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Diamond wire sawing: State of the art and perspectives

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ABSTRACT

The purpose of this paper is to give an overview of the use and potential of diamond wire for the silicon-shaping process in the PV industry. The current market and future prospects for helping to meet the goals of 2020's roadmap of thinner wafers and reduced $/W are described.

Introduction

In PV silicon wafer production, a silicon ingot is transformed into wafers by means of three successive sawing stages: squaring, cropping and wafering (see Fig. 1). The first stage consists of cutting a crystallized silicon ingot into several bricks (generally 156mm × 156mm × 250mm). During that step, the external slabs which are contaminated by the crucible and the coating of the crucible are also removed. A few centimetres of silicon are then taken off the top and bottom of these bricks by the cropping operation in order to eliminate the lowest purity silicon. Finally, wafers are obtained from the slicing operation (also called wafering) of the cropped brick by using multiple loops of a single wire.

The actual PV silicon-shaping market consists mainly of an optimized slurry-based process that started about 30 years ago, when multi-wire saws slowly began to replace inner diameter (ID) saws in the industry, and at which time wafer thicknesses went below 500µm. This sawing process consists of the association/coupling of a thin steel wire and a slurry composed of a mixture of micrometre-sized abrasive grains (typically 10µm) and a lubricant fluid. The lubricant fluid was initially made of mineral oil, but nowadays polyethylene glycol (PEG) is used. A slurry layer of 15–20µm is carried by the wire, which is slowly pushed through the silicon bricks. The multiple indentations of the abrasive grains (generally SiC) on the material create a sawing effect by abrasive wear. In the slicing equipment, the 130µm-diameter steel wire is wound around polyurethane wire-guides with a typical groove pitch of 340µm, therefore currently producing 180µm-thick wafers.

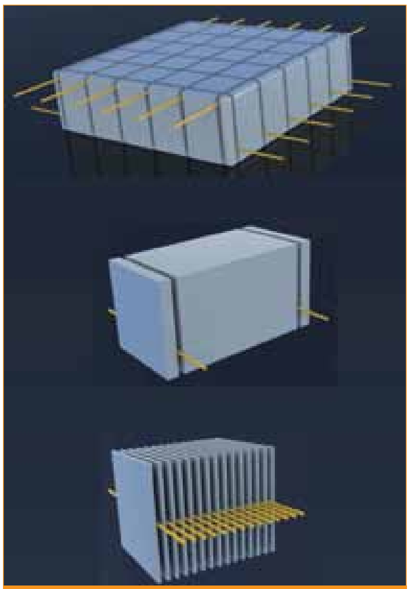
Figure 1. Successive cutting stages of the silicon (top down): squaring, cropping and wafering.

If this slurry-based technology is now well proven, its potential improvements tend to be limited. The wafer production cost reduction, which needs to be significant in the coming years, will probably be achieved by the arrival of a disruptive technology. Recently, the possible use of diamond wire created a lot of buzz with the promise of a satisfactory compromise between cost and performance, since, for example, the cutting speed is at least twice that of the steel wire and conventional slurry solution. Such wire has already been used by early supporters, mainly on squarers, as the necessary length of wire used during a cut does not exceed 500m and the associated risk of breaking it does not incur too great a financial loss.

> "Cutting with diamond wire is not an easy task and a lot of obstacles have to be overcome before this technology is widely accepted"

Nevertheless, cutting with diamond wire is not an easy task and a lot of obstacles have to be overcome before this technology is widely accepted. A change in silicon sawing technology appears to be imminent, so the purpose of this work is to give an overview of the silicon-shaping activity in the PV industry. The focus will be on the development of diamond wire technology potential and will take into account recent developments such as the crystallization of mono-like ingots.

