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 re- 
quirement of threshold dose deposition. A power function 
of photon energy, approximating the attenuation length of 
the representative LIGA resist, PMMA, and the mean pho- 
ton 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 in- 
jection molding (Abformung), all of which are primary 
steps of the LIGA process. The X-ray exposure and de- 
velopment 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 fluores- 
cent radiation is also confined laterally to no more than 
1 μm [Feiertag et al. (1997)]. In this work, the X-ray energy 
atenuated at a point within a resist is assumed to be de- 
posited 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

\[
P(t) = P_0 e^{-\mu t} \tag{1}
\]

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 ex- 
posed, according to (1). In Fig. 1, subscripts ABS, BLK, and 
PR designate an X-ray mask absorber, an X-ray mask

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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 $D_{\text{dm}}$.
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 $D_{\text{dv}}$.
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 $D_{\text{th}}$.

These exposure requirements may be expressed as inequalities of

$$q_a < D_{\text{dm}}$$  \hspace{1cm} (2)

$$q_b > D_{\text{dv}}$$  \hspace{1cm} (3)

$$q_c < D_{\text{th}}$$ \hspace{1cm} (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

$$P_c = P_a e^{-\mu_{\text{ABS}} t_{\text{ABS}}}$$ \hspace{1cm} (5)

$$P(t) = P_0 e^{-\mu_{\text{PR}} t}$$ \hspace{1cm} (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 $q_{\Pi}$ on paths I and II can be represented by

$$q_I(t) = \tau \mu_{\text{PR}} P_a e^{-\mu_{\text{PR}} t}$$ \hspace{1cm} (7)

$$q_{\Pi}(t) = \tau \mu_{\text{PR}} P_a e^{-\mu_{\text{ABS}} t_{\text{ABS}}} e^{-\mu_{\text{PR}} t}$$ \hspace{1cm} (8)

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

$$q_a = q_I(0) = \tau \mu_{\text{PR}} P_a$$ \hspace{1cm} (9)

$$q_b = q_I(t_{\text{PR}}) = \tau \mu_{\text{PR}} P_a e^{-\mu_{\text{PR}} t_{\text{PR}}}$$ \hspace{1cm} (10)

$$q_c = q_{\Pi}(0) = \tau \mu_{\text{PR}} P_a e^{-\mu_{\text{ABS}} t_{\text{ABS}}}$$ \hspace{1cm} (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, $t_{\text{ABS}}$, satisfying the exposure requirements:

$$\frac{D_{\text{dv}}}{\mu_{\text{PR}} P_a e^{-\mu_{\text{PR}} t_{\text{PR}}}} < \tau < \frac{D_{\text{dm}}}{\mu_{\text{PR}} P_a}$$ \hspace{1cm} (12)

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

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

$$\tau_{\text{min}} = \frac{D_{\text{dv}}}{\mu_{\text{PR}} P_a e^{-\mu_{\text{PR}} t_{\text{PR}}}}$$ \hspace{1cm} (14)

$$\tau_{\text{max}} = \frac{D_{\text{dm}}}{\mu_{\text{PR}} P_a}$$ \hspace{1cm} (15)

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

$$t_{\text{ABS}} = l_{\text{ABS}} \left[ \frac{\kappa D_{\text{dv}}}{D_{\text{th}}} + \frac{t_{\text{PR}}}{t_{\text{PR}}} \right]$$ \hspace{1cm} (16)

where $l_{\text{ABS}}$ and $l_{\text{PR}}$ 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 $\tau_{\text{min}}$ and the maximum exposure time $\tau_{\text{max}}$ to be applied to a real X-ray exposure are obtained as

$$\tau_{\text{min}} = \frac{D_{\text{dv}}}{\sum_{E} \mu_{\text{PR}}(E) P_a(E) e^{-\mu_{\text{PR}}(E) t_{\text{PR}}}}$$ \hspace{1cm} (17)

$$\tau_{\text{max}} = \frac{D_{\text{dm}}}{\sum_{E} \mu_{\text{PR}}(E) P_a(E)}$$ \hspace{1cm} (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, $t_{\text{ABS}}$, to be applied to a real X-ray mask becomes

$$t_{\text{ABS}} \approx \frac{\sum_{E}^N P_a(E) t_{\text{ABS}}(E)}{\sum_{E}^N P_a(E)}$$ \hspace{1cm} (19)

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