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High volume fabrication of laser targets using MEMS techniques

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Abstract. The latest techniques for the fabrication of high power laser targets, using processes developed for the manufacture of Micro-Electro-Mechanical System (MEMS) devices are discussed. These laser targets are designed to meet the needs of the increased shot numbers that are available in the latest design of laser facilities. Traditionally laser targets have been fabricated using conventional machining or coarse etching processes and have been produced in quantities of 10s to low 100s. Such targets can be used for high complexity experiments such as Inertial Fusion Energy (IFE) studies and can have many complex components that need assembling and characterisation with high precision. Using the techniques that are common to MEMS devices and integrating these with an existing target fabrication capability we are able to manufacture and deliver targets to these systems. It also enables us to manufacture novel targets that have not been possible using other techniques. In addition, developments in the positioning systems that are required to deliver these targets to the laser focus are also required and a system to deliver the target to a focus of an F2 beam at 0.1Hz is discussed.

1. Introduction

There have been target fabrication activities in the UK for a number of years both at the HELEN laser in AWE and the Vulcan Laser in the Central Laser Facility at Rutherford Appleton Laboratory [1]. These facilities have supported experiments on laser systems that require targets at relatively low volumes. The technologies that have been used to deliver targets to these systems has not vastly changed over time with precision machining, thin film coating, and precise hand assembly being the core activities of a target fabrication group. However since the development of the Vulcan Petawatt laser in 2002 [2], there has been a marked increase in the number of high intensity laser facilities across the world and therefore an increase in the number of shots available. This allows the experimental community to carry out a wider variety of experiments and therefore utilise a wider



variety of target types. Recent laser developments that involve the laser moving from flash lamp to diode pumped designs have led to the possibility of switching from experimental based laser facilities to application based facilities. With this transition from large single shot facilities, such as Vulcan, to much higher repetition rate systems, such as the Astra Gemini laser which is a 2 beam Petawatt (PW) system with 0.5PW in each beam with the ability to operate at rates of approximately 1Hz [3], these systems are no longer shot limited. These application based facilities require large volumes of relatively simple, high specification targets but conventional techniques are not equipped to deal with this demand.

As shot numbers have increased by two orders of magnitude it is clear that to be able to deliver a sufficient number of targets to the laser facilities the existing fabrication techniques need to be expanded. Initially, for simple target geometries, these numbers could be provided using basic fabrication techniques such as ‘float off’ foils mounted over an array of holes, or using clamp raster mounts to give large numbers of targets in a small puck [4]. Experiments carried out on these target types gave the first indications of application based experiments that could be carried out in the future [5]. There is however a limit to the target geometries that can be produced using these techniques with 2D foil targets being the only viable type that can be produced, and while useful for simple ion acceleration experiments the more complex and scientifically interesting targets cannot be fabricated in high enough numbers to utilise the shots available. It should also be noted that targets, such as 10 nanometer thick gold foils, are extremely fragile and when floated over a hole of 400-500 microns diameter the yield is significantly compromised compared with thicker materials and low enough to make the experiments target resource limited. In some cases this can be overcome by making the mounting aperture smaller but other experiments require specific larger target geometries. Some high-strength target materials, such as Diamond-Like-Carbon (DLC) allow thin films in the range of 2-5 nanometers to be produced [6] and this has improved results but the yield is still low and to fully utilise the laser facilities high repetition rate capabilities requires an almost prohibitive target fabrication resource. It is also apparent that due to the high shot numbers, the fundamental science experiments using simple target geometries are completed within a few months of the facility opening and therefore to undertake more complex experiments a more complex target is required. The cutting edge of conventional target fabrication techniques cannot in its current state deliver complex targets in high volumes.

In addition there is also the challenge of inserting high numbers of targets into the interaction chamber and thence to the laser focus at a speed comparable with the laser shot rate; this includes problems that are encountered when trying to align targets within short timescales. It is clear that any fabrication process that would produce targets that are precisely and reproducibly located to within a micron is ideally suited to these high rep rate applications.