Advantages, challenges and roadmap

In the wafering operation, because the price of diamond wire per km is more than a hundred times more expensive than steel wire, a wire break can compromise the cost of ownership (COO) of the whole slicing operation and diamond wire adoption. On the other hand, as the volume of production of diamond wire increases, and other industries such as sapphire for LED applications and PV squaring operations with diamond wire ramp up, the price of diamond wire will consistently go down. In addition, any other improvement of the COO is always welcome for promoting quick adoption. For example, recycling a part or the totality of silicon kerf obtained during diamond wire slicing of silicon could dramatically change the picture.

Since more than 40% of the total cost of a finished module is the cost of the wafer itself [1], a substantial amount of money can be saved on PV systems by optimizing the wafering process. For several reasons, indications are that without the arrival of a disruptive technology such as diamond wire this will not be possible on the scale that groups of industrials (e.g. SEMI PV Group) have planned for the horizon of 2020 [2].

The first – and probably most important – expense item to reduce is the amount of silicon used per wafer. That is why one of the PV market goals is to slowly but surely reduce the wafer thickness as well as the kerf loss over time (silicon wasted during cutting). ITRPV Roadmap wafers [2] shows that in order to get to the $1/W grid parity goal in 2020, the wafer thickness should be reduced from 180µm to 100µm, and the kerf loss of currently 150–160µm should also be reduced to about 100µm (see Fig. 2).

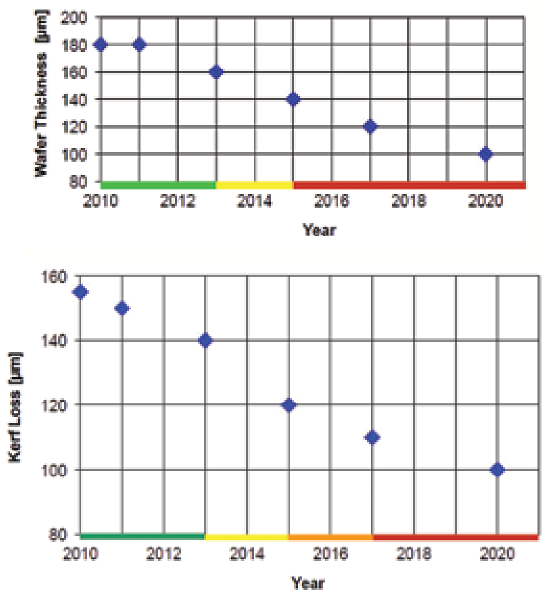

Figure 2. Roadmap of wafer thickness and kerf loss reduction.

Credit: Images reproduced with permission from the ITRPV Roadmap [2].

Today, world leaders in wafering technology use about 100m of 120µm (or 130µm) steel wire in order to obtain a single wafer. Almost no diameter reduction is observed during cutting (only 2–3µm) since the wire acts only as the carrier of the slurry which does the actual cutting. Nevertheless it is still a challenge for the wire to undergo further reductions in diameter without the risk of compromising the cut when 3000 to 5000 wafers are cut at a time. As regards kerf loss, a reduction to 100µm would necessitate wire of diameter 75 to 80µm that is capable of cutting more than 5000 to 8500 wafers of thickness 100µm on equipment similar to today's. Once again, that does not seem to be achievable without major changes. This is why all the interest in diamond wire has arisen and appears to make sense.

With 60% of the wafering market being for multicrystalline silicon wafers [3], which corresponds to 70% of the crystalline market, the production cost of a single wafer is pretty much as low as it can get, especially with the current downturn in the economy that has created stockpiles of consumables which in turn has led to suppliers decreasing their selling price dramatically. Today's total available market (TAM) for consumables for the squaring operation is around \$7 million, and around \$800 million for the whole wafering operation (discussed later). Taking into account that the individual costs for the steel wire, SiC, PEG, recycling operation of slurry and all surrounding consumables for the wafering operation have all been largely optimized, and independent of the equipment used, the cutting operation costs around \$0.5 per wafer as shown in Fig. 3. That is the reason why opportunities to economize significantly on the current cost of slurry process consumables seem to be limited.

