Challenges and Opportunities for 157 nm Mask Technology

Jan Mulkens\textsuperscript{a}, Christian Wagner\textsuperscript{b},
Kevin Cummings\textsuperscript{c}, Richard George

\textsuperscript{a}ASM Lithography, De Run 1110, 5503 LA Veldhoven, The Netherlands
\textsuperscript{b}Carl Zeiss, D-73446 Oberkochen, Germany
\textsuperscript{c}ASM Lithography, 8555 S River Parkway, Tempe, AZ, USA
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ABSTRACT

157 nm lithography is a strong contender for 100 nm and 70 nm technology. Although feasibility studies did not identify any strong evidence that 157 nm lithography was not viable, several technological challenges still must be faced. CaF\textsubscript{2} has been found to be an optical material that is practical for lens and illumination elements. Initially, the use of CaF\textsubscript{2} materials for the reticle substrate was investigated. Its high thermal expansion, however, virtually excludes its use as a mask material. Recent measurements of modified fused silica have shown sufficient transmission of 157 nm for its use in lithographic masking. The residual absorption in modified-quartz masks is expected to give rise to thermal effects, but the choice of a non-Cr-based absorber may reduce the reticle heating effect. When considering mask design rules of 100 nm and 70 nm lithography, CD requirements become more critical. Even with NA values exceeding 0.7, the $k_1$ value for 70 nm resolution exposed with 157 nm wavelengths will be low. Consequently, the mask error factor (MEF) is expected to increase further resulting in a larger reticle contribution to the overall CD budget. A counter measure for this would be a change in stepper reduction ratio from 4X to 6X. For 6" reticles only, this would result in smaller field sizes; but with 7" or 9" reticles, field sizes could become comparable to those available in current 4X Step & Scan Systems. The advantages and disadvantages of a change in the reduction ratio are discussed.

Keywords: 157 nm lithography, stepper reduction ratio, reticles

1. INTRODUCTION

Momentum has been building-up towards the use of 157 nm wavelength radiation in optical lithography. The main reason for the revived interest in 157 nm, is the technological difficulty found in the development of non-optical successors to the current lithographic equipment. In addition, promising results in F\textsubscript{2} laser performance\textsuperscript{[1]} and optical material performance\textsuperscript{[2]} highlighted the potential of 157 nm lithography. It is possible that F\textsubscript{2} lithography will bridge the gap between 193 nm (ArF) and next generation lithography (NGL). The Advanced Lithography Critical Review meeting of June 1999\textsuperscript{[3]} placed 157 nm lithography as the main contender for the 70 nm technology generation, with a possible early implementation for the 100 nm technology. The timing of the introduction will depend on the extendibility of 193 nm lithography.

The problems in the introduction of 157 nm lithography are comparable to the ones encountered in the initial stages of 193 nm technology. The major laser suppliers have shown output levels of around 20 watt with the F\textsubscript{2} laser source, with repetition rates close to 2 kHz\textsuperscript{[4,5]}. Recent improvements in measurement technology have shown that a natural spectral bandwidth of $\sim$ 1 pm can be achieved. This is fully compatible with catadioptric projection lens designs. Cymer has proposed concepts based on injection-locking configurations for high power line-narrowed lasers that are compatible with all refractive optics. The feasibility of this approach has not yet been proven.

In comparison to 193 nm lithography, the variety of optical materials that can be used for 157 nm lithography is limited. The absorption of fused silica is too high for it to be used as the main material in the optical system. Only the fluorine-based crystals show an absorption that is low enough for its use. In practice, however, only CaF\textsubscript{2} is seen as a suitable material for lens elements. CaF\textsubscript{2} is already a common material in 193 nm optics, but 157 nm lenses require a significant increase in both the quality and quantity of the material. Modified fused silica can be used as a reticle material, although it has a higher absorption than CaF\textsubscript{2}. Some transmission loss through the reticle can be allowed because of the short length of the optical path. Recent publications\textsuperscript{[6,7,8]} claim that the transmission parameters for uncoated mask substrate material with a thickness of 6.35 mm, exceeds 70%.
For Step & Scan systems, the high absorption of 157 nm photons by \( \text{O}_2 \), \( \text{H}_2\text{O} \) and \( \text{C}_n\text{H}_m \) molecules is seen as our biggest challenge in the development of this new technology. Adequate \( \text{N}_2 \) purging of the optical path is necessary to keep the contamination levels of the system gases at the ppm level. In addition, the absorption from material or gases adsorbed to (or in-between) the surfaces of the optical elements can become significant. Illumination and projection optics are already purged for 193 nm Step & Scan systems, but the purging in the reticle and wafer stage compartments will be new for the 157 nm technology. The purging of the compartment between the reticle and the pellicle will be a significant challenge.

