Advanced micromachining combining nanosecond lasers with water jet-guided laser technology

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ABSTRACT

This paper presents the first scribing results obtained by combining a short-pulse 10ns green laser with the water jet-guided laser technology. A number of high-potential applications are presented, from the grooving of low-k silicon wafers, the scribing of metallic and amorphous Si layers of thin film solar cells, the grooving of SiC wafers, and dot marking of Si wafers. The combination of a short pulse laser beam with the water jet-guided laser technology offers a new industry-proven alternative for grooving and scribing processes, providing superior speed and quality compared to legacy laser technologies.

Keywords: Laser, micromachining, short pulse, water jet-guided laser, grooving, dot marking

1. INTRODUCTION TO LASER MICROJET TECHNOLOGY

The water jet-guided laser technology, first presented in 1994 [1,2], has found a broad range of applications in the precision micromachining field. The water jet-guided laser (also called Laser MicroJet® or LMJ®) is used today in a wide range of industrial fields, such as semiconductor, solar, electronics, medical, tooling [3], high-brightness LED [4], watch and automotive industries.

Its principle is to couple a high power, pulsed laser beam into a hair-thin, low-pressure water jet. A schematic of the principle is shown in Figure 1. The beam of a high power Q-switched diode-pumped solid-state (DPSS) laser is transmitted by fibre optic cable to an optical head. There it is focused through a transparent window into a nozzle placed at the bottom of a thin water-filled chamber. Pure de-ionized, degassed and filtered water is introduced into the water-filled chamber with a pressure ranging from 50 to 600 bar, depending on the nozzle diameter. Larger nozzle diameters require a smaller water pressure. Typical nozzle diameters range from 20 μm to 150 μm. The cylindrical water jet exiting the nozzle guides the laser beam by means of total internal reflection at the water/air interface, similarly to conventional glass fibers. When it reaches the work piece, the laser ablates the material by melting and vaporization.

The capabilities and performances of this process are different from those of conventional dry lasers. First, because the water jet is cylindrical and the guided laser beam parallel, kerf walls are highly parallel. The working distance – corresponding to the stable length of the jet – can be several centimeters long, depending on the jet diameter. Working distances in excess of 15 cm are possible with the largest nozzle diameters. Given the long working distance, there is no need for expensive focus control optics. Second, the water jet-guided laser prevents heat damage to the material by cooling the cutting edges in between the laser pulses. Third, contamination is greatly reduced, as the water jet develops a high kinetic energy that efficiently removes the molten material generated by the laser ablation. Contamination by particle deposition is avoided thanks to a thin water film that covers the wafer surface during the cutting process. The particles, already cooled down by the water jet, cannot adhere to the wafer. The mechanical force of the water jet onto the wafer is negligible (<0.1N) due to the small jet diameter and the low water pressure. This leaves the material unscathed when exposed to the bare jet. The process does not generate chipping or micro-cracks. As a comparison, the assist gas jet used in conventional laser cutting applies a force of around 1N, ten times higher than the water jet-guided laser. Water consumption is very low, averaging about 1.5l/hour.

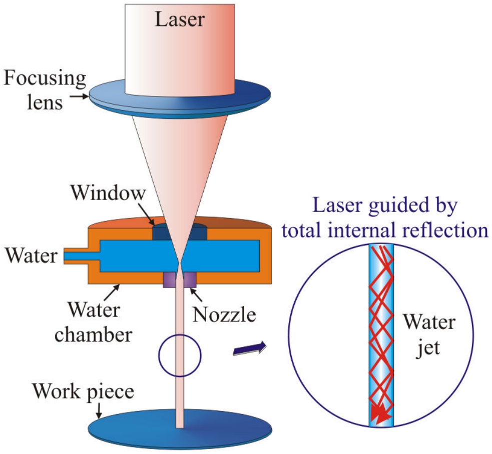

Figure 1: Basic principle of the water jet-guided laser technology.

Different Nd:YAG laser sources with wavelength of 1064 nm working in pulsed or Q-switch regimes have been used with the water jet-guided laser technology. Flash-lamp-pumped and diode-pumped infrared lasers were implemented. In recent years, new laser technologies such as disc and fiber lasers have been deployed with success in a wide range of demanding applications, where the LMJ system operates in 24/7 production environments.

