COHERENT

White Paper

Economical, High Precision Laser Processing

There is an ongoing trend in a number of industries towards the processing of materials with smaller and higher precision features; examples include semiconductor fabrication, display manufacture, micromachining, and biomedicine. The most demanding of these applications are now being addressed with lasers having pulsewidths in the picosecond regime. However, for some of the most cost sensitive applications, picosecond laser technology offers sufficient throughput, but is not an economically viable option. Less complex laser sources, with pulsewidths in the 600 ps range, can sometimes achieve the required processing precision for these uses, while still meeting cost constraints. This whitepaper examines the laser technology used to produce this type of output, and reviews some of its current applications.

Why Shorter Pulsewidths?

In laser micromachining of numerous different materials, shorter pulsewidths have proven to deliver better results in terms of higher spatial resolution, better depth control, enhanced edge quality, and minimized peripheral thermal damage. For very short pulsewidths, namely those in the 15 ps range, this improved processing occurs because the laser/material interaction operates on a fundamentally different mechanism than what occurs with nanosecond regime pulses. Specifically, nanosecond pulses remove material through a photothermal interaction, in which material is heated up until it is vaporized. In contrast, ultrafast pulses remove material by photoablation. In this process, the high peak fluences drive multiphoton absorption which strips electrons from the material, which then explodes away because of repulsion. Because photoablation involves directly breaking the molecular or atomic bonds which hold the material together, rather than simply heating it, it is intrinsically not a hot process.

Building a system which produces ultrafast pulses, and which also delivers extensive performance features and industrial reliability, necessarily entails some complexity. That makes these lasers too costly for some applications which might benefit from their improved processing capabilities.

Fortunately, it is also possible to obtain many of the advantages of ultrafast laser processing using simpler lasers having pulsewidths in the 600 ps range, even though this pulsewidth is not short enough to drive photoablation. There are two primary reasons for this.

The first of these relates to the fact that every material has an ablation threshold (the minimum peak intensity required to vaporize and remove material). For a given pulse energy, a shorter pulse delivers more of its total energy above this threshold power, where it goes into performing the desired process (cutting, drilling, etc.). In contrast, much of the energy of a longer pulse simply goes into simply heating the material.

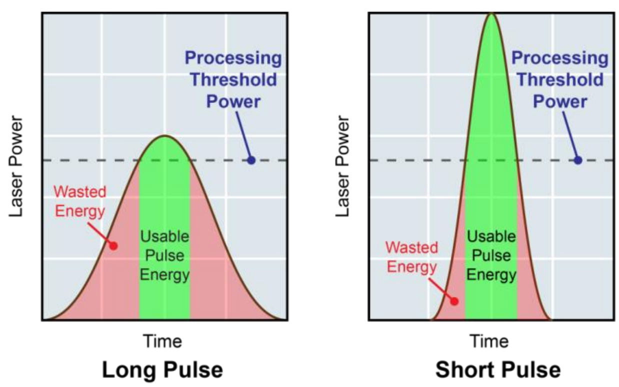

Figure 1. With longer pulses, much of the laser energy only contributes to heating – heat which can spread into surrounding material and cause damage known as the heat affected zone (HAZ). With shorter pulses, a higher proportion of the pulse energy is delivered above the threshold power level, maximizing processing, while minimizing the HAZ.

The second benefit of shorter pulsewidths is that more of the absorbed laser energy is carried away within the ejected, vaporized material before it can flow into the surrounding material. This effect is most pronounced in thermal conductors, like metals, and less so in thermal insulators, like plastics. As a reference point, in an intermediate material like silicon dioxide, heat can spread over 1 µm in less than 10 ns. Achieving a sub-micron HAZ therefore requires pulses shorter than 10 ns in this material.

Economical, Short Pulse Technology

It is possible to construct an economical laser with pulsewidths in the 600 ps range by taking advantage of the inherent relationship between pulsewidth and other resonator parameters (these are summarized in the table). Specifically, this is achieved by reducing cavity length, while carefully managing other resonator properties, including repetition rate, pump power and cavity losses.

