modules.

Light and dark current (*I)* – voltage (*V)* measurements of μ-cells were carried out at room temperature using a d.c. source meter (model 2400, Keithley) and a 1000W full-spectrum solar simulator. For individual microcells the reported figures of merit are based on the spatial dimensions of the μ-cells, without accounting for coupling of light through the edges. Module level efficiencies are reported using both the aperture area (i.e., includes blank spaces between the cells; 0.95 cm × 0.63 cm) and the active area (i.e., only the silicon area exposed to incoming flux; 0.50 cm × 0.57 cm). In all cases, we used a diffusive backside reflector during measurements. Certainly there is a contribution from diffuse illumination and from the inter-cell areas but this inherent feature of the reported devices is a further benefit as it provides more power per unit area of device. Electrical characterization of performance during bending involved mounting of a complete module on to the outer surfaces of glass tubes with a radius of curvature of 4 mm. Light and dark *I–V* measurements at various bending geometries and bending radii were performed at ambient conditions. Fatigue tests were also performed, where one cycle corresponds to bending a module to a given radius and then relaxing it to the flat state.

Figure 1b shows a scanning electron microscope (SEM) image of partially undercut μ-cells, tethered to the host wafer via anchor points at their ends; the widths, lengths and thicknesses were ~45 μm, ~1.5 mm and ~15 μm, respectively. The μ-cell layouts were fabricated such that p^+ and n^+ doped regions alternate from cell to cell, as shown in the colorized SEM image in figure 1b. The green, red and grey areas represent phosphorus doped regions (1.30 mm long), boron doped regions (0.15 mm long), and undoped regions (0.05mm), respectively. This design provides access for top side contacts, thereby facilitating the wiring of individual cells for metal interconnection in series, in a monolithic fashion.

Figure 2a provides a schematic illustration of transfer printing μ-cells (via an elastomeric stamp; PDMS) for integration into modules. The μ-cells are tethered onto the host wafer via anchor points [11] as illustrated in figure 2b. Placing the PDMS stamp on the surface of the μ-cells, followed by quickly lifting the stamp,[12] removes the μ-cells from the host wafer (figure 2c). Insets in figure 2b and 2c show a close up of the anchor regions before and after retrieval of the stamp, respectively. The PDMS stamp is used to print the cells onto a layer (~ 30μm) of photocurable polyurethane (NOA 61; Norland Optical Adhesive) spin coated onto a glass slide (carrier substrate). Metallization via sputter coating of Cr/Au (5 / 600 nm) followed by photolithography and etching of the exposed metal defined interconnect wiring. For flexible systems, a second layer of NOA (30 μm thick) cast on top of the printed arrays placed the fragile elements (i.e., metal and Si) close to the neutral mechanical plane of modules completed by removal from the carrier substrate. Figure 2d illustrates a module consisting of 768 μ-cells connected in series. The metallization factor for this layout is ~ 16 %, defined as the fraction of device area covered in an individual microcell.

Figure 3a depicts a high resolution SEM image of a section of the high voltage minimodule which depicts the device layout. Figure 3b shows the *IV* characteristics of a typical, individual μ-cell. The solar conversion efficiency varied between 6-8% with open circuit voltages (Voc) between 0.44-0.48 V, current densities (J_{SC}) of 23-26 mA/cm^2, maximum power (Pmax) output of 3-4 μW and fill factors of 0.67-0.68. Efficiencies in the current devices are limited by low Jsc and Voc values possibly due to carrier recombination at the metal contacts. Figure 3c shows the *IV* characteristics for different numbers of rows of μ-cells (128 μ-cells per row) connected in series. An individual row fabricated in this way shows maximum voltage and power outputs of ~ 51 V and 0.37 mW, respectively. As shown in figure 3c, increasing the number of rows leads to systematic and expected changes in the characteristics, with voltage outputs of 51 V, 104 V, 155 V and 209 V for 1, 2, 3, 4 rows, respectively. Silicon solar cells with conventional dimensions would require much larger areas to generate the voltages produced here. The inset in Fig. 3c shows the maximum power (1.55 mW) from a 0.95 cm × 0.63 cm module composed of 512 μ-cells. The aperture area and active area efficiency for this minimodule is 2.8% and 5.2%, respectively. Figure 3d presents the scaling properties of the number of μ-cells interconnected in series and the corresponding voltage and maximum power outputs. The results scale in an almost linear fashion, as expected. Such arrays of μ-cells can also be wired in parallel for high current applications, therefore allowing for a wide range of voltage and current requirements depending on the target application.

