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Defect detection in multi-crystal solar cells using clustering with uniformity measures ☆

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ABSTRACT

Solar cells that convert sunlight into electrical energy are the main component of a solar power system. Quality inspection of solar cells ensures high energy conversion efficiency of the product. The surface of a multi-crystal solar wafer shows multiple crystal grains of random shapes and sizes. It creates an inhomogeneous texture in the surface, and makes the defect inspection task extremely difficult. This paper proposes an automatic defect detection scheme based on Haar-like feature extraction and a new clustering technique. Only defect-free images are used as training samples. In the training process, a binary-tree clustering method is proposed to partition defect-free samples that involve tens of groups. A uniformity measure based on principal component analysis is evaluated for each cluster. In each partition level, the current cluster with the worst uniformity of inter-sample distances is separated into two new clusters using the Fuzzy C-means. In the inspection process, the distance from a test data point to each individual cluster centroid is computed to measure the evidence of a defect. Experimental results have shown that the proposed method is effective and efficient to detect various defects in solar cells. It has shown a very good detection rate, and the computation time is only 0.1 s for a 550×550 image.

1. Introduction

Solar cells are very important in recent years as an attractive alternative of energy resources. Solar cells are mainly based on crystalline silicon in the photovoltaic industry. Compared to monocrystalline solar cells, multicrystalline solar cells dominate the current market shares due to lower material and manufacturing costs.

Since defects in solar cells degrade the conversion efficiency and usable lifespan, the inspection of solar cells is very important in the manufacturing process. The surface of a multiicrystalline solar wafer shows multiple crystal grains of random shapes and sizes, as seen in Fig. 1(a). Fig. 1(b) presents the CCD-captured images of a multicrystalline solar cell. The vertical thin metal lines are finger electrodes. They supply current to the two horizontal bus bars. The crystal grains appear randomly in the surface. The solar cell images thus involve inhomogeneous textures.

Texture analysis techniques [1] in image processing have been used for defect detection of various material surfaces. They mainly aim at uniform or homogeneous texture surfaces. Local textural features or descriptors are extracted either from the spatial domain [2–5] or from the spectral domain [6–10] of a texture image. Discriminant classifiers are then applied to separate local defects from the homogeneous background. They cannot be directly extended to the inspection of heterogeneous surfaces.

Defect detection using machine vision methods has been studied extensively in the literature. However, most of the methods can only handle uniform surfaces, or textured surfaces with homogenous/repetitive patterns. The target object in this study is multi-crystal solar cells that contain heterogeneous textures. A defect-free solar cell surface may involve various texture patterns in different regions. This makes the inspection task extremely difficult. Image processing techniques have also been applied to the inspection of solar wafers and solar cells. Fu et al. [11] developed a machine vision algorithm to detect cracks in solar cells. The method can only identify cracks that show distinct high-contrast gray levels in the cell edges. Pilla et al. [12] used the thermographic technique to intensify cracks in solar cells. A simple thresholding can then separate the defects from the uniform surface. Warta

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[13] reviewed different sensing techniques to intensify defects and impurity in solar cells.

Tsai et al. [14] presented an anisotropic diffusion algorithm for detecting micro-cracks in multicrystalline solar wafers. The diffusion process removes the crystal-grain background, and retains only the crack. The method is very effective and computationally fast, but it can detect only micro-cracks. It cannot be directly used for other defect types. Li and Tsai [15] proposed a machine vision algorithm to detect saw-mark defects in the solar wafer cutting process. The Fourier transform is used to remove the crystal grain background. A Hough-like line detection process is then applied line by line in the filtered image to detect possible defect points. It can detect only the specific saw-mark defects. Chiou and Liu [16] used a near infrared imaging system to highlight micro-cracks in solar wafers. The method works only when the sensed micro-crack is significantly darker than the crystal grains. It may falsely detect a dark, thin defect-free crystal grain as a defect.

