Microsystem Technologies 6 (2000) 99–102 © Springer-Verlag 2000

The influence of mask substrate thickness on exposure and development times for the LIGA process

S.K. Griffiths, A. Ting, J.M. Hruby

Abstract Optimizing mask substrate thickness is an important practical concern in the X-ray exposure of PMMA resists for LIGA. An overly thick substrate necessitates long exposure times due to excessive beam filtering, while a substrate too thin leads to long development times due to low absorbed doses at the PMMA bottom surface. To assist in this optimization, we have developed numerical models describing both the exposure and development of a PMMA resist. These exposure and development models are coupled in a single interactive code, permitting automated adjustment of mask substrate thickness to yield the minimum of a prescribed cost object function that depends on both the exposure and development times. Results are presented for several synchrotron sources and over a wide range of the PMMA thickness.

1 Introduction

Many factors influence the design of X-ray masks used in exposing PMMA resists for the LIGA process [1, 2, 3]. 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 filtering of the X-ray beam 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.

To help investigate the influence of mask substrate thickness on exposure and development times, we have developed coupled models of the LIGA exposure and development processes. These models are used here to parametrically study tradeoffs between exposure and development time and to directly discern the optimum substrate thickness. Sample results are presented over a wide range of the PMMA resist thickness and mask substrate thickness for exposures at the ALS (Lawrence Berkeley), SSRL (Stanford) and NSLS (Brookhaven) sources. 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.

2 Numerical model

The exposure model describes one-dimensional, multi-wavelength X-ray transmission through an arbitrary set of filters, transmission through the mask absorber and substrate, and the subsequent profile of energy absorption through the thickness of the PMMA target. These transmission and absorption processes are modeled using wavelength-dependent transmission and absorption cross-sections. Scattering is included only as effective forward and backward scattering along the main direction of beam propagation, and elastic scattering and florescence are not yet considered. Under these restrictions, the attenuation of beam power is described by

$$p_{o,k} = p_{i,k} e^{-\rho\sigma_{t,kl}} \qquad (1)$$

where $p_{i,k}$ is the incident beam power at some photon energy E_k, $p_{o,k}$ is the transmitted power, ρ is the material density, $\sigma_{t,k}$ is the transmission cross-section of the material at photon energy E_k, and l is the thickness of the filter or absorber. Thus the remaining power at any wavelength after any set of filters can be computed by sequential analysis, each time using the transmitted power from the previous filter as the incident power for the next. The mask absorber and substrate can be treated in the same manner. The incident power on the first filter is simply the synchrotron output, properly adjusted to account for the beam length.

The local wavelength-dependent dose rate in the PMMA is computed from the local transmitted power $p_{i,k}$ at a

Received: 15 July 1999/Accepted: 23: August 1999

S.K. Griffiths, A. Ting, J.M. Hruby
Sandia National Laboratories, Livermore, CA 94551-0969, USA

Correspondence to: S.K. Griffiths

Development of the LEX-D code was funded in part by a Sandia LDRD and in part by the Sandia Materials Science Research Foundation. The present study was funded by the Sandia Revolution in Engineering Program. Sandia is a multiprogram laboratory operated by Sandia Corporation for the United States Department of Energy under contract DE-AC04–94AL85000.

This paper was presented at the Third International Workshop on High Aspect Ratio Microstructure Technology HARMST '99 in June 1999.

given position in the PMMA and the wavelength-dependent adsorption cross-section.

$$q_k = \rho \sigma_{a,k} p_{i,k} \quad (2)$$

The local total dose rate, dQ/dt, is then obtained by summing the wavelength-dependent doses over all photon energies,

$$\frac{dQ}{dt} = \sum_k q_k \delta E_k \quad (3)$$

where δE_k is one-half of the width of the band of photon energies between E_{k-1} and E_{k+1}. For a constant synchrotron source, the total dose is finally obtained by multiplying this total dose rate by the exposure time.

Dissolution rates during development generally depend on both the kinetics of the reaction and on the transport of PMMA fragments away from the dissolution surface. In the present study, however, we consider only those cases for which the transport rates far exceed the kinetic-limited dissolution rate. This condition is usually satisfied when the feature aspect ratio does not exceed about two, when the PMMA thickness is less than about 100 μm, or when sonic agitation is used to sufficiently increase transport rates in small deep features. In this limit, the linear development rate is

$$\frac{dy}{dt} = U_0 \quad (4)$$

where y is the instantaneous location of the dissolution surface measured from the PMMA top surface, and U_0 is the kinetic-limited development rate at a given dose and temperature.

