Technical Communication

Effect of Shot Number on Femtosecond Laser Drilling of Silicon

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Silicon wafer drilling has been under heavy investigation for some time already. Several different laser types and methods have been introduced to different applications. In the industry usually the nanosecond lasers are used. Femtosecond lasers have been considered as high cost and not suitable for the industrial production. At present femtosecond lasers offer really high pulse energies and good reliability, and also high repetition rates and relatively high pulse energies are possible in the sub picosecond range. Processing accuracy with femtosecond laser is very good and heat input is negligible in the processed surface. In this paper we demonstrate the effect of the number of pulses in silicon wafer drilling with a femtosecond laser in free air. Silicon wafers used were p–type, [100] oriented and double-side polished. From the experiments we can see that the drilled hole depth increases rapidly until a turning point is reached, and the ablation rate becomes much smaller. The transition occurs at around several hundreds to 1000 shots.

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1. Introduction

Laser micromachining can be applied in microelectronics or microsystems packaging basically in two ways: in chip dicing and in via drilling. Typically the processing accuracy with a femtosecond (fs) laser is very good and the heat input is negligible in the processed surface [1, 2, 3, 4] which is a preferred property e.g. in via drilling.

Through silicon via (TSV) technology is becoming more important within the packaging of semiconductor devices since it allows a compact interconnection technology, an excellent electrical performance and a possibility for 3D stacking of silicon chips [5, 6]. In 3D integration much shorter wire lengths are possible allowing the use of higher frequencies, less power consumption, and smaller devices. Thus, TSV technology leads to a small packaging footprint and high packaging density that is a requirement in modern wireless communication products.

TSVs are mainly fabricated by employing deep reactive ion etching (RIE) or laser drilling [6]. Also other techniques such as anisotropic KOH etching and photo assisted electro-chemical etching are applicable. Both RIE and KOH etching require the design of photolithographic masks and the deposition of a suitable masking layer to define the via structures. In laser processing the masks become unnecessary and therefore laser drilling provides a potential for a more flexible manufacturing process with very low cost.

The laser material interaction involves complex processes like heating, melting, vaporization, ejection of atoms, ions and molecules, shock waves, plasma initiation, and plasma expansion. The resulting crater and laser-induced plasma are dependent on the laser beam parameters, pulse duration, energy and wavelength, solid target properties and the condition of the surrounding environment.

Fs lasers with short pulse duration are interesting tools for ablation because the sub picosecond pulse duration is less than a typical thermalization time. Due to a short thermal diffusion length a high precision ablation is possible with fs lasers. Another good property of the short pulse duration is that the beam does not have time to interact with the laser induced plasma and by this way the energy is fully coupled into the target [7].

Even though fs lasers have a possibility for very high intensities, many authors have confirmed that the low fluence regime (<10 J/cm^2) would be most beneficial for the material ablation. Even at a low fluence regime with fs lasers there will be a melt present after the pulse and a melt ejection due to different processes like explosive boiling, thermo capillary forces, plasma recoil pressure etc [8, 7, 9, 10, 11]. When very low fluences are used the processing speed is also very low. In the industry one has to make some trade off between the quality and the processing speed. Some authors have used a vacuum chamber for enhancing the process quality because vacuum makes the ablated material to exit more freely from the hole. Vacuum will also prevent the molten material from interacting with oxygen in the air. An additional advantage of the vacuum chamber is that also the beam will not interact with the ambient air. Thus, higher fluences of the fs pulses can be used since the ionization of the air and its harmful side effects like self focusing can be avoided.

In some cases the debris from the drilling process becomes a problem. Some authors have used a DI-water washing during drilling to satisfy the most demanding cleanness requirements with an efficient cleaning process [12, 13] The simultaneous washing during drilling allows the processed target to have a soluble sacrificial water layer deposited on the surface prior to the laser machining and washed off directly after the machining. Any debris produced during the laser drilling process that is not captured by the vacuum system is trapped in the sacrificial water layer and removed during the wash process.

