Diamond wire process monitoring

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Abstract

Major progress has been made in the PV industry in the last five years as a result of the extensive use of diamond wire during silicon wafering operations. Productivity has increased and costs have fallen to the point where the price of a monocrystalline wafer cut with diamond wire is approaching the price of a multicrystalline wafer cut using slurry. Since multicrystalline silicon still dominates the PV market, it is essential that this area quickly adopt diamond wire technology; however, because of the intrinsic inhomogeneity of this material its precise characterization, as well as a characterization of the diamond wire cutting process, will be required in order to fully reap the benefits. In this context, the monitoring of the cutting process will become mandatory to ensure both the expected productivity and the required wafer quality at an industrial level.

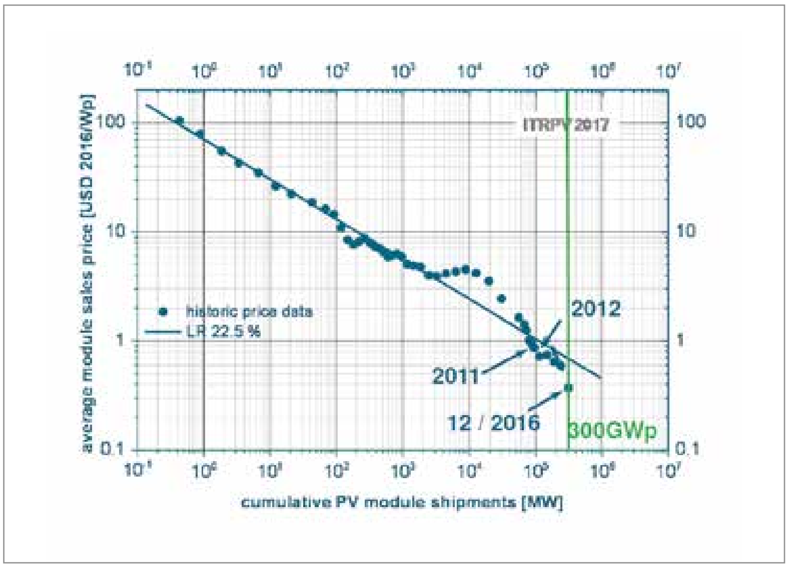
Introduction

As was rightly anticipated in a previous article by CEA-LITEN in 2012 [1], diamond wire technology has made significant progress in the PV industry in the past five years, mainly for cutting monocrystalline silicon. The main reason for this is its higher cutting ability than conventional wafering technology, namely steel wire and slurry, which is still the main technology used today in the industry for cutting multicrystalline silicon wafers [2–4].

The rapid market share progression of diamond wire wafering technology for monocrystalline silicon since 2012 has happened as a result of many favourable factors coming into play:

- The official price of diamond wire was around \$150/km in 2012, whereas today it is around \$45/km when bought in large quantities.
- The wire diameter used in 2012 was 120μm, whereas now it is often 70μm.
- The cutting time using slurry was approximately five to seven hours, whereas the cutting time using diamond wire is currently close to two hours.
- The total thickness variation (TTV) of the slurry wafers was typically between 20 and 30μm, whereas the TTV of wafers cut using diamond wire is typically between 5 and 15μm using state-of-the-art wafering equipment.
- The equipment cost used to be close to \$1m, whereas for high-end diamond wire cutting equipment it is now half of that, and even less for the low-cost equipment that has swiftly been developed in recent years.

Figure 1. Average module sales price vs. cumulative PV module shipments.



Courtesy of ITRPV 2017

In consequence, the production costs associated with monocrystalline wafers have fallen by more than 30% in the past five years. Since the PV market cost reductions are still following the same trend as in the past 50 years (Fig. 1), and because some of the above-mentioned advantages have appeared much more quickly than anticipated (in particular, the decreases in diamond wire price and diameter), the reductions in wafer thickness forecast by the industry roadmap have not really materialized, because kerf loss has already been reduced by 40%.

Diamond wire technology has been particularly well suited to monocrystalline silicon, since such high-quality material does not present defects, such as grain boundaries and/or inclusions. The fast-growing diamond wire technology in the wafering industry for monocrystalline silicon has driven the market to the point where around 90% of this material is now cut using diamond wire. The cost of monocrystalline wafers cut using diamond wire is very close to the cost of multicrystalline wafers cut using the slurry process; this is driving the PV industry (where 70% of the market is still multicrystalline silicon) to use diamond wire technology as well. While some issues – such as the problematic compatibility of the surface obtained using diamond wire and acidic texturization used for multicrystalline – are on their way to being resolved, the inhomogeneity of the multicrystalline material remains intrinsic to its particular crystallization process.

