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Technical Note

Sidewall profiles in thick resist with direct image lithography

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Abstract

Maskless lithography is an increasingly popular method of micro-patterning in research settings. This technical note presents methods for controlling the feature size and sidewall profile of thick-resist features, when exposed using maskless direct imaging systems. Maskless lithographic systems use focussed, uncollimated light, and therefore do not naturally produce the vertical sidewalls that may be required for soft lithography and other secondary processes. We explore exposure dose energy, placement of the focal plane, and the use of multiple focal planes to optimize features in thick (∼800 μm) SU-8 resist. We find that placing the image plane at the mid-height of the resist film produces structures with a good compromise of sidewall angle and feature sharpness. We also find that using multiple exposures at multiple heights can produce sidewall angles that are stable over a range of dose energies.

Keywords: SU-8, exposure, maskless lithography

(Some figures may appear in colour only in the online journal)

1. Introduction

Maskless lithography is an increasingly popular method of micro-patterning in research settings [1, 2]. One particularly convenient implementation of maskless lithography uses a light microscope, laser or LED, and digital light processor (DLP) to form an image of the desired pattern onto the substrate, a method termed direct imaging lithography.

This method is much faster than laser-scanning systems, where a raster scanning method exposes one pixel at a time. For research labs, direct imaging lithography reduces the time from idea to device by eliminating the need for a photomask, without introducing exceedingly long write times for wafer-scale jobs.

Conventional, non-stepped, mask-based photolithography uses collimated light. In SU-8 and other thick resists, the collimated light naturally produces 2.5D structures with vertical sidewalls [3, 4]. The verticality of such structures is largely dependent on the illumination parallelism [5], but also on the transmittance or absorption of the illuminating light by the resist film [6, 7]. These structures have been very useful in a range of micro devices including microfluidics, MEMS, and photonics [8]. SU-8 resists have also been used to produce truly 3D structures using layer by layer multi-exposures, inclined and rotated substrates, grayscale lithography, holographic, and 3D laser lithography [2, 9].

Maskless lithography systems have recently become more common, in some cases replacing mask aligners. However, the capability for maskless systems to create high aspect ratio structures is limited, because the exposing light is not collimated. This is because, the image of the mask pattern is blurred away from the focal plane, manifesting itself as rounded corners. This defocussing also leads to structures, whose size is more closely linked to dose energy than it would be in a conventional system. This characteristic makes it challenging

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to create vertical sidewalls in resist layers whose thickness is comparable to the depth of focus of the imaging system. This characteristic has been called the 'diabolo effect' when seen in high resolution stepped lithography systems, and has been used to create 3D structures, including enclosed channels in positive photoresist [10].

Gosh *et al* have shows high aspect ratio and sub-wavelength features using multiple exposures at different focal planes in SU8 resist using laser direct writing [11, 12]. They introduce the importance of the depth of field and note that time delays between exposures may be significant. Recently Chen *et al* argued that multiple exposures at different heights should be used when the resist thickness is much larger than the depth of focus [13]. They argue that the number of exposure planes needed is determined by the thickness of resist divided by the depth of focus. In this paper, we investigate the effect of the number of focal planes, and characterize the effect of this strategy on the sidewall profile and the feature size. We work with a very thick resist (800 μm) using 385 nm exposure illumination.

2. Methods

2.1. SU-8 processing

Thick resists for MEMS, such as SU-8 and KMPR are negative tone resists that use UV, x-ray, or e-beam energy to release a strong acid. The acid catalyzes a cross-linking reaction that leads to a heat and chemically resistant epoxy [9]. SU-8 processing is comprised of: (a) film creation (typically through spin coating for thin films (<200 μm), or casting for thick films (up to 7 mm in Kim *et al* [6]) (b) Softbake—minutes to hours at 95 °C to drive off a carrier solvent. The amount of solvent remaining has an effect on exposure and development. Not removing the solvent completely can lead to swelling and wrinkling during development. (c) Exposure with patterned light. (d) Post exposure bake (PEB), allowing the photoacid to catalytically crosslink the polymer. (e) Development, where the un-exposed resist is dissolved in PGMEA (Propylene glycol monomethyl ether acetate), typically minutes for thin films and up to an hour for thick films (>0.5 mm). The volume of material retained after development is a function of the exposure dose, the duration of the post-exposure-bake, and the duration of development.

