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Pulsed Laser Ablation for Volume Micro-Optical Arrays on Large Area Substrates

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ABSTRACT

Laser micromachining by ablation is an established technique for the production of 2.5D and 3D features in a wide variety of materials. Mask projection techniques using excimer lasers have been used to fabricate microstructures on large panels where diamond turning and reflow techniques have reached their limits. We have developed 3D structuring tools based upon UV laser ablation of polymers to create large arrays of repeating micro-optical features. Synchronization of laser pulses with workpiece movement allows layer-by-layer growth of deep structures with outstanding repeatability. Here, we show recent developments in laser structuring with the combination of half-tone and binary mask techniques. Significant improvements in surface quality are demonstrated for a limited range of structures.

Keywords: Micromachining, ablation, MEMS, MOEMS, half-tone

1. INTRODUCTION

Pulsed laser ablation has become a very powerful tool in the field of micro-engineering. High quality, industrially robust lasers operating from near-IR to UV are available with a wide range of beam characteristics. Whilst femtosecond lasers are becoming more common in research institutes, nanosecond processing based upon both solid-state and gas lasers are more common in industrial environments[1].

Laser scribing tools based upon highly coherent diode-pumped solid state (DPSS) lasers offer a simple but reliable way of patterning thin film materials[2]. Low beam divergence and high repetition rate allow these lasers to be focused to a small, intense, spot and rapidly scanned across a workpiece. Recently, such laser systems have been used to scribe isolation lines on several layers of solar panel components[3]. Alternatively, solid-state lasers can be used with beam homogenizing optics to allow mask projection techniques to be used. Rapid patterning of transparent conductive layers such as indium tin oxide (ITO) can be achieved with such laser systems[4].

Micromachining of 2.5D and 3D features by laser ablation has been demonstrated in a variety of materials[5]. Thermally conductive materials such as metals and semiconductors can be micromachined using the highly intense focused spot of Nd:YAG lasers operating at either fundamental, frequency doubled or tripled wavelengths. Polymers have lower thermal conductivity and usually absorb strongly at UV. Processing of polymers at longer wavelengths usually requires high power and results in undesirable thermal damage. Conversely, modest fluence levels of a few hundred mJ/cm^2 are sufficient to achieve ablation rates of a few hundred nm per shot with UV making them ideal for large area processing with excimer lasers.

Laser processing of MEMS and MOEMS structures has been widely publicized in recent years[6,7]. Often, such laser processed parts are used for replication by electroforming and hot embossing or injection moulding. This allows the unit cost of up to several thousand dollars per part to be reduced to a few dollars or less. Microlens arrays formed from a laser ablated mould are widely used in elements of rear projection televisions and mobile display screens to improve the viewing angle and/or contrast of the screen.

2. MICRO-OPTICAL ARRAYS BY LASER ABLATION

Excimer lasers offer high pulse energy and low spatial coherence allowing parallel processing of many parts with an easily homogenized laser beam. The geometry of complex features can be controlled using precisely defined chrome-on-quartz photomasks, such as those used in lithography. Hence, 3D features can be grown using layer-by-layer removal of the outlying material.

2.1. PROJECTION LASER ABLATION

Typical excimer laser machining systems employ some form of beam homogenization unit to improve the surface quality of the patterned substrate. Most notable is the double array of refractive lenses also known as a fly's eye arrangement. An example of this setup is shown in figure 1 below.