Suitable resists for 157 nm technology are still under development. The main problems that have to be solved are related to the absorption of the chemical materials used. Thin film resist application could become common practice for 157 nm. Further, the bi-level and the CARL processes are promising.

In this paper we will present an analysis of the issues involved in the mask making for 157 nm lithography. There are more challenges for the 157 nm mask technology than the development of a new substrate material. There is also the issue of increased reticle heating effects due to the higher absorption of the fused silica substrate. The choice of an absorber material with a higher reflection coefficient could reduce the effect of heat absorption on opaque patterns. Care must be taken, however, to make sure the stray light in the illumination and projection optics is adequately controlled. A new pellicle material must be found for 157 nm reticles. Initial results reported by Mitsui\[9\] show that transmission values higher than 90% are possible, however, transmission uniformity and pellicle lifetime is yet to be proven.

Surface contamination of the reticle will be critical and it is possible that the coverage of the surfaces with water or hydro-carbons will dramatically affect the reticle transmission and the transmission uniformity. To make sure the surfaces are sufficiently clean, special measures are necessary in the manufacturing and shipment of reticles. The CD and overlay budgets for 100 nm and 70 nm lithography will continue to put pressure on the reticle requirements. In fact, it is anticipated that the CD control on reticle will become an increasingly large part of the overall CD budget. In the low k1 imaging region, higher mask error factors (MEF) and more stringent optical proximity correction (OPC) may be expected. Reticle cost, together with the tighter controls on defects, may be a considerably large factor in the overall cost of ownership for the 157 nm technology. Emerging technologies, however, offer new opportunities. In order to reduce some of the burden on the mask producers industry, a change in the stepper reduction ratio is possible. In this paper we evaluate the advantages and disadvantages of a 6X system when compared to a “standard” 4X system. The impact on Step & Scan system performance and costs is shown as well, together with the consequences for existing 4X fabs considering the introduction of 157 nm technology.

### 2. STEP & SCAN PARAMETERS

The main design parameters of the Step & Scan exposure system are necessary to support high volume wafer production for 70 nm design rules. Some of the design parameters determine directly the conditions under which the 157 nm masks will be used. Table 1 gives an indication of the reticle-related design parameters of a possible Step & Scan tool. In this paper, the parameters in Table 1 are used as a baseline for the analysis of the reticle performance and its effects in 157 nm exposure systems.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>maximum lens NA</td>
<td>0.75 ... 0.85</td>
</tr>
<tr>
<td>reduction ratio</td>
<td>4X ... 6X</td>
</tr>
<tr>
<td>corresponding k1 @ 70 nm</td>
<td>0.33 ... 0.38</td>
</tr>
<tr>
<td>laser power</td>
<td>20 W ... 30 W</td>
</tr>
<tr>
<td>laser pulse energy</td>
<td>(~ 10 \text{ mJ})</td>
</tr>
<tr>
<td>estimated pulse energy on reticle</td>
<td>(~ 25 - 50 \mu\text{J/cm}^2)</td>
</tr>
<tr>
<td>exposure duty cycle</td>
<td>~ 50 %</td>
</tr>
<tr>
<td>estimated # pulses per 300 mm wafer</td>
<td>@ 10 mJ/cm(^2) resist sensitivity 40 k – 70 k</td>
</tr>
</tbody>
</table>

