A Pattern Defect Inspection Method by Parallel Grayscale Image Comparison without Precise Image Alignment

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Abstract—For automatic visual inspection of patterns on printed wiring boards and/or patterned wafers, this paper presents a new defect detection method for grayscale images without precise image alignment. Most of the conventional visual inspection algorithms based on grayscale reference comparison require precise image alignment with precision of subpixel or within \( \pm 1 \) pixel; however, it is difficult to succeed the precise image alignment in every image. While a defect inspection method without precise image alignment has been previously proposed for binary images, the expansion to grayscale images we discuss is indispensable for detecting more minute defects. We propose dynamic tolerance control based on grayscale morphology to reduce false defects on pattern edges, and use gray dilation operation so that a weakness of the original method for binary images, an inability to detect the absence of minute patterns, is overcome. Theoretical analysis and experimental results show that the proposed method is capable of detecting subpixel-sized defects, and has practical detection performance.

I. INTRODUCTION

In automatic visual pattern inspection field for printed wiring boards (PWB) and/or patterned wafers, the reference comparison method that compares an inspected image with a reference image is widely used. The ability to detect subpixel-sized defects is required particularly for wafer inspection because of optical resolution limits. Therefore, several inspection methods which detect subpixel-sized defects by grayscale chip-to-chip (or die-to-die) reference comparison have been developed, and a system that has higher precision and higher speed is required because pattern size is becoming smaller and chip areas are becoming larger [1].

Though several methods have been proposed for pattern inspection, they need precise image alignment with precision of subpixel or within \( \pm 1 \) pixel [2], [3], [4]. However, when an inspected object itself is slightly distorted or rotated, misalignment caused by such distortion or rotation brings the false defects. On the other hand, we have disclosed the reference comparison method without precise image alignment for binary images [5]. We call this method "PCSR-B" (Parallel Comparison with Staggered References for Binary images) for convenience. PCSR-B is a very effective algorithm in that there is no false detection caused by misalignment. Therefore, we developed PCSR-G ("G" means grayscale images) algorithm based on PCSR-B algorithm to achieve inspection that has higher precision without increasing spatial resolution.

In this paper, we describe the old PCSR-B algorithm first in Section II, and propose the new PCSR-G algorithm in Section III. In Section IV, we discuss the theoretical defect detection ability of PCSR-G. Then we show experimental results in Section V, and estimate hardware resources in Section VI.

II. CONVENTIONAL PCSR-B ALGORITHM

A. Basic Algorithm

Fig. 1. Concept of PCSR-B
Problem 2: It has the possibility that minute defects are overlooked.

Problem 1 arises clearly from the above algorithm, and Fig. 2 shows the cause of Problem 2. When there is a minute pattern on the boundary between successive reference inspection blocks (Block#N and Block#N+1), and that pattern is not present in the inspected image, disappearance of the pattern may not be able to be detected because there is no difference between the inspected image and the shifted reference images, as shown in the figure.

III. EXPANSION TO NEW PCSR-G ALGORITHM

A. Reduction of False-Defects on Pattern Edges

First, we discuss the problem of false defects on the pattern edges, and the solutions to the above problems will be stated later. When the Exclusive-OR operations for binary images are expanded to subtraction and absolute operations for grayscale images, the dispersion of the pixel values on pattern edges by sampling errors causes false defects. Since PCSR-B detects the clusters of the difference, the false defects on pattern edges were reduced, while it could not detect one pixel-sized defect or smaller. In PCSR-G, we propose dynamic tolerance control based on grayscale morphology [6].

We apply gray dilation and erosion operations with 3 x 3 structure element (SE), and make the maximum and the minimum tolerance images from the reference image as

\[ \text{Rmax}(x, y) = R(x, y) + p(\text{max}_{p,q}(R(x-p, y-q)) - R(x, y)), \]  
(1)

and,

\[ \text{Rmin}(x, y) = R(x, y) - p(\text{min}_{p,q}(R(x-p, y-q))) - R(x, y)), \]  
(2)

where Rmax and Rmin are the maximum and the minimum tolerance images of the reference image (R), and \( R_{\text{max}}(x, y) \) and \( R_{\text{min}}(x, y) \) represent the pixel values at coordinate \( (x, y) \) of \( R_{\text{max}} \) and \( R_{\text{min}}. \) Both \( p \) and \( q \) are integer values from -1 to +1, and \( p \) is a real value from 0.0 to 1.0 for controlling the tolerance level (We call \( p \) "edge tolerance parameter").

