Lasers in Manufacturing Conference 2015

Scanned Mask Imaging: The economical approach to high resolution micro-machining using UV solid state lasers

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Abstract

Two methods currently exist for micro-structuring materials by laser: mask projection and direct write. This paper outlines a novel and alternative method called Scanned Mask Imaging (SMI), the resulting quality of SMI is comparable to that of excimer laser mask projection systems, but delivered at a fraction of the cost and burden of ownership. SMI has the potential to unlock the development of novel micro-machining techniques via programmable illumination patterns and dual plane imaging optics. Advantages of this new Scanned Mask Imaging method compared with conventional excimer laser based mask projection systems are discovered and summarized in this paper.

Keywords: Micro-machining; Scanned Mask Imaging; Mask projection; UV; Solid state lasers; Ablation; Imaging

1. Introduction

“Mask Projection” and “Direct Write” are the two methods most widely used for micro-structuring of materials by laser. In mask projection systems, excimer lasers are typically used. They can achieve high quality ablation at high resolution, but the machines have a high capital cost and regular laser maintenance is required. For the direct write method, solid state lasers are better suited due to their high coherence, allowing the beam to be focused to a small spot. These systems are flexible to operate, and usually much cheaper to own and maintain than an excimer system. However with direct write, it is very difficult to ablate arbitrary patterns with both fine and large scale features, and to maintain depth control in complex 3D structures. This paper explores a new method for micro-structuring materials where a UV multi-mode solid state laser and scanner are used to illuminate a photo-mask. An image of the mask is subsequently projected and de-magnified onto the substrate through a projection lens. This method is called Scanned Mask Imaging. This process effectively ablates arbitrary features down to a resolution of a few microns, a process which direct write methods are unable to achieve. SMI can achieve ablation quality comparable to that of excimer laser systems, at a fraction of the cost with greater ease of installation and maintenance of the hardware.

2. Laser Mask Projection with Excimer Lasers

2.1. Excimer Laser Features

Excimer lasers are the highest average power pulsed sources available in the ultraviolet region and systems with outputs up to many hundreds of watts at wavelengths of 248nm and 308nm are in use for a wide range of micro-machining applications. The outputs are characterized by high (up to 1J) energy pulses at modest (up to a few 100Hz) repetition rates. With pulse lengths in the 20ns range pulse powers over 50MW are readily achievable. Excimer lasers emit beams with poor temporal and spatial coherence having large (200 to 300pm) bandwidth and a very high number of modes ($M^2 > 50$) which make them ideal for mask imaging. Since the output beams are large (e.g. 10 x 30mm), with asymmetric and highly divergent properties, complex beam shaping and homogenizing optics are essential to transform the beams to the required shape and uniformity required for illumination of a mask which is subsequently imaged onto the substrate by a projection lens. The illuminated area of the mask is projected onto the substrate by a lens of suitable resolution and reduction factor (typically 3x to 5x) to give a fluence suitable for ablation of organic or thin film materials. Such an optical system can be most readily used for step and repeat ablation patterning but the complex optics have relatively poor transmission, so the maximum area that can be exposed at the substrate with a single pulse at an appropriate (around 1J/cm2) fluence is a few tens of mm2. Hence schemes have been devised to increase the processible area at the substrate.

2.2. Excimer Laser Approach

The excimer laser based approaches can achieve excellent micro-machining results [1] with feature resolutions down to a few microns, with good depth uniformity and depth control. However, the cost of ownership of excimer laser based production systems is very high due to the high capital cost of the lasers, the complexity and short lifetime of the homogenization and projection optics at UV wavelengths, and the frequent replacement of laser parts. There is a burden of limited gas lifetime and the need to renew the gas in the cavity to maintain laser output. This has limited the adoption of high resolution micro-machining using mask projection for many manufacturing applications, particularly those related to sub-component manufacturing for mobile consumer electronics.