On the other hand, assuming that the use of diamond wire allows cutting at twice the speed of the slurry process on the same or equivalent equipment cost basis as today, the corresponding part of the capex will decrease proportionally. Additionally, even though today the cost of the slurry and diamond processes might

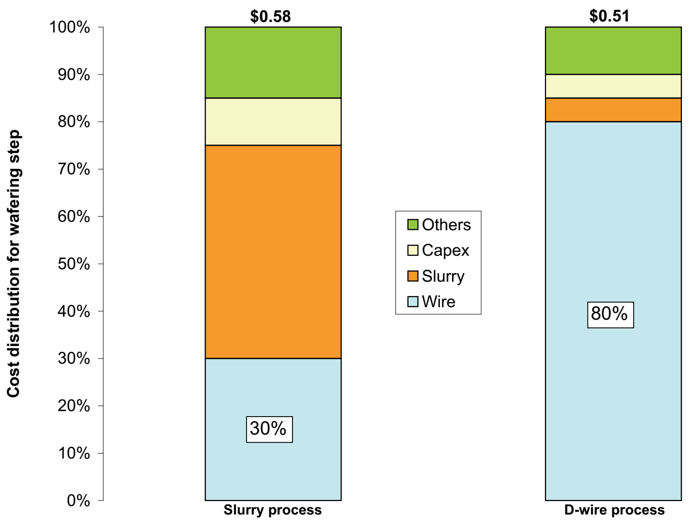

Figure 3. Cost distribution for the wafering step.

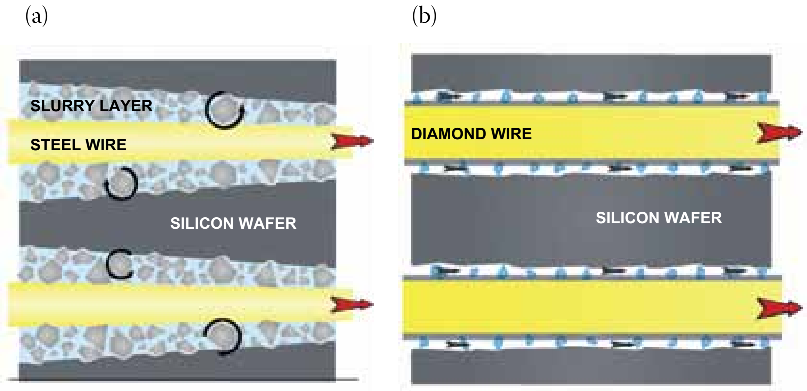

Figure 4. Wafer sawing process with (a) slurry and (b) diamond.

be comparable when in competition with each other, the removal of slurry preparation and recycling while moving towards diamond wire will eventually reduce the cost of the overall slicing operation as the cost of diamond wire falls. Moreover, as shown in Fig. 4, the better total thickness variation (TTV) observed using diamond wire will definitely be needed when the wafer thicknesses approach 100µm. Despite all of its advantages, diamond wire sawing is not without complications; the process will be discussed next.

Towards diamond wire

Diamond wire has long been used for cutting hard substances such as sapphire, SiC and other materials and has proved to perform better than slurry (by cutting twice as fast) and to be cost effective once the process has been optimized. But cutting multicrystalline silicon is not the same as cutting hard, homogeneous, single crystals such as the ones just mentioned above. In fact, the first tests in late 1990 and early 2000 of cutting silicon ingots using the same diamond wire used in the sapphire industry were a disaster: the steel wire surface entirely covered with diamonds quickly became clogged by silicon kerf and did not cut anymore, and consequently rapidly led to wire breakage. Today's diamond wires sold for the PV industry no longer have their entire surface covered with diamonds (< 10% coverage), and the cleaning of the diamond wire is essential for maintaining its cutting effectiveness and ensuring a satisfactory lifetime.

