International Core Journal of Engineering Volume 8 Issue 2, 2022
ISSN: 2414-1895 DOI: 10.6919/ICJE.202202_8(2).0013

Review on Surface Defect Detection Methods of Solar Cells

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Abstract

This paper summarizes the production process of solar cells, analyzes the types and causes of common defects, analyzes the surface defect detection method of solar cells, reviewed the artificial physics method and machine vision method, introduces the traditional image processing method and deep learning detection method, analyzes the characteristics of the detection methods, discusses the future research ideas, and discusses the development direction.

Keywords

Solar Cell; Defect Detection; Machine Vision; Deep Learning.

1. Introduction

In recent years, with the rapid development of global economy and industrialization, the large consumption of coal, oil and other non-renewable energy sources has caused increasingly serious environmental problems. Therefore, people gradually start to develop renewable clean energy such as solar energy, water energy, wind energy and geothermal energy, among which solar energy comes from solar thermal radiation energy and green clean energy [1] with the advantages of high energy quality, high safety and wide popularity.Solar photovoltaic power generationtechnology is a typical application technology of solar energy[2]. It converts solar energy into electric energy, which can be applied in batches to road lighting and traffic lights and other scenarios, which can better alleviate the current energy shortage and environmental pollution problems. Solar cells are an important part of the solar photovoltaic power generation system, and their product quality seriously affects the power generation efficiency. In the multiple manufacturing processes such as slicing, cleaning and velvet making, and back passivation, solar cells are prone to the production environment, human causes, mechanical pressure and other multiple factors, which will inevitably produce a variety of defects, such as black spots, scratches, grille breaks, cracks and other[3].The application of defective solar panels in life will have problems such as low power generation efficiency, short service life of components, and in serious cases may even cause electricity danger, resulting in unnecessary casualties and economic losses. Therefore, it is necessary to detect solar cells on the surface, eliminate defective cells, to further improve the cell yield rate.

2. Fabrication Materials and Processes

Silicon is the main material for making solar cells at present. According to the orientation of crystal nucleus growth and crystal forming surface during solidification of monocrystalline silicon, it can be divided into monocrystalline silicon and polycrystalline silicon, and finally monocrystalline silicon cells and polycrystalline silicon cells are made. The main manufacturing process of battery is shown in Figure 1:

ISSN: 2414-1895 DOI: 10.6919/ICJE.202202_8(2).0013

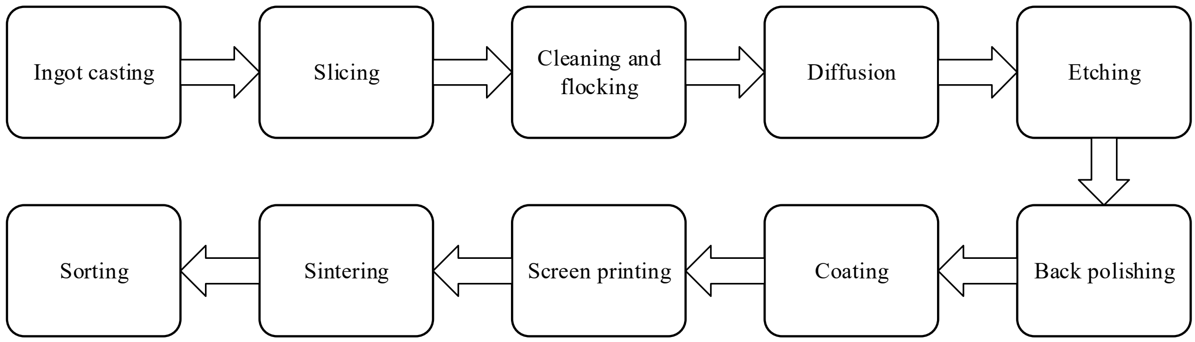

Figure 1. Main manufacturing process of battery

Ingot casting: melt the silicon material and pull it into a cylindrical silicon ingot;

Slicing: the silicon ingot is cut into sheets with regular shape (usually square sheets) and uniform thickness by diamond wire or other methods, with a thickness of about 180 ~ 200 microns;