Frequency-doubled Q-switched DPSS and disc lasers operating at 532nm and 515nm have since become the standard laser sources for most LMJ applications due to their excellent compatibility with water absorption spectrum. The only constraint on the laser wavelength is that it must be compatible with the water transmission spectrum, which has a minimum in the green region of the optical spectrum. The absorption coefficient α in the water jet is the lowest (α = 4E-4 cm^{-1}) at a wavelength of 532nm. The absorption coefficient is about 500 times higher at 1064nm (α = 0.2 cm^{-1}). The light transmission over a 2.5cm water jet is as high as 99.9% at 532nm, and 60% at 1064nm. This means that the light absorption at 532nm can be neglected.

Frequency-tripled (355nm) UV lasers have also been used with success in some specific applications, such as low-k wafer grooving or sapphire wafer cutting [5].

Table 1 below shows typical pulse duration, pulse frequency and energy per pulse characteristics of lasers used in the past with the water jet-guided laser technology.

Table 1. Parameters of the Synova lasers

	Pulsed lasers	**Q-switched lasers**
Pulse duration	80 – 250 µs	100 – 1500 ns
Pulse frequency	1 – 1000 Hz	8-50 kHz
Energy per pulse	0.01 – 20 J	<30 mJ

In this paper we present the first micromachining results obtained with short-pulse (10ns) Q-switched frequency-doubled DPSS lasers. The short pulse duration allows to reduce the heat affected zone (HAZ) near the domain irradiated by the laser beam, which is desirable in a number of grooving and marking applications, as described in Section 3. The following Section describes in more details the laser used for the experiments described in the rest of the paper.

The main motivation for evaluating a short-pulse laser was to test applications that proved difficult when processing with the conventional lasers listed in Table 1.

2. SHORT-PULSE LASER DESCRIPTION

The grooving and scribing applications presented in Section 3 were performed using a compact end-pumped Nd:YVO4 laser with the fundamental output wavelength of 1064 nm [6]. A second harmonic generation (SHG) module was appended to the infrared output to obtain 532 nm green light. The laser produces short 10 ns laser pulses at about 11 W average output power. The Q-switch repetition rate ranges from 15 to 300 kHz. The TEM_{00} laser has a M^2 smaller than 1.3. The full angle beam divergence is smaller than 1mrad. The pulse-to-pulse stability is better than 5% RMS.

Besides the laser main cavity and SHG, the unit includes a chiller and a power supply. In the latter, two laser diode modules with 26 W each of 808 nm pump power are integrated, together with their power supply, fans and control electronics for the laser head and communication. The light from the pump diodes is guided to the main laser cavity using two optical fibers.

The laser was characterized at different diode current levels and repetition rates. The average power is shown in Figures 2a and 2b, the pulse width is shown in Figure 3, and the corresponding peak power is shown in Figure 4.

At the laser output the beam was focused into a 150 μm fiber in order to facilitate the integration with the LMJ optical head. The focusing optics consisted of a beam expander and a focusing lens, mounted outside of the laser chassis.

At 100% diode current the average laser power, measured at the laser output (before the optical fiber), increases from 5 W at 15 kHz to 13 W at 40 kHz. At higher repetition rates the average power goes down. At 200 kHz, the average power is 3 W.

The pulse width at 100% diode current, shown in Figure 3, increases from 8 ns at 20 kHz to 16 ns at 100 kHz. The peak power, shown in Figure 4, decreases from 45 kW at 20 kHz to 5 kW at 100 kHz. The pulse energy at 100% diode current is 310 μJ at 20 kHz and 62 μJ at 100 kHz.