Kinetic-limited development rates normally depend on the development temperature and local total dose [4], but may additionally depend on the dose rate and mean photon energy of the dose. In our general development model, the kinetic rate is computed from the PMMA molecular weight after the dose. This final molecular weight is computed from the initial molecular weight, a cross-linking yield, and a main-chain scission yield that depends on the mean photon energy of the absorbed dose. For simplicity, however, here we employ a kinetic-limited development rate that depends only on the total dose and development temperature. The form of this relationship is

$$U_0 = a \frac{(Q/b)^c}{1 + (Q/b)^c} e^{-\frac{E_a}{R}\left(\frac{1}{T} - \frac{1}{T_r}\right)} \quad \text{where} \quad E_a = \frac{\alpha}{1 + (Q/\beta)^\kappa} \quad (5)$$

Parameters for the activation energy used here are $\alpha = 139$ kJ/mol, $\beta = 8.32$ kJ/cm^3 and $\kappa = 2.38$. $T_r = 308$ K (35 °C) is a reference temperature. The parameters a, b and c for GG developer are 13.6 μm/min, 4.6 kJ/cm^3, and 3.8 respectively, for all synchrotron sources. Additional details of the exposure and development models have been reported previously [4, 5].

These exposure and development models are coupled in a user-friendly code known as LEX-D. This code additionally contains algorithms to automatically adjust exposure time, beam filter thickness and mask absorber thickness. By these adjustments, the user may prescribe (as inputs) doses at both the top and bottom surfaces of the PMMA and a maximum dose in masked regions under the mask absorber or, equivalently, an allowable extent of feature sidewall dissolution. The code then computes the necessary filter or mask substrate thickness, mask absorber thickness and exposure time.

3
Sample results

In this study, we limit our attention to a mask substrate fabricated from silicon. The PMMA is assumed to have an initial molecular weight of 3×10^6 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 1 mm. In this case we see that the exposure time increases very strongly with increasing substrate thickness and exceeds 340 hours (2 weeks!) for a substrate thickness of only 100 μm. At the same time, 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 20 hours. 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. Note that these conditions and source were selected to show the problems

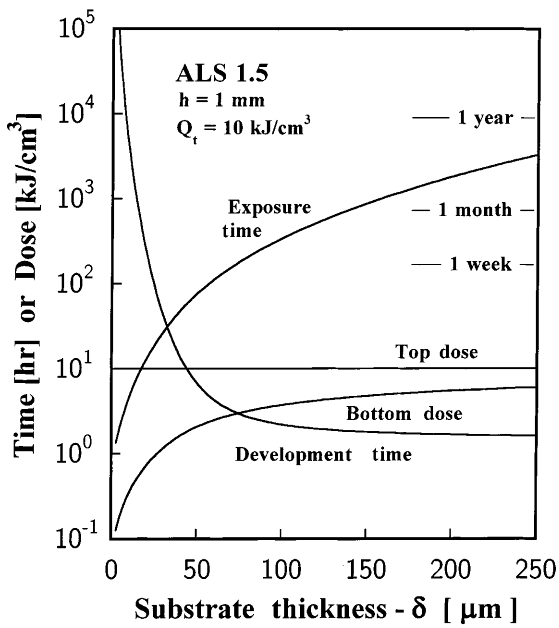

Fig. 1. Increasing the mask substrate thickness increases the exposure time but reduces the development time. Results are based on a 1 mm PMMA thickness and top-surface dose of 10 kJ/cm^3

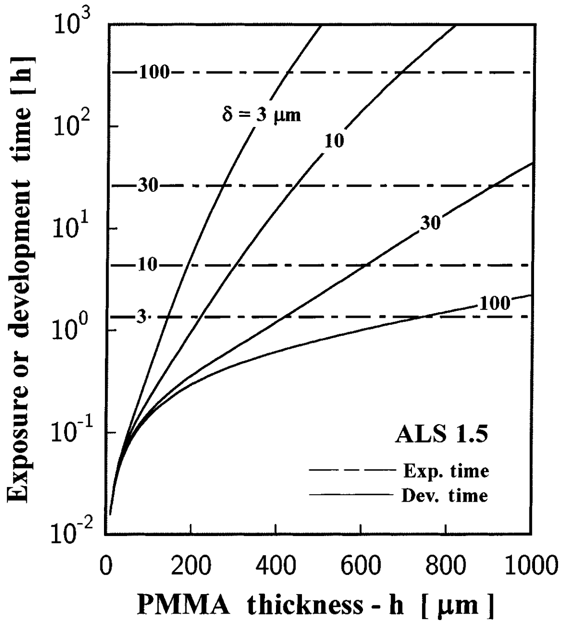

Fig. 2. Excessive exposure or development times define an optimum substrate thickness for each PMMA thickness and place a practical limit on the maximum PMMA thickness for exposure at a given source

