Built-in Lens Mask Technology for Generating Three Dimensional Image based on Computational Lithography

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A novel technology to create 3D shape image with single exposure to single mask will be presented. The mask is a general mask available for the conventional lithography, but its pattern layout is calculated based on the theory of the built-in lens mask (BILM) technology and totally different from the target object shape. The technology creates the same image as a projection exposure lithography creates just by exposing the mask, because a function performed by lens and mask is embedded into the mask pattern. We will also introduce a concept of the virtual exposure system by which 3D image can be easily designed. BILM covers functions performed by the virtual exposure system, too. We will demonstrate that BILM can create a clear 3D image using examples applying it to i-line proximity exposure through the optical lithography simulation.

Keywords: Optical lithography, 3D image, Aerial image, Built-in lens mask

1. Introduction
Optical lithography is one of the most important technology for mass production of micro-devices. Projection optical lithography used in semiconductor devices allows us to fabricate nanometer scale pattern of thin film layer with high accuracy and high productivity [1]. Representative technologies having been contributed to the improvement of the patterning ability of the projection lithograph are phase shifting mask and computational lithography in addition to the reduction of the wave length. Most efforts in those technologies have been made for fabricating 2D patterns on flat plain. However, a demand for 3D patterning has been getting stronger in fabrication of recent MEMS like microfluidic devices [2].

It is difficult to make 3D pattern with high productivity using the current optical lithography. There have been some trials like patterning with gray tone mask or multiple exposure to object on tilted stage, but available pattern shapes are very limited. We have to use focused beam method for patterning of general shapes. However, the method is undesirable for low cost mass production, because it takes too long time due to scanning the whole 3D shape by small point.

We have been proposed built-in lens mask (BILM) technology where functions equivalent with projection exposure system with lens and mask are provided just by exposure to mask [3-5]. The mask pattern of BILM is calculated from the model of the projection exposure system based on optical lithography theory [6]. Here, we don’t have to use actual exposure system for the definition of the model. We can design the exposure system going beyond the restriction of the actual exposure system. The above design allows us to create 3D aerial image by single exposure to BILM. In this paper, we will provide the method to calculate BILM to create 3D aerial image. We will demonstrate 3D aerial image creation through the simulation applying BILM to proximity exposure.

2. Theory of built-in lens mask (BILM)

2.1. Basic concept of BILM
First, we will explain a concept of built-in lens
mask technology. Figure 1 schematically shows the comparison between projection exposure and built-in lens mask. Intensity of the aerial image generated on the image plain of the projection system by coherent exposure is calculated from Eq. 1.

\[
\begin{align*}
I_0(x,y) &= |E(x,y)|^2 \\
E(x,y) &= \int [a(x - p, y - q) \cdot P_{NA}(p,q) \cdot \exp(-2\pi i(x \cdot p + y \cdot q))dpdq] \\
a(\xi,\psi) &= \int A(X,Y) \cdot \exp(2\pi i(\xi \cdot X + \psi \cdot Y)dXdY)
\end{align*}
\tag{1}
\]

Here, \(A(x,y)\) is mask function and \(a(\xi,\psi)\) is Fourier transform of it. \(P(p,q)\) is a pupil function of the lens. \(NA\) is numerical aperture of the lens and defines the integration range of the calculation of \(E(x,y)\). Here, we ignore coefficient for the normalization of the aerial image. Since the above equations express the aerial image on the focal point of the projection exposure system, the dependence on the vertical direction of the image plain isn’t included in it. Thus, \(E(x,y)\) is propagation wave at the focal point. \(I_0(x,y)\) is the intensity of the propagation wave at the focal point. Propagation wave at the distance of \(Z\) from the focal point is expressed by Eq. 2.

\[
E_Z(x,y) = \int [a(x - p, y - q) \cdot P_{NA}(p,q) \cdot \exp(-2\pi i(x \cdot p + y \cdot q)) \cdot \exp(-\frac{2\pi iZ}{\lambda \sqrt{1 - (p^2 + q^2)}})]dpdq
\tag{2}
\]

Here, we consider the mask \(B_Z(X,Y)\) whose transmittance distribution \(b_z(X,Y)\) and phase distribution \(\theta_z(X,Y)\) are defined by Eq. 3.

\[
\begin{align*}
B_Z(X,Y) &= b_z(X,Y)e^{2\pi i\theta_z(x,y)} \\
b_z(X,Y) &= \text{Re}\{E_Z(X,Y)\} \\
b_z(X,Y) &= \text{Im}\{E_Z(X,Y)\}
\end{align*}
\tag{3}
\]

We can see that the intensity of the aerial image exactly same with the Eq. 1 is generated at the distance of \(Z\) from the mask by coherent exposure to the mask \(B_Z\) as shown in Fig. 1. The mask defined by Eq. 3 is built-in lens mask (BILM). BILM provides the same aerial image as a projection exposure system without using a lens. We have demonstrated the above theory by the

Fig. 1. Relationship between the projection exposure system and built-in lens mask (BILM).
experiments using proximity exposure in the previous work.