This paper discusses why, in the authors' opinion, the monitoring of the diamond wire cutting process is extremely important for further improvements of this technology, for all types of material, namely monocrystalline, mono-like [5–9] and multicrystalline silicon. As a reminder, mono-like silicon ingots are obtained in directional solidification system (DSS) furnaces by melting silicon above monocrystalline seeds sitting at the bottom of a crucible. The goal is to only melt a portion of the seeds and begin directional solidification from the bottom to the top. Ultimately, a full monocrystalline G6 ingot is obtained. Such material offers an electrical performance close to that of monocrystalline silicon, but with the high-productivity advantage from the use of DSS furnaces.

> “An increase in productivity cannot happen without a highly controlled wafering process.”

Why process monitoring?

As explained in the introduction, major improvements in the diamond wire wafering process have been made in the past five years; those process enhancements have mainly been possible by improvements in wire performance and decreases in diamond wire diameter, as well as by higher wire speeds, which allow a higher cutting speed. As always, PV roadmaps predict that further improvements will be necessary in the future.

A 30 to 40% increase in wafering productivity is expected/needed by 2027. The authors believe that for the multicrystalline silicon wafers producers to remain competitive, they will quickly need to master the diamond wire process in order to reap the same benefits that the monocrystalline silicon wafers producers already enjoy. An increase in productivity demands further reductions in wire diameter, reductions in wafer thickness and improvements in wafer quality, which cannot happen without a highly controlled wafering process.

Even today, wafer specifications are given mainly in terms of wafer geometry, electrical characteristics and relative cleanliness; there is no mention of wafer surface morphology, subsurface damage (SSD), mechanical behaviour and morphological defects.

As the trend of the PV market is to move towards thinner wafers, it is very important to determine what level of wafer quality can be achieved today. First, while the monocrystalline silicon crystallization process prevents precipitates from forming in the material (making it fairly easy to cut using diamond wire), the nature of the multicrystalline silicon crystallization process makes it difficult to completely avoid certain contaminations. Silica crucibles coated with silicon nitride produce impurities that diffuse into the silicon at high temperatures and might precipitate in the form of silicon nitride. The graphite environment of the solidification furnaces leads to saturation of the silicon with carbon, which can precipitate at the solid–liquid interface during directional solidification, thus creating SiC inclusions. It is well known that diamond wire can be used to cut hard materials, such as silicon nitride or silicon carbide [10,11]; however, it is not possible for a diamond wire designed and used for cutting silicon to efficiently cut small inclusions of silicon nitride or carbide that are present within the silicon.

With the use of high-resolution infrared characterization equipment developed by the French company B.E.A, the presence of large precipitates can be observed in 156mm × 156mm silicon bricks (Fig. 2). As can also be seen in the infrared images, very large differences in size and density of precipitates in the material can occur, depending on the crystallization conditions and/or the brick position in the crucible. Clearly, the wafering operation should not be driven using identical processes on those silicon bricks. If tempted to do so, the cut would result in poor wafer quality at the locations where excessive precipitate density is visible on the infrared images [12]; moreover, wire breakage could even occur due to more rapid damage to the wire.

Apart from using different processes, another solution would be to allow excessive wire consumption in order to find a process that gives satisfactory results in all cases (which would therefore lead to a smaller potential cost reduction of the cutting step). Fig. 3 shows different precipitates that can be observed in the silicon using a scanning electron microscope (SEM).

As a result of the use of graphite-rich heating elements in the furnaces, and of the use of silicon-nitride-coated silicon crucibles, the technology

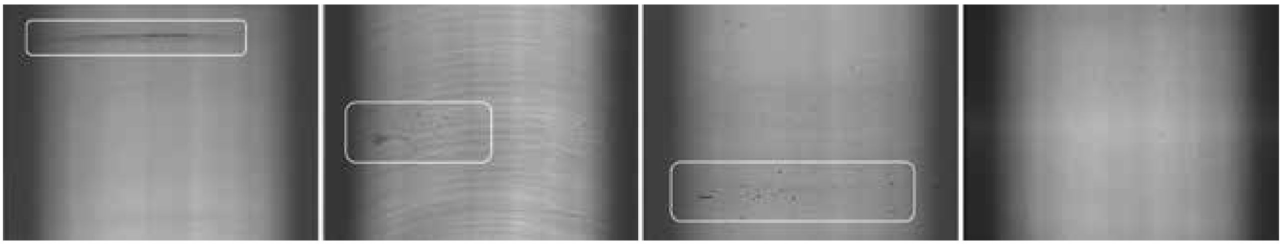


Figure 2. Infrared images of a selection of silicon bricks. Precipitate-rich areas are identified by the white rectangles.

Courtesy of B.E.A

used in the PV industry to produce G6 ingots makes the formation of precipitates in the silicon inevitable. Furnace and process optimization have a tendency to cause the precipitates to appear in zones that will ultimately be removed from the ingot (sides, bottom-part/red zone, top-part/segregated impurities); however, the difficulty in producing precipitate-free ingots tends to demonstrate the need for a precise understanding of wire behaviour and process monitoring in order to cut those ingots efficiently using diamond wire.

What sort of monitoring?

