Laser Machining of Silicon using Diode-Pumped Solid State & CO₂ Lasers

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Abstract

Laser cutting and scribing of silicon has been investigated for a number of years but cut quality and speed problems have stopped the process gaining wide industrial acceptance. This process is now receiving more attention due to the advent of high average power ultra-violet diode-pumped solid-state lasers, whose reliability has been demonstrated in industry for applications such as printed circuit board via hole drilling. In this work, the performance of these lasers in this demanding application has been assessed on standard wafer materials and some novel approaches to improving cut quality have been investigated.

Keywords: diode-pumped solid state, ultra-violet, silicon, wafers, cutting, CO₂.

Introduction

Laser cutting of metals has for some years been a very well established process in industry and the majority of high average power lasers, mainly CO₂ lasers, are sold into industry for cutting, most commonly, sheet steels. For some time another industrial laser sector has been growing and that is in the area of precision laser cutting. As is always the case, both the applications and the lasers and have developed together and diode-pumped solid state lasers have been increasing in terms of average power and reliability to meet these new applications. A number of industries have benefited from these precision cutting applications, notably, the medical device industry [1] and the electronics industry. The laser that has now brought the level of reliability and throughput required for 24 hour operation in industry is the diode-pumped solid state laser (DPSS).

The first application to open up within the electronics industry was the drilling of through hole and blind vias in FR4 and flex circuits for the printed circuit board industry. DPSS lasers are now established as the dominant technique that allows the drilling of sub 50 µm diameter holes with speed and accuracy.

Silicon wafer re-sizing is already an established laser cutting application but wafer re-sizing is performed at the start of the production cycle. At this point, unpopulated, bare wafers, > 700 µm thick, can be laser cut using high average power CO₂ lasers at up to 500 watts continuous wave (cw) power, at high speed, typically 60”/min. Most importantly, at this point in the early stages of the production cycle, wafers and dies will be heavily etched and cleaned and any trace of the thermal processing associated with the cutting operation is removed. A degree of thermal damage is therefore acceptable.

Another concurrent development, driven by the same demand for higher and higher packaging densities is the development of thinner and thinner silicon wafers, sub 200 µm wafers are now regularly being employed in certain applications. In one European project, the aim is to develop sub 50 µm wafers by 2005 [2]. This opens up a range of other challenges and opportunities for
laser processing. Is it possible to cut at high enough speed and reduce thermal damage to minimize post-processing? The work presented here contributes to this discussion.

There are therefore two distinct methods by which silicon wafers may possibly be laser machined, both are currently widely used techniques but generally in very different industrial sectors. For the purposes of this work, they are referred to as macro and micro-machining. The first, macro-machining, is the use of high power CO$_2$ lasers with an assist gas delivered co-axially with the laser beam through a machining head. CNC controlled X and Y high-speed manipulation of the part beneath the beam or manipulation of the beam and machining head is used. This approach is almost exclusively employed for laser cutting most types of steel. The assist gas, usually oxygen, contributes significant additional energy to the cutting process, and hence to the cut speed. For most other metals, the benefit from using oxygen as an assist gas is minimal and hence a high pressure non-reactive gas is used to remove molten material from the cut. This approach is often used for laser machining stainless steels and for non-metals where a high quality cut is required. This approach, using high speed wafer manipulation, a laser cutting head and an assist gas, either air or nitrogen, is currently used for wafer resizing.

The second micro-machining approach is to use galvanometer scanning of the laser beam over a limited area of the wafer. In conjunction with CNC controlled X and Y axis manipulation of the wafer beneath the beam, complete wafers may be machined. In this galvanometer scanning approach, the direct application of an assist gas is ruled out. This approach is also typically used for micro-machining in conjunction with lower average power DPSS lasers where very high galvanometer scanning speeds are possible. If only relatively small volumes of material are to be removed, then this approach is preferred.