A unique aspect of the printing approach to integration is the ability to assemble μ-cells on sheets of plastic, in a scalable, deterministic and high throughput manner, for the fabrication of flexible and rollable PV modules, in optimized neutral mechanical layouts. Figure 4a shows an optical image of a high voltage flexible PV module conformally wrapped around a glass tube with a radius of curvature of ~ 7 mm. For a unit cell as shown in the inset of Fig. 4b, analytical modeling gives the strain at position z as $\varepsilon = \left(z - z_0\right)/R$ for bending perpendicular (y-direction) to the interconnect direction, where R is the bending radius, $z_0 = a - t/2 - \left(1/2\right)\left(a+b\right)\left(a-t-b\right)/\left[a+b+t\left(E_{Si}/E_{NOA}-1\right)W_{Si}/W\right]$ is the position of neutral mechanical plane, E_{Si} and E_{NOA} are the Young's moduli of silicon and NOA, and a, b, t, W_{Si} and W are the geometry parameters as shown in the inset of Fig. 4b.[3] The maximum strain in the silicon is

$$\varepsilon_{\max}^{Si} = \frac{t}{2R}\max\left[\left|1+\frac{a-t-b}{t+\frac{t^2}{a+b}\left(\frac{E_{Si}}{E_{NOA}}-1\right)\frac{W_{Si}}{W}}\right|, \left|1-\frac{a-t-b}{t+\frac{t^2}{a+b}\left(\frac{E_{Si}}{E_{NOA}}-1\right)\frac{W_{Si}}{W}}\right|\right] \tag{1}$$

Since the metal is very thin, its strain approximately equals to the strain at the top surface of silicon and is obtained as

$$\varepsilon_{\max}^{metal} = \frac{t}{2R}\left[1+\frac{a-t-b}{t+\frac{t^2}{a+b}\left(\frac{E_{Si}}{E_{NOA}}-1\right)\frac{W_{Si}}{W}}\right]. \tag{2}$$

Based on experimental structures and geometry layouts, maximum strains in the μ-cells and metal interconnects are less than 0.4% for bending radii of 2 mm perpendicular (y-direction) to the interconnect direction.[3] Figure 4b presents finite element modeling of the distribution of strain for outward bending to a radius of curvature of 4 mm along (x-direction) the interconnect direction, while figure 4c shows the *IV* characteristics of such modules in a flat state (un-bent), bent along (x-direction) and perpendicular (y-direction) to the interconnect direction and under a twisting deformation (45°). The results in figure 4c and mechanical fatigue test of up to 1000 cycles show little or no changes in the *IV* characteristics consistent with the analytical modeling results.

In conclusion, this work demonstrates a compact Si solar module capable of producing high voltage outputs in mechanically flexible designs. Demonstration experiments show voltage and power outputs >200V and >1.5 mW, respectively, and bendability to radii of curvature down to ~2 mm without significant changes in the solar cell figures of merit. These results illustrate some advantages of modules that rely on m-cells and printing based assembly techniques..

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Notes and references

1 D. M. Bagnall and M. Boreland, *Energy Policy,* 2008, **36**, 4390.

2 Y. Sobajima, S. Nakano, M. Nishino, Y. Tanaka, T. Toyama, and H. Okamoto, *J. Non-Cryst. Solids,* 2008, **354**, 2407.

3 J. Yoon, A. J. Baca, S. I. Park, P. Elvikis, J. B. Geddes, L. F. Li, R. H. Kim, J. L. Xiao, S. D. Wang, T. H. Kim, M. J. Motala, B. Y. Ahn, E. B. Duoss, J. A. Lewis, R. G. Nuzzo, P. M. Ferreira, Y. G. Huang, A. Rockett, and J. A. Rogers, *Nat. Mater.,* 2008, **7**, 907.

