Lithography alignment method based on image rotation matching

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Abstract. In this paper, we propose a lithography alignment method based on digital image processing technology for the proximity-contact lithography system. We perform image processing such as edge detection and image segmentation on the input image to obtain the edge image of the alignment mark; then we use straight line detection to obtain the angle of the image and rotate the image; finally, we use the template of the alignment mark to perform image matching to obtain the position of the alignment mark. The algorithm is tested on a proximity-contact lithography machine. The results have proved that the algorithm can use any shape of pattern for lithography alignment and therefore is highly adaptable and has a wide range of applications.

1. Introduction

Lithography systems can be divided into three types: contact photolithography, proximity photolithography and projection photolithography. Wherein the projection system of the lithographic resolution lithography is high, but the complexity of the system structure and high cost. The proximity-contact lithography system is one of the key equipment in chip production and experimental manufacturing due to its simple structure and low cost, and it still occupies a large proportion of use. In the production process of the chip, multiple exposures are required. For each exposure, the mask needs to be aligned with the previously exposed pattern to determine the correct position relationship. Therefore, the alignment accuracy directly determines the complexity of the chip and the quality of the product. As one of the three core technologies of lithography systems, alignment technology generally requires alignment accuracy of 1/7 to 1/10 of the finest line width. There are many methods for lithography alignment, but in the proximity-contact lithography system, the most common is video image alignment. The earliest video image alignment method is to use a microscope to directly observe the cross and box geometric marks on the mask and the silicon wafer, and achieve visual alignment by adjusting the relative coordinate positions of the two. With the improvement of lithography resolution, image acquisition systems such as CCD are gradually used to acquire digital images, and the relative offset of the two images is calculated through image algorithms, and automatic lithography alignment is realized by computer control [1-3]. This method is widely used in proximity lithography systems [4,5]. Feldman and others of Louisiana State University designed a dual-focus alignment system that enables the CCD imaging system to simultaneously obtain two large images of alignment marks [6,7]. In addition, N. Li, W. Zhang, Stephen Y. Chou and others also used
the cross-frame alignment scheme in the study of nanoimprint lithography overprinting process experiments [8]. Although much progress has been made at home and abroad, alignment methods are generally limited to specific alignment marks. As the application fields of lithography are becoming wider and wider, there are more and more types of alignment marks, even some photolithography processes no longer design special alignment marks, but directly use photolithography patterns or silicon wafer outlines as alignment marks for alignment. Due to the limited process adaptability of traditional alignment algorithms based on specific marks, this paper proposes an alignment algorithm based on template matching that can be applied to various alignment marks, photolithography patterns, silicon wafer contours and other geometric patterns.

2. Image alignment algorithm
Image alignment is that the imaging system sends the mark image of the mask and the silicon wafer to the computer via the CCD for calculation, and feeds it back to the workpiece table motor to achieve position adjustment. Because the field of view of the CCD is limited, the lithography machine can perform pre-alignment operations to ensure that the alignment marks are located in a certain range. Take the box and cross mark as an example, the mark images before and after alignment captured by the CCD are shown in the figure below.

![Figure 1. Physical diagram of alignment mark before and after alignment](image)

This paper mainly studies the alignment algorithm after the CCD captures the mark. Figure 2 shows the intermediate results of each step (the picture is cropped and the main part is retained).

![a) Edge detection](image)
![b) Image segmentation](image)
2.1. Edge detection
Edge detection is the most commonly used method to segment images based on gray scales changes. In this paper, Canny algorithm is selected as the edge detection method. The Canny algorithm satisfies three requirements: an edge should be found and there is no false response, the position of the edge point is as close to the real edge as possible, and only one point is returned for detection of a single edge point [9]. After the edge detection of the image collected by the CCD using the Canny algorithm, the edge pattern of the alignment mark, as well as some false edges and noise, can be obtained, as shown in Figure 2 a).