Laser micro-machining of silicon has for some time been the preserve of Excimer lasers, these have been until recently the only laser type able to reliably machine micron scale features. The Excimer laser performance is due mainly to the short ultra-violet wavelength that gives much shorter absorption depths and good material removal efficiencies. The arrival of highly focusable, industrialized 355 nm DPSS lasers has led to their increasing use for a range of silicon machining applications where sub 100 μm features are required. Some of these are encroaching on applications previously thought only to be possible using Excimer lasers. 355 nm DPSS laser processing becomes more valuable as wafers become very thin, the distance between dies is reduced and laser power increases to the point at which wafers can be cut with few passes.

The average power available from fully industrialized DPSS systems emitting in the ultra-violet part of the spectrum is continuing to increase, for tripled wavelengths, the state-of-the-art is 7 watts with good prospects for increasing the average power even further. Similarly, electrical conversion efficiencies of the diodes used for pumping is now up to 50% in some cases, leading to greatly increased laser wallplug efficiencies.

**Laser Machining of Silicon**

There is a huge potential for using lasers in the manufacture of semiconductors and semiconductor devices, and a great deal of effort has been put into developing these applications. An excellent review of a large body of work on these annealing, recrystallization and silicide and silica formation techniques is given in [3]. There is recently published information on laser drilling of silicon [4] and machining of silicon [5] using even shorter pulses and still smaller feature sizes using femtosecond lasers. Work has also been published on a combined laser and
water jet technique [6] and there has also been work published on machining of silicon for solar cell manufacture [7].

Key to any understanding of laser material processing of silicon is the absorption behavior at specific laser wavelengths. Below 1 µm wavelength, beam transmission through silicon is negligible [8] and table 1 [9] shows that optical absorption depth (1/α) decreases dramatically with wavelength.

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>0.25</th>
<th>0.5</th>
<th>1.06</th>
<th>10.6</th>
</tr>
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<tbody>
<tr>
<td>1/α</td>
<td>6 nm</td>
<td>500 nm</td>
<td>200 µm</td>
<td>1 mm*</td>
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</table>

* this figure is very dependant on dopants

Table 1 showing optical absorption depth (1/α) for crystalline silicon

Table 1 suggests that a 355 nm laser beam has a significant advantage over longer wavelengths for material removal in that surface absorption should lead to more efficient absorption and coupling of the laser beam. Static room temperature results on one of many variables almost certainly do not accurately reflect the highly dynamic laser cutting process. Reflectance also changes, but is perhaps a less dramatic effect. Many models have been proposed to explain individual material removal mechanisms involved in laser cutting of silicon. This limits their usefulness to a single narrow set of experimental conditions. A general, wider ranging mathematical description of the process needs simultaneous consideration of the different mechanisms and their interrelationships, a general summary follows:

The process starts with single or multi-photon material excitation and instantaneous generation of heat occurs increasing absorption of the beam to the point at which vaporization occurs. Other possible mechanisms are explosive-type removal of solid material, plasma generation, alteration of the optical properties of the material and direct bond breaking. Although some sources claim that at the much shorter 355 nm wavelength, any plasmas that are generated are transparent to the laser beam [10], other authors have explained experimentally determined material removal thresholds for multiple laser pulse percussion drilling in terms of plasma and plume blocking of the beam [11]. If an assist gas is used as opposed to a beam scanning technique, then further gas and molten material flow mechanisms may also complicate a full analysis of the process. Hence an empirical approach is taken to identifying and optimizing the significant variables in the laser cutting process. Another semi-quantitative approach used by some authors for assessing the laser machining process has been to determine a figure for material removal efficiency [12], often measured in terms of µm³/pulse or µm³/µJ.

One final aspect of the DPSS laser micro-machining process that has not been too widely discussed in the literature is cut quality. In common with all laser cutting processes, there are several effects that need to be quantified to make a real assessment. Amongst these are heat-affected zone, cut surface roughness, debris and micro-cracking and by the very nature of the process, many of these are present in all micro-machining applications. A problem arises in that these defects are often so small that they are very difficult to identify and quantify using conventional metallurgical techniques.

