Equations of exposure time and X-ray mask absorber thickness in the LIGA process

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Abstract The LIGA X-ray exposure step was modeled into three inequalities from exposure requirements. From these inequalities, equations for the minimum and maximum exposure times required for a good quality microstructure were obtained. An equation for the thickness of an X-ray mask absorber was also obtained from the exposure requirement of threshold dose deposition. A power function of photon energy, approximating the attenuation length of the representative LIGA resist, PMMA, and the mean photon energy of the X-rays incident upon an X-ray mask absorber were applied to the above mentioned equations. Consequently, the trends of the minimum and maximum exposure times with respect to mean photon energy of X-rays and thickness of PMMA were examined and an equation for the maximum exposable thickness of PMMA was obtained. The trends of the necessary thickness of a gold X-ray mask absorber with respect to photon energy of the X-rays and PMMA thickness ratio were also examined. The simplicity of the derived equations has clarified the X-ray exposure phenomenon and the interplay of exposure times, the attenuation coefficient and the thickness of an X-ray mask absorber, the attenuation coefficient and the thickness of a resist, and synchrotron radiation power density.

1 Introduction
The LIGA process was first developed at the Karlsruhe Nuclear Research Center in Germany in the early 1980s [Becker et al. (1986)]. Since then, it has been applied successfully to various fields such as micromechanics, micro-optics, and microfluidics. Its application areas have been expanded to movable microstructures for sensors and actuators, using sacrificial layers [Bley et al. (1991) and Guckel et al. (1994)].

The LIGA is a German acronym for X-ray lithography (Lithographie), electroplating (Galvaniformung), and injection molding (Abformung), all of which are primary steps of the LIGA process. The X-ray exposure and development steps are governed by the X-ray dose deposited in resist. Malek et al. (1994) performed X-ray exposures, matching the ratio of the X-ray dose deposited in the upper part of PMMA to that in the bottom part of the PMMA to about 6. The traditional method to satisfy the exposure requirements is to tune the contrast ratio, the ratio of the maximum X-ray dose deposited in the upper part of resist to that under an X-ray mask absorber, to 200 [Malek et al. (1996)].

In this work, the basic principles for the X-ray exposure step are derived directly from exposure requirements and applied to PMMA and a gold X-ray mask absorber. Exposure times, the maximum exposable thickness of PMMA, and the necessary thickness of a gold X-ray mask absorber are presented.

2 X-ray exposure principles
The bond breakage of resist depends on the X-ray dose deposited in the resist. Photons absorbed in resist atoms generate photoelectrons, Auger electrons, and fluorescent radiation. These electrons and radiation are deposited in the nearby resist atoms through secondary Thomson and Compton scatterings. Thus, the X-ray power transfer through these events is mostly confined to the local range, which is laterally less than 1 μm [Feldman and Sun (1992)]. The fluorescent radiation generated in the substrate under the resist by X-rays is deposited in the bottom part of the resist. But the range affected significantly by the fluorescent radiation is also confined laterally to no more than 1 μm [Feiertag et al. (1997)]. In this work, the X-ray energy attenuated at a point within a resist is assumed to be deposited only at that point of the resist and the secondary exposing effects are neglected.

The power density $P(t)$ of monochromatic X-rays at depth $t$ in a medium is represented as

$$P(t) = P_0 e^{-\mu t}$$  \hspace{1cm} (1)

where $P_0$ and $\mu$ are the power density at the top surface of the medium and the attenuation coefficient of the medium, respectively. Figure 1 depicts the power density of monochromatic X-rays along the X-ray path when exposed, according to (1). In Fig. 1, subscripts ABS, BLK, and PR designate an X-ray mask absorber, an X-ray mask
blank, and a resist, respectively. The path I represents the path of the X-ray passing directly into the resist without going through the X-ray mask absorber. Path II represents the path of the X-ray passing through the resist after transmitting the X-ray mask absorber. \( P's \) are power densities of the synchrotron radiation at each point.

The following three exposure requirements must be met by an effective X-ray exposure [Bley et al. (1991) and Malek et al. (1994, 1996)].

1. The X-ray dose deposited in the upper part of resist (a) must be smaller than the damaging dose \( D_{dm} \).
2. The X-ray dose deposited in the bottom part of the resist in the region to be developed (b) must be greater than the development dose \( D_{dv} \).
3. The X-ray dose deposited in the upper part of the resist under an X-ray mask absorber (c) must be smaller than the threshold dose \( D_{th} \).

