KERF-FREE WAFERING FOR HIGH-VOLUME, HIGH-EFFICIENCY c-Si CELL

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ABSTRACT: Kerfless silicon wafer-making equipment has been suggested as a cost-effective alternative to the wire saw method. The potential benefits include greater materials utilization efficiency and lower cost. Until recently, EFG and ribbon technologies (both liquid-solid phase crystallization kerf-free methods) were the only real "kerf-free" methods that have been industrialized to any scale. Commercial efforts have now been abandoned as uncompetitive with the steadily improving performance of wiresaw-based wafering of mono- and multi-crystalline Si ingots. To become competitive and gain traction against modern wiresaw-based wafering, kerfless methods must support a sub-100µm thickness roadmap while preserving monocrystalline wafer electrical quality and high mechanical strength. Only solid-phase kerfless wafering with a substitutional to ultra-thin absorber thickness range can compete. One such kerfless technology is ion beam-induced cleaving of crystalline silicon, demonstrated as capable of producing high quality c-Si wafers in thicknesses ranging from 20 microns to 150 microns. Progress of this promising technology in the form of wafering equipment at SiGen is described and demonstrates its low-cost wafering potential.
Keywords: c-Si, Manufacturing and Processing, Substrates, Kerf, Wafering

1 INTRODUCTION

The Solar PV industry grew approximately 90% in shipments in 2010 achieving more than 15GW. This strong surge in demand challenged the industry's ability to ramp capacity, leading to shortages in multiple segments within the supply chain. The shortages were predominantly in polysilicon, wafers and inverters. A similar situation was observed in 2008 that resulted in unsustainably high polysilicon feedstock prices that negatively impacted the industry. Polysilicon plants require multi-billion dollar investments and years to ramp to capacity. These cyclical imbalances in supply and demand will continue to happen without a better alternative to address the waste in material in the wafering process. Some measures in the wafering process are being adopted to mitigate the problem using thinner wafers and lowering kerf losses. At best, these measures using traditional multi-wire slurry saws or diamond wire saws offer a partial solution.

Eliminating high absorber material loss while allowing thin and ultra-thin crystalline silicon PV has been a "Holy Grail" of the crystalline silicon PV industry for decades. Generally called "kerf-free" or "kerfless" wafering, the fundamental approach is to substitute slurry saws with an alternative waste-free wafering technology. Figure 1 shows the fundamental improvement in material utilization by eliminating a physical sawing thickness such as a wire with abrasives.

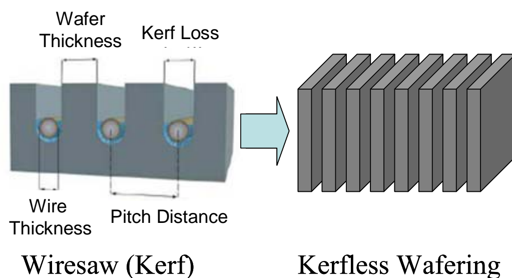

Figure 1: Wiresaw and kerfless wafering of silicon starting material

Should a kerf-free wafering technology become practical and compatible with high-volume PV wafering operations, the potential cost savings are first-order with game-changing implications for the PV industry and competing thin-film approaches [1-3].

1.1 Modern wiresaw technologies and capabilities

Wire-sawing is the predominant wafering method for crystalline commercial-scale mono- and multi-crystalline PV production. There are two main embodiments of wiresaw technology. Multi-wire slurry saws (MWSS) are the most prevalent and compatible with both mono- and multi-crystalline silicon. MWSS 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.

Another more recent variant is the fixed abrasive wiresaw that utilizes a diamond-coated wire to reduce or eliminate the need for slurry. The substantially higher cost of the diamond-coated wire is offset by the promise of multiple wire re-use, faster cutting speeds, lower cost of the slurry, and possible reclaim of the silicon kerf.

Wire sawing suffers from the fundamental problems of kerf-loss (inherent to all sawing processes), significant thickness variation and wafer brittleness, high operating expense, and severe technical barriers to further reductions in wafer thickness.

Due to the use of wire as the cutting medium, fundamental costs are irreducible and material inefficiencies exist and are likely to continue. Additional satellite equipment for wet clean steps, wet singulation and slurry recycling are also required and further increase cost of the wafering step. The process remains one of the highest cost contributors to crystalline silicon PV manufacturing and has been the driver to find practical lower cost wafering alternatives. Only the lack of viable alternative technologies has kept wiresaws dominant in silicon PV wafering.

Figure 2 shows the PV value chain and the wiresaw wafering process that not only wastes 50% or more of the upstream polysilicon feedstock value but is in itself an expensive process step in material use and complex multi-equipment sets.

