Digital-division-mask technique by binary coding for microstructure fabrication

NINGNING LUO[a,b,*], YIQING GAO[b], ZHIMIN ZHANG[b], MENGCHAO XIAO[b]
[a] College of Automation Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] Key Laboratory of Nondestructive Test (Chinese Ministry of Education), Nanchang HangKong University, Nanchang 330063, China

We present a new lithography technique, namely digital-division-mask technique by binary coding, which is developed for forming microstructure relief and improving the edge lithography resolution. The microstructure relief is firstly transformed into multiple binary patterns and then they are superposed on a photoresist-coated silicon substrate in sequence. The mechanism for improvement of image edge sharpness by using division method is disclosed, and the division principle is described. As a result of the digital-division-mask lithography, positive photoresist patterns of zigzag gratings with a period of 16μm and 64μm are fabricated.

1. Introduction

Microstructures have wide applications in many areas such as integrated optics, optical sensors and optical interconnects as well as optical communications. Consequently, microstructure fabrication technique is attracting more interest. At present the typical techniques for microstructure fabrication include direct writing [1] and graytone mask lithography. However, they are encountering problems of either high cost equipment and low speed or high cost mask. In recent years, many papers reported the application of Texas Instruments' DMD for digital lithography because of its inherent advantages such as high brightness, high resolution and control flexibility, etc., [2-7].

According to reference [4,8], DMD-based digital lithography system usually includes light source, collimation lens, integrator lens, DMD chip, reduction lens, wafer stage and computer. For the reduction lens, it can be regarded as a low-pass filter because of its finite transmission aperture. As is known, the loss of high-order diffraction representing the image edge information will lead to the edge blur of exposure pattern. The loss of high-frequency energy can be greatly reduced by decreasing the distance between DMD and reduction lens. However, DMD is a reflective spatial light modulator. When DMD operates, the angle between incident light and reflective light is 24°, which restricts the decrease in distance between DMD and reduction lens. The working characteristics of DMD and reduction lens determine the decline in transverse resolution of DMD-based digital lithography system. Consequently, we have reported the digital-division-mask technique to

solve the problem of losing high-order diffraction caused by the finite transmission aperture of reduction lens. In reference [9,10], a group of low-frequency patterns are displayed on DMD one by one and exposed for the same exposure time. However, the mask-division method was not detailedly demonstrated. In this paper, we present a new division method, which is based on the principle of DMD work. And these division masks have different exposure time. Experiments confirm that the digital-division-mask technique is effective for the improvement of edge lithography resolution.

2. Design of digital-division mask by binary coding

2.1. Diffractive limitation

According to the diffraction grating theory, when the parallel beam is normally incident on the grating plane, the diffraction phenomenon will follow the grating equation

$$\sin\theta = k\lambda f_d, \qquad k = 0,\pm1,\pm2,\cdots\cdots \qquad (1)$$

Where f_d is the grating frequecny, θ is the diffraction angle and λ is the incident wavelength. k represents the diffraction order number. Taking any fixed values for k and λ, we conclude that the diffraction angle θ increases with the increase of grating frequency f_d. Due to the finite transmission aperture of reduction lens, reflected light with large diffraction angle can't be received by it. As is known, light with big diffraction angle usually corresponds to high-order diffraction, which represents

the edge information of mask. Accordingly, the edge lithography quality obviously declines due to the loss of high-order diffraction. The loss of large-diffraction-angle light increases with the decrease in critical dimension of mask, as shown in Fig. 1.
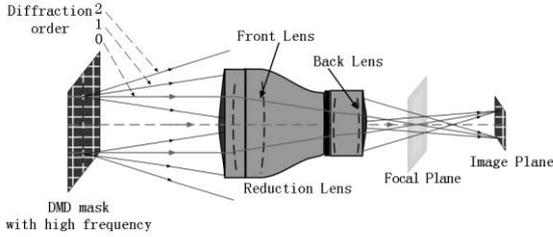
(a) high-frequency mask imaging by reduction lens
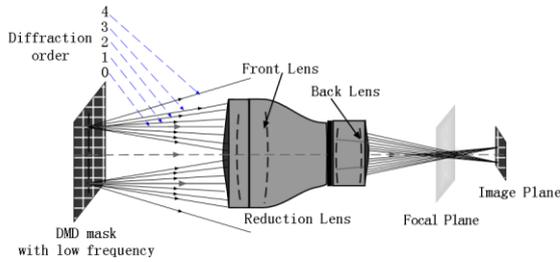
(b) low-frequency mask imaging by reduction lens

Fig. 1. DMD mask imaging by reduction lens.

