Effect of diamond wire saw marks on solar cell performance

Hubert Seigneur\textsuperscript{a,b,c}\textsuperscript{*}, Eric J. Schneller\textsuperscript{a,b}, Narendra S. Shiradkar\textsuperscript{a,d}, and Winston V. Schoenfeld\textsuperscript{a,b,c}

\textsuperscript{a}Florida Solar Energy Center, University of Central Florida, Cocoa, FL 32922, USA
\textsuperscript{b}c-Si Division, U.S. Photovoltaic Manufacturing Consortium, Orlando, FL 32826, USA
\textsuperscript{c}CREOL, the College of Optics and Photonics, University of Central Florida, Orlando, FL 32826, USA
\textsuperscript{d}Jabil Inc., St. Petersburg, FL 33702, USA

Abstract

Diamond wires from several manufacturers were investigated in term of their impact on wafer quality and cell performance. It was identified that under identical ingot sawing conditions the diamond wire make had an impact on the resulting cell performance. Several cells exhibited defects that remained with the cell even after the saw damage etching process. These defects were investigated in terms of their impact on various solar cell performance parameters. This analysis was performed using photoluminescence imaging and spatially resolved quantum efficiency and reflectance measurements. The diamond wire marks were observed to have the largest impact on the local short-circuit current density across the cell.

1. Introduction

The photovoltaic industry utilizes multi wire slurry saw to slice silicon ingots into wafers of appropriate thickness for cell manufacturing [1]. This process, although effective, exhibits several drawbacks including large waste and relatively slow processing speeds. To overcome these shortcomings, diamond wire sawing processes have been developed in recent years [2-4]. Alternatively, the downsides of diamond wire sawing are the high cost of the wire...
itself and the extensive damage created at the surface of the wafers. The damage has been shown to vary greatly
from wire to wire [3, 5] and from one sawing process to another [3, 6]. The generated damage consists of
amorphization of the silicon, pits, and periodic structures, the so-called pilgrim waves. It was recently suggested that
these pilgrim waves would have an impact on cell production [6]. The impact is especially observed during
texturing, where the standard industrial texturing process for slurry-based sawing does not work as well for diamond
wire sawing [7].

Furthermore, the random nature of the pilgrim waves in addition to the direct correlation between the diamond
particle size and surface damage depth [3] lead us to believe that for a given sawing and cell fabrication process, the
choice of the diamond wire can affect the solar cell performance. Such result is consequential as much as solar cell
manufacturers, while using established unvarying processes, typically have multiple wafer suppliers. Because each
supplier evidently employs a different diamond wire and sawing process, cell manufacturers may need to look into
adequate specifications for incoming wafer surface properties with respect to the dominant pilgrim wave type in
addition to the usual lifetime, average thickness, and total thickness variation. Accordingly, in this work, we seek to
show evidence of the impact of the diamond wire make and saw marks on solar cell performance. We do so by
varying only the wire make while using matching sawing and cell manufacturing processes.

2. Experiment

Wafers were cut from two Czochralski (CZ) ingots using diamond wire from three different manufacturers under
identical conditions. We used the Takatori WSD-K2 diamond wire saw to perform the cuts at 600 m/min wire speed,
0.6 mm/min table speed, and a 1m/min fresh wire feed rate, and Aquaslice coolant (5%). Each wire had identical
core diameter (120 μm) and diamond size distribution (10-20μm). We used 0.35 mm pitch work rollers, resulting in
approximately 200 μm thick wafers. We were able to saw as many as 28 wafers at a time using the WSD-K2 R&D
saw. Cutting a limited number of wafers helped keeping the resistivity, oxygen concentration, and lifetime constant
across the sample set. We also processed all the wafers as part of the same batch. Therefore, we can reasonably
attribute changes in cells performance to changes in the diamond wire make. In reality though, diamond wire sawing
is a dynamic and convoluted process with complex interactions between sawing parameters, wire properties, and
coolant properties. In this work, we assume those interactions are the same for all diamond wires.

A cleaning step was performed using a KOH based cleaner from Process Research Products called Ultraclean
PFS (2%) in an ultrasonic bath (50Hz) for 4 minutes at 60°C, followed with a DI water rinse. It has been shown that
there exist significant interactions between wafer cleaner types from wafer producers and cell manufacturers
texturing processes [8]. All wafers were subjected to the same cleaner/texturing process. After that, the wafers were
sent to a fabrication facility, and solar cells were fabricated using a standard aluminum back surface field process
fabrication process. We started with SDE/texturing, then the emitter diffusion/oxidation, followed by PECVD SiN,
edge isolation, and metallization. Shunting issues at the cell edges due to a slight mismatch between these lab-
produced wafers and the standard size printing screen at hand required that the cells were cut with a laser to an area
of 13.5 x 13.5 cm² (some of the wafers were cut out of an ingot a bit larger than 200mm). All the cut solar cells I-V
characteristics were measured. Spatially resolved photoluminescence and quantum efficiency analyses were
performed to identify which performance parameters are most affected by the diamond wire induced defects.

