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Nondestructive inspection, testing and evaluation for Si-based, thin film and multi-junction solar cells: An overview

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ABSTRACT

Solar energy is one of the fastest growing renewable energy resources. It is extremely important to improve the reliability and availability of solar energy systems and to further reduce the operation and maintenance (O & M) cost. Solar cells and modules are considered as one of the most critical components in solar energy system because they convert solar energy into electricity. Flaws and damages are inevitable during either the fabrication or the service life of a solar cell or module. Thus, nondestructive inspection, testing and evaluation (NDI, NDT & NDE) for solar cells and modules are required in both manufacturing quality control and in-service inspection. In this work, a fully, in-depth and comprehensive review of NDT & E techniques for Si-based, thin film and multi-junction solar is reported based on an orderly and concise literature survey. Firstly, the developments and case comparison studies of electromagnetic, sonic and ultrasonic, optical, thermal, near-infrared, terahertz and mechanical test NDT & E for Si-based solar cells especially in the last three years are reviewed in detail. Next, the developments of NDT & E methods for film and multi-junction solar cells are also reviewed. After that, the strengths and limitations of these NDI and NDT techniques are concluded through comparison studies. Analytic hierarchy process (AHP) is used to compare 7 kinds of NDT methods which include photoluminescence (PL), electroluminescence (EL), illuminated lock-in thermography (ILIT), dark lock-in thermography (DLIT), resonance ultrasonic vibration (RUV), optical NDT and lamb wave air coupled ultrasonic testing (LAV-UT). In addition, the development tendencies for solar cell and related NDT & E are predicted. This work will serve as a guide for performance testing, failure analysis, quality control and health monitoring of Si-based cells, thin film and multi-junction solar cells and play an important role in solar energy safety control and cost saving.

1. Introduction

With the gradual warming of the global climate, the increasingly serious environmental pollution and the depletion of fossil energy, it is urgent to find efficient and practical renewable energy. Solar energy is one of the fastest growing renewable energy resources, and it is going to have remarkable share in the energy market. With the growing interest to quality and cost problems, much attention has been devoted to the development of reliability based maintenance or condition based maintenance. Solar cells and modules are considered as one of the most critical components in solar energy system because they convert solar energy into useful power. On the one hand, some flaws may occur in the manufacture process of cells. On the other hand, solar cells are facing harsh and complex service environment and could be damaged by moisture absorption, sleet, ultraviolet irradiation, atmospheric corrosion, fatigue, or lightning strikes etc. Thus, a lot of flaws and

Abbreviations: AE, Acoustic emission; AHP, Analytic hierarchy process; CCD, Charge coupled device; CIGS, Copper-indium-gallium-selenide; DLIT, Dark lock-in thermography; EBIC, Electron beam induced current; EBSD, Electron backscatter diffraction; EDX, Energy-dispersive X-ray; EL, Electroluminescence; EQE, External quantum efficiency; ESPI, Electronic speckle pattern interferometry; FEA, Finite element analysis; HTS-SQUID, High critical temperature superconductor superconducting quantum interference device; ILIT, Illuminated lock-in thermography; InGaAs, Indium gallium arsenide; IP, Image processing; IQE, Internal quantum efficiency; LAC-UT, Lamb wave air coupled ultrasonic testing; LBIC, Laser beam induced current; LIC, Quantitative lock-in carrierographic; LIT, Lock-in thermography; LTEM, Laser terahertz emission microscopy; MCR, Multivariate curve resolution; MPP, Maximum power point; MV, Machine vision; NDE, Nondestructive evaluation; NDI, Nondestructive inspection; NDT, Nondestructive testing; NDT & E, Nondestructive testing and evaluation; NIR, Near-infrared; O & M, Operation and maintenance; PCR, Photo carrier radiometry; PL, Photoluminescence; PLI, Photoluminescence imaging; PT, Photo thermal; PTBD, Photo thermal beam deflection; PTR, Photo thermal radiometry; PV, Photovoltaic; PWT, Projected wavelet transform; RUV, Resonance ultrasonic vibration; SAM, Scanning acoustic microscopy; SE, Secondary electron; SEAM, Scanning electron acoustic microscopy; SEM, Scanning electron microscope; SHM, Structural health monitoring; SWIR, Short-wave infrared; Si-CCD, Silicon-based charge coupled device; SP, Signal processing; SI, Spectral imaging; STC, Standard test conditions; SWIR, Short-wave infrared; TEM, Transmission electron microscopy; THz, Terahertz; ULIT, Ultrasound lock-in thermography; USE, Ultrasound energy; VDCC, Voltage dependent charge-collection; VTD, Vapor transport deposition