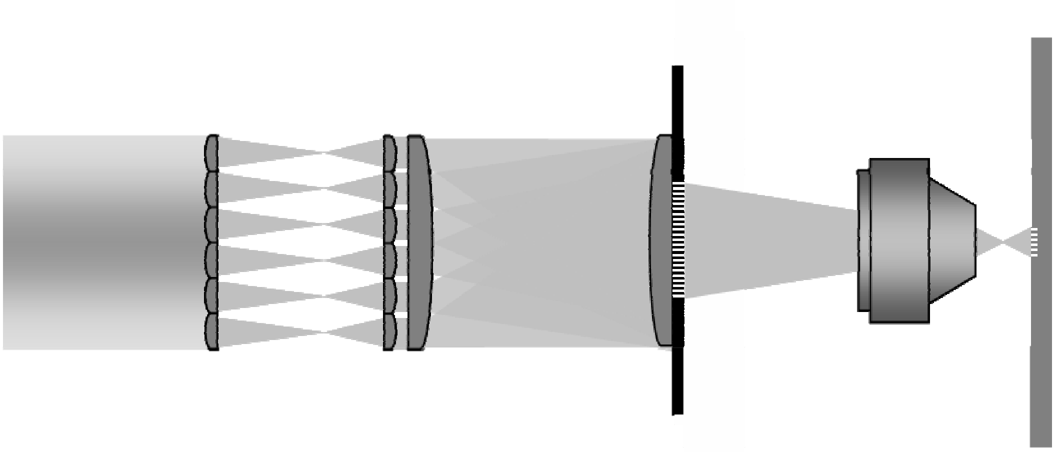

Fig.1. Typical optical system for excimer laser micromachining. Uniform illumination is achieved at the mask plane using superposition of beamlets from a multi-lens homogenizer.

2.2. 1D ARRAYS

Elongated features such as prisms and grooves with a variety of cross-sectional geometries can be made using mask projection laser ablation and workpiece dragging. In this arrangement, the workpiece is moved at constant or variable speed whilst undergoing ablation. The geometry of the feature in this case is defined by the shape of the aperture and the operating parameters of the laser system such as the fluence and speed of the stage movement. Figure 2 shows an illustration of how 1D prisms or v-grooves are made using this technique, together with a SEM picture of a sample v-groove.

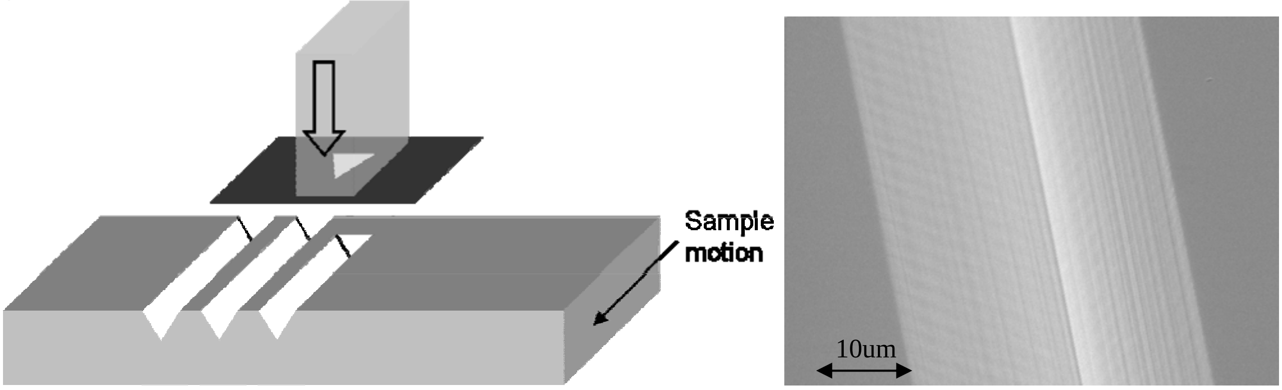

Fig. 2. Workpiece dragging method for producing 1D structures. Uniform illumination of a triangular aperture causes more material to be removed towards the centre of the groove.

2.3. 2D ARRAYS

Workpiece dragging also enables 2D arrays of features to be created by a simple rotation of the workpiece between process steps. In the case of a prism, machining two prism arrays, separated by a rotation step would result in a 2D array of pyramids. Additionally, the packing and dimensions of such pyramids could be controlled by the rotation angle and operating fluence for each step. However, most micro-optical features required in display applications, e.g. spherical lenses, cannot be defined by a simple superposition of two 1D functions. In this case, it is necessary to use a mask containing 2D information about the feature profile.