After generation of \( R_{\text{max}} \) and \( R_{\text{min}}, \) each pixel of the inspected image \( I \) is compared with these reference images, and the difference image \( D \) with tolerance values is calculated by the following operation.

\[
\begin{cases}
D(x, y) = R_{\text{min}}(x, y) - I(x, y); \\
D(x, y) = I(x, y) - R_{\text{max}}(x, y); \\
D(x, y) = 0;
\end{cases}
\]

Actually the maximum and the minimum tolerance images \( (I_{\text{max}}, I_{\text{min}}) \) are also generated from the inspected image, and the original image (reference or inspected) which has bigger tolerance range (max.-min.) is compared with the other tolerance images to prevent the overlooking of the defects which exist on narrow line and space pattern.

B. Solution to Defect Detection Failures on Boundaries

Problem 2 in Section II-B is caused by inspecting with subdivided inspection blocks. In order to avoid this problem in PCSR-G, we propose shifting the entire inspection block with respect to the reference image in one-pixel increments over a specified horizontal and vertical range. The search for difference in exclusive-OR images for PCSR-B becomes a search for maximum values in difference images for PCSR-G. Shifting the inspection block in this way is equivalent to applying a maximum value filter or a gray dilation operation to the image.

C. Details of PCSR-G Algorithm

The structure of PCSR-G is shown in Fig. 3, and the processing flow is as follows:

1) Obtain \( R_{\text{max}}, R_{\text{min}}, I_{\text{max}} \) and \( I_{\text{min}} \) as mentioned in III-A.

2) Make multiple shifted \( R_{i,j}, R_{\text{max}i}, \) and \( R_{\text{min}i} \) images, where \( i, j \) are the number of shifted pixels in vertical and
Fig. 4. An example of repeated pattern inspection

3) Compute the difference images \((D_d)\) by the following operation.

\[
\begin{align*}
&\text{if} \ (R_{\max}(x, y) - R_{\min}(x, y)) \\
&\quad< (I_{\max}(x, y) - I_{\min}(x, y)) \} \\
&\quad\text{if} \ (I(x, y) < R_{\min}(x, y)) \\
&\quad\quad D_{ij}(x, y) = R_{\min}(x, y) - I(x, y); \\
&\quad\text{else if} \ (I(x, y) > R_{\max}(x, y)) \\
&\quad\quad D_{ij}(x, y) = I(x, y) - R_{\max}(x, y); \\
&\quad\text{else } D_{ij}(x, y) = 0; \\
&\quad\text{else if} \ (R_{ij}(x, y) < I_{\min}(x, y)) \\
&\quad\quad D_{ij}(x, y) = I_{\min}(x, y) - R_{ij}(x, y); \\
&\quad\text{else if} \ (R_{ij}(x, y) > I_{\max}(x, y)) \\
&\quad\quad D_{ij}(x, y) = I_{\max}(x, y) - I_{\min}(x, y); \\
&\quad\text{else } D_{ij}(x, y) = 0; \\
&\text{else } \\
&\quad \text{if} \ (R_{ij}(x, y) < I_{\min}(x, y)) \\
&\quad\quad D_{ij}(x, y) = I_{\min}(x, y) - R_{ij}(x, y); \\
&\quad\text{else if} \ (R_{ij}(x, y) > I_{\max}(x, y)) \\
&\quad\quad D_{ij}(x, y) = I_{\max}(x, y) - I_{\min}(x, y); \\
&\quad\text{else } D_{ij}(x, y) = 0; \\
&\quad \text{else} \\
&\quad\quad D_{ij}(x, y) = I_{\min}(x, y) - R_{ij}(x, y); \\
&\quad\quad D_{ij}(x, y) = R_{ij}(x, y) - I_{\max}(x, y); \\
&\quad\quad \text{else } D_{ij}(x, y) = 0; \\
&\end{align*}
\]

4) Make the dilated images \((D_{dil})\) from \(D_{ij}\) by gray dilation operation with the \(K \times K\) sized SE, where \(K\) is greater than \(2P\).

5) Get the minimum value image \((D_{\min})\) by detecting the minimum values from \(D_{dil}\) as

\[D_{\min}(x, y) = \min_{i = -P, -P+1, \ldots, P} \{D_{dil}(x, y)\}. \quad (3)\]

6) Detect the defects by binarizing the \(D_{\min}\).

