Studying the impact of depth of focus on 3D profile of negative photoresist material: a simulation approach

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Abstract

For quality patterning of microstructures, it is essential that all process parameters are optimized to ensure well-developed 3D profile of the resist. Advances in direct laser lithography have provided maskless and rapid prototyping methods of manufacturing microstructures. Among all other process parameters, the quality of the patterned structure is critically affected by the depth of focus adjustments of the laser spot. In this study, a simulation approach is adopted and the LAB Module of GenISys lithography simulation software is implemented to determine the optimum depth of focus for negative photoresist material. Modeling and studying straight-line structure at different focusing depths at constant exposure dosages is carried out in this work. At the constant dosage of 45 mJ/cm^2 , the $15 \mu\text{m}$ depth of focus yields the best quality for the 3D resist profile.

Keywords Depth of focus · Direct laser lithography · LAB Module · Photoresist material

Nomenclature

DLL	Direct Laser Lithography
DOF	Depth of Focus
NA	Numerical Aperture
CM	Confocal Microscopy
SEM	Scanning Electron Microscopy
FIB	Focused Ion Beam
AR-N	All resist-Negative
PAC	Photo-Active-Compound Image

1 Introduction

Direct laser lithography (DLL) techniques have enabled rapid prototyping and enhanced manufacturing of 3D structures [1]. The performance of the direct laser lithography system is evaluated mainly based on the system parameters pertaining to the laser-writing tool and the light source [2]. Effective lithography system requires

a precise laser focusing and a complete crosslinking of the photoresist [3]. Precise focusing enhances the performance and the resolution needed for the fabrication [4]. Working at the optimum depth of focus (DOF) is essential to realize better structural qualities [5]. Experimental cases are evaluated from the literature to indicate the impact of depth of focus. Among the early studies exploring the effects of focus experimentally, work of Mack and Kaufman [6] and Mack [7] provided insight of DOF and exposure with line width information using optical lithography. In the experimentation, the resolution of the beam and depth of focus is determined by numerical aperture (NA) used. In addition, experimentally, it is noted that resolution is good when the wavelength is short, and shorter wavelength results in smaller limits of DOF [8]. DOF issues can limit the resist profile for higher aspect ratio during etching. Due to DOF issues, experimentally, thin photoresist layers are used ideally just as in the depth of cutting in micro-cutting [9, 10]. The investigation of

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Jaenen et al. [11] through simulation and experimentation comparison illustrated 5 different cases of focusing depths and generated profile. Figure 1 shows the photoresist cross-sectional view simulated and experimentally viewed using SEM at constant exposure dosage of 1800 mJ/cm^2 and photoresist thickness of $13.2 \mu\text{m}$. It was observed that by moving focusing toward the bottom, the uniformity of the edges was seen with higher area of bonding to bottom wall.

In the experimental approach, the patterned surfaces of microstructures can be investigated using confocal microscopy (CM), scanning electron microscopy (SEM), and focused ion beam (FIB) [12]. Optimizing for better resolutions, based on the experimental approach only, takes more time as it requires more experimental iterations going back and forth with the repeated need to observe the produced structures [13]. Hence, the computational lithography techniques assist with cutting the time and the cost of studying many system parameters. The simulation tools, like LAB Module of GenISys, were claimed to reduce the optimization time of optical parameters compared to that spent using experimental approach [14]. After evaluating the simulation models of Dr. LiTHO and GenISys LAB Module from literature, LAB Module was selected for simulation in this study [15]. When examining the SPR 955-CM photoresist material, the results obtained by the LAB Module simulation were claimed to be in close agreement with the experimental results [16].

2 Direct laser lithography

Laser lithography techniques are utilized for submicron and nanoscale patterning [17]. The selection of a suitable lithography technique is determined based on the processing speed, cost, and the performance scalability [18]. Even though there are many lithography techniques, direct laser lithography (DLL) is becoming popular for manufacturing 3D structures [19]. DLL technique was implemented, as well, for manufacturing nanostructures for Photonics [20]. By removing the need for masks, this technique reduced fabrication efforts [21]. Henceforth, many designs were incorporated with flexibility to produce more complex 3D microstructures [22]. The continuous wave (CW) laser was used to produce 3D microstructures [23]. CW ultraviolet (UV) laser was used with a 405 nm wavelength and 0.85 numerical aperture (NA) for direct lithography [24].

