FIRST DEMONSTRATION OF HIGH VOLUME MANUFACTURING OF KERF-FREE POLYMAX™ WAFERS

A. Brailove, S. Kang, A. Fujisaka, F. Henley
Silicon Genesis Corporation
145 Baytech Drive, San Jose, CA 95134 USA
Tel: +1-408-228-5858
Fax: +1-408-228-5859
abrailove@sigen.com

ABSTRACT: A novel kerfless wafer-making process has been developed and introduced over the last several years. The PolyMax™ process is based on ion beam-induced cleaving of crystalline silicon and has been demonstrated to be capable of producing high quality c-Si wafers in thicknesses ranging from 20 microns to 150 microns. Progress on the development of production-grade equipment to perform this process at commercial rates is reported here. The design and performance of the first production-grade implantation tool is described, along with early wafering results. The developmental progress of several alternate cleaving technologies is also discussed. Finally, plans for future development of the equipment and a conceptual plan for a factory based on the PolyMax equipment are presented.
Keywords: c-Si, Manufacturing and Processing, Substrates, Kerf, Wafering

1 INTRODUCTION

1.1 Need for kerf-less wafering

Today, the incumbent technology for silicon wafering is wire-sawing. Wire-sawing uses an array of fine parallel wires moving at high speed across the side of a silicon brick. The brick and wires are sprayed with a slurry of abrasive particles carried in a lubricating fluid, and are slowly moved downward through the silicon, abrading ever deeper grooves, until finally the brick is cut completely through into wafers.

At today's wafer thicknesses around 150 microns, approximately 50% of the silicon ingot is wasted in the form of kerf-loss: silicon that is reduced to sawdust [1]. The potential for cost savings simply by eliminating this waste is widely recognized, and has been well quantified [2].

1.2 Need for thinner wafers

Conventional PV cells are so thick that most of the light absorption occurs near the top surface. This represents an additional inefficiency in the use of polysilicon starting material. Migrating c-Si PV toward thinner wafers holds the promise of very significant reductions in manufacturing costs.

1.3 Limits of wire-sawing

Although wire-sawing has been broadly adopted for commercial-scale mono- and multi-crystalline PV production, as a manufacturing technology it is poorly matched to the future needs of the PV industry [3,4]. Wire-sawing is a relatively crude mechanical process which suffers from the twin problems of kerf-loss (inherent to all sawing processes), and severe technical barriers to further reductions in wafer thickness [5]. This scaling problem is apparent when one considers the possibility of making thinner wafers by simply packing wire saw wires closer together: the absolute kerf-loss, thickness variation, and surface roughness all remain basically unchanged in absolute terms, but they quickly consume a prohibitively large fraction of the wafer thickness as the wafer gets thinner.

1.4 The PolyMax™ Process

During the past several years Silicon Genesis Corp has developed and reported [6,7] on a new process for producing full size c-Si solar wafers with essential zero-kerf. We have demonstrated repeatable production of high quality wafers as thin as 20 microns.

SiGen's PolyMax™ process is a cyclic, two-step process: Implant-Cleave-Repeat. First, a high energy proton beam is directed at the top surface of a silicon brick. The protons (or other ions) are implanted in a thin layer at a controlled depth under the surface of the silicon. Then, the silicon is induced to fracture, or *cleave*, in a highly controlled manner, along the cleave plane defined by the implanted ions. A single wafer of silicon is released and the process is repeated on the newly exposed surface of the brick. The use of cleaving, rather than sawing, eliminates the waste due to kerf.

1.5 Particle physics leads to scalability and thin wafers

Wafer thickness is controlled by the depth, or *range*, of the implanted protons. The proton range is determined in turn by the energy of the proton beam, which can be made highly stable and precise. Other than energy, the only thing that determines the proton range is the unchanging physics that govern how energetic protons interact with silicon.

An important consequence of this physics is that the width of the proton range distribution gets smaller as the range gets smaller; therefore thinner wafers have lower roughness. By tying wafering to a stable, scalable, physical process like implantation rather than to a mechanical process like wire-sawing, PolyMax removes the barriers to producing extremely thin, low-cost wafers.