A Technique known as Synchronized-Image-Scanning (SIS) has been developed to exploit the high pulse energy and low repetition rate of the excimer laser[8]. Using this method, 3D features are grown in a layer-by-layer way to generate an array of identical structures over a large area. Figure 3 illustrates how this can be achieved using a single mask pattern illuminated by a large uniform laser beam.

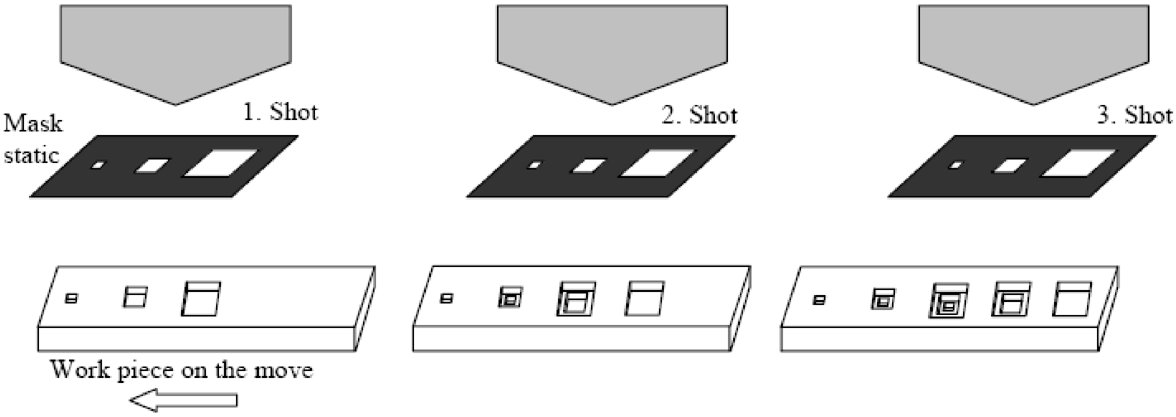

Fig. 3. Formation of 2D arrays of microstructures by Synchronised-Image-Scanning, (SIS). Layer-by-layer removal of material builds up features according to the mask geometry.

In the case of shallow structures, <50um deep, the layer-by layer formation of the features allows precise control of their geometry. The design of such a mask is a non-trivial task if the geometry is complex and we have developed algorithms to generate mask patterns for such complex shapes. For deeper structures, far beyond the depth of field for the system projection lens, require careful consideration of defocusing to ensure the correct shape is produced. Figure 4 shows a 2D array of lenses fabricated by SIS.

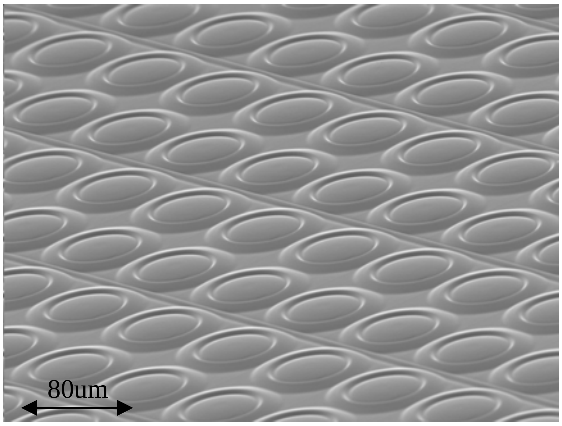

Fig. 4. Fresnel lenses produced by Synchronised-Image-Scanning, (SIS). Complex surface geometries are easily produced by laser ablation due to the layer-by-layer removal of material.