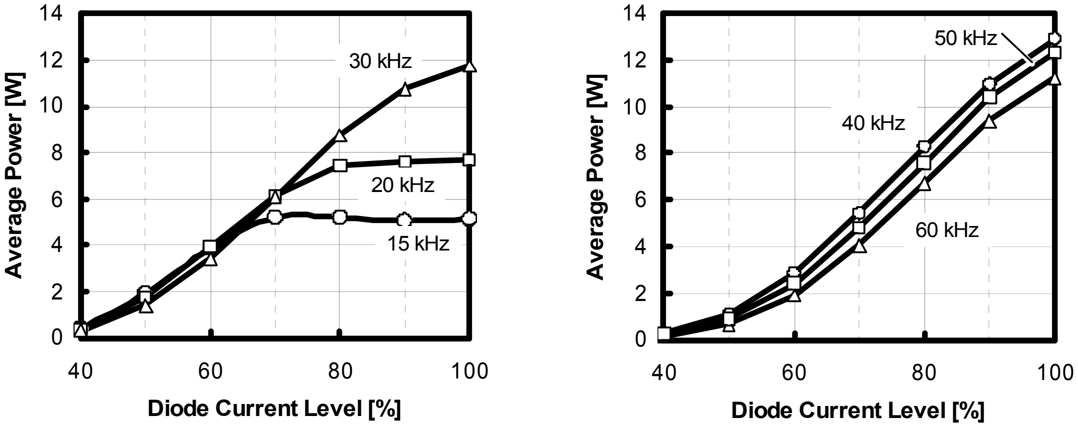

Figure 2a: Measured average power as a function of the diode current level, for different repetition rates.

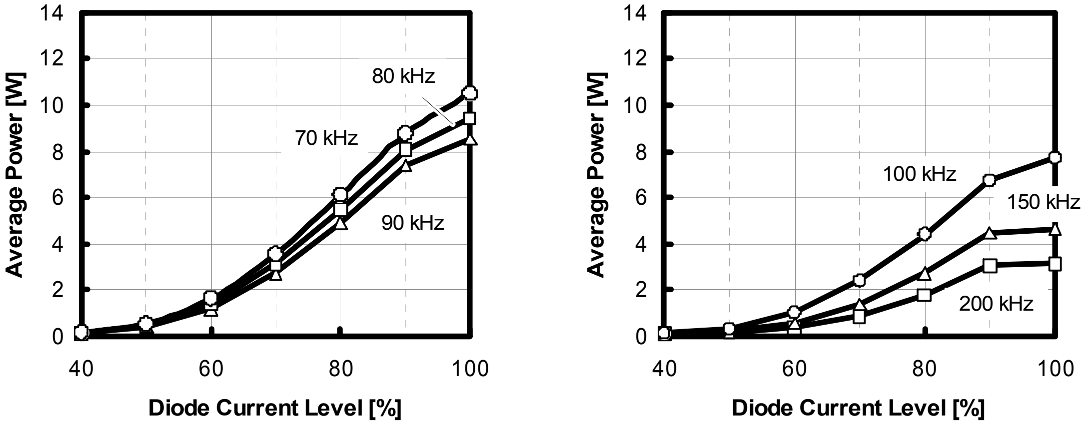

Figure 2b: Measured average power as a function of the diode current level, for different repetition rates.

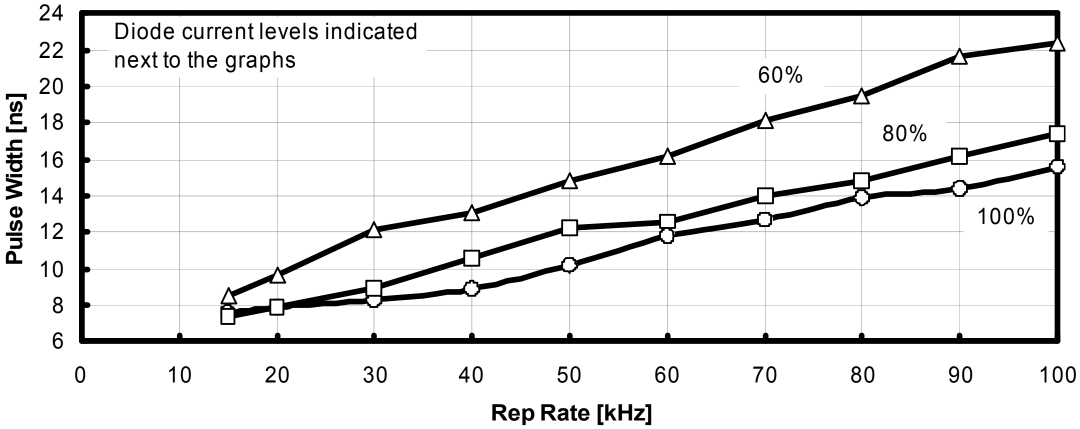

Figure 3: Measured pulse width as a function of the repetition rate, for different diode current levels.

