Laser drilling up to15,000 holes/sec in silicon wafer for PV solar cells

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ABSTRACT

One approach to realize a back contact solar cell design is to 'wrap' the front contacts to the backside of the cell [1]. This results in significantly reduced shadowing losses, possibility of simplified module assembly process and reduced resistance losses in the module; a combination of measures, which are ultimately expected to lower the cost per watt of PV modules. A large number of micro-vias must be drilled in a silicon wafer to connect the front and rear contacts. Laser drilling was investigated using a pulsed disk laser which provided independent adjustment of pulse width, repetition rate and laser power. To achieve very high drilling rates, synchronization of the laser pulses with the two-axis galvanometer scanner was established using a FPGA controller.

A design of experiments (DOE) was developed and executed to understand the key process drivers that impact the average hole size, hole taper angle, drilling rate and hole quality. Laser drilling tests were performed on wafers with different thicknesses between 120 µm and 190 µm. The primary process parameters included the average laser power, pulse length and pulse repetition rate. The impact of different laser spot sizes (34 µm and 80 µm) on the drilling results was compared. The results show that average hole sizes between 30 – 100 µm can be varied by changing processing parameters such as laser power, pulse length, repetition rate and spot size. In addition, this study shows the effect of such parameters on the hole taper angle, hole quality and drilling rate. Using optimized settings, 15,000 holes per second are achieved for a 120 µm thick wafer with an average hole diameter of 40µm.

Keywords: Laser drilling, MWT back contact solar cells

1. INTRODUCTION

Today, wafer-based crystalline silicon photovoltaic cells demonstrate the highest commercial efficiencies at the lowest production cost. Improved manufacturing efficiencies alone will not be sufficient to significantly lower cost and continue down the historic path for the module price index [2]. Further, advancement in materials and cell design are required and back contact cells using metal wrap-through (MWT) technology are one approach to achieve this. Main adavntages include significantly reduced shadowing losses, possibility of simplified module assembly processes and reduced resistance losses in the module, all aiming to lower the cost per watt of PV modules.

Drilling for wrap through designs require a large number of micro-vias in silicon wafer that after metallization connect the front and rear contacts [3]. Dependin of the hole quantity and hole size, a single laser source might not be capable to drill all holes within the required cycle time. Selecting the right laser source and optimizing the process efficiency is important to maximize the utilization provided by a single source. As an alternative, multiple source can be applied to meet throughput requirements, however higher capital cost and increased floor space must be taken into account. Flexible IR lasers provide independent adjustment of the pulse energy, pulse width and the temporal shape of the pulse. This allows for optimizing of each parameter individually, as changes in frequency do not affect the pulse width. Systems with pulse energies of several millijoules and pulse width reaching into the nanosecond regime have been commercially available. Such systems have already proven to provide efficient cutting processes for specific productivity and quality requirements [4].

This paper describes aspects of optimizing material removal rates for laser drilling of silicon using an IR disc laser. Using optimized settings, a drill rate of 15,000 holes per second is achieved for an average power of only 20.2 W using only two laser pulses per hole to drill through 120 µm thick wafer.

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2. EXPERIMENTAL SETUP

The experimental setup for laser drilling of silicon wafers is shown in Figure 1. It consist of a pulsed disc laser (Jenoptik IR 70), a galvanometer scanner (Scanlab) with a f-theta lens and a focal length of 163mm, a vacuum fixture mounted on vertical cnc axis and an off-axis vision system. An adjustable beam expander is placed in the collimated beam. Using different beam expansion factors, the collimated beam size changes and different spot sizes at focus are achieved. Percussion drilling was performed using the rapid-fire burst function of the laser. Here, arrays of holes were generated by moving the laser spot from one hole location to another while keping the beam stationery during the drill cycle. The number of pulses (shots) is timed by the laser control. To achieve synchronous on-the-fly drilling, a field programmable gate array (FPGA) was adapted to the laser system. The FPGA-controller has a temporal resolution of less than 100ns and synchronizes the start of the scanner motion with the pulsing of the laser. As a result the laser beam can be guided multiple times at high speeds along the same path and each laser pulse will hit the same spot with high precision enabling synchronized on-the-fly drilling. Benefits are higher drill rates due to the lack of time consuming acceleration and deceleration ramps at each hole and an improved heat distribution compared to the percussion drilling process. On the fly-drilling is a very efficent approach for drilling a larger number of holes with small hole-to-hole spacings. Large hole-to-hole spacing are limited by the maximum scanner speed and minimum repetion rate of laser source. In this case, the percussion drilling mode is applied.