Cleaning and flocking: after washing the silicon wafer, put it into hydrofluoric acid to chemically corrode its surface, resulting in a pyramid like suede structure, which can reduce the reflectivity of sunlight and increase light absorption, so as to improve the photoelectric conversion efficiency of the battery wafer;

Diffusion: phosphorus diffusion is carried out on one side surface of silicon wafer to make PN junction;

Etching: remove the PN junction to prevent short circuit of the battery;

Back polishing: polishing the back of silicon wafer by acid or alkali polishing technology;

Coating: a layer of silicon nitride film, commonly known as antireflection film, is coated on one side of the formed PN junction. Plasma enhanced chemical vapor deposition (PECVD) technology is usually adopted. This operation can reduce light reflection, produce passivation on the surface, reduce the recombination of minority particles on the surface of PN junction and increase efficiency;

Screen printing: metal electrodes are printed on the front and back of the silicon wafer. The role of the electrodes is to collect a few carriers generated by photovoltaic effect;

Sintering: the circuit printed in the screen printing stage is sintered and formed into a whole with the silicon chip, and the battery chip is obtained after the end of this stage;

Sorting: test the performance of the battery and select the battery with different efficiency for sorting.

3. Imaging Mode

At present, there are four main imaging methods of solar cells: visible light imaging, infrared thermal imaging, photoluminescence and electroluminescence[4]. The images formed by different imaging methods have different image characteristics. Visible light imaging is the simplest and easiest to build, but this method can only image the appearance of the battery, and cannot obtain internal information. Therefore, it is only suitable for detecting appearance defects such as stains, missing angles and color differences; Although infrared thermal imaging and electroluminescence imaging can obtain the internal and external information of the battery, they both need to power on the battery. Direct contact with the battery is easy to cause secondary pollution to the battery. The use of photoluminescence (PL) can not only image the surface and internal defects of the battery at the same time, but also do not need to contact the battery during acquisition, which is more favorable for subsequent defect detection.

ISSN: 2414-1895
DOI: 10.6919/ICJE.202202_8(2).0013

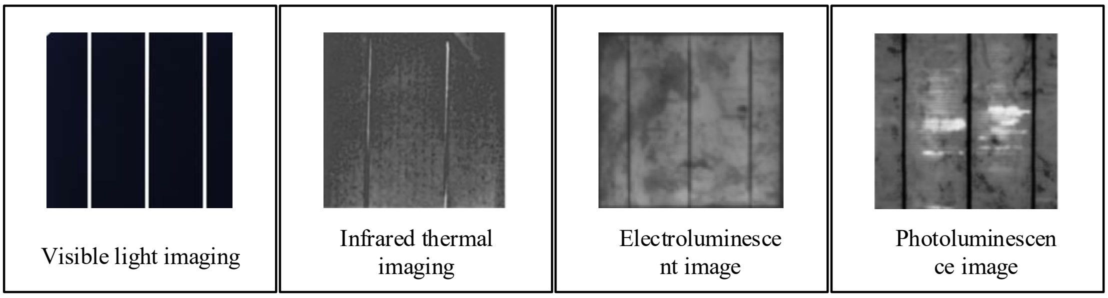

Figure 2. Imaging mode of solar cell

4. Defect type

The manufacturing process of solar cells is complex, and various defects are easy to occur in the manufacturing process. Analyzing the source of defects is very helpful for defect detection and the improvement of production process. Table 1 lists the common defects on the surface of solar cells and the causes of defects.

Table 1. Common defects and causes

Defect type	causes
Missing corner, damage, hole and scratch	Accidental cutting and collision
Black spot, broken grid, foggy blackening	Production process defects
Stain, wheel print, fingerprint	Human factors and untidy production environment

5. Research Status of Battery Defect Detection Methods

Solar cell is an important part of solar photoelectric conversion system. It has the advantages of low material cost, high conversion efficiency and long service life. However, the particularity of the inherent texture on the surface of the battery and the diversity of defects increase the difficulty of defect detection. The existing defect detection methods of solar cell surface can be divided into the following two kinds: artificial physics method and machine vision method [5]. In machine vision, according to whether it is necessary to extract features manually, it can be divided into defect detection methods based on traditional image processing and deep learning.