### 3. 157 nm MASK SOLUTIONS

At the start of 157 nm lithography research, one of the main problems identified was the type of mask substrate material. The material used for 248 nm and 193 nm lithography (fused silica) is opaque to 157 nm light; thus, alternative mask solutions were sought. One solution appeared to be the use of 157 nm transparent materials such as \( \text{CaF}_2 \) or \( \text{MgF}_2 \). These fluoride-based crystals, unfortunately, have a large coefficient of thermal expansion (\( \alpha \)) that give relatively large registration errors during the e-beam writing of the mask. The coefficient of thermal expansion is approximately 40x larger for \( \text{CaF}_2 \) and approximately 20x larger for \( \text{MgF}_2 \) when compared to fused silica. Experimental work on prototype \( \text{CaF}_2 \) masks\[10\] has shown that in addition to registration problems, there are also problems with...
surface polishing, chrome deposition and processing. These problems must be solved before CaF$_2$ masks are suitable for volume production.

One of the problems to overcome is the thermal expansion. One of the solutions could be the implementation of a reflective mask technology which uses a substrate material similar to Zerodur. The main problem with this approach is that too many modifications would have to made on the current mask infrastructure. These are mainly the differences in mask reflector and absorber parameters, especially in inspection and repair tooling. Therefore, the introduction of reflective mask technology for 157 nm lithography is not seen as a solution in the required time frame.

It has now been found that complicated mask substrates for 157 nm lithography are not necessary. With the development of new fused silica materials, 157 nm masks will be very similar to the ones used for 248 nm and 193 nm. Using low content OH- or ‘dry’ fused silica [7,8] or F-doped fused silica [6], acceptable transmission values for 6.35 mm thick reticle substrate are possible. The thermo-elastic and chemical properties of these modified fused silica materials are very similar to those of ‘conventional’ fused silica. Consequently, no large changes in the infra-structural for 157 nm substrates should be necessary.

3.1 Modified Fused Silica Transmission

Since September 1998, various suppliers have provided transmission data on samples of modified fused silica. In Table 2, there is a summary of the published transmission. The numbers shown include the Fresnel reflection losses of approximately 12%. If future projections of the intrinsic absorption levels are made, it is possible to show that the loss in transmission for 157 nm masks will be less than 15%. Further reduction in the transmission loss could be made by the application of anti-reflective coating on the substrate, but this would lead to a more complex fabrication process.

Table 2  Literature data of transmission of modified fused silica samples (scaled to 6.35 mm thickness).

<table>
<thead>
<tr>
<th>Source</th>
<th>Transmission [6 mm]</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nikon</td>
<td>86%</td>
<td>presented @ 157 nm review 6/99</td>
</tr>
<tr>
<td>Corning</td>
<td>~74%</td>
<td>presented @ 157 nm review 6/99</td>
</tr>
<tr>
<td>Heraeus</td>
<td>~53%</td>
<td>presented @ 157 nm workshop 2/99</td>
</tr>
<tr>
<td>Asahi</td>
<td>75% - 85%</td>
<td>presented @ 157 nm review 6/99</td>
</tr>
<tr>
<td>MIT/LL</td>
<td>86%</td>
<td>presented @ 157 nm review 6/99</td>
</tr>
</tbody>
</table>

To investigate the properties of a range of materials, we have done transmission measurements and life-time testing at the test set-up of Lambda Physik. These measurements were made on various fused silica samples obtained from different suppliers. In Figure 1a it shows the measured transmission values (T). The findings are within the ranges shown in Table 2.

In addition to initial transmission loss, transmission degradation is also important. In general, mask life is limited. For DRAM manufacturers, mask usage seldom exceeds 10,000 wafers and for logic and ASIC manufacturers, the number of wafers exposed is even lower. To estimate the DRAM manufacturers’ requirements, about 200 dies per wafer and about 200 pulses per die with approximately 0.1 mJ/cm$^2$ at the
wafer level were assumed. This also assumed 10 mJ/cm² resist sensitivity. This gives a final total dose of approximately 5 kJ/cm² per reticle.

Marathon testing done on some of the test samples shows that, for the worst case dosage on the reticle, the transmission loss can be less than 5 % (Figure 1b). The data above suggests that the materials shown in Table 1 should be suitable in the production time frame.

After considering the transmission, transmission uniformity is an important parameter for 157 nm mask substrates. This is discussed in more detail in section 3.5.

