Industrial Ultrafast Lasers Enable Precision Microprocessing

In semiconductor microelectronics production, display fabrication, medical device manufacture and many other industries, there is an increasing trend towards higher precision processing. Specifically, this means cutting, drilling and marking of parts with smaller feature sizes and greater accuracy, and with reduced effect on surrounding material. In the past, most precision processing applications relied on lasers with nanosecond pulsewidths or ultraviolet output (or both). But, these traditional sources cannot always service this new, demanding class of applications. As a result, some applications are now turning to lasers with ultrafast (picosecond or femtosecond) regime pulsewidths to accomplish these tasks. This article reviews the benefits of ultrafast processing and highlights some typical applications.

Ultrafast Processing Benefits

The goal of micromachining is the creation of micron-scale features, such as holes, grooves and marks, with high dimensional accuracy, while avoiding peripheral thermal damage to surrounding material. In other words, precise, clean cuts and marks with minimal heat affected zone (HAZ).

There are two basic mechanisms by which a laser can precision drill, scribe, cut or mark a material. Many traditional applications rely on infrared and visible Q-switched lasers, which have pulsewidths in the tens of nanoseconds range, and which remove material via a photothermal interaction. Here, the focused laser beam acts as a spatially confined, intense heat source. Targeted material is heated up rapidly, eventually causing it to be vaporized (essentially boiled away).

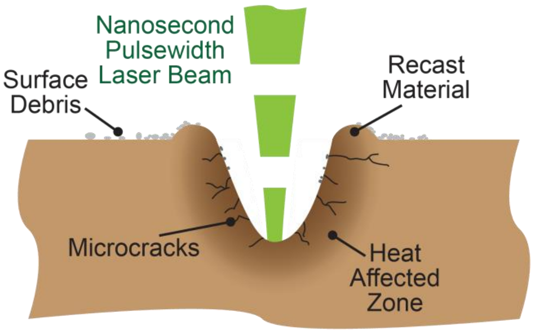
The advantage of this approach is that it enables rapid removal of relatively large amounts of target material (particularly considering the multi-kHz repetition rates at which Q-switched lasers typically operate). Furthermore, nanosecond laser technology is well established, and these sources are highly reliable and have attractive cost of ownership characteristics. However, for the most demanding tasks, peripheral heat affected zone (HAZ) damage (e.g., delamination of surface coatings, microcracking) and/or the presence of some recast material, can present a limitation.

One way of minimizing the size of the HAZ is to employ a nanosecond laser having output in the ultraviolet (UV), rather than in the visible or near infrared. UV light is strongly absorbed by most materials. This limits how far the laser light penetrates into the part and therefore reduces the HAZ.

The second mechanism for laser material removal is based on photoablation. This can be performed with ultrafast lasers because their short pulsewidths lead to very high peak powers (megawatts and above). These high peak fluences drive multiphoton absorption which strips electrons from the material, which then explodes away because of Coloumb 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. Also, when using ultrafast pulses, the laser processed material is removed in such a short timeframe that the ablated material carries away most of the energy before heat can spread into the surrounding material. Together, these effects result in significantly reduced heat affected zone. Plus this is very clean process, leaving no recast material and thereby eliminating the need for elaborate post-processing.

Another major advantage of ultrafast processing is that it is compatible with a very broad range of materials, including several high bandgap materials (e.g. glass, sapphire, certain polymers) that have low linear optical absorption and hence are difficult to machine with existing, commercially available lasers. More specifically, the technique is “wavelength neutral,” that is, nonlinear absorption can be induced even if the material is normally transmissive at the laser wavelength.

Photothermal Interaction



Photoablation

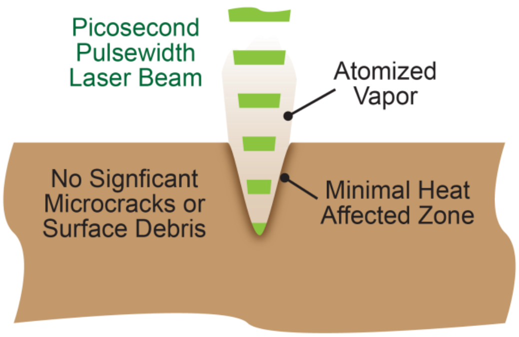


Figure 1: Schematic of the major differences between ultrafast processing and processing with longer pulsewidth lasers.

