The Influence of Mask Substrate Thickness on Exposure and Development Times for the LIGA Process

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Many factors influence the design of x-ray masks used in exposing PMMA resists for the LIGA process. One important factor is the exposure time. Overly thick mask substrates will absorb too much of the beam energy, requiring exposure times that may run to several days. Another important factor is the top-to-bottom dose ratio. Most synchrotron sources produce sufficient low-energy photons that some measure of beam filtering is required to obtain acceptable dose ratios in thick resists. Large top-to-bottom dose ratios must generally be avoided since the top-surface dose cannot be increased without bound and low bottom-surface doses yield very long development times. A mask substrate of appropriate thickness may thus conveniently serve as the required beam filter. Since very thin substrates are difficult to manufacture, thinning the substrate and filtering the beam elsewhere is not desirable. Finally, the mask absorber thickness is an important factor in mask design because increasing the absorber thickness increases the size of the smallest absorber feature that is practical to form. X-ray absorption in the substrate shifts the remaining spectrum toward higher photon energies, increasing the absorber thickness needed to maintain a fixed dose contrast, so a thin mask substrate may be preferred when producing features of very small size.

To help optimize mask design for the LIGA process, we have developed numerical models describing both x-ray exposure of the PMMA resist and development of the exposed part. The exposure model addresses multi-wavelength, one-dimensional x-ray transmission and absorption through multiple beam filters, the mask absorber and substrate and through the PMMA resist. This model additionally contains algorithms to automatically adjust exposure time, beam filter thickness and mask absorber thickness so as to yield prescribed doses at both the top and bottom surfaces of the PMMA, as well as a prescribed maximum dose in masked regions under the absorber. The development model describes the one-dimensional evolution of the dissolution front, taking into account the local absorbed dose through the PMMA thickness. Local dissolution rates are computed from phenomenological relations based on measured kinetic-limited development rates and a quasi-empirical expression accounting for advective and diffusive transport of PMMA fragments from the dissolution surface to the open mold top. The development model additionally includes an equation describing the lateral sidewall development rate. This equation is integrated in time over the period of development to yield the extent of sidewall dissolution.

These coupled models are used here to investigate the influence of mask substrate thickness on exposure and development times and on the minimum thickness of the mask absorber required to provide a specified allowable extent of feature sidewall dissolution. Sample results are presented over a wide range of the PMMA resist thickness, mask substrate thickness and substrate materials for exposures at the ALS, SSRL and several other sources world wide. We find that tradeoffs between the exposure and development times serve to define an optimum substrate thickness for each source and further identify for each source a practical limit on the maximum resist thickness.

In the present abstract we limit our attention to a mask substrate fabricated from silicon and a mask absorber that is gold. The PMMA is assumed to have an initial molecular weight of $3x10^6$ g/mol and is developed in GG solvent at 35 C. Figure 1 illustrates the fundamental tradeoff between exposure and development times as the mask substrate thickness is varied. Here the x-ray source is the ALS synchrotron operating at 1.5 GeV, the top surface dose is fixed at 10 kJ/cm^3 and the thickness of the PMMA resist is 1000 µm. In this case we see that the exposure time increases very strongly with increasing substrate thickness and exceeds 340 hours (two weeks!) for a substrate thickness of only 100 µm. Reducing the top dose to 5 kJ/cm^3 reduces the exposure time by only a factor of two, so this is clearly not acceptable. In contrast, the development time grows rapidly as the substrate thickness is reduced and exceeds 100 hours for any thickness below about 25 µm. Thus a practical optimum substrate thickness lies between 25 and 100 µm, somewhere near 35 µm. This yields exposure and development times that are both about 24 hours. Of course the true optimum depends on the relative values of exposure and development time. However, the dependence of both times on the substrate thickness is so strong near this optimum that only a slight increase or decrease in substrate thickness will place either the exposure or development time outside the practical range. The marginal nature of this optimum indicates that exposure of a 1000 µm PMMA resist is near or just outside the