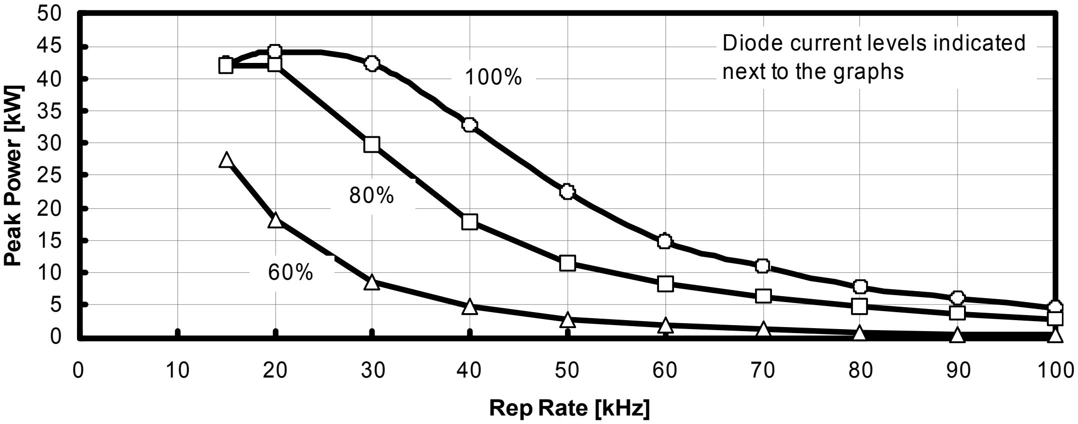

Figure 4: Extracted peak power as a function of the repetition rate, for different diode current levels.

3. APPLICATIONS WITH SHORT-PULSE LASER

The laser described in the previous Section was used in combination with the water jet-guided laser technology to groove and scribe a number of materials. The main results are summarized in this Section.

3.1 Low-k silicon wafer scribing

The constant need of better die performance has led researchers in the semiconductor field to turn toward new materials with a low dielectric constant ($k < 3.0$). Use of materials with a k value lower than SiO_2 has reduced the capacitance of the interconnect structure. In tandem with the replacement of aluminum, interconnects with copper reducing structural resistance, paving the way for this major improvement by permitting a market-relevant reduction of the interconnect delay. The term "low-k wafers" is imprecise because it covers several different classes of materials, all performance enhancing. Product features are shrunk; power consumption is lower; and signal integrity is improved. Despite the performance advantages, this emerging technology has also imposed new challenges for manufacturers. Comparatively, the chemical, thermal, and mechanical behaviors of low-k wafers are quite different from traditional materials, making them very difficult to integrate. The impact is especially strong when it comes to highly sensitive operations, such as dicing. Developing new approaches to satisfy the requirements of manufacturers in terms of quality and yield has become a necessity. Various dicing solutions conceived to respond to the low-k wafer requirements have been tested.

Low-k wafers tend to peel and chip during the dicing process due to the brittleness and fragility of the top layers, consisting mainly of oxides, metals and silicon. Due to these specific characteristics, conventional dicing techniques are unsatisfactory. Alternatives are required.

As wafers become thinner, more brittle, more complex, and multi-layered, sawing with diamond blade saws has become a challenge. New technologies are called upon to match the current evolution in the industry. If diamond saws are used, dicing speeds are obligatorily decreased (down to 2 to 3 mm/s). Even with such drastic speed reductions, chipping and cracking formation due to mechanical stress are unavoidable in most cases of low-k wafer dicing. Furthermore, the blades are subjected to high wear, consequently having a short life, imposing high blade consumption and incurring high running costs.

The water jet-guided laser technology, well suited for low-k Si wafer dicing, has already been implemented with success in wafer fabs. New experiments, performed with the short-pulse laser described in the previous Section, are described hereafter. The goal is to use a hybrid approach, by removing the delicate interconnect layers with the LMJ process and subsequently dicing the silicon wafer completely using a blade saw.

Scribing tests were performed on a 200 µm thick low-k wafer. An 80 µm nozzle was used, which delivers a water-jet diameter of 72 µm. A laser repetition rate of 70 kHz and a diode current of 100% were used. The average power was 8.4 W. A single pass was performed at a speed of 70 mm/s.

Figure 5 shows the dicing street before and after the scribing step. The overall scribing quality is excellent, and there is no damage outside the dicing street. The resulting scribing edges are smooth and straight. A scribing depth bigger than 30 µm was easily obtained. In a second step this wafer was cut through with a diamond blade.

