ULTRATHIN AND FLEXIBLE SINGLE CRYSTAL SILICON MINI-MODULES

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ABSTRACT: There is a high interest for having power on demand through ultra-light, highly-efficient, and flexible photovoltaic systems. Currently, the most efficient technologies are based on a rigid format using single crystal materials and the flexible ones are based on not so efficient polycrystalline or amorphous materials. We present a new method to produce ultrathin and flexible solar cells made of single crystal crystalline silicon. We propose the use of ultrathin (<20 µm) segmented silicon (less than 1 mm in diameter) created with microsystems tools and techniques. The processing of the cells, including passivation and metallization, was done on standard thickness wafers with standard tools. The cell design is a back, point contact, interdigitated cell. The finished cells were transferred onto a 100 µm thick flexible glass substrate with patterned metal traces. Interconnections between the cell and substrate were formed with a solder reflow step. The first demonstration module prototypes transferred and connected 474 micro cells all at once. The conversion efficiency of the mini module was 12.4% with a total V_{oc} = 7.8V. The principle shown here can be used to transfer the cells onto other flexible substrates (i.e. polymers) and achieve an ultra-light, highly efficient, and flexible photovoltaic system.
Keywords: c-Si, Si Films, Back Contact, Flexible Substrate

1 INTRODUCTION

The world is filled with various shapes and contours: natural terrain, large manmade structures, vehicles, handheld devices, and even the human body. Miniaturized PV cells can be designed to fit aesthetically and cost effectively into many of these objects, providing power automatically without human thought or attention.
Our team’s development of microsystems enabled PV [1] shows specific ways to use tools and techniques from the semiconductor, LCD, and microsystems industries to design, simulate, fabricate, assemble, package, and characterize photovoltaic systems with microscale PV cells. Through this methodical process for mass production, the conversion efficiency of commercial microscale PV cells can be improved to the full potential of the semiconductor material and evolving system designs.

In addition, the material costs of the overall PV system can become of lesser significance than manufacturing costs. If and when that happens, PV technology can migrate from its currently shallow cost reduction trajectory [2] to one that is noticeably steeper. While that transition may never attain the cost reduction slope of the integrated circuit or LCD industry, it can ultimately make microscale PV cells the lowest cost electricity option for at least three application markets - mobile power, wholesale electricity from solar utility farms, and retail electricity from flat commercial rooftops.

In contrast with the current policy and subsidy-driven market for photovoltaics, these three distinct applications provide a diversified and consequently less capricious market to nurture the emergence of a microscale PV industry. Just as lithium ion battery development for the laptop computer industry enabled the migration of this energy storage technology to electric vehicles, microscale PV products for these three distinct applications can provide the scale and necessary revenue stream to develop new microscale PV technologies for other nascent applications.

The current flexible PV market is led by copper indium gallium diselenide (CIGS) followed by amorphous silicon (a-Si), and organic (OPV) modules. Commercial products have achieved up to 12.6% [3] efficiencies in CIGS, 6.7% in a-Si [4] and about 2% in organics [5]. Despite improvements over recent years of these technologies, the flexibility and the shade tolerance of these products are relatively low. The power to weight ratio can also be improved significantly. In contrast, commercial products using crystalline silicon have surpassed the 20% conversion efficiency [6] but only in rigid and relatively heavy formats. In the past, it has been proven that efficiencies above 20% are theoretically possible in thicknesses of only 1µm given a Lambertian light trapping scheme and excellent passivation [7]. Experimentally, efficiencies close to 15% have been achieved in 14 µm of silicon [8].

2 APPROACH

We propose the use of ultrathin and segmented silicon [9] fabricated with microsystems tools and techniques to create flexible, compact, and lightweight solar cells and modules. The use of microsystem techniques has the potential to provide unique power configurations (high voltage in small areas) and better performance [10]. The processing of the cells, including passivation and metallization, was done on standard thickness wafers. This approach resolves yield problems associated with processing thin wafers (i.e., wafer breakage) and issues related to high temperature incompatibility of handling substrates. In addition, with this process, the handle wafer remains available for processing additional PV cells.

The receiving substrate used is a patterned ultrathin (100 µm) and flexible glass substrate. The use of glass could lead to better options for integration of PV into new form factors, such as building integrated PV, power generating portable structures, and curved surfaces. Figure 1a shows a SEM image of the backside of a hexagonal 20 µm thick, 720 µm cell attached to the wafer. The posts protruding from the cell are solder bumps. Fig. 1b shows the flexible 100 µm thick glass receiving substrate. The receiving substrate was patterned with metal traces and connection sites that align with the cells on the wafer.

