Maskless Lithographic Pattern Generation System upon Micromirrors

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ABSTRACT

In this study, we focus our attention on the generation of a complex lithographic pattern on a huge substrate with no manipulation of the light beam shape and with a uniform reflection angle. To increase robustness and the flexibility of the lithographic pattern generation method, the process is conceptualized as dual pattern recognition in two contrary views, which are the substrate's view and the micromirror's view. The lithographic pattern generation method through dual recognition is devised. Then, a prototype maskless lithography system using the devised method is implemented. To ensure the system works, maskless lithography is performed to fabricate actual wafers. The results verify that the method is robust and flexible enough to generate lithographic patterns in any possible lithographic configuration. Moreover, the system is precise enough to attain the lithographic quality required by display panel manufacturers.

Keywords: Maskless Lithography, Micromirror Array, Lithographic Pattern.

1. INTRODUCTION

Conventional lithography using masks has been the workhorse in the field since it was invented in the 18th century. Even now, most of the lithography carried out use masks. Due to the problems caused by masks such as expense and time in fabricating the masks, contamination by masks, disposal of masks, and the alignment of masks, research of maskless lithography was initiated recently and it is growing rapidly and broadly.

Recently, devices using micromirror arrays such as the Digital Micromirror Device (DMD) by Texas Instruments Inc. (TI) and the Spatial Light Modulator (SLM) have brought innovation to the field of microdisplays [1-5]. The DMD and SLM are considered as the successful solution to digital light processing and Micro Electronic Mechanical System (MEMS). Nowadays, many new application fields for them have emerged, and one of them is maskless lithography [3-8].

In comparison with other maskless lithography technology, maskless lithography using micromirrors possesses superior features. Those may be enumerated as sufficient throughput for highly customized patterns, higher but precise resolution, fine lithographic quality, efficiency in cost and time, and so on. However, these are feasible if, and only if, each system developer could set up an excellent optic unit and an accurate lithographic pattern generation unit.

To generate lithographic patterns for maskless lithography, millions of micromirrors in the micromirror array need to be addressed and adjusted, individually and instantaneously. The task of providing a stream of lithographic pattern signals proper to the relative movement of the substrate for the micromirror controller is neither simple nor easy.

Several lithographic pattern generation methods can be found in the literature [3-7]. Some of them are registered as patents in the U.S. [3,4,5,7]. But, those were good only through excessive manipulation of the reflected light beam from its original shape and angle, or limited to the generation of typically structured patterns being composed of lines rather than arcs. These have faltered in the generation of unusual patterns with the square shaped light beam such as the one from a mirror pixel in the DMD.

To obtain high resolution with a uniform reflection angle, the Ball semiconductor Inc. proposed pattern generation methods based on refocusing the light beam into different shapes such as a circle (point)[6,7]. However, the application fields may be limited to small sized patterns such as wafers, besides the fact that their methods require extra optic devices for grating.

On the other hand, due to the fast growth of the Flat Panel Display (FPD) market, the size of FPD Panel has increased in dimension to being 2 m by 2 m and over, and the complexity of lithographic pattern structure has also increased.

Therefore, it may be impossible to generate a lithographic pattern for a FPD panel using pattern generation methods available at this moment.

The failure of pre-existing methods in generating unusual lithographic patterns with the reflected light beam in its original shape with a uniform reflection angle is expected, since the methods were developed focused on the beam. Because of their familiarity with lithography using masks, the reflected beam was their primary concern not the pattern. Most of the pre-existing criteria for the reflection of the mirror had been developed upon the reflected beam. Depending on the number and angle of reflections upon a specific shape and size of the reflected beam, the exposed space such as the line width or the line space was initially determined. Then, by the predetermined exposed spaces with specified reflections, the lithographic pattern generation was performed accounting for the pattern space. This method never worked whenever an unpredicted pattern appeared, thus this method is neither robust nor flexible.