During diamond wire cutting, the main consumable is the wire itself, in contrast to the slurry process, in which different consumables assure the success of the process, specifically steel wire, SiC abrasive and polyethylene glycol (PEG) lubricant. The quality of the diamond wire is therefore extremely important.

Over the past six years the team at CEA has developed diamond wire characterization techniques in order to help the French company Thermocompact in the development of diamond wires for silicon applications, and to gain knowledge about the diamond wire cutting process. Optical microscopy and/or SEM are always useful tools for getting an idea of the precise wire morphology (see Fig. 4); on the other hand, these tools also present the inconvenience of only being able to inspect local/small areas. Typical diamond wire spools are about 50km long, and a lack of diamonds over just a few centimetres of the wire can be disastrous to the cut should the steel wire make contact with the silicon. Thus, microscopy is not the most appropriate tool for studying diamond wires.

Bidirectional optical micrometres make it possible to study the wire morphology along two different axes at 90° to each other. High acquisition frequencies allow very precise morphology studies, while lower acquisition frequencies allow very long portions of the wire to be studied – eventually the entire spool. The measurement principle is illustrated in Fig. 5, and typical data obtained from the micrometer are given in Fig. 6.

After further interpretation, such measurements yield a lot of the information needed to anticipate the wire behaviour inside a wire saw; this information is reported in Table 1, along with what the consequences might be if the studied factor is out of specification. Some other wire characteristics are mentioned, along with the possible monitoring techniques.

From the authors' own experiences, it is known that if the longitudinal homogeneity is poor (a lack of diamonds over a few centimetres of wire), then the risk of wire breakage is high. The same conclusion is drawn if the radial homogeneity is poor (a lack of diamonds around the periphery of

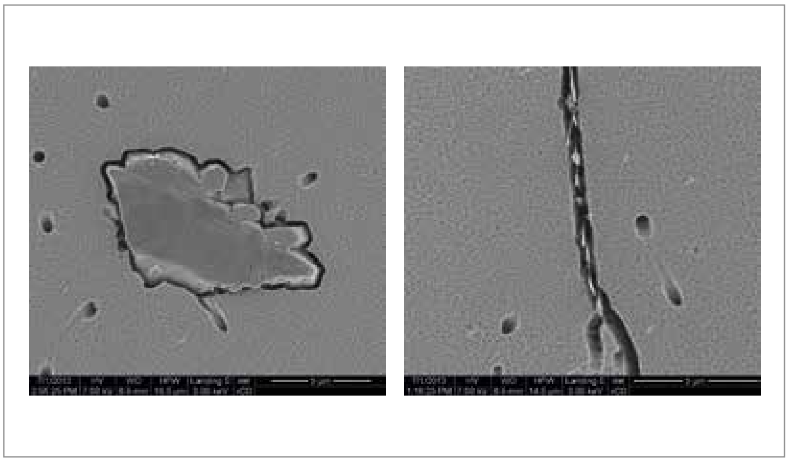
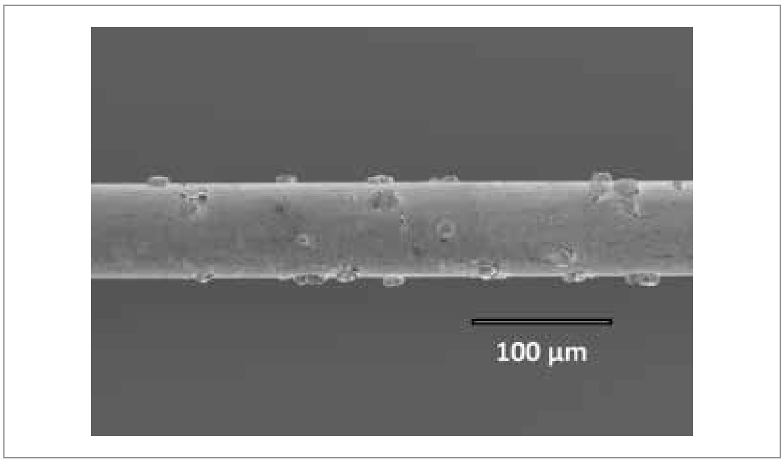


Figure 3. SEM images of SiC (left) and Si_3N_4 (right) precipitates inside the silicon matrix.



Courtesy of Thermocompact

Figure 4. SEM image of a diamond wire typical morphology.

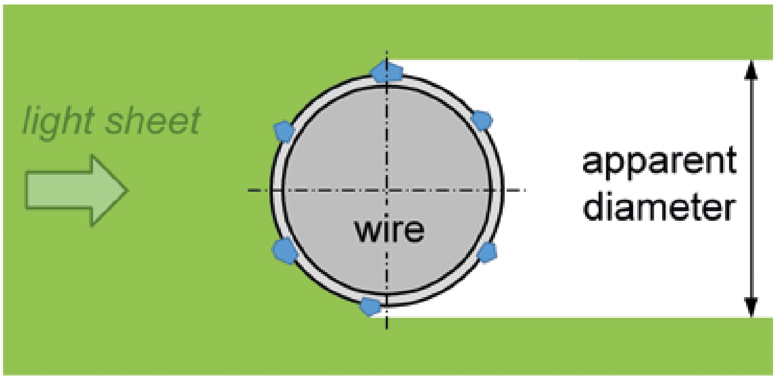


Figure 5. The measurement principle using an optical micrometer to characterize diamond wire.