2.2. Principle of digital-division mask by binary coding

To achieve better lithography quality, we proposed a digital-division mask technique by binary coding. With this technique, the microstructure relief can be divided into a group of binary patterns. These binary patterns are exposed in sequence on the same position. The superimposed exposure of multiple binary patterns takes the place of single exposure of original graytone mask.

According to the demand for relief profile, we can obtain the desired exposure dose function $E(x,y)$. Then $E(x,y)$ is quantified into the distribution of gray pattern $e(x,y)$. The exposure dose function toward the photoresist can be expressed as

$$E(x, y) = e(x, y) \cdot t(x, y) \qquad (2)$$

where $t(x,y)$ is the exposure time. Then the distribution of gray pattern $e(x,y)$ is divided into N pieces of binary patterns $e_i(x,y)$ by binary coding, so Eq.(2) can be written

$$E(x, y) = \sum_{i=1}^{N} e_i(x, y) \cdot t_i(x, y) \qquad (3)$$

where $t_i(x,y)$ is the exposure time corresponding to the binary pattern $e_i(x,y)$. Three problems exist in Eq.(3). The first is the appropriate value of N. The second is the dividing method of graytone mask. The last is how to determine the exposure time of each binary pattern.

2.2.1. Determination of N

Two aspects should be considered when choosing N. One is the edge quality and the other is the fabrication efficiency. For large values of N, the increase of exposure frequency leads to the low fabrication efficiency. For small values of N, the edge quality can't be effectively improved. The appropriate value of N can be determined by A, which represents the number of quantified gray levels.

$$N = ceil\left(\log_2 A\right) \qquad (4)$$

2.2.2. Method of binary coding

DMD commonly uses 8-bit words, representing 2^8 or 256 possible gray levels. When DMD operates, the graytone pattern is transformed into 8-bit electrical words. Then it's input into the memory element of each micromirror, beginning with the most significant bit (MSB). Based on the principle of DMD, we propose a method of binary coding to divide the gray pattern into binary patterns. Four DMD pixels have been chosen to illustrate the binary coding method, as shown in Fig. 2 and Fig. 3. In Fig. 2, the quantified level 255 is supposed. N is equal to 8, which can be calculated by Eq.(4). Eight pieces of binary patterns can be obtained according to the binary coding method. They are given in Fig.3.
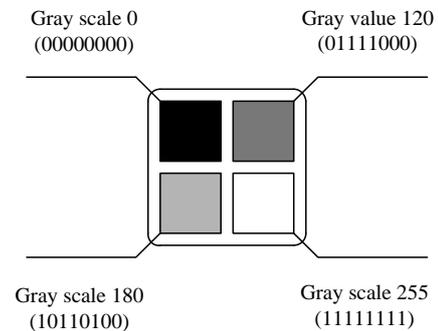
Fig. 2. Gray pattern including four pixels.

(a) pattern from the first bit (LSB)