3. Effect of wire type on cell performance

Wires from three manufacturers were used each having the same diameter (120 μm) and diamond size
distribution (10-20μm). The wire sawing process along with the cell fabrication (including the saw damage removal
step) was identical for each wafers produced from the three wire types. The effect of using different diamond wires
on the performance of solar cells was investigated. The statistical analysis shows that wire three clearly outperforms
the others resulting in up to 0.15% higher mean efficiency. The improvement in the efficiency is driven by current,
voltage and shunt resistance gains.
Fig. 1. One-way ANOVA plots of solar cell parameters as a function of diamond wires.

Table 1. Summary of solar cell parameters as a function of diamond wire

<table>
<thead>
<tr>
<th>Solar cell parameter</th>
<th>$I_{sc}$ ($A$)</th>
<th>$V_{oc}$ ($V$)</th>
<th>$r_{sc}$ - att (Ohm)</th>
<th>$r_{sh}$ - Dark (Ohm)</th>
<th>$FF$ (%)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wire 1 (Mean)</td>
<td>6.861</td>
<td>0.640</td>
<td>3.8e^{-3}</td>
<td>1.31e+2</td>
<td>78.12</td>
<td>18.84</td>
</tr>
<tr>
<td>Wire 1 (Std Error)</td>
<td>0.010</td>
<td>0.004</td>
<td>0.18e^{-3}</td>
<td>0.13e+2</td>
<td>0.14</td>
<td>0.05</td>
</tr>
<tr>
<td>Wire 2 (Mean)</td>
<td>6.871</td>
<td>0.639</td>
<td>4.0e^{-3}</td>
<td>0.91e+2</td>
<td>77.81</td>
<td>18.77</td>
</tr>
<tr>
<td>Wire 2 (Std Error)</td>
<td>0.013</td>
<td>0.005</td>
<td>0.21e^{-3}</td>
<td>0.16e+2</td>
<td>0.16</td>
<td>0.06</td>
</tr>
<tr>
<td>Wire 3 (Mean)</td>
<td>6.877</td>
<td>0.641</td>
<td>3.8e^{-3}</td>
<td>1.6e+2</td>
<td>78.21</td>
<td>18.92</td>
</tr>
<tr>
<td>Wire 3 (Std Error)</td>
<td>0.012</td>
<td>0.005</td>
<td>0.22e^{-3}</td>
<td>0.17e+2</td>
<td>0.18</td>
<td>0.06</td>
</tr>
</tbody>
</table>

The results show that under identical silicon material properties, sawing, cleaning and solar cell fabrication conditions, the make of the wire has an impact on the overall cell performance. These results strongly suggest that the construction of the wire (i.e. type/concentration of diamond, plating metal types/thicknesses, or the wire manufacturing process itself) may have an impact on the uniformity and extent of saw damage; that is in addition to the already proven fact that larger diamond particles create deeper damage [3] (Please note that the diamond wire...
particle size distribution was the same for all wires, about 10-20 μm). Further experimentation with wire properties will enable us to clearly identify which wire property other than the diamond size is impacting solar cell performance. Additionally, for this experiment, we did not check the type of pilgrim waves present on each wafer. We suspect that the wire resulting in improved performance may have generated more “type 2” pilgrim waves than the others under the sawing conditions used, resulting in minimum saw damage. When saw damage is lowest, the standard process used in this work for SDE/texture evidently removes all damage and performance improves. The opposite is also true. If the other wires produce greater damage, the standard process for SDE/texture may not be able to remove all damage causing decreased performance. Table 1 summarizes mean values and the standard error for all solar cell parameters for each of the diamond wires. Fig. 1 shows the results of the statistical analysis that was performed.

4. Effect of pilgrim wave defect on cell performance

Several studies have suggested that the damage induced during the diamond wire sawing process may impact the cell performance [3,4]. Additional studies have shown that an appropriate etching process, referred to as the saw damage removal, can effectively eliminate the micro-scale (μm scale) damage due to the diamond wire saw process [8]. Other studies have indicated, in agreement with the results in this work, that a relatively larger (mm scale) periodic structure may remain even after the saw damage etch [6]. These features are a result of the forward to reverse variation in the wire pulling direction as it slices through the ingot. These features have been referred to as pilgrim waves resulting from the various pilgrim modes of the diamond wire during sawing [6]. Although the microscale damage can be eliminated during the saw damage etching process, these larger periodic features on the surface of the wafer can remain throughout the cell fabrication process. In this work select cells were identified for advanced spatially resolved analysis to understand what impact these pilgrim waves have on the various performance parameters.