In this study, we focus our attention on the generation of a complex lithographic pattern on a huge substrate with no manipulation of the light beam shape and with a uniform reflection angle. We aim to develop a robust and flexible lithographic pattern generation method for micromirror based maskless lithography, especially for unpredicted lithographic patterns. To attain our goal, we conceptualize the lithographic pattern generation process as dual pattern recognition in two contrary views, which are the substrate's view and the micromirror's view.

The lithographic pattern generation method through dual pattern recognition in two contrary views is proposed. The method consists of two major procedures, besides the loading of the CAD data into the memory and the transmission of the binary coded pattern to the micromirror controller. The first is the pattern recognition procedure upon the substrate. The first proceeds in two steps: 1) extraction of pattern boundary and 2) construction of a region based pattern. The second is the pattern recognition procedure upon the micromirror. The second proceeds in three steps: 1) confirmation of the micromirror dependent region, 2) extraction of the micromirror dependent region, and 3) construction of the stream of binary patterns for the micromirror upon substrate scrolling.

To verify the method, a prototype system is implemented. The implemented system is composed of a lithographic pattern generation module, a signal interchange module that handles the real time communication with hardware components, and a Graphical User Interface (GUI) that enables the lithography equipment operator to view and control various operations of the system. For the validation of the system, micromirror based maskless lithography using the system is carried out to fabricate actual wafers. The results prove that the method is robust and flexible enough to generate a lithographic pattern in any possible lithographic configuration and the system is precise enough to attain the lithographic quality required by display panel manufacturers.

2. LITHOGRAPHIC PATTERN GENERATION PROCESS

In maskless lithography using micromirrors, the micromirror array works as a virtual mask to write patterns directly onto substrates. Throughout the maskless lithography in concern, all the micromirror controller does is digitally control the light reflection off the micromirrors, i.e., it gives the approval of reflection as on or off without changing reflection angles. Therefore, the operation of maskless lithography equipment might be thought of as simple.

However, in reality, it is not. Sending the approval of on/off for millions of micromirrors to the controller is more complicated than thought, especially when reflection by a rotated micromirror array is unavoidable. It is even more troublesome to construct the proper lithographic region when projection onto a scrolling substrate is required.

Unfortunately through the maskless lithography in concern, both reflection by rotated micromirror array and projection onto a scrolling object are imposed. To improve lithographic quality, the micromirror array is rotated counterclockwise at a small angle relative to the longitudinal axis assigned as substrate scrolling direction. Therefore, devising a customized pattern generation method, entirely from the loading of the lithographic pattern data up to delivering it to the micromirror controller, under constraints such as micromirror array rotation and substrate scrolling is inevitable.

Figure 1 shows the flow of the lithographic pattern generation process. The function of the first procedure is loading the Computer Aided Design (CAD) data written in Drawing eXchange Format (DXF) through parsing of the CAD data.

The function of the second procedure is recognition of the pattern upon the substrate, and it is associated with two routines. The extraction of the pattern boundary is accomplished through the reconstruction process of geometric entities with open loops into closed loops. The construction of the pattern region is done by set operations on polygons upon computational geometry.

The function of the third procedure is recognition of the pattern upon the micromirror, and it is associated with three routines. The confirmation of the micromirror dependent lithographic pattern region is performed in accordance with the micromirror configuration. The extraction of the micromirror dependent pattern is accomplished to determine the binary reflection based on the area ratio. The construction of the stream of binary patterns with the binary reflection information for the micromirror is done in accordance with the substrate scrolling.

The function of the last procedure is the transmission of the binary coded pattern to the micromirror controller for lithography upon micromirror performance.
In this section, the detail of the lithographic pattern generation process is discussed using an illustrated example of a pattern shown in Fig.2 following the pattern generation flow shown in Fig.1.

2.1 DXF Formatted CAD Data Loading

To ensure the capabilities of the devised pattern generation method, the testing of pattern generation is performed before it is applied to an actual maskless lithography using micromirrors. Figure 2(a) shows the CAD data of an example pattern in DXF format loaded into the memory. Through parsing of the CAD data, geometric entities are considered to be lines, arcs, and circles. Then, each of the parsed geometric entities is reconstructed as an abstract entity for a polygonal region in terms of the prescribed definitions in this study.