2 IMPLANTATION EQUIPMENT

2.1 Implanter Design

Silicon Genesis Corp. has designed and developed a production-grade ion implantation tool capable of performing the PolyMax process at commercial rates. This first-of-its-kind tool has just started operation at SiGen's plant in San Jose, CA. Figure 1 shows the key components of this tool.

2.2 Accelerator

The *accelerator* contains a plasma ion source fed by hydrogen gas. The ion source ionizes the hydrogen and generates a relatively low energy beam of protons. This

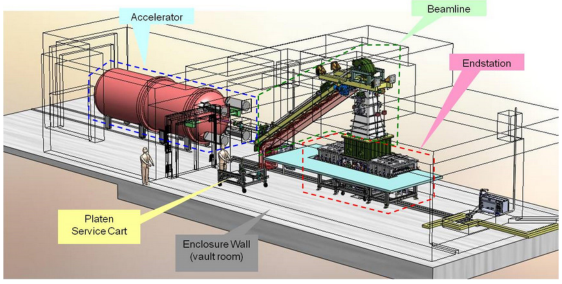

Figure 1: Ion Implanter Tool

beam is then accelerated in vacuum to energies of several MeV as it passes down the length of the accelerator. The system shown in the figure has an energy that is adjustable from 2 to 4 MeV, resulting in wafers ranging in thickness from about 50 to 150 microns, respectively.

2.3 Beamline

At the exit of the accelerator, the proton beam enters a *beamline* which transports the protons to the target. The beamline is an evacuated pipe surrounded by several types of electromagnets, including dipole magnets for bending the beam and quadrupole magnets for focusing the beam.

A final scanning magnet is used to deflect the beam and scan it in two dimensions in a manner akin to a conventional CRT. The beam can be scanned over the silicon target under full computer control, allowing arbitrary dose patterns to be applied to the silicon bricks.

2.4 Endstation and Brick Handling

The third key component of the system is the *endstation*, shown in figure 2, which handles the silicon bricks during implantation.

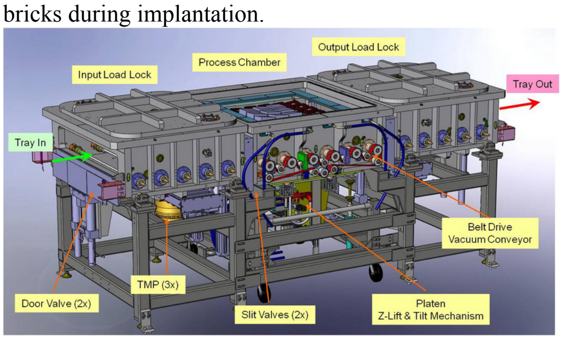

Figure 2: Endstation

The endstation is an inline, high-vacuum processing system comprising three chambers: an input load-lock, a process chamber, and an output load-lock. The three chambers are isolated from each other by large slit valves. The system is highly pipelined to minimize latency between batches of bricks: while one batch of bricks is being implanted, the next batch is being loaded into the input load-lock and pumped down, and a just-completed batch is in the output load-lock being vented to atmosphere and unloaded.

Bricks are carried through the endstation on trays. The system, as currently configured, processes trays of 36 bricks of the 156 mm form-factor in a 6x6 array. The bricks may be up to 100 mm thick. The system is also designed to handle 64 bricks of the 125 mm form factor with a change of process kit. Trays of bricks are moved through the endstation on powered roller-wheels, driven from outside the vacuum by servo motors coupled to timing belts.

The proton beam carries an extraordinarily high power that is turned into heat when it strikes the silicon. When a tray of bricks enters the process chamber, the bricks are automatically clamped to water-cooled blocks to remove this heat. SiGen has developed several proprietary technologies for managing these high heat loads and effectively cooling the bricks in vacuum.

The implanter is equipped with both an infrared thermal camera and a visible-light camera that look at the top surfaces of the bricks. They are used for temperature measurement as well as diagnostic purposes. IR camera images captured during testing (not typical of normal processing) are shown in figure 3. They illustrate the programmable beam scanning capabilities. A dedicated real-time computer controls the scanning of the ion beam, integrating the proton current collected on the bricks and terminates the implant when the desired dose has been reached.