A new negative photoresist material (Allresist GmbH company, AR-N 4400 [CAR 44]) was proved suitable for high aspect ratio applications [25]. This material is selected, here, due to its crosslinking response for wavelength ranging between 250 and 436 nm .

Using the simulation approach, our main objective here is to determine the optimum depth of focus with DLL technique for patterning quality 3D resist profiles (see Fig. 2). The study parameters are set according to the simulation tool requirements.

Fig. 1 Comparison of simulation photoresist profile and experimental SEM [11]

Fig. 2 Negative photoresist curing using direct laser lithography (DLL)

3 Methodology

3.1 Simulation approach

The simulation approach is adopted in order to examine the quality of 3D resist profiles produced using the negative photoresist material, AR-N 4400 (CAR 44). By using GenlSys lithography simulation software, LAB Module is formulated in order to serve as a platform of simulating for the maskless lithography system DLL. The LAB Module comprises all the necessary tools to model and simulate the laser lithography as well as the resist. Its layout option provides initial support for drafting the required shape.

3.2 Modeling

In our simulation, a single layer of rectangular shape, with the dimensions of 10 μm in width and 500 μm in length, is drafted on the layout platform. Figure 3 illustrates the created layer. Here, we focus our study on the simple straight-line structure, which is fundamental to all other shapes.

While creating the layout, it is essential to set the global coordinates and the origin on which the tool is operating. Though we focus our study on a single layer of the negative photoresist AR-N 4400 (CAR 44), the layout platform provides the options to keep one layer on top of the other should there is a need for more than one coating step on the substrate.

3.3 Tool

Laser simulation tool requires defining the region of observation, the stack, the laser tool parameters, and setting up the simulation, analysis, and the labeling. A small region of observation (40 μm by 40 μm) was selected to observe the contour variations more closely. The stack definition included data pertaining to the loading of photoresist properties as well as the selection of the substrate.

The glass substrate was selected, and AR-N 4400 (CAR 44) properties were inserted along with the 35 μm coated layer.

As tool parameters, the machine type as Gauss with 405 nm wavelength and 0.85 NA was set. Based on the material data sheet, the exposure dosage limit at 50 mJ/cm² was selected. Concerning the wafer processing, the beam size FWHM was set as 240 nm.

Simulation setting included mainly the selection of periodicity on the x- and y-axes. According to the selected region of observation, periodicity is set along the length of the drawn line shape.

The analysis output settings included an aerial image, bulk image, and PAC (Photo-Active-Compound Image). These three options were employed to obtain all sets of information. Only the focus exposure matrix was used to analyze the focus setting of the tool for each case of constant exposure dosage. These were adjusted based on the number of cases intended for simulation. Hence,

Fig. 3 Single layer of rectangular shape (simple straight-line structure)

eight cases of focus setting, at different (ten) exposure dosages, were studied. For each case, the focus setting is inspected from the reference top surface of the layer (35 μm) throughout its whole depth ending at the layer-wafer touching point (0 μm) with a 5.0 μm decrement. At the same time, the constant exposure dosage was increased from 5 to 50 mJ/cm^2 for all eight focus setting cases. With that, the results covered 80 different cases, as illustrated in Fig. 4.

There were no labels added, and the tool settings were completed. After the simulation, the results of the focus exposure matrix were obtained all together, and each case was viewed separately. The focus exposure matrix is customized to view cases of interest such that the columns of the matrix represent the exposure dosages and rows present the focus setting cases. The best cases were selected based on the well-developed intensity profile within the resist after being subjected to exposure dosage. The best cases are illustrated in Fig. 4, and 3D resist profile was observed for each case as illustrated in Fig. 5.

4 Results and discussion

According to Horváth et al. [26], shifts in the focus level distorted the microstructure. Focusing on the appropriate depth resolution, the 3D structure is observed that it can be improved with localizing extreme ultraviolet light [27]. Observing the focus setting in an ascending manner from top to bottom provided an inspection view of the different patterns while being prepared [28]. Hence, our simulation results were obtained in an organized manner through FEM observing the sectional view as shown in Fig. 4. Observing the contours and intensity distribution in the resist stack, the best cases were sorted as magnified in Fig. 4. These cases were selected at three constant exposures of 40, 45, and 50 mJ/cm^2 each at 10 μm and 15 μm focus setting cumulating to six cases. The 3D resist profiles are illustrating the quality of produced microstructures. According to Fig. 5, as the intensity is increasing at constant focus setting, there is more shrinkage in the regions away from the focus domain. For the focus setting of 10 μm , the line width is well developed on the top surface of the resist with increasing the exposure dosage. Though the shrinkage at the top surface seemed to aid the uniformity of the 3D profile, the shrinkage at the lower dramatically damaged the uniformity of the line width. Among the 10 μm focus setting cases, higher 3D quality profiles are observed at 40 and 45 mJ/cm^2 .

