ULTRATHIN FLEXIBLE CRYSTALLINE SILICON: MICROSYSTEMS ENABLED PHOTOVOLTAICS

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ABSTRACT

We present an approach to create ultrathin (<20 μm) and highly flexible crystalline silicon sheets on inexpensive substrates. We have demonstrated silicon sheets capable of bending radii as small as 2 mm without damaging the silicon structure. Using Microsystem tools, we created a suspended sub-millimeter honeycomb segmented silicon structure anchored to the wafer only by small tethers. This structure is created in a standard thickness wafer enabling compatibility with common tools. The procedure allows all the high temperature steps necessary to create a solar cell to be done while the cells are on the wafer. In the transfer process, the cells attach to an adhesive flexible substrate which, when pulled away from the wafer, breaks the tethers and releases the honeycomb structure.

We have previously demonstrated that sub mm and ultrathin silicon segments can be converted into highly efficient solar cells, achieving efficiencies up to 14.9% in thicknesses of 14 μm. With this technology, achieving high-efficiency (>15%) and highly-flexible PV modules should be possible.

INTRODUCTION

Reducing the thickness of crystalline silicon wafers has evolved in the solar industry. As of 2010, most of the silicon solar cell companies were working with 6 inch wafers with thicknesses between 180 and 200 μm. In addition, a significant portion of the crystalline silicon material is lost during sawing. The effective material usage is equivalent to a wafer with a thickness of 310-475 μm depending on the thickness of the cut wire. Although there is a strong cost driver to use thinner wafers, handling wafers thinner than 180 μm is challenging while maintaining adequate yield. Another problem with thin wafers is the need for higher quality passivation. Due to the closer proximity of surfaces to collection points in thin wafers, a slow surface recombination velocity is crucial for high efficiencies.

Microsystems Enabled Photovoltaics (MEPV) is a technique to create solar cells relying on tools from the microsystems and integrated circuit (IC) industry [1]. The use of these tools could improve yield, efficiency, and uniformity of solar cells with a mature and scalable material base and processing know-how. Other groups around the world have taken advantage of these techniques to produce small and thin solar cells [2, 3].

In previous efforts [4,5], our group produced functional ultrathin silicon solar cells. Their size ranged from 250 μm to 10 mm in diameter and the thicknesses ranged from 14 to 20 μm. Fig. 1 shows a scanning electron microscope (SEM) picture of a 1 mm, back contacted, crystalline silicon solar cell with interdigitated radial contacts. Through the research it was seen that one of the most critical parameters for high efficiency in these ultra thin structures was passivation. The process on the first generation of cells was only capable of passivating the back side of the cell, leaving the front side unpassivated. Further processing of the cell after release was done to create a front passivation. After optimization of designs and research in passivation our group was able to obtain efficiencies as high as 14.9% in thicknesses as thin as 14 μm [6].

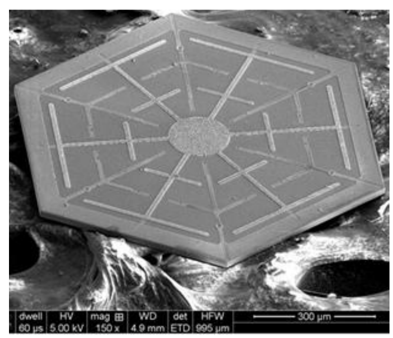

Figure 1 SEM picture of a 1 mm in diameter, 20 μm thick solar cell produced with microsystem tools.

Passivating the front of the cells after release is challenging and cannot be done with standard processing tools. Thus, we propose a design capable of performing full passivation while the cell is still attached to the wafer. The basic idea is to have the cell anchored to the substrate through very small tethers. The tethers leave an empty space between the front of the cell and the substrate. This way, a thin layer of nitride or oxide can be grown on the surfaces while the cell is still attached to the substrate. Fig. 2 shows the representation of the proposed cell attached to the substrate through the tethers (anchors).

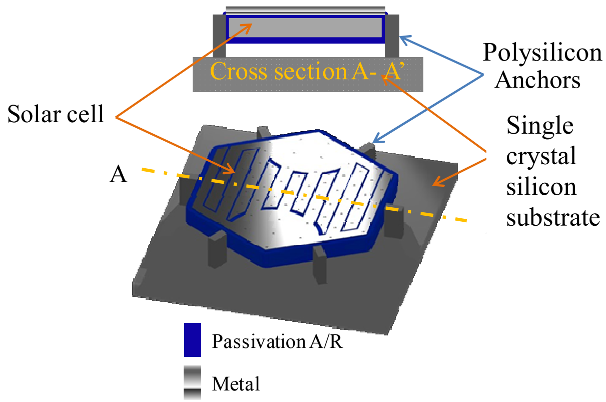

Figure 2 Suspended solar cell design that enables full passivation while still attached to the wafer.