3. Scanned Mask Imaging with UV multi-mode solid state laser

3.1. SMI Optical System

Scanned Mask Imaging is based on the use of high power frequency tripled (355nm), Q-switched, multimode, diode pumped solid state (DPSS) YAG lasers. These lasers have beam output characteristics that differ to excimer lasers, operating with pulse repetition rates generally in the few kHz to few tens of kHz range with pulse energies up to a few mJ. Highly robust commercial units are available with powers up to 80W from a single cavity, with typical pulse lengths in the range 50 to 100ns. Output beams are entirely suitable for mask imaging having poor spatial coherence (M^2 in 10 to 25 range) and are axisymmetric in shape and divergence so require only simple optics to propagate. Unlike excimer lasers the DPSS laser temporal coherence is high as the bandwidth is only a few pm which simplifies the manufacture of high resolution imaging optics. As the DPSS laser single pulse energy is much lower than that from an excimer laser, in order to obtain the same fluence at the substrate a much smaller spot is required. The SMI beam is reshaped to create a square spot with quasi-top hat distribution, which is then raster scanned in 2D over the mask area. The image of the mask is reduction imaged onto the substrate to give an appropriate fluence. SMI technology gives imaging resolution and ablation rates similar to those of an excimer system, but with significantly simpler optics and dramatically lower cost of ownership.

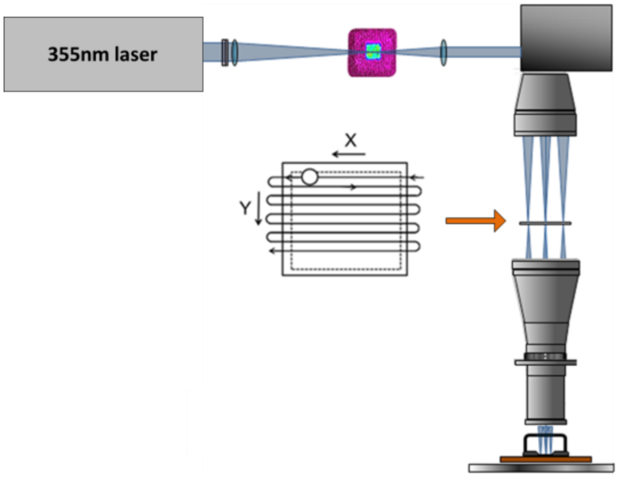


Fig. 1. SMI optical system

Fig 1 shows a schematic diagram of the optical system used for SMI. The laser beam is expanded using a simple telescope, and shaped and homogenized by a Diffractive Optical Element (DOE) to form a square (approx. 1 x 1mm), flat top beam at the beam waist of a plano-convex lens. The plane of homogenization is imaged onto the mask using an infinity imaging system consisting of a second singlet and the telecentric f-theta scan lens following a 2D galvo scanner. The divergence of the beam after the beam waist at the mask is defined by the homogenizer, the first singlet and the lenses in the infinity imaging system.

3.2. SMI System Design

The design considerations for the SMI mask imaging system are exactly the same as for an excimer mask imaging system. The magnification of the projection lens is chosen to be the lowest possible (to minimize mask size) but at the same time give the desired fluence at the substrate for a spot size at the mask giving a fluence well below the damage threshold of about 100mJ/cm2 [2] for a chrome on quartz mask or 250mJ/cm2 for an Al on quartz mask. A lens demagnification of 3.5 is used for the current lens, offering a good compromise between high resolution and fluence (up to 2J/cm2) at the substrate, whilst limiting the mask size which limits the maximum mask scan speed requirements. The lens is of double telecentric type with field of 20 x 20mm and a numerical aperture of 0.11 giving a theoretical limiting resolution of 3µm. Illuminating the mask with a flat top, homogenous beam offers several advantages over the approximately Gaussian multimode beam profile directly from the laser. It lowers the peak fluence of the beam, reducing the risk of damaging the mask, as well as reducing the percentage of the beam with a fluence below the ablation threshold of the substrate. It also reduces the coherence length of the beam further which is beneficial for imaging as it increases the partial coherence factor of the imaging system reducing diffraction effects at the edge of ablated features in the substrate [3]. The mask is mounted on a stage to allow precise overlay of multiple images at the substrate to create 3D structures in materials. The accuracy of the registration of the two images is dependent on the mask alignment to the mask stage, the accuracy of the stage itself and the magnification of the imaging system, with registrations much better than a few µm at the substrate being easily achievable.