The laser drilling of silicon is investigated in this study. The idea was to see if the fs laser would be beneficial compared to pico- or nanosecond lasers in the industrial silicon laser drilling. Beneficial means that is the drilling speed fast enough for the industry. Efficiency of drilling is more than just efficiency of the first pulse [14] since behaviour of material removal changes when hole gets deeper [4]. Defects inside the hole are not covered in this paper even though they are important in the application [15]. Results have been evaluated based on optical measurements and scanning electron microscope (SEM) investigations.

2. Experimental

A femtosecond laser system from Quantronics used in this study is presented in the Figures 1 and 2. The laser type is Integra C2.0 with a maximum of 2 mJ pulse energy at 1 kHz pulse repetition rate. The pulse width is 130 fs. The wavelength of the laser is 790 nm. The pulse energy is attenuated with an external polarization dependent cube and a computer controlled polarizing window. After the pulse energy is attenuated the beam is divided into two separate beams. The other part of the beam is introduced to a scan head (Q-Beam) and the other to a normal processing head (Q-Mark). In this study we used f50 and f100 mm optics. The raw beam diameter is 8 mm before focusing.

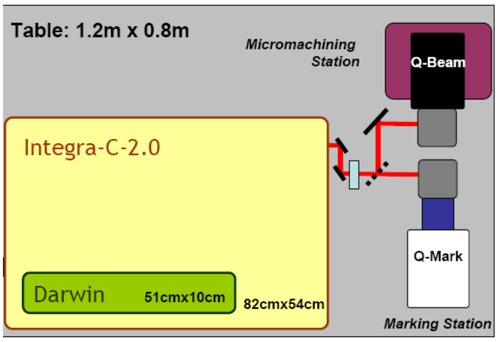


Fig. 1 A schematic layout of the laser processing system

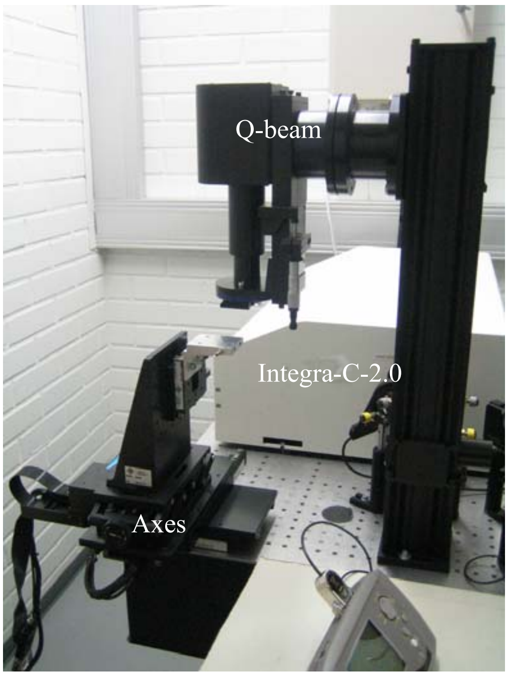


Fig. 2 The actual laser processing setup.

Aerotech ALS-130 axes together with an NView software are used for the sample positioning and the movement in an xy plane. The beam focus is adjusted to the sample surface (z-movement) with an Aerotech manual axis ATS-25-12DM.

The silicon wafer used in the experiments was of p-type, [100] oriented and double side polished. The thickness of the wafer was 380 µm. The targeted hole diameters were 50 µm with the f100 and 30 µm with the f50 optic. The beam was focused on the top of the wafer.

At first we needed to do a series of tests to find suitable process parameters where there are enough pulses to go through the whole wafer. This was done by shooting from 1 to 32000 pulses to the wafer at 1 kHz pulse repetition rate. All holes were shot in a row. After the laser processing the silicon wafer was diced with a Disco DF651 dicing saw along the line of the laser processed holes. After the dicing the sidewall was polished. From Figure 3 we can see that the through penetration can be achieved around 1000–4000 pulses.