To understand how these diamond wire defects impact the short-circuit current, quantum efficiency measurements were utilized. These measurements were performed using a Tau Science FlashQE measurement system. With each individual measurement taking approximately 1 second, it is possible to obtain spatially resolved quantum efficiency and reflectance measurements over the entire area of full 135 mm X 135 mm cells in less than 1 hour. The resolution is approximately 100 by 100 pixels with a circular illumination diameter of 4 mm for each measurement. An average QE spectra is obtained by taking the spatially resolved average, excluding edge regions and busbars. An example of the EQE for several cells is shown in Fig. 2. It should be noted that this EQE data has not been normalized or corrected for shading losses.

![External Quantum Efficiency](image)

Fig. 2. Spatially resolved average of the external quantum efficiency for several cells with and without saw marks.
To quantify the results, it is instructive to convert the spectrally dependent external quantum efficiency into a short-circuit current ($J_{sc}$) using the following equation:

$$ J_{sc} = \int SR(\lambda) \cdot I_{AM1.5}(\lambda) d\lambda $$

where $SR(\lambda)$ represents the spectral responsivity of the cell in A/W and $I_{AM1.5}(\lambda)$ represents the incident spectra of the air mass 1.5 solar spectrum in W/m². This formula can also be applied to the reflectance spectra to obtain an effective loss in $J_{sc}$ due to reflectance. The reflectance spectra were separated into two components using a linear extrapolation of the reflectance data beyond 850 nm. Any reflectance above this linear extrapolation in the long wavelength range of the spectrum is attributed to rear surface reflectance [9]. The remaining reflectance data is associated with front surface effects.

Photoluminescence (PL) images were taken using a BT Imaging PL system with an 808 nm laser as the illumination source. The results were processed following the techniques described by Glatthaar et al. [10]. Maps of open-circuit voltage, dark saturation current density and series resistance were calculated. All parameter maps were analyzed to identify which parameters are most affected by the diamond wire defects.

Fig. 3 displays the quantum efficiency and reflectance results for a cell with saw marks. These defects led to approximately 0.5 mA/cm² variation in $J_{sc}$ in a regular pattern across the cell. The affected area was estimated to be approximately 40% of the cell resulting in an absolute loss in $J_{sc}$ of approximately 0.2 mA/cm². After inspection of the reflectance data it was observed that this loss was largely due to reflectance off of the front surface. This suggests that the pilgrim wave features on the surface of the wafer influence the uniformity of the surface texturing leading to enhanced reflection. In addition to the reflectance loss, there may also be some increased parasitic absorption within the anti-reflection coating or within the emitter. The magnitude of the parasitic absorption is much smaller than the effect of the reflectance.

The electrical properties of the same cell were investigated using PL imaging as shown in Fig. 4. There is little to no impact of the striations on the electrical performance of the cell in terms of $J_{sc}$, $V_{oc}$ and $R_s$. The calibration
constant used in the PL calculations is also shown to compare the belt marks that are observed in the back surface reflectance map. These results suggest that only the optical properties of the front surface are affected impacting only the short-circuit current of the device. These defects do not appear to be recombination active or associated with resistive effects.

5. Conclusion

The impact of diamond wire type on the cell performance was investigated. It was found that under identical sawing conditions and cell fabrication processes, the wire manufacturer impacted the final cell performance by up to 0.15 % in absolute mean efficiency. Although the wire diameter and diamond size distribution were similar for all wires, the wire construct (concentration and type of diamond particles, the plated metal, the plating process, etc) impacts the saw damage and ultimately the cell performance.

Spatially resolved analysis was performed using quantum efficiency measurements along with PL imaging to quantify the impact that diamond wire saw marks have on the performance parameters of the solar cell. The defects observed in this study remained even after the saw damage removal step. These defects exhibited periodic behavior, indicating that they are a result of cyclic variation in the wire pulling direction during the sawing process. These defects, referred to as pilgrim waves, had a measurable impact on the local short circuit current across the device. This was largely due to the local variations in the reflectance of the front surface. The defects observed in this study had little impact on carrier recombination or series resistance.

Acknowledgements

This material is based upon work supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, in the Solar Energy Technologies Program, under Award Number DE-EE0004947.

References

[5] Brooker R, Seigneur H, and Schoenfeld V. Correlating Wafer Surface to DW Saw Profile and Wire Wear. (Submitted and Accepted for 2016 IEEE PVSC conference in Portland OR.)