The pulsed IR disc laser emits radiation at 1030 nm wavelength and can provide maximum average power of 65 W @ 30 kHz. The repetition rate can be selected from 8 - 100 kHz and the pulse length can be adjusted from 200 - 1100 ns. Figure 2 shows the power and energy characteristics of disc laser. The understanding of the energy and power characteristics of this laser is important to take advantage of its flexible parameter selection. An important feature is that the pulse length can be set independently of the repetition rate allowing high flexibility in parameter selection. The laser provides the highest high pulse energies (> 6 mJ) at low low rep rates (8 kHz).

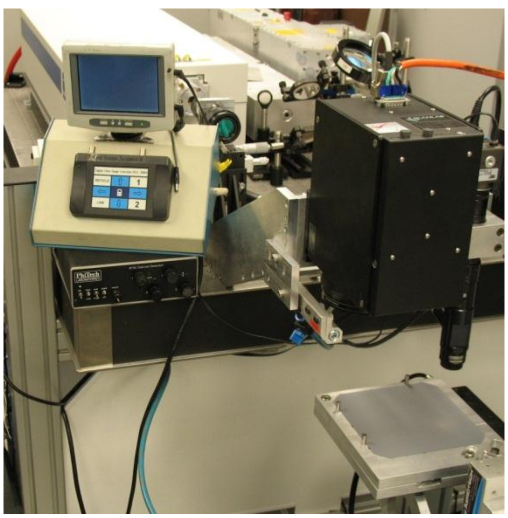


Figure 1. Experimental setup for laser drilling

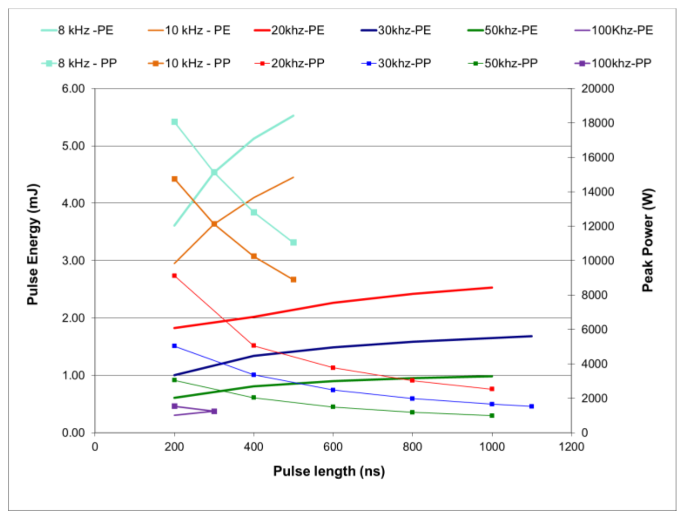
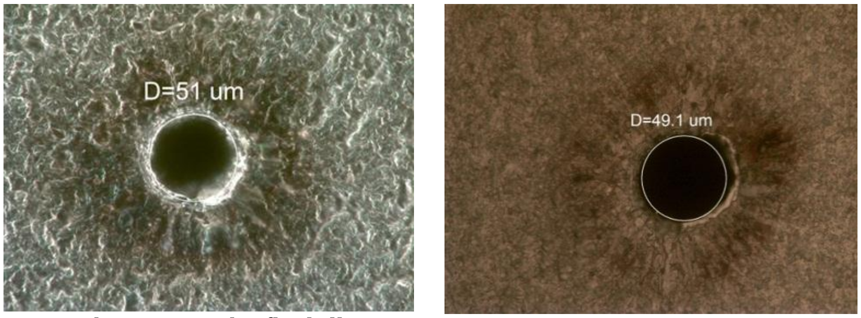


