Study of Wire Electrical Discharge Machining for Poly-silicon

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1. Introduction

As much as 90% of solar cells are manufactured through the semiconductor process of silicon wafer. Therefore, silicon has become a major material for solar cells. Additionally, solar cell manufacturers have expanded factories, causing insufficient capacity for refining silicon ingot and raw materials, and skyrocketing prices. Worse, the insufficient capability has hindered solar cell market growth. Therefore, enhancing silicon ingot efficiency and maximizing silicon wafer capacity have become critical issues.

The silicon wafer is typically manufactured through the Multi-Wire Saw. Silicon ingot is wafered into 200~240μm with kerf loss around 150~210μm. The loss reaches 42%~46% of the original silicon ingot. To acquire more silicon wafer, two possible strategies are available lowering silicon wafer thickness and minimizing kerf loss. However, the best wafer thickness, limited by chips arising from the back-end process, can only be kept at 200 μm. Currently, monocrystalline silicon ingot or polycrystalline ingot used in solar cells, suffers from huge silicon loss during cutting or wafering. Therefore, minimizing silicon loss during solar wafer machining has become a critical issue for lowering the production cost of and machining groove width, surface roughness and how to reduce kerf loss in the silicon wafer slicing process has become an important issue. Experimental results showed that pulse-on time and open circuit voltage had significant effects on cutting speed, machining groove width, and surface roughness; since pulse-on time and open circuit voltage will each increase peak current, thus producing greater discharge energy. Other factors, such as wire speed and flushing rate, did not have large effects on processing. Nevertheless, appropriate setting adjustments did lead to some improvements in cutting speed, machining groove width. Increasing wire tension led to improvements in machining groove width. Experiments demonstrated that the WEDM process can indeed be applied to the slicing of poly-silicon materials. In the near future, the application of WEDM manufacturing technologies to solar energy-related industries might create a significant competitive advantage.

In this study, the wire electrical discharge machining (WEDM) process was used to machining poly-silicon semiconductor materials (2-3Ω·cm) used in solar cell. A series of experimental parameters was selected to examine the influence of various machining parameters on cutting speed, machining groove width, surface roughness and how to reduce kerf loss in the silicon wafer slicing process. Experimental results showed that pulse-on time and open circuit voltage had significant effects on cutting speed, machining groove width, and surface roughness. Increasing wire tension led to improvements in machining groove width. Experiments demonstrated that the WEDM process can indeed be applied to the slicing of poly-silicon materials. In the near future, the application of WEDM manufacturing technologies to solar energy-related industries might create a significant competitive advantage.

2. Experimentation

Poly-silicon is a new material cut by WEDM and its material is formed by casting monocrystalline materials of various resistivities, as sketched in Fig. 1. In this experiment, difficulties bar employing WEDM to machine poly-silicon because the poly-silicon contains high resistance, ranging from 2-3 Ω·cm. The P-type poly-silicon workpiece was affixed between two conductive plates and connected to the positive electrode of the power supply [6] and the negative electrode to the conductive block of the wire electrode, as shown in Fig 2. The wire electrode is brass with a diameter of 0.2 mm and Table 1 shows the machining conditions.

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test indicate that the wire electrode did not break and was not in contact with the poly-silicon workpiece during the machining processes. Next, the current study then measured the machined groove width of the poly-silicon workpiece formed by WEDM using an optical microscope (OM) and a scanning electron microscope (SEM) to observe morphologies of the wire sawing related defects on the workpiece surfaces. Third, the experiment measured surface roughness of the poly-silicon by a precise profilometry. The centre-line average shows the method of representing surface roughness to evaluate how WEDM parameters affect the surface finish.

3. Results and discussion

3.1. Effects of parameters on cutting speed

3.1.1. Effects of pulse-on time and open voltage

Figure 3 indicates that the cutting speed goes higher as pulse-on time, because, as pulse-on time increases, stronger power is available between the anode and the cathode, thus strengthening discharge energy. In Figure 3, every cutting speed derived on each pulse-on time is the optimum value. Figure 4 shows that the cutting speed raises as open circuit voltage. Because the increase in open circuit voltage strengthens discharge energy and further increases evaporative and smelting volume generated by materials, the increase in MRR heightens the cutting speed. This is because the higher the open-circuit voltage, the stronger the electric field intensity and the easier it is to break electric field intensity between the electrode and the workpiece for discharge.