3. RECENT ADVANCEMENTS IN MICRO-OPTICAL STRUCTURING

Generating microlenses with low F-numbers is difficult to achieve with many micro-processing techniques. Steep gradients at the boundary of the lens provide particular difficulty for laser processing and an inherent wall angle usually remains. Furthermore, the layer-by-layer growth of deep features can result in a series of stepped images being observable where the surface gradient is low. This additional surface roughness is undesirable and is easily observable in the centre of convex microlenses, see figure 5.

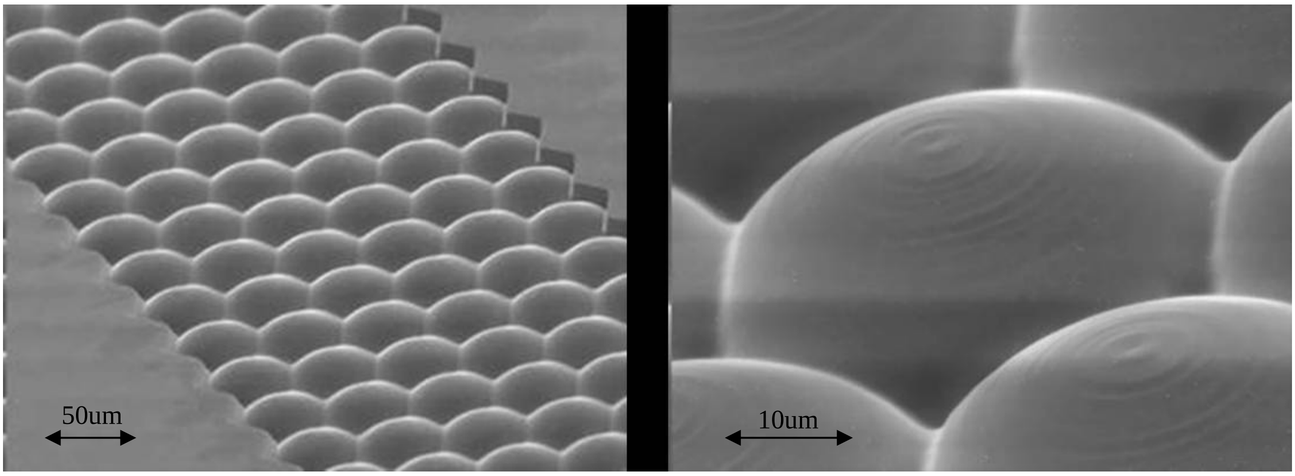

Fig. 5. Microlenses made by synchronized-image-scanning (SIS) in polycarbonate. Surface roughness can result from finite number of apertures in mask array.

The additional surface roughness can be reduced by post-processing with laser polishing techniques[9]. This technique removes high frequency surface roughness by causing localized reflow in the polycarbonate from a small number of laser shots at modest fluence. However, angular dependence in the ablation rate of polymers becomes important at high angles of incidence and can act to deform the initial shape of the feature[10]. We have developed a technique combining SIS and halftone mask patterns in order to reduce the surface roughness without any post processing step.

3.1. HALFTONE-SIS

Halftone masks offer a way of varying the local transmission of a photomask through diffractive methods[11]. Unlike true greyscale technology such as high energy beam sensitive (HEBS) glass masks, halftone allows a large number of ‘grey’ levels using standard chrome-on-quartz photomasks. This method is preferable since the mask writing tools are less specialized and masks usually have very short lead times. Furthermore, standard chrome-on-quartz photomasks have been widely used in high-power projection laser ablation and have proved they are reliable for withstanding long process runs without damage. Figure 6 shows typical structures machined into polycarbonate using static halftone ablation at 248nm.