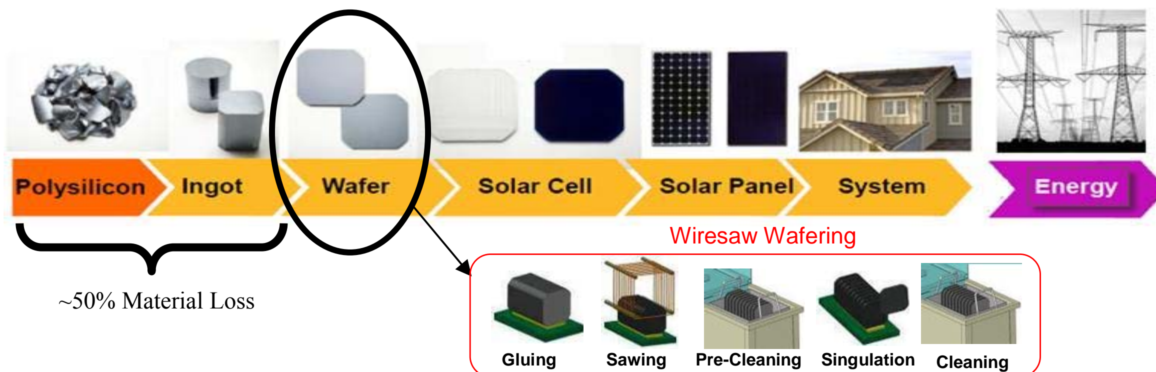

Figure 2: Wafering within the crystalline silicon PV value chain

1.2 Kerfless wafering technologies

Despite the fundamental drawbacks, the wiresaw process has undergone impressive evolutionary improvements in the important areas of yield, quality, kerf loss, productivity and thickness reduction. It would be naïve to consider wiresaw technology (and the general PV industry for that matter) as a static metric in which to compare kerfless technologies. In essence, wiresaw cost and capability improvements along with recent trends toward lower cost and readily available polysilicon feedstock has generated a set of requirements that kerfless technologies must possess in order to compete.

Figure 3 shows a pictorial of the Darwinian selection of kerfless technologies currently underway resulting from the confluence of the evolutionary improvements in cost and capability of crystallization and wiresaw technologies and the lowering of polysilicon feedstock price. As time progresses, kerfless technologies can become obsolete due to fundamental limitations in either cost or wafer quality/characteristics afforded by the specific approach. Over the last 35+ years, over 20 variants of kerfless wafering have been proposed but few have demonstrated a lasting potential to be competitive in cost and quality [4].

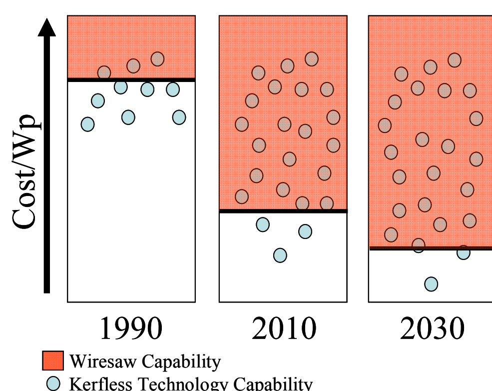

Figure 3: Pictorial of the cost/efficiency competitiveness of various kerfless technologies with steadily improving wiresaw capabilities over time

As depicted in Figure 4, the various kerfless wafering technologies can be well categorized by which of the three phases of silicon is used to fabricate a silicon substrate of desired dimensional and electrical specifications.

There are numerous methods that have been tried to cost-effectively fabricate a wafer from one of the three silicon states. The efforts expended underline the industry-wide need to find a more cost-effective and practical wafering substitute to the present sawing technology.

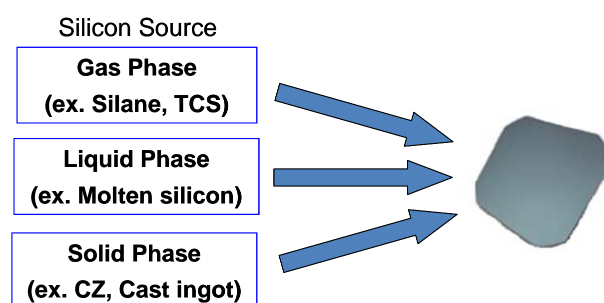

Figure 4: Alternative wafering technologies using the three available phases of silicon [4]

Generally, gas-phase and liquid-phase kerfless wafering technologies attempt to gain benefits from circumventing one or both of the Siemens or FBR polysilicon feedstock and mono/multi crystallization. This however comes at a great risk of contamination, low electrical lifetime and conversion efficiency, excessive thickness variation and wafer brittleness.