One limitation of ultrafast processing is that it provides lower material removal rates, and ultrafast lasers have been more costly than long pulse laser sources. As a result, ultrafast processing is typically reserved for applications that demand the greatest possible precision, quality and smallest HAZ.

Ultrafast lasers are currently commercially available with output from the infrared to the ultraviolet. Generally speaking, UV ultrafast lasers deliver the best results in terms of high precision and minimal HAZ. This is because the high photon energy of the UV photons facilitates a more efficient non-linear absorption, and can also be focused to the smallest spot sizes (due to diffraction). Plus, the remaining linear absorption of the UV light prevents the energy from penetrating very far into the material. This added benefit of UV and ultrafast has to be balanced against the greater output powers infrared and visible picosecond lasers offer. The higher output power can translate into higher ablation rates and thus lead to higher throughput.

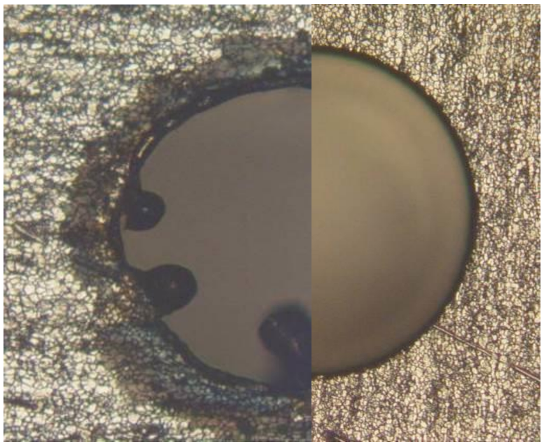


Figure 2: Comparison of a 200 µm diameter hole drilled in stainless steel with a nanosecond laser (left) and a picosecond laser (right). The picosecond laser produced a cleaner hole with less recast material and a smaller HAZ.

High Value Marking

Industrial applications utilizing ultrafast lasers can be broadly categorized into three groups: specialty marking, micro-structuring and thin film ablation.

Many different laser types are used for marking in a wide range of industries. Often these applications are highly cost sensitive, in terms of capital equipment cost and cost per mark. However, there is an increasing need for “high value” marks, typically involving higher precision marks on more expensive products. These conditions can sometimes justify the use of a more sophisticated and costly laser source, such as an ultrafast laser.

So called “black marking” is an excellent example of high value laser marking. This is a technique, used by a manufacturer of tablet computers, to place text and serial numbers on the anodized aluminum case of some of their products.

In black marking, the output of a picosecond laser is focused so that beam waist occurs below the surface of the aluminum, and only at this point of focus is the laser intensity high enough to drive multiphoton absorption. The laser creates a microstructure within the aluminum that traps light, and therefore appears black, while the overlying aluminum oxide anodization layer remains clear and unchanged. The result is a high contrast mark that does not wear off and which is also smooth to the touch.

Figure 3:"Black marking" produces a high contrast, subsurface mark on anodized aluminum.

Black marking offers two important benefits that justify its higher cost as compared to traditional laser marking techniques. First, it creates a mark that is extremely difficult to counterfeit or alter. Second, this type of marking has a distinct and pleasing appearance and feel, which helps the manufacturer to maintain their brand image of high quality and superior styling.

Micro-structuring Metals, Tungsten Carbide and Diamond

Ultrafast lasers are being used increasingly to perform micro-structuring in the automotive industry. One technique uses the laser to make an array of small pits on the surface of a part. These pockets hold oil due to surface tension and thereby prevent aspartic (direct metal on metal) contact. As a result, this treatment can significantly reduce the friction on moving parts, compared to conventionally polished surfaces.

The ultrafast laser is most useful for this type of micro-structuring on parts that don't have flat surfaces, and which have intricate shapes. These types of surfaces are difficult to process using mask projection techniques based on excimer lasers. This isn't an issue with ultrafast lasers, because their output is focused to a single spot; a combination of part and laser movement can then be used to rapidly process even the most complex surface geometries. Another advantage of the ultrafast laser is that it is compatible with a wide range of materials, especially including hard metals, such as various types of steel and titanium alloys.