In other word, function of the projection exposure system with lens and mask is embedded into the mask pattern. The mask pattern is calculated based on the model of the designed projection exposure system, as shown in Eqs. 2 and 3. The designed projection exposure system should be mathematical formation of Eq. 2, but we are able to remove some physical limitations in actual projection exposure system to design it. This is a key advantage of BILM. That advantage allows us to create 3D aerial image by single exposure to 2D mask.

2.2. 3D aerial image creation

Here, we introduce an idea for creating 3D aerial image by BILM. First, we defined the function \( f_i(x,y,z) \) shown in Eq. 4.

\[
f_i(x,y,z) = \int a_i(x-p,y-q) \cdot P_{NA}(p,q) \cdot \exp(-2\pi i (x \cdot p + y \cdot q)) \cdot \exp\left(\frac{2\pi i (z-Z_i)}{\lambda \sqrt{1-(p^2+q^2)}}\right) dp dq
\]

\[
a_i(\xi,\eta) = \int A_i(X_i,Y_i) \cdot \exp(2\pi i (\xi \cdot X_i + \eta \cdot Y_i)) dX_i dY_i
\]

(4)

The function \( f_i \) corresponds to the projection exposure system consisting of a mask \( A_i(X_i,Y_i) \) and a lens \( P_{NA} \) with the focal point of \( Z_i \). If we make a mask \( B_i(x,y) \) defined by the Eq. 5 and expose it, the intensity of the aerial image generated at the distance of \( z \) from the mask is expressed by Eq. 6.

\[
B_i(x,y) = f_i(x,y,z = 0)
\]

(5)

\[
I_0(x,y,z) = \left| f_i(x,y,z) \right|^2
\]

(6)

We can create a target shape in the direction of \( x \) or \( y \) by making a mask pattern \( A_i(X_i,Y_i) \) almost same with the target shape. However, there isn’t a freedom to control the target shape in \( z \) direction, because the focal point of \( Z_i \) is constant parameter in the actual projection exposure system.

Next, we consider a function \( F \) defined by a linear combination of \( f_i(x,y,z) \), as shown in Eq. 7.

\[
F(x,y,z) = \sum_i \alpha_i \cdot f_i(x,y,z)
\]

(7)

Even in this case, if we make the mask \( B(x,y) \) defined by the Eq. 8 and expose it, the intensity of the aerial image generated at the distance of \( z \) from the mask is expressed by Eq. 9.

\[
B(x,y) = F(x,y,z = 0)
\]

(8)

\[
I_0(x,y,z) = \left| F(x,y,z) \right|^2
\]

(9)

There is a number of combination of mask \( A_i(X_i,Y_i) \) and focal point \( Z_i \) in the Eq. 9. Control ability of the shape of the aerial image in \( z \) direction at each \( (x,y) \) position is provided by merging various combinations of mask \( A_i(X_i,Y_i) \) and focal point \( Z_i \). Here, we call each function \( f_i(x,y,z) \) by Eq. 4 as elementary exposure system, because it corresponds to the actual projection exposure system. We call the function \( F(x,y,z) \) defined by Eq. 7 as virtual exposure system, because it is impossible to merge multiple exposure systems in actual world. Once we successfully design the virtual exposure system which creates target 3D image, the image is exactly reproduced by single exposure to BILM defined by Eq. 8. The BILM can covers such virtual exposure system which goes beyond the physical limitations of actual exposure system.