Figure 2. Power and energy characteristics of disc laser

3. PERCUSSION DRILLING VERSUS ON-THE-FLY SYNCHRONOUS DRILLING

To determine the accuracy of FPGA control percussion drilling and synchronous on-the-fly drilling were compared. All process parameters were kept identical except the travel speed, which only applies to the synchronous on-the-fly drilling process. It was kept at 8 m/s. Studies on drilling hole arrays show that through drilling on the 190 µm thick wafer is consistently achieved after 10 pulses. This confirms a very high accuracy of FPGA controller in synchronizing the laser pulsing with the scanner motion. Also, trials were conducted for a speeds ranging from 2 m/s to 15 m/s and showed very consistent results. Further proof was provided by the hole shape. Holes drilled in synchronized mode exhibit very good roundness even at highest speed of 15 m/s. Figure 3 shows the measured hole size of 51 and 49.1 µm for synchronous on-the-fly drilling and percussion drilling respectively.



Synchronous on-the-fly drilling   Percussion (stationery) drilling

Common parameters:

Average power:	16.1 W
Pulse energy:	0.81 mJ
Pulse length:	400 ns
Spot size:	34 µm
Wafer thickness:	190 µm
Repetition rate:	20 kHz

Required number of pulses to drill through: **10**

Figure 3. Drilling results from synchronous on-the-fly drilling and percussion drilling along with process parameters

4. RESULTS AND DISCUSSIONS

A series of synchronized on-the-fly drilling tests were performed to investigate the impact of process parameters such as pulse energy (PE), pulse length (PL), repetition rate (RR), peak power (PP), spot size and wafer thickness on the processing results. The required number of pulses/hole, drill rate, resulting hole shape & size, taper angle, hole quality and process efficiency were determined for different parameter combinations. For all the trials, the scanning speed was set to 8 m/s and the line spacing was 1.5 mm.

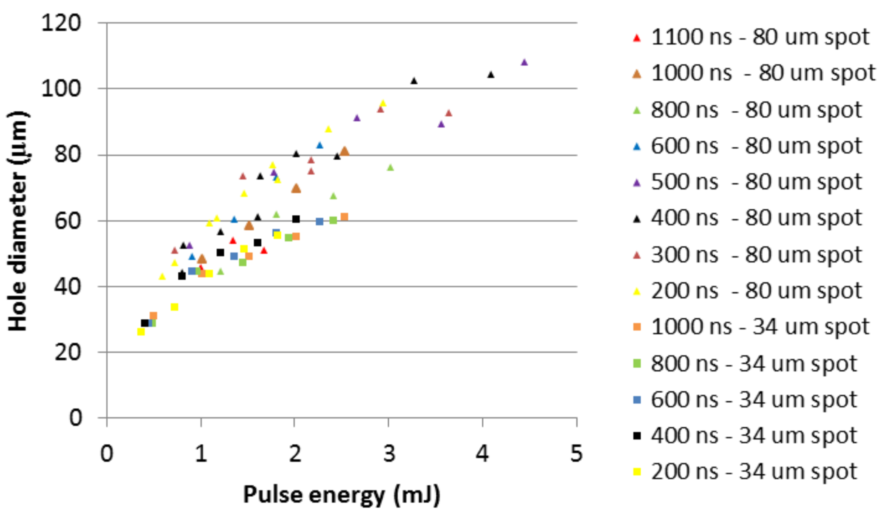


Figure 4. Average hole diameter versus pulse energy for 190 µm thick wafer at different PL and spot size

