# Fine Diamonds With Laser Machining

## *UV tools make quick work of the world's hardest material.*

by C. Paul Christensen

Of all materials, diamond is harder than any known solid, while also exhibiting the highest values for elastic modulus, atomic density, Debye temperature and thermal conductivity at room temperature. Diamond is chemically inert, and is highly transparent throughout a broad range of the optical spectrum. It is a wide bandgap semiconductor that may be useful at high temperatures or high voltages.

These properties, along with the ease of growth of diamond films by chemical vapor deposition, have made the material desirable for potential applications such as heat spreaders, optical windows, x-ray lithography masks, low-friction and wear-resistant surfaces, cutting-tool coatings and active electronic devices.[1]

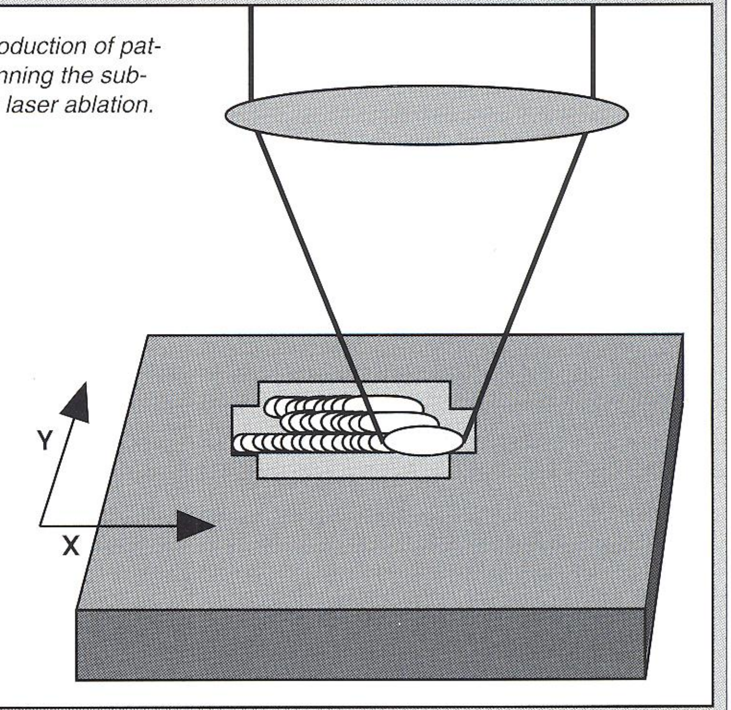

**Figure 1.** *Production of patterns by scanning the substrate during laser ablation.*

Because of the hardness of diamond-like materials, mechanical grinding, polishing and cutting is time-consuming and costly. Fabrication and shaping problems are compounded by the fact that many potential applications require a high degree of precision and spatial resolution. The availability of simple and affordable techniques for shaping and patterning on spatial scales in the micron to millimeter range is expected to significantly enhance the utility of diamond as a structural, electronic and optical material.

### The old ways

Most current diamond-fabrication technology has evolved from techniques used in fabrication of gemstones and diamond tools from naturally occurring diamond. For the most part these techniques are based on diamond-on-diamond abrasion processes involving saws, polishing wheels and similar tools.

However, lasers have also been used in the diamond industry for rough shaping of industrial diamond and removal of flaws from gems.[2] Laser etching of a diamond surface involves a two-step process: localized graphitization of the illuminated surface area, followed by sublimation and ablation of the optically absorbing but thermally insulating graphite film.

Fundamental and second-harmonic wavelengths of Nd:YAG lasers are currently used for many diamond-cutting and -drilling applications. However, it has been demonstrated that pulsed ultraviolet lasers offer a number of advantages for precise etching of diamond surfaces.[3,4,5]

### Fine sculpture

In comparison to infrared and visible wavelengths, ultraviolet radiation is much more strongly absorbed by many diamond-like substrates so that the graphitization step in ablation can be achieved with relatively low laser energy and a well-defined interaction volume. This allows more control over the etching process, produces higher spatial resolution and prevents damage to subsurface material. It also enables use of smaller lasers.

