High Power UV Laser Machining of Silicon Wafers

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As the demand for semiconductor devices based upon ever-thinner silicon substrates continues to increase, mechanical techniques suitable for dicing wafers appear to be approaching their practical limits. Recent advances in power scaling have now enabled reliable ultraviolet-wavelength lasers to be considered to offer a flexible solution to this dilemma. This paper presents new data on the machining of thin silicon wafers using a high average power 355-nm wavelength pulsed laser. In particular, the concept of pulse repetition-rate scaling of the effective cutting speeds was investigated to determine the preferred direction for further laser development efforts.

Keywords: Laser-cutting, UV, silicon, diode-pumped solid-state lasers

1. Introduction

The purpose of the work described in this paper was to investigate the cutting of thin (<300 µm) silicon wafers with an ultraviolet-wavelength high repetition-rate Q-switched laser. A cutting strategy in which repeated passes of a tightly focused laser beam were made along a straight line until a through-cut was established was employed to determine the fastest effective cutting speed as a function of the pulse energy, repetition rate, and spatial overlap of successive pulses for several different nominal wafer thickness values.

This multi-pass cutting strategy was chosen in preference to single-pass cutting as a means of minimizing thermal damage to the material immediately adjacent to the cut line as well as reducing the total processing time (maximizing the effective cutting speed). It was hoped that this study could provide guidance to assess the most effective means of apportioning the available time-averaged laser power, specifically addressing the relative effectiveness of operating the laser at high pulse energies with a comparatively low pulse repetition frequency (PRF) as opposed to employing lower energy pulses at higher PRF.

2. Experimental procedure

The laser used for these experiments was a frequency-tripled diode-pumped solid-state Nd:vanadate laser (355-nm wavelength, 25-nsec pulse width) capable of delivering average power levels exceeding 15 watts to the raw silicon work surface. The collimated laser output was directed through a galvanometer-based computer-controlled scan head with a post-scanner telecentric lens that yielded a calculated spot diameter of 14 microns at focus over a scan field approximately 70 millimeters in width. However, the beam imprint observed on the wafer surface due to a single pulse was found to be ~25 microns in diameter for all the pulse energy values considered in this study, and it was this larger apparent spot size that was assumed when calculating the effective spatial overlap between successive pulses.

Figure 1 indicates the three discrete pulse energy ($E_{\text{pulse}}$) values (150, 230, and 308 µJoules, respectively) and the specific PRF values (30, 40, 60 and 80 kHz) chosen for this study, contrasted with the available laser performance envelope (dashed line).

![Figure 1](image-url) Nominal laser pulse energies as a function of pulse repetition rate employed for Si cutting trials; dotted line indicates maximum available energy at work surface.

An additional variable in these tests was the focal spot slew rate, $V_{\text{slew}}$ (specified in millimeters/sec), alternatively expressed in terms of the focal spot separation, $\beta$. This non-dimensional factor, defined as the distance traversed across the sample surface between successive laser pulses normalized by the effective focal spot diameter (assumed to be 25 microns for all cases in this study) and reported as a percentage, describes the effective spatial overlap independent
of the PRF. $\beta$ was varied at each selected PRF in discrete steps ranging from 5% (95% spatial overlap) to 50% (at the highest slew rates considered for any PRF). All tests were conducted in air at ambient pressure.

To evaluate the variation in cutting speed as a function of wafer thickness, three different sample thickness values were investigated: 156 microns, 216 microns, and 276 microns, respectively. All wafers were specified in a (1,1,1) crystal orientation and positioned during testing so that the scan lines were oriented at 45° to the alignment flat of the wafer to minimize the initiation of cracks from the endpoints of the scans. Wafers were simply supported along their edges in a custom-built vacuum chuck with the area reserved for cutting trials suspended several millimeters above the surface of the holder, in an effort to minimize undesirable interactions between the samples and back-reflections or debris that might be generated from the underlying material following laser breakthrough.