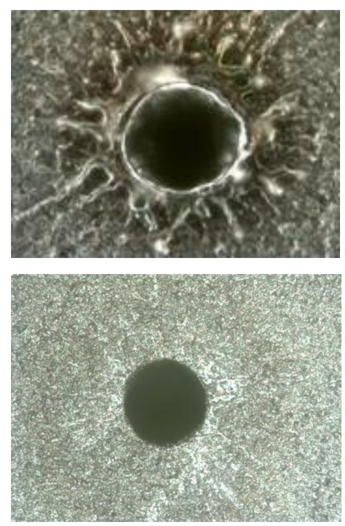


Figure 5. High (upper) and low (lower) melt spatter and recast attached to drilled hole entrance for different process parameters

To understand the effect of pulse energy on the hole size, synchronous on-the-fly drilling was performed with incremental increase in the average laser power at different pulse length (PL). Figure 4 shows the average hole diameter versus the pulse energy for at different PL and spot sizes. The average hole diameter was calculated as the mean of entrance and exit diameter. The hole diameters represent drilling parameters that require the minimum number of pulses to drill through a 190 µm thick wafer. For these tests, different repetition rates of 10, 20 and 30 kHz were investigated for 80 µm spot while only 20 kHz was used for the 34 µm spot.

A minimum average hole size of 26.2 µm and a maximum of 108.2 µm was achieved in 190 µm for the investigated parameter ranges. In all cases, the average hole size increases with increasing PE. For same PE, different average hole sizes are achieved at different parameter settings for PL and spot size. Similarly, same hole size can be achieved using different combination of parameter setting of PE, PL and spot size. For best process efficiency, it is important to determine the optimum combination of PE, PL and spot size that results in a specific hole size. Selection of parameters can significantly influence the formation of heat affected zone and recast layer at the hole entrance site and at the hole wall. Figure 5 shows the hole surface at the entrance with high (upper) and low (lower) melt spatter and recast attachment While the hole sizes are comparable(~Ø50 µm), clear differences in hole quality based on the parameter selection are noted.