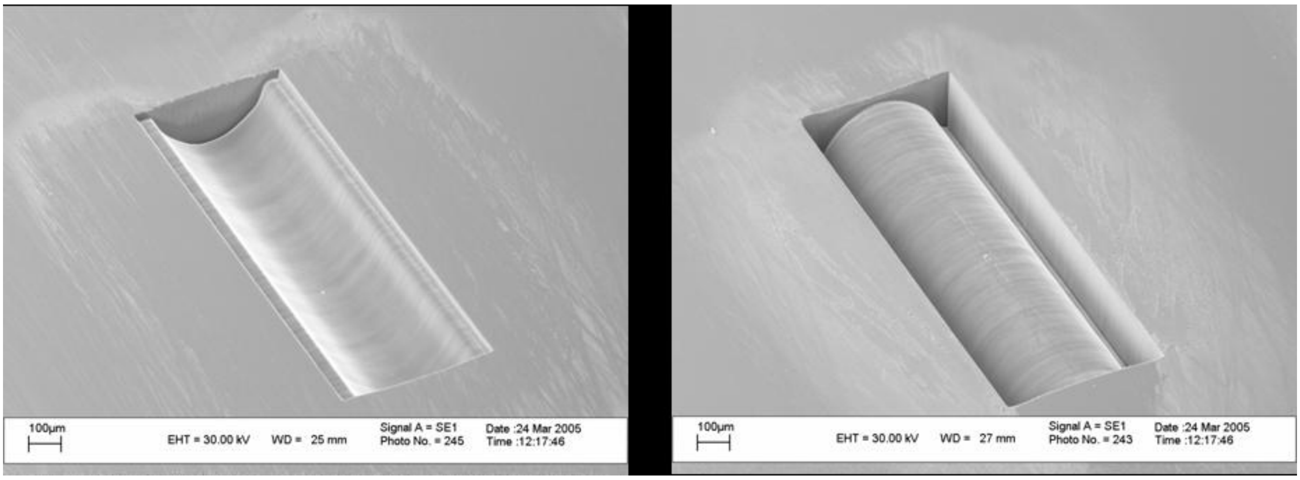

Fig. 6. Cylindrical microlenses machined into polycarbonate using static halftone ablation at 248nm. Surfaces typically exhibit low surface roughness due to the wide range of ‘grey’ levels in the mask.

Hundreds of ‘grey’ levels are available using half-tone masks and simple design procedures can be adopted to generate mask patterns for a wide range of structures. The effective transmission step between neighboring transmission levels is typically less than 1% and structures with stepped surfaces are usually avoidable. By combining the halftone technique with standard SIS, it is possible to manufacture large arrays of microstructures with various geometries and low surface roughness. Figure 7 shows an illustration of how the techniques are combined on the mask.

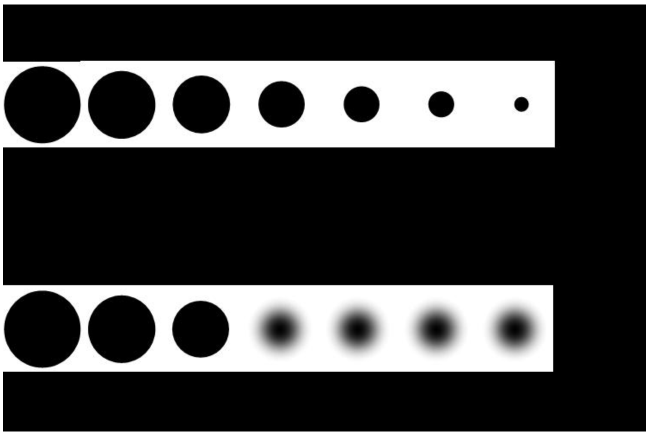

Fig. 7. Illustration of halftone-SIS combination. One or more contours on the SIS mask are replaced by halftone elements to reduce surface roughness.

Halftone elements produce local transmission regions with areas less than 1umx1um on the workpiece. We have machined features with lateral sizes ranging from 1mm to 7um with halftone masks, where the shape of the feature is defined by a finite number of pixels. The surfaces from such features typically exhibit good profile accuracy with outstanding surface roughness. Figure 8 shows a microlens array produced with haftone-SIS. This technique can be easily scaled to allow several m^2 of processed area.