2.2 Recognition of Pattern upon Substrate

2.2.1 Extraction of pattern boundary

The boundary of the pattern is extracted by the conversion of geometric entities with open loops into polygonal entities forming closed loops. Figure 2(b) shows the boundary of the example pattern extracted from the CAD data. In Fig2(b), the diameter of the circle is in between 50μm and 700μm, and the space between them is given in between 30μm and 200μm.

2.2.2 Construction of pattern region

The construction of the pattern region proceeds as follows. Each enclosed region extracted from the pattern boundary is considered as a polygonal entity. The polygons A_1 and A_2 are extracted from the pattern boundaries B_1 and B_2 as shown in Fig.2(b). To manipulate overlapping polygons, set operations on polygons upon computational geometry are performed. For this specific example, set operations on polygons may be written as:

$$
\begin{aligned}
P_{12} &= (A_1 - B_1) + (A_2 - B_2) - 2(A_1 - B_1) \cap (A_2 - B_2) + B_1 + B_2 \\
A_1 &= \{\, r, \varphi \mid r \le R_1,\ 0 \le \varphi \le 2\pi \} \\
A_2 &= \{\, r, \varphi \mid r \le R_2 / \cos(0.5\eta\pi - \varphi),\ 0 \le \varphi \le 2\pi,\ \eta = (\text{int})[(45 - 180\varphi/\pi)/90] \,\} \\
B_1 &= \{\, r, \varphi \mid r = R_1,\ 0 \le \varphi \le 2\pi \} \\
B_2 &= \{\, r, \varphi \mid r = R_2 / \cos(0.5\eta\pi - \varphi),\ 0 \le \varphi \le 2\pi,\ \eta = (\text{int})[(45 - 180\varphi/\pi)/90] \,\}
\end{aligned}
\tag{1}
$$

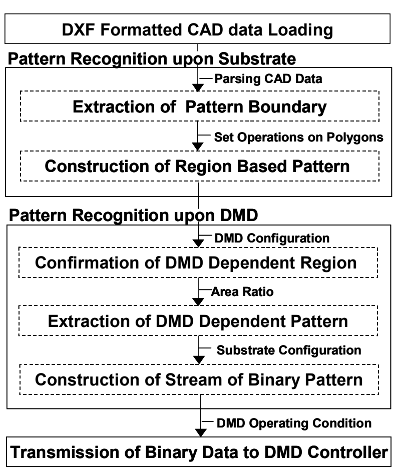


Fig. 1. Lithographic pattern generation flow.

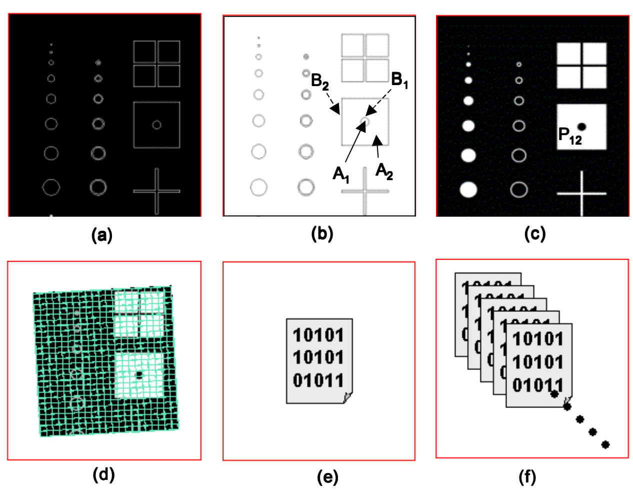


Fig. 2. Lithographic pattern generation process.

where, R_1 is the radius of the circle A_1 and R_2 is the radius of the inner circle which fits in the square A_2. Then, the valid interior regions such as P_{12} in Fig.2(c) are kept as the pattern region for lithography.