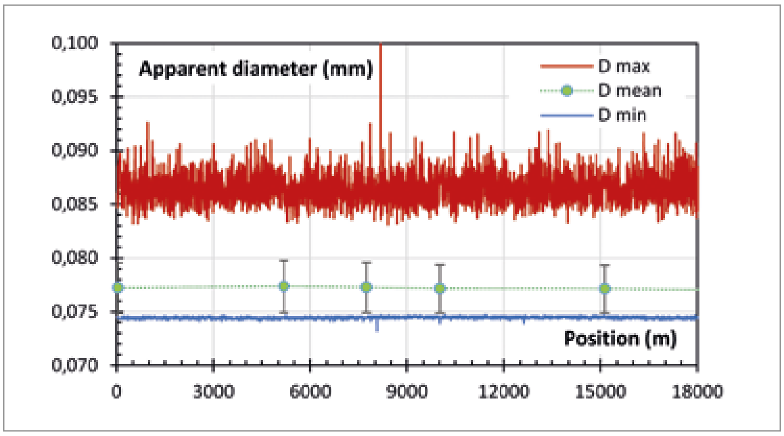


Figure 6. Optical micrometer inspection of new diamond wire.

Wire characteristic	Consequence during a cut	Possible monitoring	Wafers characteristic
Longitudinal homogeneity	Lack of diamonds results in wire breakage	Wire inspection	Poor wafer quality (TTV and mechanical)
Radial homogeneity	Lack of diamonds results in wire breakage	Wire inspection	Poor wafer quality (TTV and mechanical)
Diamond size	Larger diamonds allow faster cutting but create more surface damage	Wire inspection Bowing sensors in the wire saw	Wafer quality (TV, TTV and mechanical)
Number of diamonds/mm	The smaller the number of diamonds, the more pressure put on them and the more material removed	Wire inspection	Wafer quality (mechanical)
Diamond shape	The more angled the shape, the more material removed but the greater the surface damage	Microscopy, SEM	Wafer quality (TTV, roughness, SSD)
Binder thickness	The thinner the coating, the more the diamonds stick out and the more material removed	Wire inspection	
Binder composition	The higher the abrasion resistance, the longer the wire life	Chemical analysis	
Mechanical resistance	The higher the mechanical performance of the wire, the greater the wire tension that can be used and the less the bowing during the cut	Pulling test and fatigue test	Wafer quality (TTV)

Table 1. Important wire characteristics for predicting the cutting behaviour of diamond wire.

the wire). It is also well known from the literature that larger diamonds remove more silicon material [13]; a faster process can therefore be used, but large diamonds create more damage to the surface and subsurface. In addition, large diamonds increase the kerf loss created by the wire, and rougher surfaces decrease the mechanical properties of the wafers. A compromise invariably has to be found by weighing these advantages and disadvantages.

The number of diamonds/mm at the surface of the wire is very important. For a given cutting process, a low density of diamonds results in more pressure on each individual diamond; this leads to larger silicon chips being removed by a diamond, resulting in a higher cutting efficiency of the wire, which can be observed by less wire bowing in the wafering equipment. However, as the diamonds machine the silicon their cutting ability decreases (crushing, polishing) and the force applied to them increases; this force can exceed the mechanical bond between the diamond and the binder, in which case the diamond will be removed from the surface of the wire. The subsequent deficiency in diamonds results in wire breakage. A compromise therefore also has to be found between the initial number of diamonds present at the surface of the wire, the cutting process that can be used, and the final number of diamonds present at the surface of the used wire after cutting. A greater initial number of diamonds may reduce the cutting efficiency, but it will ensure the longevity of the wire and/or lower wire consumption [14].

Rounded diamonds allow cutting in a ductile mode under certain conditions; this results in a very good surface quality but the cutting process is extremely slow [15]. In contrast, sharp diamonds remove silicon in a fragile mode, creating chipping at the silicon surface but allowing a fast cutting process.

The thinner the binder, the greater the protrusion of the diamonds, which results in fast cutting (or in the removal of large chips of silicon), but increases the risk of diamond detachment from the wire surface.

The more resistant to silicon abrasion the binder the better, but most diamond wire manufacturers today use electrodeposited nickel. (Resin-bonded diamond wires also exist but are not discussed in this paper [16].)

As diamond wire has seen a rapid decrease in diameter in recent years, the mechanical characteristics of the steel used in this type of wire have improved, and so wire tension can be kept as high as possible during the cut. The higher the tension, the smaller the bow; the smaller the bow, the better the wafer quality. As an example, a wire tension of 12N is used on 70μm diamond wire, whereas 28N is used on 120μm diamond wire.