### 3.2 Absorber Materials

Early work at RIT\[^{11}\] suggested that the optical density requirements for Cr absorbers could be critical at a wavelength of 157 nm. As a result, other absorbers (e.g. tungsten) were proposed. Using the published bulk absorbance and reflection data for various metals\[^{12}\], we compared the reflectivity and optical density of an 80 nm thick metallic absorber layer, for 248 nm, 193 nm and 157 nm light. The calculated optical density is shown in Figure 2a and the obtained reflectivity values are shown in Figure 2b.

As Figure 2a clearly shows, tungsten (W) has the highest absorbance, although Mo and Al could also be considered. It can be seen, however, that the absorbance of a Cr film at 157 nm is only slightly lower than it is at 193 nm and 248 nm. Increasing the Cr-thickness from 80 nm to 88 nm already brings the 157 nm optical density to the same level as it is at 248 nm. It is recommended that chromium film is used for 157 nm, rather than replacing Cr with another metal absorber.

With the increased absorption from a 157 nm lithography reticle (primarily from the substrate), it is possible to consider absorber materials that are also highly reflective. Figure 2b suggests that W, Mo and Al would be suitable for high reflectivity absorbers (compared to Cr at 157 nm). In addition, these metals have good dry-etch processing characteristics. Before high reflectivity absorbers are investigated, the consequences of implementing such components in the optical projection system must be considered. Reflections from the reticle back into the illuminator can lead to uniformity errors. For high reflectivity masks, these illumination-uniformity errors must be corrected. This is usually done by using adaptive-gray filters; however, the gray filter correction would need to be calibrated to the reticle. This results in the undesirable process of creating uniformity filters for each mask. If it is assumed that the reflections on the illuminator are about 1%, a reflection of 35% on the mask could reduce the uniformity by 0.35%.

It should be noted that the reflectivity of current low-reflectivity-chrome masks is different for the front and the rear sides. Low reflectivity chrome is designed for a reflectivity of 11% at 365 nm. In Figure 3, results of reflectivity measurements done at 193 nm are shown. It can be seen that the reflectivity towards the illuminator side is comparable to the value shown in Figure 2. The reflectivity of the chrome towards the wafer side, however, is much lower but not equal to 11%.

The reflections between the wafer and reticle cause flare and thus introduce contrast loss of the image. Flare and other contrast-reducing aberrations (wave front and machine vibrations [msd]) must be tightly controlled in
order to make low k1-processes feasible. When they are compared to the reflections which are directed to the illuminator, these reticle-wafer double reflections are more important.

A first order approximation of the contrast loss is shown here in Eq. 1:

\[
\text{Contrast loss} = 2 \times T^2 \times R_{\text{wafer}} \times R_{\text{reticle}} \quad (\text{Eq.1})
\]

The most apparent way to control the reflection induced flare, is to use low reflectivity masks. If it is assumed that the required contrast loss is <1% with a 50% lens transmission and a 10% wafer reflectivity, then with Eq.1 it can be derived that the requirement for reticle reflectivity should be less than 20%.

### 3.3 Contamination Effects

It is expected that surface contamination by airborne contaminants will be a major problem for 157 nm masks. In Figure 4, the spectral absorption of various potential contaminants is plotted against wavelength. If the absorption values at wavelengths of 157 nm and 193 nm are compared, the absorption levels of all the materials increase by more than four orders of magnitude. Note that the increase is even larger for an adsorbed H2O-film.

For the Step & Scan system, these values make it necessary to have tight control of the purging of the optical areas. These requirements will also be necessary for the reticle industry. The handling of the reticle during manufacturing, repair and transport is considered to be particularly important. This is different from the current procedures.

To show the atmospheric surface deposition on masks, we measured the transmission of modified fused silica samples, before and after cleaning. The relative transmission change is shown in Figure 5. Because of surface contamination we observe a transmission loss varying from 4% and 8% for two surfaces.

During the exposure, 157 nm light may interact with contaminants in the optical path. The effect of these interactions must be investigated. At best, some of the contamination may be cleaned by the laser. At worst; there is a possibility of a surface reaction with absorbed materials and this could cause thermally-induced damage. Finally, the repair of defects on the reticle must leave the surface clean and free to allow transmission at 157 nm. This will, undoubtedly, alter many of the current repair processes now being used or under development. In these, the surface of the reticle is flooded with a gas that deposits or etches material on
the reticle under a beam of photons or particles. Only those processes that cause little residual contamination will be effective for 157 nm lithography.