2.3 Recognition of Pattern upon Micromirror

2.3.1 Confirmation of micromirror dependent region

As mentioned earlier, the micromirror frame is rotated counterclockwise at a small angle relative to the longitudinal axis that is assigned as the substrate scrolling direction. To account for the counterclockwise rotation of the micromirror frame, the pattern region is considered as being rotated clockwise from the longitudinal axis. Then, the coordinate transformation relevant to micromirror rotation and substrate misalignment may be written as:

$$\begin{bmatrix} z_1^* \\ z_2^* \end{bmatrix} = \begin{bmatrix} \cos\theta^* & \sin\theta^* \\ -\sin\theta^* & \cos\theta^* \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} + \begin{bmatrix} -z_{10}\cos\theta^* - z_{20}\sin\theta^* \\ +z_{10}\sin\theta^* - z_{20}\cos\theta^* \end{bmatrix} \tag{2}$$

where, $\vec{z}$ is the reference coordinate vector upon CAD data loading, $\vec{z}^*$ is the floating coordinate vector relevant to micromirror rotation and substrate misalignment, (z_{10}, z_{20}) is the reference coordinate of the floating origin relevant to micromirror rotation and substrate scrolling, and θ^* is the floating angle which is the sum of the micromirror rotational angle and the substrate misalignment angle.

The rotated pattern region is then projected onto the micromirror frame. The part of the region mapped onto the micromirror array is extracted from the pattern region. By rotating the extracted part of the pattern region counterclockwise back to its original position, the region is confirmed as the lithographic pattern region upon micromirror rotation at each scrolling step as shown in Fig.2(d).

2.3.2 Extraction of micromirror dependent pattern

For robustness and flexibility, we devise a unique criterion, the area ratio, for the on/off approval for the reflection of the micromirror. This is the ratio of the area occupied by the pattern per unit micromirror. The on/off reflection for each mirror is determined comparing the occupied area of the pattern per unit micromirror to the user specified area ratio. Then, the result of on or off reflection is converted into binary data as the micromirror dependent pattern step as shown in Fig.2(e).

Figure 3(a) shows the configuration of the dimensionless parameters based on the Field Of View (FOV): which are the area ratio, ($a^* = a/FOV^2$), the exposure intensity ($e^* = e/FOV$), and the pattern thickness ($t^* = t/FOV$). The area ratio (a^*) may be written as a function of pattern thickness (t^*) as:

$$\begin{aligned} a^* &= w(0,b_1)\cdot\left[\ 0.5\cdot(\tan\theta+\cot\theta)\cdot t^{*2}\ \right] \\ &+ w(b_1,b_2)\cdot\left[\ (\tan\theta+\cot\theta)\cdot\left(\sin\theta\cdot t^* - 0.5\cdot\sin^2\theta\right)\ \right] \\ &+ w(b_2,b_3)\cdot\left[\ 1-0.5\cdot(\tan\theta+\cot\theta)\cdot\left(\sin\theta+\cos\theta-t^*\right)^2\ \right] \end{aligned} \tag{3}$$

so that the maximum of the area ratio, $a^*_{\max}\left(\ t^*_{\max}\right)$, is equal to 1. The exposure intensity (e^*) may be written as a function of pattern thickness (t^*) as:

$$\begin{aligned} e^* &= w(0,b_1)\cdot\left[\ (\tan\theta+\cot\theta)\cdot t^*\ \right] \\ &+ w(b_1,b_2)\cdot\left[\ (\cos\theta)^{-1}\ \right] \\ &+ w(b_2,b_3)\cdot\left[\ (\tan\theta+\cot\theta)\cdot\left(\sin\theta+\cos\theta-t^*\right)\ \right] \end{aligned} \tag{4}$$

so that the integral of the exposure intensity, $\int_o^{t^*_{\max}} e^*\ dt^*$, equals to 1. Where, the square wave function, $w(b_i,b_j)$ in Eqn.(3) and Eqn.(4), is defined using unit step functions as:

