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Compressive light beam induced current sensing for fast defect detection in photovoltaic cells

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ABSTRACT

In this paper, a fast and efficient defect location system utilizing compressive sensing is proposed for detecting defects in solar cells. It measures the total output of the sample solar cell under excitation of patterns displayed by a liquid crystal display. Then the defects are located compressively by solving a convex problem using a small number of photo-electric current measurements — far fewer than the total possible number of testing points. The feasibility of proposed method and its detection performance were evaluated. The experimental results indicate that a sparse distribution of defects can be compressively located using measurements whose number is about 30–60% of all possible testing points and that the detection speed can be increased by a factor of 10–15 while retaining a reasonable accuracy. An additional advantage of the proposed detection system is that no mechanical moving components or optical lens are used and thus no mechanical instabilities or optical distortions are introduced. This advantage in particular means that there is significant potential to further improve the detection speed since electrical measurements can be very fast. Overall, the proposed method has significant potential for improving the efficiency and speed of inspection and classification of industrial photovoltaic devices.

1. Introduction

Industrial solar cells are large-area junctions that can contain structural and processing-induced defects such as wafer cracking, breakage, or electrode breakdown; these defects strongly affect the performance, lifetime, and reliability of solar cells. Thus, quick and precise evaluations of solar cells during production are required to reproducibly obtain high efficiency and reliable performances in crystalline Si cells fabricated using mass production processes.

Several approaches have been investigated in the past to locate defects and shunts in solar cells. The photoconductivity decay method (Ghannam et al., 1994), which uses microwave reflection, is widely used to check the collection efficiency; however, it requires good surface passivation to guarantee a high detection accuracy. The electron beam induced current (EBIC) (Kittler et al., 2002; Reuter et al., 2011) method measures the variation of the induced solar cell current under the electron beam of a scanning electron microscope (SEM) that is directed onto a solar cell. The spatial resolution of EBIC is very high and thus it has become one of the best ways to assess the quality of solar cells in the laboratory. However, the scanning area is limited owing to the size of the telescope's lens; further, the high vacuum atmosphere requirement of EBIC greatly restricts its applications, especially in industrial applications. Additionally, a side effect of using EBIC to measure organic solar cells is that the electron beam causes irreversible damage to the organic layers (Reuter et al., 2011). The electroluminescence (EL) method (Fuyuki and Kitiyanan, 2008; Fuyuki et al., 2005) captures the infrared light emitted by a heated solar cell under forward bias conditions. The emitted weak light with wavelengths of around 1000–1200 nm can be captured by a cooled Si-CCD camera in less than 1 s in a dark room. Further, the detection area simply depends on having a suitable optical lens system and thus has a wide range of 1 cm^2–1.5 m^2. However, the EL method has the disadvantage that it can only assess radiative recombination and thus cannot provide a comprehensive assessment of the performance of a solar cell.

The spectroscopic laser beam induced current (LBIC) (Acciarri et al., 2002; Kaminski et al., 2004; Ragaie and El-Ghitani, 1986) method measures the variation of the induced current under excitation by a local photon beam at the surface of a solar cell. The advantage of LBIC compared with the EBIC and EL methods is that parameters such as wavelength, voltage bias, and light intensity can be varied, which allows for a comprehensive assessment of the performance of a solar cell (Geisthardt and Sites, 2014b;

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Orlov et al., 2013). However, the primary disadvantage of LBIC is the long processing time, which has greatly limited its industrial applicability.

In a LBIC measurement, the light beam is moved relative to the sample to reach every testing point within the testing area. In currently reported LBIC systems, this procedure is implemented either by translating the beam across a fixed sample with a technique based on the use of rotating mirrors (Acciarri et al., 2002; Carstensen et al., 2003) or by moving the sample with a precisely controlled motor across a fixed laser beam (Geisthardt and Sites, 2014a,b; Kaminski et al., 2004; Lim et al., 2015). Therefore, the processing time using LBIC is generally a combination of the time in which the motion is executed and the measurement time. Obviously, the time taken for the mechanical positioning is much longer than that for the electrical measurement. The authors in reference (Geisthardt and Sites, 2014a) modified the step-wait-measure procedure in the LBIC method to create a procedure with simultaneous movements and measurements, which reduces the required time for LBIC by at least a factor of 5 with little or no loss in the positional and measurement accuracy. However, this method introduces mechanical instabilities and the scan duration is still too long for industrial applications.

Another problem of LBIC systems are their low efficiency in seeking and locating defects. Since every measurement is taken point by point in series, the entire testing area has to be traversed to avoid missing any defect points even if the defect area is quite small. In reality, the defects or the structure of the defects of a solar cell are so sparsely scattered (typically only a few percent of the total testing points are defects) that the measurements are highly correlated and the resulting mapping image is rather compressible. In other words, the mapping image of a solar cell using LBIC contains a lot of redundancy, indicating that there is significant potential to improve the defect seeking efficiency by eliminating the information redundancy during the sensing stage. The recent advances in signal processing called compressive sensing (CS) have shown that a signal with a lot of redundancy can be reconstructed from highly incomplete information. And most recently, the current response mapping method of photovoltaic devices using the theory of CS has been introduced (Hall et al., 2016; Koutsourakis et al., 2016, 2015). At the same time with our work, a CS-based experimental setup of LBIC (Koutsourakis et al., 2017) has been built at the National Physical Laboratory using Digital Micromirror Devices and proved the built system is ideal for current mapping of both polycrystalline silicon cell and small thin film research samples at laboratory level.