Although requiring more preparation and cost upstream of the wafering process, solid-phase kerfless wafering has the unique benefit of using substantially better starting material that support high-efficiency cell designs with excellent uniformity and repeatability.

Kerfless wafering approaches have been recently compared by their energy use, complexity, scalability, and the reported and expected achievable wafer quality [4]. Table I shows a partial list of technologies assembled from public sources [5]. Clearly, sparse wafer/absorber information exists for most of the technologies. In many cases, the electrical and mechanical absorber data is uncompetitive and may only support a lower cost business strategy for a short time (eventually landing it within the red zone in Figure 3).

1.3 Gas-phase kerfless wafering technologies

At the heart of any gas-phase kerfless method is a deposition of an absorber layer by CVD, plasma-enhanced processes or the like. What distinguish the method from a lower-efficiency thin-film silicon process (such as amorphous silicon thin-film) are the thickness of the absorber layer and the optional release of the deposited film for processing and attachment to a final support. Although

Company	Phase	Name	Silicon Source	Product	Substrate Area Reported	Throughput Potential	Absorber Material Quality	Cell Efficiency	Time to Ramp
Solexel**	**Gas**	PSI Process licensed from ISE-Bayern	Special CVD Reactor	Film on Substrate	156mm Special Shape	Med-High	Lifetime >100us	**15% Reported**	Long
Crystal Solar**	**Gas**	CVD on silicon	Special CVD Reactor	Film on Substrate	Full Wafers	Med-High	Lifetime >15-30us	**15% Reported**	Long
Ampulse	**Gas**	Hot-wire CVD	Special CVD Reactor	Film on Substrate	Full Wafers	Med-High	Little Information Available	None Reported	Long
Evergreen Solar	**Liquid**	String Ribbon	Melt	**Substrate**	**Proprietary Size 80mm 200um**	**High**	Small Grain Multicrystalline	**~15%**	**Closed**
Solivo A.G.	**Liquid**	String Ribbon	Melt	**Substrate**	**Proprietary Size 80mm 135-200um**	**High**	Small Grain Multicrystalline	**~13.5% Module Efficiency**	**In Production 220MW**
1366	**Liquid**	Direct Wafering	(Melt on Ceramic Form)	**Substrate**	**156mm Wafer 200um**	**High**	TTV Poor No Other Information	"1.5% less than mc-Si" [6]	**Short Substitutional?**
Varian	**Liquid**	Floating Silicon Method (FSM)	Melt	**Substrate**	None Reported	**High**	None Reported	N/A	**Short Substitutional?**
IMEC	**Solid "Thin"**	SLIM-Cut	CZ	Thin Film	10cm^2	Low-Medium	TTV Poor Low Lifetime? Brittle?	10%	Long
Astrowatt	**Solid "Thin"**	SOM/BCSOM	CZ	Silicon on Metal	100mm Diameter	**High**	TTV Poor Low Lifetime? Brittle?	Est. 6-8% from Literature Data	Medium-Long
Twin Creeks	**Solid "Thin"**	Thin-film cleave on substrate	CZ	Film on Substrate	None Reported (Proprietary)	**High**	None Reported (Proprietary)	None Reported	Medium-Long
SiGen	**Solid Full-Range**	PolyMax	CZ	**Substrate**	**156mm Wafer 20-120um**	**High**	**Lifetime > 200us Mechanical good TTV Good**	**> 16%**	**Short Substitutional**

** Process Restart

Table 1: Comparison of various kerfless wafering methods

this technology does have potential for higher efficiency than its thin-film counterpart, lifetime of the absorber (linked to cell efficiency) and process complexity (ex. epitaxial growth, release and bond) are tightly connected. Either commercialization areas afforded by gas-phase kerfless wafering (higher efficiency at higher cost or lower efficiency at lower cost) have become and will remain uncompetitive due to the recent sharp decline and continuing lowering of high-quality crystalline wafer and solar module prices of superior conversion efficiency [7].

1.4 Liquid-phase kerfless wafering technologies

Recently, Evergreen Solar, yet another liquid-phase kerfless wafering method in commercial production closed its doors [8]. This follows other efforts in liquid-phase kerfless wafering that have either halted production (such as Wacker Schott Solar's EFG efforts closing in 2009) or have never started manufacturing [9,10]. The reason stems from the gradually worsening value proposition of liquid-phase kerfless wafering due to its lackluster absorber quality and cost compared to multi- and mono-crystalline silicon made using standard methods. The fundamental cost proposition has eroded from its introduction decades ago include the following reasons:

1.4.1 Lack of an ultra-thin thickness roadmap

When this method was introduced, realizing significant polysilicon feedstock savings using direct liquid-solid phase crystallization in a wafer thickness format occurred because the wiresaw wire guide roller pitch exceeded 500µm. However, current wiresaw wire pitch has fallen to 250-400µm and will likely go even lower in the near-future. All liquid-phase approaches (i.e. EFG, ribbon, CDS, and others) have shown great difficulty in achieving good absorber yield and quality for standard (ex. 156mm square wafers) much below 200µm. As a result, its "kerfless" material efficiency advantage becomes moot if the liquid wafering substrate thickness exceeds next-generation wiresaw processes yielding stronger high-efficiency 160-190µm wafers.

