UV Laser Micro-Materials Processing Of MEMS, Microfluidics, Sensors, LEDs and Other Miniature Devices

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ABSTRACT

The emerging demands of medical device micro-machining – from drug delivery systems to cell sorting and more – require extremely precise, tight tolerances, high repeatability, and cost-effective processing. Short-wavelength (157-193nm) UV VUV Excimer lasers have proven ideal for such applications particularly with regard to processing difficult materials such as borosilicate glass, quartz, fused silica, and PTFE, exhibiting the ability to execute complex features with large-area and ganged processing capabilities and characteristic smooth cuts in such applications as precise drilling of microscopic apertures. However, the characteristics of short-wavelength UV VUV Excimer laser beam configurations are unique, with drawbacks that balance advantages. For example, short wavelength UV cannot be transmitted through air and must be transmitted through either a vacuum or inert system. In addition, the laser beam itself must be controlled and configured, and this is the role of the VUV Beam Delivery System (BDS). This paper will examine the role and configuration of the BDS in short-wavelength Excimer laser processing, and the specific requirements for a BDS enabling the practical and cost-effective research/commercial application of Excimer lasers to medical device micromachining.

Keywords: excimer, laser, micro-machine, ablation, absorption, beam, shapers.

Emerging challenges in micro-machining, particularly in biomedical applications, include the need to process materials at faster speeds; to process a wider range of materials; and to process them with greater precision, repeatability, and to micro-machine features of increasingly smaller dimensions with ever-tighter tolerances. Many of these applications are beyond the capabilities of mechanical micro-machining, and must be processed with lasers.

Examples of these cutting-edge technologies include lab-on-a-chip, micro-fluidics, drug delivery systems, biosensors, cell sorters, cell trapping, gene sequencing, hemo cytometers, nozzles, MEMS, micro filters, and more. These applications may require complex features, holes, cones, channels, sample chambers etc. of microscopic size, of uniform and consistent size, with certain essential characteristics that may include sharply-defined features, smooth walls, optically clear surfaces and to be produced with high repeatability and at production speeds sufficient to make their production economically feasible. In one example, laser-scribing of glass slides for cell counting replaces manual or mechanical diamond-scribing; in another instance, lasers etch patterns on glass bio-detection sensors that would otherwise be chemically etched - more slowly and at much higher cost per piece.

A wider range of materials – from certain glass types to PTFE, quartz and fused silica – complicate matters. Some cannot be mechanically machined at all to achieve the required features or tolerances; and although they can be micromachined using lasers, some materials cannot be properly or effectively machined by all lasers. For such applications, short-wavelength, Excimer UV lasers are proving to be the best choice due to their unique capabilities and beam characteristics.

Different materials absorb laser energy differently; the greater the absorption of the material, the easier it is to machine it cleanly and consistently. Many materials can be effectively micromachined with longer-wavelength lasers (e.g., Nd:YAG); however many materials such as certain types of glass, cannot tolerate longer wavelengths without cracking; other materials will exhibit rough holes and edges that do not meet the strict requirements of the application. Difficult materials (such as quartz and fused silica) can be effectively processed using short wavelength (157nm) Excimer lasers. Other difficult material can be processed at 193nm such a UV transparent glasses such as borosilicate and sensitive polymers such as nylon, PMMA and PET. They excel at direct write, high-speed, high aspect ration hole drilling, thin film patterning applications and are well suited to many of these cutting-edge medical device micro-machining applications. Due to the high absorptivity of short-wavelength UV by the material, micro-machining is crisp, precise, and repeatable. The process itself is known as photo-ablation.

Excimer lasers are high average power UV laser sources with many significant features and characteristics that make them ideal for high-resolution materials processing. Excimer lasers operate at a variety of user-selectable UV wavelengths from 157nm to 351nm. This allows processes to be optimized based on absorption; e.g., sub-micron layers of materials can be removed with each laser pulse. This characteristic alone makes Excimer lasers remarkably different from other laser types.

Short UV Excimer laser wavelengths can be projected onto material with very high resolution. Even with the use of simple lenses to shape and direct the beam, micron resolution is easily achieved.