In this paper, we propose a novel compressive LBIC (CLBIC) diagnostic method for fast defect detection of industrial solar cells. In the proposed CLBIC system, the illuminated front side of the solar cell is contacted to a liquid crystal display (LCD). Multiple testing points in the testing area of the solar cell are simultaneously illuminated by the displayed pattern of the LCD and the photocurrent induced by the entire testing area is obtained as one measurement value. Then the mapping image can be reconstructed after conducting measurements far fewer than with the standard LBIC method. The CLBIC system has neither moving parts nor lens, thus does not introduce any mechanical instability or optical distortion during the detection. Therefore, the positioning procedure of the standard LBIC method and the optical focusing step can be omitted. Moreover, since the light source is just a LCD, the proposed CLBIC system can be easily manufactured and is of low cost. These advantages significantly reduced the scanning speed and the scanning complexity of the CLBIC method and make it very suitable for large-scale industrial applications.

The rest of the paper is organized as follows. In Section 2, the theory of the CLBIC method is briefly introduced. Section 3 describes the proposed CLBIC system in detail. The experiment results and discussions are presented in Section 4. Then an application in realistic detection is presented in Section 5. Finally, Section 6 concludes the paper.

2. Theory of the CLBIC method

A vector is k-sparse if it has at most k ($k \ll n$) large coefficients while the remaining coefficients are small or zero. The theory of CS states that, with a high probability, a n-dimensional signal vector $\mathbf{x}$ that is k-sparse (or $\mathbf{f} = \sum_{i=1}^{n} x_i \psi_i = \mathbf{\Psi x}$, which is k-sparse in some domain $\mathbf{\Psi} = (\psi_1, \ldots, \psi_n)$) can be recovered from $m(m << n)$ linear combinations of measurements. It can be obtained given the measurement matrix $\mathbf{\Phi} \in \mathbb{R}^{m \times n}$ and the observation vector $\mathbf{y} \in \mathbb{R}^m$, which is given by

$$\mathbf{y} = \mathbf{\Phi f} = \mathbf{\Phi \Psi x}. \tag{1}$$

Recovering $\mathbf{x}$ or $\mathbf{f}$ from $\mathbf{y}$ can be achieved through solving the l_1-minimization problem

$$\min_{\mathbf{x}} ||\mathbf{x}||_{l_1} \quad s.t. \mathbf{y} = \mathbf{\Phi f}, \quad \mathbf{f} = \mathbf{\Psi x} \tag{2}$$

The so-called sensing matrix $\mathbf{A} = \mathbf{\Phi \Psi} \in \mathbb{R}^{m \times n}$ satisfies the restricted isometry property (Candes, 2008) or has, in most practical scenarios, a low mutual coherence (Donoho and Elad, 2003; Donoho and Huo, 2001).

In a solar cell the current map of the testing area is a two-dimensional (2D) image Θ of r-rows and c-columns, which can be stacked in a n-dimensional signal vector with $n = rc$. The current response of the normal testing points are denoted by zeros (i.e., the loss of the photoelectric conversion efficiency is zero), and the current response of the defect containing testing points are denoted by non-zeros. The testing points on the busbars and fingers do not generate current response are also non-zeros but their affect can be removed using prior knowledge. After a proper transform the resulting signal consists of mostly zeroes and just a few non-zero elements, namely the current signal of an industrial solar cell is sparse under certain domain. Thus the current signal of an industrial solar cell can be corresponded to a k-sparse n-dimensional signal vector with $k \ll n$.

Noticed that the induced current has a linear response for the intensity of the incident light beams; thus, the measurement procedure can be expressed as follows:

$$y_i = \boldsymbol{\varphi}_i \mathbf{f} = \sum_{j=1}^{n} \varphi_{i,j} f_i, i \in [1, m], \tag{3}$$

where y_i is the i-th element of the observation vector $\mathbf{y}$ and $\boldsymbol{\varphi}_i$ represents the i-th row of the measurement matrix $\mathbf{\Phi}$.

Fig. 1 shows an example of the sensing procedure with 9 testing points at a sampling ratio of 0.44 (4 values); each $\psi_{i,j}$ is the intensity of the light beam of the i-th control pattern at the j-th measurement point and every f_i represents the factor of the photoelectric transformation efficiency of the solar cell at the j-th measurement point. Therefore, y_i is the variation of the induced current corresponding to the i-th control pattern. After collecting m measurements to form a vector $\mathbf{y}$, one can recover the entire current map of the solar cell by solving (2).

Conversely, for the two-dimensional (2D) image Θ, the total-variation norm of the 2D entity $\theta_{i,j}$, which can be interpreted as the norm of the gradient, *i.e.*,

$$\begin{aligned} ||\Theta||_{TV} &= \sum_{i,j} \sqrt{(\theta_{i+1,j} - \theta_{i,j})^2 + (\theta_{i,j+1} - \theta_{i,j})^2} \\ &= \sum |(\nabla \theta)_{i,j}| \end{aligned} \tag{4}$$