3.1.2. Effects of wire speed and flushing rate

In addition to acting as the electrode for discharge, brass wire can also carry the chip off the machining area. A suitable wire speed stabilizes discharge, void the chip smoothly and further enhance stability during the machining process. Figure 5 indicates that by raising the wire speed to 11.0 m/min, the best cutting speed gradually heightens. In the experiment of cutting poly-silicon material with WEDM, although increasing the wire speed elevates the cutting speed, a higher wire speed raises the machining cost.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open circuit voltage (V)</td>
<td>150 ~ 250</td>
</tr>
<tr>
<td>Pulse-on time (μs)</td>
<td>2 ~ 12</td>
</tr>
<tr>
<td>Pulse-off time (μs)</td>
<td>30</td>
</tr>
<tr>
<td>Wire speed (m/min)</td>
<td>8.31 ~ 20.94</td>
</tr>
<tr>
<td>Wire tension (N)</td>
<td>3 ~ 9</td>
</tr>
<tr>
<td>Flushing rate (l/min)</td>
<td>0.5 ~ 4.5</td>
</tr>
<tr>
<td>Dielectric fluid</td>
<td>De-ionized water</td>
</tr>
<tr>
<td>Water temperature (°C)</td>
<td>22°</td>
</tr>
</tbody>
</table>
Figure 6 indicates that the flushing rate has a certain effect on the machining rate. The cutting speed curve relatively rises with the increased flushing rate. When the flushing rate is under 2.5 L/min, the cutting speed drops slightly. Because a smaller flushing rate cannot fully effectively cool down the wire electrode and wash off chips, MRR is thus relatively lower and the machining rate cannot be effectively raised.

3.2. Effect of parameters on machining groove width

3.2.1. Effects of pulse-on time and open circuit voltage

In Figure 8, while pulse-on time increases, machining groove width increases with increased pulse-on time due to higher discharge energy. Figure 9 shows the SEM of the machining groove after WEDM and indicates that the crack on the groove surface caused by the machining groove at 12μs of pulse-on time is more obvious than it is at 2μs.

Figure 10 shows the influence of open circuit voltage on machining groove width. In this Figure, machining groove width increases apparently with the elevation of open circuit voltage, a logical result. The increase in open circuit voltage raises the electric field intensity and power cut occurs easily between the electrode and the workpiece. Breaking through the insulation for discharge is easy while the interval is large.
3.2.2. Effects of wire speed and flushing rate

Figure 11 and 12 show that, in this experiment, the increase in wire speed and the flushing rate helps narrow machining groove width. The chips generated during WEDM cannot be eliminated effectively so chips sticks on the workpiece surface. Secondary discharge occurs frequently during machining. Therefore, a proper wire speed and a flushing rate are critical factors during the machining process because the minimize chip effect on the machining groove width.

Fig. 11. Wire speed versus machining groove width

Fig. 12. Flushing rate versus machining groove width

3.2.3. Effect of wire tension

Higher tension value typically reduces vibration on the wire electrode caused by pressure from discharge and further minimizes the machining groove width. As in Figure 13, while wire tension heightens, the machining groove width becomes much smaller. After the tension exceeds 7N, the difference is ignorable because the wire tension reaches its critical value for machining poly-silicon in 15mm high. Brass wire will not be affected by flushing arising from any line width problem, resulting in vibration on wire electrode. Also, a larger tension value heightens possible wire breakage during the machining process. Figure 14 shows the SEM for the machining groove width.

Fig. 13 Wire tension versus machining groove width

(a) Wire tension = 3N        (b) Wire tension = 7N

Fig. 14 SEM micrographs of machining groove width for different wire tensions

3.3. Roughness of cutting surface

3.3.1. Effect of pulse-on time

As Figure 15 shows, during wire electrical discharge machining on poly-silicon, increased pulse-on time raises surface roughness. This is because discharge energy increases with pulse-on time. Meanwhile, craters on the machining surface also become larger and further worsen roughness. Figure 16 shows the SEM micrographs of the machining surface.

Fig. 15 Pulse-on time versus surface roughness
3.3.2 Effect of open circuit voltage

As Figure 17 shows, raising open circuit voltage heightens surface roughness of the poly-silicon because, when raising open circuit voltage, peak current also increases concurrently while peak current elevation is the major cause for escalating surface roughness.

5. Conclusions

This study discusses the influences of WEDM parameters on machining poly-silicon. The conclusions are as follows:

1. Increasing pulse-on time and open circuit voltage influence cutting speed the most. Increasing both also increases energy supply. Material remove rate rises accordingly. However, the increase in both heightens the peak current, further increasing machining groove width and worsening surface roughness.

2. Raising wire speed and flushing rate improves cutting speed, machining groove width and surface roughness. However, as the flushing rate reaches a certain level, its improving effect on the machining rate becomes unapparent.

3. Strengthening the tension significantly improves the machining groove width because wire electrode vibration decreases.

4. WEDM obtains a particular geometry shape of poly-silicon material.

REFERENCES