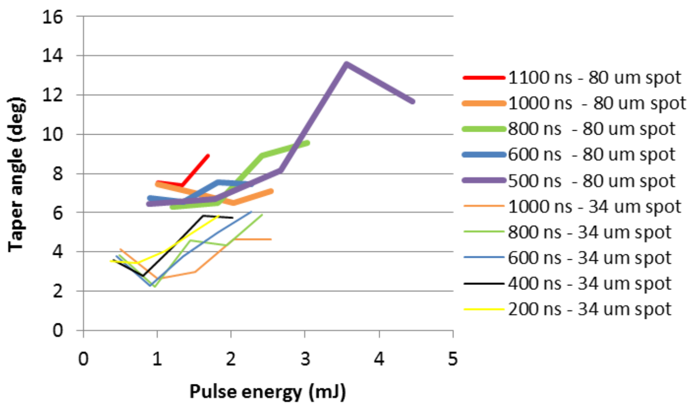


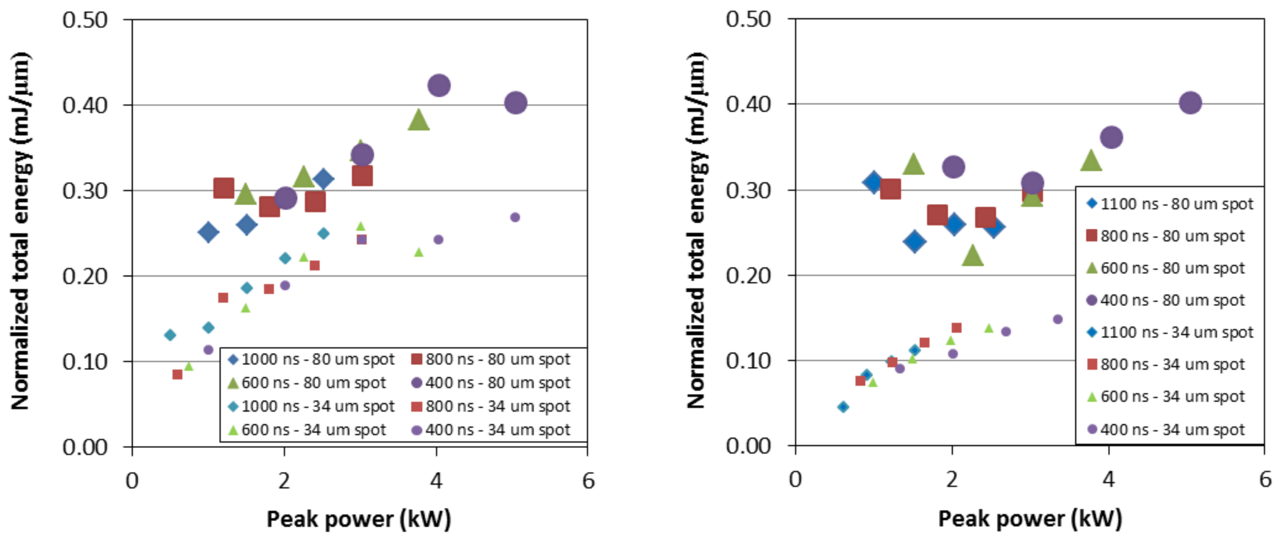
Figure 6. Taper angle versus pulse energy for 190 µm thick wafer at different PL and spot size

The results for the hole taper angle versus the pulse energy is shown in Figure 6 for a 190 µm thick wafer and two different spot sizes. Thicker and thinner colored lines represent spot sizes of 80 µm and 34 µm respectively. Interestingly, for 34 µm spot, taper angle initially decreases from 3.5 – 4 degrees to < 3 deg with increasing PE, but then increases after PE reaches 1 mJ. In contrast, for the 80 µm spot, the taper angle increases with increasing PE for PL ≤ 800 ns. For PL of 1100 and 1000 ns, there is a slight decrease in taper angle before it increases. At very high pulse energies (>3 mJ/pulse), taper angle reaches a maximum value of 13.6 deg. To minimize the taper angle a smaller spot size is required along with optimal settings for PL and PE. Minimum taper angle of 2.3 deg is achieved for 0.9 mJ PE, 800 ns PL and 34 µm spot.

Total energy per hole required for drilling was calculated based on the minimum number of pulses and the corresponding pulse energy. To understand the relationship between peak power and total energy, it is important to take into account the hole size, since it affects the required total energy per hole. Therefore, the total energy per hole is divided by the hole diameter and is referred to as normalized total energy (NTE) (vertical axis in Figure 7). Higher NTE indicates that higher energy input is required for drilling. For 190 µm thick wafer and 80 µm spot, the NTE increases gradually for PL of 1000, 600 and 400 ns. For example, it increases from 0.25 to 0.31 mJ/µm when PP is increased from 1 to 2.5 kW for 1000 ns PL. For 800 ns PL, NTE first decreases with increasing PP but increases again after PP of 2 kW is reached

Applying the smaller spot size of 34 µm, the NTE value increases with increasing PP for all investigated PL settings. However, the increase starts at PP of only 0.75 kW and requires only 0.1 mJ/µm. For the 120 µm thick wafer and 34 µm spot size, the change in NTE with PP is similar to what was observed for 190 µm thick wafer. In contrast, for 120 µm thick wafer and 80 µm spot size, the NTE initially decreases with increasing PP for all different PL's of 1100, 800, 600 and 400 ns. After it reaches PP of about 2 kW, it increases with increasing PP.

For the larger spot size, NTE ranges between 0.2 and 0.42 mJ/µm for both, 120 and 190 µm wafer thickness. For the smaller spot size, NTE ranges between 0.08 and 0.27 mJ/µm for 190 µm wafer and between 0.04 and 0.15 mJ/µm for 120 µm wafer. Note that for smaller spot size of 34 µm, the difference in NTE for 190 and 120 µm wafer is same as the wafer thickness. But for 80 µm spot, there is no difference between the NTE for different wafer thicknesses. Therefore, it can be concluded that lower NTE results in improved process efficiency when larger spot size is used for drilling thicker wafer and smaller spot size for thinner wafer.