2.3. Example of 3D image creation by virtual exposure system

Here, we will explain how to make 3D image by virtual exposure system in a simple example. Figure 2 shows the relationship between the virtual exposure system of the BILM and elementary exposure systems constituting it. Here, virtual exposure system consists of two elemental exposure system. One is a exposure system \( f_i \) with mask \( A_1 \) and focal point \( Z_1 \), the other is \( f_2 \) with mask \( A_2 \) and focal point \( Z_2 \). Virtual exposure system \( F \) is defined by \( F = f_1 + f_2 \). The aerial image created by the virtual exposure system \( F \) is \( \left| F \right|^2 = \left| f_1 + f_2 \right|^2 \). The aerial image of \( \left| f_1 + f_2 \right|^2 \) is different from the aerial image of \( \left| f_1 \right|^2 + \left| f_2 \right|^2 \) created by multiple exposure of elemental exposure systems. Some shapes cannot be created by \( \left| f_1 + f_2 \right|^2 \) due to interference between \( f_1 \) and \( f_2 \). However, if images \( I_1 \) and \( I_2 \) are very close to each other, an finer aerial image can be created by \( \left| f_1 + f_2 \right|^2 \) than \( \left| f_1 \right|^2 + \left| f_2 \right|^2 \). It goes well in many cases to define virtual exposure system by elemental exposure systems corresponding to each part of target.
We will show the intensity of aerial image created by the virtual exposure system designed by the above concept in Fig. 3. Here we consider the line pattern L on x axis defined between L_A and L_B. We assume to use i-line (wavelength = 365 nm) for exposure light. We divide the line L into small segment L_i whose length is smaller than the exposure wave length. We make a mask pattern A_i corresponding to each segment. We define focal position Z_i to each segment. Here, the focal position of the elementary exposure system to the segment at L_A is 0μm, and the focal position to segment at L_B is -15μm. The focal position to each segment L_i changes linearly from 0μm to -15μm depending on its position. Then, we define each elementary exposure system with each mask pattern A_i and the focal position Z_i. The intensity of aerial image calculated from Eq. 9 is shown by the contour graph in the figure. From the figure, we can see that the virtual exposure system provides a clear 3D image whose shape in the z direction is well controlled.

There is the depth of the focus (DOF) as another parameter to define the shape of aerial image in z direction in addition to focal position. DOF is determined by numerical aperture (NA) of the lens and wave length λ, as shown in Eq. 10.

\[
DOF \propto \frac{\lambda}{NA^2}
\]  

(10)

For example, we can create an image with wide DOF and an image with narrow DOF at the same time by virtual exposure system, as shown in Fig. 4. The intensity of aerial image created by the virtual exposure system designed by the above concept is shown in Fig. 5. Each elementary exposure system is defined in the same manner with what is explained in Fig. 3, but NA_i to each segment changes instead of focal position Z_i. Z_i=0 is
applied to every elementary exposure system. The intensity of aerial image created by the virtual exposure system is shown by the contour graphs in the figure. Intensity distribution on x-y plane at focal point is also shown in the figure. Here, we adjusted coefficient $\alpha_i$ in Eq. 7 to compensate the difference of the intensity depending on NA. From the figure, we can see that the ratio of the width of the image in z direction to the width in y direction is controlled by making such virtual exposure system.

As shown in the above, the easiest way to define virtual exposure system is to merge every elementary exposure system consisting of mask pattern $A_i(X_i,Y_i)$ and focal point $Z_i$ corresponding to each part of 3D target shape. Then, the design of the virtual exposure system is completed by optimizing coefficient $\alpha_i$ in Eq. 9 so as to minimize the difference of the shape between the calculated aerial image and the target image. Once we complete the virtual exposure system, BILM is easily calculated from the Eq. 8. 3D image created by virtual exposure system is exactly reproduced by single exposure to BILM.

3. Results and discussion

A way to demonstrate the theory of BILM under
the current available infrastructure is to apply it to proximity exposure mask. Experimental demonstration to 2D patterns has been already reported in our previous work. Here, we will demonstrate 3D image creation by using the conventional optical simulation. Namely, we make the mask data for i-line ($\lambda = 365$ nm) proximity exposure and input it the conventional optical simulator.

Considering the feasibility in actual mask, we define the mask data by patterns with the transmittance of 1 and the phase of 0 degree or 180 degree. The method to make the mask data from BILM function $B(x,y)$ is shown in Fig. 6. A whole mask area is divided into small square area whose width $w_p$ is shorter than a half of the wave length of exposure light. We regard the mask as pixel array where each pixel is defined by the small square area. We calculate the average transmittance $T_i$ and the average phase $\theta_i$ in each pixel area from BILM function $B(x,y)$. Here, the transmittance is normalized so as that $\max\{T_i\}=1$. Mask pattern size $w_i$ in each pixel is determined from the average transmittance $T_i$ in each pixel, as shown in Eq. (10). The phase of mask pattern in each pixel $\phi_i$ is determined from the condition shown in Eq. (11).

$$w_i = w_p \sqrt{T_i} \quad \text{Here,} \quad 0 \leq T_i \leq 1$$

$$\begin{align*}
\text{if} & \quad 0 \leq \theta_i \leq 90 \quad \text{or} \quad 270 < \theta_i \leq 360 \quad \text{then} \quad \phi_i = 0 \\
\text{if} & \quad 90 < \theta_i \leq 270 \quad \text{then} \quad \phi_i = 180
\end{align*}$$

Since the transmittance of every mask pattern is 1, effective transmittance of each pixel becomes equivalent to $T_i$.