As explained in an earlier section, the development of a technique that allows the determination of most of the important characteristics of a diamond wire has been extremely fruitful in understanding the correlation of wire behaviour and its morphology. In order to determine the characteristics, in situ monitoring of the cutting process was necessary.

> "A characterization method that makes it possible to follow the bowing of the wire during the cut has been developed."

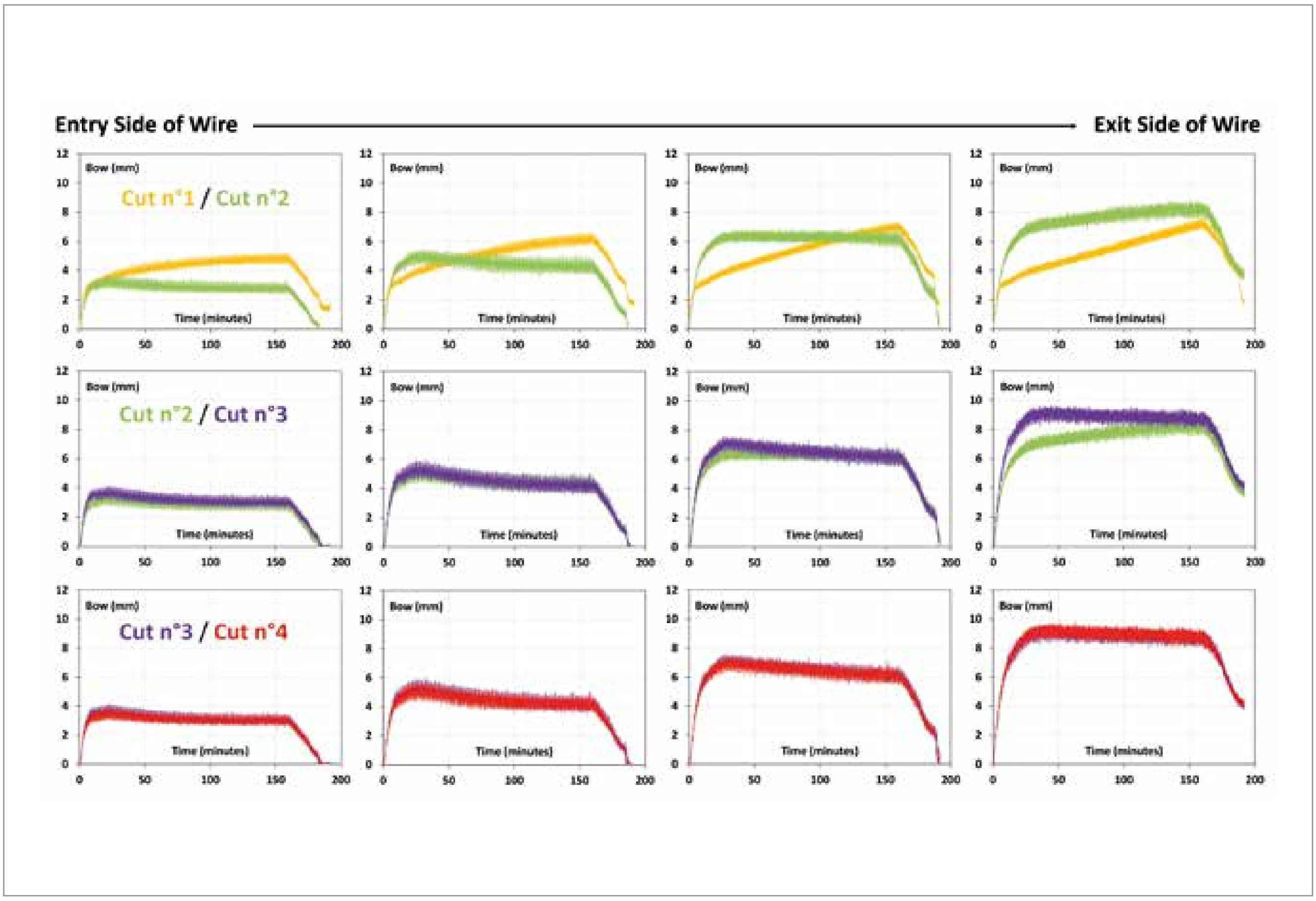


Figure 7. Evolution of the bowing along the wire web during four consecutive cuts.

A characterization method that makes it possible to follow the bowing of the wire during the cut has been developed by the team at CEA-LITEN. As many sensors as required can be distributed along the wire web in order to study the cutting behaviour of different wires and/or different processes. In the example shown in Fig. 7, four sensors monitor the bowing of the wire web from the entry side of the wire (new wire) to the exit side of the wire (used wire). These results were obtained using a state-of-the-art Meyer Burger DW288+S3 wire saw and 500mm-long monocrystalline silicon ingots.