SEGMENTED SILICON SHEET FABRICATION

The fabrication method begins with a silicon-on-insulator (SOI) wafer and uses hydrofluoric acid (HF) chemistry for releasing the suspended silicon structures. Fig. 3 shows cross sections and front views of the process flow used to create the silicon honeycomb structure.

Mechanical analysis provided guidance on the design limitations with respect to different variables: cell sizes, buried oxide thicknesses, stresses caused by capillary forces and spinning, the tape release forces, etc. Based on the restrictions, an assortment of hexagonal segments sizes (250, 375, 500, 750, and 1000 µm in diameter) were created on the 20 µm device layer of an SOI wafer. Also, for each size the anchor characteristics were changed in number (3, 6, 12 or 18), position (vertex or edge), and shape (spring or straight).

In order to produce these structures, we began by depositing 300 nm of low stress silicon nitride and a 1 µm thick silicon oxide on a 6 inch, 700 µm thick, 2 Ω-cm, SOI, p-type, (100) oriented wafer (Fig. 3A). The wafers were next patterned with 2.2 µm thick photoresist and etched using a deep reactive ion etch process to create 20 µm deep trenches down to the buried oxide (BOX) layer of the SOI wafer forming the shape of the anchors and their frame (Fig. 3B). A wet etch created a cavity in the BOX allowing the anchor to connect to the handle wafer (Fig. 3C). A 2 µm thick poly-silicon layer was deposited to fill the previously fabricated trenches to create both the anchor frame and the anchors (Fig. 3D). The layer deposited was chemically and mechanically polished (CMP) leaving the anchor plugs intact (Fig. 3E). Then, another pattern and deep etch process defined the release holes and the edges of the hexagonal silicon structures. The final etch (Fig. 3F) was performed with a wet etch in a 49% HF solution with Tergitol™ at room temperature for 70 min to suspend the silicon structure by selectively etching the BOX and leaving the silicon intact.

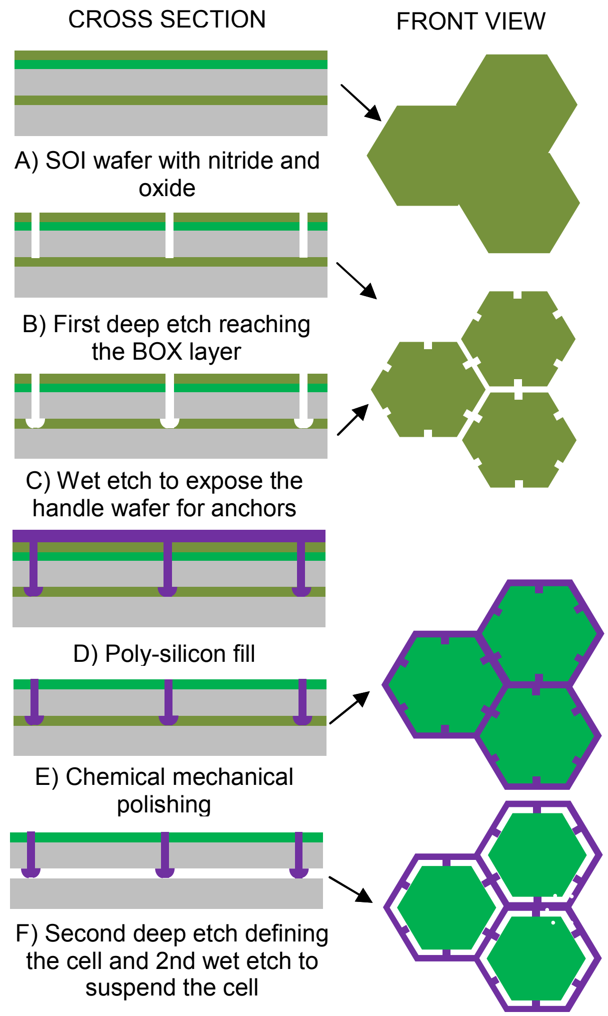

Figure 3 Cross section illustrating the process flow for the creation and suspension of the thin silicon sheet.