For several years, companies such as Diamond Wire Technology have sold equipment that is capable of cutting silicon rods for use as seeds in Siemens reactors, and many companies today offer the possibility of cutting silicon ingots or supply silicon cropping equipment using diamond wire. The leading equipment manufacturers all have squaring equipment for Gen 5 ingots that today is able to cut with diamond wire. But with the arrival of 350µm-diameter structured wire on slurry squarers that can achieve cutting speeds of up to 2mm/minute, the difference in COO in favour of diamond wire that appeared obvious when the 'traditional' 250µm structured wire used for years was cutting at 1mm/minute maximum is not so obvious anymore. The difference between squaring and cropping of the ingots vs. wafering also needs to be made clear. For wafering, kerf loss is critical, but for cropping and squaring, it is not so much of an issue. It is certain that in the coming years all new PV fabs will go with diamond wire squarers, even if the wire diameter is a bit larger than today, simply for the amazing potential for high cutting speeds and for avoiding the hassle of slurry preparation.

Regarding the wafering operation with diamond wire, everyone is now becoming curious to know whether or not it will slowly replace its longtime competitor – steel wire and slurry – and if so, when that will happen. Apart from silicon not being as high on the hardness scale as sapphire and SiC (materials traditionally cut with diamond wire), monocrystalline ingots with only one crystal orientation are fairly similar to those materials in terms of cutting properties. As a matter of fact, almost the whole Japanese market for monocrystalline cells now uses wafers that have been cut with diamond wire. Furthermore, during the 2011 PVSEC conference, Norsun announced that it was in the process of switching its whole

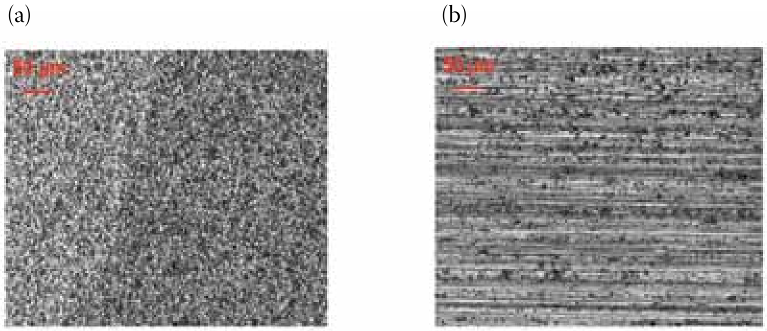

Figure 5. As-cut wafer surface with (a) slurry process, and (b) diamond process.

	Diamond wire process	
	Pluses	Minuses
Wire	**Price: potential to decrease (by 2 or 3) is high** Diameter: high reduction potential	**Price: currently high (~$150-200/km)** Very few manufacturers of good-quality wire
Cutting performance	**Twice as fast** Better TTV Increased productivity	**Difficulties in cutting mc-Si (heterogeneous)** Vibrations management **Wire breakage risk**
Water-based coolant	Ease of use Cheaper **Opens possibilities for recycling kerf** Cooling properties	Silicon deposit on equipment Reaction of Si with water: H2 risk Vibrations management
PEG-based coolant	Dampening effect of PEG on vibrations Recycling of PEG already exists	Price Need to remove PEG to recycle kerf
Equipment	**Initial capex reduction (by ~2)** Potential reduction in the size of equipment Cooling power much lower than with slurry Less power required to drive wire Reduction in price of equipment	New equipment needed or retrofitting of existing equipment
Consumables	Reduction in quantity of consumables	Long-term contracts for SiC recycling will delay adoption Wire: the strategic consumable
Conclusion	**Thinner wafers with better TTV** Maturing market should reduce COO over years	

Table 1. Summary of the pluses and minuses of the diamond wire process.

plant of monocrystalline wafers to using diamond wire technology.

