

Production of novel 3D microstructures using excimer laser mask projection techniques

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ABSTRACT

Excimer laser ablation is used in conjunction with mask projection techniques to produce novel and complex microstructures. Special multiple-mask techniques have been developed which, together with synchronised workpiece motion and laser firing, are used for the manufacture of features such as micro-channels, ramps, contoured surfaces with channels etc. These new techniques allow planar microstructures to be combined and superimposed onto curved or multi-faceted shapes, thereby enabling hitherto unobtainable structures to be produced. Details are given of the techniques used along with examples of the types of structures which have been produced.

Keywords: excimer lasers, ablation, mask projection, microstructures

1. INTRODUCTION

There are many industrial sectors such as microelectronics, telecommunications, automotive, aerospace, semiconductor and biotechnology which are evolving rapidly. This evolution is accompanied and fuelled by increasingly-stringent demands on the production technologies used where features such as high feature resolution, high speed of processing, low unit cost of manufacture, production of novel geometries and rapid prototyping capabilities are all of vital importance. In the last few years, these needs have been met by pulsed laser micro-processing and excimer laser-based techniques which are now a key enabling technology in many fields allowing the rapid advances made recently to continue unabated.

The advantages offered in microengineering by the use of excimer lasers are numerous but include:

- Delivery of energy with high precision and directionality
- Non-contact machining
- Micron-sized features possible
- Interaction time with the material is short (~20-40nsec)
- Excellent control of depth
- Small heat-affected zone (HAZ)
- Accuracies on the scale of nanometres possible
- Processing speeds can be high
- Many different types of materials can be processed

The above characteristics mean that many microstructures can be produced effectively with excimer laser systems which are not possible with conventional etching or machining methods and hence excimer laser systems have become the most advanced for ultra-high precision micro-engineering applications.

Many areas are advancing rapidly from the use of the unique structures that can be produced by excimer laser micromachining techniques. In particular, micro-fluidic systems, where one or more fluids are mixed, separated or transported, are utilising laser-produced features to great benefit and features such as ramps, reservoirs, channels and contoured shapes are being incorporated into production devices. Sensors, especially in biological and biotechnological applications, are also combining multi-faceted structures in their design since whole devices of 2D and 3D features can now be produced from excimer laser micromachining systems.

2. EXCIMER LASER ABLATION

Most laser micromachining applications require some form of patterning or removal of material. This removal of material by the direct interaction with the laser is termed *laser ablation* and is shown schematically in figure 1.

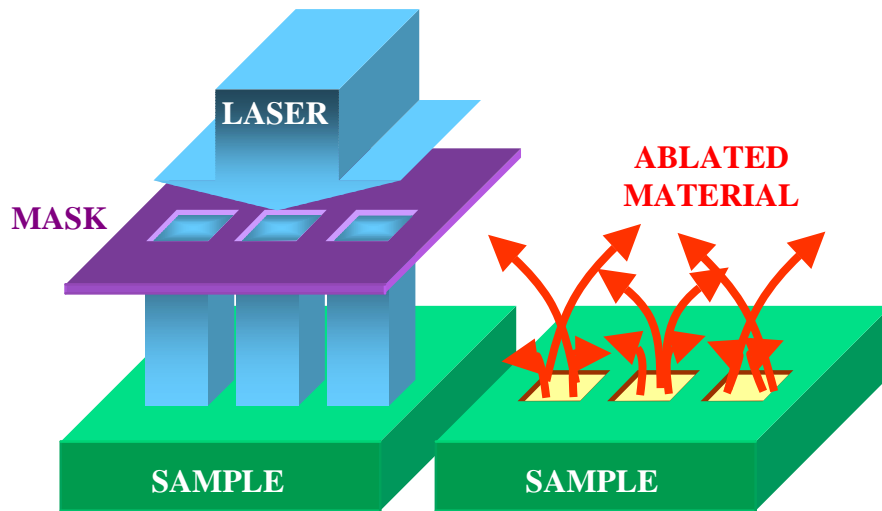


Figure 1. Laser Ablation - the direct removal of material by laser interaction

The process by which material is removed by ablation is as follows: the material absorbs the excimer laser light; the intense UV photons break inter-molecular bonds in the sample; this leads to a rapid increase in the number density of particles in the exposed area; the dissociated particles are explosively ejected from the exposure site.