4. Scanned Mask Imaging Pilot System Results

4.1. SMI and Excimer comparison

A disadvantage of DPSS laser based SMI compared to mask imaging with an excimer laser is the limitation in available wavelengths. 355nm is the shortest wavelength presently available (at a competitive price) from DPSS lasers whereas excimer lasers can operate at high power down to 248nm. However many production excimer laser micromachining applications involve materials that allow the use of lasers that operate at 308nm and these materials (polyimide, resins, SU-8, etc) generally respond equally well at 355nm. Because of the up to 100x higher repetition rate of a DPSS laser compared to an excimer laser the local average power density on the material during ablation can be very much higher for similar fluences and shots delivered per unit area. If an energy dose of 20J/cm2 (20 shots x 1J/cm2) is required to ablate structures to a certain depth (e.g. 10µm) then a DPSS laser delivers this dose in at most a few ms (e.g. 2ms) whereas an excimer laser takes many 10s of ms (e.g. 70ms). Hence local short timescale thermal effects can sometimes detrimentally affect ablation quality with the SMI system for some materials. Use of a high speed galvanometer scanner to deflect the beam across the mask gives complete flexibility in how the mask is raster scanned giving full control over the time between consecutive shots on a given part of the substrate to eliminate such effects.

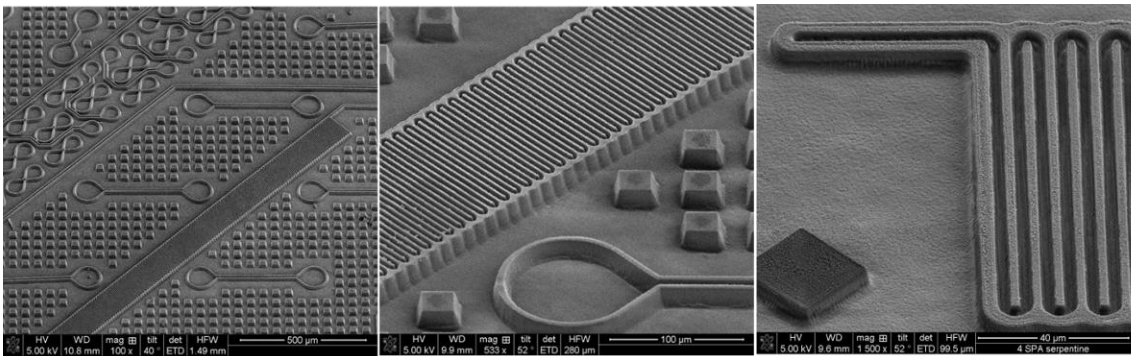
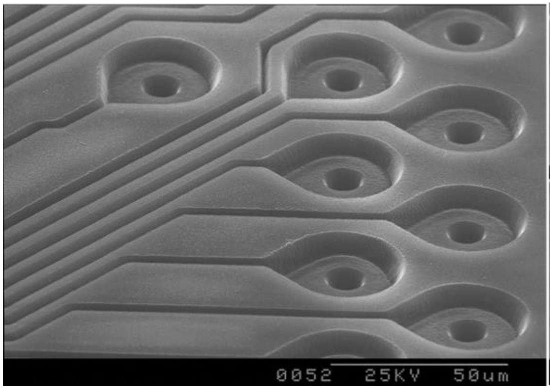


Fig. 2. 10µm deep structures in BTXTM. Design courtesy of Amkor

4.2. SMI's Advanced Capabilities

The SMI system has been used with a 20W average power DPSS laser to micro-machine structures in a range of organic materials including polyimide and polyimide type materials widely used for micro-electronics devices (e.g. proprietary materials such as ABF, UltimaxTM, BTXTM, etc). Typical ablation rates of these materials are in the range 0.5 to 0.7µm/shot at a fluence of 1J/cm2. Fig 2 shows a series of SEM images of structures micro-machined to a single depth of 10um in BTXTM by SMI using a single mask. The inter-digitated structure, appropriate for micro-fluidic applications has line/space dimensions of 3µm/3µm and an aspect ratio of 3.

Multiple depth structures can be formed by mask exchange. Fig 3a shows a 2 layer structure relevant to laser embedded conductor (LEC) redistribution layers in IC substrates and organic interposers. The material is 20µm thick BTXTM on a copper clad core and the dual depths are made by sequentially projecting the images from 2 different masks. 10µm diameter vias are positioned in 30µm pads connected to 3µm wide traces on a pitch of 6µm.



