

Femtosecond Pulsed Laser Direct Writing System for Photomask Fabrication

B.K.A.Ngoi, K.Venkatakrishnan, P.Stanley and L.E.N.Lim

Abstract-Photomasks are the backbone of microfabrication industries. Currently they are fabricated by lithographic process, which is very expensive and time consuming since it is a several step process. These issues can be addressed by fabricating photomask by direct femtosecond laser writing, which is a single step process and comparatively cheaper and faster than lithography. In this paper we discuss about our investigations on the effect of two types of laser writing techniques, namely, front and rear side laser writing with regard to the feature size and the edge quality of the feature. It is proved conclusively that for the patterning of mask, front side laser writing is a better technique than rear side laser writing with regard to smaller feature size and better edge quality. Moreover the energy required for front side laser writing is considerably lower than that for rear side laser writing.

INTRODUCTION

Photomasks are important prerequisites for microfabrication and semiconductor industries. At present they are fabricated by lithography process. But the main issues with the lithography process are that they are expensive especially for masks with submicron features and time consuming because it is a several step process and it uses photoresist which requires more time for transferring the pattern to the mask. Moreover the critical dimension of the mask is limited by the wavelength of the light beam. E-beam lithography is a better technique

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than photolithography as it can produce fine patterns with linewidth and edge resolution considerably finer than possible with photolithography. However this also is a time consuming process as it involves photoresist for image transfer. Also the electron backscattering effect limits the minimum line width attainable in e-beam lithography. Also the minimum line width depends on the sensitivity of the photoresist, according to the following relation

$$(L_{\min})^2 = \frac{N_m e}{S}$$

where N_m is the minimum number of electrons that will certainly expose an area. Hence in order to get high resolution a less sensitive photoresist should be used which will increase the time required for the fabrication of the mask². In order to address all these issues a novel technique has been developed for the fabrication of photomask, using femtosecond laser, the details of which has been reported separately. The novel technique is based on transferring the pattern to the mask by directly ablating the absorbing layer of the mask (Gold-chrome) with femtosecond laser pulses. In this paper, the two methods of transferring the pattern to the mask, and their effect on the size, edge quality and the melt zone of the photomask feature are compared and studied in detail. One way of transferring the pattern to the mask is to direct the laser beam on the coating side in order to remove the absorbing layer as illustrated in Figure 1, which is addressed in this paper as front side writing. Another method is to direct the laser beam through the quartz plate in order to remove the coating from the rear side as illustrated in Figure 2 which is addressed as rear side writing.

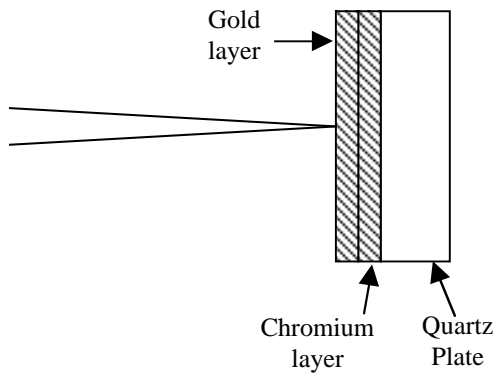


Figure 1. Front Side Laser Machining

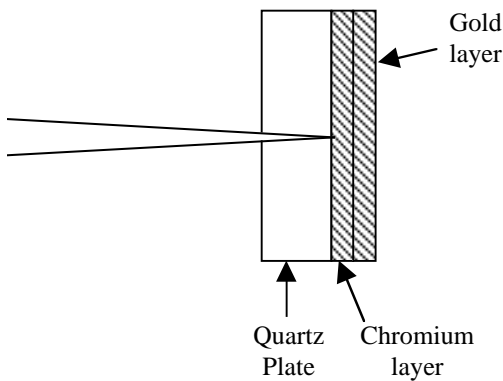


Figure 2. Rear Side Laser Machining

The rear side writing is generally employed for laser deposition where the laser beam after removing the layer from rear side will deposit on the substrate placed close to the coating side^{3,4}. However in this work, rear side writing was investigated for patterning the photomask and the results are compared with that of front side writing and the physical mechanism involved in these two processes are discussed in detail.