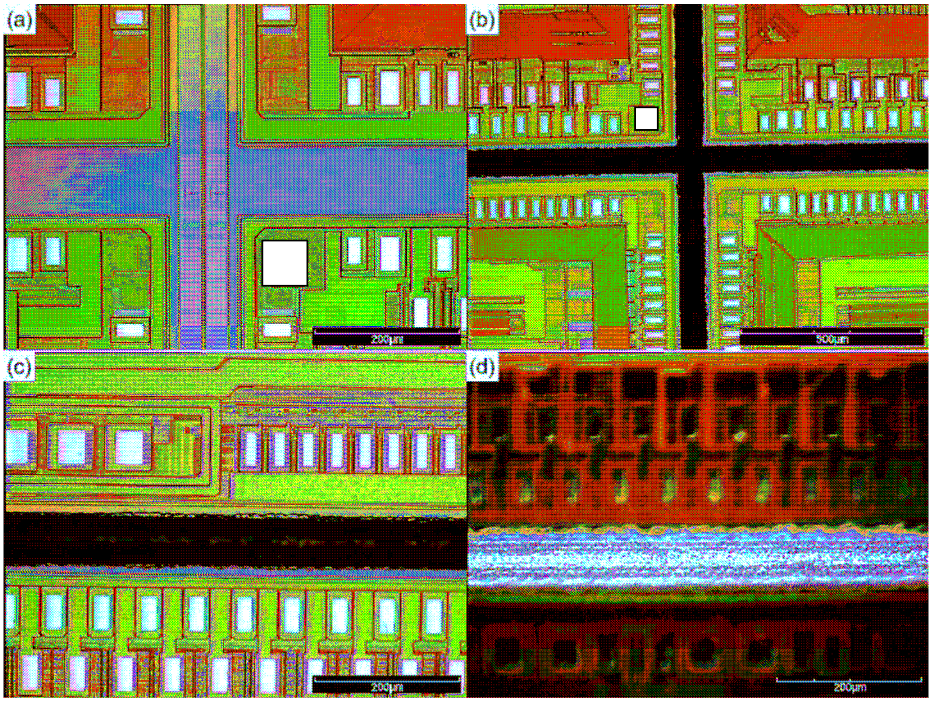

Figure 5: Pictures of low-k wafer scribing. (a) Dicing street before scribing. (b) – (d) Kerf afer grooving step.

3.2 P3 step of thin film solar cell processing

In order to make photovoltaic power generation an economically viable option, the cost of solar cell devices has to be lowered. Nowadays most solar cells are manufactured from crystalline Si substrates with a typical thickness of 200 to 300 µm. Since the base material for these devices is electronic-grade Si, a large part of the cost of the final solar cell is related to the active material. In order to reduce these costs, a transition is under way from bulk crystalline Si solar cells to thin-film technologies with reduced usage of active material in the device. These thin films can consist of crystalline, multicrystalline, or amorphous silicon. In addition, II-VI polycrystalline compounds like CdTe or ternary compounds like CuIn(Ga)Se2(S)-alloys are being investigated and developed. In the case of thin films of Si, there is a broad range of deposition technologies. Important efforts are under way to develop more efficient ways to remove these thin layers. Dry lasers are currently being implemented for the P1, P2 and P3 steps, but the thermal damage associated with the laser can cause severe process limitations. The Laser MicroJet is now also being implemented to remove layers in the thin film solar market.

The use of the Laser MicroJet to remove a metal backreflector layer of 0.1 to 0.5 µm thickness and an amorphous layer of 1 to 2 µm thickness (see Fig. 6) was investigated using the short-pulse laser described in Section 2. This is the so-called P3 step in the thin film manufacturing process.

A water chamber with a 50 µm diameter nozzle was used. The laser repetition rate was 60 kHz and the diode current 100%. The average power was 11 W, the pulse width 12 ns and the peak power 15kW. Both layers of the P3 process were removed with one pass at a speed of 1000 mm/s. As can be seen on Fig. 6 (c), the TCO layer remains intact and the isolation is excellent.