$$w(b_i,b_j) = u\left(\ t^*-b_i\right) - u\left(\ t^*-b_j\right), \quad (b_i < b_j) \tag{5}$$

with the step boundaries $b_1 = \sin\theta$, $b_2 = \cos\theta$, and $b_3 = \sin\theta+\cos\theta$. Then, using Eqn.(3)- Eqn.(5), the exposure intensity (e^*) may be rewritten in terms of the area ratio (a^*) as;

$$
\begin{aligned}
e^* &= w(0,b_4)\cdot\left[\ \sqrt{2\cdot(\tan\theta+\cot\theta)\cdot a^*}\ \right] \\
&+ w(b_4,b_5)\cdot\left[\ (\cos\theta)^{-1}\ \right] \\
&+ w(b_5,b_6)\cdot\left[\ \sqrt{2\cdot(\tan\theta+\cot\theta)\cdot\left(\ 1-a^*\right)}\ \right]
\end{aligned}
\qquad (6)
$$

where, $b_4 = 0.5\cdot\tan\theta$, $b_5 = 1 - 0.5\cdot\tan\theta$, and $b_6 = 1$. Figure 3(b) shows the relation of area ratio (a^*), exposure intensity (e^*), and pattern thickness (t^*) obtained by Eqn.(3)-Eqn.(6). As anticipated, Fig.3 insists that our reflection criterion is proper and reliable.

2.3.3 Construction of stream of binary patterns

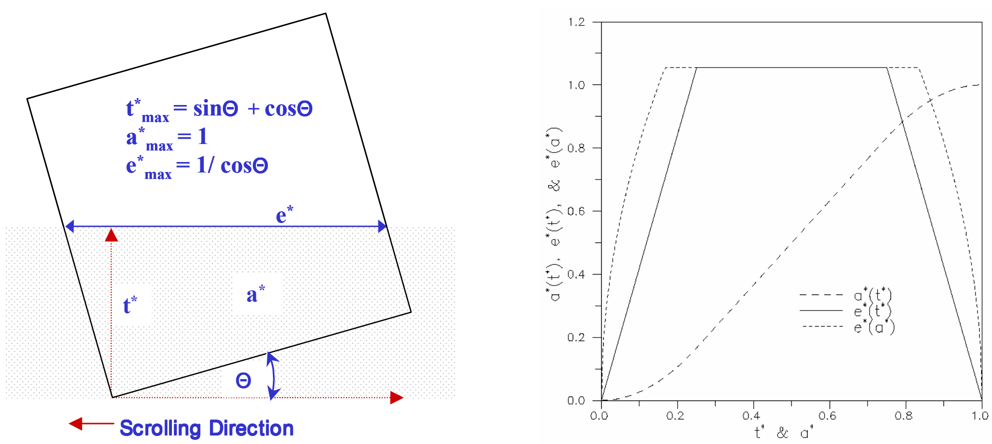
The construction of the stream of the binary data in accordance with the substrate configuration is not hard in the proposed method, since the binary reflection information is contained in the pattern at this stage. The stream of binary data is generated in the sequence of substrate scrolling step by accumulating the binary reflection information contained in the pattern at every substrate location as shown in Fig.2(f).

Figure 4(a) shows the boundary of the test pattern extracted from the test CAD data. In the test CAD data, the diameter of the circle is in between 50μm and 700μm, the space between them is given in between 50μm and 200μm, the width of polygons representing lines lies in between 30μm and 50μm, and the space between them is given in between 30μm and 50μm. Figure 4(b) shows the lithographic pattern generated upon the stream of binary coded pattern data.

To generate testing patterns, the pitch is assigned to be 2μm with 10μm of FOV. The area ratio is assigned as 0.8 with 5° rotation of the micromirror frame. A total number of 3700 frames are used to irradiate the total area of the testing pattern. Thus, the lithographic pattern region shown in Fig. 4(b) is obtained by the accumulation of 3700 frames. The results show that the proposed method is capable of generating a proper lithographic pattern region.