Since many materials absorb very strongly in the UV, the ablation depth per laser pulse is quite small but this means that the depth of ablation can be controlled very precisely ($\sim 0.1\mu\text{m}$). The short wavelength also permits the fine imaging of excimer lasers. Hence, excimer laser ablation allows fine resolution, high machining quality and precise depth control - factors which make it the technique of choice for many applications.

3. MASK PROJECTION

The implementation of excimer laser ablation is most commonly achieved by *mask projection* methods where, as shown in figure 1, the mask defines the exposure area at the sample. The mask most-commonly consists of a thin chrome metal layer on a quartz substrate although since chrome masks have a damage threshold of $\sim 100\text{mJ}/\text{cm}^2$, work at energy densities higher than $\sim 100\text{mJ}/\text{cm}^2$ requires the use of multi-layer dielectric masks. Simple masks can also be made from thin metal sheets.

Mask projection has the following advantages:

- the mask is remote from the machining and hence does not suffer from debris damage
- the use of a de-magnifying projection lens allows the constraints on the mask manufacture to be reduced
- de-magnification means that the laser fluence at the mask is lower than at the sample, hence prolonging the mask lifetime
- the remoteness of the mask from the workpiece allows independent motion of the mask
- multiple patterns can be superimposed on the sample by changing the masks.

The use of mask projection allows great flexibility in the types of processing which are possible and the geometries of the structures which can be produced. This article describes some of these techniques and how they allow multiple structures to be produced directly from a single micromachining system.

A typical excimer laser beam delivery system for mask projection has the layout as shown in figure 2.

The laser beam is shaped and homogenised to illuminate the mask. This ensures that the exposed area of the mask has a uniform intensity distribution, since variations in intensity lead to depth variations in the image during ablation, and hence can be a problem. The mask is then imaged onto the sample by high resolution projection optics.

The laser processing can be achieved while (i) the mask and workpiece are stationary, (ii) either the mask or workpiece are moving or (iii) both the mask and workpiece are moving in synchronism. This latter case is termed *synchronised mask scanning* and can be used to pattern large (1000s mm²) areas with micron-sized features of a non-repeating pattern.

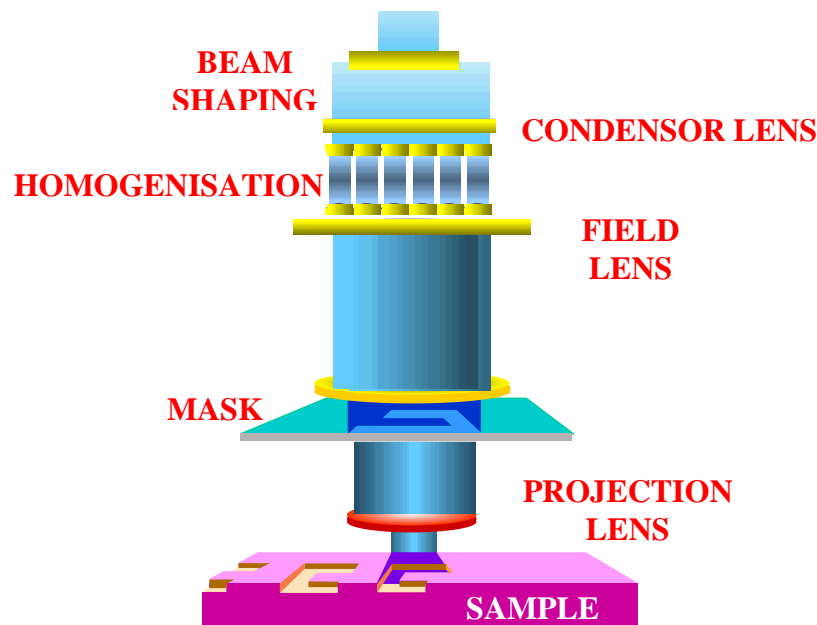


Figure 2. Schematic diagram of excimer laser mask projection system.