The debris generated when cutting silicon is in the form of very finely divided material, this adheres to the cut edge and is also re-deposited around the immediate machined area unless precautions are taken.
A possible explanation for the generation of micro-cracks has been taken from the literature [13]. The cracking may be caused by two mechanisms, either hot cracking caused by the presence of a heat affected zone (HAZ) or by solidification cracking of the recast layer. The unique electrical properties of silicon are well known, its inherent mechanical limitations are not so well known outside the semiconductor industry. This inherent lack of ductility certainly differentiates it from many other materials, making it a very challenging material to laser cut. Not only is cracking and chipping a problem, but cut surface roughness and the unavoidable generation and re-deposition of debris also contribute to the challenges. These problems are compounded as certain precision machining operations are now required at a much later stage in the production process, when wafers are populated and the re-deposition of machining debris on these populated areas is precluded.

**Laser Cutting of Silicon - Experimental trials**

To study the differences between the macro and micro cutting regimes, silicon wafers were cut by both processes and assessed visually and in terms of cut quality. At this stage, cut quality was determined by a qualitative assessment of surface roughness, cracking and debris generation.

**Macro-cutting with CO\textsubscript{2} lasers**

To demonstrate the different laser cutting regimes, three different series of laser cutting trials were performed. The first two were done with high average power, high pulse energy CO\textsubscript{2} lasers. These lasers were operated in the following conditions that were typical of those used currently for manufacturing operations. Wafers were polished 720 \textmu m thick polycrystalline silicon.

1) Slow flow CO\textsubscript{2} laser (Coherent 525)
   - At 230 Hz, 1 ms pulse length, 350 watts, 1.5 J per pulse.
   - 100 psi compressed air.
   - Cut speed 60”/min (1.5 m/min)

2) Slab CO\textsubscript{2} laser (Coherent K500 Diamond)
   - (a) At 5 kHz, 100\mu s pulse length, 500 watts.
   - (b) At 1 kHz, 500 \mu s pulse, 500 watts
   - 60 psi compressed air
   - Cut speed 280”/min
   - Cut speed 440”/min

**Micro-cutting with DPSS lasers**

The third series of trials and the major focus of this work is laser cutting of silicon using Diode Pumped Solid State lasers. In this case, thinner 216 \mu m wafers were cut using multiple passes with the DPSS laser. Cutting parameters are given in tables 2 & 3.

3) DPSS Laser (Coherent AVIA)

The AVIA 355-7000 laser is a diode-pumped solid-state q-switched laser that provides ultra-violet output at 355nm with pulse repetition rates from single shot to 100kHz. The laser consists of the laser head and power supply connected by an umbilical. The umbilical contains fiber optic cables that transmit light form the diode bars in the power supply to the laser head and also houses electrical and RF cables that provide control and monitoring signals between the laser head and power supply. The laser head contains the optical elements, circuit boards, an acoustic-optical Q-switch and a shutter. The major optical elements in the hermetically sealed head include a proprietary crystal set as the gain medium, a crystal as a second harmonic generator.
(SHG) and an additional crystal as a third harmonic generator (THG). The laser gain medium is used in an end-pumped geometry, with the pump power provided by fiber-delivered diode bars.

Optical Set-up

The 3.5mm collimated output of the laser was directed unexpanded into a Scanlab HurryScan 10 scan head with mirrors coated for 355nm light. The beam waist was focused on the top surface of the silicon wafers. Focusing of the beam was accomplished with a telecentric scan lens (f=100mm) with a field area of 90 x 90mm.

![Image](image1.png)

**Figure 1 Wafer cutting set-up**  **Figure 2 Laser operating envelope**

The calculated spot size at the focus is 16 µm but effective measured hole sizes on silicon are generally much larger, ~ 40 µm. The calculated spot size is used to derive irradiance (power density) as this then becomes independent of material properties.