2.2. Image segmentation
Due to the extremely small distance between the mask and the silicon wafer in the proximity-contact lithography system, the photoresist is prone to contamination of the mask. In order to eliminate the influence of image contamination, it is necessary to segment the alignment mark from the edge image. First, the edge image is processed by the morphological closing operation, to connect the small gaps in the edges. After that, the connected domain segmentation is performed, and the pixels connected together in the eight connected regions in the image are assigned the same positive integer, so that the positive integers of the unconnected parts are different, and a label matrix equal to the image is obtained. The number of occurrences of each positive integer in the mark matrix is counted. The object corresponding to the positive integer with a larger statistical value is mainly the edge pattern of the alignment mark, while the part with a smaller statistical value corresponds to the pollution area, noise or false edge. Since the image contains the alignment mark pattern of both the mask and the silicon wafer, it is necessary to divide the two marks separately. The CCD is usually located above the mask, the mask mark is generally located in the center of the field of view, and the silicon chip mark may appear anywhere in the field of view depending on where the silicon chip is placed. There are also cases where the silicon chip mark is blocked by the mask mark, and some silicon chip marks are outside the field of view. First, segment a more complete labeled image from the image. The specific steps are as follows:

1) Assuming that the marker matrix is \( H(x,y) \), define a matrix \( H_1(x,y) \) and \( H_2(x,y) \) of the same size as the marker matrix, and set all the elements to 0.
2) Extract the pixels whose elements are the same positive integers in the label matrix, that is, copy each connected domain in \( H(x,y) \) separately to \( H_1(x,y) \). If the connected domain satisfies the following conditions, the corresponding pixel is set to 1 in \( H_1(x,y) \). a) The number of element points in the connected region is greater than the threshold \( T_1 \). b) The minimum inscribed circle radius of the connected area is greater than the threshold \( T_2 \). c) The length-to-width ratio of the smallest bounding rectangle of the connected area is less than the threshold \( T_3 \). Among them, \( T_1, T_2, \) and \( T_3 \) are all thresholds designed according to the shape of the alignment mark.
Perform the above operations on all connected domains in \( H(x,y) \) in turn, remove the patterns of other structures on the silicon wafer, noise, and meaningless edges, keep the mask and the silicon wafer alignment marks, and get the image matrix \( H_1(x,y) \).

3) Repeat step 2) and change the thresholds \( T_1, T_2, T_3 \) in step 2) to thresholds \( T_4, T_5, T_6 \), which are thresholds designed according to the mask alignment marks. Since the mask alignment marks are usually complete in the image, the image matrix \( H_2(x, y) \) of the mask alignment marks can be separated by this method.

4) Let \( H_1(x,y) = H_1(x,y)-H_2(x,y) \), get the incomplete image matrix \( H_1(x,y) \) of the silicon alignment mark, as shown in Figure 2 c) and 2 d).

2.3. Image rotation

After obtaining the image of the alignment mark, a template matching algorithm needs to be applied to the two images to obtain the position coordinates of the center point of the image. Due to the angular difference between the mask and the silicon chip relative to the pixel coordinate system of the CCD image, the angular deviation between the acquired alignment mark image and the template is positively correlated with the error of the image matching algorithm. In order to avoid the failure of the image matching algorithm and improve the accuracy of the algorithm, before using the image matching algorithm, the alignment mark image needs to be rotated to make it the same direction as the template.

To use the Hough transform to extract straight lines from the labeled image. The straight line in the marked image is expressed as \( y = kx + q \) in the coordinate system. After converting to polar coordinate form \( \rho = m \cos \theta + n \sin \theta \), establish a new parameter coordinate system with \( \rho \) and \( \theta \) as the coordinate axes, then a curve in the new coordinate system represents the collection of all straight lines passing through a certain point in the original coordinate system. When the number of curves exceeding the threshold \( T \) intersect at the same point, we can consider that there is a straight line corresponding to the point in the mark image, and the length exceeds the threshold \( T \), which is a component line segment of the alignment mark. The angles of all straight lines obtained by the Hough transform are used for fitting, and the deviation angle \( \theta \) of the image is calculated. According to the obtained angle \( \theta \), based on the binary image characteristics of the edge image, select the nearest neighbor interpolation method with a small calculation amount, and use the coordinate transformation formula to rotate the image to obtain an image with the same direction as the template:

\[
\begin{bmatrix}
  x_2 \\
  y_2
\end{bmatrix}
= 
\begin{bmatrix}
  \cos \theta & -\sin \theta & 0 \\
  \sin \theta & \cos \theta & 0 \\
  0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
  x_0 \\
  y_0 \\
  1
\end{bmatrix}
\]  

(1)

2.4. Template matching

The biggest advantage of template matching is that it does not depend on the integrity of the alignment mark image, and only a part of the alignment mark image can be used to calculate the center position of the mark. During the alignment process, it is inevitable that the mask alignment mark and the silicon wafer alignment mark will block each other, and template matching can better handle this situation.