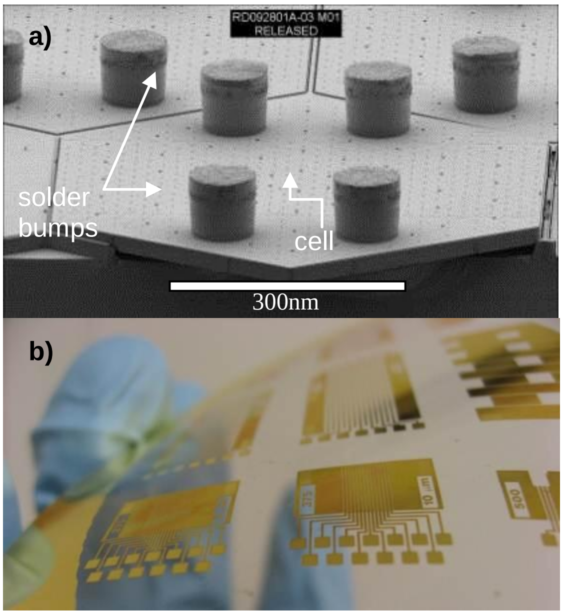

Fig 1 a) SEM image of a micro solar cell b) picture of flexible glass substrate with metallized interconnects.

3 DESIGN

The design of these solar cells is very similar to the design of integrated circuits. Our group used commercial design software (AutoCAD® and Tanner EDA's L-Edit™). The design consists of different layers (represented as a different color) as shown in Figure 2. Each layer corresponds to one photolithographic mask. Every mask has a set of process steps associated with it. Through the use of a series of process steps, the cell fabrication is accomplished.

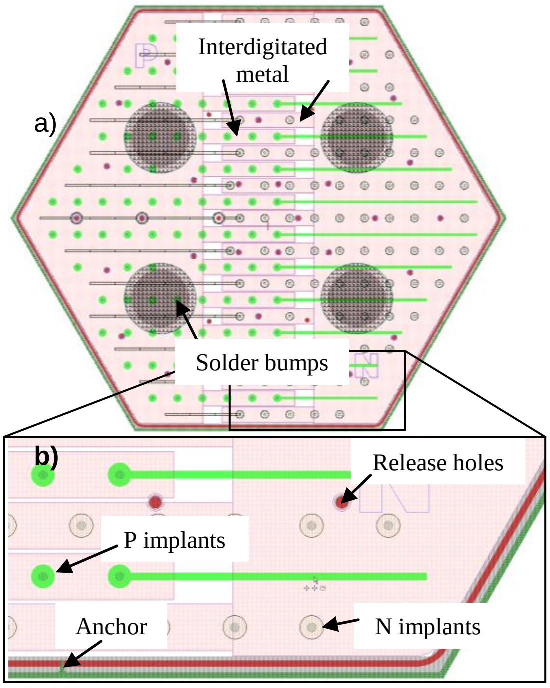

Fig 2 a) Design of solar cell in L-Edit b) Zoomed section showing details about the structure.

4 PROCESSING

The process presented here is a combination of two independently demonstrated concepts: 1) The creation of functional solar cells in ultrathin substrates [8] and 2) the concept of creating detachable ultrathin passivated silicon flexible sheets [9]. The two concepts together with the implementation of wafer bumping (solder micro bumps) enabled implementation of this technology.

The steps to create the ultrathin, passivated suspended silicon have been described elsewhere in detail [9]. Here we summarize the first steps and expand on the different processes in making a fully working cell. Figure 3 shows the steps needed to create the bumped cells.