190 µm thick wafer

120 µm thick wafer

Figure 7. Normalized total energy versus peak power for 190 µm and 120 µm thick wafer at different PL and spot sizes

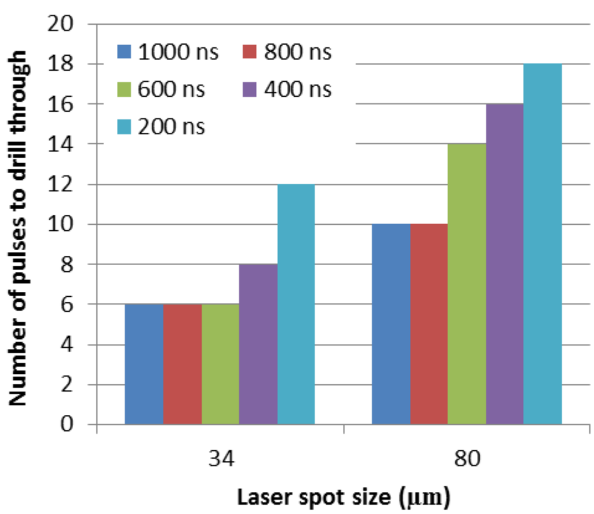


Figure 8. Number of laser pulses to drill through the wafer versus laser spot size for 190 µm thick wafer

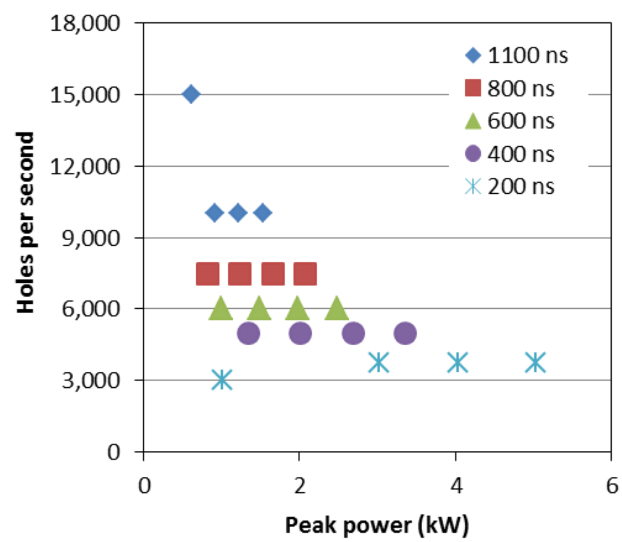
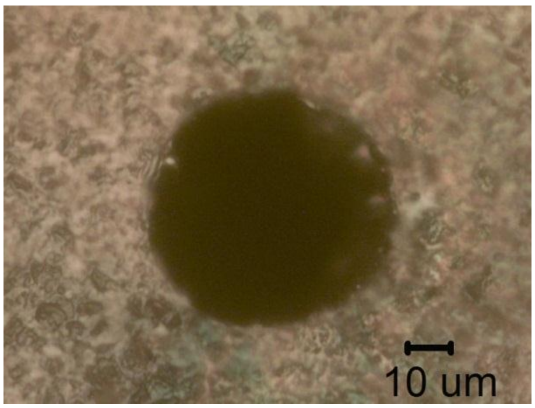


Figure 9. Drilling rate (holes/sec) versus peak power for 120 µm thick wafer

Figure 8 shows the number of laser pulses required to drill through 190 µm wafer at two different laser spot sizes (34 and 80 µm). Six pulses are required for PL of 1100, 800 and 600 ns using the 34 µm spot. This number increases to 8 and 12 for shorter PL of 400 and 200 ns respectively. For the 80 µm spot, the number of pulses is 10 for 1100 and 800 ns and increases gradually to 14, 16 and 18 for PL of 600, 400 and 200 ns resp. Clearly, higher number of pulses to drill through a wafer is required for larger spot size at same PL. The minimum number of pulses to drill through a 190 µm wafer is 6 and is only achieved at highest PL of 1000 ns at 20 kHz. The corresponding maximum drill rate is 3,333 holes/sec.