3.4 Reticle Heating Effects

Reticle heating is evaluated by a Figure of Merit (FoM) comparison (see Appendix 1 for a definition). The FoM is used to measure the effect of the overlay errors that are heat induced. Overlay errors are scaled to the critical dimension. The main input parameters of the FoM are absorber reflectivity, substrate absorption and pattern density. Table 3 gives some typical pattern density numbers for various layer types.

Table 3  Pattern density numbers for typical mask layers.

<table>
<thead>
<tr>
<th>Level</th>
<th>% absorber</th>
</tr>
</thead>
<tbody>
<tr>
<td>active</td>
<td>10 - 40 %</td>
</tr>
<tr>
<td>contact</td>
<td>~ 90%</td>
</tr>
<tr>
<td>gate</td>
<td>40 -50 %</td>
</tr>
<tr>
<td>metal</td>
<td>20 – 40 %</td>
</tr>
<tr>
<td>via</td>
<td>95 %</td>
</tr>
</tbody>
</table>

The absorber material reflectivity and the substrate absorption was varied, and the FoM was compared to the data found for I-line (0.35 \(\mu\)m), KrF (0.18 \(\mu\)m) and ArF (0.10 \(\mu\)m). The calculations presented in Figure 6 are done once for low density patterns (~15%) and once for high density patterns (~85%). If the increased substrate material absorption at 157 nm is considered, especially for a low pattern density, increased heating effects will be observed. In order to stay below the I-line level for low pattern density numbers, the maximum absorption in fused silica should be < 0.07 /cm (~80% reticle transmission including Fresnel losses). As expected, at a high pattern density, the absorber reflectivity is a sensitive parameter in the reticle heating effect. Compared to the I-line case, however, even with an extremely high absorption on the absorber, the FoM at 157 nm is significantly lower. It can be concluded, therefore, that a higher reflection of the absorber material is not necessary at 157 nm.

3.5 Transmission Uniformity

Possibly the critical area for 157 nm mask performance will be transmission uniformity. The lower transmission of the bulk material, the high sensitivity for surface contamination and the expected higher losses in the pellicle material will affect the allowed dose-uniformity budget. For example, in a 248 nm resist process for 180 nm dense lines, the non-uniform dose errors give approximately 1.5% CD variation per % dose error. Assuming a similar relative value for 157 nm lithography, uniformity requirements; including mask, projection optics and pellicle; will be < 1 %. Table 4 shows a proposed transmission uniformity budget. The uniformity number is defined as a half-range value.

Table 4  Proposed transmission uniformity budget.

<table>
<thead>
<tr>
<th>Step &amp; Scan system</th>
<th>0.7 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reticle substrate</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Pellicle</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Reflections to illuminator</td>
<td>0.4 %</td>
</tr>
<tr>
<td>Total (rss)</td>
<td>1.0 %</td>
</tr>
</tbody>
</table>

In principle, reproducible uniformity errors in the mask substrate can be corrected when dedicated spatial attenuation filters are used in the Step & Scan system. For the example shown in Figure 7, the non-corrected uniformity error of approximately 3% can be reduced to 0.3%. It is expected that the 6" substrate in the near future will give the necessary performance.

Figure 6  Reticle heating induced overlay FoM as a function of absorber reflection and bulk absorption coefficient.

Figure 7  Measured transmission uniformity of prototype 6" mask substrate.
Not shown in Table 4 is the birefringence-induced non-uniformity. The effect of residual birefringence in the mask substrate is dependent on the concept of the projection optics. Optics based on a polarizing beamsplitter concept are the most sensitive. A birefringent reticle turns the orientation of the polarization in a similar way to a quarter wave or a half wave plate. If the polarization of the light is perpendicular to the direction of the beam splitter system, light is lost in the cube.