Experimental Set-up

The mask blank is made of a quartz substrate sputtered with layers of chromium and gold. Quartz is chosen as the substrate because of its

expansion coefficient and higher ablation threshold. The thickness of the quartz plate is around 3 mm. It is then sputtered with a chromium layer of thickness 50 nm. Over the chromium layer is sputtered another layer of gold of thickness 100 nm to form the opaque layer. Chromium and gold are good absorbers of UV radiation used in the lithography process and chromium can enhance the adherence of gold with the quartz plate. The required pattern is then transferred to the mask by directly etching the gold-chromium layer with high precision and at varying pattern dimensions using femtosecond laser pulses. The pulse energy is controlled in such a way that only the opaque layer of gold-chrome is removed without affecting the transparent quartz substrate. The advantage with femtosecond lasers is that even sub-wavelength structures can be machined since machining will be localised near the focus. Moreover the heat affected zone is negligibly small compared with excimer and Nd:YAG lasers with nanosecond pulsewidths which are most commonly used for micromachining^{5,6}. The laser beam is manoeuvred with high positional accuracy, scanning speed and spatial resolution using an acousto-optic deflection system⁷ so that any complex feature can be transferred to the mask.

Experiments were carried out using a chirped pulse amplification (CPA) Ti:Sapphire laser system which can generate pulses with pulse duration of 150 fs at a pulse repetition rate of 1 kHz. The fundamental wavelength of the laser beam is 800 nm. It is then passed through a second harmonic generator crystal to generate a wavelength of 400 nm. The beam is scanned over the mask blank with a patented non-mechanical scanning system^{8, 9,10}. A quarter wave plate is used in order to convert the polarization of the beam from s-polarization to circular polarization since circular polarization is best suited for machining complex features¹¹.

The mask blank is mounted onto a precision Newport three axis stage where three compatible ultra-precision 850G actuators drive the stage to translate the mask blank in between machining. But during machining, the stage and hence the mask blank is kept fixed and only the beam is scanned over the surface for machining, to avoid stage vibrations from affecting the feature size during machining.

Results and Discussion

In this discussion, the effect of two methods of photomask fabrication namely front and rear

side laser writing, on the feature size, edge quality and melt zone of the feature (for the same energy) are discussed in detail. A detailed analysis of physical mechanism involved in these two methods has also been carried out. Figure 3 and Figure 4 shows the SEM pictures of the front and rear side laser machining of mask blanks at 53 nJ pulse energy. For rear side writing only the energy incident at the interface between the coating and the quartz plate is considered taking into account the loss due to absorption and reflection of the quartz plate. The transmission of the quartz blank was found to be 91% and hence in the case of rear side writing only 91% of the incident energy is available for ablating the coating. Therefore more energy is required for material removal in rear side writing when compared to front side writing.

By comparing Figure 3 with Figure 4, it can be noted that feature size obtained from rear side laser machining is 1.3 μm whereas for front side laser machining, the feature size is 1 μm for the same machining energy (53nJ- energy reaching the film). This difference in the feature size can be attributed to the two different types of material removal processes associated with front and rear side laser machining. In case of front side laser machining, the laser pulses are incident on the coating side first and the material gets removed by ablation, resulting in uniform material removal. For rear side laser machining, the laser beam passes through the quartz plate and machines the rear side of the coating first. In this case, since the beam travels through the quartz plate first, due to higher refractive index of the medium ($n=1.5$) the focal depth of the beam decreases which should result in a decrease in the focused beam spot size. Moreover the energy reaching the film also is lesser compared with that for front side writing, due to absorptive and reflective loss in the quartz plate. When the energy is less only a small region at the center of the beam has energy sufficiently greater than the threshold of the material as denoted by D1 in Figure 7. Due to the above mentioned reasons, the ablated feature size in the photomask was expected to be lesser for rear side writing than that for front side writing. But contrary to our expectations, the feature size for rear side writing is more than that for front side writing. This can be explained based on micro-explosion occurring within the target. For rear side writing when the beam is incident at the quartz-coating interface ablation is not possible since the excited region is internal to the target (quartz-coating interface). The ultrafast energy

deposition creates very high temperatures and pressures inside the region¹², which results in 'micro-explosion'. Due to this, larger volume of material gets removed resulting in a bigger feature size for rear side writing.

