Thin Films for Phase-shift masks

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1 Optical lithography

Optical lithography is the process used by semiconductor chip manufacturers to transfer integrated circuit (IC) patterns through a mask on to a silicon wafer. Commonly the mask is a fused quartz plate, 6”x 6” x 0.25” thick, with an opaque Cr film about 100 nm thick. Openings in the mask, corresponding to the IC features, allow light from an optical projection system (called a stepper because the exposure is a step and repeat process) to irradiate a photosensitive polymer (photoresist) layer coated on the silicon wafer. After resist development, or its selective removal (positive resist) in the pattern of the circuit design, the silicon is now exposed to allow etching, metal deposition, ion implantation or other processing, followed by removal or ‘stripping’ of the photoresist. To make a modern, complex microprocessor or memory chip requires as many as 20 iterations of this process with different but complementary (and critically aligned) masks (or mask set). One limitation of optical lithography is that there is a minimum feature size that can be imaged on the wafer, determined by the optics of the stepper, the wavelength of the imaging light, and the particular process (e.g., contrast of the photoresist material). As the minimum feature size is reduced, speed and density in chips increase as does the cost of the optical lithography tool substantially. Fortunately, a number of strategies have been developed to extend the usefulness of any optical lithography generation. One of these optical extensions is the phase-shift mask. It can enhance resolution beyond the wavelength-imposed diffraction limit. Since some fraction of the light used in lithography is coherent, phase-shift masks work by destructive optical interference to enhance imaging contrast. In this paper, we will discuss a systematic materials approach for designing thin film phase-shift masks.

In optical lithography, the resolution (R) of the image formed by the projection stepper can be expressed as:

\[
R = k_1 \left( \frac{\lambda}{NA} \right)
\]

where \(\lambda\) is the wavelength of the imaging light, \(NA = \sin \theta\) is the numerical aperture of the projection lens, and \(k_1\) is a constant for a specific lithographic process. Another important lithographic parameter besides resolution is the depth of focus (DoF). A larger DoF means that the process is more tolerant to departures in wafer flatness and photoresist thickness uniformity. DoF is expressed as

\[
DoF = k_2 \left( \frac{\lambda}{NA} \right)^2
\]

where \(k_2\) also depends on the specific lithographic process, and in most practical optical systems is \(\sim 1\). From these two equations, we see that the minimum feature size can be reduced by
imaging with shorter wavelength light, using a lens with higher numerical aperture, or improving the process (smaller $k_1$) such as with a phase-shift mask or a higher contrast photoresist. In Table 1, Table 1 we calculate values of $R$ and DoF for current production optical steppers that operate at 365 nm and 248 nm, and for future systems that will operate at 193 nm and perhaps at 157 nm. Production at 193 nm is anticipated by about 2001, and future development of 157 nm lithography systems is fast gaining support in the semiconductor community.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>365 nm (i-line)</th>
<th>248 nm (KrF)</th>
<th>193 nm (ArF)</th>
<th>157 nm (F₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NA</td>
<td>0.6</td>
<td>0.65</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Minimum feature size ($\mu$m)</td>
<td>0.25</td>
<td>$0.25 \rightarrow 0.15$</td>
<td>$0.15 \rightarrow 0.10$</td>
<td>$0.10 \rightarrow 0.07$</td>
</tr>
<tr>
<td>$k_1$</td>
<td>0.41</td>
<td>$0.65 \rightarrow 0.39$</td>
<td>$0.54 \rightarrow 0.36$</td>
<td>$0.45 \rightarrow 0.31$</td>
</tr>
<tr>
<td>DoF ($\mu$m)*</td>
<td>± 1.0</td>
<td>± 0.59</td>
<td>± 0.4</td>
<td>± 0.32</td>
</tr>
</tbody>
</table>

* $k_2 = \pm 1$

From Table 1 we see that the same resolution (e.g., 0.15 $\mu$m) can be achieved with greater process latitude (larger $k_1$) using shorter wavelength (193 nm versus 248 nm) light for imaging. For greater process latitude $k_1 > 0.6$ is desirable, while leading-edge processes require $k_1 \sim 0.5$. However, future technologies with still smaller feature sizes will necessitate working at $k_1 \leq 0.4$ with reduced DoF.