1.4.2 Lower wafer quality and mechanical strength

The rapid crystallization of the liquid-phase processes causes stress, high dislocation densities and multi-crystallinity in the resulting film with correspondingly lower cell efficiencies and increased brittleness. Lowered contaminant segregation compared to CZ ingot pulling or cast ingot growth can further lower lifetime due to increased contamination.

For these reasons, liquid-phase kerfless methods have a lower efficiency ceiling that can reduce or eliminate the basic cost advantages. In selecting competitive wafering technologies, any cost advantage of an alternative technology is eliminated if the module efficiency is lowered by 1.5% [11]. This efficiency gap is especially apparent for liquid-phase wafering when compared to what is achievable using modern silicon crystallization equipment.

1.5 Competitive kerfless wafering requirements

The fast-changing cost and quality improvements of mono- or multi-crystalline wafer-based technologies have served to cull many of the proposed kerfless technologies over the last 10 years and will continue to shape the landscape upon which kerfless wafering technologies must compete. In recognizing the predominance of the incumbent wiresaw wafering methods and its relatively low impact on crystalline quality, the following requirements for kerfless technologies to compete become evident:

1.5.1 Equivalent lifetime & cell efficiency

This is an absolute requirement to effectively compete in cost and quality. Lifetime and in turn cell efficiency cannot be compromised. When compared to mono-crystalline

wafers for example, the kerfless absorber must have lifetime in the hundreds of microseconds with appropriate surface passivation.

1.5.2 Ability to support high-efficiency cell designs

Some gas-phase kerfless wafering technology supporters argue that as cell thickness becomes ultra-thin (ex. 50µm or less), carrier lifetime has less impact on cell efficiency and thus can be relaxed. Although this can be true for traditional front/back contacts cell designs where carrier transport is predominantly along the thickness direction, advanced back-contact and selective emitter high-efficiency cell designs require low recombination lateral carrier transport. Therefore thin silicon absorbers for high-efficiency cell designs also require high lifetime.

1.5.3 Substitutional to ultra-thin thickness roadmap

The main benefit of kerfless wafering should span from substitutional to ultra-thin. A large thickness roadmap capability would allow current PV cell manufacturers to use less expensive kerfless wafers in their present lines but also support a thickness range down to ultra-thin (sub-50µm) for its unique access to extreme cost savings.

1.5.4 Good mechanical strength

Mechanical strength, usually measured as a surface stress to fracture using mechanical gauges, is an important requirement to achieve good cell/module manufacturing yields and good reliability in the field. Since most kerfless wafering processes are different, the mechanical strength of the resulting wafer can be quite different. At least, the kerfless technology must have equivalent mechanical strength of a wiresaw process for substitutional thicknesses but have sufficient mechanical strength allowing high yield PV production down to ultra-thin thicknesses.

1.5.5 Good dimensional repeatability

Good dimensional accuracy and repeatability in roughness, thickness (total thickness variation or TTV) and wafer size are important for achieving the highest and most repeatable cell efficiency.

1.5.6 Use of existing equipment infrastructure

To take advantage of the tremendous plant and equipment investments and the economies of scale that help improve manufacturing efficiencies, competitive kerfless technologies should utilize the existing equipment infrastructure as much as possible. Such a focused approach would also tend to lower the complexity of integrating new kerfless manufacturing technology and improve rate of adoption.

Table 2 shows how well each of the three kerfless wafering technology categories can support these competitive requirements. From the comparison, it is clear that the only category able to meet every requirement is a subset of solid-phase kerfless wafering called "full-range" (meaning all thicknesses can be addressed by the technology). Although thin solid-phase wafering methods may have higher lifetime than gas-phase absorbers, its low thickness renders it incapable of utilizing present equipment infrastructure and thus necessitate a proprietary cell line and process.

The only known full-range solid-phase kerfless wafering process is SiGen's Polymax™ process described below. Wafer characterization results will also be presented.