C. Application to Repeated Patterns

Fig. 4 shows an example of PCSR-G applied to repeated pattern inspection, such as the PWB for LSI packages or patterned wafer chips. In PCSR-G, defects are detected as original size or dilated size depending on that type. Therefore, as shown in the figure, when inspection is executed with replacing an inspected image and a reference image one after another, a defect can be detected in the same size with the original defect by "AND" operation of those results, at the same time the defective chip can be specified. Problem 1 in section II-B can be solved by using the repetition of the pattern as mentioned above.

IV. DEFECT DETECTION ABILITY IN PCSR-G

In this section, we discuss the theoretical defect detection ability in PCSR-G with ideal images which have no noises and gray value dispersions.

A. Defect Detection Probability without Edge Tolerance

When there are defects that are smaller than one pixel on inspected patterns as shown in Fig. 5, the differences between the defects and the reference patterns, \(D_d\), take the range of

\[D_d \in \left(-V_{pb}/4, V_{pb}/4\right), \quad (4)\]

where \(V_{pb}\) is the difference between a gray value of patterns and a gray value of backgrounds, and \(S_d\) is the size of a defect. We assume that a pixel output of a sensor is proportional to the area of pattern or background within that pixel.

On the other hand, the differences of the normal edges with no defects between an inspected image and a reference image, \(D_e\), become

\[0 < D_e < V_{pb}/2, \quad (5)\]

because PCSR-G also compares the inspected image and the reference image at the position where the reference image is shifted one pixel each other, and selects the minimum difference.

Therefore, when we assume that many edges exist randomly in an image, the defect detection probability without edge tolerance, \(P_d\), is given by

\[P_d = \begin{cases} 0 & : S_d < 0.5 \\ 1 & : S_d > 2.0 \\ \frac{4S_d - 2}{3S_d} & : \text{otherwise} \end{cases} \quad (5)\]

where \(D_{\max}\) and \(D_{\min}\) denote the maximum and the minimum values of \(D_d\) and \(D_e\) respectively.

The relation between \(S_d\) and \(P_d\) is shown in Fig. 6. The graph shows the defect detection probability in the ideal images is
Defect Detection Probability

![Graph](image)

Fig. 6. Defect detection probability without edge tolerance

Defect Detection Probability

![Graph](image)

Fig. 7. Defect detection probability with edge tolerance

B. Defect Detection Probability with Edge Tolerance

When the edge tolerance processing described in III-A is used, the defect detection probability changes by that defect type ("isolated" or "edge"). In a case of isolated defects like Fig. 5(a), the differences of the normal edges between an inspected image and a reference image, $D_r$, is expressed by

$$0 \leq D_r \leq (1 - \rho) \cdot (V_{pb} / 2),$$

while the differences of isolated defects are equivalent to (4). Consequently, the defect detection probability of isolated defects, $P_{id}$, becomes

$$P_{id} = \left\{ \begin{array}{ll} 0 & : S_d < (1 - \rho) / 2 \\ 1 & : S_d > 2 - 2\rho \end{array} \right. ,$$

and the relations between $P_{id}$, $S_d$, and $\rho$ are shown with solid lines in Fig. 7.

Then the differences of the edge defects, $D_e$, like Fig. 5(b) take the range of

$$\{(S_d - 2\rho) / 4 \cdot V_{pb} \leq D_e \leq (S_d - \rho) \cdot V_{pb}\},$$

therefore, the defect detection probability of edge defects, $P_{ed}$, is given by

$$P_{ed} = \left\{ \begin{array}{ll} 0 & : S_d < (1 + \rho) / 2 \\ 1 & : S_d > 2 - 2\rho \\ \frac{4S_d - 2p - 2}{3S_d} & : \text{otherwise} \end{array} \right. ,$$

and the curve of $P_{ed}$ is shown with broken lines in Fig. 7.

Though the detection ability would be dropped by noises or gray value dispersions in real images, it was proved that PCSR-G had theoretically the subpixel-sized defect detection ability from the above discussion.

V. EXPERIMENTS

A. Effect of Edge Tolerance Operation

Fig. 8 shows an effect of the edge tolerance operation described in III-A. As shown in Fig. 8(c), sampling errors of
pattern edges cause a lot of false defects (white pixels represent detected defects). Fig. 8(d) shows an inspection result that the tolerance values were made only from a reference image. The false defects by sampling errors were disappeared, but it could not detect the defect because the difference of the defect was also tolerated. However, the proposed tolerance operation could detect that defect with no false defects as shown in Fig. 8(e). Those results were binarized by same threshold.