High aspect ratio structures are enabled by highly collimated light and low optical absorption (high transmittance). Vertical sidewalls are not possible using short wavelength UV lithography, because of high absorption, leading to an overexposed upper layer and under-exposed bottom layer. Furthermore, the absorption of SU-8 increases with exposure, leading to negative sidewall angles and in extreme cases, overhanging structures. Some absorption of light by the upper layers is unavoidable, but Jin *et al* showed that absorption increases with soft-bake time from 10 to 40 h [4]. Optimal SB times must balance adequate solvent removal without introducing excessive UV absorption.

The following is our process for 1–2 mm thick SU-8 films on silicon. The substrate is prepared by solvent cleaning and 5 min of 250 W oxygen plasma (March PX-250). SU8-2100 (MicroChemicals) is weighed onto the substrate based on the desired volume and thickness for a given diameter. Resist is spread into a circle that is smaller than the wafer diameter. Using a level hot plate, the wafer is soft-baked at 65 °C for 10 min, then 95 °C for 10 h. While baking, the wafer is placed under a dish with a spout. Prior to exposure, a brief reheat to 95 °C may be needed to remove surface wrinkles. Exposure is described in more detail later. The PEB is one hour at 95 °C using 4 °C min^{-1} temperature ramping. We develop upside-down in PGMEA for 1 h with occasional gentle agitation. The thickness of resist varies by ± 6% over the middle two thirds of the area.

2.2. Exposure system

This work focusses on the use of direct imaging lithography. Conventional masked lithography uses collimated light. We use a MicroWriter ML3 Baby+ from Durham Magneto Optics, fitted with a 385 nm LED light source and a 10 × 0.3 numerical aperature (NA) objective, which focusses patterns generated by a DLP chip onto the substrate. The DLP pixel pitch is 0.49 μm and the power at the focal plan is fixed at 2.1 W cm^{-2}.

Before exposure, the user adjusts the focal plane of the objective to a desired plane. The DLP chip projects a checkerboard pattern of yellow light, which is is reflected by the substrate and, to a lesser extent, the top surface of the resist. When the resist thickness is less than about 10 μm, we are not able to differentiate the two surfaces. This occurs when the depth of focus of the objective is comparable to the separation between the planes. By depth of focus, we mean the axial distance over which an image appears to be consistently in-focus, and hence we estimate our depth of focus to be about 10 μm.

It is worth noting that translations made to the imaging lens (microscope objective) along axial direction is not identical to the resulting translation of the image plane. Instead, moving the objective lens down by a distance d_a causes the image plane in the resist to move down by a larger distance dr The ratio of these distances can be calculated using Snell's law, the NA of the objective, and the index of refraction in the resist (n_r). The NA varies from 0.61 at 530 nm to 0.60 at 385 nm, as the index of refraction of SU-8 resist changes from 1.59 to 1.62.

3. Results and discussion

3.1. Single focal plane position

We observed that changing the image focal plane has a significant effect on feature shape. Figure 1 shows 400 μm-wide rectangles with 400 μm spacing in 800 μm thick SU-8 2100 (MicroChemicals GmbH). Other small features are not quantified here. When the image is placed at the bottom of the resist, sharp corners appear at the bottom, accompanied by rounded