(b) pattern from the second bit

(c) pattern from the third bit

(d) pattern from the fourth bit

(e) pattern from the fifth bit

(f) pattern from the sixth bit

(g) pattern from the seventh bit

(h) pattern from the eighth
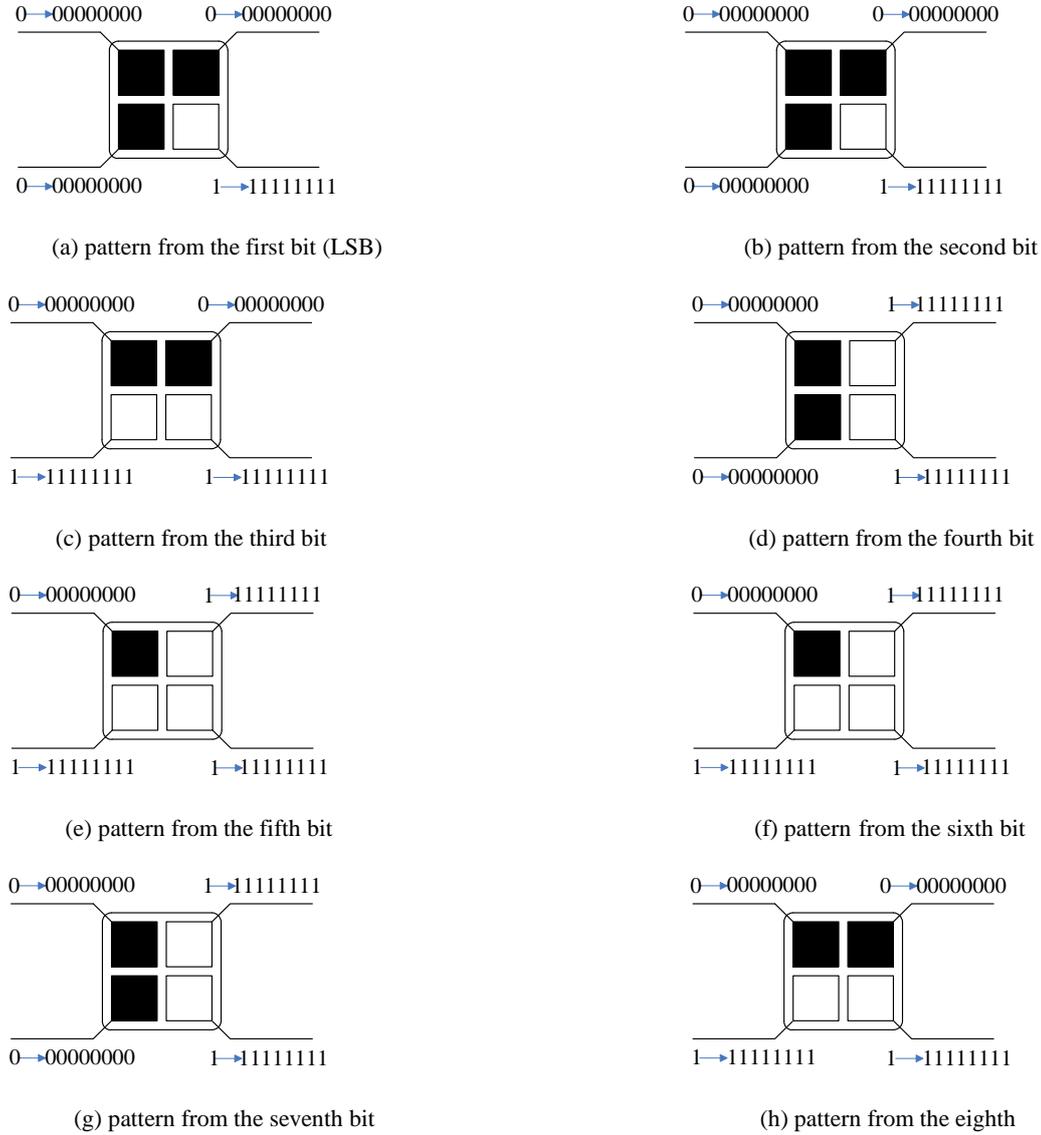
Fig. 3. Binary patterns including four pixels.

In Fig. 2, gray values of 0, 120, 180 and 255 are firstly transformed into 00000000, 01111000, 10110100 and 11111111 respectively. Then we successively take a corresponding bit of each pixel, beginning with the least significant bit (LSB). If 0 is taken, the pixel is filled with black. If 1 is taken, the pixel is filled with white. For instance, the LSB of 01111000 is 0 and the upper right pixel is filled with black and the new coding is 00000000, as shown in Fig. 3(a).

2.2.3. Determination of exposure time

According to the above analysis of the binary coding method, the division method is based on the value of each bit input into DMD. When DMD operates, binary pulse width modulation (BPWM) is adopted, namely, each bit in DMD word represents a different time

duration. From LSB to MSB, each bit consumes half the next bit time. Hence, the exposure time is determined by the bit order of forming the binary pattern. If the exposure time consumed by the pattern from the first bit is assumed to be t, the exposure time of each division pattern can be described as follows

$$t_i = 2^{i-1} \cdot t \qquad t = 1,2,3,\ldots\ldots \quad (5)$$

3. Simulation

Based on above division-mask technique by binary coding, the division patterns of zigzag grating have been obtained. To confirm the division-mask technique by binary coding, we simulate the overall exposure dose by overlapping the exposure dose from all the division patterns. The exposure time of each division pattern is

calculated by Eq.(5). During simulation, the linear photosensitization of photoresist is supposed. For division mask, calculation of the total superimposed exposure includes several steps: firstly calculating the intensity distribution of each division mask after being imaged on photoresist, then calculating exposure distribution of each division mask, finally summing the exposure of all division masks. When choosing the intensity distribution model in the image plane, the type of light source in lithography system should be considered. The mercury lamp, which has poor coherent, is usually adopted as light source in UV lithography system. When the light propagates to the mask plane, it becomes partially coherent light according to the Van Cittert-Zernike theorem. Hence, the theory of partially coherent imaging is chosen for simulation. Fig.4 is the simulation result of the superposition exposure dose. Simulation results indicate that the superimposed exposure of division masks can reconstructure the original relief.