B. Basic Performance Test

We examined the basic ability of defect detection in PCSR-G and the conventional subpixel alignment method [3] by using glass plates which patterned lattice pattern with 10um line patterns and various sized defects (3um-20um) to confirm the validity of PCSR-G. An example of the sample image which scanned the sample board by CCD line sensor camera with 8um resolution and a transparency illumination is shown in fig. 9. The relations between the defect size and the capture rate (or defect detection rate) with ρ=0.5 in PCSR-G are shown in Fig. 10. Here the capture rate (CR) is given by

\[
CR = \left( \frac{N_t}{N_d} \right) \times 100 \% ,
\]

where \( N_t \) is the number of detected true defects, \( N_d \) is the number of existing true defects, and the number was counted by 8-connected neighbourhoods.

\[\text{Ideal Probability (}\rho=0.5\text{)}\]

\[\text{Conventional algorithm}\]

\[\text{PCSR-G}\]

Fig. 10. Capture rate (Defect detection rate) by basic sample

The number of evaluated defect samples consists of 100 per each size, and it contains 50 isolated defects and 50 edge defects. The graph represents the whole performance of both the isolated defects and the edge defects, when thresholds were set so that the false defects might become zero. The result shows that PCSR-G has higher detection ability in comparison with the conventional subpixel alignment method, however, that is a little inferior to ideal ability because the line width is too narrow.

C. Performance Test Using Wafer Patterns

We applied PCSR-G to complicated wafer patterns, which were captured by SEM (Scanning Electron Microscope). An example of the inspection results is shown in Fig. 11. Though the inspected image (a) was rotated intentionally, PCSR-G was able to detect only the true defect. Over a range of sample images as shown in TABLE I, the average CR was more than 80% and the false alarm rate (FAR) was less than 30% when the threshold was set automatically based on the standard deviation of the difference image. Here, FAR is given by

\[
\text{FAR} = \frac{\text{Number of False Alarms}}{\text{Number of True Defects}} \times 100 \%
\]

TABLE I

<table>
<thead>
<tr>
<th>Wafer defect sample images</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wafer sample</td>
</tr>
<tr>
<td>Line width</td>
</tr>
<tr>
<td>Imaging device</td>
</tr>
<tr>
<td>Pixel resolution</td>
</tr>
<tr>
<td>Number of images</td>
</tr>
<tr>
<td>Image size</td>
</tr>
<tr>
<td>Pixel quantization</td>
</tr>
<tr>
<td>Defect categories</td>
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<td>Defect size</td>
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by using sample images. The proposed algorithm overcame
the problems that a conventional algorithm for binary images
had, and theoretical analysis showed that the proposed
algorithm had an ability of detecting subpixel-sized defects.
Furthermore, experimental results suggested practical
detection performance, and we confirmed that the system
which could execute the proposed algorithm at the speed of
more than several hundreds MPPS could be realized by
reasonable hardware resources.

In the near future, we will make the high-speed inspection
hardware, and apply to PWB and/or wafer inspection systems,
at the same time we will improve the algorithm, for example,
threshold optimization, reduction of false defects by
automatic defect classification and so on.

VIII. REFERENCES

[1] B.E. Dom and V. Brecher, "Recent advances in the
automatic inspection of integrated circuits for pattern
defects," Machine Vision and Applications No.8,
Springer-Verlag, 1995, pp. 5-19.
AUTOMATED SYSTEM FOR SUBMICROMETER
DEFECT DETECTION ON PATTERNED WAFERS."
Optical Microlithography and Metrology for
172-177.
Nakagawa, "Precise Visual Inspection for LSI Wafer
Patterns Using Subpixel Image Alignment," Proceedings
of 2nd IEEE Workshop on Applications of Computer
"Automated visual inspection of LSI wafer patterns using
a derivative-polarity comparison algorithm," Applications of Digital Image Processing XIV, vol.1567,
VISION, GRAPHICS, AND IMAGE PROCESSING 35,
[7] K. Watanabe and A. Sugimoto, "The wafer inspection
technology that manufacturing technique requires toward
the 0.18um age," Technology & Equipment '97, Special
Issue of monthly Semiconductor World, Press Journal,
of Patterned Wafer Defect Detection Tools for General
92-99.
[9] "Virtex-II 1.5V Field-Programmable Gate Arrays," Xilinx,