A typical CCD camera cannot effectively capture fatal defects such as micro-cracks and subtle finger interruptions. The electroluminescence (EL) imaging technique [17,18] has been introduced to the photovoltaic industry to intensify the deficiencies of a solar cell. The solar cell is first excited with voltage in the EL imaging system. This causes the solar cell to emit the infrared light. A cooled Si-CCD camera then captures the infrared light. Silicon areas with high conversion efficiency present brighter luminescence in the sensed image. Deficiencies of a solar cell appear as dark regions in the EL image. Fig. 2(a) presents the EL image of a defect-free solar cell. Fig. 2(b)–(d) shows respectively three EL images with micro-cracks, breaks, and finger interruptions. The defect areas are inactive and do not emit light well. They thus generate dark regions in the EL image. Although the EL image can visually present defects as dark objects, the background also shows dark grain boundaries of the random crystal grains. Automatic visual inspection of solar cell defects in the EL image becomes very difficult. The currently available inspection machine for solar modules in the manufacturing process can automatically acquire the EL image and display it on the monitor. However, it still requires a human operator to visually identify defects from the EL image. It took the operator a few seconds per solar cell to complete the inspection. The distinctly visible defects, such as large-size breaks, can be easily identified by human eyes. However, subtle defects, such as small thin cracks, could be carelessly ignored by the operator.

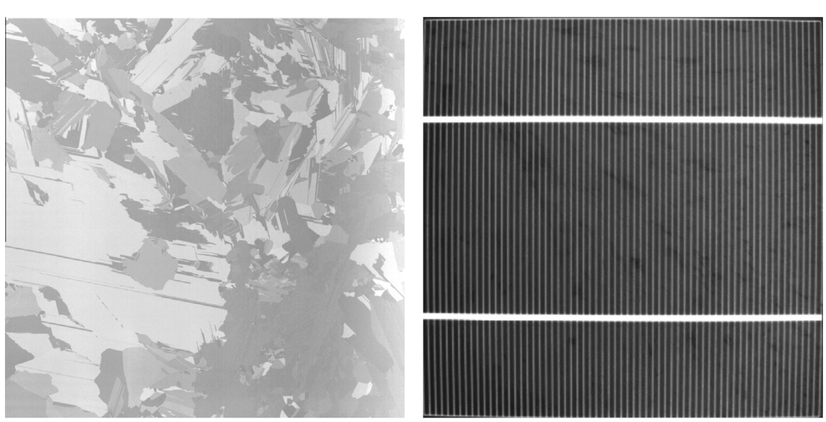
In this paper, we propose a machine vision scheme to automatically detect micro-cracks, breaks, and finger interruptions of multi-crystal solar cells in EL images. Those defects are the main sources that reduce the conversion efficiency of solar cells. They could occur during module assembly and material handling. It has been shown [19] that the breakage rate (breakage cells/total cells) accounts for 2% from manufacturing to transportation in the photovoltaic industry. The high defective rate could be a serious problem of a solar cell manufacturer.

The proposed method is based on the clustering technique. Clustering is an unsupervised classification method to separate a set of multivariate data points into meaningful groups. All members within a partitioned group present similar characteristics. Data points in different groups are distinct from each other. The fuzzy C-means (FCM) algorithm [20] is one of the most popular techniques used for clustering. Since the surface of a clear solar cell contains random crystal grains with a variety of grain patterns, the discriminative features extracted from individual crystal-grain patterns will then show a huge number of clusters in the feature space. It may require several tens of clusters to describe all possible grain patterns in a defect-free solar cell. The conventional Fuzzy C-means methods work well to partition a dataset in high-dimensional space into a few clusters. Its performance degrades as the required number of clusters increases.

In this study, we present a binary-tree partition procedure to cluster crystal grain patterns of defect-free solar cells into groups. Given a set of high-dimensional data points, the proposed clustering method first divides the dataset into two groups using the FCM. A uniformity measure of inter-sample distances in a cluster is then calculated for all current clusters, and the one with the worst uniformity is further divided into two small groups using the FCM. The partition process is repeated until the total number of clusters meets a preset value. The proposed binary-tree partition procedure can more accurately cluster a dataset involving a high number of clusters, compared to the conventional FCM.

Since a solar cell involves distinct crystal grain patterns, it is difficult to use a binary classifier to separate samples into defective and defect-free classes. Instead, we train only defect-free samples and group them into multiple clusters using the binary-tree partition procedure. Any test sample that does not show an acceptable small distance from at least one of the trained cluster centroids is then identified as a defect. In order to characterize the local properties in a solar cell image, we design a set of Haar-like features so that each pixel point defined in a small neighborhood window can be represented by the discriminative feature vector. It is expected that the feature vector of a defect point will result in distinctly large distances from all trained cluster centroids.

This paper is organized as follows: Section 2 first describes briefly the conventional FCM method. The proposed binary-tree partition procedure for defect inspection is then described in



(a) (b)

Fig. 1. CCD-captured image of a multi-crystal solar cell: (a) solar wafer and (b) solar cell.