The Overlapping Effects of Step Exposure by Laser Interferometric Lithography System

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ABSTRACT
In present study, we applied the interferometric lithography with an exposure mathematical model, and set up an experimental system to verify the validity of this model. A simple and convenient interferometric lithography system for patterning large-area with nano-scaled dimensions gratings was built. Due to the position for patterning large-area grating, a two-axis servo-motion system will be added to the original interferometric lithography system. Based on the characters of the interference, we modified an exposure model to predict the exposure condition, and then calculate the step for the next movement. From the simulation results, the best moving distance can be suggested. The different situations at the overlapping region and the interference are also simulated. The gratings at the overlapping region will be shown as three types due to different moving conditions. The experiment results can clearly be illustrated from the simulations. Finally, the results show that our interferometric lithography system and exposure model can be potentially used for fabricating uniform periodic structures.

Keywords: Laser Interferometric Lithography, Overlapping Effects

1. INTRODUCTION
Recently, periodic structures have many potential applications such as x-ray spectroscopy, electro-optics, waveguide and solar applications [1-4]. In the state of the art, lots of techniques are developing for constructing tiny periodic structures. Interferometric lithography has been recognized as an excellent tool for fabricating periodic structures with different dimensions. The capability of this technique can produce the periodic structure in the micro to nano scaled dimensions, and can record the interference patterns in resist material without using a mask.

In the common interferometric lithography system, the split laser beams are conditioned by several optical elements before interfering in resist material. Because the exposure area was limited by the spot size of laser, spherical waves or
beam expand techniques would be used in order to pattern large-area gratings. However, it is difficult to generate uniform structures in resist material with large-area, because of the hyperbolic distortion problem, [5-6]. A scanning beam interference lithography system (SBILS) was purposed by Massachusetts Institute of Technology (MIT). Gratings are fabricated by scanning the substrate on the air bearing stage. At the end of the scan, the stage steps 0.9 times the Gaussian beam 1/e²-radius over by an integer number of grating periods and reverses direction for a new scan. However, the complex SBILS is not only difficult but also expensive to set up [7-11]. In order to get the better periodic structure of large area, all these works were almost experimenting again and again, and then examined these results from the graphs of scanning electron microscope (SEM) or atomic force microscope (AFM) as the foundation of improvement for the next experiment. Finally, one could obtain the best process parameters. Obviously, it took lots of time and wasted many resources to do these series of experiments.

Therefore, how to reduce the dimension of the periodic structure and increase the pattern area by using least experimental times is important. In this paper, we modify an exposure mathematical model to describe the statuses of the photoresist with an according exposure condition and calculated the step distance of next exposure. In order to produce the uniformity gratings, a two-axis servo-motion system will accede to the original IL system to position for patterning large-area, nano-scaled dimensions grating. Finally, we set an experimental equipment to verify the validity of this model.

2. EXPOSURE MODEL FOR INTERFEROMETRIC LITHOGRAPHY

The laser light source was used in present interferometric lithography system with a Gaussian distribution. For a large beam size, we can express the electric field of laser as follows: The laser light source used in present interferometric lithography system has a Gaussian distribution. For a large beam size, we can express the electric field of laser as follows [12].

\[ E(x, y, z) = E_0 \times \exp\left(-\frac{r^2}{w_0^2}\right) \times \exp(-j\vec{k} \cdot \vec{r}) \]  \hspace{1cm} (1)

\[ r = \sqrt{x^2 + y^2} \]  \hspace{1cm} (2)

where \( r_k \) is the propagating distance of the wave, \( E_0 \) is the amplitude at \( r_k = 0 \), \( w_0 \) represents the beam size at \( r_k = 0 \), \( r \) is the position within the beam, and \( \vec{k} \) is the propagation vector of the wave. In interferometric lithography the transverse electric (TE) mode is usually selected. Theoretically, the intensity distribution of the interference can be expressed as

\[ I = \left| \langle \vec{E}_1 + \vec{E}_2 \rangle \right| \]  \hspace{1cm} (3)

Finally, the interference intensity coupled with a Gaussian distribution \( I \) at the exposure surface can be derived as:

\[ I = I_{\text{on}} + I_{\text{off}} \left[ 1 + V \cos \left( \frac{2\pi}{\rho} \right) \right] \exp \left[ -2 \left( \frac{x^2}{w_{\text{eff}}^2} \sec^2 \theta \right) - \left( \frac{y^2}{w_{\text{eff}}^2} \right) \right] \]  \hspace{1cm} (4)
where $w_{0x}, w_{0y}$ represent the beam size along the x and y directions, $I_{01}, I_{02}$ represent the light intensity of the two interference beams at central maximum, $V$ is the visibility of the interference fringe, $\theta_i$ is the interference angle, and $P$ is the interference period given by:

$$P = \frac{\lambda}{2\sin \theta_i}$$  \hspace{1cm} (5)

where $\lambda$ is the wavelength of the light source.

### 3. PERIODIC STRUCTURE FABRICATION

In this study, we use interferometric lithography system to generate one-dimensional gratings on the substrate of 2 inches in diameter. Then, we employ the experimental result to verify the validity of this model. Figure 1 is a simplified schematic of our interferometric lithography system. In order to pattern larger-area gratings, a XY servo-motion system will accede to original interferometric lithography system. The exposure light source that we choose is a He-Cd laser (wavelength = 441.6 nm, maximum output power = 50 mW, coherent length = 10 cm). The structure period $p$ is determined by formula (5). In this system, spatial filters were used to reduce high frequency noise and lenses were used to collimate the beam after the spatial filter and thus eliminate the hyperbolic distortion. After passing through all the components of this system, a power meter was used to measure the intensity of interference beams. The total power of the laser beams on resist is about 1 mW.