2 Phase-shift masks

But phase-shift masks can improve resolution without loss of DoF. Since optical interference does not depend critically on a perfectly focused image, phase-shift masks can actually increase DoF in comparison to traditional Cr masks. Two types of phase-shift mask are commonly used in lithography: they are the alternating aperture phase-shift mask and the embedded attenuating phase-shift mask. Figure 1 compares the imaging process for a traditional Cr mask and a simple form of the alternating aperture phase-shift mask. Each mask has two closely spaced openings. Because the imaging light is an electromagnetic wave, it has both an electric field amplitude and a phase; the radiance or dose needed to expose the photoresist is proportional to the square of this amplitude. When light passes through adjacent apertures in the Cr mask, the amplitude profiles broaden due to diffraction and spatial filtering of the optical system. At the wafer, the electric field amplitudes overlap and interfere constructively because the light is at least partially coherent. At the wafer, the intensity of the light, which is proportional to the total amplitude squared, is large everywhere and the resist will also be exposed between the apertures, blurring the separate features together. In the simple phase-shift mask, light that traverses one of the apertures is phase-shifted $180^\circ$. Again the electric field
amplitudes of light passing through the two apertures broaden, but because one component is phase-shifted 180°, they interfere destructively, such that the net amplitude of the imaging light becomes zero (or dark) between adjacent apertures or features. The light intensity passing through the separate apertures is now resolved at the wafer and therefore resolution of imaged features is enhanced.

Figure 1. Comparison of the imaging process for a traditional Cr mask and a simple form of the alternating aperture phase-shift mask

The alternating aperture phase-shift mask is particularly well suited to printing closely spaced lines. Typically, it provides a 50% improvement in resolution compared to traditional binary Cr masks. In a practical mask design, the quartz substrate is etched to produce the 180° difference in phase-shift. There are, however, limitations in the use of alternating phase-shift masks, especially when the features to be printed are in complicated circuit patterns. An unwanted result is that the abrupt transition between 0° and 180° always prints as a dark line, and it can bridge or short circuit isolated lines in some circuit designs. Although there are strategies to circumvent this, implementing them adds complexity to the mask design, especially for intricate circuits.

The other type of mask is the embedded attenuating phase-shift mask. It is schematically illustrated in Figure 2. This mask allows some (typically 6-18%) of the imaging illumination, phase-shifted 180°, to be transmitted by the mask in the normally opaque areas of a corresponding Cr binary mask. In this case, the fraction of light that passes through the partially transparent mask is 180° out of phase with light propagating through an opening in the mask. Again, even though the out of phase electric field amplitude is only a fraction of the non-shifted light amplitude passing through the aperture, their profiles interfere destructively (net amplitude

is zero between apertures) and sharper contrast and improvement in DoF is achieved in imaging. While attenuating phase-shift masks do not afford as much resolution enhancement as the fully transparent alternating aperture masks, EAPSMs can be fabricated to work for complex circuit patterns using conventional mask making techniques, making them attractive for replacement of Cr binary masks when printing features with sub-wavelength resolution. EAPSMs are particularly suited to printing contacts and isolated clear circuit features with special off-axis illumination. In the following sections we describe materials design of EAPSMs.

![Figure 2. The embedded attenuating phase-shift mask is shown schematically.](image)

### 3 EAPSMs: materials and optical design

Reviews of different materials approaches for optical design of EAPSMs have been discussed in several recent publications. A common strategy is to use non-stoichiometric materials, e.g., MoSi$_2$O$_y$N$_z$, SiN$_x$, or CrO$_x$F$_y$, of which the main chemical constituent, SiO$_2$, Si$_3$N$_4$, or CrF$_3$, is transparent at the lithographic wavelength. Non-stoichiometric materials are attractive because their optical properties can be tuned simply by adjusting the reactive gas (e.g., O$_2$, N$_2$, CF$_4$) content during sputtering, which also changes the film’s chemical composition. An advantage is that the EAPSM is a single layer material that can be produced in most sputtering tools. The disadvantages of non-stoichiometric materials are that they may be unstable to further chemical oxidation, causing unwanted changes in optical properties, and there is usually a strong dependence of optical properties on deposition conditions, making reproducible manufacture of EAPSMs very challenging. In addition, the process can vary spatially because of local differences in pumping speed for reactive gases, and also with time as the sputtering target ages.