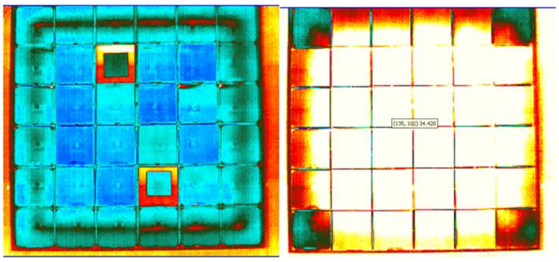

Figure 3: Infrared thermal camera image of beam on bricks. Left: square pattern demonstrates control of beam. (The two red rings are special bricks for testing purposes). Right: blanket implant of central 16 bricks.

2.5 Throughput & Productivity

The implantation system is designed to have a throughput of about 185 bricks per hour (of the 156 mm size). This corresponds to one tray every 12 minutes or one brick every 20 seconds, on average. The endstation was designed so that mechanical handling and load-lock cycling would not be in the critical path of the process, insuring that valuable beam-time would not be wasted. Initial testing has shown that the endstation is easily capable of supporting this requirement.

2.6 Shielding & Radiation

As can be see in figure 1, the implanter system is located inside a two room concrete vault for radiation shielding. The largest source of radiation is prompt gamma radiation at energies of a few MeV, generated when protons strike silicon inside the endstation. The concrete walls surrounding the endstation are therefore relatively thicker.

Prompt gamma radiation at lower energies and lower fluxes is also produced by the accelerator itself, requiring a thinner shield surrounding the accelerator as shown in the figure.

When the proton beam is off, no prompt radiation is produced. Furthermore, the system has been designed to minimize delayed radiation due to proton activation of beamline materials, enabling service personnel to access the equipment safely after only a short waiting period.

It is anticipated that improvements in accelerator technology will eventually eliminate the need for all concrete around the accelerator. Additionally, all radiation fluxes increase rapidly with proton energy, so as the industry evolves toward thinner wafers and lower energies, the thickness of the shielding surrounding the endstation will also drop significantly.

3 CLEAVING EQUIPMENT

A variety of different approaches are available for the cleaving step of the PolyMax process. The current method to produce wafers uses a thermal process performed in a customized rapid thermal processing tool. In this approach, a high surface thermal flux generates a thermo-elastic stress within the patterned brick implant layer that is engineered to exceed the required fracture strength in a well controlled manner, cleaving a thin silicon layer from the brick with high yield.

SiGen is also actively developing alternate cleaving approaches that apply external energy to the silicon, localized around the cleave plane. The goal of this development effort is to induce cleaving at lower thermal budgets with higher throughput. These techniques include the use of lasers and other proprietary thermo-mechanical approaches.

4 INITIAL PROCESS RESULTS

4.1 First Wafers

SiGen has previously reported on the production of 150, 50 and 20 micron thickness wafers [6,7]. These wafers were produced using single-brick, research-grade implanters targeted primarily at process development. The production-grade PolyMax implanter described above has recently begun operation and has now produced its first wafers.

Figure 4: 156 mm pseudo-square wafer and brick

Figure 4 shows one of the first wafers produced by this system. The wafer is a 156 mm pseudo-square form factor, shown sitting atop (and shifted slightly from) the silicon brick from which it was cleaved.

4.2 Proton Range Distribution

During initial testing, the PolyMax implanter has been operated at approximately 3 MeV yielding wafers of about 85 micron thick. Figure 5 shows a comparison of the proton depth distribution measured experimentally by SIMS (blue) and a SRIM simulation (gray). The curves have been normalized to the same height and aligned slightly depth-wise to account for small uncertainties in energy and SIMS depth measurement.