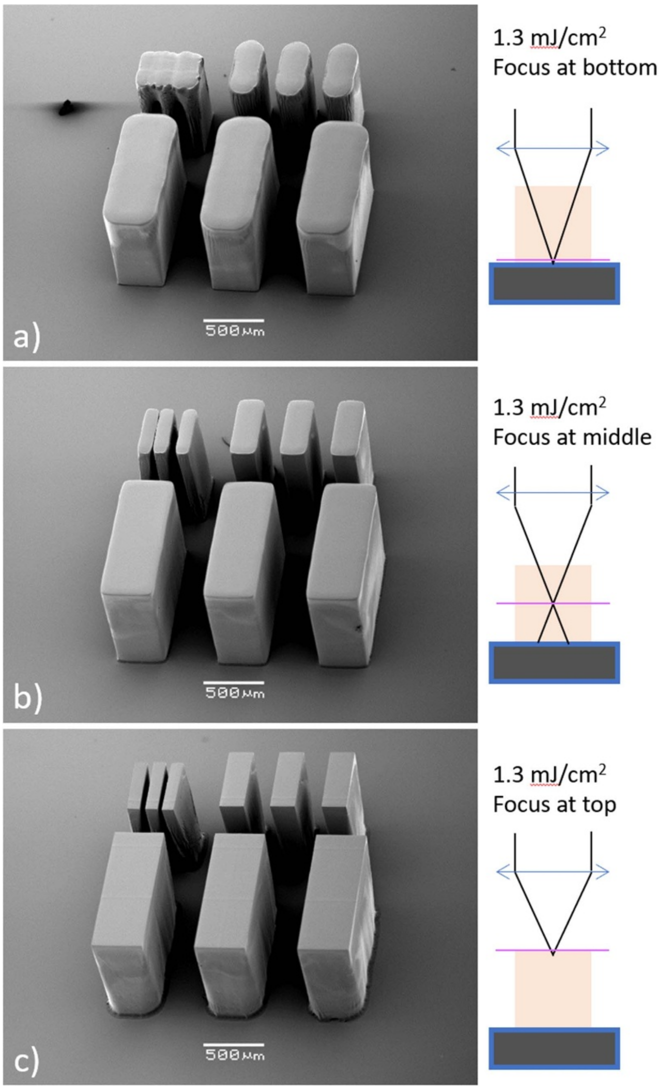

Figure 1. Comparison of structures when focussing the image at different heights within the resist. Focus at the (a) bottom of the resist layer, (b) middle of the resist layer and (c), the top of the resist layer.

