Reducing wire wear by mechanical optimization
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Reducing wire wear by mechanical optimization of equipment in diamond-wire wafering

Joël Peguiron1, Ramon Mueller1, Jürg Zanetti1, Simon Habegger1, Martin Burri1 & Fabrice Monti di Sopra2
1 Meyer Burger Ltd, Gwatt (Thun); 2 Meyer Burger Technology Ltd, Gwatt (Thun), Switzerland

ABSTRACT
Diamond wire is the main cost factor in wafer manufacturing: understanding the mechanisms limiting the wire lifetime is therefore of great economic importance. In this paper, wire characterization methods are described and applied to investigate the wear of diamond wire. The insights obtained lead to the conclusion that two main wear patterns can be distinguished: the first is the necessary cutting wire wear (CWW) originating from the interaction of the wire with the material to be cut, and the second is the undesirable non-cutting wire wear (NCWW), primarily due to interaction of the wire with itself. In an innovative new machine set-up, NCWW has been reduced to a minimum, resulting in an increase in diamond-wire cutting performance.

Introduction
The manufacturing of silicon wafers for PV applications is experiencing a technological change: diamond-wire machining, also known as fixed abrasive sawing (FAS) technology [1,2], is currently replacing slurry machining, or loose abrasive sawing (LAS) technology [3]. This technology change affects not only the process of silicon wafering using a multiple-wire saw, but also all other silicon-cutting processes of the PV value chain, such as ingot cropping and squaring. The main cost factor in FAS technology is the diamond wire itself [2,4]. The maximum length of time in operation of diamond wire, known as wire lifetime, is primarily limited by the wear of the wire. Despite these factors, there are only a limited number of studies to date that look at the wear of the diamond wire during sawing [5,6]. This paper presents an investigation of diamond-wire wear, focusing on its impact on the manufacturing equipment.

The paper is structured as follows. First, a detailed cost-of-ownership calculation showing the contribution of the diamond wire is presented, followed by a review of experimental methods available for analysing diamond-wire wear. The features and origins of diamond-wire wear, focusing on the implications for the manufacturing equipment, are then examined. Finally, some preliminary results demonstrating the high performance of typical diamond wires on optimized equipment are provided.

Wire contribution to the total cost of ownership
Meyer Burger is continuously reducing the wafer manufacturing cost for its customers by developing innovative slicing solutions. In the following showcase (Fig. 1) the structure of the manufacturing costs with diamond-wire technology and the contribution of diamond-wire wear to the wafer manufacturing cost will be explained. The example is based on Meyer Burger’s current offering and state-of-the-art process parameters. The calculation tool has been developed

Figure 1. Cost-of-ownership calculation: (a) total wafer manufacturing costs (crystallization–inspection); (b) production line processing costs (non-silicon); (c) distribution of wafering costs.
by Meyer Burger and is based on a very detailed cost-of-ownership model.

First of all, the material costs are separated from the processing costs (Fig. 1(a)). The material costs are given by the spot market price and the material yield (wafer per kilogram of silicon), whereas the processing costs are driven by operational expenditures (OPEX) and investment for equipment (CAPEX). In this example it is seen that the processing costs contribute roughly two-thirds to the wafer manufacturing cost.

The next step is to split up the processing costs for the different process steps of a complete wafer production line (Fig. 1(b)). To reduce complexity, the cropping, squaring, grinding and gluing processes are grouped in ‘pre-wafering’, whereas de-gluing, cleaning, measuring and packing are summarized in ‘post-wafering’. Looking at this graph it becomes obvious that besides crystallization, which is a very energy-intensive process, the actual slicing of bricks into wafers is one of the largest cost contributors, with one-quarter of the total processing costs.

Furthermore, the cost of the wafering process step can be divided into its main cost drivers, revealing that the wire is responsible for more than half of the costs (Fig. 1(c)). At the end of the cost-of-ownership calculation, all three percentage values are multiplied and the wire cost contribution is obtained. In the example presented here, the wire cost contribution to the total cost of ownership is 9%. According to pvinsights.com [7], the 2013 average price for 8-inch mono-crystalline silicon wafers was US$1.2. Depending on the wafer manufacturers’ margins, a wire cost of 8% to 10% per wafer can be assumed. It now becomes evident how much the diamond wire contributes to wafer manufacturing costs and how the reduction of wire consumption will significantly impact these costs. If the wire consumption of a wire saw were reduced by just 10%, the operational cost of one machine with an annual output of 3.5 million wafers could be decreased by US$35,000.