The features which are produced in the sample are a function of the mask shape, the relative motions of the mask and the sample and the firing of the laser. The following section will describe the production of different structures using a system such as that shown in figure 2.

4. MICROSTRUCTURES

4.1 Static Ablation

The simplest form of mask projection involves the laser beam illuminating a stationary mask. The mask pattern is projected onto a static workpiece and so the mask shape is ablated into the sample. This method is suitable only for the cases where the beam size is larger than the mask shape. This, however, can be easily ensured in many cases by appropriate choice of mask and demagnification of the projection lens.

Static ablation can be used to produce features such as blind holes (e.g. reservoirs in fluidic systems) or via holes (e.g. connecting devices), or combinations of different structures produced by changing masks in between static ablation. Typical examples are shown in figure 3.

Large areas of samples can be covered with discrete features using static ablation by employing the technique of step-and-repeat machining, where the sample is translated laterally after each process step has been completed. The step-and-repeat technique can be extended by also changing the mask in between the process steps and this means that various different discrete shapes can be produced, either side-by-side or superimposed onto one another.

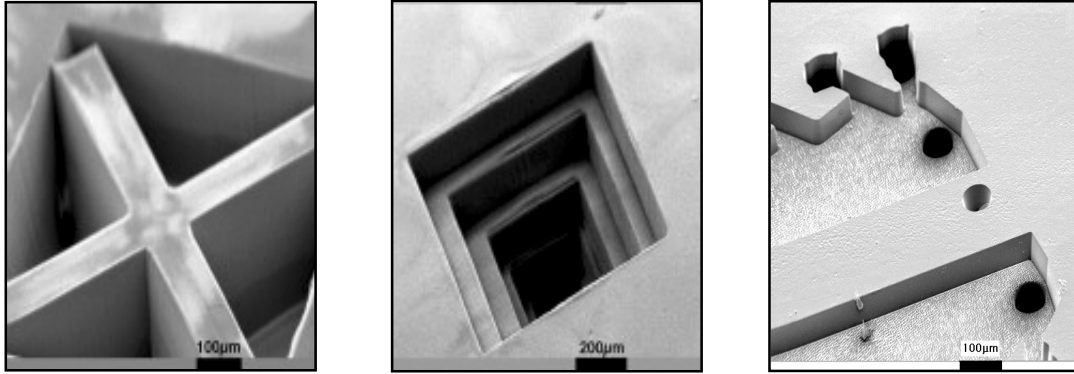


Figure 3. Microstructures ablated in polymers by static mask projection

4.2 Microchannels

Structures such as channels can be produced when the mask is kept fixed in position and the sample is moved while the laser is firing. This is termed *workpiece dragging*. The shape of the mask determines the cross-section of the channels while the motion of the workpiece while the laser is firing determines the path which the channels follow. Many channels can be produced at the same time as long a mask with the appropriate number of shapes can be produced (and as long as those shapes lie within the beam area at the mask).

Figure 4 shows microchannels produced in polyester with a krypton fluoride excimer laser (at 248nm) where the cross-sections have been altered by using different mask shapes.

