

The Influence of X-Ray Fluorescence on LIGA Sidewall Tolerances

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Secondary radiation is a well-known source of potential dimensional error in the LIGA micro-fabrication process [1-4]. During x-ray exposure of the PMMA resist, some primary photons from the synchrotron source are absorbed in the PMMA substrate. This absorption produces both high-energy electrons and fluorescence x-rays. Photoelectrons are known to affect PMMA adhesion to the substrate, but these are generally absorbed over a very small distance and so do not strongly affect structure accuracy. In contrast, fluorescence photons are absorbed over large distances, several millimeters in some cases. Since fluorescence is emitted isotropically, a portion of this radiation is absorbed in masked regions of the PMMA. During subsequent development, this increased dose may result in substantial dissolution of feature sidewalls, leading to dimensional errors between the patterned mask absorber and the final plastic or electro-formed metal part. Secondary radiation emitted from the mask substrate may similarly contribute to sidewall dissolution and the accompanying degradation of accuracy [4].

Previous computational studies of the LIGA process have addressed in some detail the two-dimensional distribution of the increased dose due to both fluorescence and electrons [2-5]. However, there has been relatively little study of the effects of this distribution on the two-dimensional history of development [5]. Generally, the final sidewall profile has been estimated based on contours of the total dose. This approach provides fair agreement with measured results under somewhat limited conditions, but cannot address the varying times each portion of the sidewall is exposed to the developer. It also does not take into account that the development rate of PMMA varies smoothly with the dose down to 0.2 kJ/cm^3 or less [4].

To help improve the capability for computing LIGA sidewall tolerances, we have developed coupled models addressing both exposure and development. The one-dimensional multi-wavelength model of primary x-ray-transport describes the spectrum of the synchrotron output, x-ray transmission through any beam filters, transmission through the mask, and transmission and absorption in the PMMA resist. This model also describes the two-dimensional emission, transport and absorption of fluorescence x-rays generated within the PMMA substrate. Emission from both the open and masked regions of the substrate are considered. X-ray emission in the substrate is governed by the spectrum and spatial distribution of the absorbed primary radiation and the fluorescence yield of the substrate material. The development model is based on a front tracking algorithm that advances the dissolution front in proportion to the local dissolution rate and normal to the local front geometry. The dissolution rate is computed using the local total dose and developer temperature [6]. These two-dimensional radiation and development models describe either planar (trench and web) or axisymmetric (post and hole) geometries.

Sample calculations of the development history, based on kinetic-limited development rates, are shown in Figures 1 and 2 for silicon and nickel substrates, respectively. In both cases, the source is SSRL ($\lambda_c = 2.66 \text{ \AA}$), the PMMA thickness is 1 μm , the mask consists of a 100 μm silicon substrate with a 15 μm gold absorber, and the development temperature is 25 C. The primary bottom dose in the PMMA is 5 kJ/cm^3 ; the primary dose under the absorber is about 110 J/cm^3 . Light solid curves represent evolution of the development front over 10-minute increments, while the heavier curves are spaced by one hour up to a final time of 5 hours. Additional time beyond full development of the feature may be considered time required to complete the development of other features on the same resist. The dashed curves are computed contours of the fluorescence dose. Only the bottom 100 μm of the resist is shown; the times discussed are measured from first arrival of the dissolution front at the top of this region.

In Figure 1 we see that the dissolution front for PMMA on a silicon substrate initially advances into the exposed region at a fairly constant rate and that the front remains quite flat. Sidewall dissolution during this period before the front first reaches the substrate is less than 1 nm. Over the next four hours, the dissolution front encroaches about 20 nm under the absorber in a small region near the substrate. The height of this region is comparable to the absorption length of PMMA at the k-shell energy for silicon (16 μm at 1.8 keV). Thus fluorescence does not significantly affect sidewall tolerances for the case of a bare silicon substrate.

In Figure 2 we see that sidewall dissolution for exposure on a nickel substrate is very substantial. After the first hour, the maximum sidewall dissolution is about 200 nm. Over the next four hours this increases to just over 2 μm , and the affected height exceeds 100 μm . This is again consistent with the PMMA absorption length at the k-shell energy for nickel (1500 μm at 8.3 keV). Note the initial development rate here is higher than that in Figure 1 and that the front is slightly bowed due to the larger (and nonuniform) fluorescence dose. Also note that the lateral development rate under the absorber is fairly constant over this time and that the sidewall profile does not resemble contours of the dose.

Based on these and similar calculations, we find that the maximum fluorescence dose at the edge of a wide absorber varies from about 4% of the primary dose for an aluminum substrate, to 5% for silicon, up to roughly 20% for titanium, nickel and copper. Further, the fluorescence dose is independent of the substrate thickness when the thickness is large, but is proportional to the thickness when the thickness is small compared to the absorption length in the substrate material at the fluorescence energy. Metallization layers of even a micron or so on an otherwise transparent substrate may thus contribute significantly to the total dose. Finally, we find that the influence of fluorescence radiation on the developed sidewall profile may be very sensitive to the size of positive features when the feature size is small and that the extent of sidewall dissolution increases markedly with increasing development temperature.

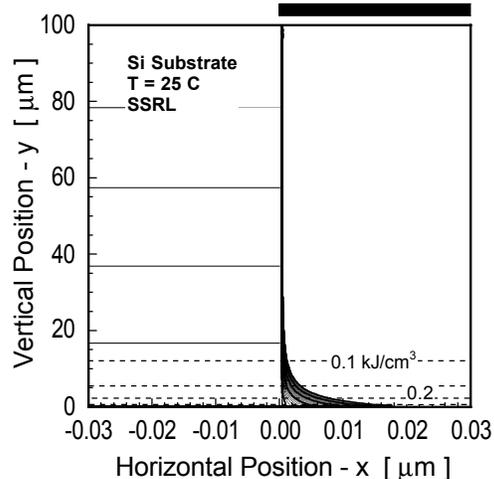


Figure 1. Development history for PMMA on a bare silicon substrate. The sidewall profile encroaches only about 20 nm under the absorber edge following a 5 hour development period.

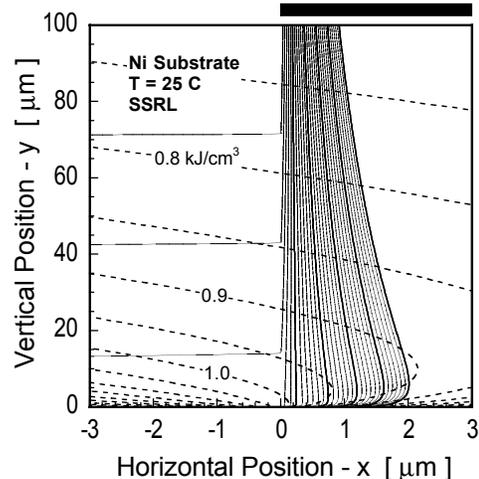


Figure 2. Development history for PMMA on a nickel substrate. The sidewall deviation just exceeds 2 μm after 5 hours; deviation increases to 10 μm for development at 35 C.

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