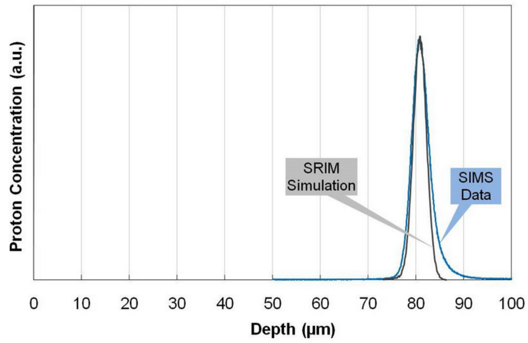

Figure 5: Proton Range Distribution

This figure beautifully illustrates the extraordinary narrowness of the proton range distribution in silicon. Since cleaving occurs inside this implanted layer, the narrowness of the layer establishes a precise wafer thickness and results in wafers with low roughness. As discussed earlier, this range distribution becomes narrower at lower energies, causing roughness to scale down with wafer thickness.

In wire-sawing, numerous *mechanical* parameters must be controlled with great difficulty [8, 9] to achieve stable wafer production. This challenge grows rapidly more difficult as wafers get thinner. In contrast, ion implantation is independent of all mechanical parameters, being governed purely by ion collision *physics*. PolyMax wafers circumvent the thickness barriers faced by wire-sawing allowing them to be made much thinner.

4.3 Thickness Variation and Lifetime

Thickness measurements have been made on the first 13 wafers produced by the equipment described above. Figure 6 shows average wafer thickness (solid line) and the within-wafer maximum and minimum thickness (broken lines) based on 9 measurement points on each wafer.

Wafer-to-wafer thickness variations are roughly +/- 1 micron. Thickness variations across each wafer are of a similar magnitude. These results are better, by an order of magnitude, than can be achieved by any wire saw.

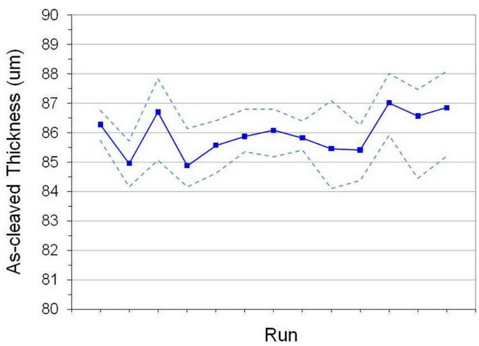

Figure 6: Wafer thickness run chart showing wafer-to-wafer average thickness (solid line) and within-wafer thickness max and min (broken lines).

First lifetime measurements exceed 100 microseconds after 10% thickness removal per side, allowing high-efficiency solar cell fabrication.

5 FACTORY DESIGN

5.1 Factory Design

The details of how PolyMax wafering equipment is integrated into a complete wafer production factory depends on the expected scale of the production line and the specific choices made regarding the level of automation, redundancy, and production team size, etc.

5.2 Circulating Brick Flow

One important feature of the PolyMax process has a direct impact on the factory design: it is a *cyclic* process in which one wafer is sliced from each silicon brick on each implant-cleave cycle. Thus, the bricks continually circulate back and forth between the implant and cleave equipment hundreds or thousands of times, depending on the wafer thickness, until the brick is consumed.

Figure 7 shows a portion of a wafering line in which palletized bricks circulate on a racetrack-shaped inter-tool conveyor. On one side of the inter-tool conveyor is a row of implanters (rear) and on the other side (front) is a row of cleave tools. Bricks are shunted off the inter-tool conveyor to feed each tool and processed bricks are routed back to the conveyor. A work-cell (front, center) is located on a spur of the inter-tool conveyor for loading, stocking, and resurfacing damaged bricks when necessary. In a fully automated factory the bricks and possibly individual wafers will be tracked and routed using bar codes.

