Anisotropic Diffusion based Micro-crack Inspection in Polycrystalline Solar Wafers

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***Abstract*— Polycrystalline solar wafer consists of various crystals so the surface of solar wafer shows heterogeneous textures. Because of this property the visual inspection of micro-crack is very difficult. In this paper, we propose the anisotropic diffusion-based micro-crack detection scheme for polycrystalline solar wafers. In the proposed method, anisotropic diffusion is based on the application of diagonal-kernel and cross-kernel in parallel. Experimental results show that the proposed method has better performance of micro-crack detection than conventional anisotropic diffusion-based methods on a cross-kernel.**

***Index Terms*— anisotropic diffusion, heterogeneously textured, solar wafer, micro-crack inspection, defect detection**

I. Introduction

Since various assembly lines became automatic, the machine vision systems have rapidly spread to the semiconductor, display, metal, and steel industries and have been used successfully in various fields. The main objective of the machine vision system used in solar wafer manufacturing is to detect the defects on surface of solar wafers. In this paper, we propose the micro-crack detection scheme for polycrystalline solar wafers. The proposed method is to apply the anisotropic diffusion based on a diagonal-kernel and conventional cross-kernel in parallel.

The anisotropic diffusion model was first introduced by Peron-Malik in image processing for edge detection and scale-space description [1]. It has been widely used as an adaptive edge preserving smoothing technique for edge detection, image restoration, image smoothing, image segmentation and texture segmentation.

The traditional machine vision defect detection algorithms based on spatial domain have been applied to timber inspection [3], carpet inspection [4] and metal inspection [5] and based on frequency domain have been applied to fabric [6], wafer [7] and steel quality inspection [8]. The disadvantage of these methods is that they can be applied only if the surface for inspection is uniform or repetitively patterned.

However, the polycrystalline solar wafer consists of various crystals so the surface of solar wafer has heterogeneous textures. Therefore, the conventional algorithms cannot be applied to this problem. Tsai *et al.* introduced the anisotropic diffusion based defect detection scheme, in which anisotropic model was based on cross-kernel [2]. In this paper, we applied a diagonal kernel in parallel with Tsai *et al.* method [2]. It shows better performance for defect detection.

This paper is organized as follows. Section 2 overviews the micro-crack properties in polycrystalline solar wafer. Section 3 overviews the conventional and proposed anisotropic diffusion model. Section 4 shows the experimental results from polycrystalline solar wafer images. The performance comparison with the Tsai *et al.* method is also discussed. Section 5 gives the conclusion of our research.

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II. Micro-crack properties in Polycrystalline Solar wafer

A. Micro-crack properties in polycrystalline solar wafer images

The micro-crack in polycrystalline solar wafers has two main features: low gray-level and high gradient magnitude [2]. Fig. 1 displays a partial solar wafer image that contains a diagonal micro-crack on the center of the image. If the width of the crack is wide then the gray-value of the pixels is low.

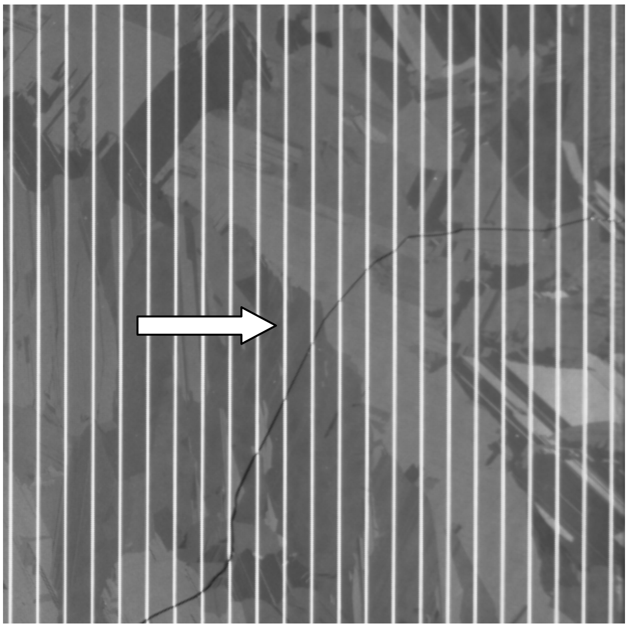

Fig. 1. Micro-crack in polycrystalline solar wafer

ISBN: 978-988-18210-3-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

B. The limitations of conventional algorithms

Generally, in the semiconductor and display industries, there are two defect detection schemes of the automated visual inspection system. The first method is to use the image subtraction and the second method is to use the statistical properties in ROI (region of interest). In the former, the reference and test images are subtracted and the difference area is detected, while in the latter the ROI for inspection is set up using reference image and the defect is detected by statistical properties of the ROI in test image (e.g., mean, standard deviation, etc.). These two methods require that brightness of ROI in the test and reference image should be uniform. If the variation of gray-value of ROI on test images for each production is large, then the above-mentioned approaches are not available. Fig. 2 shows the defect detection scheme by statistical properties in ROI and Fig. 3 shows that the defect detection scheme by image subtraction.