Firstly, the images of the mask and the silicon wafer are collected separately, and the image of the alignment mark is extracted from the image as a template to obtain the template matrix \( h_1(x, y) \), \( h_2(x, y) \). Normally, template matching requires the template to slide on the target image with a single pixel as a unit, and perform a metric calculation at each position to calculate the degree of matching between the position template and the target image. This method has a large amount of calculation, and when the image size increases, the amount of calculation increases exponentially, which is not suitable for real-time calculation of large images. Based on the characteristics that the object images are all binary images, this paper designs an image matching method for binary images. Suppose the size of the matrix \( h_1(x,y) \) is \( m_1 \times n_1 \), and the size of the matrix \( h_2(x,y) \) is \( m_2 \times n_2 \). Calculate the mask alignment mark matrix \( H_1(x,y) \) and the mask template matrix \( h_1(x,y) \) to obtain the matrix \( G_1(x,y) \):
Similarly, use the silicon wafer alignment mark matrix $H_1(x,y)$ and the silicon wafer template matrix $h_2(x,y)$ to obtain $G_2(x,y)$:

$$G_2(x,y) = \sum_{m_2}^{m_1} \sum_{n_2}^{n_1} h_2(m_2, n_2) H_2(x + m_2, y + n_2)$$ (3)

Each element in the matrix $G_1(x,y)$ and $G_2(x,y)$ represents the correlation degree of the template at the corresponding position of the alignment mark matrix. When the alignment mark is complete, the maximum point of correlation is at the position where the mark and the template completely overlap, that is, the center position of the alignment mark, as shown in Figure 2 c). When the alignment mark is occluded, the remaining part of the incomplete mark partially overlaps the template at the maximum correlation degree, and is also located at the center of the alignment mark.

Suppose the coordinates of the maximum point in $G_1(x,y)$ are $(x_1, y_1)$, and the coordinates of the maximum point in $G_2(x,y)$ are $(x_2, y_2)$. Substitute the coordinates into the following formula to obtain the center coordinates $(X, Y)$ of the alignment mark in the original image:

When rotating $\theta$ clockwise:

$$\sigma = \tan^{-1} \left( \frac{x + \frac{m - 1}{2} - \frac{1}{2} - x \sin \theta}{y + \frac{n - 1}{2} - x \sin \theta} \right)$$ (4)

$$Y = \sqrt{\left(x + \frac{m - 1}{2}\right)^2 + \left(y + \frac{n - 1}{2} - x \sin \theta\right)^2} \tan^2(\sigma - \theta) + 1, X = Y \cdot \tan(\sigma - \theta)$$ (5)

When rotating $\theta$ counterclockwise:

$$\sigma = \tan^{-1} \left( \frac{x + \frac{m - 1}{2} - y \sin \theta}{y + \frac{n - 1}{2}} \right)$$ (6)

$$Y = \sqrt{\left(x + \frac{m - 1}{2} - y \sin \theta\right)^2 + \left(y + \frac{n - 1}{2}\right)^2} \tan^2(\sigma + \theta) + 1, X = Y \cdot \tan(\sigma + \theta)$$ (7)

2.5. Coordinate calculation

The silicon chip and the mask usually design two sets of alignment marks. The center coordinates of the left and right marks of the silicon chip are respectively $(X_{A1}, Y_{A1})$ and $(X_{A2}, Y_{A2})$, and the center coordinates of the left and right marks of the mask are $(X_{M1}, Y_{M1})$ and $(X_{M2}, Y_{M2})$ respectively. Then there are:

The offset of the mask relative to the silicon wafer in the X direction and in the Y direction:

$$\Delta X = \frac{(X_{M1} + X_{M2}) - (X_{A1} + X_{A2})}{2}, \Delta Y = \frac{(Y_{M1} + Y_{M2}) - (Y_{A1} + Y_{A2})}{2}$$ (8)

The rotation angle of the mask relative to the silicon wafer:

$$\Delta \theta = \frac{(Y_{M1} - Y_{A1}) - (Y_{M2} - Y_{A2})}{d}$$ (9)

3. Experiment

The experiment was carried out on the URE-2000/35 lithography machine produced by Institute of Optics and Electronics Chinese Academy of Sciences, and the algorithm performance was tested under various conditions. The number of pixels in the X-direction and Y-direction of the CCD of the proximity-contact lithography machine is 3072pixel×2048pixel, and the unit pixel is 2.4μm×2.4μm.
The optical magnification of the objective lens is 6 times. The workpiece table is equipped with three displacement motors to control the movement of the wafer table in the X direction, the Y direction and the rotation of the angle \( \theta \). Use the cross mark and the box mark to carry out the experiment. The box mark has a total length of 0.5mm, a line width of 0.05mm, and the cross mark has a total length of 0.6mm and a line width of 0.06mm. A pre-alignment mechanism is designed on the mask clamp and the silicon wafer stage to ensure that the alignment mark appears in the CCD field of view.

