More Problems with PSM

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In the last edition of this column, we talked about one of the most vexing problems with alternating phase shift masks – phase conflicts. Arbitrary layouts of brightfield patterns will almost always result in numerous regions where 0 to 180º phase transitions occur (resulting in the printing of a dark line), but where printed features are not wanted. While design and layout methodologies might be found to resolve these conflicts for most, if not all, cases, and double exposures can be used where single exposure solutions are not possible, there are other problems that must also be fixed if alternating PSMs are to become practical. In particular, when phase shifting a small space by etching the quartz, the phase and amplitude transmittance of the space is a function of the space width.

The most common way of shifting the phase of light on a photomask is to change the thickness of quartz that one ray of light must pass through compared to another ray. This is most commonly done by etching the quartz under one space by a set depth *d* while leaving the quartz of an adjacent space unetched (Figure 1). Since the phase change of light as it travels some distance *d* through a material of index *n* is given by $2\pi\nu\delta/\lambda$, a phase shift between two different paths of the light is controlled by the distance traveled through materials of different refractive indices. For the PSM shown in Figure 1, the nominal phase difference between the two adjacent spaces would be $2\pi(\nu-1)\delta/\lambda$ where *n* is the refractive index of the quartz and the air is assumed to have an index of one. From this equation it is easy to see that the ideal etch depth to give a *p* phase shift would be $\lambda/2(\nu-1)$. These equations can also tell us how an error in etch depth turns into an error is phase. For 193 nm lithography, that translates into about 0.9º phase error per nanometer etch depth error.

The above equations relating phase change to etch depth make an important assumption – that the light is traveling vertically. However, as light goes through the etched quartz hole, it begins to diffract at the bottom of the hole and its directions deviate from a straight line. The smaller the hole, the greater this diffraction effect. This causes a difference in the actual phase of the light compared to the geometric "straight line" approximation, and this difference is a function of the size of the etched space. If these phase errors were not bad enough, diffraction through the etched space causes a second problem: some of the diffracted light doesn't even make it out of the hole. As a result, the etched quartz space appears dimmer than the unetched space, creating an intensity imbalance in addition to the phase error (Figure 2). As with the phase error, the degree of intensity imbalance is spacewidth dependent.

Obviously, the real, physical effects of trying to create a 180º phase shift by etching the quartz as described above are very bad for lithography. The intensity imbalance causes the two adjacent spaces to print as different linewidths, and the phase imbalances cause these spaces to have different best focus settings. How can these problems be fixed? There are a number of possibilities.
In the *dual trench* method (Figure 3a), both the unshifted and shifted spaces are first etched to some depth, then the shifted space is further etched to create the desired phase shift. This approach can reduce both the phase errors and the intensity imbalance, though not perfectly for all space widths, and it complicates the mask-making process. In the *undercut etch* method (Figure 3b), the shifted space is etched somewhat isotropically, causing some undercut of the chrome. This widening of the etched space reduces the intensity imbalance appreciably. However, to get the intensity imbalance to approach zero, the amount of undercut can become excessive, causing possible reliability problems with the overhanging chrome. Finally, the biased space approach (Figure 3c) uses an OPC tool to *bias the etched* space larger in order to eliminate the intensity imbalance. This bias can be adjusted as a function of the space size and pitch in order to eliminate intensity

imbalance across the full range of features. In general, none of these approaches is perfect at eliminating the phase error as a function of size and pitch.

The most common approach to alternating PSM manufacturing today is to combine the biased space approach with a small amount of undercut. While not perfect, it can provide very good intensity balance and minimum phase error. To determine the best undercut amount and the optimum bias for each etched space, rigorous simulation of the electro-magnetic effects of light transmission through the mask topography is required. KLA-Tencor's PROLITH with the Mask Topography Option is the ideal tool for these types of simulations.

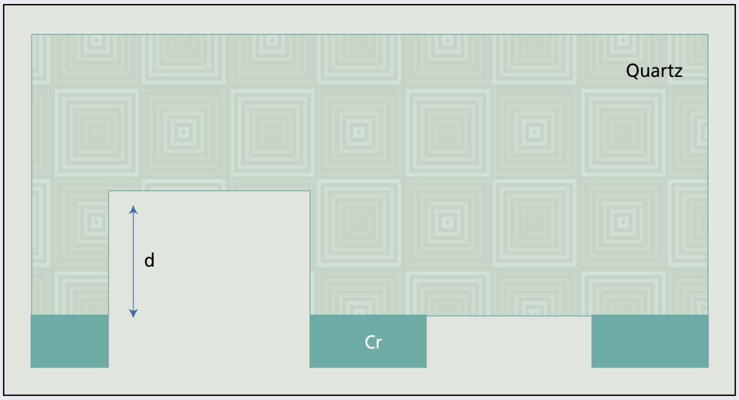

Figure 1. Example of a simple alternating phase shift mask manufacturing approach.

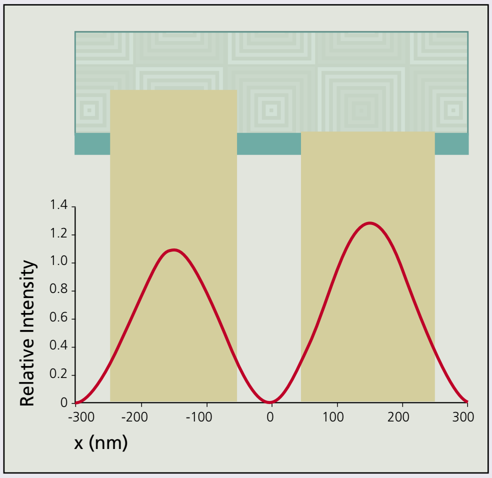

Figure 2. Intensity imbalance shown for an alternating phase shift mask of equal lines and spaces.

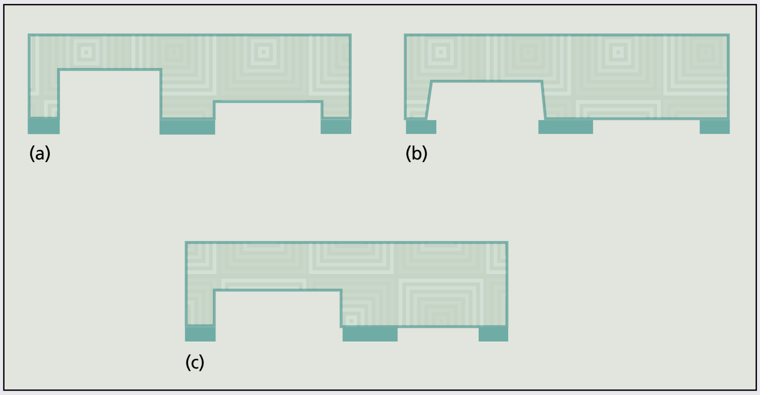

Figure 3. Different approaches for fixing the phase error and intensity imbalance in alternating PSM: a) dual trench, b) undercut etch, and c) biased space.