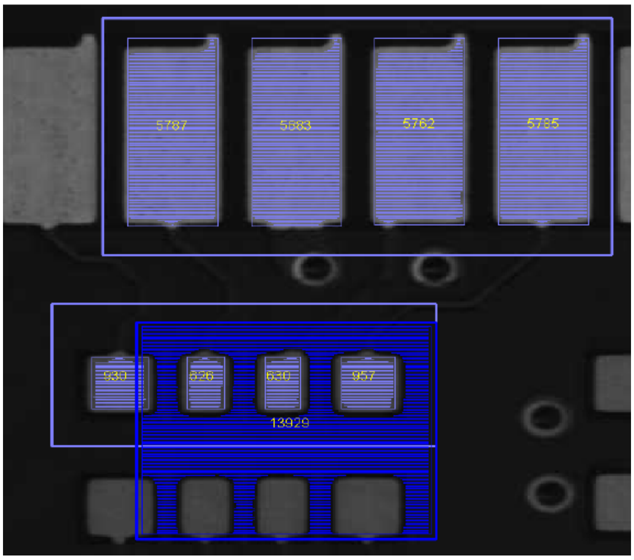

Fig. 2. Defect detection scheme by statistical properties in ROI

Fig. 3. Defect detection scheme by image subtraction

As can be seen from Fig. 1, the surface of polycrystalline solar wafer is very irregular and varies with each product. Therefore, detection of the micro-crack on these wafers is a very difficult issue.

To solve this problem, Tsai *et al.* introduced the anisotropic diffusion based defect detection scheme that was anisotropic model based on cross-kernel [2].

III. Anisotropic Diffusion Model

A. Micro-crack properties in polycrystalline solar wafer images

Anisotropic-diffusion model was first introduced by Perona-Malik in image processing for scale-space description and edge detection. It has been used as an adaptive edge-preserving smoothing process for texture segmentation and image segmentation. It is diffusion filter using the pixel information from cross-kernel [1].

In the anisotropic diffusion model (1), $\mathbf{I}_t(x,y)$ denotes the gray-level at coordinates (x,y) of a digital image at iteration t. The cross-kernel represent the gradients of four neighbors in north, south, east and west directions, respectively, i.e.,

$$\mathbf{I}_{t+1} = \mathbf{I}_t(x,y) + \frac{1}{4}\sum_{i=1}^{4}\left[c_t^i(x,y)\cdot\nabla I_t^i(x,y)\right] \tag{1}$$

Anisotropic diffusion uses the cross-kernel in Eq. (2) and smoothes the neighbors in the north, south, east and west direction pixels. However, if we use the gradient magnitude directly, the edge will be smoothed, and therefore, we cannot preserve the edge. Hence, we need the diffusion coefficients $c_t^i(x,y)$.

$$\begin{aligned}\nabla\mathbf{I}_t^1(x,y) &= \mathbf{I}_t(x,y-1) - \mathbf{I}_t(x,y)\\ \nabla\mathbf{I}_t^2(x,y) &= \mathbf{I}_t(x,y+1) - \mathbf{I}_t(x,y)\\ \nabla\mathbf{I}_t^3(x,y) &= \mathbf{I}_t(x+1,y) - \mathbf{I}_t(x,y)\\ \nabla\mathbf{I}_t^4(x,y) &= \mathbf{I}_t(x-1,y) - \mathbf{I}_t(x,y)\end{aligned} \tag{2}$$

$$c_t^i(x,y) = g\left(\nabla\mathbf{I}_t^i(x,y)\right) \tag{3}$$

B. Tsai, Chan and Chao diffusion model

The micro-crack in polycrystalline solar wafers has both low gray-level and high gradient magnitude in image. The Tsai *et al.* introduced the anisotropic diffusion based defect detection scheme that was anisotropic model based on cross-kernel [2]. The proposed method smooths the micro-crack and preserves the pixel-value of all pixels in the faultless region. After this process, the subtraction between diffused image and original image will significantly intensify the micro-crack in difference image. After that, the micro-crack in difference image can be detected.