Cutting multicrystalline silicon wafers with diamond wire, however, is a challenge. The inhomogeneity of the material, the different orientation of the grains and the precipitates located in the grain boundaries make it a lot more difficult to cut than monocrystalline silicon. That does not mean it is impossible, but today's industry leaders in equipment and diamond wire technology have announced that twice as much wire is necessary for cutting a multicrystalline wafer as a monocrystalline wafer (about 2m per wafer instead of 1m), without a guarantee that in the long term the COO will be much better in the event of too many wire breakages.

Mechanisms during cutting and their consequences on as-cut wafers

In both the slurry and the diamond methods, the wire sawing effect is due to the physical phenomenon of abrasive wear during the sliding of one body on another. Nevertheless, two radically different mechanisms of abrasion can be distinguished as shown in Fig. 4.

Sawing with slurry involves free abrasive particles capable of having distinct movements from those of either the wire or the silicon. It has been precisely described in the past that the so-called three-body abrasion mode involved in slurry sawing embraces the fact that the role of the steel wire is only to carry the slurry to the silicon. The abrasion itself is done by multiple indentations of SiC grains on the surface of the silicon [4]. On the other hand, in diamond sawing the abrasive diamond particles stuck to the wire realize a two-body abrasion which can be represented by multiple scratches. This mechanical difference between free and bind abrasive particles has an impact on the wafer or surface created by sawing.

> "The total thickness variation (TTV) of wafers cut with diamond wire is better than with slurry and ranges from approximately 7 to 15μm."

A first difference concerns the wafer thickness shape. Since everyone in the industry is now cutting in a one-way mode in which the wire is carried through in a single direction at about 15m/s, the slurry layer around the steel wire of about 15μm on one side of a silicon brick decreases as it passes through a silicon brick, therefore resulting in tapered wafers with a standard TTV of around 15 to 20μm (Fig. 4a). Moreover, independent of the method of cutting using either a back-and-forth (or pilgrim) mode or a one-way mode, the 'squishing' effect observed with slurry while passing through silicon does not exist with diamond wire. The TTV of wafers cut with diamond wire is better than with slurry and ranges from approximately 7 to 15μm.

The abrasion mechanism involved also has an influence (on a smaller scale) on the surface roughness. These differences are evident in Fig. 5, which shows two examples of surface conditions – after slurry sawing and after diamond sawing.

In Fig. 5(a), the slurry as-cut wafer reveals the multiple indentations of SiC on silicon; cross-section imaging shows that about 5–6μm of subsurface damage (SSD) is due to that abrasion mode. Diamond wire composed of diamonds surrounded by a nickel layer deposited onto a steel wire does not yield the same final surface characteristics. The abrasion mode in this case is a two-body mode whereby the diamonds remove the silicon by plastic deformation in front of the diamond grain [5]. In this case, the surface of an as-cut wafer appears as shown in Fig. 5(b): the silicon removal creates lines on the surface. Cross-section imaging indicates only about 2–3μm of SSD resulting from the different abrasion mode.

Performance of diamond wire

Even though everyone using diamond wire today in the PV industry has not necessarily fully understood and optimized the procedure compared to the slurry process that has been in use for decades, diamond wire has demonstrated its potential to cut a lot faster than steel wire and slurry in the future. As described in the following paragraphs, the potential for wafering, especially on monocrystalline or mono-like silicon ingots, is obvious. It has