4 S. Pizzini, *Appl. Phys. A-Mater. Sci. Process.,* 2009, **96**, 171.

5 L. V. Mercaldo, M. L. Addonizio, M. Della Noce, P. D. Veneri, A. Scognamiglio, and C. Privato, *Appl. Energy,* 2009, **86**, 1836.

6 Andrew William (Aranda Blakers, AU), Weber, Klaus Johannes (Aranda, AU), United States (2007); P. J. Verlinden, A. W. Blakers, K. J. Weber, J. Babaei, V. Everett, M. J. Kerr, M. F. Stuckings, D. Gordeev, and M. J. Stocks, *Sol. Energy Mater. Sol. Cells,* 2006, **90**, 3422.

7 A. J. Baca, J. H. Ahn, Y. Sun, M. A. Meitl, E. Menard, H. S. Kim, W. M. Choi, D. H. Kim, Y. Huang, and J. A. Rogers, *Angew. Chem.-Int. Edit.,* 2008, **47**, 5524; H. C. Ko, A. J. Baca, and J. A. Rogers, *Nano Lett.,* 2006, **6**, 2318.

8 A. J. Baca, M. A. Meitl, H. C. Ko, S. Mack, H. S. Kim, J. Y. Dong, P. M. Ferreira, and J. A. Rogers, *Adv. Funct. Mater.,* 2007, **17**, 3051.

9 M. Niggemann, W. Graf, and A. Gombert, *Adv. Mater.,* 2008, **20**, 4055.

10 P. Ortega, S. Bermejo, and L. Castaner, *Prog. Photovoltaics,* 2008, **16**, 369.

11 M. A. Meitl, X. Feng, J. Y. Dong, E. Menard, P. M. Ferreira, Y. G. Huang, and J. A. Rogers, *Appl. Phys. Lett.*, 2007, **90**.

12 M. A. Meitl, Z. T. Zhu, V. Kumar, K. J. Lee, X. Feng, Y. Y. Huang, I. Adesida, R. G. Nuzzo, and J. A. Rogers, *Nat. Mater.*, 2006, **5**, 33.

Figure Captions

Figure 1. (a) SEM cross-sectional view of partially undercut microcells. **(b)** Colorized SEM image of an array of microcells on a source wafer, ready for printing illustrating the selective doping areas and microcell layout. Green regions correspond to phosphorous doped area (n^+), red regions are boron doped area (p^+) and gray areas are un-doped Si.

Figure 2. (a) Schematic illustration of the transfer printing process used to fabricate high voltage PV minimodules. SEM image of fully undercut μ-cells tethered onto a Si wafer ready for printing **(b)** and **(c)** SEM image of the Si wafer after retrieval of the μ-cells. Insets in (b) and (c) shows close up views of the anchor geometries before and after pickup **(d)** Optical image of a completed minimodule consisting of printed microcell arrays metal interconnected in series by Cr/Au metal grid lines.

Figure 3. (a) SEM image of a section of a high voltage minimodule depicting the device layout. The lighter regions (rectangular features) in the image of 3a correspond to the Au metal contacts. **(b)** Current-Voltage characteristics of an individual high voltage Si microcell. **(c)** Current-Voltage characteristics of rows of Si microcells metal interconnected in series from left to right 1 row(blue), 2 rows(green), 3 rows(red) and 4 rows(black). Inset depicts the maximum power output of 512 microcells. **(d)** Scaling properties for voltage and power outputs of different microcells interconnected in series.

Figure 4. (a) Optical micrograph of a flexible high voltage module conformally wrapped a glass tube. **(b)** Color contour plot of calculated bending strains (ε_{xx}) through a cross-section of a high voltage minimodule, bent outward along the cell width direction at a bending radius of 4 mm. Inset depicts the unit cell of the flexible modules, which is used to deduce the analytical modeling results. **(c)** Current-Voltage characteristics of a high voltage minimodule in un-bent flat state, bent along the cell width and the metal interconnect pad width and under a twisting deformation (45 °).