PHOTO ABLATION

The method of materials removal with Excimer lasers is unique and a direct function of the laser's characteristic form and energy type. Known as laser (photo) ablation, this occurs when small volumes of materials absorb high peak power laser energy. When matter is exposed to focused excimer light pulses, the energy of the pulse is absorbed in a thin layer of materials, typically <0.1μm thick, due to the short wavelength of deep UV light. The high peak power of an excimer light pulse, when absorbed into this tiny volume, results in strong electronic bond breaking in the material. The molecular fragments that result expand in a plasma plume that carries any thermal energy away from the work piece. As a result, there is little or no damage to the material surrounding the feature produced. Each laser pulse etches a fine sub-micron layer of material; the ejecting material carries the heat away with it. Depth is obtained by repeatedly pulsing the laser; depth control is achieved through overall dosage control.

BEAM DELIVERY SYSTEMS

The Beam Delivery System (BDS) Directs laser energy onto process material; it determines laser power density on the target, determines the size and shape of the beam on the target; and motion control systems are sometimes used for auto-focus, or for articulated beam positioning relative to process material. Excimer laser beams differ from other types of lasers in that the beam covers a generally wide area comparatively, and is characterized by a 'flat-topped' as opposed to Gaussian shape. Excimer laser beams can cover relatively large areas of material with effective processing results.

Excimer laser beams are not perfectly uniform in intensity over the area of the beam and therefore only a portion of the area of the beam is usable for high-uniformity materials processing. In some cases, only the most uniform section or "filet" of the beam will be selected for use, and the non-uniform section of the laser beam will be discarded.

High-quality optics (CaF_2) is part of a VUV BDS; optical techniques are employed to use a larger fraction of the available laser power. Furthermore, due to the premium price associated with UV photons, high beam utilization – known as the Beam Utilization Factor, or BUF – in many cases is a key economic factor, which can qualify or disqualify an otherwise technically feasible application. Beam efficiency enhancers, a.k.a. beam shaping optics and beam homogenizers, can be employed to shape the beam and simultaneously make the laser energy uniform.

Near-field imaging involves the use of a mask to project a pattern of laser light onto a part. The features contained in a pattern are then etched into the target material, at a magnification determined by the relative positioning of the optical elements. Near-field imaging can be used to project a mask image onto a workpiece so that complex features can be patterned. This technique is the basis for excimer laser micromachining in many materials processing systems.

High performance doublet or triplet imaging lenses made from Caf2 are used to improve the image quality over larger fields of view improve the grid distortion as well as the spot size uniformity and minimum spot size achievable. A limitation to just one lens material makes the imaging lens design a significant engineering task. Due to losses in the optics, it is desirable to minimize the number of elements. This places constraints on the accuracy and surface finish of the lenses.

To efficiently use a higher percentage of the available UV Excimer laser beam energy, optical techniques are employed to ensure uniform irradiation over large areas in effectively three dimensions. Imaging optics are used to control feature accuracy over larger fields of view (2-D). Beam shaping or beam homogenizer techniques are used for exposure control (3-D).

The unique nature of Excimer laser beams includes both strengths and weaknesses. The wide nature of the beam allows the beam, through near-field imaging and masks, to be divided up and thus perform multiple tasks simultaneously (such as drilling multiple holes in a part) for maximum BUF; however, beam shapers, homogenizers, and other optical elements of a BDS are required to configure the beam for maximum effectiveness, these being somewhere between the laser and the target.

Short-wavelength UV laser energy's Achilles' heel is air. While longer wavelength laser energy can transmit through air with (depending on the type/wavelength) negligible loss of energy or efficiency, short wavelength – 157nm – UV cannot, and must be transferred through either a vacuum or through an inert gas that will transmit the laser beam without appreciable loss. Indeed, even the presence of 1ppm O_2 in the vacuum or purged BDS will result in degradation and loss of efficiency of the beam, as well as generation of contaminants and ozone that will further absorb the laser energy and reduce its effectiveness dramatically. Therefore, the different modules and elements in the BDS must also comprise a system that is either evacuated or purged with an inert gas (N_2 purification is required) that will facilitate transmission of the UV laser beam.