2. MEMS fabrication for laser targets

MEMS fabrication techniques rely on three basic steps: deposition, patterning and etching. These additive and subtractive steps are repeated as often as required, in the appropriate order until the finished device is manufactured. The basic substrate is usually a silicon wafer; the deposition steps are provided by various sputter and thermal coating tools; the patterning by optical or e-beam lithography, as deemed by the resolution required, and the etching is either wet (e.g. acidic or alkaline solutions) or dry (plasma). These processes enable the fabrication of 2 and 2 ½ dimensional structures on the nanometer scale with high accuracy and repeatability in high numbers. A typical example of a MEMS device manufactured in the semiconductor/MEMS industry would be the accelerometers in car airbag safety systems [7] where micro-mechanical parts are integrated with microelectronics. We are now using these technologies to produce a range of targets in higher volumes than previously produced and to a high specification. It should be noted that to produce these targets significant infrastructure is required and includes not only advanced deposition, patterning and etching tools but also high quality

cleanroom facilities to ensure that there is no particulate contamination. This is essential when working with devices that can be of the order of one micron in size as any debris or dirt can damage the targets and render it unusable

2.1. *Simple thin foil targets*

The simplest target that can be produced is a thin foil suspended over a small hole. Such targets can be divided into two categories: 1) Standard thin foil targets such as those used in radiation pressure acceleration experiments in the hole-boring regime have thicknesses in the micron scale and 2) Ultra-thin foils which are used in the light sail regime which are considerably thinner, in the nanometre scale.

Standard thin films require a foil, coated onto a release layer, to be ‘floated off’ onto the surface of water. The foil is then picked up using a bespoke mount which includes a hole which defines the target area of freestanding foil. This is a labour intensive process and does not lend itself to high target numbers. MEMS techniques allow the yield of such targets to be greatly increased as the plastic foil can be coated directly onto a wafer substrate which will eventually become the target mount.

In the simplest case chemical vapour deposition (CVD) techniques are used to deposit a parylene polymer thin foil directly onto the surface of a wafer. The reverse side of the wafer is then coated with an optical resist, such as AZ9260, and is then placed in a mask aligner for UV exposure through a photo mask patterned with the desired array of target holes. After development the remaining resist protects specific areas of the wafer whilst leaving the other areas exposed for further processing. Using deep reactive ion etching (DRIE) the exposed areas of the wafer can be etched, stopping at the silicon/parylene interface leaving a suspended parylene foil over an array of holes (Figure 1& 2). The geometry and position of this hole can be closely controlled during the design stage of the mask and this allows for accurate and quick target positioning in the target chamber by referencing these drawings. An addition benefit of coating the parylene onto the surface of a polished silicon wafer is that it produces a foil that has a similar surface roughness as the original surface of the silicon wafer. This is an important requirement for certain classes of experiment (TNSA ion acceleration) that rely on the foil being perfectly flat on the scale of the laser focus as the ion beams generated in the acceleration mechanism propagate normal to the target surface.



Figure 1. The etched holes on the rear (polished) surface of a silicon wafer.

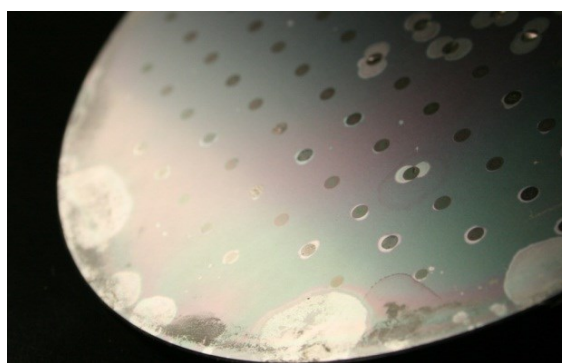


Figure 2. A suspended Parylene (CH) film over open apertures in the silicon wafer.

Characterisation data of at a range of positions on the parylene foil measured using a white light interferometer show the roughness across a random sample is consistent with the surface roughness measured from the unpolished side of the silicon process wafer.