CHARACTERIZATION

After the structures were fabricated, we used a clear adhesive film (1027 from Ultron Systems) to detach the silicon structures from the wafer and transfer them to the film. Through this process we evaluated the success rate of different designs in being able to suspend the design (not sticking to the handle wafer) as well as successfully transferring the cells onto the tape as seen in Fig. 4.

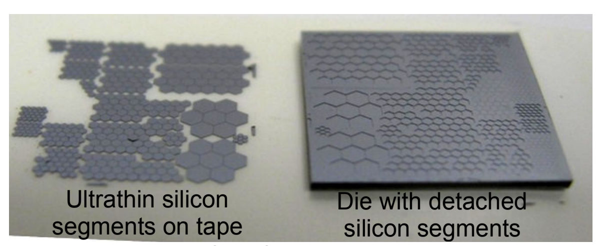

Figure 4 Tape transfer of ultrathin silicon segments.

All designs were successfully suspended except for the 1 mm silicon structures with 12 or less anchors. In the transfer, most of the designs succeeded except the 250 µm structures with more than 3 anchors, and the 375 µm structures with more than 6 anchors.

After performing the transfer tests for the segmented silicon sheet, an experiment was performed to see if a silicon nitride AR/passivation layer could be deposited in a conformal manner on the front (exposed) and back (hidden) side of the suspended structure while they were still attached to the handle wafer.

LPCVD nitride was used to deposit 70 nm of silicon nitride on the structures using a furnace. Fig. 5 shows the results of the thickness and uniformity of the coating on the back of the silicon pieces.

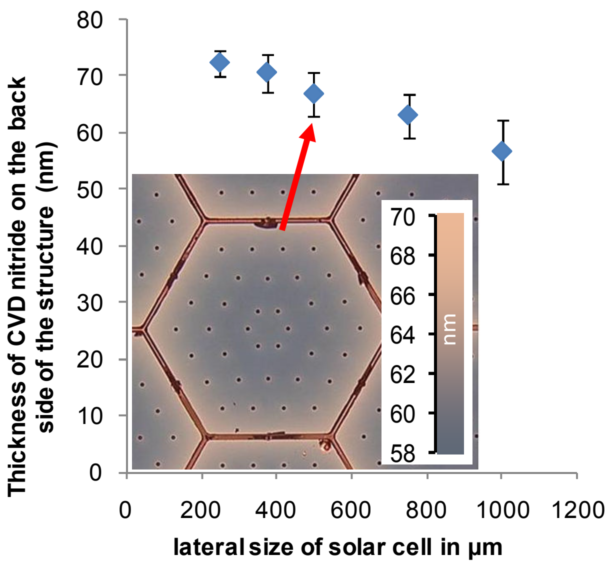

Figure 5 Thickness of nitride on the back side of the die after CVD deposition. Inset shows the back of a 500 µm segment with a color scale for thickness.

Fig. 5 reveals that the thickness and uniformity increased as the size of the structure decreases. The inset shows a microscope picture of a 500 µm diameter silicon segment with a color coded bar for the nitride thickness across it. The edges of the structure have a thicker coating and the center of the structure has the thinnest.

Finally, a second set of photolithographic masks were designed with only 750 µm structures with 12 anchors. With these silicon structures, some prototype flexible silicon sheet demonstration pieces (up to 1.25" X 5" in size) were put together to show the feasibility of the technique for larger areas. Fig. 6 shows a 1.25"X 2.5" (silicon area) ultrathin and flexible silicon sheet.

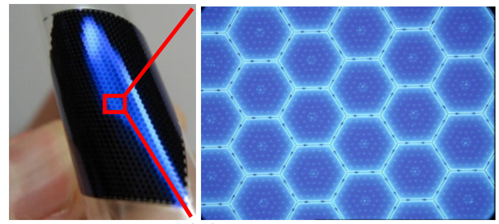

Figure 6 Prototype of flexible solar panel: clear film covered with 20 µm thick segmented crystalline silicon structures.

CONCLUSIONS

We presented an approach to create ultrathin (<20 µm) and highly flexible silicon sheets that are transferrable to inexpensive substrates. The technology relies on microsystem tools to create a honeycomb segmented film that is detachable from the wafer through small breakable anchors. Before being transferred to the flexible substrate, the structures received a coating of LPCVD nitride. The measurements showed that smaller cells are preferred in order to have a more uniform nitride thickness on the back side. Finally, a prototype for a flexible solar panel was fabricated.

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