**Wire performance**

In the wafering process, the wire consumption can be quantified by the wire length used to cut one wafer (m/wafer) or, alternatively, by the area cut per wire length (cm²/m), called wire performance. This second definition has two advantages: it is independent of the wafer area and it is easily transferable to other cutting processes, such as ingot cropping and squaring. In this paper it is thus preferable to speak of wire performance rather than wire consumption.

In order to maximize the wire performance, it is necessary to extend the wire operation time (wire lifetime) by as much as possible. In practice, this means that the same piece of wire needs to be reused many times for cutting. This is achieved with a so-called pilgrim motion of the cutting wire: after a forward motion of typically a few hundred metres, the wire motion direction is reversed; a few hundred metres of backward motion follow, and the direction is reversed again. This pilgrim cycle is continuously repeated. A renewal of the cutting wire is ensured by choosing a forward motion length that is slightly longer than the backward motion length. This amount of additional wire feed per cycle governs how long the wire will be in operation, thereby controlling the wire lifetime or wire performance. This procedure is known as pilgrim motion with continuous new-wire feed.

**Wire analysis methods**

One straightforward wire analysis method is to measure the wire diameter with a micrometre gauge. This method yields information about the outer diameter of the wire, which comprises the core wire, the diamonds and the diamond-bonding coating. It is a non-destructive method, so the wire can be used for further cutting after the measurement. (Results obtained with this method are shown in Figs. 4 and 6.)

For the wafering process, information about the wire diameter can be derived from the wafer thickness. This is because a measure for the total kerf width is obtained by subtracting the wafer thickness from the pitch of the wire web. Additional information about the distance between the outer diameter of the wire and the wafer surface is necessary in order to determine the wire outer diameter from the wafer thickness. On the assumption that this distance remains constant, a change in the wire outer diameter can be inferred from a change in the wafer thickness. (Examples of wafer thickness analyses are shown in Figs. 3 and 5.)

Direct observation of the wire can be made using optical microscopy. In practice, however, the use of a scanning electron microscope (SEM) is necessary in order to achieve a resolution high enough to characterize the state of the wire. An application of this measuring technique to investigate wire wear is presented in the next section (see also Figs. 2, 4 and 6).

**Wire wear features**

To investigate the features of wire wear, an SEM analysis of a typical commercially available wafering wire (wire type...
X) was performed, the results of which are shown in Fig. 2. The new wire, shown in Fig. 2(a), was used in a series of four silicon wafering cuts performed with the continuous new-wire feed procedure described above, with a wire performance of 250cm²/m. At the end of such a series, the wire web contains wire at all wear stages, from new wire (at the wire-in end of the web) to maximally used wire (at the wire-out end of the web), shown in Fig. 2(b). An analysis of the different wear stages of the diamond wire can thus be carried out simply by investigating wire samples from different locations in the used-wire web. Close-up views of the diamonds at the successive operation stages identified [6] are shown in the bottom row of Fig. 2: coated diamond ((c), new wire), active diamond ((d), 60cm²/m), broken diamond ((e), 90cm²/m) and pulled-out diamond ((f), 170cm²/m). The indicated wire performance values were estimated at the location from which the wire sample had been taken.

A reduction in the wire outer diameter is typically observed with increasing wear performance. This reduction can be related to features observed on used-wire images (Figs. 2(b), (d), (e) and (f)), such as deformation and removal of the coating of the diamond-containing protrusions, diamond breakage and diamond pull-out. Other observations with increasing wire performance include an increase in the cutting forces and in the wire bow. These phenomena are all believed to be related to wire wear.

**Origins of wire wear**

The descriptive analysis of wire wear given above leaves a fundamental question unanswered: what mechanisms cause wire wear? There is virtually nothing in the literature regarding this question, despite the importance of wire wear for wafer production costs.