2.2. Ultra-thin foil targets

These targets have applications in ion acceleration experiments where a foil of a few nanometres in thickness is accelerated by a different mechanism, namely ‘break-out afterburner’ [8] or in induced transparency experiments [9]. Targets are conventionally fabricated using the same techniques as described earlier but due to the thin nature they are inherently more fragile and yield rates can be as low as 5% making them very labour intensive and therefore not an idea target for higher repetition rate experiments and high volume fabrication. MEMS processing techniques can also be used for the manufacture of this type of target, and combined with material choices that exhibit a higher strength than standard foils the yield of the targets can be increased dramatically.

In one such example a thin foil (5nm) of tantalum nitride (TaN) was deposited using an atomic layer deposition (ALD) process onto a silicon wafer [10] with the thickness measured post deposition by ellipsometry to be 4.46nm. ALD was chosen as it is a relatively low temperature technique that provides highly uniform, conformal, pin-hole-free films with excellent control over film thickness. This wafer had an interface layer grown between the bulk and the ALD TaN to allow for etching without the damage of the foil and a resist protection layer was also then placed onto the target material. Subsequent processing produced a large number of targets on a single wafer (figures 3 and 4) with an almost 100% yield.

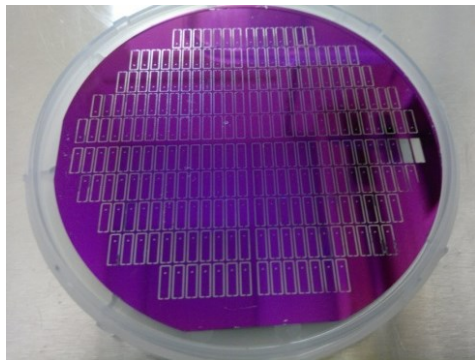


Figure 3. The silicon wafer with a TaN coating and etched through features.

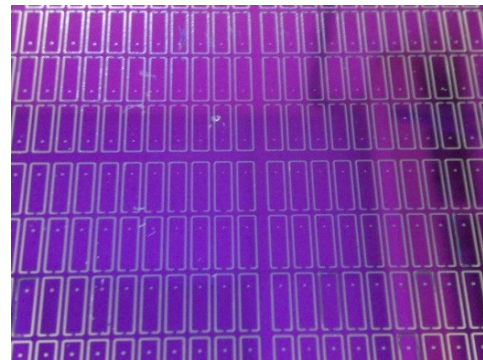


Figure 4. View showing the 300 micron target aperture on a 2x7mm target mount.

An interesting feature of these target foils is that there is a surface form that is created by etching away the rear of the wafer and exposing the target. This form is dependent on the thickness of the TaN layer with an increase in surface topography observed as the TaN layer becomes thinner. This is illustrated by the data given in table 1, which shows the height of the highest part of the target foil above the surface of the silicon wafer.

Table 1. The difference between the highest part of the target sample and the surface of the silicon wafer for a number of target thicknesses.

| Thickness (μm) | Height above wafer (μm) |
|-----------------------------|--------------------------------------|
| 5nm | 14.55 |
| 10nm | 14.60 |
| 15nm | 12.40 |
| 25nm | 2.68 |

Analysis of the surface form of the targets shows that for a 25nm target there seems to be much flatter and more uniform structure to the target and a smaller deviation from the surface of the silicon wafer. The surface topography is believed to be due to internal stress in the target and further work is required to investigate this.

2.3. Microdot targets

In some experiments using facilities such as Free Electron Lasers (FELs) it is important that the laser intensity is uniform across the area of interest, in other experiments the target material of interest may be required to only be very small to ensure that it can be heated efficiently by the laser pulse. Therefore the thin foil is reduced from a continuous area to a micron scale dot. Certain geometries lend themselves to be coated using standard thin film techniques though a mask that can be prepared by, for example, photo etching. There is however a limit to the minimum size of mask that can be produced that can give well defined features, and for thicker coatings a gaussian distribution is observed in the 'dot'. Certain materials are not amenable to being evaporated using directional means such as thermal or electron beam coating and are better sputtered, however this process is not an ideal process for coating through masks and therefore a more refined approach is needed.