Parameter	Pulsewidth decreases as this parameter...	Output power increases as this parameter...
Resonator length	Decreases	Increases
Repetition rate	Decreases	Increases
Pump light intensity	Increases	Increases
Emission cross section	Increases	Increases
Cavity losses	Increases	Decreases

Table 1. Relationships amongst laser resonator properties and output parameters.

In the Coherent Helios series of diode-pumped, solid-state lasers, our engineers have pushed the miniaturization of the cavity and its components to the very limit. The result is an effective cavity length of a few millimeters, resulting in pulsewidths of around 600 ps. The near-IR output of this miniaturized oscillator is a fairly modest 1 Watt at a repetition rate of 50 kHz, due to the small gain crystal. A master oscillator power amplifier (MOPA) arrangement is therefore used to reach a higher final output power. The use of a similarly miniaturized single amplifier stage provides 2.5 W of average power (50 µj at 50 kHz), while two amplifier stages can deliver 5 W of average power (100 µj at 50 kHz) at 1064 nm. This high peak power also supports very efficient but economical extra-cavity frequency doubling. Specifically, Coherent Helios lasers offer up to 3 W of average power (60 µj at 50 kHz) of output at 532 nm. Both the amplifiers and the doubling optics are monolithically integrated with the sealed laser head. Even though these free space lasers are highly miniaturized, the cavity has been designed to deliver a circular beam with excellent mode quality by carefully matching the crystal size to the cavity dimensions, and thus the mode volume of the intracavity beam. Typically, these lasers deliver $M^2 < 1.25$, making them well-suited to high precision tasks. Another important design feature of Coherent Helios lasers is the use of an active Q-switch. This enables the laser to be operated at the precise repetition rate which optimizes the combination of pulsewidth and pulse energy (and therefore output power). Also, it allows the timing jitter of the pulse repetition rate to be actively minimized. This is particularly important in applications, such as thin film scribing, in which the beam is moved rapidly, resulting in low spot overlap. Without good control over jitter, it is possible to get gaps in the scribe, rather than a continuous line. A number of laser micromachining applications are now turning to these lasers because they deliver some of the advantages of industrial ultrafast lasers, while, in some cases, costing only a tenth as much.

Applications

Glass marking has emerged as an important application for lasers. Glass is used in an increasing number of products, including displays, medical packaging, bottles, and for architectural purposes. Marking can be used to place logos, serial numbers and bar codes on glass. The visibility of laser produced marks can be varied by adjusting laser parameters. This enables the production of clearly visible marks for esthetic appeal or product personalization (e.g. putting an individual's name on a product), as well as barely visible marks, such as might be used for anticounterfeiting purposes. When laser marking glass, it is critical that the process not introduce any microcracks, as these can weaken the material and make it more subject to breakage. This is particularly problematic when processing the newest breed of strengthened glass products, which are made more resistant to scratches and cracks through a chemical or thermal hardening process. The newest technique in this area is so-called "color marking" because the mark exhibits a rainbow-like color effect when viewed under the proper lighting. Color marking actually involves ablating just a few nanometers of material from the surface of a glass or sapphire substrate. Again, it is critical that the marking process produce a smooth variation in surface profile, without any cracks. The Helios laser operating at 532 nm has proven to be a very effective source for this process, while it hasn't been possible to achieve the same, crack free quality with longer (nanosecond) pulsewidth lasers. In particular, the Helios laser enables a large process window for crack free marking. It can be used with pulse energies of 40 to 60 µJ at beam diameters of about 20 µm. The visibility of the color marks can be varied over a wide range by choosing the proper laser parameters.

Figure 2: Color mark on glass, produced using a Helios laser operating at 532 nm.