Kerfless Technology	Equivalent lifetime & cell efficiency	Ability to support high-efficiency cell designs	Substitutional to ultra-thin thickness	Good mechanical strength	Good dimensional repeatability	Use of existing equipment infrastructure
Gas-Phase	-	-	-	N/A	N/A	-
Liquid-Phase	-	-/o	-/o	-	o	+
Solid-Phase "Thin Only"	-/o	o	-	N/A	N/A	-
Solid-Phase "Full-Range" (SiGen)	+	+	+	+	+	+

Table 2: Comparison of kerfless approaches to meeting competitive wafering requirements

2. SIGEN SOLID-PHASE KERFLESS WAFERING TECHNOLOGY

SiGen has been developing solid-phase kerfless wafering equipment and technology that can meet every kerfless competitive requirement mentioned above.

The process technology, called PolyMax™, 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.

The basic system consists of a high-energy hydrogen implant subsystem and an advanced controlled-cleaving subsystem that together are able to successively detach wafers from a shaped ingot [12-17]. Since the tool can make thicker "substitutional" wafers using standard silicon brick cropping and shaping equipment, it readily integrates into the existing PV equipment infrastructure.

2.1 Implanter Design

The first step of the PolyMax™ wafering process is performed by Silicon Genesis' production-grade proton implantation tool. This first-of-its-kind tool started operation in 2009 at SiGen's plant in San Jose, CA.

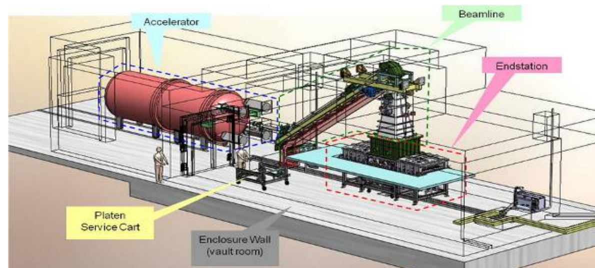

Figure 5: Ion Implanter Tool

Today, the tool is operating at about 60% of its rated beam current and roughly 85% of its rated maximum energy. Implantation of full-sized, $1m^2$ trays of silicon bricks has been demonstrated. Figure 5 shows the key components of the implanter, including the proton accelerator, the beamline, and the endstation. These main elements are housed within a concrete radiation shielding vault. Each of these elements is described in more detail below.

2.2 Accelerator

The accelerator is a DC electrostatic linear accelerator that produces a proton beam up to a maximum energy of 4 MeV. The accelerator vessel contains an ECR microwave plasma ion source at the high voltage terminal potential. The ion source is fed by hydrogen gas which is ionized by microwave energy to form a plasma. Ions extracted from this plasma are initially accelerated to a few tens of kV. This low energy beam is subsequently analyzed through a sector magnet to select only protons and eliminate the unwanted H_2^+ and H_3^+ components. Finally, the proton beam is accelerated through the main acceleration column to its final full energy, ranging from 2 to 4 MeV, resulting in wafers ranging in thickness from about 50 to 150 microns, respectively.

2.3 Beamline

The high energy protons from the accelerator are transported to the target through a vacuum *beamline.* The beamline is a pipe surrounded by a variety of special-purpose electromagnets, including dipole magnets for bending the beam and quadrupole magnets for focusing the beam.
Just before reaching the target, the beam passes through a final two-dimensional scanning magnet that deflects the beam laterally in any direction allowing the beam to be scanned over the surface of the silicon target. The beam can be scanned dynamically over a roughly 1m x 1m square area under full computer control, allowing arbitrary dose patterns to be applied to the silicon bricks. The tray configuration and fast scanning inherently provides the means of developing patterned dose and thermal profiles across each brick, a key element of the high productivity cleaving process.

2.4 Endstation and brick cooling

The endstation, shown in Figure 6, is the third main element of the implanter tool. The endstation transports and cools trays of silicon bricks during implantation.

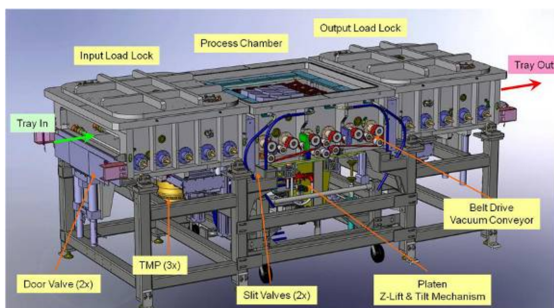

Figure 6: Endstation

The endstation is an inline, turbo-pumped, vacuum processing system comprising three chambers. In the center is the process chamber which supports and cools a tray of silicon bricks while they are being implanted. On either side of the process chamber are vacuum load locks: one for tray input, and one for tray output. These load locks are isolated from the process chamber by large slit valves through which the trays of bricks pass. Of critical importance in the design was to achieving a high beam utilization rate so as to utilize the proton beam in the most efficient possible way. Accordingly, the implanter is pipelined so that there is minimal latency between trays: while one tray of bricks is being implanted, the next tray is being loaded into the input load-lock and pumped down, while an implanted tray is moved to the output load-lock to be vented to atmosphere and unloaded.