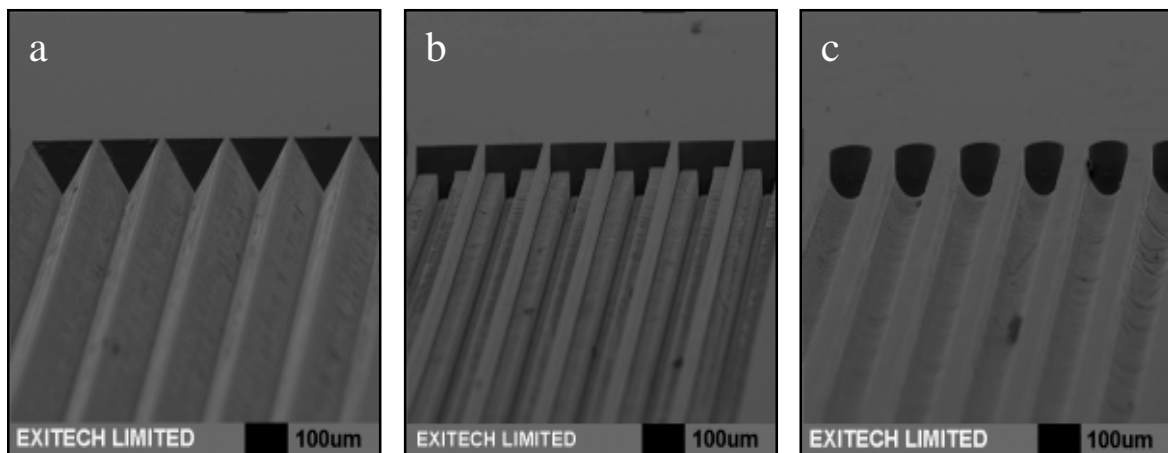


Figure 4. Microchannels produced with (a) a triangle mask, (b) a 'T'-shaped mask and (c) a circular mask.

The smoothness of the channels is largely determined by a combination of the mask quality, the shot overlap as the sample moves (i.e. the speed of the sample motion) and the material. There is, of course, fundamental limitation on the length of the channels - only that imposed by the stages used for positioning the workpiece.

By programming the workpiece to move in a non-linear path, a channel of a predefined shape can be produced. Figure 5 shows some microchannels which follow a curved path. The cross-section of any channel, of whatever contour, is still determined by the mask shape and only appropriate programming of the workpiece motion is necessary to produce the contour path of the channels.

The types of channels shown in figures 4 and 5 are useful for many microfluidic systems where fluid flow and transport are of crucial importance. They can be combined with other micromachined features such as reservoirs, holes, other channels, sensors elements etc. to make a multi-functional system.

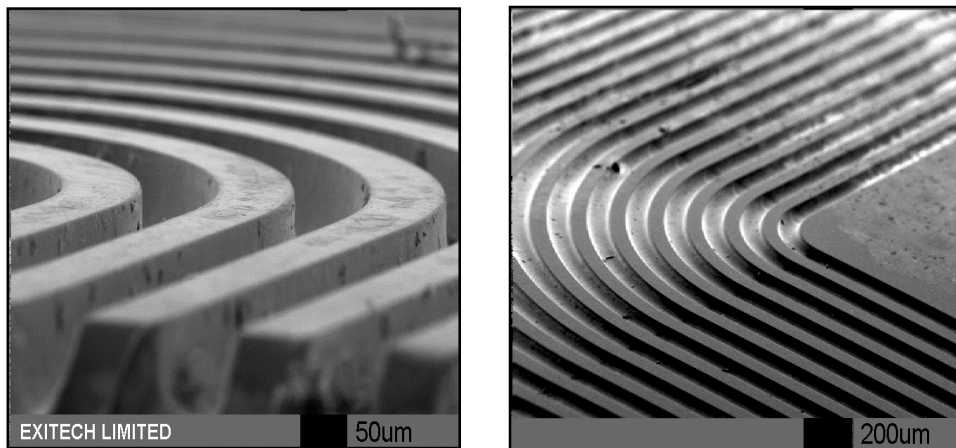


Figure 5. Curved microchannels produced by workpiece motion

4.3 Curved Surfaces

The production of micro-optical components is also becoming increasingly important in systems which can combine the detection, generation or manipulation of light, often integrated together with other micromachined devices on a single chip. There is a lot of research underway in the use of different techniques for the manufacture of micro-optic devices but we have demonstrated the principle producing micro-optics using the technique of workpiece dragging.

An array of micro-lenses produced using workpiece dragging is shown in figure 6. The production of these arrays involves the same process as that for making circular cross-section channels, except that the mask used is the inverse to the one used for the channels, i.e. it is an opaque spot rather than a hole.