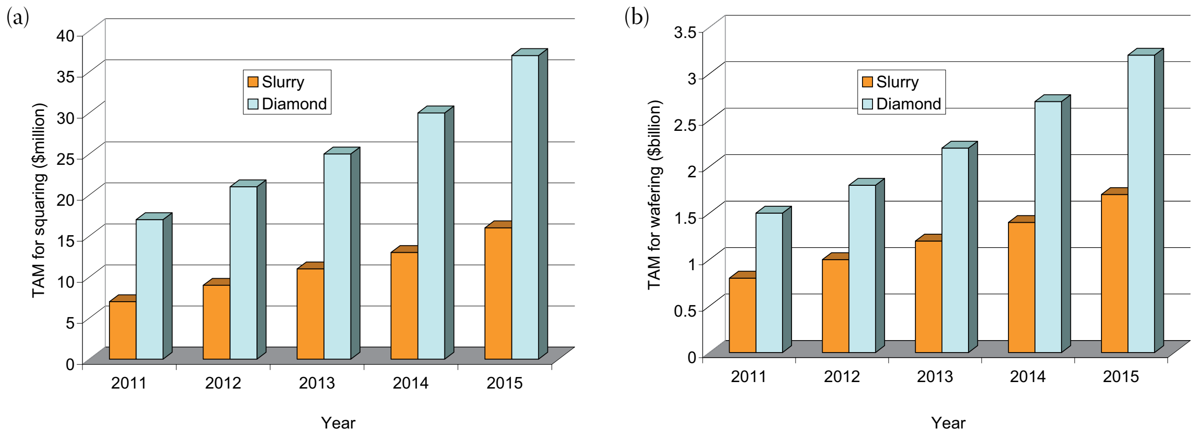

Figure 6. TAM of consumables for (a) squaring and (b) wafering operations.

already been mentioned that it is possible to cut monocrystalline wafers with a table speed of at least twice that of slurry. This has a significant impact on what form the silicon-shaping industry will take in the coming years. Table 1 summarizes the pluses and minuses of diamond wire compared to slurry.

The main assets of diamond sawing appear to be its capacity to cut at more than double the speed of the slurry method, increasing de facto equipment productivity and reducing the length of wire required. This technology also allows numerous potential improvements: a better TTV, the possibility of recycling Si powder, a reduction in wire diameter and a reduction of the number of consumables.

The adoption of diamond wire means that most of the difficulties from the saw and the slurry management are transferred to higher demands on wire characteristics. Probably the most important of these are a stronger mechanical resistance and a good diamond particle insertion inside the external coating. The latter requirement is one that is far from easy to meet, since diamond wire has a more complex structure than steel wire. This fact is accentuated if the wire diameter is further reduced. Because of these difficulties, the diamond wire manufacturers are limited to only the very competent and well-known ones (ASAHI, DWT) and the market prices are kept high. Furthermore, the difficulty in producing a defect-free wire over a length of many kilometres explains why diamond wire is currently only used in short versions – for squaring and cropping – and less frequently for wafering.

Equipment and processes also have to be developed or improved in order to allow diamond wire sawing to conquer the PV market. For example, it must be mentioned that there is a pressing need to limit wire vibration so that thinner wafers and a better surface finish can be obtained, and that a reliable process is necessary for cutting heterogeneous material such as multicrystalline silicon. Despite its drawbacks, the diamond wire process seems to be the future of silicon shaping in the PV industry, including the wafering stage.

Different strategies

Even though it is becoming more and more apparent that within the next five years diamond wire technology is going to make significant progress, in the current PV context, in which competition is extreme in terms of cost reduction and in which becoming one of the industry leaders is everyone's goal, there is no global strategy for the industry. Diamond wire manufacturers are all trying to match the very few leaders such as Asahi Diamonds, Diamond Wire Technology and a few others in terms of quality, when lowering the price is essential in order to entice clients to switch from one solution (steel wire + slurry) to the other (diamond wire).

At the same time, compared to the old industry scenario in which the four main consumable costs were each absorbing a proportion of the cost (PEG, SiC, wire, slurry recycling), moving to diamond wire implies that the wire suddenly takes almost the whole consumable cost for itself. Knowing this, the previous providers of consumables are all trying to delay the arrival of the new diamond wire process. Assuming that the whole market used a single kind of wire (steel for slurry or diamond), the TAM for consumables for wafering with diamond wire was as much as $1.5 billion in 2011 and could be as much as $3.2 billion in 2015 as seen in Fig. 6(b).