During the cutting speed trials a sequence of 2-cm long parallel scan lines separated from each other by at least 1 millimeter (to minimize interaction between adjacent scans) were laid down upon the wafer sample surface. To evaluate the effective cutting speed for a given operating condition (fixed pulse energy, PRF, and pulse separation) repeated unidirectional scans along a single line were made until the desired number of passes, $N$, had been completed.

The scan starting position was then incremented and the process repeated for different values of $N$. Additional scans were made while increasing $N$ until through-cuts were established and then further increased, until the removal rate of additional silicon with successive scans was judged to be negligible. Figure 2 illustrates a typical progression in the observed slot depth with increasing $N$.

![Figure 2](image)

**Figure 2.** Cross-sections of slots cut in a 156-micron thick silicon wafer sample with increasing number of passes, $N$ ($E_{\text{pulse}}=230\mu J$, $PRF = 60kHz$, $V_{\text{slew}}=300mm/s$, $\beta = 20\%$).

Figure 3 presents a sequence of images obtained by back-lighting the central sections of several successive wafer through-cuts, labeled with the corresponding value of $N$ employed to generate the visible gap. Note that initial wafer breakthrough does not occur simultaneously along the full scan line for smaller values of $N$, and in fact it typically requires about twice as many more sweeps to substantially clear the kerf of the cut. Additional sweeps open the gap only slightly further and mainly smooth the cut edges while clearing out residual debris that tends to clog the gap.

![Figure 3](image)

**Figure 3.** Back-lit images of through-cuts in a 216-micron thick silicon wafer illustrating the increase in open area obtained by increasing the number of passes, $N$ ($E_{\text{pulse}}=150\mu J$, $PRF = 30kHz$, $V_{\text{slew}}=75mm/s$, $\beta = 10\%$).

By converting the back-lit digital images recorded in color to gray-scales and applying an appropriate intensity thresholding condition, a quantitative measure of the extent of cut clearance achieved as a function of $N$ could be obtained. A white pixel count for each binary image was made and normalized by the count corresponding to the image with the largest value of $N$, so that the relative open area as a function of $N$ may be directly inferred from this ratio.

![Figure 4](image)

**Figure 4.** Percentage open slot area (referenced to maximum obtained value) as a function of the number of passes.

To neglect unavoidable variations in the slew rate due to acceleration and deceleration of the beam-deflecting mirrors near the beginning and the end of scan lines, only the cen-
term most portions of test cuts were considered when evaluating the number of passes required to satisfy the through-cut criteria. A good correlation between a 50% maximum white pixel count and >90% unobstructed opening along the cut centerline was established and adopted as the quantitative definition of a through-cut. (For the particular example shown in Fig. 4, the through-cut condition was satisfied for \( N = 15 \).) The associated value of \( N \) was then used to calculate the effective cutting speed \( V_{\text{eff}} = V_{\text{slew}} / N \).

3. Representative Results

Some representative results from this study appear in the following sequences of graphs. Restrictions on the length of this paper preclude the inclusion of all the results accumulated in this study, but those shown here have been selected to be representative of some of the general trends suggested by the data.

3.1 Variation in effective cutting speed with PRF

The first sequence of graphs (Figs. 5 – 8) illustrates the variation in the effective cutting speed as a function of the \( \text{PRF} \) measured for the thinnest wafer considered (156-micron thickness). Each graph in this set of four corresponds to a specific value of \( \beta \), and each individual data set linked by a single line within each plot is associated with a specific pulse energy value, as labeled. The indicated spot separation and the corresponding single-pass slew rate were increased monotonically in this sequence, from the slowest rate of 37.5 mm/sec (at a \( \text{PRF} \) of 30 kHz and \( \beta = 5\% \)) to a maximum of 1000 mm/sec (at a \( \text{PRF} \) of 80 kHz and \( \beta = 50\% \)).