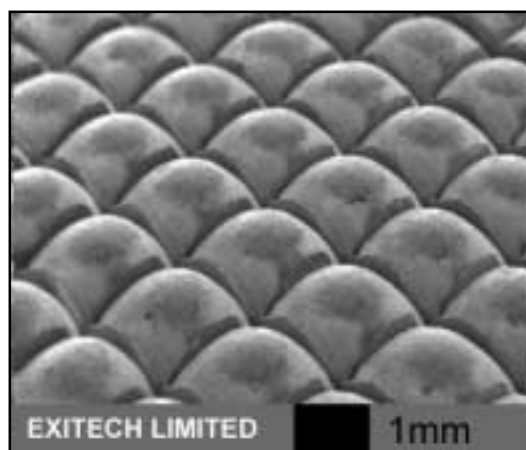


Figure 6. Lens arrays produced by workpiece dragging

The shape of the mask spot determines the curvature of the ablated sample. If the workpiece is moved in one direction only, then a cylindrical element is produced. Repeating this procedure at an orthogonal direction to the first scan then produces the curved element. Arrays can be made by either dragging a mask of numerous spots or by "stitching" together single scans by stepping the workpiece in between scans.

This technique may not be suitable for ultra-high precision curvatures required for high quality optical transfer devices but will probably be more attractive for light collection systems where low aberrations and high conformity to a specified curvature are not issues. The attraction of workpiece dragging for the production of these arrays is that it is a simple and quick technique and so may be appropriate for low specification optical systems.

4.4 Linear Ramps

While channels are produced by only moving the workpiece, ramps can be produced by keeping the workpiece fixed and translating the mask. All the other criteria which were mentioned in the production of microchannels apply in the case of ramps but, of course, the features which are produced are different.

Figure 7 shows single and multiple ramps of different types produced in polyester with a 248nm excimer laser.

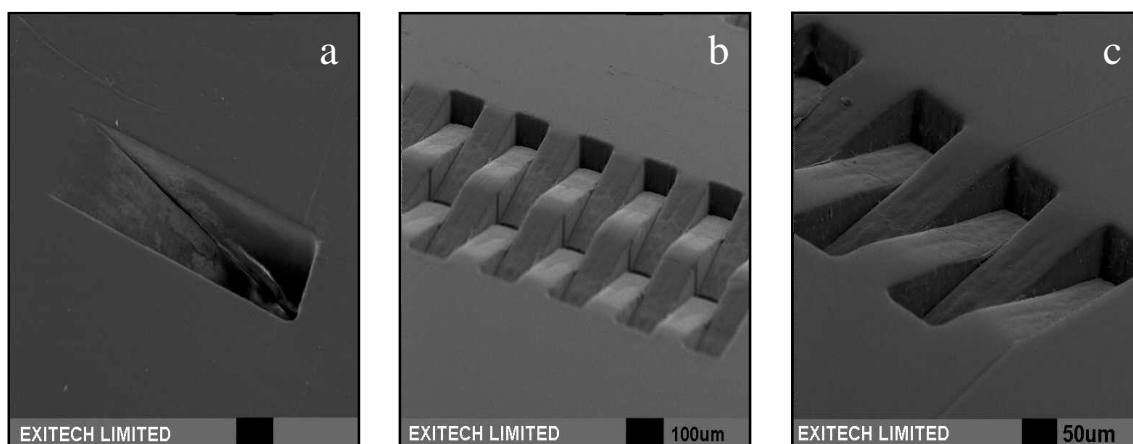


Figure 7. Linear ramps produced by mask dragging

In the production of ramps such as those shown in figure 7, the dimensions of the ramp to be produced are defined by aperturing the beam so that it is the right shape and size at the mask (a simple rectangle in the case of figure 7a). To produce the linear ramp, an opaque mask is translated across the beam aperture while the workpiece is stationary and the laser is firing. This means that as the opaque mask moves across the beam aperture, it ensures that a linearly varying change in the numbers of laser shots at the sample is produced. This change of numbers of shots with position along the beam aperture leads to a linear depth variation in the ablation of the material and hence produces a ramp. This technique for the production of masks is termed *mask dragging*.

In the samples shown in figure 7, the motion of the mask across the beam was linear and hence the ramps are linear. The ramps can have a curved shape if the motion of the mask is adjusted accordingly.