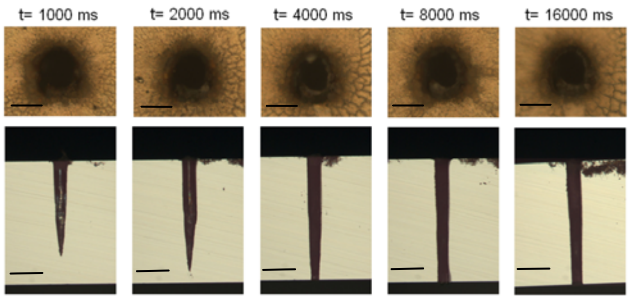


Fig. 3 Holes drilled into silicon using 244 µJ pulse energy with f50 optics in focus. Pulse count from the left to the right is 1000, 2000, 4000, 8000 and 16000 pulses per hole. The scale bars drawn into the pictures are for 40 µm in the holes and 100 µm for the cross-sections.

Estimation of the exact hole depth was not very easy because the dicing of only one line of laser processed holes precisely through the center of the holes was challenging. Thus the the exact depths could not be measured because the sawing was a bit off. This is why the next set of experiments was done using a parameter matrix shown in the Figure 4.

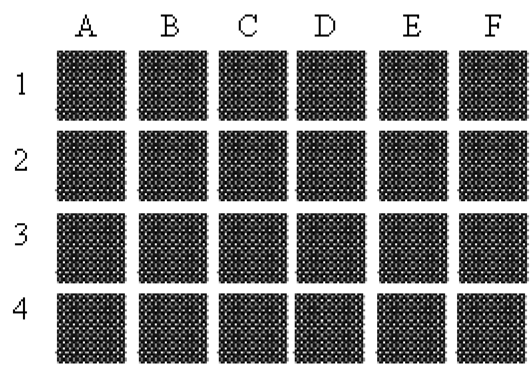


Fig. 4 The layout of the parameter matrix used in the laser processing tests.

The size of one sub matrix in Figure 4 was 11 times 11 holes. Each matrix was processed with six different shot numbers: 125, 250, 500, 1000, 2000, and 4000 (columns A–E). In addition four different pulse energies were used: 850, 525, 244 and 117 µJ (rows 1–4). In one sub matrix the hole to hole distance was 500 µm. With these matrixes the dicing of the samples through the middle of the hole became easier and more accurate data was achieved.

3. Results and discussion

The depth of the holes was measured from their side profiles after dicing. No polishing was done this time. Calculated values for the laser spot sizes are 10 µm for the f50 optics and 20 µm for the f100 optics. The beam quality is taken into account in the calculations. From Table 1 shows the beam intensity values for the different pulse energies that were used.

Table 1 Intensities (in J/cm^2) used with different focusing optics and pulse energies .

	f50	f100
850 µJ	1082	271
525 µJ	668	167
244 µJ	311	78
117 µJ	149	37

These intensities are very high compared to many other authors' [4,16] drilling experiments but the aim was to drill through as fast as possible without a vacuum chamber. From Figure 5 it can be seen that increasing the pulse energy after a certain point does not increase the drilling speed. Using the f50 optics it takes 4000 pulses to get through when the pulse energy is 117 µJ. When the pulse energy is doubled the hole can be made twice as fast and only 2000 pulses are required to drill through the wafer. When again doubling the pulse energy the drilling speed is nominally increased. At 850 µJ the drilling is not faster anymore but a lot of side effects appear. The wafer surface is heavily damaged on the edges of the drilled hole and the hole looses its round shape. The same effect is already visible with a 525 µJ pulse energy. The most probable cause for this is the laser induced breakdown and plasma which are also regocnized by other authors [14, 17].