Wafers manufacturers are all trying to be one of the first to cut with diamond wire at a lower cost than cutting with slurry, while equipment manufacturers do not have the same strategy. When Meyer Burger Group clearly set its roadmap when buying DWT in 2009, all the other companies such as AMAT, TOYO and NTC did not get specifically involved in the diamond wire manufacturing activity. AMAT, for example, is taking advantage of its joint patent with Arcelor Mittal [6] on structured wire to currently promote its thick version for squarers and a new, thin version for wafering to make the most of the well-proven slurry-based technology.

As part of reflecting on how to improve the wafer cost in the PV industry, there is also another approach: thinking 'out of the box' and not cutting silicon at all. Companies like Sharp have been working on making wafers by directly dipping a porous substrate into melted silicon and have demonstrated an efficiency of 14.8% [7]. The company 1366 Technologies recently announced that it was in the process of industrializing its direct wafer technology [8]. SiGen announced that it had sold two industrial-scale prototypes of ion implantation for manufacturing 85µm-thick monocrystalline wafers, having earlier achieved a record 20µm thickness [9]. RGS Development B.V. in the Netherlands is developing an industrial process for making direct wafers on substrates [10], while the idea of making kerf-less wafers has been given up by other companies such as Schott solar with their edge-defined film-fed growth (EFG), Evergreen with their string ribbon technologies and Astropower with their moulded wafers technology. Despite these efforts on kerf-less solutions, none of them seems to be ready to replace silicon shaping in the short term. It appears that none of these techniques combines cost, quality and productivity, although not all the necessary information on which to base such a statement is yet readily available.

Alignment of two disruptive technologies

Sometimes two things happen at the same time and make something that seemed far-fetched suddenly appear plausible. This could be what is happening in the PV industry today. As everyone knows, two subjects created a lot of buzz last year: mono-like ingots and diamond wire. Without being clearly linked to each other, they could actually make many things happen at the same time. Mono-like ingots are created by using seeds of monocrystalline silicon deposited at the bottom of a crucible in order to melt standard solar-grade feedstock on the top part – and only the top part – of the seeds. The standard crystallization process follows to obtain a mono-like Gen 5 ingot. Depending on the process control, the ingot can be partially mono in the centre with some multi on the sides, or almost fully monocrystalline.

> "Despite the technical challenges, including the manufacturing of stronger wires of thinner diameter and the capability of cutting inhomogeneous materials such as multicrystalline silicon, diamond wire certainly seems to be a potential solution for replacing the slurry process."

Teams have been working on the mono-like ingot process for many years in different parts of the world; at our laboratory [11–13] an active development of the process is now underway to produce Gen 5 mono-like ingots in an industrial-scale furnace in order to obtain the best quality. On the silicon-shaping activity front, since it is known that diamond wire cuts monocrystalline ingots more easily than multicrystalline ones, the structural, chemical and mechanical properties of the wafers are being investigated in order to develop the best cutting process using diamond wire. This is the goal of a current collaboration with Thermocompact, a French manufacturer of electrical discharge machining (EDM) wire that is moving towards saw wire manufacturing.

Conclusions

PV roadmaps are guiding the industry towards improving the wafering processes, mostly by reducing the amount of silicon used to produce each wafer. As the slurry process reaches its limits, diamond wire appears to be a possible alternative to continue in that direction with the arrival of a disruptive technology. Despite the technical challenges, including the manufacturing of stronger wires of thinner diameter and the capability of cutting inhomogeneous materials such as multicrystalline silicon, diamond wire certainly seems to be a potential solution for replacing the slurry process. Such a step would, however, involve significant changes in the silicon-shaping market, mostly through the transfer of the cost of the equipment to the cost of the main consumable, that is the diamond wire. Nevertheless, the change should reduce the overall COO. Even though, of all the emerging kerf-less technologies, none yet seems ready to capture a significant part of the market, this developing technology is definitely one long-term strategy to keep an eye on.

Acknowledgements

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