4.5 Multiple Shapes

By combining some of the techniques already described, structures which have multiple contours in different dimensions can be produced. Examples of some of these structures are shown in figure 8.

The general principle which is involved here is that the overall shape of the feature, i.e. the outside boundary, is defined by an aperture at the mask plane. If any structures are to be included inside this shape, then this is also contained in a mask. The structures may or may not be contained in the same mask as the outside shape, depending on the exact application.

If the structures need to be combined with some contoured profile (e.g. a ramp), then this is achieved by superimposing an appropriate shape at the mask plane, as in mask dragging. Hence, the overall shape, with or without structures inside is, is produced by synchronised scanning and the contoured profile is imparted on this shape by the use of a shaped aperture. This technique for producing multi-dimensional features is termed *synchronised overlay scanning*.

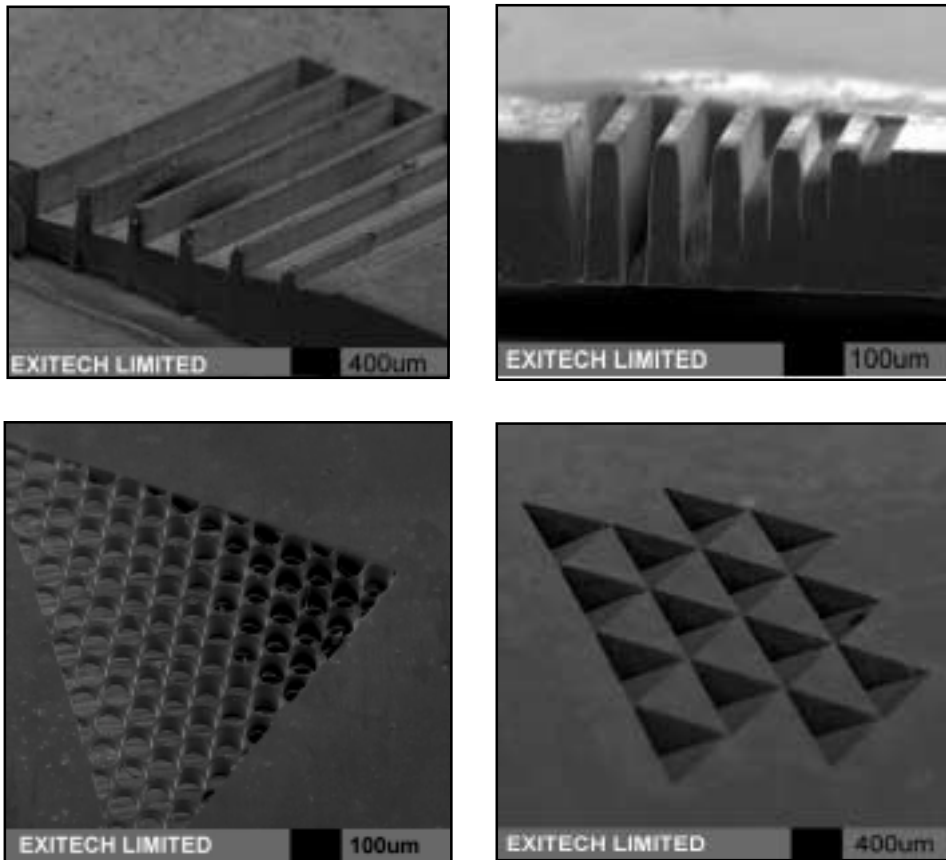


Figure 8. Multi-faceted structures produced in polymers by overlay synchronised scanning technique

5. SUMMARY

New developments in laser applications are promoting the need for more elaborate techniques for the production of novel microstructures. Excimer laser ablation, which has become established in many areas as an production-worthy process, is at the forefront of these new microstructuring techniques and we have demonstrated new processing methods which allow multi-dimensional micro-structures to be made. The advantages of the mask projection techniques which have been presented are that they are relatively simple, very flexible, have a relatively high processing speed, only involve one or two steps and that a single system can be used for a wide variety of applications.

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