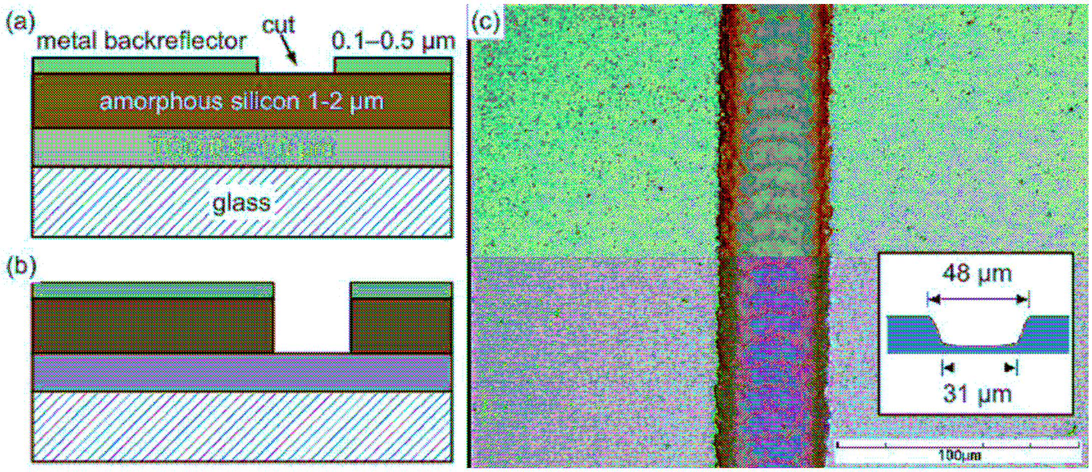

Figure 6: (a) & (b) show a cross section of the structure. (c) Microscope image of the cut for the process step in (b).

3.3 SiC grooving

There is currently much interest in the use of silicon carbide (SiC) as a semiconductor material in electronics, where its high thermal conductivity, high electric field breakdown strength and high maximum current density make it more promising than silicon for high-powered devices.

Grooves in 50 µm thick SiC wafers were performed with the Laser MicroJet. The customer-supplied samples had photoresist on most of the wafer area, but the cuts had to be performed there where the wafer was free of photoresist. A repetition rate of 70 kHz and an average power of 10 W were preferred. The kerf width, obtained with 50 µm nozzles, was about 48 µm. One single pass, with a grooving speed of 20 mm/s, was sufficient to achieve the 20 µm deep grooves.

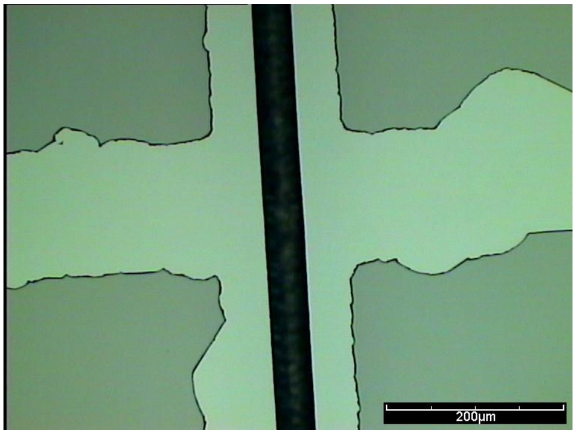

Figure 7: microscope image of a 20 µm deep groove in a 50 µm thick SiC wafer.

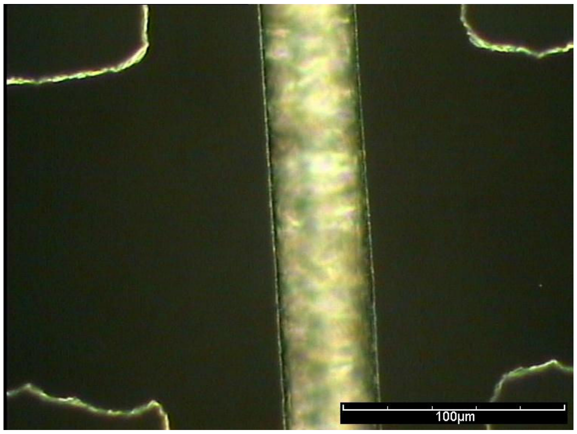

Figure 8: top side view of the groove (dark field illumination), with focus on the top of the groove.

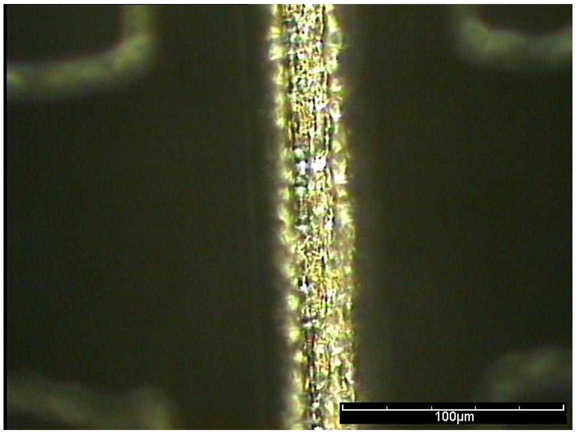

Figure 9: top side view of the groove (dark field illumination), with focus on the bottom of the groove.