![Fig. 1 Schematic of experimental arrangement for interferometric lithography system](image-url)
A 2-inch silicon wafer was spin coated with S1813 positive resist at rotational speed of 5000rpm. Then, the wafer was soft baked at 100°C for 120 seconds. The thickness of the photoresist was about 1.5µm after all these steps. Relying on the above process parameters, we calculate the step distance between exposure areas by exposure mathematical model. For one-dimensional gratings, the two wavefronts were combined on the resist at 30 seconds once. Then, the servo-motion system was position one step. The distance was calculated by our exposure mathematical model. After exposing process, the wafers was developed for 15 seconds in MICROPOSIT MF-321 developer, rinsed with deionized water and hard baked at 130°C for 120 seconds. Finally, we obtain the uniform photoresist periodic structures of gratings on 2-inch silicon wafer.

4. RESULTS AND DISCUSSIONS

For large area exposing with small beam size, multi-exposure by moving the sample or the light source is necessary. In this study, the XY servo-motion system is applied to move the sample. In order to obtain uniform exposure of the whole area, a moving step of the motion stage is needed. Figure 2 shows the simulation results of the summation of the intensity at different moving steps. The intensity variations are about 0.2% to 11% as the moving steps rising from 0.5 to 2.5 mm. The intensity uniformities of the three moving steps of 0.5, 1 and 1.5 mm are better than 0.5%, but for exposure distance of 1.5 cm, it is needed moving about 30, 15 and 10 steps respectively.

Further, we consider the effects of summation of the intensity at different moving steps in X and Y direction (the single exposing time is 30 seconds and expose 6 times along X and Y direction respectively, and develop time is the same as 15 seconds). The sum of its intensity distribution in two directions is shown in Figure 3(a). When the displacement distance is in the range from 0.5 to 1.5 mm, we can obtain a uniform distribution of flat structure. But from the simulation result shown in Figure 3(b), we can find a phenomenon that the displacement distance is over 1.5
mm, the boundary of the adjacent exposing area will present a sine wave distribution. For the sum of intensity around the boundary area (E) is lower than both sides, the structure is not neutralized completely by the developer after developing, and cannot obtain a flat structure with an extensive area of the uniform depth. The structure is shown in Figure 4. It is suggested that one should choose the less exposure steps to reduce the errors from the moving system.

Fig. 3(a)(b) The simulation results of summation of the intensity at different moving steps in XY direction

Fig. 4 The SEM image of the exposure overlapping area E

For fabricating large area gratings, there are usually three kinds of situations that will be observed at the interface of the overlapping area: straight gratings, no gratings and straight gratings with bending at the interface. As the stage moving distance is integral times of the fringe period, the straight gratings will be obtained. Figure 5 shows the SEM image of the exposure overlapping area. To examine the overlapping area, the gratings at the interface are all in a straight line, and depict in figure 6. It could be supposed that the connection of the interference fringes is very well.
Figure 7(a) shows the simulation result of intensity distribution as the fringe move a distance of half period. The part of B is the overlapping area, and it could be observed that the intensity is all the same at this region. It is not hard to conclude that the photoresist under this area will develop away after development. Figure 7(b) shows the SEM image of the exposure overlapping area. Examining the overlapping area (as part B in figure 7(a)), there is nothing that can be observed, but the gratings are constructed outside the overlapping region (as part A in figure 7(a)) and depict in figure 8. It can be deduced that the stage is just moving a distance of times of half period.
Fig. 7(a) The Intensity distribution as the fringe moves a distance of half period; (b) The SEM image of the exposure overlapping area.

Fig. 8. The gratings outside the overlapping region (A)

Figure 9(a) shows the simulation result of intensity distribution as the two fringes partially connected to each other. It can be observed that the overlapping region (region B) is a little bit deviated from the un-overlapping region (region A). It is implied that the gratings at the interface will be bended after development. Figure 9(b) shows the SEM image of the bending grating at the interface of the overlapping region. The period of the grating is about 900 nm. The grating at the overlapping region is deviated about 125 nm from the un-overlapping one. It should be noticed that as the period of the grating decreased, the bending phenomenon would become more apparent.
5. SUMMARY

In present study, we proposed the interferometric lithography with an exposure mathematical model, and set up an experimental system to verify the validity of this model. A simple and convenient interferometric lithography system for patterning large-area, nano-scaled dimensions gratings was set up. Due to position for patterning large-area grating, a two-axis servo-motion system will be added to the original interferometric lithography system. Based on the characters of the interference, we modified an exposure model to predict the exposure condition, and then calculate the distance for the next step. From the simulation result, it is suggested that as the uniformity are good, the larger step should be chosen to reduce the errors from positioning system. The different situations at the overlapping region and the interference are also simulated. The gratings at the overlapping region will appear as three types due to different moving conditions. The straight gratings, no gratings and straight gratings with bending at the interface will be constructed as the positioning system moves a distance of integral, half and partial times of the period of interference fringe. The results can clearly be observed by scanning electron microscope (SEM). Experimental results show our Interferometric lithography system and exposure model can be potentially used for fabricating uniform periodic structures.

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