Silicon wafer micro-cutting parameters

An off-axis low pressure N$_2$ jet was used to aid in removing the particulate silicon from the target zone during processing. In these trials, a 216 µm thick polycrystalline silicon wafer was used. Trials were performed over a range of repetition rates as shown in table 2. The pulse energy, which is the main variable in these trials, was adjusted by changing the repetition rate of the laser.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Set</th>
<th>kHz</th>
<th>τ, ns</th>
<th>W at work</th>
<th>μJ</th>
<th>Peak (kW)</th>
<th>Area (10$^6$ cm$^2$)</th>
<th>GW/cm$^2$</th>
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<tr>
<td></td>
<td>A</td>
<td>30</td>
<td>20.7</td>
<td>6.35</td>
<td>211</td>
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<td></td>
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<td>6.88</td>
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<tr>
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<td>22.6</td>
<td>6.66</td>
<td>133</td>
<td>5.9</td>
<td>1.99</td>
<td>2.9</td>
</tr>
</tbody>
</table>

**Table 2 DPSS Laser parameters**
Results and Analysis

CO₂ laser cutting

Figure 3 (a) SEM picture of slow flow CO₂ laser cut surface, 60”/min, 720 μm thick wafer

Figure 3 (b) Optical photo of slab CO₂ laser cut surface, 440”/min, 720 μm thick wafer

Figure 4 SEM picture of slab CO₂ laser cut surface, 280”/min, 720 μm wafer

Figures 3 & 4 show the full depth of the cut surface of the 720 μm thick wafer, figure 3 shows a large amount of damage and recast layer. Figure 4 shows a limited amount of relatively large debris globules re-deposited on the top surface of the cut.
Figure 5 shows 3D profiles obtained from the DPSS laser cut surfaces examined using a Veeco Interferometer Profiling System, model no. NT 3300. These were taken at the upper surfaces of the cut and clearly show a trend towards a smoother cut at higher repetition rates and lower pulse energies.

Figure 6 shows DPSS laser cut slot, 50 kHz parameters

Figure 7 (a) & (b) Slot cut with 50 kHz parameters, high & low mag, cleaned
Figure 8 showing high quality cut surface, 50 kHz parameters

Figure 9 Cross section of laser cut, 50 kHz parameters

Figure 9 is a transverse cross section prepared from the sample shown in figure 8. This has been prepared at a slight angle to the cut surface, hence the curved profile.

**Discussion of Processing Results**

The high power CO₂ laser cuts exhibit not surprisingly very rough surfaces due to the high pulse energies and gas flows associated with the process. The optical micrograph in figure 3(b) shows evidence of large cracks that appear to follow the crystal planes of the 100 material. The slab laser cut at 200"/min (figure 4) appears to be of high quality. Further investigation is required to investigate sub-surface damage. There is also evidence of the large debris generated during the high energy cutting process.

For the DPSS cutting and slotting, there appears to be a definite correlation between pulse frequency and surface roughness. By varying pulse energy, a correlation between speed and quality can be obtained. The re-deposition of debris in the area of the laser cut is one of the more notable features of this process. The debris appears to be agglomerations of very fine powder-like material that is only weakly attached to the surface. Additional precautions need to be taken if debris-free surfaces are required. Figure 6 shows debris typically associated with the laser cutting process. Figure 8 shows a very high quality cut surface. Although striations associated
with the laser pulsing are visible on the cut surface, these are so small as to have a very limited effect on overall surface roughness. Figure 9 shows a materialographic cross section of the cut surface showing no defects associated with the laser cutting process.

Conclusions

Three very different types of laser have been used to cut thick and thin silicon wafers. The cut surfaces associated with the high average power CO\textsubscript{2} lasers are very rough in some cases and there is evidence of severe cracking along crystal planes. A diode-pumped UV solid-state laser system has been used to successfully cut thin silicon wafers. Using UV laser light, high quality, low surface roughness cut edges can be accomplished. No evidence of cracking has been identified associated with cuts made with the UV laser. Close-to-optimum parameters for a particular wafer type and thickness were readily identified using a simple series of experimental trials.

Tom Corboline and Dr. Tony Hoult are Applications Specialists for Coherent’s Laser Applications Center.

References