The light $\Delta I$ that will be transmitted through the 1st beam splitting surface and the change in uniformity $\Delta u$ is estimated as:

$$\Delta I = \Delta u = \sin^2(\pi dx/\lambda) \sim (\pi dx/\lambda)^2$$

(2a)

where $d$ is the reticle thickness and $x$ is the local birefringence (this assumes the worst case scenario). Thus, for a given uniformity variation, $\Delta u$, the birefringence specification is:

$$x = \frac{\lambda (\Delta u)^{1/2}}{(\pi d)}$$

(3)

Therefore, a birefringent-induced uniformity change of <0.1% gives a birefringence specification of < 2.5 nm/cm.

### 3.6 Requirements for 157 nm Blanks and Pellicle

Table 5 shows a summary of the requirements necessary for mask blanks that are to be used for lithography at 157 nm. Shown also are the requirements that affect the imaging performance (scattering, surface flatness and wavefront distortion) and the overlay performance (surface flatness and pellicle frame induced placement error). In addition, the 'well known' requirements on defects for substrate, absorber layer and pellicle are shown.

#### 4. STEPPER REDUCTION: 6X VERSUS 4X

Extending optical lithography to the 70 nm node, will give lighter control of the mask patterning requirements. Table 1 shows that, even with extreme high NA projection systems, k1 values below 0.4 will be used. Thus, both imaging enhancements and reticle enhancements will be important at the critical level. To reduce the current problem of meeting specification for critical masking, it has been suggested that the stepper reduction ratio for future lithography systems be changed\[13\]. A good alternative would be a change from 4X to 6X.

**Table 5** Reticle blank and pellicle requirements for 157 nm

<table>
<thead>
<tr>
<th>Pellicle</th>
<th>Target Value</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial transmission</td>
<td>&gt; 90 %</td>
<td>1.5 E9 pls @ 25 μJ/cm2</td>
</tr>
<tr>
<td>relative transmission loss</td>
<td>&lt; 5 %</td>
<td>non correctable</td>
</tr>
<tr>
<td>transmission uniformity</td>
<td>+/- 0.4 %</td>
<td>non correctable</td>
</tr>
<tr>
<td>scattered light</td>
<td>+/- 0.2 %</td>
<td></td>
</tr>
<tr>
<td>wavefront distortion</td>
<td>&lt; 0.01 lambda</td>
<td></td>
</tr>
<tr>
<td>image placement error</td>
<td>3 nm</td>
<td>non correctable</td>
</tr>
<tr>
<td>particles in film</td>
<td>none &gt; 8 μm</td>
<td></td>
</tr>
<tr>
<td>scratches</td>
<td>none &gt; 60μm</td>
<td></td>
</tr>
<tr>
<td>stains</td>
<td>none &gt; 200 μm</td>
<td>stain causing scattering</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reticle substrate</th>
<th>Target Value</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial transmission</td>
<td>&gt; 80 %</td>
<td>1.5 E9 pls @ 25 μJ/cm2</td>
</tr>
<tr>
<td>relative transmission loss</td>
<td>&lt; 5 %</td>
<td>non correctable</td>
</tr>
<tr>
<td>transmission uniformity</td>
<td>+/- 0.4 %</td>
<td>non correctable</td>
</tr>
<tr>
<td>scattered light</td>
<td>+/- 0.2 %</td>
<td></td>
</tr>
<tr>
<td>surface flatness</td>
<td>&lt;350 nm</td>
<td>within inspection area for 100 nm node</td>
</tr>
<tr>
<td>surface flatness</td>
<td>&lt;200 nm</td>
<td>within inspection area for 70 nm node</td>
</tr>
<tr>
<td>birefringence</td>
<td>&lt; 2.5 nm/cm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Reticle absorber</th>
<th>Target Value</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>absorber optical density</td>
<td>OD 3</td>
<td></td>
</tr>
<tr>
<td>absorber reflectivity towards lens</td>
<td>&lt; 20%</td>
<td>@ 157 nm</td>
</tr>
<tr>
<td>absorber reflectivity towards illuminator</td>
<td>30% - 40 %</td>
<td>@ 157 nm</td>
</tr>
<tr>
<td>pinholes</td>
<td>none</td>
<td>&gt; 1 μm</td>
</tr>
<tr>
<td>defect size</td>
<td>&lt; 80 nm</td>
<td>100 nm technology node</td>
</tr>
<tr>
<td>defect size</td>
<td>&lt; 60 nm</td>
<td>70 nm technology node</td>
</tr>
</tbody>
</table>
Table 6 shows some of the critical patterning requirements for masks to be used at the 100 nm and 70 nm technology nodes. The requirements for a possible 4X or 6X implementation are given. It is obvious that 6X masking will be less difficult than 4X masking. Consequently, 4X masks will be more expensive.