Figure 9 shows the drilling rate in holes/sec for 120 µm thick wafer using a spot size of 34 µm. The results are shown for different PL and PP. For an decrease in PL from 800 to 400 ns, the drill rate reduces sharply from 7,500 to 5,000 holes/sec. However, the drill rate remain unchanged even when the peak power increases for these PL's. In contrast, a drill rate of only 3000 holes/sec is achieved at short PL of 200 ns. The highest drill rate of 15,000 holes/sec is achieved at 1100 ns corresponding to lowest peak power of 0.61 kW. Only two laser pulses are required to drill through the 120 µm thick wafer at repetition rate of 30 kHz and speed of 8 m/s. The average power is only 20.2 W and total energy per hole is 1.34 mJ. The uniqueness of this data point emphasize the requirement of optimal processing parameters required to achieve 15,000 holes/sec drill rate. Applying higher peak power (0.92 kW) at PL of 1100 ns, increases the number of laser pulses required to drill through to three and therefore the drill rate drops to 10,000 holes/sec. Figure 10 shows the 'as is' entrance and exit surfaces of drilled holes at drill rate of 15,000 hole/sec. The holes are round in shape and does not show any significant melt attachments. The measured entrance and exit holes size is 52 and 26 µm respectively and the resulting taper angle is 6.2 degrees.



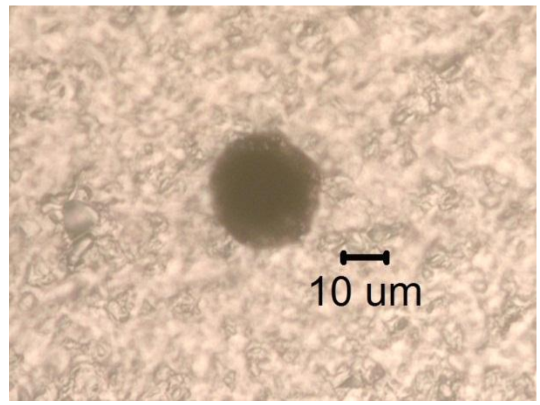


Figure 10 Hole entrance (left) and exit (right) at drill rate of 15,000 holes/sec

5. SUMMARY AND CONCLUSIONS

Laser drilling of silicon wafers MWT application was conducted using an IR pulsed disc laser. The impact of process parameters such as pulse energy, peak power, pulse length, repetition rate, laser spot size, total energy/hole on the hole drilling process has been investigated and processing results such as hole size and shape, taper, accuracy, pulses per hole to drill through, process efficiency and drill rate have been determined. High repeatability and accuracy achieved by FPGA controller was confirmed for synchronous on-the-fly drilling by comparing the results with percussion drilling. Minimum average hole size of 26.2 µm and maximum of 108.2 µm was achieved in 190 µm thick wafer. Although , same hole size can be achieved using different combination of parameter setting of PE, PL and spot size, it was shown that the selection of parameters can significantly influence the formation of heat affected zone and recast layer at the hole entrance and exit site. The results showed that the taper angle can be reduced by applying a combination of smaller spot size and optimization of process parameters such as PL and PE. Total energy per hole required for drilling was compared for two different wafer thicknesses and two different spot sizes. It was found that it is more efficient to drill thicker wafers with larger spots and thinner wafer with smaller spot sizes. The analysis of the number of pulses to drill through the wafer and corresponding drilling rate showed these to be strongly affected by processing parameters especially the pulse length. Using optimal process parameters, a drill rate of 15,000 holes/sec is achieved in 120 µm thick wafer using only two pulses per hole.

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