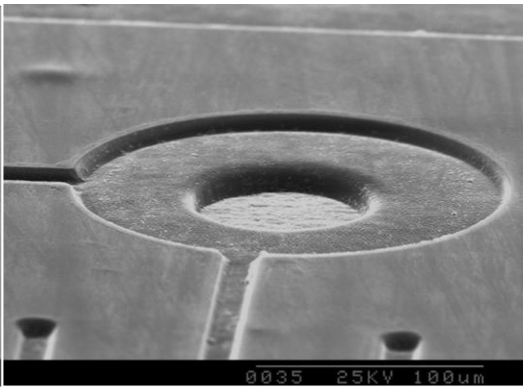


Fig. 3a. 2 layer ICP structures in UltimaxTM,

Fig. 3b. 2 layer ICP structures in UltimaxTM,

Fig 3b shows a different method to create vias in pads using a single mask. In a first stage the upper layer with traces and 180µm diameter pads is formed by SMI following which the 80µm diameter vias are drilled through to the base copper using a point and shoot aperture imaging process. In the aperture imaging process a circular aperture to define the via is inserted at the homogenizer output plane. The aperture is imaged onto the mask and subsequently onto the substrate to form a via of the correct diameter. The scanner positions the image of the aperture at appropriate pad locations on the mask and the beam passes through the mask to create vias within the pads at the substrate. More complex multi-depth structures can be formed using multiple masks. Fig 4 shows images of multi-depth structures formed in polyimide by SMI using a sequence of 4 different masks. Each layer is 5µm deep.

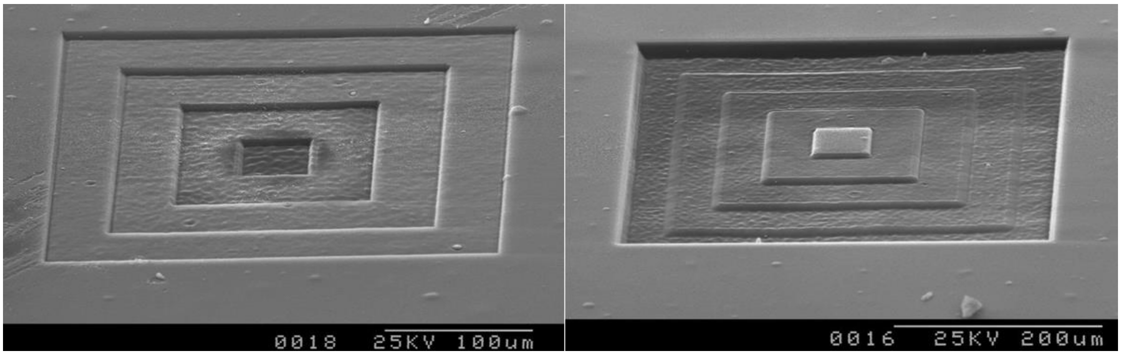


Fig. 4. Multiple depth structures in polyimide,

When 3D structures with features that vary gradually in depth such as ramps, slopes, depressions or domes are required, SMI has considerably more flexibility than excimer laser mask projection systems. Because SMI scans the mask area in 2D with a beam that is much smaller than the image size using a galvo-scanner it is possible to selectively scan the mask and vary (on the fly) one or more of a) the beam scan speed, b) the pulse overlap pattern and c) the laser pulse energy, which may be applied to any particular region of the image projected from a single mask to achieve the desired depth profiles. Selective mask scanning can also be used to accurately control ablation depth with high accuracy for both large and small feature on a mask and readily overcome the well know problem of enhanced ablation rate for a given fluence for smaller features and at the edges of larger features caused by plume/beam interaction effects.

5. Conclusions

Scanned mask imaging using a UV DPSS laser has been introduced as an alternative to excimer laser mask projection systems for high resolution ablative micro-machining.   The resulting quality is comparable to that of excimer laser systems, but delivered at a fraction of the cost and burden of ownership, with structures down to 3µm line width and spacing demonstrated. The SMI method is proving to have unlocked the potential for development of novel micro-machining techniques via programmable illumination patterns and dual plane imaging optics.

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