Many of the wire wear features described above – such as deformation and removal of the coating of the diamond-containing protrusions, diamond breakage and diamond pull-out – suggest a mechanical origin of wire wear, or at least a major mechanical contribution to it. This observation leads to the next question: where does mechanical contact with the wire occur? The cutting process itself obviously leads to mechanical contact of the wire with the material to be cut. However, other mechanical contact with the wire occurs during the entire process: contact of the wire with the coating material of the wire guide rolls, pulleys and wire

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Figure 2. SEM analysis of a typical wafering wire (type X): (a) new wire; (b) used wire with a wire performance of 250cm²/m. Successive stages of the diamonds during operation: (c) coated diamond (new wire); (d) active diamond (60cm²/m); (e) broken diamond (90cm²/m); (f) pulled-out diamond (170cm²/m).
spools; contact of the wire with itself on the wire spool during winding and unwinding; and contact of the wire with itself in wire pairings (which sometimes happens when two wires laterally deviate in such a way that their kerfs merge). Thus, these considerations lead essentially to a distinction between wire wear that is directly related to contact between wire and material during cutting, and wire wear that has other sources. It is proposed to refer to the former as cutting wire wear (CWW) and to the latter as non-cutting wire wear (NCWW). To minimize wire costs it is clear that CWW should be kept to a minimum for a given cutting performance, and that NCWW should be avoided as much as possible.

The next task would be to investigate which types of mechanical contact with the wire contribute to NCWW, and then quantify these contributions. This task turns out to be quite difficult, because contributions to CWW and to NCWW can overlap on the same piece of wire. This is best seen in the case of wire pairings which, if they occur, impact wire that is cutting at the same time (see Fig. 5 for an example).

**Wire contacts**

In the remainder of this paper the focus will be on the mechanical contact of the wire with itself that occurs on the wire spool during winding and unwinding. To investigate whether this contact influences the cutting process, one can (for example) perform an analysis of the wafer thickness, yielding indirect information about the outer diameter of the wire used to cut the wafers concerned; wafers cut by wire that, because of the pilgrim motion, moved back to the spool and into the web again are then compared with wafers cut by wire that did not leave the wire web during the cut. The results of such an analysis are shown in Fig. 3.

Monocrystalline silicon wafers of format 125mm (6") were cut using a commercially available diamond wire (wire type Y) with a conventional multiple-wire saw and measured on a Hennecke wafer inspection system. The individual thickness-measurement points were averaged in 25mm-wide strips along the feed direction; the results obtained were then averaged over packages of 40 consecutive wafers. Among the 1022 wafers measured in total, three wafers, with thicknesses greater than 180µm, were excluded from the analysis.

The mean values obtained for the second, third and fourth 25mm strips are represented by downward-pointing triangles, squares and upward-pointing triangles respectively (see the diagram on the left of Fig. 3). The wafer range cut by the wire that moved back to the spool and into the web is represented by hollow symbols, whereas the range cut by

![Figure 3. Wafer thickness analysis for a cut with a commercially available diamond wire (type Y) using a conventional multiple-wire saw. The thickness measurements were averaged over 25mm-wide strips along the feed direction (illustrated at bottom left) and over 40 wafers. Hollow symbols show the range cut by wire that moved back to the spool and into the web again, whereas solid symbols show the range cut by wire that did not leave the web.](image-url)
the wire that did not leave the wire web is represented by solid symbols. The wire that was unwound from the new-wire spool and wound again because of the pilgrim motion and the continuous new-wire feed reached almost the middle of the ingot (hollow symbols on the left side of the graph in Fig. 3). On the used-wire side of the ingot, a free wire web remained that was longer than the pilgrim motion length, so that the wire which reached the used-wire spool did not move back to the cutting part of the wire web. Consequently, all wafers of the used-wire half of the ingot were cut by wire which did not leave the wire web (solid symbols on the right side of the graph in Fig. 3).

Comparing the different curves in Fig. 3, it can be seen that the mean wafer thickness increases during the cut (from downward-pointing triangles to upward-pointing triangles). This indicates a reduction in the wire outer diameter as a result of wire wear. A comparison of hollow symbols and solid symbols reveals that the increase in wafer thickness is greater in the range cut by the wire that moved back to the spool and into the web again, indicating additional wire wear. The mechanism responsible for this additional wire wear is easily identified: during winding and unwinding on the wire spool, the wire comes into contact with itself and the diamonds damage neighbouring segments of wire. SEM images of the sections of wire that were repeatedly wound and unwound on the spool show typical scratches perpendicular to the wire; these are visible in Fig. 2(b), adding further support to the neighbouring damage hypothesis.