These exposure requirements may be expressed as inequalities of

\[
q_a < D_{dm} \quad (2)
\]

\[
q_b > D_{dv} \quad (3)
\]

\[
q_c < D_{th} \quad (4)
\]

where \( q_a, q_b, \) and \( q_c \) are X-ray doses at points a, b, and c, respectively. Applying (1) to the X-ray mask absorber and the resist, the power density \( P_c \) at the point c and power density \( P(t) \) at depth \( t \) within the resist are represented as

\[
P_c = P_a e^{-\mu_{ABS} t} \quad (5)
\]

\[
P(t) = P_0 e^{-\mu_{PR} t} \quad (6)
\]

The X-ray dose deposited in depth difference \( \Delta t \) of the resist during exposure time \( \tau \) is \( \tau[P(t) - P(t + \Delta t)] \). Thus, the X-ray doses \( q_I \) and \( q_{II} \) on paths I and II can be represented by

\[
q_I(t) = \tau \mu_{PR} P_a e^{-\mu_{PR} t} \quad (7)
\]

\[
q_{II}(t) = \tau \mu_{PR} P_a e^{-\mu_{ABS} t} e^{-\mu_{PR} t} \quad (8)
\]

From (7) and (8), X-ray doses \( q_a, q_b, \) and \( q_c \) at points a, b, and c are obtained as

\[
q_a = q_I(0) = \tau \mu_{PR} P_a \quad (9)
\]

\[
q_b = q_I(t_{PR}) = \tau \mu_{PR} P_a e^{-\mu_{PR} t_{PR}} \quad (10)
\]

\[
q_c = q_{II}(0) = \tau \mu_{PR} P_a e^{-\mu_{ABS} t_{ABS}} \quad (11)
\]

Applying (9), (10), and (11) to inequalities of (2), (3), and (4) yields inequalities of the exposure time \( \tau \) and the thickness of the X-ray mask absorber, \( t_{ABS} \), satisfying the exposure requirements:

\[
\frac{D_{dv}}{\mu_{PR} P_a e^{-\mu_{PR} t_{PR}}} < \tau < \frac{D_{dm}}{\mu_{PR} P_a} \quad (12)
\]

\[
t_{ABS} > \frac{1}{\mu_{ABS}} \ln \left[ \frac{\tau \mu_{PR} P_a}{D_{th}} \right] \quad (13)
\]

The left and right side terms of (12) may be defined as the minimum exposure time \( \tau_{min} \) and the maximum exposure time \( \tau_{max} \), respectively:

\[
\tau_{min} = \frac{D_{dv}}{\mu_{PR} P_a e^{-\mu_{PR} t_{PR}}} \quad (14)
\]

\[
\tau_{max} = \frac{D_{dm}}{\mu_{PR} P_a} \quad (15)
\]

By substituting \( \tau \) in (13) by \( \kappa \tau_{min} \) to incorporate a real exposure time with a safety factor \( \kappa (>1) \), \( t_{ABS} \) can be redefined as the necessary thickness of an X-ray mask absorber by

\[
t_{ABS} = \frac{1}{\mu_{ABS}} \ln \left[ \frac{\kappa D_{dv}}{D_{th}} + \frac{t_{PR}}{t_{PR}} \right] \quad (16)
\]

where \( t_{ABS} \) and \( t_{PR} \) are attenuation lengths of both an X-ray mask absorber and a resist, which are inverses of those attenuation coefficients.

Synchrotron radiation has a broad photon energy bandwidth and the attenuation coefficients are functions of photon energy \( E \). Thus, the minimum exposure time \( \tau_{min} \) and the maximum exposure time \( \tau_{max} \) to be applied to a real X-ray exposure are obtained as

\[
\tau_{min} = \frac{D_{dv}}{\sum_{E} \mu_{PR}(E) P_a(E)e^{-\mu_{PR}(E) t_{PR}}} \quad (17)
\]

\[
\tau_{max} = \frac{D_{dm}}{\sum_{E} \mu_{PR}(E) P_a(E)} \quad (18)
\]

where \( \sum_{E}^{N} \) indicates the sum of values of functions over the entire photon energy range of the synchrotron radiation.

Taking the weighted mean of (16) over the whole power spectrum of the X-rays incident upon an X-ray mask absorber, the necessary thickness of an X-ray mask absorber, \( t_{ABS} \), to be applied to a real X-ray mask becomes

\[
t_{ABS} \approx \frac{\sum_{E} P_a(E) t_{ABS}(E)}{\sum_{E} P_a(E)} \quad (19)
\]

where \( t_{ABS}(E) \) designates (16).