Large facilities may have the resources to build large and complex evacuated beam delivery systems, but these are not flexible and not economically feasible for the average user or for most commercial use. In addition to being costly to custom manufacture, such systems lack the flexibility to process a high product mix or conduct research. For example, an Excimer BDS may include a movable/changeable mask or series of masks; telescoping parts; field lenses; and turning mirror blocks. Moving parts are not especially compatible with attempts to maintain a tightly sealed vacuum system with the needed <1ppm O_2 required for optimum beam transmission.

BDS CONFIGURATION

A practical Beam Delivery System for 157 and 193nm Excimer laser processing consists of multiple interchangeable modules used to control the intensity and fluence of the laser beam as well as its shape and distribution. These can include variable attenuators; telescopes; field lenses; turning mirror blocks; beam splitters; beam dump; multi-position mask changers; power meter modules; and more. For example, it is known that as an Excimer laser ages, its beam quality changes (not necessarily deterioration, but this is also included as a factor). This fact can affect process control and therefore must be addressed. Beam power meters are used in-line in the BDS to monitor beam shape and strength. In such modules, the beam may be redirected to the meter – either in whole, thus interrupting the beam, or in part (sampling a certain few percent of the beam), by redirecting a slice of it during processing, by one or more mirrors in the module. Thus, a vacuum system is rendered impractical.

A more cost-effective and flexible approach is to employ a purged system. Inert gases such as pure nitrogen and argon are effective transmitters of Excimer laser beams. The BDS is designed such that certain modules have ports for the introduction of slightly pressurized inert gases that flood the system. Controlled leakage at specific points (such as the connection of a movable part such as an actuator to the outside) allows slight egress of gas to the outside at any point where contaminants (ambient air) might otherwise enter the system. The result is a modular, quickly interchangeable and configurable BDS suitable for commercial and research purposes with the needed flexibility to allow frequent beam characteristic changes as well as mask changing and adjustment.

The Excimer laser user has varying options with regard to inerting the BDS. Certainly there is a cost factor involved with the use of high-purity nitrogen ($\leq$1ppm O_2; a requirement) or other gases. High-purity bottled gases are easily obtainable; high-volume users may wish to purchase nitrogen generating equipment and optional high-purity filters to achieve the needed purity levels for the BDS. Of course, higher-volume usage will mean more frequent O_2 filter changes to maintain gas purity, at higher cost with increased frequency of changeouts.

High purity components are a necessary part of the BDS, and by this we mean, more specifically, the lack of contaminants or potential contaminants. A sealed purged system will naturally require gaskets of some sort to maintain the integrity of the inert gas fill and ensure cost-efficient use of gases. However, over millions of laser pulses, repeated discharges cause organic materials within the BDS exposed to UV laser light to degrade under the intense UV exposure that occurs during lasing. These organic materials can be gaskets, lubricants, etc. In the process of degrading, they outgas in the process and bring contaminants into the system. These UV absorbing impurities cause the laser light output to fall over time. Thus, it is important that BDS components are free of grease and lubricants, and that gaskets are shielded from contact with UV laser light, through design.

CONCLUSION

Short-wavelength (157-193nm) UV VUV Excimer lasers are emerging as a precise, cost-effective technology for meeting the emerging demands of medical device micro-machining. The ability to machine complex patterns with extreme accuracy and repeatability, due to the flexibility of the UV VUV laser system and its characteristic clean cut, makes these systems well suited to handling the tight tolerances required, and the ability to process a multitude of ordinary and exotic materials. 157nm systems are currently in production, but these systems require careful attention to multiple details (such as gas composition, etc.) in order to operate repeatably and cost-efficiently. More research is needed, certainly, and process engineering; however, the promise of cost-effective and commercially viable UV VUV laser micromachining is great and will enable the advancement of new medical technologies where older technologies and approaches have already proven to be inadequate or economically unfeasible.