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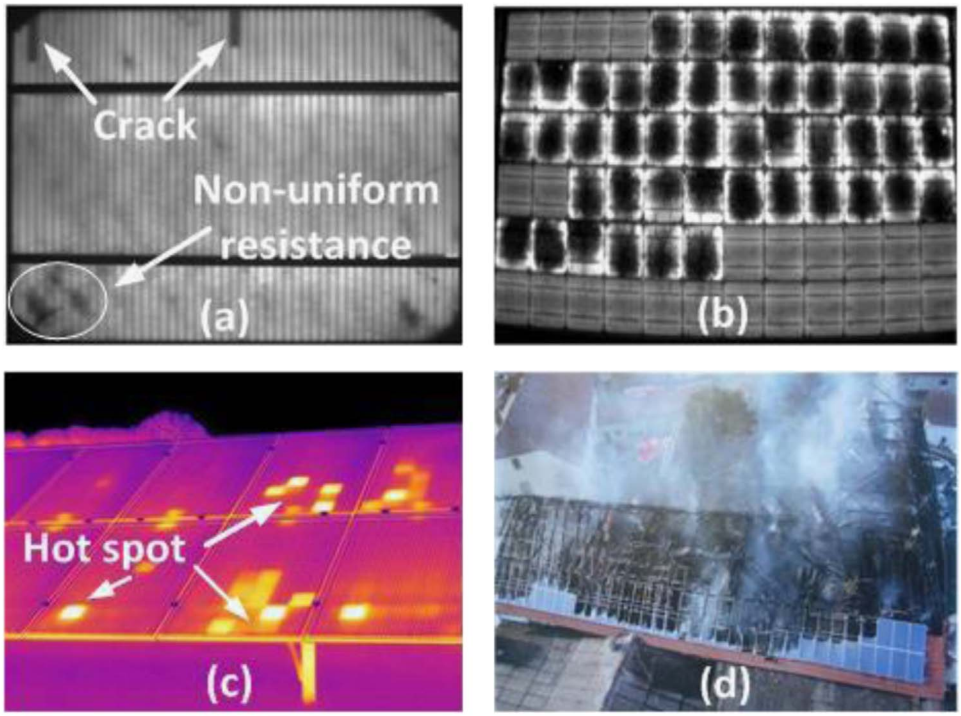

Fig. 1. (a) Monocrystalline silicon solar cell with defects; (b) photovoltaic module failure in large areas; (c) hot spots of in-service PV modules; (d) damaged photovoltaic modules in the explosion of PV plant.

damages may be sustained by solar cells and modules. Fig. 1(a) shows the monocrystalline silicon solar cell with some defects; Fig. 1(b) shows photovoltaic module failure in large areas; Fig. 1(c) shows the hot spots of in-service PV modules; Fig. 1(d) shows damaged photovoltaic modules in the explosion of PV plant.

Aside from developing more advanced cells and modules to improve the availability, another effective way would be to apply reliable and cost-effective nondestructive testing & evaluation (NDT & E) and inspection. Therefore, it is necessary to perform the NDT & E in order to avoid cell failure. Nowadays, a plenty of NDT & E techniques based on electrical parameters, electromagnetic field, ultrasonic and sonic, optics, electromagnetics, thermography, infrared radiation and radiographic have already been investigated. Some NDT & E and inspection techniques have shown the potential and advantages while some others are faced with problems due to their natural limitations. A few simple reviews of NDT & E and inspection techniques for Si-based solar cells and modules have been done [1–5]. **However, these works are focused on Si solar cells and wafer, while the developments and trends about thin film and multi-junction solar cells have not been reviewed yet.** In this paper, a fully, in-depth and comprehensive review of NDT & E and inspection techniques for Si-based solar cells especially in the last 3 years and for **thin film and multi-junction cells** was reported based on an orderly and concise literature survey.

One of The objective of the review is to provide a detailed guide for the research, improvement, innovation and use of current NDT in performance testing, failure analysis, quality control and health monitoring of Si-based, thin film and multi-junction solar cells, while the other is to show the requirement of solar cell industry on NDT and predict the development trends for NDT. The rest of the paper is organized as follows. Firstly, the developments of NDT & E for **Si-based solar cells in the last 3 years** are reviewed in detail in Section 2. Next, the developments of NDT & E for **thin film and multi-junction cells** are reviewed respectively in Sections 3 and 4 followed by the comparison and summary for several NDT & E techniques, which are concluded in Section 5, followed by trends in solar cells and NDT are predicted in Section 6. Finally, the conclusions are outlined in Section 7.

2. Development of NDT & E for Si-based solar cells

Si-based solar cells mainly refer to monocrystalline silicon, amorphous silicon and polycrystalline silicon solar cells. In mass and industrial production, monocrystalline silicon solar cells have advantages of the highest conversion efficiency, being the most mature technology and with high reliability. In the process of research & development, manufacturing, and service, many Si-based solar cells will produce various defects and damage, which will affect the normal performance of solar cells. These cracks and defects can be categorized into macro cracks and micro cracks (μ-cracks) according to their width and sizes. The cracks with size smaller than 30 μm in width are usually referred to as μ-cracks [6]. The cracks are further classified according to their position as either facial or superficial cracks. Depending on the size, it is difficult to quantify these facial cracks with one's naked eyes [7]. Next, the development and case studies of electrical, electromagnetic, sonic and ultrasonic, thermal, infrared, and optical NDT & E for Si-based solar cells will be reviewed.

2.1. Electrical testing and electromagnetic NDT

Electromagnetic nondestructive testing is a test method used to judge the internal damage and related properties of materials by the change in electrical or magnetic properties. In recent years, with the development of electronic technology, especially the development of computer technology, the research of electromagnetic nondestructive testing and the development of instrument and equipment have made great progress. At present, we can use electromagnetic nondestructive testing method to detect the defects in PV modules.

2.1.1. DC electrical parameters testing

Recent progress in the Si-based solar cell technologies has introduced novel cell designs and advanced material processing methods, as