5.1 Artificial Physical Method

Silicon series solar cells are composed of PN junction semiconductors, which contain different impurities. When excited by electricity or light, the semiconductors will generate a certain voltage or emit photons . Therefore, scholars apply current source, voltage source or strong light on solar cells to measure the current or voltage inside semiconductors for defect detection. This defect detection method using the physical conductivity of solar cells is called artificial physical method.

Li Tianzhen et al.[6] and Zhang WuJie et al.[7] use circuit knowledge to detect defects, add current source or voltage source to the battery and analyze the current or voltage flowing through the solar cell, so as to judge whether there are surface defects of the solar cell. Wen et al.[8] proposed a crack detection method based on electronic speckle interferometry. The electronic speckle patterns of normal samples and defect samples are obtained through the equipment for comparative analysis to complete the defect detection. This method is applicable to the crack detection on the surface of battery. Gabor a m et al. Developed the defects by applying enhanced light irradiation on the back of the cell, and pressed the glass side of the module at each unit position by hand to complete the separation of most closed cracks[9]. Because this method directly contacts the components of the solar cell, it is likely to cause accidental damage to the solar cell.

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Some scholars also proposed the acoustic vibration detection method. In the defect detection, tsuzukik et al.[10] first obtained the acoustic wave generated during the resonance of the battery, and then completed the crack defect detection according to the acoustic wave difference between the defect sample and the normal sample. Belyaev a proposed the ultrasonic resonance method based on longitudinal resonance to detect the common crack defects in the surface defects of battery chips. The external piezoelectric transducer is integrated with a high-sensitivity ultrasonic probe and a data acquisition card based on frequency response to detect the defects. This method enables the real-time detection of solar silicon chips in the production process [11]. Zhou et al.[12] Proposed a detection method based on resonant ultrasonic vibration. This method uses the characteristics of different densities of the complete area and damaged area of the battery board, takes the density as the separation standard, realizes the segmentation of the defect area, and then completes the defect detection.

5.2 Defect Detection Method based on Machine Vision

Machine vision technology is a comprehensive application technology, mainly including computer software and hardware technology, image processing technology and human-computer interaction technology. It is widely used in target detection and image processing, and has achieved great success. More and more researchers use machine vision technology to detect the defects of solar cells. The main detection process can be summarized as follows: image the surface of solar cells, extract the defect characteristics of solar cells by using various methods of machine vision, and then complete the defect detection. Because of its great advantages in detection speed and accuracy, it has gradually become the mainstream detection scheme.

5.2.1 Defect Detection Method based on Traditional Image Processing

The solar cell defect detection method based on traditional image processing mainly uses digital image processing and other technologies to analyze the solar cell image, mainly from the aspects of image brightness, color and pixel characteristics [13].

Wu Shijie et al.[14] after analyzing the characteristics of El image of solar cell, used Fourier transform to reconstruct the image, which is mainly used to eliminate the defects in the original image, calculated the difference between the eliminated defect image and the original image, and then completed the defect detection task ; Zeng Jigang[15] proposed a surface defect detection method of battery chip based on image segmentation, which uses the combination of gamma filtering and Otsu method to realize defect detection. The former is used to enhance the image and effectively enhance the characteristics of the defect area, and the latter is used for segmentation. Finally, judge whether the image has defects. This method can only detect defects on silicon chips without printed electrodes. Tsai d m et al. Proposed a defect detection scheme for the micro crack of the battery[16], which uses the LED lamp to illuminate and the CCD (electrically coupled device) camera to obtain the image of the battery, and proposed an anisotropic diffusion model, which adjusts the diffusion coefficient based on the characteristics of gray and gradient, subtracts the diffusion map from the original map, enhances the micro crack, and then combines the binary threshold processing and morphological operation, It can effectively segment the fine cracks in the image. Huang Yonghua et al.[17] carried out two-level threshold segmentation on the basis of image preprocessing. This method can distinguish three regions: normal, fault and aging. After analyzing the shortcomings of simple threshold segmentation, Li Qiao and others proposed a defect detection method based on local adaptive threshold processing method and region growth method. By combining the advantages of the two methods, the best threshold can be obtained to detect insignificant battery defects[18]. However, the algorithm only has a certain effect on the defect detection of monocrystalline silicon. In addition, Sun Zhiquan and others proposed a defect method combining morphology, convexity analysis and dynamic threshold segmentation. This method can have a good detection effect on the defects of edge damage and poor printing, and the average detection accuracy is 98.5% [19].