## 4.1 Field Sizes

The major disadvantage of a large reduction is the smaller field size that is obtained when 6" reticles are used. With one reticle the field size for 6X is limited to $17 \text{ mm} \times 22 \text{ mm}$. The die size could be increased by using a double exposure with two masks, then stitching the two sub-fields together on the wafer. Another alternative is introducing 7" or 9" reticles. With 6X reduction and 7" mask substrates, field sizes of 21 mm x 26 mm are possible. With 6X reduction and 9" masks, 25 mm x 32 mm are possible.

The change in mask substrate dimensions will have an impact on the mask making infrastructure. It will be necessary to develop new tooling. This development will be greater for 9" reticles than for 7" reticles, thus making 7" masks a more realistic option.

## 4.2 Cost of Ownership

Related to a smaller field size is the reduction in throughput, both for the critical tool and the non-critical tools currently operating with the 26 mm x 32 mm scanner field. On the other hand, 6X masks are expected to be less expensive for the Step & Scan tools and the cost of the smaller field optics will be significantly less.
To investigate the impact of a possible introduction of a ‘medium-field’ 6X tool, estimates on Cost of Ownership (COO) for various product types and chip sizes were made. Die sizes varying from 8 mm x 7 mm to 25 mm x 25 mm were considered. Mask utilization numbers are varied from 500 wafers per mask (WpM), representing a typical ASIC manufacturer, to 5000 WpM, representing a DRAM factory.

Figure 8 shows an evaluation of wafer throughput. The results (in relative numbers) for three potential 157 nm Step & Scan system designs are given. For various die sizes, the throughput on a 4X-6” mask tool is compared to the throughputs on a 6X-6” and a 6X-7” tool. For all the die sizes, the corresponding scanned field is chosen such that the exposed field is maximized. For those die sizes that do not fit within one exposed field, it is assumed that there are two masks with a stitched exposure.

It was found that for the smaller die sizes (<17 mm x 22 mm), on average, the throughput for a 6X-6” mask tool was approximately 25% lower than the 4X-6” mask tool. A 7” mask would have had an average throughput of approximately 90% of the 4X-6” mask tool. With a stitched two-reticle exposure, necessary for the larger die sizes, the throughput penalty can be as high as 50%.

Exposure tool productivity is reduced when the stepper field size is reduced, but the stepper capital costs would benefit from a reduced field size. It is estimated that the costs of a 17 mm slit size lens are approximately 50% less than that of the 26 mm slit. The equivalent costs for a ~22 mm slit size lens (comparable to a 6X-7” mask) are approximately 25% less. It is also considered that a 6X mask will cost less than a 4X mask. In addition, the cost per layer for a consumer with low reticle usage will benefit from using the latter. When the throughput numbers and the estimated tool costs are calculated, the cost per layer for the three potential tool designs can also be calculated. The potential utilization of 3000 wafers per mask (WPM) was investigated. It was assumed that 6X masks would cost 30% less than 4X masks. It was found that, on average, the throughput loss was compensated for by the reduced mask costs and tool costs. For other mask utilization and/or larger differences between 6X and 4X mask costs, the 6X cost of operation is even better than 4X. As shown in Figure 9, the cost reduction with 6X could reach 50%, depending on mask costs and mask utilization.

In a production environment, however, the total exposure costs are only partly determined by the critical level tool. The percentage for ‘non-critical’ or ‘medium-critical’ layers will be ~70%. For 100 nm and 70 nm technology we expect that the majority of these non-157 nm exposure systems will be 4X Step & Scan with field sizes of 26 mm x 32 mm. Limiting the usable field of these existing systems to the reduced field size of the 157 nm tool, will lead to a throughput loss. To minimize the penalty in throughput on the non-critical tools, it is necessary to maximize the number of dies in the field. Consequently, the critical and non-critical tools need to match non-concentrically. Figure 10 shows the results of the COO evaluation for the 4X, non-157 nm tooling; this includes concentric matching (i.e. limit the field size to the one of the 6X system), and non-concentric matching.