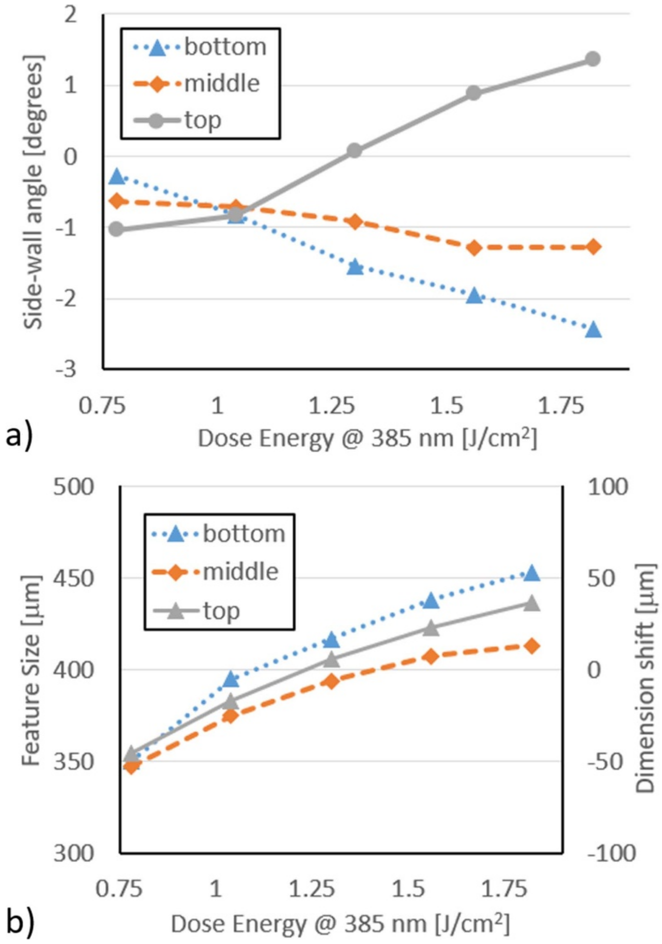

Figure 2. Plots of sidewall angle (a) and feature size (b) versus dose energy at different focal planes. The sidewall angle is affected by the choice of focal plane and dose energy. Focussing in the middle gives nearly vertical sidewalls with less dependence on exposure energy. Absorption in the resist leads to a tendency toward negative sidewall angles. (b) The feature size increases with dose energy.

features near the top. Conversely, when the image is focussed at the top of the resist, we see sharp corners at the top of the resist and rounded features at the bottom. Placing the focal plane at mid-height is a good compromise.

Figure 2 shows how the dose energy affects the sidewall angle and the feature size. Feature size is the average of measurements at the top and bottom of the feature. Sidewall angle is calculated using the difference between the two measurements. In conventional lithography, higher doses lead to slightly larger features and less undercut in negative tone resists. We consider this conventional undercut to be a negative sidewall angle. Pyramid shaped features that are wider at the base than at the top have a positive sidewall angle.

We find that higher doses lead to larger features (figure 2(b)), as in conventional lithography. Unlike conventional lithography however, the sidewall angle depends on the focal position. Vertical sidewalls are possible when focussing the mask image on the top surface, but the image will inevitably be out of focus at the bottom of the resist film.

3.2. *Multiple focal planes*

It is possible to separate the exposure process into multiple images at different heights and different doses. In figure 3 we compare features created using a one, two and three focus positions. The total energy is 1.3 J cm^{-2} in each case with each exposure receiving an equal portion. Figure 4 shows how sidewall angle and feature size changes with dose energy.

There is little difference in the feature shape, corner sharpness, or size using the single, double and triple exposure strategies. This finding clarifies the prediction by Chen *et al* [13] who predicted that the number of planes is given by the thickness divided by the depth of focus. The number of planes needed is almost certainly much fewer than 80, which was calculated as 800 μm/10 um.