Peng x et al.[20] proposed a micro crack detection method for battery. This method uses image segmentation combined with Gaussian filter and Hough transform to detect defects. Although this

ISSN: 2414-1895 DOI: 10.6919/ICJE.202202_8(2).0013

method can detect obvious cracks, the success rate of detecting hidden small cracks is not high; According to the characteristic structure of the visible light image, Feng Bo et al.[21] proposed a crack detection scheme for solar cells, improved the penetration algorithm and tensor voting algorithm, analyzed the potential crack pixels by using the penetration algorithm, and then removed the noise by using the tensor voting algorithm. This scheme realizes the defect detection and location, which can not only effectively detect the cracks in the solar cells, The location information of defects can also be obtained, but the algorithm is prone to misjudgment when the imaging quality is poor. Zhang WuJie and others[22] analyzed the different characteristics of surface defects of solar cells, and designed the corresponding detection schemes according to the characteristics of different defects. Aiming at the problem of the shape damage of the battery, the defect detection method by fitting is proposed; Analyze the characteristics of holes, cracks, surface pollution and grid disconnection, and design a method combining sub shadow and multi template matching for defect detection. Ji Wangcun[23] proposed an image processing method based on region monitoring threshold segmentation. This method can highlight the defective region of the battery, remove the isolated breakpoint noise by median filter, and then use morphological processing to improve the texture connectivity of the defective region, so as to complete the defect detection task. However, the defect recognition rate is not high enough because there are few characteristic parameters used in the experiment.

5.2.2. Defect Detection Method based on Deep Learning

With the rapid development of computer software and hardware, its computing power and analysis ability are greatly improved. People gradually use computers to simulate human visual characteristics and complete object detection and recognition. In recent years, the deep learning model represented by convolutional neural network (CNN) has achieved a series of successes in the field of computer vision (CV). Researchers began to explore the possibility of applying deep learning to solar cell defect detection. The defect detection method based on deep learning came into being, Its main feature is the use of depth network for defect feature extraction, which can further improve the accuracy and speed of detection.

Wang Xianbao et al. Proposed a defect detection method for solar cells based on deep trust networks (DBN). This method uses sample features to establish and train DBN, uses BP (back propagation) algorithm to fine tune parameters, and finally realizes rapid detection of solar cells by comparing reconstructed images with defect images[24]. However, when facing high-pixel images, The network training process becomes very difficult. Liu Zhongde and others[25] took the texture and color features of the battery as defect recognition, input the feature matrix composed of the two features into the network for training, improved it by using the maximum likelihood method and adaptive time estimation method, optimized the depth confidence network parameters and improved the stability of the algorithm. Deitsch s et al.[26] proposed the defect detection scheme of solar cell El diagram. This method combines support vector machine (SVM) and convolutional neural network (CNN) to identify defects. Through experimental analysis, the average accuracy is 88.42%. Li Mengyuan combines the advantages of convolutional neural network and deep belief network, designs the structure of deep convolutional belief network, learns the input battery image layer by layer, and uses the learned high-level features for defect recognition. The recognition accuracy of defect image is 96%[27]. However, due to less defect types adopted during network training, the applicability of the model needs to be improved. Yan Weixin et al. Proposed a workpiece defect detection algorithm based on deep learning, verified the feasibility of the two-stage target detection algorithm fast r-cnn in defect location and detection, and proposed an anchor frame setting scheme to solve the problem of low detection accuracy of small defects, which greatly improved the effectiveness of the model[28]. Wu Lichun et al.[29] proposed a surface defect detection method based on template matching. For common appearance color defects, the color histogram based on his space is used for detection. For the situation that subtle defects are easy to be affected by noise, the author trained a normalized RBF classifier to detect broken grids. The results show that this method has short calculation time and high recognition rate. Wang Yannianproposed an accurate battery defect segmentation and detection

ISSN: 2414-1895 DOI: 10.6919/ICJE.202202_8(2).0013

algorithm by improving u-net network[30]. The dense connection structure is introduced to alleviate the gradient disappearance problem; At the same time, in order to retain the detailed characteristics of defects, batch normalization layer and relu activation layer are added behind each convolution layer; In addition, the dual attention mechanism of space and channel is introduced. The former helps to suppress noise, and the latter highlights the defect area, so that the method can segment complex defects with higher accuracy and robustness.