A quantitative statement about the amount of additional increase in wafer thickness in the range cut by wire that was repeatedly wound and unwound on the spool, or about the amount of additional reduction in the outer diameter of such wire, is not possible at this stage. One reason for this is that the NCWW in question overlaps with other wire wear contributions in the cutting wire web. In the authors’ experience the result shown in Fig. 3 is a rather extreme example and should therefore not be presumed to be a quantitative reference for the magnitude of the represented NCWW contribution. It has also been observed that the strength of this effect can depend on the wire type.

A reduction in the wire outer diameter has also been measured during air cuts, which are wafering cuts executed without a material load in the wire saw. By means of a series of experiments, it has been found that the amount of reduction in wire diameter measured can be decreased by a careful adjustment of the wire management system. In summary, it can be reported that an outer diameter reduction of at least 0.4µm per 100 winding and unwinding cycles on the spool is typically observed.

### Wire wear reduction during the wafering process

The wire wear mechanism during winding and unwinding on the spool, which was described above, suggests that cost savings can potentially be achieved by optimizing the wafering equipment. Indeed, the wire management system...
of conventional wafering equipment was developed for loose abrasive sawing (or slurry) technology. In that technology, contact of the wire with itself is harmless, because the wire does not carry any cutting particles (i.e. diamonds), which can damage other sections of wire coming into contact, thereby reducing cutting performance. By contrast, in fixed abrasive sawing technology the results presented above show that the contact of the diamond wire with itself can result in additional wire wear. Furthermore, multiple reuse of the same wire, which means multiple winding and unwinding cycles, is necessary for cost-saving reasons. The technology change from loose to fixed abrasive sawing therefore requires an optimization of the wire management system.

Meyer Burger has implemented these findings and developed a multiple-wire saw prototype with a wire management system allowing multiple reuse of the wire while minimizing wire contact during winding and unwinding. Preliminary results obtained using this optimized wire saw are shown in Figs. 4 and 5.

An air cut was performed with a typical commercially available diamond wire (wire type X – the same type as in Fig. 1). The outer diameter of the used wire after 500 winding and unwinding cycles was compared with the initial diameter. No reduction in the wire outer diameter was observed within the measurement precision of ±0.3µm (Fig. 4(a), left). This represents a considerable improvement with respect to the reduction of at least 2µm typically observed in the same conditions using conventional equipment. A silicon wafering cut series with a wire performance of 420cm²/m was performed using wire of the same type. Likewise, a series of six consecutive cuts with a wire performance of 500cm²/m was performed with another commercially available wire (wire type Y – the same type as in Fig. 3). In both X and Y cases, the used wires were free of perpendicular scratches typical of mechanical damage due to winding and unwinding, and still featured active diamonds, as can be seen in the SEM images (Fig. 4(b), X at the top and Y at the bottom). A comparison of the outer diameter measurements of these wires revealed different amounts of reduction as a function of wire performance for both wire types (Fig. 4(a)).

The results of a thickness analysis of the wafers (125mm format) in the second cut series, sawn using wire type Y and a wire performance of 500cm²/m, are shown in Fig. 5. As in the previous analysis (see Fig. 3), the thickness measurements obtained by the Hennecke wafer inspection system were averaged in 25mm-wide strips along the feed direction.

Figure 5. Wafer thickness analysis for a cut series with a commercially available diamond wire (type Y) using a multiple-wire saw prototype that minimizes wire contact. The thickness measurements were averaged over 25mm-wide strips along the feed direction (see key on the left) and over 40 wafers. The hollow symbols show the range cut by the wire that moved back to the spool and into the web again, whereas the solid symbols show the range cut by the wire that did not leave the web. The red cross indicates the approximate location of a wire pairing which occurred at the beginning of the fifth cut; the red arrow shows the range attained by the wire affected by the pairing. The green bar on the right of the graph represents the measured reduction in outer diameter of the wire used in the cut series (see Fig. 4, wire type Y).
and the results were then averaged over packages of 40 consecutive wafers, excluding single wafers with thicknesses above 180µm.