The number of passes corresponding to the defined through-cut condition at the extremes of this subset of the parameter space explored was as few as \( N = 5 \) for \( \beta = 5\% \) and \( E_{\text{pulse}} = 308 \text{ microJ} \) at \( \text{PRF} = 30 \text{ kHz} \) (yielding \( V_{\text{eff}} = 8.0 \text{ mm/sec} \)) and as many as \( N = 39 \) for \( \beta = 50\% \) and \( E_{\text{pulse}} = 150 \text{ microJ} \) at \( \text{PRF} = 80 \text{ kHz} \) (\( V_{\text{eff}} = 26.0 \text{ mm/sec} \)).

\( E_{\text{pulse}} \) would be expected to converge at the origin, since \( V_{\text{eff}} \) should become negligible as the \( \text{PRF} \) (and correspondingly the average power) goes to zero.

![Fig. 6 – Effective cutting speed for 156µm wafer, \( \beta = 10\% \).](image6)

A couple of trends emerge from an examination of these results. (Similar results were observed for the thicker wafer samples, although the associated cutting speeds were slower, as will shortly be shown.)

![Fig. 7 – Effective cutting speed for 156µm wafer, \( \beta = 20\% \).](image7)

First, unsurprisingly, higher effective cutting speeds are obtained for higher \( \text{PRFs} \), as might be anticipated given the associated increase in average power delivered to the working surface for a fixed pulse overlap and pulse energy with an increase in the \( \text{PRF} \). However, at least for the 150-\( \mu \text{J} \) low pulse-energy case there seems to be some suggestion that the enhancement in throughput is somewhat better than would be expected if the scaling was based solely upon average power (although given the uncertainties in precisely determining a value for \( N \) this should not be considered a definitive conclusion).

Compare for example the results obtained with 150-\( \mu \text{J} \) pulses at 40 kHz to those obtained for the same pulse energy at 80 kHz; if the cutting speed was directly proportional to average power, then a simple doubling of speed would be expected, whereas in every example shown here the rate is at least slightly more than doubled. This may be indicative of an enhancement in the cutting efficiency associated with the increase in average power that occurs as the \( \text{PRF} \) increases for a fixed value of the nominal pulse energy.
Second, in all cases higher cutting speeds are obtained for higher pulse energies, although the enhancement is less pronounced for small spot separations than for larger values of $\beta$. This observation prompts the consideration of a correlation of the effective cutting speed with the spot separation.

### 3.2 Variation with spot separation

The variation in effective cutting speed with the laser spot separation exhibits rather different and apparently nonlinear behavior, as documented in Figs. 9 – 11. Note that again it is reasonable to expect that all curves should converge on the origin, since as the spot separation and associated slew rate drop to negligible values the effective cutting rate should also go to zero.

Fig. 9 – Results for 156-μm thick Si wafer, $PRF = 30$ kHz.

The most striking common feature of these plots is the rapid increase in effective cutting speed as the pulse separation increases from zero to a few percent, followed by a subsequent flattening of the curves as the pulse separation approaches one half the apparent focal spot size. From the viewpoint of practical laser-cutting process design, this behavior suggests that the effective cutting speed for mid-range spot separation values ($15% < \beta < 50\%$) will be fairly insensitive to the precise value of $\beta$ chosen. This could be a real convenience and potential advantage in that variations in the spot separation are inevitable due to acceleration and deceleration of the moving beam, especially in situations involving intricate geometries.

Fig. 10 – Results for 156-μm thick Si wafer, $PRF = 40$ kHz.

Fig. 11 – Results for 156-μm thick Si wafer, $PRF = 60$ kHz.

Similar results were obtained for the other two wafer thicknesses considered, with one additional aspect worth mentioning. For the thickest wafers (276 microns), the effective cutting speed curves appeared to actually peak at a $\beta$-value of ~10%. This result deserves further investigation, although admittedly laser cutting of such comparatively thick silicon substrates is not generally considered competitive with traditional mechanical dicing methods such as diamond saw-cutting.

### 3.3 Variation with wafer thickness

A comparison of the effective speeds obtained for the different wafer thicknesses yields some interesting results as well. The following plots are divided into two groups, corresponding to two different $PRF$ values. In the first sequence (Figs. 12 – 14) each plot gives the results obtained for a comparatively low $PRF$ of 30 kHz and one specific value of the spot separation, as labeled ($\beta = 10\%$, 20%, or 50%, respectively). In the second sequence of three plots (Figs. 15 – 17), analogous results for a comparatively high $PRF$ of 60 kHz and the same $\beta$ values are shown.