The diffusion coefficients function of the Tsai *et al.* diffusion model for micro-crack detection is given by

$$g(\nabla\mathbf{I}, f) = \frac{1}{1+\left[f(x,y)\cdot\left(\dfrac{K}{\nabla\mathbf{I}(x,y)}\right)^2\right]} \tag{4}$$

and $f(x,y)$ is given as

$$f(x,y) = \frac{\mathbf{I}_0(x,y)}{255} \tag{5}$$

ISBN: 978-988-18210-3-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

where $f(x,y)$ is the normalized gray-level of an original image with 8-bit display, i.e. and K is the regularization parameter.

The difference image between original image and diffused image is then defined as

$$\nabla \mathbf{I}(x,y) = \left| \mathbf{I}_0(x,y) - \mathbf{I}_T(x,y) \right|, \forall (x,y) \quad (6)$$

In order to segment micro-crack defects in the difference image, we use the simple statistical control limit to set up the threshold. It is given by

$$\mathbf{B}(x,y) = \begin{cases} 0, & if\ \Delta \mathbf{I}(x,y) > \mu_{\Delta I} + C \cdot \sigma_{\Delta I} \\ 255, & otherwise \end{cases} \quad (7)$$

where $\mu_{\Delta I}$ and $\sigma_{\Delta I}$ are the mean and standard deviation of the difference image, and C is a control constant.

In order to remove the noisy pixels in the binary image, the noise-removal process proceeds as follows.

$$\begin{aligned} &If\ \mathbf{B}(x-1,y)+\mathbf{B}(x,y)+\mathbf{B}(x+1,y)=0, \quad or \\ &\quad \mathbf{B}(x,y-1)+\mathbf{B}(x,y)+\mathbf{B}(x,y+1)=0, \quad or \\ &\quad \mathbf{B}(x-1,y+1)+\mathbf{B}(x,y)+\mathbf{B}(x+1,y-1)=0, \quad or \\ &\quad \mathbf{B}(x-1,y-1)+\mathbf{B}(x,y)+\mathbf{B}(x+1,y+1)=0, \quad or \\ &then \\ &\quad let\ \hat{\mathbf{B}}(x,y)=0 \text{ (retain the defect point)} \\ &else \\ &\quad let\ \hat{\mathbf{B}}(x,y)=255 \text{ (remove the noisy point)} \\ &end \end{aligned} \quad (8)$$

After post-processing, some pixels of the micro-crack are also erased. In order to refill the disconnected micro-crack region, a filling process is carried out right after the noise-remove process.

$$\begin{aligned} &If\ \hat{\mathbf{B}}(x,y)=0\ and\ \mathbf{B}(x+i,y+j)=0, \\ &then \\ &\quad let\ \hat{\mathbf{B}}(x+i,y+j)=0, \\ &\quad for\ any\ (x+i,y+j)\in N(x,y). \\ &end \end{aligned} \quad (9)$$

C. Proposed diffusion model

The conventional diffusion model uses four neighbors in the north, south, east and west. Therefore, it reflects the four neighbors' pixel information well, but it cannot reflect the diagonal pixel information [2].

The micro-crack in polycrystalline solar wafer can occur in all directions. Therefore, the conventional method has a drawback that it cannot reflect the diagonal pixel information. In this paper we propose to apply the anisotropic diffusion based on a diagonal-kernel in parallel with conventional cross-kernel.

The difference image between original and diffused images of the north, south, east and west directions is defined in Eq. (10) as

$$\nabla \mathbf{I}_{NSWE}(x,y) = \left| \mathbf{I}_0(x,y) - \mathbf{I}_T^{NSWE}(x,y) \right|, \forall (x,y) \quad (10)$$

In Eq. (11), the difference image between original and diffused images of the diagonal directions is then defined as

$$\nabla \mathbf{I}_{diagonal}(x,y) = \left| \mathbf{I}_0(x,y) - \mathbf{I}_T^{diagonal}{}_T(x,y) \right|, \forall (x,y) \quad (11)$$