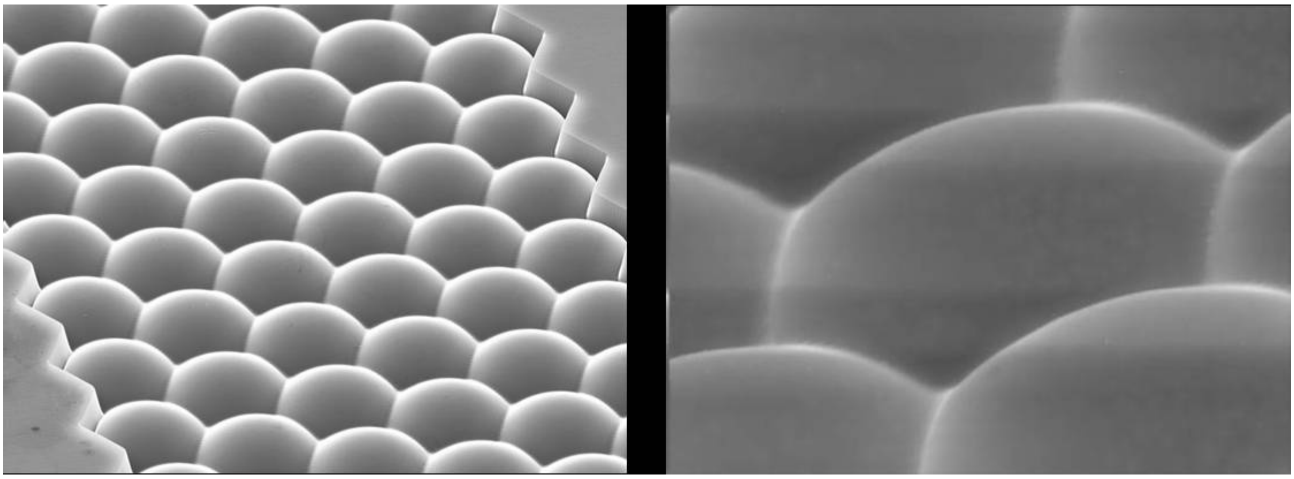

Fig. 8. Microlenses from halftone-SIS. Stepping from SIS ‘slices’ has been eliminated and the transition between adjacent ‘grey’ areas is not apparent.

Surface roughness measurements in the central ~15um of the lens were made with a Zygo white light interferometer. Line roughness in this region was calculated as ~10nm Ra, comparing favorably with diamond turning and greyscale lithography.

There are two competing technologies for creating arrays of micro-optical features, greyscale lithography and diamond turning. Greyscale lithography followed by transfer of photoresist profiles into harder materials by anisotropic etching is limited to smaller, typically wafer based, machines[12]. Diamond turning can offer an alternative to the laser ablation technique for lenses larger than 50um and is scaleable to large area processing. In cases where it is preferable to directly machine into a hard material such as glass, diamond turning is the only viable solution. However, features with circular asymmetry, such as aspherical lenses with different radii in each axis, are very difficult to achieve with diamond turning. Such lenses offer significant benefits over circularly symmetric lenses in display applications where the field of view requirements are different in the horizontal and vertical axes. Fabrication of a master mould by laser processing, followed by replication by electroforming and hot embossing is the ideal way to create such lens arrays.

4. CONCLUSION

Laser machining by ablation has been shown to provide a reliable way of producing a range of microstructures and direct machining of polycarbonate with excimer lasers has been demonstrated for a variety of feature geometries. The combination of halftone and synchronized-image-scanning (SIS) has been introduced as a way of producing high quality microstructures on large area substrates. Halftone-SIS offers surface quality comparable with other more established techniques such as diamond turning and greyscale lithography, whilst also easily scaleable to several m^2 of processing area.

5. REFERENCES

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