The mean values obtained for the second, third and fourth 25mm strips of the first cut are represented by downward-pointing triangles, squares and upward-pointing triangles respectively in Fig. 5 (as in Fig. 3). The mean values obtained for the third (central) strips of the five subsequent cuts are represented by different symbols and colours (see the key at the left of Fig. 5). As before, the wafer range cut by the wire that moved back to the spool and into the web again because of the pilgrim motion is represented by hollow symbols, whereas the range cut by the wire that did not leave the wire web is represented by solid symbols. A free wire web that was longer than the pilgrim motion length remained on the used-wire side of the ingot, so that the wire which reached the used-wire spool did not move back to the cutting part of the wire web.

In this case a fairly regular increase in wafer thickness is observed over the cut series, and no additional increase is observed in the range cut by wire that moved back to the spool and into the web again (hollow symbols), compared with the range cut by wire that did not leave the wire web (solid symbols). A somewhat stronger increase is observed in the used-wire half of the ingots during the fifth and sixth cuts. A wire pairing occurred at the beginning of the fifth cut: the approximate location of this pairing is represented by a red cross in Fig. 5, and the range attained by the wire affected by the pairing is indicated by a horizontal red arrow. The observed additional wafer thickness increase corresponds well with this range and can thus be attributed to the wire pairing. Because of the otherwise moderate increase in wafer thickness, the series of six cuts could be completed despite the occurrence of the wire pairing.

The outer diameter reduction measured for the wire used in the cut series, shown in Fig. 4 (wire type Y), is indicated by a green bar on the right of Fig. 5. This reduction is in good agreement with the observed wafer thickness increase outside the range of the wire pairing, indicating a good correspondence between these two wire characterization methods.

The results presented above demonstrate that high wire performance can be achieved using wafering equipment that minimizes wire contact during winding and unwinding. The amount of increase which can be gained, and the corresponding cost savings, with respect to conventional equipment depend on the wire type, as suggested by the results shown in Fig. 4. It is now the diamond-wire manufacturers’ task to develop products with maximized cutting performance instead of having to compromise because of machine-related NCWW.

### Wire wear reduction in the squaring and cropping processes

The above considerations are not specific to the wafering process and are therefore also applicable to other diamond-wire cutting processes, such as ingot squaring and cropping. Meyer Burger has developed a squaring equipment prototype that minimizes wire contact during winding and

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Figure 6. The high performance of a typical bricking wire (type Z) achieved using an ingot squaring prototype that minimizes wire contact during winding and unwinding: (a) wire outer diameter (mean and standard error out of 14 measurements) measured at various stages; (b) SEM images of the used wire after the air cut (top) and after the squaring cut series (bottom).
unwinding. The results obtained with this machine using a typical commercially available bricking wire (wire type Z) are shown in Fig. 6. Wire samples that had performed 20,000 winding and unwinding cycles in an air cut demonstrated an outer diameter reduction of only 3±3µm (Fig. 6, left) and revealed almost no mechanical deformation upon examination by SEM (Fig. 6, top right). Other wire samples with a performance of 350cm²/m that had been used in a series of ingot squaring cuts showed an outer diameter reduction of about 20µm (Fig. 6, left) and did not show any perpendicular scratches typical of mechanical damage during winding and unwinding (Fig. 6, bottom right). These results indicate a potential increase in wire performance by at least 400% with respect to conventional squaring equipment.

Conclusion

Wafer manufacturing technology is undergoing a change from loose to fixed abrasive sawing, in which diamond wire is the main consumable contributor to the wafer cost. As a consequence, the wire is reused as many times as possible in the pilgrim sawing mode, which means additional winding and unwinding cycles, as well as involving interactions between the machine and the diamond wire that have to be mastered. In this paper the contribution of wire contact during winding and unwinding to the wear of the diamond wire has been demonstrated. With careful adjustment of today's wire management systems, this NCWW contribution can be reduced to some extent. To achieve further reductions, innovative wire management systems are necessary. Meyer Burger has developed wafering and squaring equipment prototypes that minimize wire contact during winding and unwinding. The diamond-wire performance results obtained using these prototypes have led to the launch of new products for cropping, squaring and wafering, all of which use a new wire management system.

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References