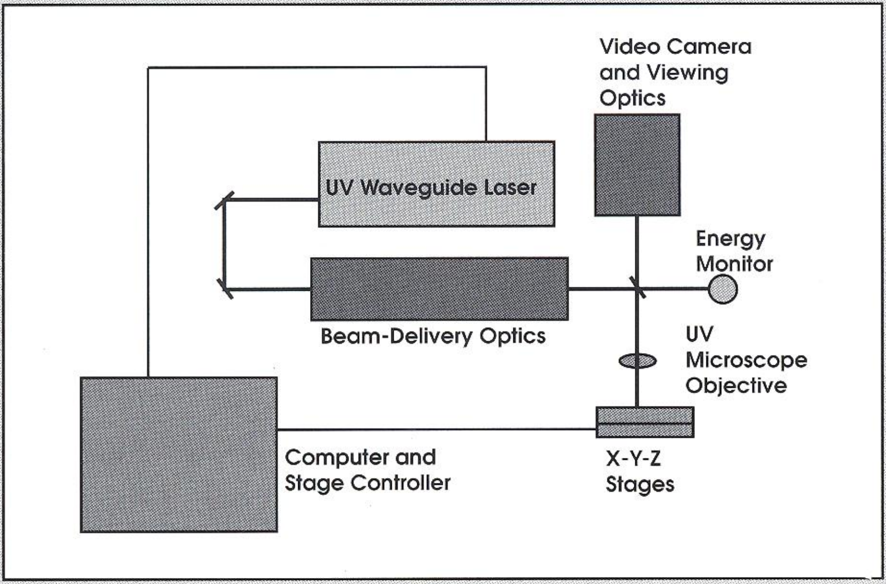


***Figure 2.*** *Laser micromachining configuration.*

Small ultraviolet lasers can shape diamond surfaces with very high precision and spatial resolution. These optical tools combine the small laser sources with high-resolution imaging and precision motion-control systems for sculpting, planarizing, marking and patterning of diamond and diamond-like materials. Applications for tools of this type are pervasive, extending from production of three-dimensional microparts to sculpting likenesses of Aunt Martha's grandchildren on a facet of her wedding ring.

The fluence required for ablation of diamond materials varies widely with the purity of the material and the wavelength of the laser source. In general, fluences between 0.1 and 10 $J/cm^2$ are required for ablation at ultraviolet wavelengths. Single-pulse ablation depth in diamond is typically a few tens of nanometers. This suggests that precise depth control should be possible in UV-laser-ablated microstructures.

Laser-energy requirements are a function of the area of laser focal spot on the worksurface. Beam divergence is also an important parameter that influences the minimum focal spot size and achievable fluence. On micron spatial scales, only a few microjoules of UV laser energy are needed to produce the fluence levels required for ablation of diamond materials.

Consequently, small UV sources, such as waveguide excimer lasers, are desirable for microstructure fabrication. The typical 50-µJ output of a waveguide KrF laser focused by an optic with numerical aperture of 0.5 will produce a focal spot of 15 to 20-µm diameter and corresponding fluence of 10 to 20 $J/cm^2$. Appropriate beam-delivery optics can produce smaller spots of the same fluence by imaging of the apertured beam.

## Computer control

Raster or serpentine scanning of the substrate under the focused beam is a simple technique that allows arbitrary shapes to be drawn using a CAD/CAM program and then etched into a diamond substrate without an intermediate mask-generation step.

During the raster motion, the laser output is gated on and off to produce the desired geometry. Use of a CAD/CAM program as a graphical interface allows long sequences of motion commands associated with complex shapes to be generated with a minimal amount of programming.

Since the time needed to generate a pattern is proportional to the laser pulse repetition rate, most practical tools will incorporate a high-repetition-rate laser.