2.4 Transmission of Binary Data to Micromirror Controller

The binary pattern data is transmitted to the micromirror controller in accordance with micromirror performance. In this study, an electronic board with a data transit speed of 2500 frames per second is used to play the role of deliverer.



(a) (b)

Fig. 3. Configuration and relation of dimensionless parameters.

3. LITHOGRAPHIC PATTERN GENERATION SYSTEM

To attain our goal of generating a pattern for an actual lithography using the devised pattern generation method, a prototype system is implemented. The implemented system is mainly composed of the lithographic pattern generation module, the signal interchange module that handles the real time communication with the hardware components of the radiation control unit and the stage control unit, and the Graphical User Interface (GUI) that enables the lithography equipment operator to view and control various operations of the system.

The main window of the prototype system for lithographic pattern generation is shown in Fig.5. The exposure control window, management toolbar, and the process display window are shown on the left top, on the left bottom, and on the right, respectively. As shown in Fig.5, the user specified inputs to the implemented system are the origin of the

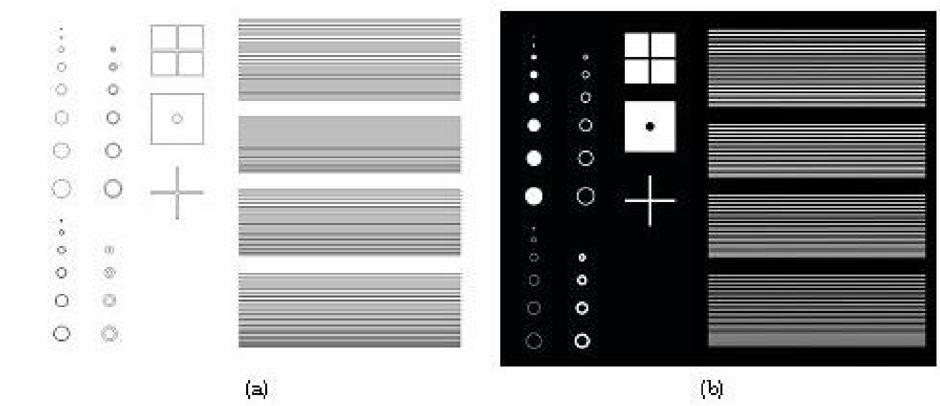


Fig. 4. CAD data and lithographic pattern generated by proposed method.