![Figure 3. Photo of mask aligner](image)

When the mark is in normal condition, the mark is blocked, and the image is contaminated, alignment exposures are performed 15 times respectively.

![Figure 4. Physical diagram of alignment mark](image)

Count the exposure results in the three cases. According to the CCD resolution, optical magnification and error detection conditions, the alignment displacement deviation in the X and Y directions is less than 1\( \mu \)m as a successful alignment. The experimental results are shown in the table below.

|                  | X direction average offset (\( \mu \)m) | X direction alignment success rate (\( \leq 1 \mu \)m) | Y direction average offset (\( \mu \)m) | Y direction alignment success rate (\( \leq 1 \mu \)m) | Alignment success rate (\( \leq 1 \mu \)m) |
|------------------|------------------------------------------|-----------------------------------------------------|------------------------------------------|-----------------------------------------------------|------------------------------------------|
|                  |                                          |                                                     |                                          |                                                     |                                          |
This algorithm can meet the alignment accuracy requirements under normal circumstances. In the case of marker occlusion, the traditional summation projection method will affect the position of the gray value peak value due to the occlusion of the marker and cause large errors. However, although the matching degree of this algorithm decreases when the mark is occluded, it can still meet the requirements of alignment accuracy. It can be inferred from the alignment success rate in the case of image pollution that the image processing link can eliminate the influence of image pollution to a certain extent. In the experiment, the alignment accuracy rate in the X direction is significantly higher than that in the Y direction. According to the experimental analysis, it is mainly due to the large random error of the rotating motor of the workpiece table, rather than the defect of the algorithm. The alignment accuracy can be improved by correcting the error of the workpiece table.

Use an inductance micrometer to replace the workpiece table motor for testing, move the alignment mark to the same position as the starting condition, and repeat the experiment ten times as a set of data to test the repeatability of the algorithm. A total of four sets of data are obtained, and the repeatability is 0.376μm, 0.159μm, 0.277μm, 0.001μm. According to the experimental data, the algorithm meets the requirements of alignment accuracy.

Use common lithography patterns to replace the cross-box alignment marks, and perform alignment experiments. The experimental results are shown in the following table.

| Mark  | X direction average offset | Y direction average offset |
|-------|----------------------------|---------------------------|
| Mark 1| 0.848 μm                   | 0.954 μm                  |
| Mark 2| 1.272 μm                   | 0.901 μm                  |
| Mark 3| 1.007 μm                   | 1.537 μm                  |
| Mark 4| 0.742 μm                   | 0.795 μm                  |
| Mark 5| 1.431 μm                   | 1.484 μm                  |

It can be seen from the experimental results that the accuracy of mark 1 and mark 4 is higher, indicating that the pattern with the same center position is more suitable as an alignment mark, while mark 5 has poor alignment accuracy due to the distance between the center positions of the two patterns. Mark 4 is better than Mark 1, indicating that choosing patterns with obvious differences as the silicon wafer and mask alignment mark is more conducive to alignment. The X direction of mark 2...
and the Y direction of mark 3 have low accuracy. It can be seen that the accuracy of the elongated structure is low, and the alignment mark should be a pattern with structures in both X and Y directions. In general, the algorithm does not depend on specific alignment marks, and can be lithographically aligned with patterns of any shape, including lithographic patterns, silicon wafer outlines, etc., with strong process adaptability and a wide range of applications.

4. Conclusion
This paper proposes an alignment algorithm based on video image alignment technology for proximity-contact lithography machines. The method can use any pattern alignment mark for alignment, and can also be based on photolithography patterns and silicon wafer contour alignment, and has a wide range of applications. Do exposure experiments on images under different conditions, and the measurement results meet the accuracy requirements. The algorithm can be embedded in the automatic alignment system to realize the automation of the alignment system and has good practical value.

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