Distribution for zigzag grating
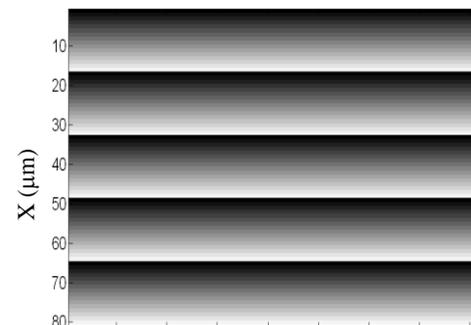
Fig. 5. Graytone mask of zigzag grating

Each period of traditional graytone mask in Fig. 5 includes 16 different gray values to modulate the exposure dose. Each step width is merely a DMD pixel. The adjacent narrow steps with different gray values have formed a high-frequency grating, which is the reason for adopting digital-division-mask technique. In order to theoretically prove the superiority of division mask, we calculate the receiving diffraction orders and the sum of diffraction energy for the graytone mask and the division patterns respectively, as shown in Table 1.

Fig. 4. Calculated exposure dose.

Table 1. Receiving diffraction orders and the diffraction energy.

mask	graytone mask	Division mask			
		pattern from the first bit	pattern from the second bit	pattern from the third bit	pattern from the fourth bit
receiving diffraction orders	0	0	0,±1	0,±1, ±3	0,±1, ±3, ±5
Sum of diffraction energy	50%	50%	81.83%	92.43%	98.8%
Sum of diffraction energy considering the exposure time	50%	3.33%	10.91%	24.65%	52.69%

The parameters used in calculation are as follows: the wavelength λ is 365 nm and the numerical aperture of reduction lens is 0.3. When the graytone mask is exposed, the reduction lens can merely receive zero-order diffraction and the sum of diffraction energy is 50%.

However, the receiving diffraction orders are up to 5 with division masks and the energy sum of all the receiving diffraction orders is equal to 91.58%, which is much higher than 50%. Above calculation results indicate that the mask-division technique can greatly increase the

number of diffraction orders received by reduction lens and effectively decrease the loss of middle and high frequency energy with edge information.

4. Experiment and results

To verify the technique described above, the zigzag gratings have been fabricated in our laboratory. Two zigzag gratings with different dimensions are designed. The tooth width of small zigzag grating is 16 μm and the big is 64 μm. The tooth height are both 5 μm.
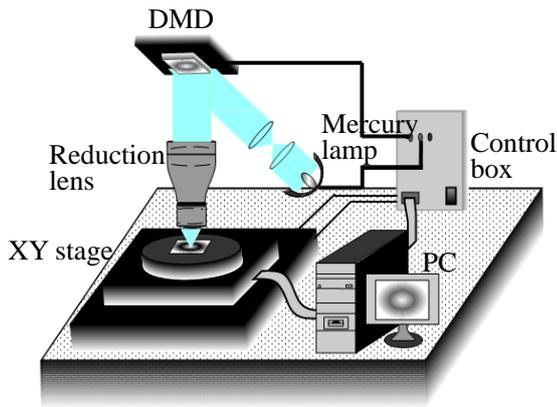
Fig. 6. Scheme of DMD-based digital lithography system.

The experimental system for DMD-based digital lithography is shown in Fig. 6. The 200W mercury lamp is used as the light source (λ=365nm). The 0.7 XGA DMD in our experimental system consists of 1024×768 square micromirrors on a pixel pitch of 13.68 μm × 13.68 μm. The image displayed by DMD takes the place of the traditional hard mask. The light reflected off the micromirrors is projected onto the photoresist coated silicon substrate with a 14× reduction lens, whose numerical aperture is 0.3. Thus, the exposed area on the photoresist of each mirror is approximately 0.977μm×0.977μm. The positive photoresist of GP28-100 was used as the photosensitive layer. The silicon substrates were spun at 2000 rpm for 30s to achieve a photoresist thickness of 5.5 μm and baked for 20 min at 90°C. Four pieces of binary gratings with different periods was then exposed on the resist-coated silicon substrate. The total exposure time of four patterns was about 150s, 80s, 40s, 20s and 10s respectively. After development in the developer of NAOH for about 70s, the photoresist profile of the zigzag grating appeared. Fig. 7 and Fig. 8 show optical microscopy and scanning electron microscopy (SEM) images of zigzag gratings with 64 μm and 16μm periods. Compared with the experimental results (in Fig. 9) by the graytone mask method, the edges of all the experimental images by the division method are more distinct, which is caused by the enhancement of high-frequency energy representing the

edge information. The experimental results reveal that the edge sharpness of photolithography pattern can be effectively improved by digital-division-mask technique and approximately continuous profile can be obtained by superposition of multiple exposure dose.

