Fundamental Limitations of LIGA X-Ray Lithography

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Feature tolerances and the minimum feature size producible by LIGA x-ray lithography are limited by many considerations. Most of these, including mask accuracy, beam divergence, fluorescence radiation, thermal deformation and feature loss of adhesion, are practical limitations amenable to improvement through determined process engineering. From a fundamental perspective, tolerances and feature size are limited only by x-ray physics: diffraction, scattering and the ejection of electrons accompanying photon absorption in the PMMA resist. Further, of these three potential limitations that are fundamental, only photoelectrons significantly limit tolerances and minimum feature size for a resist thickness between about 10 μm and 10 mm.

Previous numerical studies employing Monte Carlo methods have addressed in some detail the two-dimensional distribution of the dose near an absorber edge due to electrons [1-3]. However, there has been relatively little study of the effects of this distribution on the two-dimensional history of development [4]. Here we develop an analytical model of this dose distribution based on the Chibani point source [5] and use the computed doses to model the course of development and final sidewall profile. These computational tools are used to examine three aspects of limitations of the LIGA lithographic process: sidewall offset and slope, the minimum producible size of isolated features, and the minimum possible size of fine features on larger structures.

A sample result showing the history of development is presented in Figure 1. Based on parametric studies, we find that sidewall offsets exhibit a minimum for a bottom dose of about 3 kJ/cm^3, a top dose greater than about 9 kJ/cm^3, and a development temperature of about 20 C or less. Using these optimum conditions, we have computed the top-surface sidewall offset and mid-height sidewall slope as a function of resist thickness. Results showing the sidewall offset are shown in Figure 2 for exposures performed at various synchrotrons. We see that sidewall offset grows roughly as the 0.6 power of the resist thickness and is nearly independent of the source spectrum when the optimum conditions are employed. The source is nevertheless extremely important from a practical perspective as it strongly influences the exposure time and required mask absorber thickness.

Similar calculations of the mid-height sidewall slope show that the slope falls roughly with the square-root of resist thickness. It varies from about 1 μm/mm for a 100 μm thickness to about 0.3 μm/mm for a 1 mm thickness. These values are significantly less than the top-surface sidewall offset divided by the resist thickness, indicating that the sidewall profile at the end of development is not linear between the top and bottom of the resist.

These numerical tools are also used to investigate the minimum possible feature size. Small positive features can be produced using an offset mask absorber (wider than the feature size) to account for sidewall offset during development. In this case, the minimum possible size is roughly the product of the mid-height slope and the resist thickness. Such features are the smallest possible positive features at a given resist thickness since they taper to zero width at the top surface.

Small negative features can also be produced with the aid of offset mask absorbers, but in this case the task is complicated by the fact that the open-area dose falls as the absorber aperture becomes small and by the fact that the smallest possible aperture is zero. We find that the smallest possible trench width increases with increasing resist thickness and is roughly three times the sidewall offset given in Figure 2. Further, the width of the developed trench is nearly independent of the aperture width when the aperture is smaller than the sidewall offset. The smallest possible negative feature size is about 0.7 μm for a resist thickness of 100 μm; this increases to about 3 μm for a 1 mm thickness.

Finally, we explore the dimensional accuracy and minimum possible size of fine features patterned on the sidewalls of larger structures. Sample calculations shown in Figure 3 illustrate the dose distribution (looking down) and the lateral history of development for one such pattern. We find that sidewall protrusions having both lateral dimensions less than about five times the sidewall offset cannot be reproduced, while similar structures patterned as indentations retain credible semblance of the mask pattern even when the feature dimensions are comparable to the sidewall offset. We also find that long shallow steps and like structures having small aspect ratios can be produced, subject to the offset of Figure 2, with accuracies not limited by the dose distribution except in the vicinity of abrupt geometric variation such as a step edge.

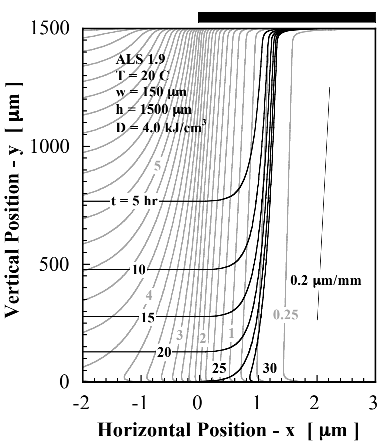

Figure 1. Dose distribution and history of development front. Dose varies rapidly near the absorber edge due to short range of electrons.

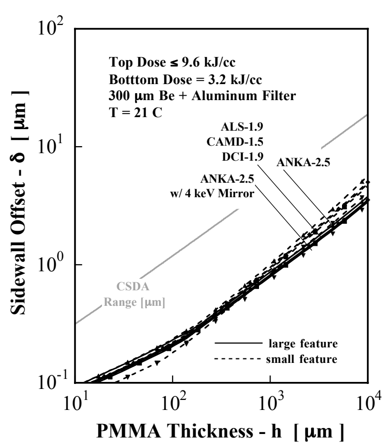

Figure 2. Sidewall offset grows with resist thickness. Small features show greater offset due to long development times.

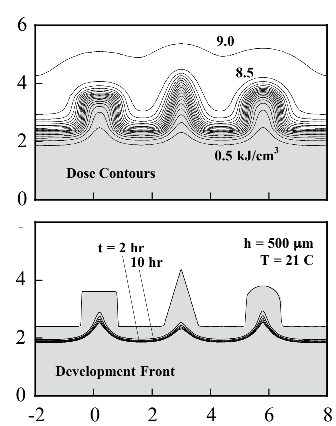

Figure 3. Dose distribution and development front for fine features on larger structure (viewed from top). Dimensions are in microns.

References

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