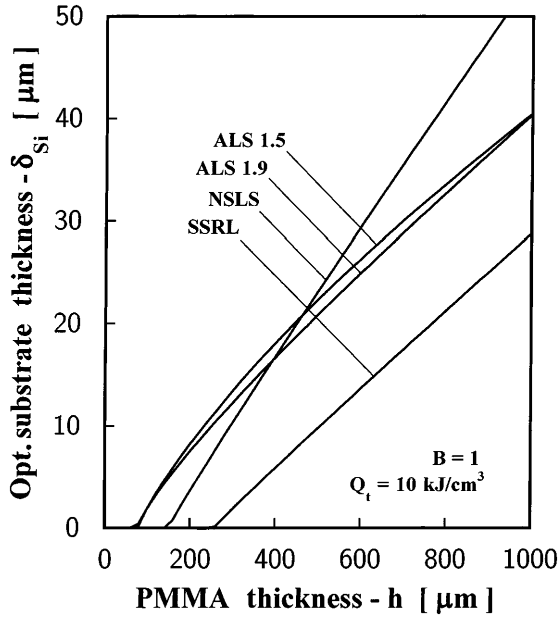

Fig. 3. Optimum mask substrate thickness depends on synchrotron beam length and total power, as well as beam spectrum. Cost object function is the sum of exposure and development times (B = 1)

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 2 illustrates the strong influence of PMMA resist thickness on the preferred thickness of the mask substrate. Here the exposure and development times for the 1.5 GeV ALS source are shown as a function of the resist thickness, while the mask substrate thickness is varied as a parameter. For each resist thickness along each curve the top dose is constant at 10 kJ/cm^3, so the exposure time is a function only of mask substrate thickness. For the ALS source at 1.5 GeV 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 1 mm, and the corresponding exposure and development times are both about 20 hours.

To more generally understand the tradeoffs between exposure and development times, we have developed a minimization algorithm for use in conjunction with the exposure and development models. This algorithm minimizes a user-specified object function, representing the total process cost, by adjusting the mask substrate thickness. One useful form of this cost object function is a simple weighted sum of the exposure and development times, given by $C = t_{exp} + Bt_{dev}$. The parameter B thus prescribes the relative values of exposure and development time. Of course the object function can be modified to include overhead times for set up, travel time, and any other contribution to the true process cost. This simple form nevertheless provides a good starting point for showing the benefits of an optimum mask substrate.

Figures 3 and 4 show the computed optimum substrate thickness and associated total process cost (in hours) for exposures made at the ALS, SSRL and NSLS sources. These results are based on an object function weight of $B = 1$ and a maximum allowable top-surface dose of 10 kJ/cm^3. The minimum total cost is always obtained for the highest top-surface dose, so the optimum top-surface dose is simply the highest value that does not in some way damage the PMMA.

In Fig. 3 we see that the optimum substrate thickness grows about linearly with the PMMA thickness, but depends on characteristics of the synchrotron source in a manner that is not intuitive. The optimum thickness for the ALS source operating at 1.5 and 1.9 GeV are very similar, while that for SSRL (3.0 GeV) is much small, and that for NSLS (2.6 GeV) may be either larger or smaller depending on the PMMA thickness. This rich behavior arises because the optimum substrate thickness depends on both the beam spectrum and total photon flux produced by each machine. For example, the NSLS source has a large ring current and a short beam length to the exposure station. These both tend to give very short exposure times for any specified dose, so increasing the substrate thickness to reduce the development time is beneficial in reducing the total process cost. In contrast, the SSRL source has a slightly higher beam energy, but the ring current is much lower and the beam length to the exposure station is longer. Because of this, the optimum substrate thickness for the SSRL source is much smaller in order to trade increased development time for a reduced time of exposure. One unexpected result of this analysis is that the exposure time given the optimum substrate