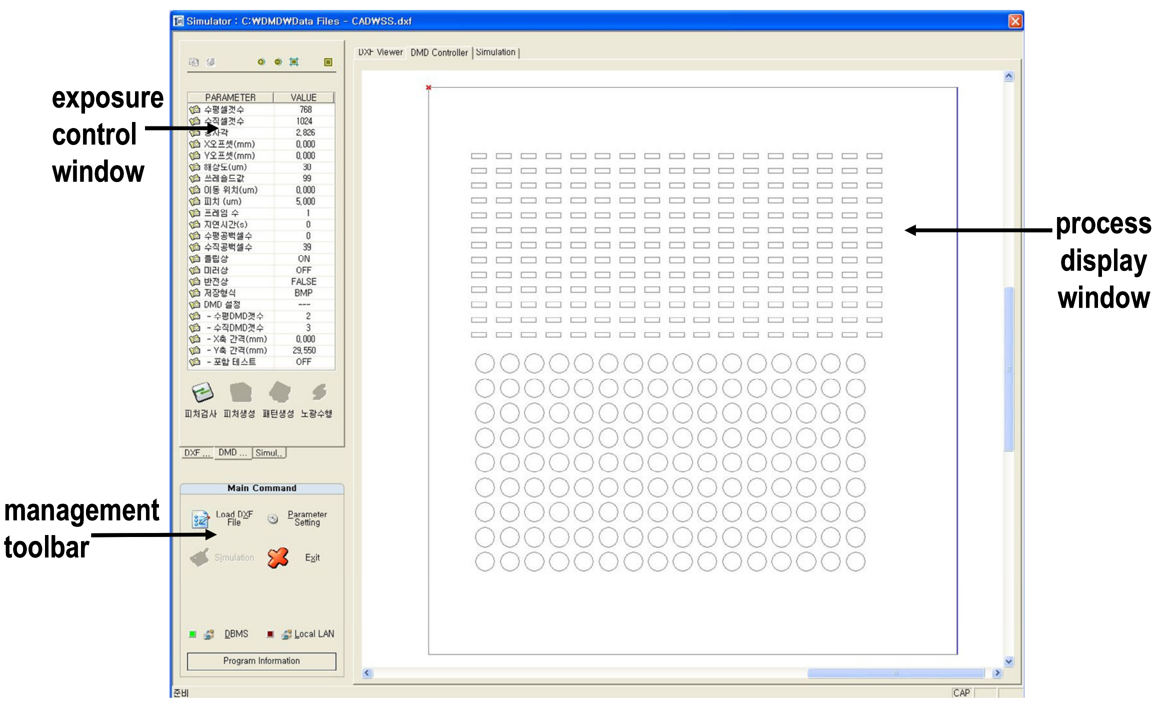


Fig. 5. Main window of implemented system.

reference/floating coordination system, angle of micromirror rotation, angle of substrate misalignment, two-directional micromirror resolution, exposure accuracy or pitch upon scrolling step, area ratio limit, the selection of normal/flip/mirror conversion of the CAD data, and so on. Therefore, the system is robust enough to handle any possible user specified mandate and even substrate misalignment.

To examine the capabilities of the system, the system is then applied to the generation of a lithographic pattern region for FPD glass fabrication. The FPD glass lithography process upon the system is shown in Fig.6. Throughout the FPD pattern generation, the pitch is assigned to be 6μm with 30μm of FOV. The area ratio is held at 0.8. A total number of 16000 frames requiring exposure are used to irradiate the total area of the FPD pattern. The CAD data of the pattern for the FPD glass, with the minimum of 140μm line space is shown in Fig. 6(a). The illustrated example showing the accumulation of 16000 frames appears in Fig. 6(b). The portion of confirmed lithographic regions for the FPD pattern is in Fig. 6(c), and the two marked sections are enlarged in Fig. 6(d) to show the predicted lithographic pattern region in detail. The obtained FPD pattern region shows that the implemented system based on the devised pattern generation method is capable of producing an actual pattern region for maskless lithography.

4. MASKLESS LITHOGRAPHY EQUIPMENT

The maskless lithography equipment for the micromirror based pattern generation system consists of three major devices. The first is the radiation device. The second is the exposure device including the micromirror controller, the micromirror, focusing optics, photo resistant coated glass substrates, and the base stage assembly and its controller. The last is the dynamic pattern control device, composed of the lithographic pattern generation system, the radiation control unit, and the stage control unit.

A schematic diagram of the maskless lithography equipment is shown in Fig.7 and a photograph of the prototype lithography equipment where the micromirror based pattern generation system is loaded is shown in Fig.8. The eXtended Graphic Array (XGA) DMD manufactured by TI has 13.68 μm of mirror (pixel) pitch and it is enlarged to 30 μm of the FOV in the present work. As shown in Fig.7, micromirrors are exposed to incoming radiation released from the ultraviolet light source. The reflection off the micromirrors is determined by the signal from the lithographic pattern generation system to the micromirror controller. Then, the light reflected off the micromirrors is projected through focusing optics onto the photo resistant coated glass substrate laid on the x-y scrolling base stage.