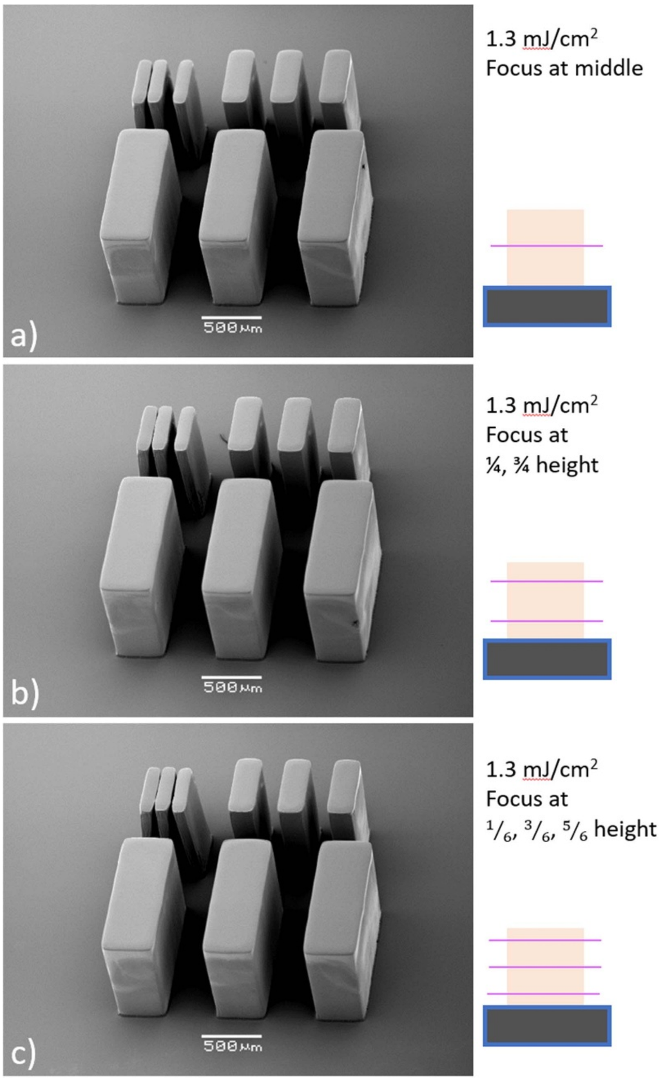

Figure 3. Splitting the exposure into multiple images at different depths with equal energies. (a) shows the same features from figure 2(b). (b) shows the effect of splitting the dose energy into two images at ¼ and ¾ of the resist thickness, and (c) into 3 images at 1/6, 3/6, and 5/6 of the resist depth.

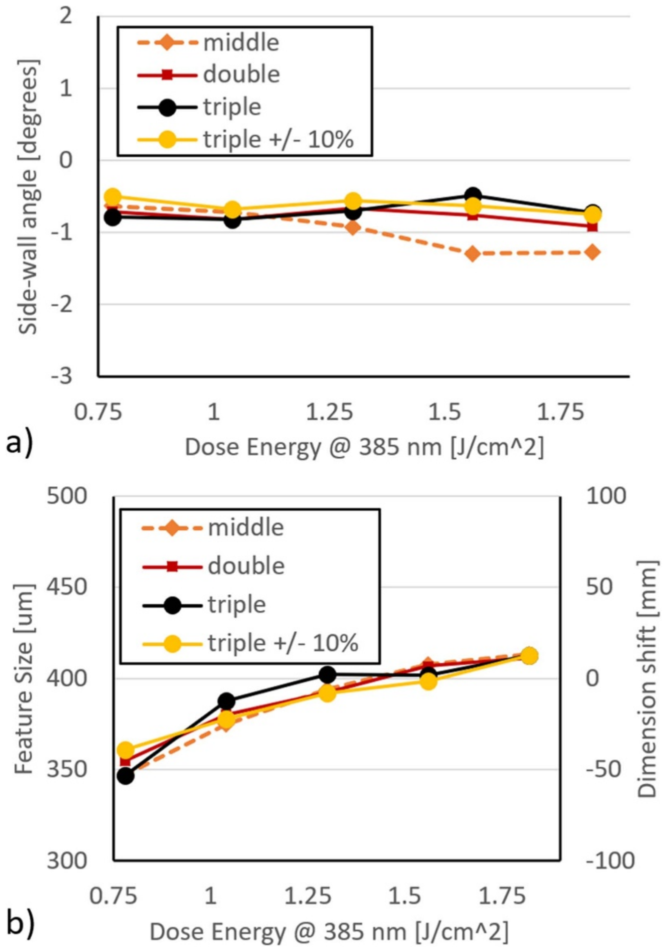

Figure 4. Comparison of sidewall angle and feature size using four exposure strategies. A triple exposure with a 10% increase in energy for the bottom image and a 10% decrease in power for the top image produce a slightly smaller sidewall angle.

All features have slightly negative sidewalls of around −0.8°. The sidewall angle for the double and triple exposure strategies is dose-independent. This is a useful feature for research labs, where protocols are not always optimized and instead rely on overexposure.

The tendency toward negative sidewalls is caused by absorption of UV in the resist. This absorption causes less energy to reach the bottom of the resist than the top. To counteract this, it is possible to slightly increase the dose for the bottom pattern, while decreasing the dose for the top pattern. The loss of 385 nm light through different thickness of SU-8 can be approximated with the help of data from Kim *et al* [6] figure 4(a) shows that by compensating the bottom/top exposures by ±10%, the average sidewall angle was reduced from −0.7 to −0.6 degrees. Further improvements are likely possible, but will depend on the transparency of the resist and hence the softbake time.