And the diagonal-kernel represent the gradients of four neighbors in northeast, southeast, northwest and southwest directions, respectively, i.e.,

$$\begin{aligned} \nabla \mathbf{I}_t^1(x,y) &= \mathbf{I}_t(x-1,y-1) - \mathbf{I}_t(x,y) \\ \nabla \mathbf{I}_t^2(x,y) &= \mathbf{I}_t(x+1,y+1) - \mathbf{I}_t(x,y) \\ \nabla \mathbf{I}_t^3(x,y) &= \mathbf{I}_t(x+1,y-1) - \mathbf{I}_t(x,y) \\ \nabla \mathbf{I}_t^4(x,y) &= \mathbf{I}_t(x-1,y+1) - \mathbf{I}_t(x,y) \end{aligned} \quad (12)$$

The reconstruction image between cross-kernel diffused image and diagonal-kernel diffused image is then defined as

$$\nabla \mathbf{I}(x,y) = \nabla \mathbf{I}_{NSWE}(x,y) + \nabla \mathbf{I}_{diagonal}(x,y), \forall (x,y) \quad (13)$$

IV. Experimental results

In this section, we present the experimental results. We use the sensed image under front LED illumination and evaluate the proposed algorithm performance. In order to evaluate the proposed method, we subtract the result of conventional method from the result of proposed method and check remaining pixels.

Fig. 4 and Fig. 5 show the result of experiment. We can check remaining pixels that are a subtraction between the result of conventional method and the result of proposed method.

V. Conclusion

We discuss anisotropic diffusion model for micro-crack defect detection in polycrystalline solar wafer. The anisotropic diffusion is widely used technique in the field of image processing.

The polycrystalline solar wafer consists of various crystals so the surface of solar wafer has heterogeneous textures. Therefore, the conventional algorithms cannot be applied to this problem. Tsai *et al.* announced the anisotropic diffusion based defect detection scheme that utilized anisotropic model based on cross-kernel. In this paper, we applied a diagonal kernel to Tsai-Chang-Chao method. It shows better performance for defect detection.

Experimental results have shown that the proposed diffusion model can be well applied to the micro-crack detection of polycrystalline solar wafers.

ISBN: 978-988-18210-3-4
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

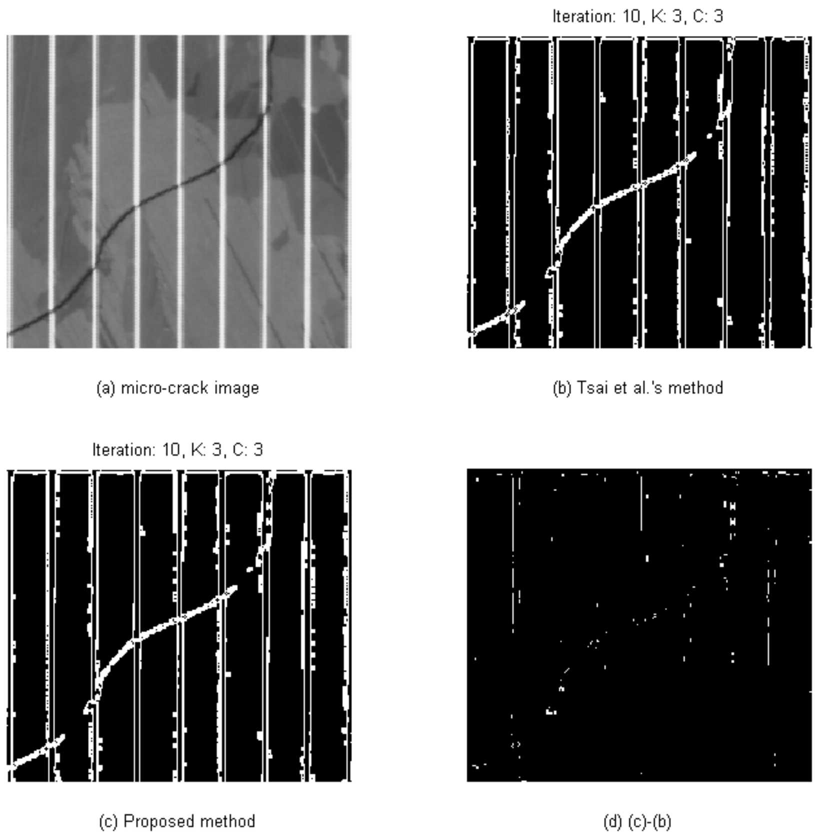

Fig. 4. Performance evaluation (a) micro-crack image, (b) Tsai *et al.*'s method, (c) proposed method, (d) the subtraction result between the conventional and the proposed method