A typical example of this type of micro-structuring is turbocharger turbine wheel shafts. These parts rotate at high speeds, and are subject to relatively large forces, so friction reduction improves operating efficiency and prolongs part life. The laser is used to produce an array of pits on the shaft, each of which is around 10-20 µm in width, 40-100 µm in length, and about 5 µm deep. These pits fill just a small percentage of the total area of the bearing surface.

Until now, some of these types of features have been produced using electric discharge machining (EDM). The major limitation of EDM is its slow speed. Additionally, it's a contact process which requires periodic replacement of the tool electrode, resulting in machine downtime. And, since the tool wears over time, the process isn't consistent. These factors increase cost of ownership for the equipment over time.

Nanosecond pulsewidth lasers have also been employed in the past for this type of micro-structuring. Their major drawback in this case is that the longer pulsewidth always results in at least some recast material around the laser produced feature. These small burs around each hole create high spots which cause friction unless additional post processing steps, such as honing, are used to eliminate them. But, this post processing adds additional cost, and can be difficult to accomplish with odd shaped parts.

While it would seem logical that a higher power ultrafast laser would enable faster processing and therefore reduce costs, in reality the opposite can be the case for this type of automotive application. This is because the takt time in most automotive production applications is limited by other, non-laser processes, such as material handling and positioning. Therefore, a higher power laser will sit idle more of the time, meaning it is underutilized, and negating the value of its higher power.

Another important micro-structuring application is the preparation of cutting edges in the machine tool industry. Ultrafast laser processing is particularly useful with hard materials, such as tungsten carbide and diamond. The non-contact, cold processing achieved with the laser removes material to produce a cutting edge which is of a very high quality and is free of chips. For materials with large granularity, the laser can even ablate a part of a diamond grain to maximize smoothness. This quality level is virtually impossible to achieve using traditional, mechanical machining methods.

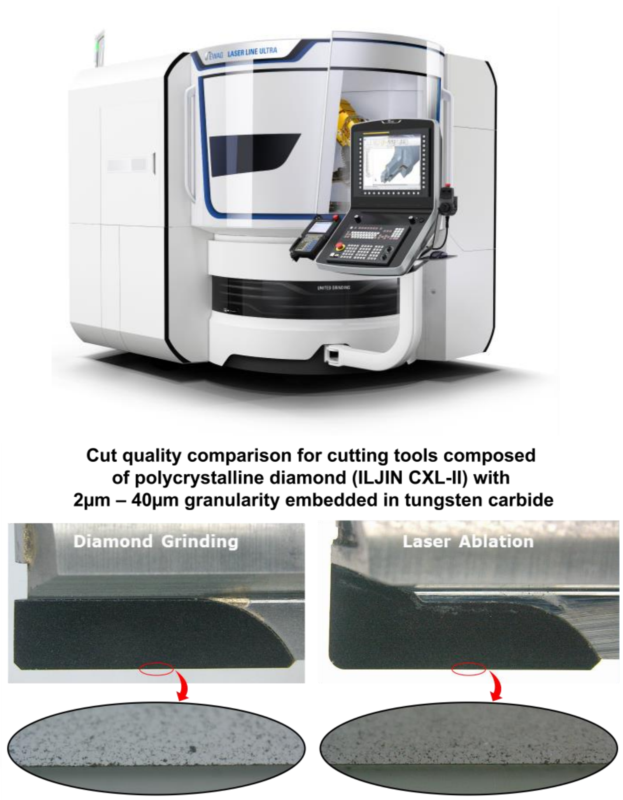


Figure 4: The EWAG Laser Line Ultra (top) is a system for fabricating diamond tools. The photos compare a tool edge prepared using traditional diamond grinding with one produced using laser ablation. The laser produced edge is smoother, with virtually no chips on the cutting edge.

Furthermore, laser processing enables the tool edge to be contoured with a precise shape, and even concave forms can be achieved. The result is both the capability for enhanced tool functionality, as well as extended tool lifetime, since it is well established that slightly rounded cutting edges wear better over time than sharper edges, which have a tendency to chip.

Thin Film Ablation

The fabrication of many microelectronic devices, flat panel displays and solar cells requires patterning of thin films of dielectric, metal and/or semiconductor materials, typically in alternating layers. For example in touch screens, it is necessary to scribe completely through transparent conductive oxide films with a linewidth and precision of around 100 µm. Traditionally, this type of patterning has been performed using some type of photolithography. However, this is a complex, multi-step process requiring a large capital investment, high fabrication costs, significant environmental concerns, and long fabrication times. As a result, alternative patterning methods based on laser micromachining have been gaining wider acceptance because these techniques involve much fewer individual steps and usually avoid wet chemistry.