3.3. High doses for 3D features

The MicroWriter ML3 is a photolithography system, not a 3D printer. Nevertheless, the possibility of three-dimensional sculpting is appealing. The machine's potential for this is closely related to the NA of the imaging optics. The divergence, or maximum angle of the light rays emanating from the edge of the aperture, of our 10 × 0.3 objective is 17.5° ($\sin^{-1}$NA). In the SU-8 resist, this becomes a slight 10.8° ($\sin^{-}1(\mathrm{NA}/n_r)$). This slight angle is helpful for making vertical sidewalls as the divergence of light energy above and below the focal plane is gradual.

One avenue toward pseudo 3D features is to use different mask patterns at different planes in the resist. We have, for example, imaged a triangle (Δ) at the bottom of the resist, and its flipped version (∇) at the top of the resist layer. We find that there is a very narrow range of exposures where the

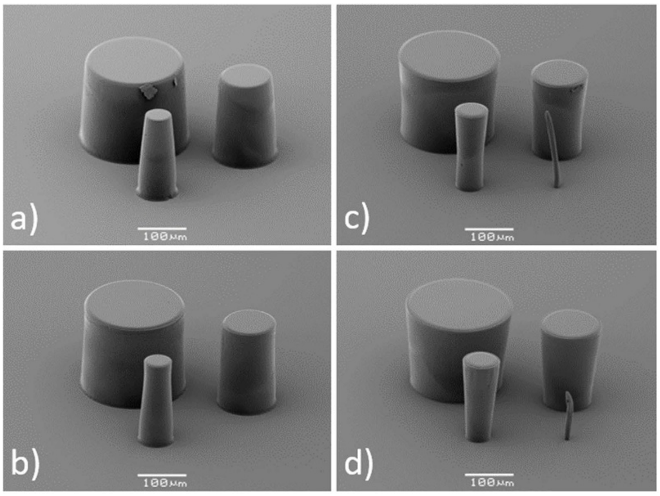

Figure 5. Higher dose energy leads to cross-linking of progressively more xxx??? in the imaging path. Positive and negative sidewall angles of up to maximum divergence in the resist are theoretically possible. At 6.1 J cm^{-2} and focal planes moving from top (a) to bottom (d) produce sidewall angles of $\pm 7°$.

desired shape is produced, but it is in an underexposed condition, where the resist softens during development.

Figure 5(a) shows the possibility of reliably creating 3D features. High exposure doses with the image focus at the top of the resist produce high positive sidewall angles. Conversely, high exposure doses with the image focus at the bottom produce high negative sidewall angles. High doses release photo-acid throughout the entire light cone, massively overexposing the focal spot, but adequatley exposing other regions above or below the focal plane. Figure 5 shows pillars with high positive and high negative sidewalls created with an exposure dose of 6.1 J cm^{-2}. The pillars in figures 5(a) and (d) have sidewall angles of $+7.2°$ and $-7.3°$ respectively.

4. Conclusions

Direct imaging lithography, which uses a digital light projection chip to form an image on or in photoresist, is a very popular method for photolithography in research and development settings. Thick (>200 μm) resists are common in MEMS and microfluidics, where the sidewall profile/angle may be an important characteristic, especially for soft lithography. The combination of thick resists and direct image lithography can present difficulties, because the resist can be much thicker than the depth of focus.

In this work we show that placing the image plane at the mid-height of the resist film produces structures with a reasonable compromise between sidewall angle and simultaneous sharpness at the top and bottom. We show that using multiple exposures at multiple heights for a 10 $\times$ 0.3 objective in 800 um thick films does not significantly improve corner sharpness or sidewall angle. However, multiple exposures at different heights does give rise to sidewall angles that are very stable over a range of dose energies. The technique also has the potential to compensate for losses in the resist and slightly straighten the sidewalls. Very high doses can be used to force sidewall angles that approach the imaging half angle given by $\sin^{-1}(NA/n_r)$, thus creating 3D structures.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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