Even though there is sharp shrinkage region near to substrate at 45 mJ/cm^2 exposure, most of the top region is uniformly patterned. The intensity profiles illustrated in Figs. 6, 7, and 8 provide potential information in arbitrating

Fig. 4 Focus exposure matrix for cases of focus setting and exposures (sectional view of the best cases is illustrated magnified on the right)

Fig. 5 The 3D resist profiles of selected cases from 10 μm and 15 μm focus setting

the quality of the 3D resist profile as well. When compared to the uniformity obtained at the peak intensities of 45 and 50 mJ/cm^2 , the intensity of 40 mJ/cm^2 provided better 3D uniformity, both at the left and right sides.

For the focus setting of 15 μm , the increase in the exposure dosage allowed the photoresist to cure more toward the focus region, that is, to shrink the region away from the focus setting. As it is clearly observed at 40 mJ/cm^2 exposure dose, the crosslinked or cured region of the resist is more in the regions away from the focus plane. In contrast, with an increase of 10 mJ/cm^2 at 50 mJ/cm^2 exposure dose, shrinkage is observed in the top and bottom regions that are away from the focus setting. However, the best-quality 3D resist profile is developed at 45 mJ/cm^2 because the edges are well developed and uniform from top to bottom unit till the substrate. By comparing intensity distribution curves

along positive and negative x-axis closer to the substrate region as illustrated in Figs. 6, 7, and 8, it can be observed that the curve is touching completely with increasing positive and negative limits on the x-axis for exposure dosages from 40 to 50 mJ/cm^2 . The inference of shrinkage affecting the regions away from the focus plane can be recognized.

Comparing both cases of focus setting, increasing exposure dosage is causing the shrinkage in the regions away from the level of focus setting. As the complete depth, which is the coated layer thickness, is 35 μm , the shrinkage of resist, away from the focus setting, is observed equally impacting the top and the bottom sides for 15 μm focus setting case. Henceforth, the shrinkage is observed strongly at the bottom than the top and not of equal impact for the 10 μm focus setting case because, at this setting, the focus level is closer to the substrate.

Fig. 6 Intensity profiles of selected cases from case **a** 15 μm and case **b** 10 μm focus setting for 40 mJ/cm^2

(a)

(b)

In contrast, for the focus setting of 15 μm case, it is closer to the middle. The peak value of intensity distribution is observed higher with the increase of exposure dosage and higher in 15 μm than in the 10 μm focus setting

case. Hence, suitable depth of focus is crucial to producing 3D resist structures as good quality was found at 45 mJ/cm^2 exposure dosage and 15 μm depth of focus. In addition, the impact of exposure dosage is controlled more by

Fig. 7 Intensity profiles of selected cases from **a** 15 μm and **b** 10 μm focus setting for 45 mJ/cm^2

(a)

(b)

the selected level of depth of focus in a direct laser lithography process as every case of the same exposure had a difference in 3D structure only due to change of depth of

focus. Using LAB-GenISys lithography simulation software, a strong optimizing tool is recognized to optimize direct laser lithography system parameters.

Fig. 8 Intensity profiles of selected cases from **a** 15 μm and **b** 10 μm focus setting for 50 mJ/cm^2

(a)

(b)

5 Conclusions

This simulation study signifies the depth of focus parameter for quality maskless lithography. The focus exposure matrix and the intensity profile of each case provided information about the impact of depth of focus. The 3D resist profiles assisted, by direct visualization, and the identification of the scenario leading to the best quality. In particular, the results obtained here showed that the best-quality 3D resist profile is obtained at 45 mJ/cm² exposure dosage and 15 µm depth of focus. The LAB Module of GenlSys lithography simulation proved a powerful tool to characterize the curing material with respect to system parameters. In future experimental work, the negative photoresist, AR-N 4400 (CAR 44), will be used to validate the simulation results. With the main feature to control the depth of focus, the experimental section is expected to also cover the same number of best cases studied using simulation. This will allow for strong crosschecking and endorsement.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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