The implanter can processes trays of 36, 156 mm pseudo-square bricks in a 6x6 array. The system is also designed to process 64 bricks (in an 8x8 array) of the smaller 125 mm square size (covering a roughly equivalent implantation area). This ability to process different wafer form-factors can be accomplished with a relatively simple change of process kit. The system is also designed to handle bricks up to 100 mm thick, allowing the production of hundreds or thousands of wafers from one brick before it must be removed from the processing line. The 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 has both high current and high energy. It therefore carries a very high power, defined as the product of the current and energy. This heat load into the silicon bricks can reach many tens or even hundreds of kilowatts. Removing this energy inside the vacuum was one of the critical engineering challenges that had to be overcome in the tool design. When a tray of bricks enters the process chamber, the bricks are automatically clamped to water-cooled blocks to remove the heat. Silicon Genesis has developed techniques for handling these high heat fluxes and efficiently removing the heat from the bricks in vacuum.

Since the silicon temperature is such a critical part of the wafering process, the implanter is equipped with an infrared thermal camera capable of monitoring the temperature of an entire tray of bricks during the implantation process. It is also equipped with a visible-light camera used for diagnosing any mechanical handling issues that might occur. An IR camera image captured during testing is shown in Figure 7. In this example, only the central area of the tray is being scanned by the proton beam, resulting in a uniform hot area in the center of the tray, surrounded by cooler bricks at the edges.

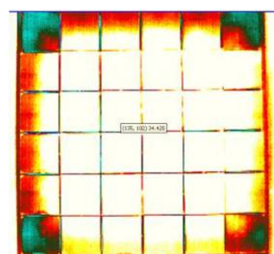

Figure 7: Infrared thermal camera image of the proton beam on bricks showing a blanket implant of the central 16 (156 mm pseudo-square) bricks. The beam over-scan onto the outer ring of 20 bricks is also visible as a cooler area at the perimeter.

The image, which is not typical of a normal implant process, serves to illustrate the tool's ability to control the spatial distribution of implanted protons. A dedicated real-time computer which controls the scanning of the ion beam also integrates the proton current collected on the bricks and terminates the implant when the desired dose has been reached.

2.5 Throughput and Productivity

For 156mm square bricks, the SiGen implanter is designed to have a throughput of about 185 bricks (wafers) per hour. This corresponds to roughly one tray every 12 minutes or one brick every 20 seconds, on average. For smaller 125 mm-sized bricks a tray of 64 bricks can be processed in approximately the same amount of time, resulting in throughputs of about 290 wafers per hour. The endstation was designed so that mechanical processes such as brick handling and load-lock cycling are not in the critical path of the tool. This insures that valuable accelerator time is not wasted waiting for mechanical handling functions. Testing has demonstrated that the endstation is easily capable of supporting these throughputs.

2.6 Shielding and radiation

There are several types of radiation generated by the implanter during normal operation. Fortunately, these are easily handled using conventional radiation protection techniques found throughout the world. These radiation controls make it possible to operate SiGen implanter tools safely in an industrial manufacturing environment.

The main source of radiation is 'prompt' gamma radiation of a few MeV. These high energy x-rays are produced when protons strike silicon. To shield workers from this radiation, the implanter is situated within a concrete vault as shown in fig. 5. The concrete walls surrounding the endstation are therefore relatively thicker since this is where most of the radiation is generated. A secondary source of prompt gamma radiation (at lower energies) is the accelerator itself. The fluxes in this case are lower, reducing the need for concrete shielding around the accelerator, as also seen in the Figure 5. When the proton beam is off, no prompt radiation is produced.

The other source of radiation is 'delayed' radiation due to proton activation of silicon and beamline materials. The beamline materials that are potentially struck by energetic protons have been carefully selected to minimize activation. In addition, the delayed radiation produced within the silicon bricks themselves decays quite rapidly, allowing service personnel to access the equipment safely after only a short waiting period.

Planned improvements in accelerator design are expected to eliminate the need for concrete around the accelerator. Additionally, all radiation fluxes increase rapidly with proton energy, so as the solar PV industry migrates toward thinner wafers and lower energies, the thickness of the shielding surrounding the endstation will be correspondingly reduced.

2.7 Cleaving technology

After the implant step defined a cleave plane within the silicon brick, a separate cleaving subsystem completes the process by detaching the silicon above the cleave plane to form a wafer.