6. Analysis of Existing Methods

According to the above description, the current surface defect detection of solar cells is analyzed. As shown in Table 2, the defect detection method based on deep learning uses the powerful feature extraction ability of deep network to extract defect features, has better algorithm sharing, and has great advantages in detection speed and accuracy, It is the main development direction of defect detection methods for solar cells in the future.

Table 2. Analysis of defect detection methods

methods	Artificial physical defect detection method	Defect detection method based on traditional image processing	Defect detection method based on deep learning
principle	It mainly uses various physical characteristics of solar cells for defect detection	The feature extractor is designed, and the defect features are analyzed by using the traditional image processing method, so as to complete the detection	The depth network is used for image feature extraction, and then the detection is completed
characteristic	Artificial physical method belongs to contact detection method. There are many human factors in the detection process, which is easy to cause secondary damage to solar cells. And to a large extent, it is limited by the experience of inspectors and testing environment. Therefore, the real-time performance of industrial testing is not high, the detection efficiency is low, and it is very limited in the application of practical engineering.	Compared with the artificial physical detection method, the machine vision detection method basically realizes the automation of defect detection. However, researchers still need to design feature extractors independently, which rely too much on the professional knowledge of designers, and the parameter adjustment process is relatively complex, which is often difficult to capture deep-seated semantic information, and the sharing and robustness of the algorithm are poor.	Deep learning does not need feature process, and driven by a large number of data samples, it can obtain deeper features and express the information contained in data samples more accurately and efficiently. Target detection has great advantages in detection accuracy and detection speed, which is more suitable for the actual detection scene. It is the mainstream direction of solar cell surface defect detection in the future. However, due to the short development cycle of deep learning, the defect detection algorithms developed at home and abroad have various limitations in practical application, and can be applied to industrial automation detection is limited.

7. Summary and Prospect

Various defects will occur in the production process of solar cells. The existence of defects seriously affects the conversion efficiency of solar modules. Defect detection will help battery manufacturers improve the yield of solar cells, analyze the causes of defects, and improve the production process of solar cells, so as to speed up the development process of solar energy industry. In recent years, with the successful application of deep learning in target detection, the defect detection of battery has a new direction. Compared with the traditional scheme, the solar panel detection method based on deep learning has great advantages in detection accuracy, detection speed and economic benefits. It has become the main direction of the development of solar panel detection in the future. However, the current research results are few, the application of engineering automation is not mature, and there are still some deficiencies:

(1) The existing solar cell defect detection network based on deep learning needs to be improved in terms of accuracy and speed compatibility;

(2) At present, most defect detection schemes are only for several types, the model is not widely applicable, and there are many limitations in practical application;

(3) In the process of image processing, due to the fineness of battery surface defects and the particularity of inherent texture, after image enhancement and image segmentation, the battery image often has the coexistence of breakpoints and defect texture, texture discontinuity and so on, which makes the subsequent detection extremely difficult;

Although a large number of research results related to solar cell defect detection based on machine vision and deep learning are published every year. However, the algorithms that can be applied to the actual detection scene are limited. Therefore, there is still much room for progress in the future to study the online real-time detection algorithm of solar cell surface defects and realize industrial detection automation.

Acknowledgments

The Project of Sichuan provincial science and Technology Department (Grant No.2018JY0386, 2020YFG0178, 2021YFG0313).

The artificial intelligence key laboratory of Sichuan province Foundation (2019RYY01).

Enterprise informatization and Internet of things measurement and control technology key laboratory project of Sichuan provincial university (2018WZY01, 2019WZY02, 2020WZY02).

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