A novel, alternative strategy that we developed to design EAPSMs are multilayers or optical superlattices. In this approach we layer an optically transparent compound (A) with an optically absorbing compound (B). We choose compounds that are either stable oxides or stable...
nitrides. When both layers are nitrides or oxides then the same gas environment can be maintained for sputtering both layers. In our laboratory we sputter the multilayers in a vacuum chamber with a rotating substrate table, whose motion is controlled by a computer. Pausing substrates under each target consecutively for programmed times determines the individual layer thickness. The multilayer pair we find attractive are Si$_3$N$_4$ (abbreviated as SiN) and TiN. With a bandgap close to 6 eV, SiN is sufficiently transparent at 6.425 eV (193 nm) for designing EAPSMs with a range of optical transmissions (6-15%) at 193 nm and 248 nm. At 193 nm, the complex index of refraction, \( N = n - ik \), is 2.45-i 0.3 for sputtered SiN and 1.3-i 0.9 for TiN. This value for SiN thin films agrees closely with published values for bulk Si$_3$N$_4$.

When the layers in the multilayer are very thin (<< 1/10 \( \lambda \)) compared to the exposure wavelength (193 nm or 248 nm), an effective medium approximation can be used to calculate the optical properties of the multilayer. That is

**Equation 3.** \( \varepsilon_s = f \varepsilon_m + (1-f) \varepsilon_d \)

where \( f \) is the fraction of TiN, \( \varepsilon_m \) and \( \varepsilon_d \) are the dielectric constants for TiN and SiN, and \( \varepsilon = (n^2 - k^2) - i 2nk \), so that the complex refractive index of the multilayer is given by \( N_s = n_s - i k_s = \sqrt{\varepsilon_s} \).

The condition for 180° phase-shift relative to air in a thin film with total thickness \( d_s \) is given by

**Equation 4.** \( (n_s - 1) d_s \approx \lambda / 2 \)

where \( \lambda \) is the exposure wavelength.

The corresponding transmission through the film is

**Equation 5.** \( T_s \approx (1-R)^2 \exp(-4 \pi k_s d_s / \lambda) \)

where \( R \) is the film reflectance, which can be calculated from \( n_s \) and \( k_s \).

As an illustration, we can calculate for ideal layering, using the optical constants measured for SiN and TiN films, phase-shift design maps for multilayer thickness \( d_s \) with 180° phase-shift and the corresponding optical transmissions versus TiN content. As shown in Figure 3, an EAPSM with 12% transmission can be designed when the TiN content is 20% and the total multilayer thickness \( d_s \) is 77.5 nm. If the periodicity of the multilayer were chosen to be 7.75 nm then 10 bilayers of 1.55 nm TiN and 6.2 nm of SiN would satisfy the film structure. Modifying the optical properties with 180° phase-shift thus translates into simply adjusting SiN and TiN thickness, and sputtering can control individual layer thickness precisely. Experimentally we find that keeping the individual SiN and TiN layer very thin also promotes uniform etching during mask fabrication and improves its radiation hardness (a mask must sustain several hundred thousand exposures without changing).
Ideal Multilayer design ‘Maps’ (thickness/%T)

%T ≈ 12%, ~20% TiN, thickness ~77.5 nm

Λ = 7.75 nm: 10 bilayers, d(TiN) = 1.55 nm, d(SiN) = 6.2 nm

![Graph](image)

Figure 3. Ideal Multilayer design ‘Maps’.

In practice, sputtered multilayers have a measured transmission and phase-shift that are somewhat smaller than calculated values, assuming ideal layering. That is, the refractive index is smaller and the extinction coefficient larger in sputtered multilayers. Figure 4 is an image taken by transmission electron microscopy of the cross section of a TiN/SiN multilayer. The image reveals a structure with a rough SiN layer that grows on an initial flat TiN layer with conformal roughening in subsequent TiN and SiN layers. The rough layers are likely due to sputtering at a relatively high pressure (10 mTorr). While it minimizes film stress, high pressure sputtering causes layer roughening, which could be responsible for an “optical mixing” effect that increases transmission loss and reduces the transmitted phase-shift.

![Image](image)

Figure 4. Transmission electron micrograph of a Si$_3$N$_4$/TiN multilayer EAPSM phase shifter.

Another important optical property is the contrast between the EAPSM and the quartz substrate at the wavelength used to inspect defects in the mask before repairing them. A mask must be defect-free! For 193 nm lithography, the inspection wavelength is 257 nm. For current inspection tools, the rule of thumb is generally that EAPSMs should have less than 40% transmission relative to bare quartz at the inspection wavelength, and SiN/TiN multilayers meet this criterion.