Helios lasers are also used to engrave and produce more traditional marks on glass and sapphire. In this case, marks are typically on the order of 10 µm deep in order to make them clearly visible. One particular application is in marking the sapphire wafers used as substrates in the production of high brightness LEDs. These marks are typically lot numbers and other identifying information placed on the sapphire after LED structures have been created, i.e., after a significant amount of cost has been built into the substrate. The major challenge here is to produce easily readable marks while having no negative impact on the surrounding circuit structures. But, this is difficult because sapphire is both extremely hard and also transparent at most laser wavelengths. In the past, some sapphire marking has been performed with nanosecond lasers, but the quality is less than optimal, and these lasers can produce microcracks in the substrate. Marking with 532 nm Helios laser now solves both these problems, and results in marks with excellent surface and edge quality, sharp detail in the marks, and an absence of peripheral damage.

Figure 3: Picosecond lasers can be used to mark sapphire, which is difficult to mark by other means due to its extreme hardness.

In addition to marking glass and sapphire, Helios lasers can also be used for cutting and scribing these and other brittle and/or delicate materials, such as silicon, which are difficult to machine using traditional mechanical methods. For example, when dicing silicon wafers used in semiconductor device fabrication, it is especially essential that the cutting process doesn't produce significant microcracks. Silicon scribing with the Helios laser results in reduced microcracking, which improves the bending strength of the material and protects the chip circuitry during bonding and other subsequent processing steps.

For cutting, scribing and hole drilling in glass and sapphire, the Helios laser offers advantages over both nanosecond and even shorter pulse, ultrafast lasers. Once again, the advantage over longer pulsewidth lasers is cut quality. Specifically, this laser produces a cleaner drilled hole, with fewer particles and less microcracking. This advantage is demonstrated clearly in the accompanying photographs.

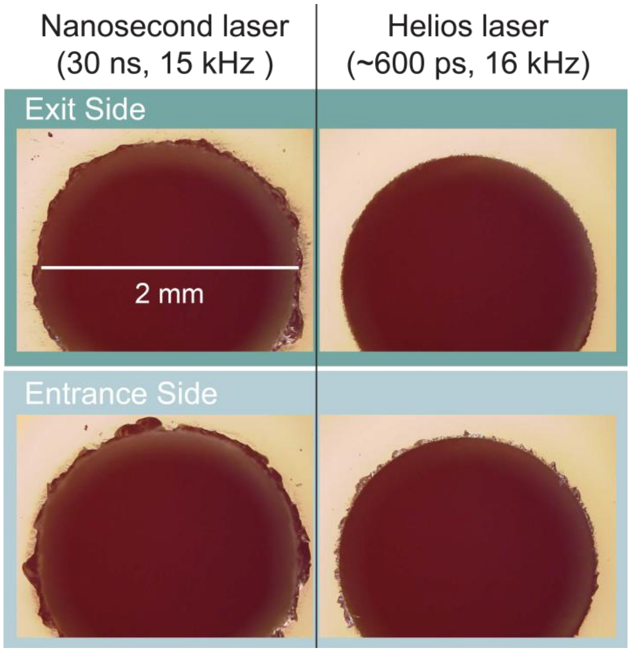

Figure 4: Comparison of holes drilled in 1.8 mm thick glass with a nanosecond and a picosecond laser. The picosecond laser produced substantially cleaner holes with less recast material. (Source LMBT 18.01.2012:ILaCoS2012)

When compared with ultrafast lasers, the Helios offers the benefit of producing higher aspect ratio holes in thicker substrates, in addition to the advantage of lower costs. The problem is that, when glass or sapphire is laser micromachined from the front surface down, the hole takes on a tapered shape. This can be remedied by starting the process from the bottom side of the substrate and working up. However, the very small particles produced during ultrafast laser processing can actually create a fluid-like slurry which tends to close up the machined hole as it is created. This problem doesn't occur when micromachining with the longer pulsewidths employed by the Helios.

Another significant application area for Helios lasers is in thin film scribing. Typical examples are the patterning of the transparent conductive oxides used in touch screens and the metals used in photovoltaics.