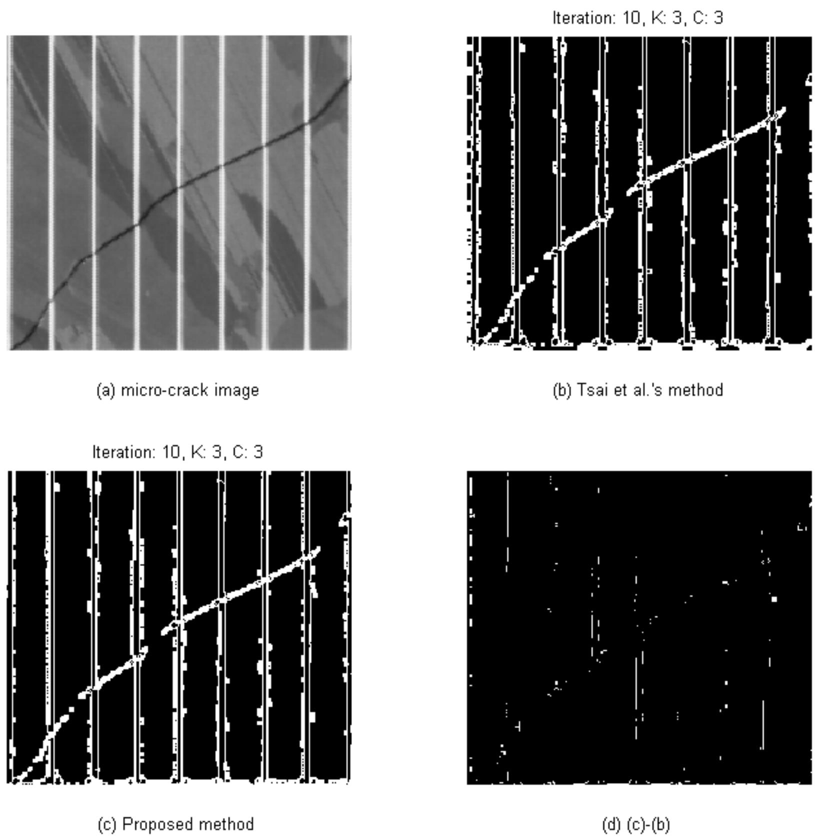

Fig. 5. Performance evaluation (a) micro-crack image, (b) Tsai *et al.*'s method, (c) proposed method, (d) the subtraction result between the conventional and the proposed method

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REFERENCES

[1] P. Perona and J. Malik, "Scale-space and edge detection using anisotropic diffusion," *Pattern Analysis and Machine Intelligence, IEEE Transactions on*, vol. 12, no. 7, pp. 629-639, 1990.

[2] D. Tsai, C. Chang, and S. Chao, "Micro-crack inspection in heterogeneously textured solar wafers using anisotropic diffusion," *Image and Vision Computing*, vol. 28, no. 3, pp. 491-501, Mar. 2010.

[3] R.W. Conners, C.W. McMillin, K. Lin and R.E. Vasquez-Espinosa, "Identifying and locating surface defects in wood," *IEEE Transactions on Pattern Analysis and Machine Intelligence PAMI-5*, pp. 573–583, 1983.

[4] L.H. Siew and R.M. Hogdson, "Texture measures for carpet wear assessment," *IEEE Transactions on Pattern Analysis and Machine Intelligence 10*, pp. 92–105, 1988.

[5] K.V. Ramana and B. Ramamoorthy, "Statistical methods to compare the texture features of machined surfaces," *Pattern Recognition 29*, pp. 1447–1459, 1996.

[6] J. Escofet, M.S. Millan, H. Abril and E. Torrecilla, "Inspection of fabric resistance to abrasion by Fourier analysis," *Proceedings of SPIE 3490*, pp. 207–210, 1998.

[7] T. Ohshige, H. Tanaka, Y. Miyazaki, T. Kanda, H. Ichimura, N. Kosaka and T. Tomoda, "Detect inspection system for patterned wafers based on the spatial-frequency filtering," *IEEE/CHMT European International Electronic Manufacturing Technology Symposium*, pp. 192–196, 1991.

[8] K. Wiltschi, A. Pinz and T. Lindeberg, "Automatic assessment scheme for steel quality inspection," *Machine Vision and Applications 12*, pp. 113–128, 2000.

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