During the experiments, a somewhat relaxed process was used: 1m/wafer using 70µm-diameter diamond wire and a process time of 180min. As usual during a diamond wire process, the wire runs back and forth from one working spool to the other, with a small amount of fresh wire feeding in on the entry side of the web during each back and forth movement.

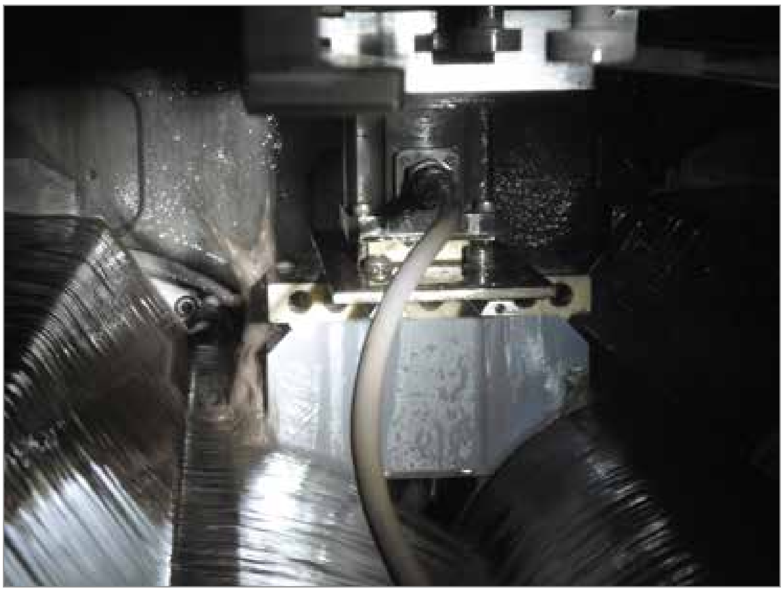


Figure 8. In situ force measurement set-up.

Under these particular conditions, it was observed that, since the process began with a completely fresh web of diamond wire, the wire bowing increased during the entire first cut, as the wire in contact with the silicon began to wear. During the first cut, in which 1m/wafer of wire was used, about two-thirds of the web was being replaced, and therefore two-thirds of the wire web reached a stabilized state of wear as fresh wire was constantly coming in from the entry side. Consequently, it was only under the fourth sensor located at the exit side of the wire web that the wire continued to wear during the second cut, as the other three sensors showed that the bowing had stabilized at different values, depending on the sensor position and on the wire wear. Finally, the behaviours of the third and fourth cuts were identical, as the bowing curves were perfectly aligned when superimposed. This proves that the