3.4 Si wafer dot marking

Laser dot marking is an efficient way to add permanent marking on ICs, MEMS or solar cells.

The Laser-MicroJet technology has been tested for dot marking on silicon with the short-pulse laser described in Section 2. Si wafers with a thickness of 670 µm were processed using a laser repetition rate of 70 kHz and an average power of 70W. Dots with a diameter of 50 to 100 µm were drilled, as shown in Figure 10. The depth of the holes was varied from 30 to 130 µm by changing the processing conditions. A speed of 2.2 ms (5.1 ms) per hole was obtained for 30 µm (70 µm, respectively) deep holes. The hole-to-hole depth uniformity is excellent, as shown in Figure 11. Figures 12 and 13 show a close-up view of a hole.

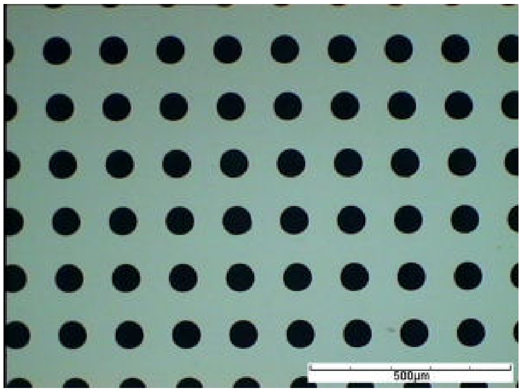

Figure 10: top side view of holes drilled in a Si wafer.

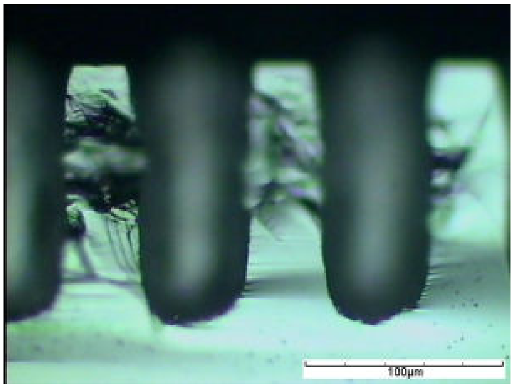

Figure 11: cross section of holes drilled in a Si wafer. The hole-to-hole depth uniformity is excellent.

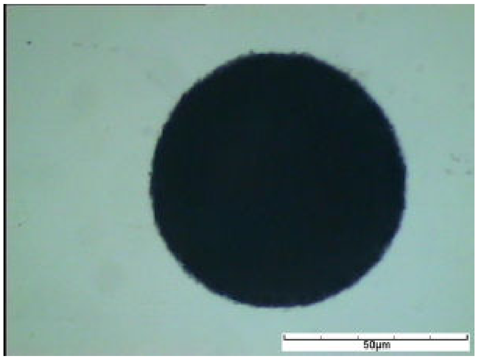

Figure 12: microscope image of a hole. Bright field image.

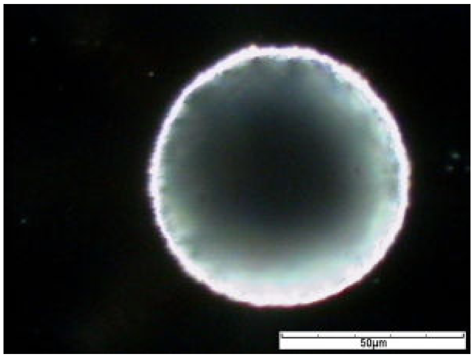

Figure 13: microscope image with focus inside a hole. Dark field image.

4. CONCLUSION

In this paper, results obtained by combining a short-pulse (10ns) end-pumped Nd:YVO4 laser with SGH module and the water jet-guided laser technology are presented for the first time. We have demonstrated that short-pulse lasers are very interesting for precision grooving and scribing applications. The technology is well suited for low-k Si wafer scribing, the fabrication of the P3 step of thin film solar cells, SiC wafer grooving and Si wafer dot marking. It is also very well suited in other applications not covered in this article, such as edge isolation of solar cells.

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