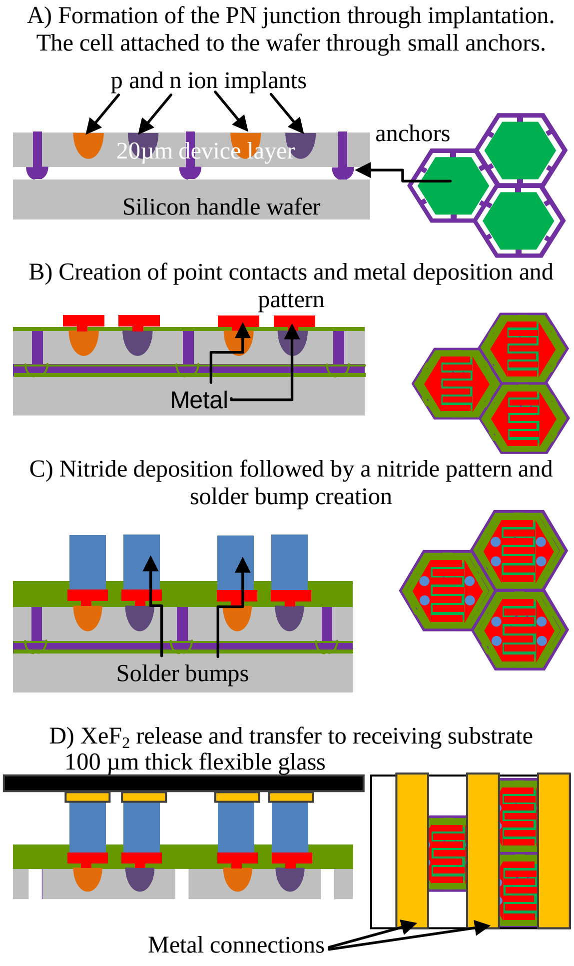

Fig 3 Steps to create a functional ultrathin solar cell module composed of multiple micro solar cells.

The cells are fabricated using silicon on insulator (SOI) wafers. The junctions are created with ion implantation through masking layers created using photolithography. Once the junctions are created, anchors that connect the cell to the wafer are defined with deep reactive ion etching (DRIE). These anchors allow passivation and antireflection (AR) coating to be done on the front, back, and sides of the cell while the cell is still attached to the wafer. After passivation, the contact formation and metallization steps follow. The last step creates the solder bumps that are later used as mechanical and electrical connections to the receiving substrate. The solder bumps are created using standard wafer bumping processes available to the microelectronics industry. In this process, a seed metal is deposited and then a photoresist layer is patterned across the wafer. Inside the features, copper and standard tin-lead solder are plated over the seed metal. The fabrication is followed by a transfer process onto a receiving substrate enabled by reflow of the solder interconnections.

A metal pattern for interconnections along with "keying" features for the solder bumps were created using photolithography. In order to transfer all the cells in the correct position, an alignment of the features in the cells with the metal traces is necessary before detachment. After alignment, the receiving substrate and the cells are heated up to 250°C to reflow the solder. After cooling, the electrical and mechanical connections are in place. The last step is detaching the handle wafer from the cells to leave the front of the cells exposed. The flexible substrate has all the interconnections necessary to create the circuit. The transfer also allows for the creation of all the interconnections through the reflow of the solder bumps. Fig 4 shows a cartoon of the detachment process. Cells are attached and interconnected to the receiving substrate at the same time.

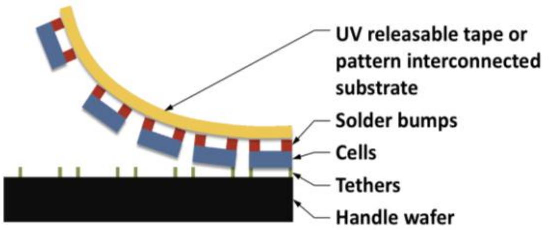

Fig 4. Detachment process of bumped cells into a patterned interconnected receiving substrate

Figure 5 shows an overlap of microscope pictures depicting the progression of steps of the transfer. Fig. 5 shows microscope pictures of a) an array of functional 720 µm diameter, 20 µm thick cells attached to the receiving substrate; b) the back of the cells when they are still attached by small tethers to the wafer. The protruding cylinders are the solder bumps; c) microscope image of the back interdigitated contact structure of the cell.

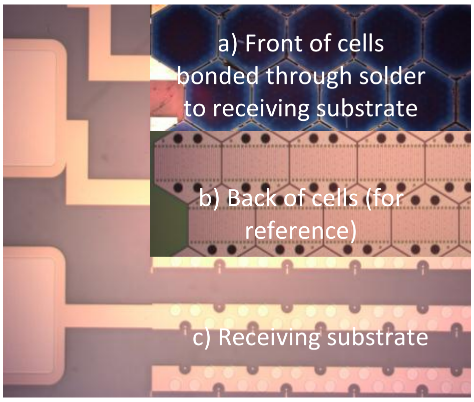

Fig. 5 Overlay of microscope pictures showing alignment of cells to receiving substrate.