4 EAPSMs: mask fabrication and printing performance

Figure 5 outlines the mask fabrication steps which impose additional demands on the EAPSM thin film: etch selectivity, chemical durability, and low film stress, besides tunable optical properties and radiation hardness needed for mask lifetime.

![Diagram of mask fabrication process](image)

**Figure 5. Mask fabrication process for Si$_3$N$_4$/TiN EAPSM phase shift photomask.**

The upper left diagram in Figure 5 illustrates the structure of our phase-shift “blank”, before processing it into a mask. The “blank” is comprised of a quartz substrate on to which is sputtered the SiN/TiN multilayer EAPSM, then an anti-reflective Cr layer, overcoated with photoresist. Our mask fabrication process involves first patterning the Cr layer using standard lithography and then replicating this pattern into the EAPSM, using the patterned Cr as a hard etch mask. This is followed by removal of Cr everywhere except around the border of the mask,

which prevents unwanted printing in adjacent die on the wafer and also maintains contrast of the alignment marks. Another use for the Cr is for a special phase-shift mask design, sometimes referred to as a tri-tone mask, in which sub-resolution (non-printing) Cr “assist” features are patterned on the EAPSM in order to prevent unwanted printing of “ghost images” by transmitted, higher orders of the diffracted imaging light.

Using the Cr as a hard etch mask in place of photoresist also avoids deleterious electrical charging of the EAPSM when writing IC patterns with an electron beam, as is common, because nearly all materials that are optically transmitting at 193 nm are also electrically insulating. But this requires processing compatibility of the EAPSM with Cr. Specifically, the Cr must be dry etched or wet etched without affecting the EAPSM. Further, it must also be tolerant to the aggressive chemicals used to strip photoresist, namely H$_2$SO$_4$/H$_2$O$_2$ mixtures at 80° C. SiN/TiN multilayers are resistant to these wet chemical etchants and can be dry etched in fluorine based chemistries with high selectivity to Cr and to the quartz substrate. Etch selectivity to quartz is important because inadvertently etching it will increase the phase-shift.

Finally, Figure 6 shows atomic force microscope images of contact holes and lines fabricated using this process in an EAPSM of SiN/TiN multilayers, and Figure 7 compares printing of nominally 190 nm contacts with 360 nm pitch with a Cr binary mask and a SiN/TiN EAPSM. The use of phase shift mask increased the DoF or process latitude of the printed contacts from ±0.2 µm to ±0.6 µm, a significant improvement.

![Atomic force microscope images](image)

**Figure 6.** Atomic force microscope images of contact holes and lines fabricated using this process in an EAPSM of SiN/TiN multilayers.
5 Future lithography generations and masks

What the next generation lithography will be beyond 193 nm is still being debated. One popular view is that optical lithography at 193 nm will be followed by optical lithography at 157 nm\textsuperscript{13}, using a F\textsubscript{2} laser and CaF\textsubscript{2} optical elements in steppers, and then there will be a transition to soft X-rays at 13 nm, or extreme ultraviolet (EUV)\textsuperscript{14,15}, as it is referred to. It seems apparent that phase-shift masks would again be important at 157 nm. However, at 157 nm, Si\textsubscript{3}N\textsubscript{4} is too absorbing to be the transparent layer in a multilayer EAPSM. A better alternative would be to layer SiO\textsubscript{2}, as the transparent layer, with Si\textsubscript{3}N\textsubscript{4} as the absorbing layer. If the substrate for the mask is CaF\textsubscript{2}, then the etch selectivity in patterning the mask will be high. If the substrate is low-loss quartz, then etch selectivity can still be adequate, if the first layer is Si\textsubscript{3}N\textsubscript{4}.

At EUV all of the optical elements, including the mask will be reflective elements, since transparent materials needed for refractive optics do not exist at soft X-ray wavelength. For EUV lithography, again the multilayer platform is relevant. Both the mask and reflective optical components under development are comprised of Mo/Si or Mo/Be multilayers with typically 40 bilayers of 40 A Mo layered with about 30 A of Si or Be. Therefore the same deposition tools and strategies used to synthesize multilayer EAPSM will also work for EUV masks. When we include the potential for direct thermal processing of wafers\textsuperscript{16} with masks that are reflective, dielectric mirrors, also made with a multilayer stack, multilayers can be considered to be the common platform for future, advanced mask designs. Finally, still further into the future, one can predict that thin film, reflective phase-shift masks may also find a role in EUV lithography.