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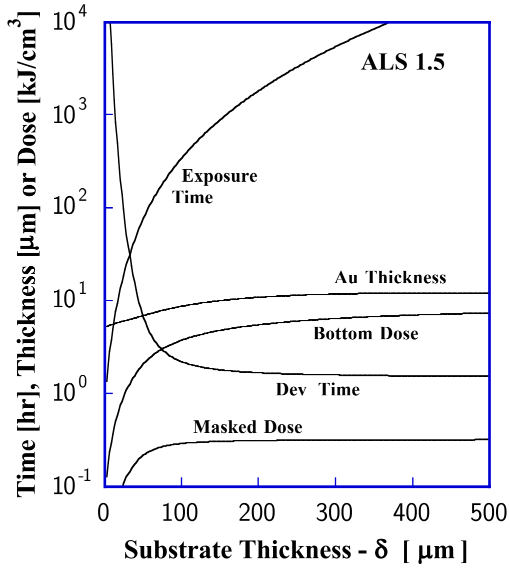
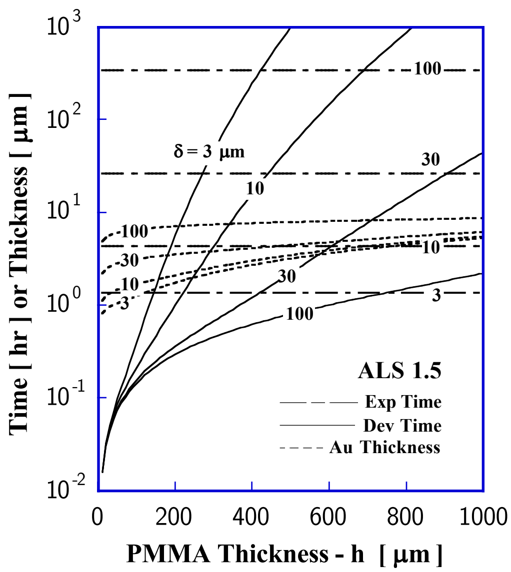
capability of this source. Note that these conditions and source were selected to show the problems encountered with very thick resists and relatively low beam energies. The ALS source operating at 1.9 GeV provides much more favorable results and is frequently used by Sandia in making LIGA exposures of thick resists.

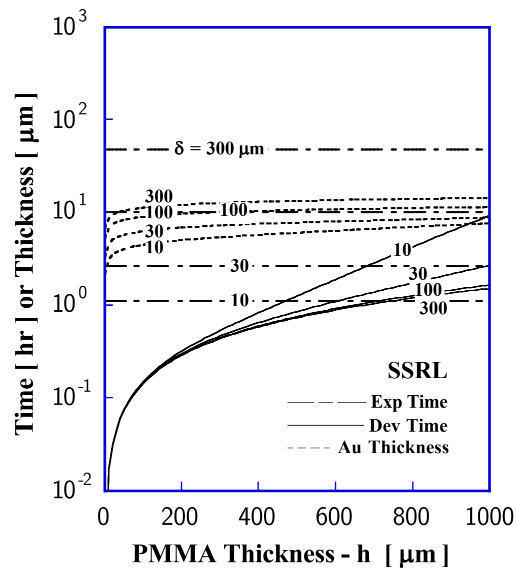
Figure 1. Increasing the mask substrate thickness increases the exposure time, absorbed bottom dose and required gold absorber thickness, but reduces the development time. Results are based on a 1000 μm PMMA thickness, top dose of 10 kJ/cm^3 and 0.1 μm total extent of sidewall dissolution.

Figure 2. Excessive exposure or development times define an optimum substrate thickness and place a practical limit on the maximum PMMA thickness for exposure at a given source. Large substrate thickness may increase minimum absorber thickness by a factor of two or more.

Figure 3. A more energetic synchrotron source dramatically reduces both exposure and development times for thick PMMA resists. In this case, fairly thick mask substrates may be used to reduce development times without excessive exposure periods.







Figures 2 and 3 illustrate the strong influence of resist thickness on the preferred thickness of the mask substrate. Here the exposure and development times for the 1.5 GeV ALS source and the 3.0 GeV SSRL source are shown as a function of the resist thickness, while the mask substrate thickness is varied as a parameter. For each resist thickness in each figure the top dose is constant at 10 kJ/cm^3, so the exposure time is a function only of the source and mask substrate thickness. For the ALS source we see that the practical optimum substrate thickness lies just below 3 μm for a 100 μm resist, yielding both exposure and development times of about 1 hour. As discussed above, the preferred substrate thickness for this source increases to about 35 μm for a resist thickness of 1000 μm, and the corresponding exposure and development times are both about 24 hours. Surprisingly, we find that the optimum substrate thickness for a 1000 μm resist at the SSRL source again lies near 30 μm. In this case, however, the exposure and development times are both about 2 hours. Thus by increasing the substrate thickness to 100 μm, the SSRL source can be used for PMMA resists well in excess of 1000 μm, while maintaining both exposure and development times below 10 hours. Finally, we note that the preferred substrate thickness depends mainly on the resist thickness and is largely independent of the synchrotron source.