Ablation depth is controlled by varying the X and Y step size between laser pulses and by adjusting the laser fluence. As successive laser pulses are overlapped on the worksurface during scanning, the net exposure of any area becomes proportional to the spatially averaged fluence of the focused beam. Consequently, pulse overlap can be used to reduce the effect of beam "hot spots" and reduce or eliminate the need for beam homogenization.

The equipment configuration used for diamond micromachining at Potomac Photonics is shown in Figure 2. A waveguide KrF laser producing 50-µJ pulses of 80-ns duration at pulse repetition rates extending to 2 kHz is used as the optical source. The laser emission is shaped and collimated by beam-delivery optics and focused onto a worksurface with a UV-transmitting microscope objec-

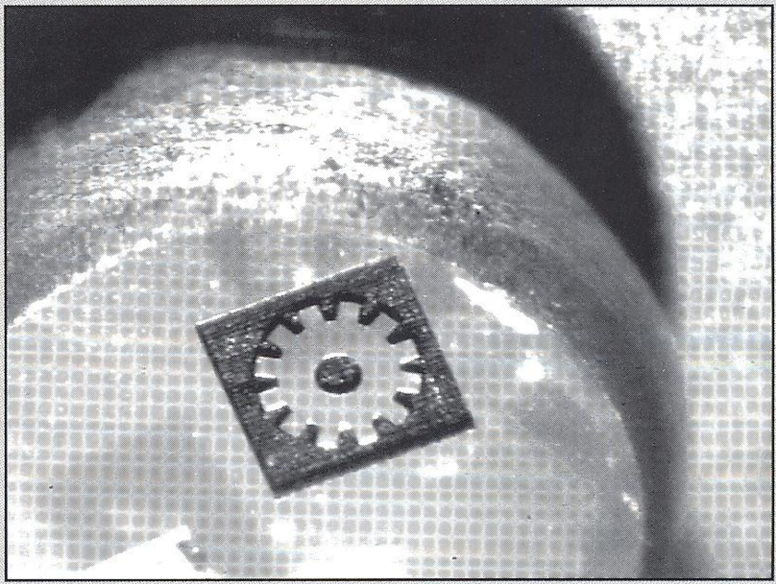

***Figure 3.*** *Gear structure formed in the surface of a polished type Ib diamond substrate by 248-nm laser ablation.*

tive. The objective also images the interaction region onto a high-resolution video camera to allow the operator to closely monitor the machining process.

The workpiece is mounted on precision X-Y stages driven by DC motors, and stage position is monitored by encoders. Computer control of stage velocity is carried out using CAD/CAM software, and laser pulsing is synchronized to stage motion.

## Almost any shape

Figure 3 shows an example of a diamond gear structure produced by the raster scanning technique. The gear is 300 μm in diameter and is fabricated on the surface of a 0.3 × 1.5-mm chip of type Ib diamond. Depth of the relief around the gear is approximately 50 μm.

The structure was formed using a laser focal spot diameter of 10 μm and a fluence of 5 J/cm$^2$. The gear shown in Figure 3 is not released from the substrate as a separate component. However, a released structure could be formed by simply using a thinner substrate.

CAD/CAM software and the direct-write approach to laser machining allows almost any shape to be generated in a diamond surface. For example, Figure 4 shows a butterfly formed in relief in a polished diamond surface by the same scanning approach used in Figure 3. In this case, the shape of the butterfly was derived from clip art, saved in a DXF format, and imported into the machining program.

Since the single-pulse ablation depth of diamond is only a few tens of nanometers, it should be possible to produce smooth, sloping surfaces with continuous height variation by UV laser ablation. Repetitive raster scanning of the sample work surface is one means of producing such three-dimensional structures. This technique forms the part by removal of material layer by layer. Production of smooth, continuous-relief surfaces by raster scanning requires optimization of scanning rates in both transverse dimensions. The opportunity exists to adjust the beam focus between scans, so that the technique is compatible with tightly focused beams that exhibit limited depth of field.