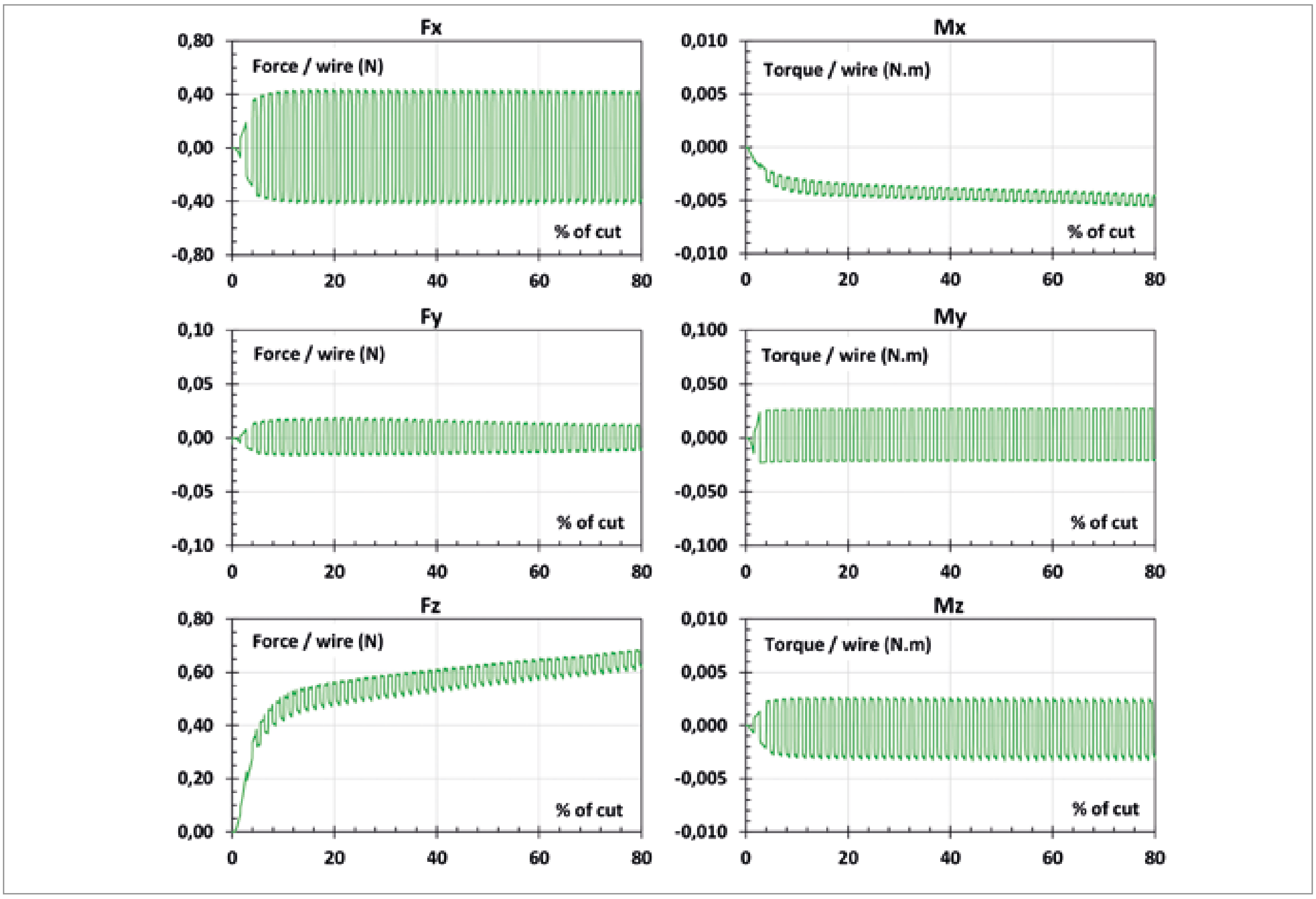


Figure 9. Force and moment components measured along three axes during silicon brick slicing.

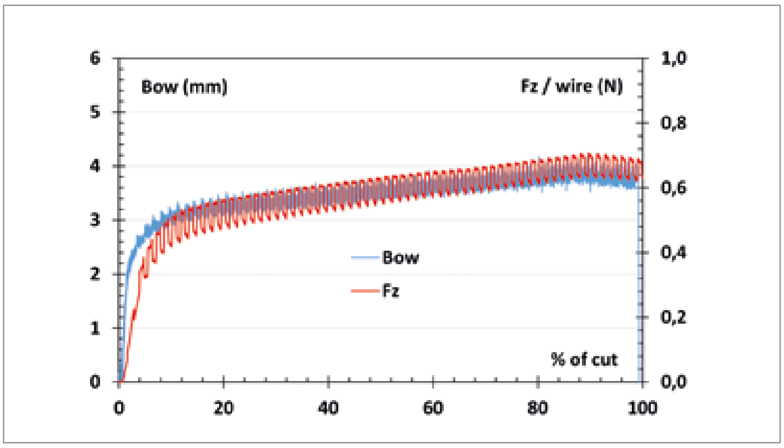


Figure 10. Force and bow measurements during the same cutting experiment.

wire quality is constant, the material is identical and the equipment process is constant as well.

Monitoring the bowing provides precious live information about wire behaviour. Wire defects or wire jumps, which can result in faster wire wear, will induce greater bowing during the cut; this can quickly be identified if monitored properly. For example, adjusting wire consumption during the cut could avoid wire breakage.

Other parameters of the cutting process, such as in situ force measurement (Fig. 8), can be monitored. As an experimental set-up to study the cutting behaviour of wire, half-height (78mm) silicon bricks, 100mm long, attached to a three-axis force sensor were used. A small wire web was created in order to cut 80mm of silicon. The device allows the monitoring of the forces F_x, F_y and F_z as well as the moments M_x, M_y and M_z during a cut. The six measurements taken from the slicing of the silicon bricks are reported in Fig. 9.

Typical oscillations are visible on the plots of the forces and/or torque during the cutting process, since a back-and-forth motion of the wire is used. Along the y axis (i.e. along the brick axis), the force and moment values are very small; as the movement of the wire is 90° to that direction, this is expected. For one wire, the force along the x axis oscillates around ±0.5N (along the wire direction). The vertical force applied by the wire web to the silicon brick increases as the cut progresses and the wire wear increases.

From these data, the friction coefficient and the cutting efficiency of the wire can be determined and correlated with the wire specification determined previously using the optical micrometer. It is interesting to note that if the bow and the vertical force are plotted on the same graph (Fig. 10), the correspondence of the curves is almost perfect. With the aid of such measurements, it can be determined in advance whether or not a diamond wire will cut silicon efficiently.

The experiments make it possible to establish the link between the wire morphology and the cutting behaviour of a new wire; however, they do not yield information about the state of the wire after cutting and the damage to the wire created by the cutting. The same optical micrometer technique mentioned earlier was therefore quickly implemented in order to study the used wires after the cuts (Fig. 11). Typical results obtained using commercial wire, for example, are given in Table 2.