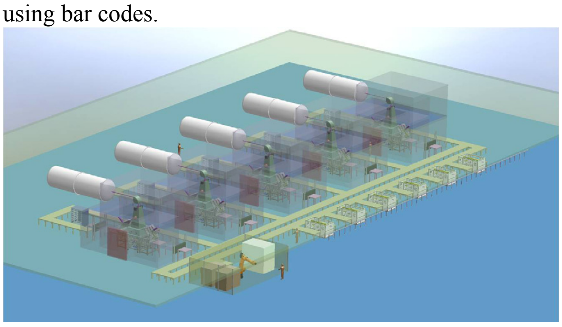

Figure 7: Kerfless Wafer Production Line

5.3 Integration with a cell line

One particular advantage of the PolyMax technology is that the process itself produces wafers that are dry, clean, and singulated. This is in contrast to wire saws which produce a messy stack of wafers stuck together with slurry. To fully exploit this inherent advantage, it makes some sense to locate cell production close to wafering. Individual wafers produced by the cleave tools are placed on a conveyor (front, right in figure 7) and transported directly to the cell production area. This avoids the additional handling associated with coin-stacking and re-singulation, and is particularly valuable in the case of ultra-thin wafers where handling must be minimized.

5.4 Factory granularity

Each implantation tool is expected to produce approximately 6 MW of wafers per year. A 300 MW plant will therefore require roughly 50 implanters. Tying together this many tools with a single inter-tool conveyor is possible, but may be inefficient in terms of factory layout and production team size. At the other extreme it may make sense in smaller, less automated plants, to pair one implanter with a cleave tool and have them operate as a unit, independently of the others. Figure 7 illustrates a compromise between these extremes in which a small cluster (five are shown, for example) of implanters are tied together with an inter-tool conveyor and operate as a production unit. This approach has several advantages: 1) cleave tool productivity can is balanced with implanter productivity, 2) the resurfacing work cell cost and work load is divided optimally across multiple implanters, 3) the floor is not obstructed by long conveyors and 4) production team sizes can be optimized.

6 CONCLUSIONS

Silicon Genesis is developing the first production-grade equipment for kerfless wafering by ion-beam induced cleaving. We have reported here on the significant progress made toward that end, including the design and successful first operation of high-productivity ion implantation equipment.

This new wafering approach will provide substantial cost reductions, first by eliminating kerf losses; second, by enabling the production of much thinner wafers for more efficient use of silicon; and finally, by reducing upstream and downstream processing costs such as excess ingot pulling capacity and slurry production and recycling that are endemic to the conventional wire saw technology.

This new technology will enable the PV industry to capture the high conversion efficiencies, environmental advantages, and decades of proven technology behind crystalline silicon, while simultaneously reducing manufacturing costs to be competitive even with thin film.

REFERENCES

[1] A. Skumanich, The Art of wafer cutting in the PV industry, Photovoltaics World, June (2009).

[2] A. Fujisaka & al., “Cleaving vs Sawing – Gaining Production Efficiency in c-Si Wafering”, Proceedings 24th European Photovoltaic Solar Energy Conference oral presentation, 2CO.4.2 (2009).

[3] R. Brendel, “Review of Layer transfer processes”, EMRS, 2007.

[4] U. Gangopadhyay & al., “Current Status in Layer-Transfer Process in Thin Silicon Solar Cell: a review”, Tran. EE Mat., Vol. 5 No.2, April 2004.

[5] J.G. Beesley & al., “Slicing 80 Micrometer Wafers – Process Parameters in the Lower Dimensions”, Proceedings 22nd European Photovoltaic Solar Energy Conference, 2BO.1.5 (2007).

[6] F. Henley & al., “Kerf-Free 20-150µm c-Si Wafering For Thin PV Manufacturing”, Proceedings 24th European Photovoltaic Solar Energy Conference plenary presentation, 2DP.2.2 (2009).

[7] F. Henley, Kerf-free Wafering: Technology Overview and Challenges for Thin PV Manufacturing, 35th IEEE PVSC (2010).

[8] A. Bohne & al., “The Influence of the Wire Sawing Process on Mono- and Multicrystalline Silicon Wafers”, Proceedings 23rd European Photovoltaic Solar Energy Conference, 2CV.5.60 (2008)

[9] A. Bidiville & al., “Towards the Correlation of Mechanical Properties and Sawing Parameters of Silicon Wafers”, Proceedings 22nd European Photovoltaic Solar Energy Conference, 2CV.3.19 (2007)