An array of 40 x 40 targets, shown in figure 5, giving up to 1600 shots was prepared using these methods. The target design was a 1 micron thick plastic support with a 5 micron diameter, 1 micron thick iron dot suspended in its center. Using a bi-layer resist combined with a number of coating processes and a lift-off process, a well-defined dot can be deposited using plasma sputtering. The bi-layer resist enables the coating to be removed from around the dot without damaging the dot coating and etching by DRIE can then expose the supporting film leaving a suspended dot target shown in figures 6 and 7.

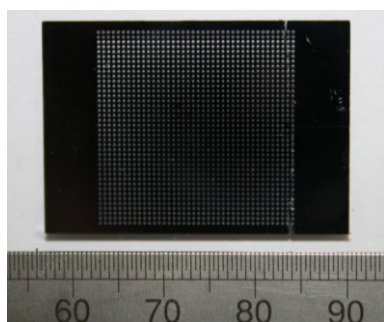


Figure 5. The 40 x 40 array of apertures on a silicon chip

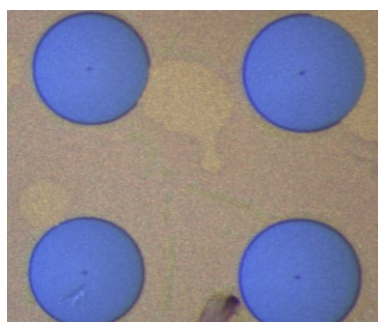


Figure 6. The suspended plastic membrane with the iron dot just visible

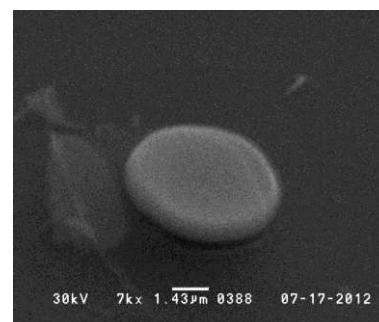


Figure 7. Characterisation of the iron dot showing a good uniformity and size

2.4. Grating targets

Gratings can be used in several ways, firstly as targets (e.g. in ion acceleration experiments), but also as diagnostic tools within the target chamber. These gratings have periods which from a several microns down to a few hundred nanometres but by using a range of MEMS processes, including optical and e-beam lithography, deposition, lift-off and deep reactive ion etching, they can be successfully fabricated.

The example shown in figure 8 is a grating structure used in ion acceleration experiments and consists of a 1 micron deep grating in the surface of a 10 micron thick parylene film. The grating consisted of 2 micron lines and 3 micron spaces. The experiment required the sidewalls of the grating to be sloping rather than vertical and this was achieved during processing by heat treatment of the mould from which the final grating was cast.

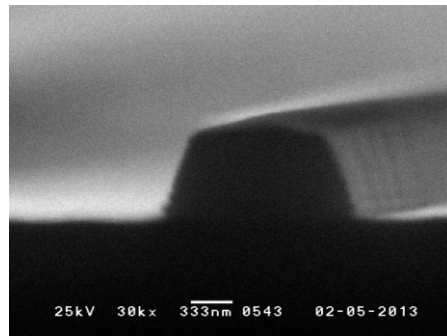


Figure 8. Cross-section of the mould from which the grating targets were cast. Heat treatment enabled the sloping wall angle to be reliably reproduced.

3. Target Positioning

A technical challenge that is inherently linked to the fabrication of targets in numbers that are suited to the next generation of high repetition rate laser systems is the ability to be able to deliver targets to the laser focus with the required accuracy and speed. There are a number of factors that will define the specification of the target positioning system but the main driver is the f-number of the focussing optic. With a larger f-number the Raleigh range of the system is longer and there is a larger tolerance on the position of the target. It is also important to take into account the type of experiment that is being carried out, for example, in TNSA ion acceleration experiments where the ion species are ejected normal to the target surface, the ability to manoeuvre the target to be perpendicular to the laser beam and therefore the diagnostics is essential. The Central Laser Facility is developing a HAMS positioning system (High Accuracy Microtarget System) for use on the Astra Gemini laser system. This system employs a F2 parabola to deliver a spot size of 2 microns and intensities of 0.5PW in its 2 beams. For each of the factors affecting the positioning of a target within the chamber the design specification has tolerances and accuracies to ensure that a fresh target can be positioned to the laser focus at the required repetition rate of 0.1Hz