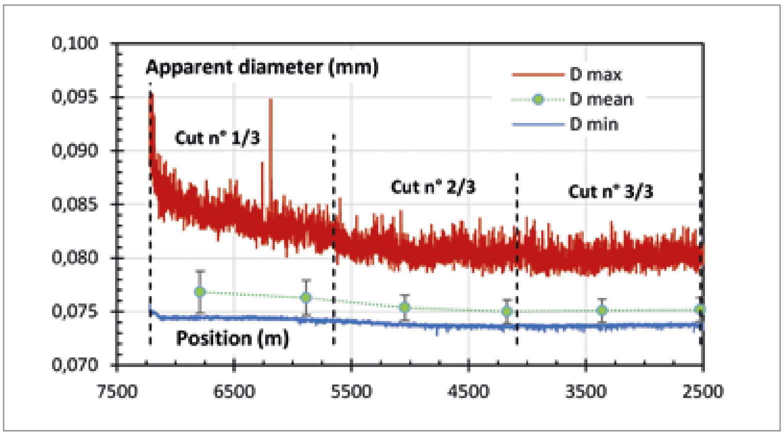


Figure 11. Optical micrometer inspection of used wire.

	New wire	Used wire	Difference [%]
Longitudinal homogeneity [%]	>95	>95	
Radial homogeneity [%]	>95	>95	
Diamond linear density [mm^{-1}]	100	80	–20
Maximum bump height (μm]	8.5	4.9	–42
Binder thickness [μm]	3.0	2.5	–17

Table 2. Typical results obtained after wire inspection before and after cutting using commercial wire.

When the quality of the wire is adequate, the decrease in bump height (diamond + binder) is around 40%; this decrease is due to the abrasion of the binder layer on top of the diamonds as well as to a certain amount of erosion/wear of the diamonds. In addition, approximately 20% of the initial quantity of diamonds present at the surface of the wire are removed during the cutting process.

As explained earlier, the cutting behaviour of monocrystalline silicon is almost solely dependent on the wire and the process being used (coolant is an important part of the process). Although it is fairly easy to empirically develop a wafering process for monocrystalline silicon, it is not the case for other materials being crystallized in DSS furnaces, such as high-performance (HP) multi or mono-like silicon. In those cases, it is extremely important to adapt the cutting process to the silicon morphology. To this end, a software package has been internally developed which allows the determination of the risk associated with the presence and density of precipitates inside the silicon bricks, in order to help predetermine the most appropriate cutting parameters for the wafering operation. Early results are encouraging and demonstrate that mono-like and/or multicrystalline silicon can be successfully cut.

In addition, the implementation of in situ diamond wire characterization during the wafering process is currently under way. One can imagine that in the near future, the cutting parameters of the wafering equipment might be made self-adaptive according to the in situ process monitoring information obtained, in order to guarantee and/or optimize wafer quality, cutting yield and wire consumption, depending on the needs of the wafer manufacturer.

Conclusions and perspectives

CEA-LITEN at INES, as a research laboratory, has developed over the last eight years an abundance of know-how, characterization techniques and data analysis methods that have helped French companies (e.g. B.E.A and Thermocompact) to design state-of-the-art equipment, such as a high-productivity closed-loop cropping machine, infrared characterization equipment and high-quality diamond wire for various applications.

As the PV industry gains maturity, wafers become thinner and cell efficiency increases, it is highly probable that wafer manufacturers will need to know and/or guarantee the detailed characteristics of the wafers they produce. These characteristics may include roughness, subsurface damage and mechanical properties, which are all extremely important in cell and module manufacturing. In order to ensure the best wafer quality, wafer manufacturers will need to carefully monitor their wafering process during the cut in order to optimize the cutting time and the wafer surface and mechanical properties; moreover, this process will need to be adapted to the material and/or the wire. This is extremely important for guaranteeing success in cutting multicrystalline and/or mono-like material efficiently in the near future.

> “In order to ensure the best wafer quality, wafer manufacturers will need to carefully monitor their wafering process during the cut.”

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About the Authors

Fabrice Coustier has been working on silicon squaring, cropping and wafering since 2002. He joined CEA-LITEN in 2010 and currently leads the silicon-shaping activity in the Laboratory for Materials and Processes for Solar Energy. Before joining INES he worked at AMAT Switzerland, Photowatt International and the University of Minnesota.

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Mathieu Debourdeau has been working in the PV field for six years, prior to which he gained 12 years’ experience in various R&D laboratories as an optical and mechanical technician. He was involved in process monitoring of silicon cutting for five years, and now works on metallization and I–V measurement of PV cells.

Nicolas Velet has spent all of his professional career working in PV, for fifteen years as a maintenance technician at Photowatt and on industrial projects. He has been participating in research activities at CEA-LITEN for seven years, making headway in this field full of novelty and change.

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Amal Chabli received her Ph.D. in electrochemistry from the Grenoble Institute of Technology in 1982 and joined CEA in 1983. As the director of research in material characterization, she is mainly involved in physical and chemical characterization of materials for micro- and nanotechnologies, including PV applications. She has authored more than 90 scientific papers.

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