One cleaving method 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.

An alternate cleaving approach applying external energy to the silicon with lower net thermal budget is under development, localized around the cleave plane using a 2-step initiation-propagation sequence to cleave the wafer from each brick with low thermal budget to the silicon brick. The scientific innovation involves the formation of an initiation area followed by a propagation pattern.

A small area at a brick corner (mm^2 to cm^2) is implanted to have a relatively higher dose that is thermally pulse treated to initiate a starting crack. This crack occurs at an edge area of the cleave plane and is designed to avoid generating cleave artifacts. A second energy source is used to propagate the cleave front from this small initiation area through the brick to fully detach the film. Figure 8 shows the initiation-propagation cleaving sequence using a corner initiation area (red) and a simulated cleave propagation sequence. The key technology in achieving high throughput is the development and use of advanced controlled propagation to limit the cleave plane dose requirement.

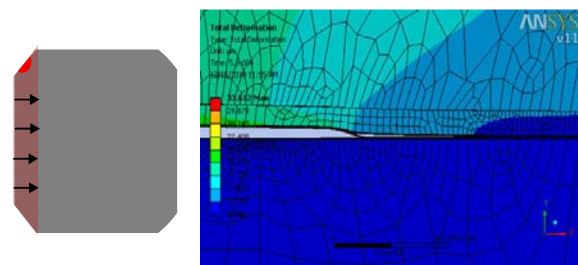

Figure 8: Initiation and controlled propagation 2-step cleave sequence on a pseudo-square brick

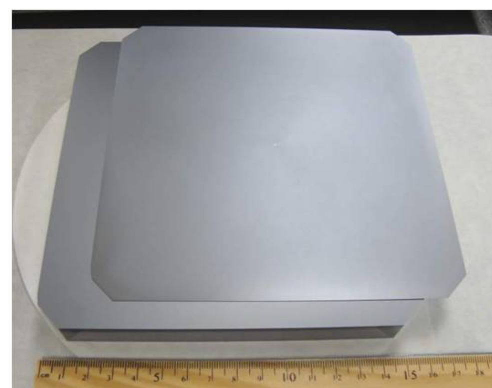

Figure 9: PolyMax™ 156 mm pseudo-square wafer and brick

3. WAFER CHARACTERIZATION RESULTS

Figure 9 shows a typical wafer after the implant-cleave process (wafer slightly shifted from its brick). Excellent wafer material quality has been previously reported resulting

from the implant and cleave technology [12-16]. The light ion implant avoids damaging the bulk silicon while the low energy (threshold) cleave process creates low defect surfaces. Both contribute to high lifetime and high mechanical strength and dimensional accuracy/repeatability.

Recently, process improvements have yielded better lifetime and mechanical strength than previously reported, both critical in high-efficiency PV cell manufacturing.

Relevant wafer mechanical and electrical results achieved using the modified PolyMax™ kerfless process on (111) Cz-Si bricks are shown in Table 3. The data supports the conclusion that these wafers have qualities exceeding the requirements outlined above.

Wafer Characteristic	Typical Wiresaw Value	PolyMax Value
Lifetime	~Brick Lifetime (>500usec)	~Brick Lifetime (>500usec)
Surface Roughness	Few Microns	0.06um to 0.4um (20-150um thickness)
Mechanical Strength	300-400 Mpa	800MPa to few GPa
Thickness Range	Higher than ~120-140um	20-150um
Thickness Variation	10-30um typical	Less than 1% over thickness range
Dimensional Accuracy (Surface)	Follows brick cropping accuracy	Follows brick cropping accuracy
120um Wafer Cost (Includes Poly)*	$0.50/Wp	$0.33/Wp
80um Wafer Cost (Includes Poly)	Not Capable	$0.27/Wp

* Scenario includes best wiresaw performance [3]

Table 3: Comparison of typical wiresaw and PolyMax™ wafer specifications and cost

The potential for cost savings by eliminating kerf waste using solid-phase kerfless wafering such as PolyMax™ is widely recognized and has been well quantified [2,3]. The yield, cost and performance impact of the new wafering technology's higher mechanical strength and tighter thickness variation are more difficult to quantify but are expected to be substantial.

3.1 Lifetime improvement and importance for high-efficiency cell designs

Two back contacted solar cell designs, namely IBC (Interdigitated Back-Contact) and EWT have been popular approaches for next-generation, higher efficiency cells. The challenge is to deliver the higher efficiency at low cost.