We make the mask data for i-line proximity exposure using the virtual exposure system shown in Fig. 3 by the above method. Here, $w_p=180nm$. In order to digitize the mask pattern size, the average transmittance is digitized by 0.1 step. Figure 7 shows generated mask pattern data and its simulation result. The mask is designed so as that the image is created in the range $z=30~45um$. Here, we show the effective transmittance defined by mask size in the Fig. 7(a) for visibility, although the transmittance of every mask pattern is 1. Phase of each pixel is shown in Fig. 7(b). Simulation result of intensity of aerial image on x-z plain is shown in Fig. 7(c). We can see the intensity of generated aerial image is 30 times higher than that of incident light. This is because incident beams going through mask aperture area much wider than that of generated image are focused. We can see 3D image can be clearly generated by the actually

![Fig. 6. A method to make digitized mask data from continuous function $B(x,y)$. Here, $T_i$ is the average transmittance defined by $B(x,y)$ in each pixel position.](image)

![Fig. 7. Simulation results applying BILM to proximity exposure mask. The unit of the coordinate in the graph is micron.](image)
feasible mask from the result.

We also make mask data made by the different digitization number to check its influence. Results where transmittance is digitized by 0.5 and 0.25 are shown in Figs. 8(a) and (b), respectively. We can see that 3D shape is maintained even by rough digitization in such simple shape case.

We will show more examples for complicated shape. Figure 9 shows the results using quadratic function curve instead of straight line in Fig. 7. Here, effective transmittance of each pixel is digitized by 0.1 step. We can see that the curve shape in z direction can be also clearly created.

From here, we will show examples of true 3D shape. The example in Fig. 10 is ridge-lines of quadrangular pyramid. Here, mask pattern size and phase are digitized by the same manner used in Fig. 9. Here, we assigned 90 degree phase difference between ridge-lines when we design mask of elementary exposure system in order to reduce interference noises between x direction patterns and y direction patterns. That is the reason why a pattern like a spiral is seen in phase distribution in Fig. 10(b). 3D positions whose intensity larger than 3.5 are plotted in Fig. 10(c). Color of each plot point shows its intensity. We also plot shadows of 3D images projected on x-y plain and z-y plain in the figure for visual recognition of 3D shape. From the figure, we can see clear 3D shape is generated.

Next example is a chain consisting of two circles shown in Fig. 11. Here, phase of BILM is digitized by 90 degree step instead of 180 degree, because it is difficult to create a closed loop shape without large noise generated by rough digitization. The last example is a barrel shape shown in Fig. 12.

Here, phase of BILM is digitized by 10 degree step to create high wall shape without digitization noise. Intensity contour of aerial image on x-y plain at z=-30 mm is shown in Fig. 12(c). Intensity contour on z-x plain at y=0 mm is shown in Fig. 12(d). As shown in the figure, the wall shape of the barrel with curve shape and high aspect ratio is well created.

Fig. 8. Simulation to check the influence of digitization. The unit of the coordinate in the graph is micron.

Fig. 9. Simulation results applying BIML to proximity exposure mask. The unit of the coordinate in the graph is micron.
Fig. 10. Simulation results applying BIML to proximity exposure mask. The unit of the coordinate in the graph is micron.

Fig. 11. Simulation results applying BIML to closed loop shape. The unit of the coordinate in the graph is micron.

Fig. 12. Simulation results using BIML with multi-phase shifting. The unit of coordinates of the graph is micron.
It is not easy to make multi-phase shifting mask for i-line proximity lithography currently. However, if reduction projection lithography with liquid crystal mask is available in the future, the above 3D images can be created by making array with enlarged size pixel by liquid crystal. This is because BILM is available for projection lithography.

4. Conclusion
We have presented a technology to created 3D aerial image by single exposure to BILM. BILM patterns to create 3D image are calculated through the design of the virtual exposure system to create the target 3D pattern. Concept of the virtual exposure system allow us to create 3D shape images easily. We have demonstrated that true 3D shape can be clearly generated by actual digitized mask pattern data through the simulation of i-line proximity exposure. Built-in lens mask is a general 2D mask same with the conventional mask excepting the pattern layout is calculated based on built-in lens mask technology. The technology could be applied to any lithograph infrastructure using 2D mask including reduction projection. BILM technology will facilitate 3D patterning with low cost and high productivity.

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