For the display and touch screen markets, a new direct patterning process called spallation is enabled by the latest generation of ultrafast industrial lasers. This novel manufacturing process can selectively remove thin films (up to a few hundred nanometers) with the required spatial resolution and without damage to the underlying layers. Moreover, spallation is a single-step, dry process that leaves almost no debris, meaning that no post-processing (cleaning) is usually required.

Spallation relies on vaporizing a small amount of material at the interface of two layers with very different absorption characteristics at the laser wavelength. The outer layer is transparent to the laser wavelength, so that the beam is absorbed at the next layer, which must be a strongly absorbing material. All the pulse energy from the laser is thus absorbed in the first few nanometers of this underlying layer. Because the absorption occurs at an enclosed interface, there is nowhere for the expanding vaporized material to escape. As a result, this catastrophic expansion of atomized material creates a shock wave that blows off the thinner of the two layers. And just as important, this laser spallation process minimizes damage to the surrounding and underlying materials, making it ideal for most thin films used in the electronics and display industries.

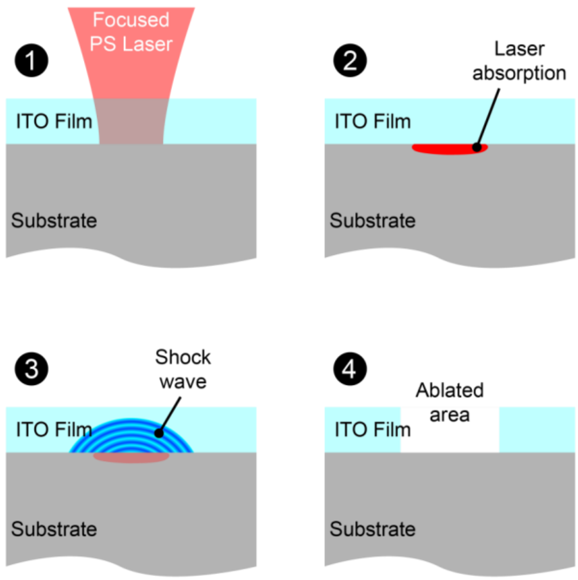


Figure 5: In spallation 1) a focused laser beam is absorbed at an interface, 2) heating occurs in a thin layer, 3) a shock wave expands out, and 4) the thinner layer is blown off.

An example of the use of spallation is in the production of solar cells. Adding a SiO_2 passivation layer has been shown to increase cell conversion efficiency. This layer must be selectively removed to make electrical contacts. The accompanying SEM photo shows an example SiO_2 thin film removal from a silicon substrate using a single, 355 nm, ultrafast laser pulse. No molten silicon or subsurface damage is visible, and no post-process cleaning is therefore required.

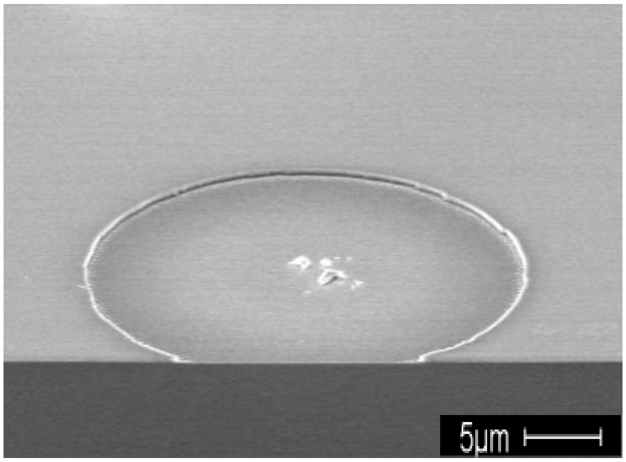


Figure 6: Removal of a SiO_2 from silicon using 355 nm picosecond pulses at an optimum fluence of ~0.11 J/cm^2.

Conclusion

In conclusion, ultrafast industrial lasers offer unique benefits for a variety of high precision processing tasks involving metals, diamond, thin films and other difficult to machine materials. Ongoing improvements in the output characteristics, reliability and cost of ownership of these lasers ensure that they will occupy an increasing market niche for applications in which quality is a primary concern.

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