3.1. Stages

An X, Z linear translation stage with a tripod attached to the top was used to allow the stages to reach the required positions. The rotation of the target is controlled by a rotation mount that sits on top of the stages. The positioning of a target was agreed to be within an accuracy of ± 4 microns in the direction of the laser (Z), to ensure it is within the laser focus to obtain the maximum intensity and a positional accuracy of $\pm 10\mu\text{m}$ in X and Y was agreed to be enough for most targets. The U and V rotation stages are required to ensure the front plane of the target is perpendicular to the laser and the W rotation is required to rotate the wheel and deliver a new target to the focal position.

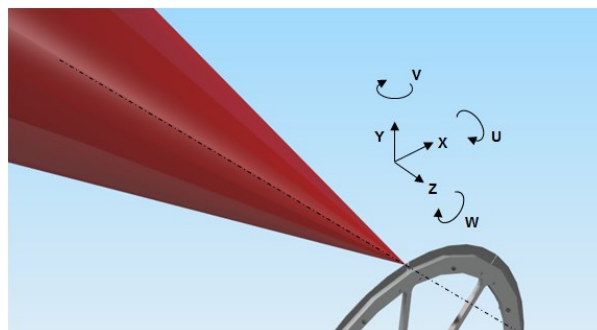


Figure 9. The coordinate system used by the HAMS.

3.2 Interface Wheel

To ensure that the targets can be attached to the stages an interface wheel is needed. This is essentially the target mount. However it can add no sources, or limited sources, of target offset due to its

manufacture or the mounting of the targets onto it. Any movement in the Z direction would take the target out of the focal plane and reduce the intensity of the laser incident on the target. A wheel was machined in a ceramic that has good thermal stability and characterised to have flatness over the mounting positions of the target to better than 2 microns. This is within the tolerance that is acceptable for the wheel as long as other sources of error do not accumulate.

3.3 Target Sections

As described earlier a number of geometries can be fabricated from silicon wafers and for the HAMS system a target section is produced that mounts on the interface wheel. This target section can be designed for a number of different target sizes but essentially the targets are patterned around the circumference of the section and then the section is mounted onto the interface wheel. Detailed characterisation of one section shows that it is flat to less than 0.5 microns and 2 sections mounted opposite each other on the interface wheel are flat to within 2 microns.

3.4 Target Alignment

Target alignment is typically achieved at the moment using retro reflections [11] however with higher repetition rates this alignment procedure is not reliable enough to reach the required shot rates due to the fact that for thinner targets imaging the rear surface is very difficult as it becomes more transparent. The CLF is developing a multi wavelength interferometer system [12] using a focussed beam onto the target to allow the positioning of targets with a higher accuracy in Z and is investigating the use of the system to be able to measure any tip and tilt in the target. Further work is being undertaken to implement a feedback loop which will eventually be able to automate the alignment of the targets and to reach repetition rates of up to 10Hz.

4. Conclusions

As the trend towards applications based systems is increasing, shot numbers have ceased to be the limiting factor in experimental campaigns and target delivery has become the critical path towards the exploitation of the laser technology. We have shown that there are a number of methods that are available using MEMS technology to deliver high aspect ratio target solutions in an effort to deliver these high target numbers however we have highlighted that there is an integrated challenge that does not only include the target fabrication. A fully engineered target stream that is designed to deliver a range of target types within a single delivery suite will allow facilities to deliver experimental campaigns to the user communities or to exploit the shot rates for application based experiments.

Over the next few years we will develop further target geometries, and fully characterise the system both for mechanical performance against specification but also for performance of each part of the HAMS system when under shot conditions.

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