Fig. 6 shows images of cells transferred onto the flexible substrates. The front side of the cell (shown here) has no shading from metal since all connections are in the back facing the receiving substrate. A total of 476 cells out of 476 on the wafer die were successfully interconnected to the receiving substrate. The cell diameter is 720 µm as measured from corner to corner in the hexagon. Fig 6a) shows a flexed polyamide substrate populated with cells (the tip of a pen is used for comparison) 6b) shows a glass substrate populated with cells and 6c) shows a zoomed image of the front of the cells. The active area of mini-module is 1.59 cm^2.

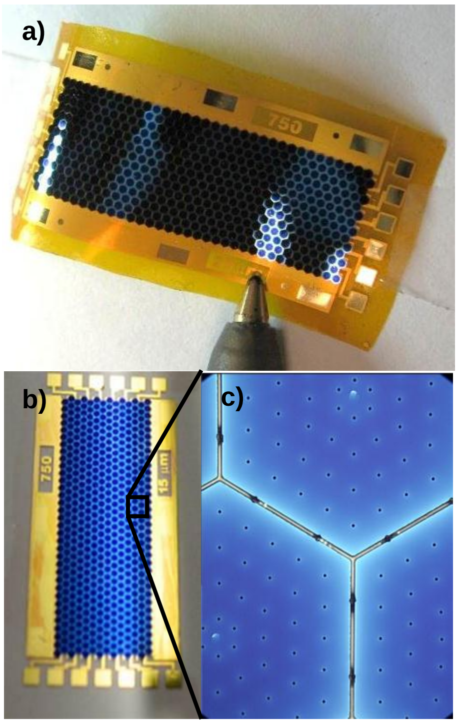

Fig 6. Finalized minimodule with interconnected cells (left) and microscope picture showing detail of front of cells (right).

Fig. 7 shows the current vs. voltage curve (I-V) of the tested minimodule (476 cells). The module is interconnected through 14 stings in series and each string has 34 cells in parallel. An OAI TriSOL 1800nm class AAA solar simulator was used as the light input. The solar spectrum was normalized to an intensity of 1000 W/m^2 (using a silicon reference cell). The I-V curve was measured using an Agilent B1500 source-meter. The area of the module represents the area of the array of cells including the area associated with the gaps between cells. An efficiency of 12.4% was the average efficiency obtained from 20 measurements and the I-V curve shown is the average of 20 curves.

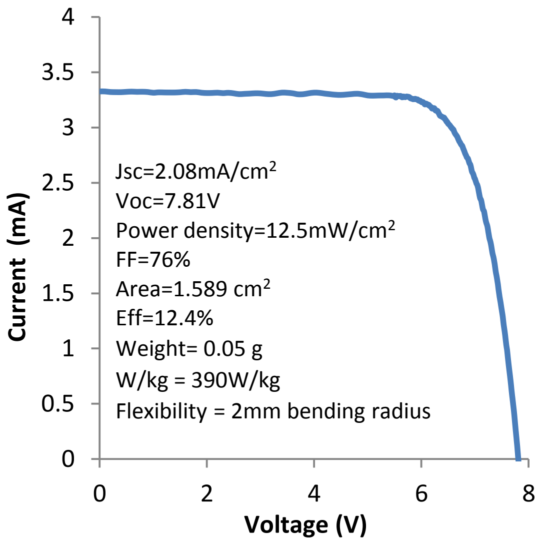

Fig. 7 JV curve showing electrical performance of minimodule.

5 CONCLUSION

We present a new approach for creating high efficiency, ultrathin, flexible solar cells. Through this effort, we were able to produce fully functional and passivated ultrathin micro solar cells with conventional microelectronics fabrication and assembly tools. Furthermore, the cells were transferred and interconnected on a patterned ultrathin glass. The mini module was composed of hundreds of microcells, 20 µm thick and 720 µm in diameter. The cells were interconnected in a series/parallel circuit. The array generated an open circuit voltage close to 7.8V under 1 sun. The total conversion efficiency was 12.4%. With this process and further enhancement of the cell efficiency, we believe efficiencies up to 20% in ultrathin and flexible substrates are possible. Through the technology presented here, our group foresees the powering of almost anything becoming as simple as exposing it to light.

6 ACKNOWLEDGEMENTS

We would like to thank Sean Garner from Corning Inc. for providing the Corning® Willow™ Glass samples, material information and processing guidelines.

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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