![Figure 8](image.png)

**Figure 8** Wafer throughput (300 mm), as a function of die size, for three potential 157 nm tool concepts.

![Figure 9](image.png)

**Figure 9** 157 nm system concept 6X-6” mask layer costs (LC) relative to 4X-6” mask concept, as a function of relative mask costs (6X / 4X). The mask utilization is used as a parameter.
We conclude that the increase in the COO for the existing non-critical and medium-critical tooling, can be limited to < 5%. This assumes, however, that different levels of the product are non-concentrically matched. If there are reasons not to implement non-concentric matching, the increase in costs can be significant. The best solution then, is to increase the field size of the critical tool. For 6X this means either to use 7" masks or 9" masks.

5. CONCLUSIONS

Recent progress in F_2 laser technology and CaF_2 lens material technology has shown that it is possible to extend optical lithography down to 157 nm. In contrast to the initial outlook, mask technology for 157 nm can be made similar to the technology currently used. The mask substrate material is modified fused silica, and the preferred mask absorber material can be chromium-based. Despite the somewhat higher absorption of the substrate material, the induced effect of reticle heating on the overlay will be low when compared to the current systems.

The remaining challenges are related to transmission uniformity and sub 100 nm patterning requirements. Uniformity will be affected by material performance, mask substrate, pellicle, and surface contamination effects. The latter will impact the manufacturing, handling and use of the mask. For all these steps, a highly clean and dry environment is necessary. Non-contaminating methods must be used to repair the reticle.

In regards to the patterning requirements, CD control is seen as the most critical parameter for 157 nm. The higher MEF values (related with low k1 imaging), and the above mentioned non-uniformity effects, will increase the CD problems. An industry-wide concerted effort will be necessary to improve mask CD control. One of the options for improvement in the Step & Scan system is to change the stepper reduction ratio from 4X to 6X. The stepper productivity penalty caused by the smaller field can be compensated by lower Step & Scan costs and lower mask costs.

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7. REFERENCES


8. APPENDIX I, HEATING FIGURE OF MERIT

Reticle Transmission:
\[
\tau = \frac{a * (1 - r)^2}{1 - a^2 * r^2}
\]
in which \(a\) is the effective bulk absorption per pass: \(a = 10^{-k * d_{at}}\) and \(k\) is the material absorption coefficient [cm] and \(r\) is the Fresnel reflection coefficient

Reticle reflection on substrate:
\[
\rho_s = r + \frac{(1 - r)^2 * r * a^2}{1 - r^2 * a^2}
\]

Reticle reflection on absorber:
\[
\rho_r = r + \frac{(1 - r)^2 * c * a^2}{1 - r * c * a^2}
\]
in which \(c\) is the reflection coefficient of the absorber material

Absorption in reticle:
\[
\alpha = 1 - p * \rho_r - (1 - p) * (\tau + \rho_s)
\]
in which \(p\) is the absorber coverage (or pattern density) of the reticle

Absorbed energy in reticle:
\[
\Phi_\text{abs} = P_{\text{ref}} * DC * \alpha
\]
in which DC is exposure duty cycle and \(P_{\text{ref}}\) is the radiation power on the reticle

Overlay error:
\[
OL \sim \alpha_r \left( \frac{1}{a_c \lambda + a_r \lambda} + \frac{L}{\lambda r \lambda} \right) \Phi_\text{abs} \sim \alpha_r \frac{\Phi_\text{abs}}{a_c}
\]

Assumptions:
1) image placement caused by bending of the reticle
2) clamping fixes the reticle ends, thermal expansion only contributer in bending forces
3) thermal conduction of reticle via reticle chuck is negligible
4) convection >> radiation heat loss; \(a_c\) is heat loss factor for convection

Figure of Merit:
\[
\text{FoM} = \frac{OL}{CD}
\]
FoM scaled with critical dimension