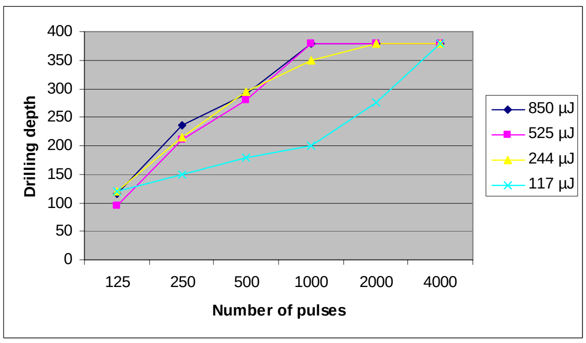


Fig. 5 Drilling depth as a function of the number of pulses with the f50 optics and at different pulse energies.

J Koga et al [17] have performed extensive research on a laser induced breakdown of air and they have found that with a 20 µm spot size the breakdown energy at the 800 nm wavelength with a 100 fs pulse length is 320 µJ. The sound produced when the air breakdown happens can be easily heard at the 580 µJ energy level. The intensities corresponding these pulse energies are in a range of 100–185 J/cm^2. This means that when the breakdown of air happens, some part of the pulse energy is lost in the ionization process and the beam focusing changes as the air properties change. The experiments made by Koga et al [17] were made in air without any target present. Hwang et al [14] had similar results when no target was present.

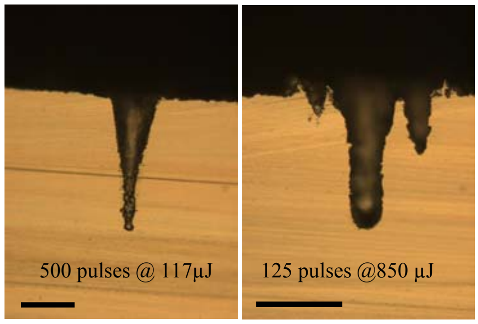
a)  b)

Fig. 6 Drilling with the f100 optics. The depth of the hole in a) is ~250 µm and in b) ~155 µm. Very heavy damages can be seen around the hole with the higher pulse energy in figure b). The length of the scale bars in both a) and b) is 100 µm.

When using the f100 optics the intensities are a lot smaller than with the f50 optics and no air breakdown should be present at the lowest pulse energies. This seems to be true since the increasing pulse energy increases the drilling rate as shown in Figure 7. When it takes 2000 pulses with the 244 µJ pulse energy to drill through the wafer only 1000 pulses is needed with the 525 µJ pulse energy. But again, the 850 µJ pulse energy does not work anymore since the upper surface of the wafer is damaged again as seen in Figure 6 b

Fig. 7 The drilling depth as a function of the number of pulses with the f100 optics and at different pulse energies.

The scale of the x-axis in the Figure 7 is logarithmic and it can be seen that the drilling rate slows down when more pulses are introduced. At the 117 µJ pulse energy the data for the 500 and 1000 pulses is misleading because the depth measurement was not made from middle of the hole and this is why the curve is not reliable at those points.

Since the drilling is done by focusing the beam on the surface of the wafer the holes are quite conical. After breaking through the wafer the additional pulses start shaping the holes more cylindrical. This can be easily seen from the Figure 3. Changing the focal position would change the geometry of the drilled hole .

Many authors like Mizeikis et al [18] have used a vacuum chamber for the femtosecond drilling experiments to improve the drilling ability. Vacuum also removes the danger of the laser induced breakdown of air or other gases. In industrial application the vacuum chamber might induce additional costs due to the part handling and the vacuum pumping time that could be a challenge for the economics of the process.

4. Conclusions

Drilling of silicon was demonstrated to work well but depending on pulse energy drilling is affected by the side effects. The effects ruin the quality and will not help in enhancing the drilling speed. Drilling depth per pulse is slowed down after couple of hundred pulses a lot. Because more pulses are needed to go through the wafer it takes longer time to finish drilling.

More work is needed to be done if industrial speeds are pursued in using similar femtosecond systems. Using of vacuum chamber is known to give better quality in drilling. Vacuum also makes the air breakdown problem disappear due there is not air to influence with the beam.

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