It is instructive to consider both a side-by-side comparison of the results for the low- and high-$PRF$ sequences, (which provides insight into the effect of a doubling of the average laser power while otherwise maintaining identical process conditions) as well as examining the progression with increasing $\beta$ within each sequence.
The detailed behavior for the two PRF values is apparently rather different. While in both sequences there is an obvious fall-off in cutting speed with increasing wafer thickness, in the lower repetition rate cases the decrease is nearly linear with increasing thickness while in the higher repetition-rate cases the rollover in speed is much more pronounced. In both sequences it appears that for a wafer thickness only slightly greater than the largest value considered here through-cuts would not be possible, at least so long as the multi-pass single line strategy employed in this study would continue to be used.

In comparing the plots above side-by-side to assess the consequences of a doubling in average power, the effective cutting speed is again consistently more than doubled by doubling the PRF. This better than linear enhancement of the cutting speed is suggestive of a “thermal assist” to the cutting process that deserves further investigation.

4. Discussion

Driven primarily by the demand for higher and higher packaging densities, thinner silicon substrates are becoming increasingly important in semiconductor device manufactur-
ing. Sub-200-µm wafers are now regularly being employed in certain applications and the trend to even thinner substrates is ongoing. For example, in one prominent European project, the development of sub 50-µm wafers is anticipated by 2005 [1]. In dealing with wafers <300 µm in thickness, alternatives to conventional mechanical cutting techniques are eagerly being sought [2]. Ultraviolet lasers have been demonstrated to provide good edge quality for slots cut in silicon [3] and the results reported here are intended to give a quantitative indication of the kinds of cutting speeds such lasers are capable of delivering.

The laser employed in this study was a prototype device that could be operated at average power levels somewhat higher than those currently available from any standard product from commercial laser vendors. In that regard the fastest cutting speeds reported here should be recognized as indicative of what should become a reasonable expectation in the near future. Nonetheless, the pulse energy range considered is covered by available devices, so the results of this investigation remain relevant even for lasers operating at lower PRF and consequently lower average power levels.

The results reported here indicate that higher cutting speeds can be anticipated to be achieved with higher laser power, regardless of whether power is increased by increasing pulse energy or by increasing PRF.

The rapid roll-off in cutting speed with wafer thickness exceeding ~250 microns is indicative of the difficulty encountered in attempting to remove material from a slot with a high depth-to-width aspect ratio. This difficulty may be associated with gasdynamic transport issues or could be indicative of other physical effects, such as a screening of the cutting surface by a laser-generated plasma. The use of a gas assist is likely to be helpful and may be considered in future work.

5. Conclusions

For the wafer cutting strategy employed in this study, a 15-watt class (average power) 355-nm wavelength Q-switched laser was demonstrated to be capable of achieving effective cutting speeds exceeding 20 mm/s for silicon wafers up to ~200 microns in thickness.

Effective cutting rates observed while employing a multi-pass single-line cutting strategy were demonstrated to scale linearly or better with PRF for a given pulse energy. This result suggests that in anticipation of even higher average laser power levels the preferable approach appears to involve increasing PRF at comparable pulse energy levels rather than boosting the pulse energy while maintaining the same PRF.

Given a wafer thickness at the upper end of the range considered, increasing pulse energy appears to be less effective than increasing PRF to increase the effective cutting speed. For such thicker wafers, a modified cutting strategy that produces a lower depth-to-width slot aspect ratio is likely to be required.

Future work is expected to involve a refinement of the methodology employed to define the through-cut condition to reduce the uncertainties in the inferred effective cutting speeds and validate the trends indicated by this study. In addition, alternative cutting strategies such as bi-directional scanning of the silicon surface and side-by-side scans to increase the slot width, perhaps with a smaller focal spot size should also be considered.

References