(a) Optical microscopy image (×400)
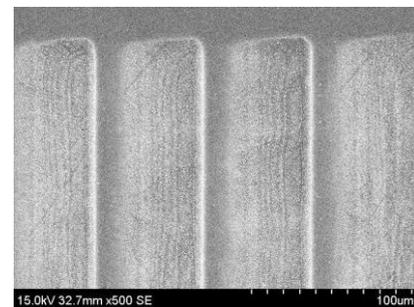
(b) SEM image

Fig. 7. Experimental result of a 64μm zigzag grating on the photoresist.

(a)Optical microscopy image (×400)
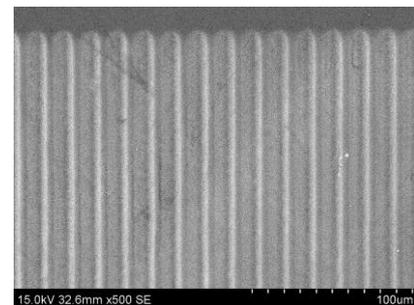
(b) SEM image

Fig. 8. Experimental result of a 16μm zigzag grating on the photoresist.

(a) Optical microscopy image (×400) of 64μm period
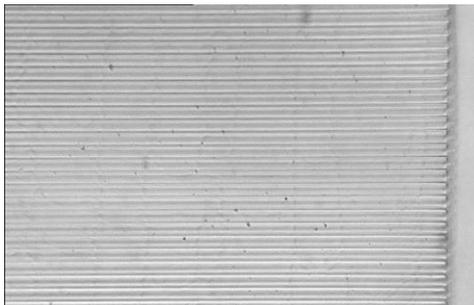
(b) Optical microscopy image (×400) of 16μm period

Fig. 9. Experimental results by the graytone mask method.

5. Conclusions

For the SLM-based digital lithography, digital-division-mask technique by binary coding is a new technique that can improve the edge lithography resolution. With the technique, the original relief can be divided into a group of patterns by using binary coding. The superimposed exposure quality of these binary patterns is superior to that of the original graytone mask. We have demonstrated the fabrication of continuous relief structures by the new technique. All the experimental results have tended to validate the method. And based on the theory of this technique, we conclude that the lower the spatial frequency of division mask is,

the better the superimposed exposure results are. Although in this paper, we use the regular binary division patterns. For achieving the lower-frequency division masks, we can divide the continuous relief structure into regular or even irregular binary patterns. Our future work will center on the fabrication of complex relief structures by using the irregular division patterns.

References

[1] M. Vlcek, H. Jain, J. Optoelectron. Adv. Mater. **8**, 2108 (2006).
[2] L. J. Hornbeck, Technical Digest of the IEEJ 14th Sensor Symposium 297 (1996).
[3] Kohrou Takahashi, Junichi Setoyama, Electr. Commun. Jpn. Part **283**, 56 (2000).
[4] Manseung Seo, Haeryung Kim, Comput. Aided Design **39**, 202 (2007).
[5] D. Brett Beasley, Matt Bender, Jay Crosky, Tim Messer, Daniel A.Saylor, Proc. SPIE **5092**, 71 (2003).
[6] Kin Foong Chan, Zhiqiang Feng, Ren Yang, Wenhui Mei, Proc. SPIE **4985**, 37 (2003).
[7] Lars Erdmann, Arnaud Deparnay, Falk Wirth, Robert Brunner, Proc. SPIE **5347**, 79 (2004).
[8] M. V. Kessels, C. Nassour, P. Grosso, K. Heggarty, Opt. Commun. **283**, 3089 (2010).
[9] Yiqing Gao, Ningning Luo, Tingzheng Chen, Min Chen, J. Mod. Optic. **56**, 453(2009).
[10] Ningning Luo, Yiqing Gao, Min Chen, Lixia Yu, Qing Ye, Optica Applicata **XL**, 239 (2010).

[*]Corresponding author. ningningluo2002@126.com