While various EWT designs do not require high material quality, the realizable cell efficiency gain is compromised when lower grade silicon is used. IBC remains a design of choice for high efficiency cell manufacturers. IBC solar cells requires higher electronic grade silicon since the minority-carrier diffusion length must be several times the distance between any point of the cell to the nearest collection junction. Although there is a reduction of the lifetime requirement with decreasing wafer thickness, the level is still quite high and usually falls within levels requiring monocrystalline silicon. For example, a 100µm thick IBC cell exceeding 95% carrier collection efficiency would require an effective minority carrier recombination lifetime exceeding 250µs, assuming the front surface recombination velocity of 50cm/s.

Figure 10 shows effective lifetime exceeding 370µs at 10^{15} cm^{-3} measured on P-type Cz-Si (111) 100µm PolyMax wafers using RF quasi-steady state photoconductance (QSSPC). The measurement was adjusted to $1{\cdot}10^{15}$ and $5{\cdot}10^{15}$ cm^{-3} minority-carrier densities, corresponding to ~0.3 and 1 Suns illumination levels respectively. Since the surface passivation used was estimated at 10-15cm/s, bulk lifetime is calculated to approach millisecond level. These levels show the fundamental capability of the implant-cleave process to support next-generation cell design and processes.

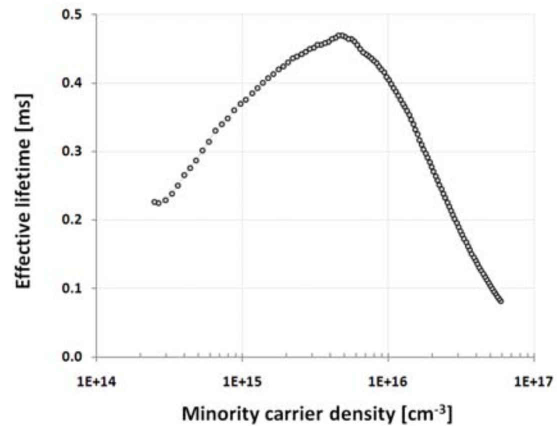

Figure 10: Effective lifetime measurement on P-type Cz-Si (111) 100µm PolyMax™ wafers using enhanced process conditions

3.2 Mechanical strength of PolyMax™ wafers

Recent 4-point bending measurements of 120µm PolyMax™ wafers compared to wiresaw prepared wafers of similar thickness were made and shown in Figure 11. The monocrystalline wafer prepared using a wiresaw process shows a strength dependence to the alignment between the bend direction and the saw marks. In sharp constrast, the SiGen PolyMax™ wafer bent to the maximum extent without breaking. These and similar results previously reported on 50µm wafers point to a unique capability to achieve high-yield cell processing using ever thinner wafers [12].

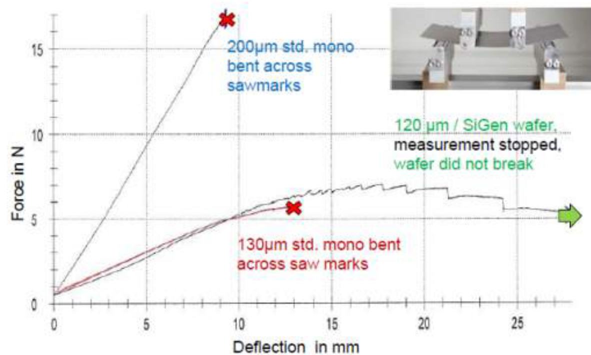

Figure 11: 4-point bending test of wiresaw and kerfless PolyMax™ wafers of about 120µm in thickness. (Data courtesy of REC, Norway and Fraunhofer CSP)

4 CONCLUSIONS

The solar PV industry is entering a new era with double digit GW demand and its supply chain should support its growth without interruptions. Module prices are expected to drop faster than cost cutting efforts, leading to a squeeze in manufacturing gross margins and perpetuating the need for government subsidies. Kerfless wafering technology has the potential to remove the bottleneck in the wafer supply chain by lowering costs, reducing the silicon usage and protecting margins for a sustainable and healthy growth in the PV industry. Silicon Genesis is developing the first production-grade equipment for solid-phase kerfless wafering over a full wafer thickness range by ion-beam induced cleaving. The technology and its ability to deliver wafers throughout a broad thickness range will keep it competitive in cost and quality over wiresaw approaches. The cost reductions occur by eliminating kerf losses; enabling the production of much thinner wafers for more efficient use of silicon; and by reducing upstream and downstream processing costs such as excess ingot pulling capacity and slurry production and recycling typical of wiresaw operations.

Other kerfless technologies based on gas or liquid-phase crystallization are not expected to deliver sustained competitive advantages due to their lower wafer quality and inability to integrate into the existing equipment infrastructure.

The promise of this new PolyMax™ wafering technology is to 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.

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