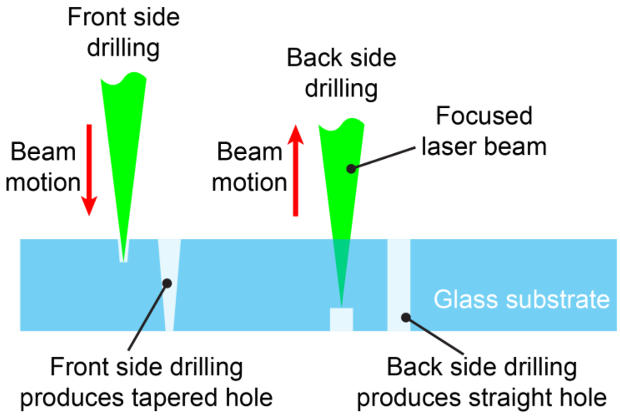

Figure 5: The Helios laser is unique in being able to produce clean, high aspect ratio holes in relatively thick glass and fused silica substrates.

For the display and touch screen markets, a direct patterning process called spallation is enabled by Helios and other ultrafast industrial lasers. Spallation can selectively remove thin films of up to a few hundred nanometers in thickness with high precision, and without damage to underlying layers. In addition, spallation is a single-step, dry process that leaves almost no debris, meaning that no post-processing (cleaning) is usually required. Spallation requires that the top, thin film layer be transparent at the laser wavelength, while the underlying layer or material be strongly absorbing at that wavelength. Under these conditions, all the laser energy is absorbed in the first few nanometers of this underlying layer. Because this absorption occurs at an enclosed interface, there is nowhere for the expanding vaporized material to escape.

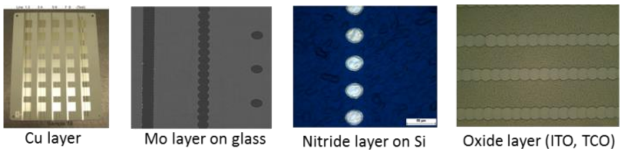

Figure 6: A gallery of diverse thin films removed with high precision using the Helios laser.

As a result, this catastrophic expansion of atomized material creates a shock wave that blows off the thinner top layer. Because spallation minimizes damage to the surrounding and underlying materials, it is ideal for most thin films used in the electronics and display industries.

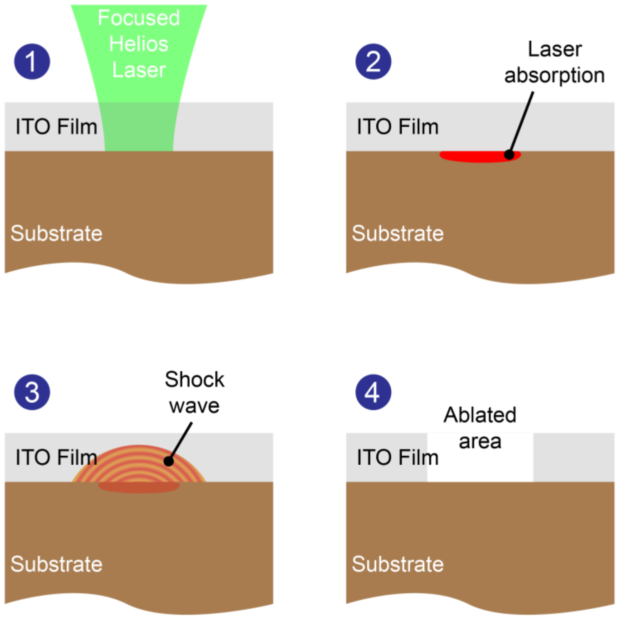

Figure 7: In spallation 1) a focused laser beam is absorbed at an interface, 2) heating occurs in a thin layer, 3) a shock wave expands out, and 4) the outer, thinner layer is blown off.

In conclusion, Helios lasers, which produce sub-nanosecond pulsewidths, provide an attractive alternative for a number of demanding laser microprocessing applications. In particular, they offer many of the same benefits in terms of process quality as more sophisticated picosecond sources, while costing substantially less. Plus, their compact size makes them easy to integrate into a wide range of systems.

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