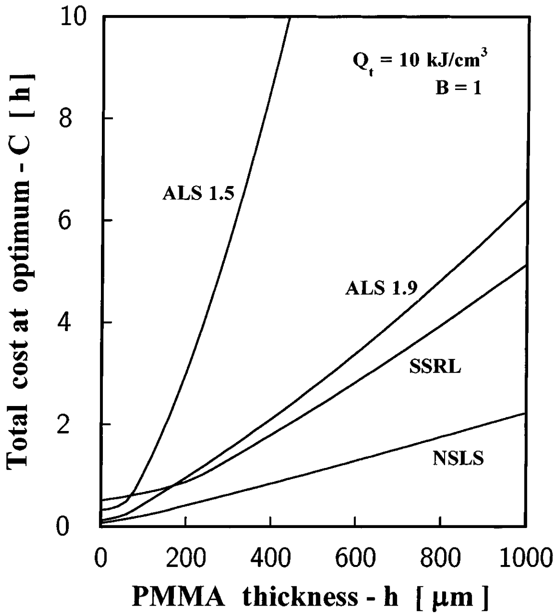

Fig 4. Total cost at optimum conditions depends strongly on source characteristics. Exposure and development times are comparable for optimum substrate thickness and exposure time

thickness decreases with increasing top dose. The reason for this is that the optimum substrate thickness falls as the top dose increases, allowing more low-energy photons to reach the PMMA surface. The increased energy flux thereby reduces the exposure time for a fixed top-surface dose, even as the top-surface dose is increased.

Figure 4 shows the computed minimum total process cost for the ALS, SSRL and NSLS sources as a function of the PMMA resist thickness. Again, the total cost is the sum of the exposure and development times in this simplified example. We see that the minimum total cost is strongly dependent on the synchrotron source and increases about linearly, or a bit more strongly, with PMMA thickness for thicknesses over about 100 µm. The breakdown of the total cost for the four sources is nearly independent of resist thickness and is conveniently expressed as the ratio of the exposure and development times. For the optimum substrate thickness, this ratio is about 1.5 for ALS at 1.5 GeV, about 1.0 for SSRL and ALS at 1.9 Gev, and about 0.5 for NSLS. Only when the PMMA thickness is very small does this ratio vary significantly.

For both SSRL and ALS at 1.9 Gev, the two sources most commonly used by Sandia, the minimized total cost is less than 7 hours for a 1 mm PMMA thickness, and the optimized exposure and development times are each under 4 hours. Note, however, that the substrate thickness required to obtain these minima differs significantly between the two sources. Exposures performed at NSLS for the same resist thickness yield a minimum total cost of about only 2 hours. In contrast, ALS at 1.5 GeV gives a minimum total cost of 10 hours for a PMMA thickness of 400 µm, and this minimum cost increases to nearly 40 hours as the resist thickness is increased to 1 mm.

4
Summary

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. These models are coupled in a single code, LEX-D. This code additionally employs algorithms to automatically adjust exposure time and mask substrate thickness. Through such adjustment, the code yields prescribed doses at both the top and bottom surfaces of the PMMA. An additional algorithm computes the optimum thickness of the mask substrate that minimizes a user-specified object function representing the total process cost. This object function depends on both the exposure and development times.

We find that exposure times in particular are very sensitive to the mask substrate thickness. For a 1 mm PMMA thickness, 100 µm silicon substrate thickness and top dose of 10 kJ/cm^3, exposure times are 10, 25 and 340 hours for exposure at the SSRL, ALS-1.9 GeV and ALS-1.5 GeV sources, respectively. The corresponding development times are 1.8, 1.9 and 2.4 hours. For the same conditions but optimum substrate thickness, these exposure times fall to 2.6, 3.4 and 25 hours, while the development times increase to only 3.0, 3.4 and 14 hours. The optimum substrate thicknesses for these three cases are 30, 40 and 42 µm based on a cost object function that is the sum of the exposure and development times.

References

1. **Becker EW; Ehrfeld W; Hagmann P; Maner A; Munchmeyer D** (1986) Fabrication of microstructures with high aspect ratios and great structural heights by synchrotron radiation lithography, galvanoforming and plastic moulding (LIGA Process). Microelectronic Eng 4: 35–56
2. **Munchmeyer D; Ehrfeld W** (1987) Accuracy limits and potential applications of the LIGA technique in integrated optics. Proceedings of the SPIE, Micromachining of Elements with Optical and other Submicrometer Dimensional and Surface Specification 803: 72–79
3. **Freiertag G; Ehrfeld W; Lehr H; Schmidt A; Schmidt M** (1998) Calculation and experimental determination of the structure transfer accuracy in deep X-ray lithography. J Micromech Microeng 7 (4): 323–331
4. **Tan MX; Bankert MA; Griffiths SK; Ting A; Boehme DR; Wilson S; Balser LM** (1998) PMMA dose studies at various synchrotron sources and exposure/development conditions. Proceedings of the SPIE, Materials and Device Characterization in Micromachining, 3512
5. **Griffiths SK; Hruby JM; Ting A** (1999) Optimum doses and mask thickness for synchrotron exposure of PMMA resists. Proceedings of the SPIE, Design, Test and Microfabrication of MEMS and MOEMS, 3680: 498–507