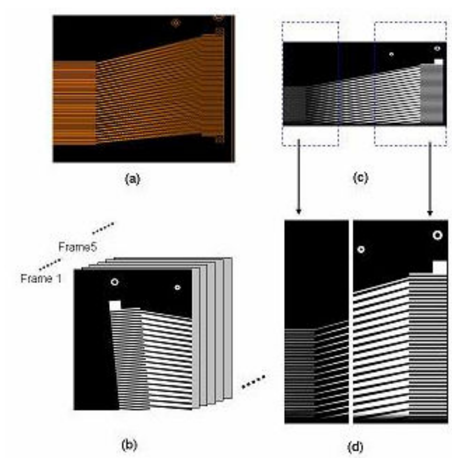


Fig. 6. Maskless lithography results.

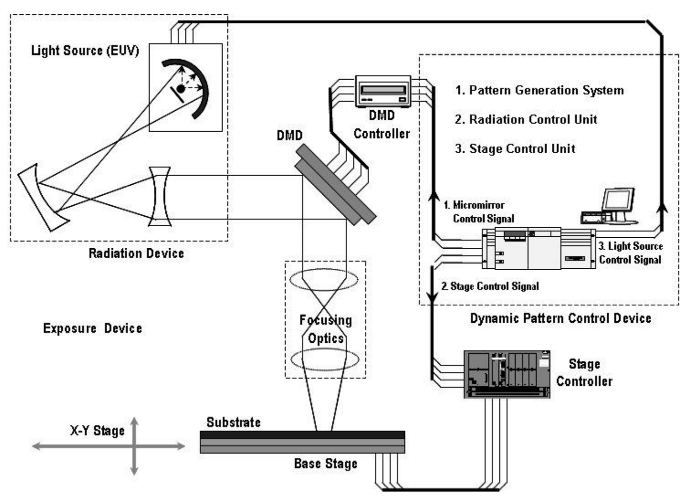


Fig. 7. Lithography equipment using micromirrors.

5. RESULTS AND DISCUSSION

For the validation of the micromirror based pattern generation system, an actual lithography is carried out to fabricate actual wafers, using the prototype lithography equipment shown in Fig.8. Electron microscope images of the patterns on the wafers are shown in Fig.9. The oblique line in Fig9(a) and the vertical line in Fig9(b) are 30 μm thick, the vertical line in Fig.9(c) is 80 μm thick, and the circle in Fig.9(d) has a 205 μm diameter. The patterns in Fig 9 were generated by 8μm pitch with 30μm of FOV, and these were developed but not etched.

The boundaries of the patterns appear to be clear enough with extremely low roughness, proving the accuracy of the system. No unacceptable manifestation of discrepancies between the input from the CAD data and the output from the actual lithography is found. The range of error is less than 3 percent, which is tolerable. As the size of FOV is increased, the error is increased due to the FOV size relatively large for patterns. The fact that the error in the thickness of the 30μm oblique line generated by 30μm of FOV is less than 0.5% insists the extraordinariness of the micromirror based pattern generation method. Overall, the results of the actual lithography verify that the devised system is capable of generating lithographic patterns precise enough to acquire content from the display panel manufacturers.

6. CONCLUSIONS

We place our primary concern on the pattern. Then, we conceptualize the lithographic pattern generation process as dual pattern recognition in the substrate's view and the micromirror's view. The micromirror based pattern generation method through dual recognition is devised for maskless lithography. Through the method, a complex lithographic pattern generation on a huge substrate with no manipulation of the light beam shape and with a uniform reflection angle becomes feasible. The conservation of the line width and the line center is always obtained. Moreover, the accuracy of the method, such as the conservation of the line width and that of the line center, is verified by the results of the actual lithography.

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Fig. 8. Prototype Equipment.

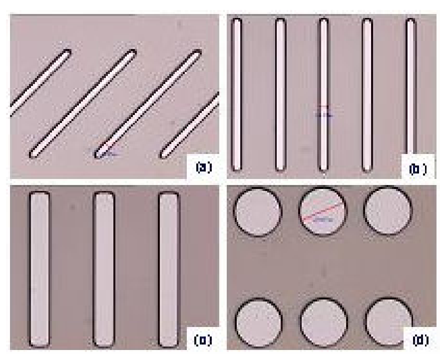

Fig. 9. Lithography results on wafers.