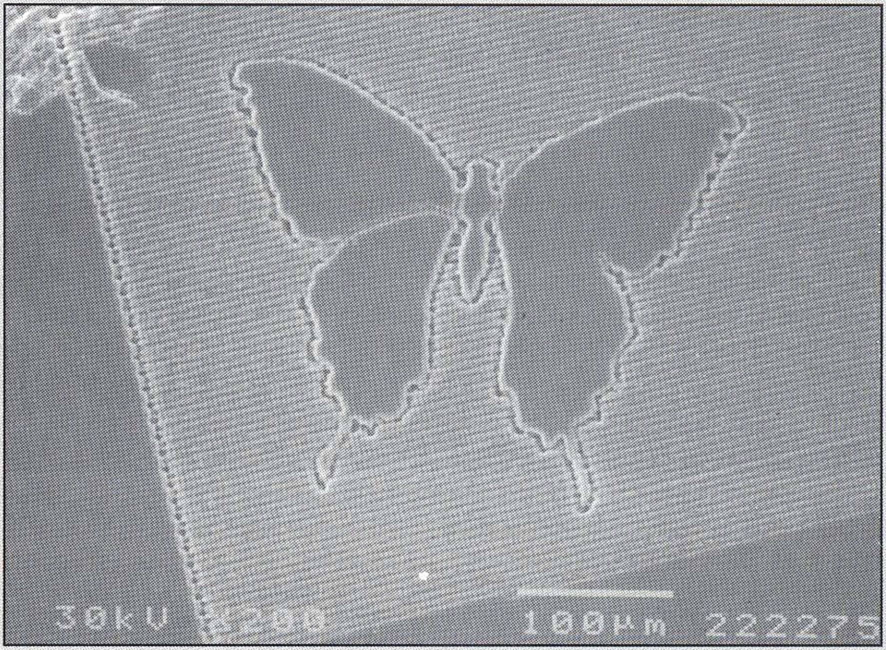


***Figure 4.*** *Butterfly formed in relief in a polished diamond surface. Overall width of the structure is 300 μm.*

## Quick work

Figure 5 shows a pyramid-like structure fabricated with a waveguide KrF laser beam of 20-μm diameter. The number of scans used to expose each side of the structure varies linearly from the shallowest portion near the center to the deepest portion near the outer edge. The resulting surface exhibits a continuous slope and has submicron roughness. The thin graphite layer produced by the laser has been removed by heating the substrate in an oxidizing atmosphere.

The continuous surface relief shown in Figure 5 demonstrates the feasibility of true three-dimensional microfabrication in diamond. Structures of this type would be nearly impossible to form with conventional mechanical tools. For UV laser optical tools, it's a few minutes' work. □

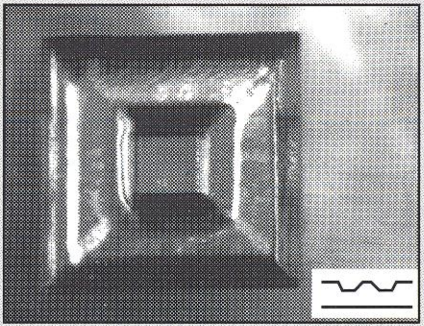

***Figure 5.*** *Top view of pyramid structure formed in relief in type Ia diamond. The substrate is tilted 15 ° from the viewing axis and its cross-sectional shape is shown in the inset. Width of the ablated region is 400 μm. Sloping sidewalls were produced by overlapping of raster scan patterns.*

## Acknowledgements

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## Meet the author

C. Paul Christensen is founder and president of Potomac Photonics Inc., a manufacturer of UV lasers and laser micromachining systems. He holds a doctorate in electrical engineering from the University of California at Berkeley and has 25 years' experience in laser systems and laser/material interactions.