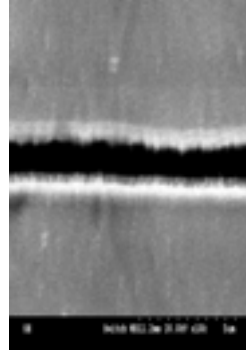


Figure 3 Front side laser machining of mask

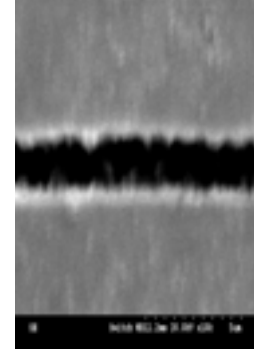


Figure 4 Rear side laser machining of mask

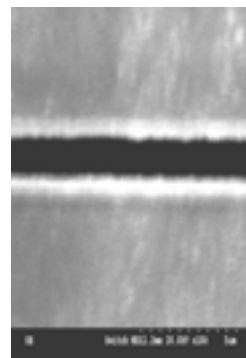


Figure 5 Front side laser machining lay

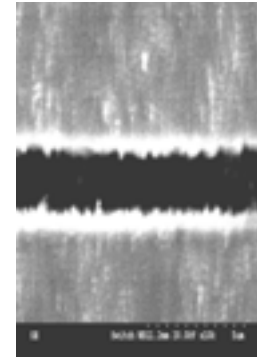


Figure 6 Rear side laser machining of mask blank at 59 nJ

And another important criterion for a photomask is good edge quality of the feature. It is very important since the feature size is of the order of microns. Poor edge quality will result in a defective mask. From Figure 3 and Figure 4, it can be noted that the edge quality of the feature is better for front side writing than for rear side writing. Since in rear side writing material is removed by explosion the coated layer gets peeled off resulting in irregular material removal and hence poor

edge quality. For front side writing, the material is removed by ablation resulting in uniform material removal and hence better edge quality.

Moreover, for front side writing, the energy can be controlled effectively in such a way that only a small region at the centre of the beam has energy sufficiently higher than the ablation threshold of the material. This will result in smaller feature size (smaller than the focused beam spot size) as illustrated by D1 in Figure 7. Even features of size $1/10^{\text{th}}$ the size of the focused beam spot can be obtained by proper control of the pulse energy. We have obtained a feature size of $0.6 \mu\text{m}$ by front side writing. But for rear side writing, more energy is required since the material has to be removed by explosion instead of ablation in order to overcome the pressure at the quartz-coating interface. In this case, larger region of the focused beam spot has energy sufficiently higher than the ablation threshold of the material resulting in bigger feature size as illustrated by D2 in Figure 7.

However the melt zone present along the side walls of the groove and the redeposited particles found in front side laser machining is comparatively lesser for rear side laser machining since the material is removed by explosion. But controlling the pulse energy and the number of pulses, melt zone and redeposited particles can be effectively controlled for front side writing. The experiments were repeated at various ablation energies and similar results were observed. Also from Figure 5 and Figure 6 it can be clearly seen that front side writing results in smaller feature size and better edge quality than rear side laser machining, for the same energy.

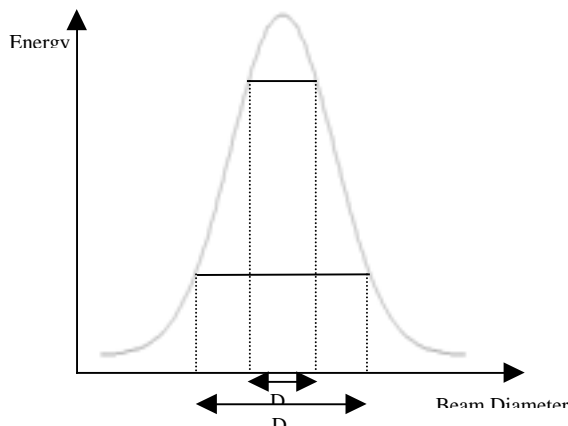


Figure 7 Effect of pulse energy on

CONCLUSION

In this paper we have studied the effect of laser machining techniques in the direct fabrication of photomask by femtosecond pulsed laser machining. The effect of two types of machining techniques, such as front side writing and rear side writing on the feature size and edge quality, were investigated and compared. From the experimental results it is observed that although the melt zone is considerably lesser for rear side laser machining, the feature size is bigger and the edge quality is poorer when compared with front side laser machining. Hence for the fabrication of photomask, front side writing is a better technique than rear side laser machining with regard to size and edge quality of the feature.

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