Towards Current Mapping of Photovoltaic Devices by Compressed Imaging

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Abstract

A new photovoltaic (PV) device current mapping method has been developed, utilizing the recently introduced compressed sensing sampling theory. The aim is to significantly reduce measurement time of Light Beam Induced Current measurements. A prototype setup has been built at National Physics Laboratory (NPL) to implement the method. Initial results are presented and illustrate the feasibility of the method.

Introduction

Spatial characterization of the optical, electrical and material properties of photovoltaic (PV) devices is used for the detection of various types of defects. These can be caused by production processes, material properties or degradation. PV device characterization techniques are important for research on new PV materials and designs, as well as for optimization of manufacturing methods. The most common methods for spatially resolved non-destructive measurements are Light Beam Induced Current Measurements (LBIC) [1], luminescence methods as Electroluminescence (EL) [2] and Photoluminescence (PL) [3] and Lock-in Thermography (LIT) [4]. This paper focusses on the first of these and tries to remedy its major drawback, the slow measurement speed.

Light/Laser Beam Induced Current (LBIC) imaging is a non-destructive characterization technique which can be used for current mapping of PV cells and modules [1]. For the implementation of such measurements, a raster scan of the sample is performed using a collimated laser source. Dependent on scan resolution, measurements can be very time-consuming and can last for several hours even with a single PV cell. Measurement time can be significantly reduced applying the recently developed compressed sensing (CS) theory [5,6]. CS-LBIC measurements combine the CS sampling theory with an LBIC system. Instead of applying a raster scan, a series of patterns are projected on the test sample by utilizing a Digital Micro-mirror Device (DMD) [7]. The number of acquired measurements M are fewer than the pixels of the final image M<<N. Thus, the problem is underdetermined and the final reconstruction of the image is achieved by means of an optimisation algorithm.

Compressed imaging applications have been reported in the literature. An initial example of a CS imaging system is the single pixel camera, developed by Duarte et al [12]. In this setup a single detector is used to capture an image. The DMD kit was introduced as a pattern generator for implementing compressive sampling. An optical system has been built in NPL for applying CS-LBIC measurements for current mapping of PV devices and will be presented in this paper.

Compressed Sensing Theory

Compressed sensing sampling allows the reconstruction of sparse signals and images from incomplete or inaccurate measurements. In compressed imaging, an N pixel image can be reconstructed from M<<N observations. For example, in JPEG image compression, most of the information is thrown away at the transformed compression stage and only the necessary elements for describing the image in the transform domain are kept (K elements). The image can be reconstructed using only these very few K elements, which provide a sparse representation of the image. The purpose of a CS imaging setup is to directly measure the K necessary coefficients for an almost exact image reconstruction, having

applied M<<N measurements for capturing an N pixel image.

A compressed representation of a signal, x, is acquired using M<N linear measurements between x and a set of test functions $\{\varphi_m\}_{m=1}^M$, forming $y[m] = \langle x, \varphi_m \rangle$ which is the actual measurement. Stacking test functions $\{\varphi_m\}_{m=1}^M$ as rows in a MxN matrix $\Phi = [\varphi_1, \varphi_2, \varphi_3, \ldots \varphi_m]$ the problem can be written as [8]:

$$y = \Phi x \qquad (1)$$

In general there is loss of information as a result from the transform from x to y, as y has significantly fewer elements than x. Since M<N, there are infinitely many solutions $\{x: y = \Phi x\}$ This is an under-determined problem. However, a measurement matrix Φ can be designed such that an almost exact approximation of signal x can be recovered from measurement y, if x is sparse or compressible. In practice, few real-world signals are truly sparse. Nevertheless, almost all of them are compressible, meaning that they can be well-approximated by a sparse signal, or are sparse after a transform [9]. This means their representation with a basis Ψ is sparse.

The signal reconstruction algorithm must take the M measurements in the vector y, the random measurement matrix Φ, the basis Ψ (transform) and reconstruct the N-length signal x or, equivalently, its sparse coefficient vector α, as $x = \Psi\alpha$ and $y = \Phi x = \Phi\Psi\alpha$. To recover the image x from the random measurements y, the traditional method of least squares (minimizing the ℓ_2 norm) fails with high probability. Instead, it has been shown that using the ℓ_1 optimization we can exactly reconstruct K-sparse vectors (K<M<N) and closely approximate compressible vectors stably with high probability. In other words the solution to the underdetermined problem is the x vector (or more precisely the α vector) with the minimum ℓ_1 norm [10]:

$$\hat{x} = argmin\|x\|_1 \text{ subject to } \Phi x = y \qquad (2)$$

This is a convex optimization problem that conveniently reduces to a linear program known as basis pursuit [5][11].

CS-LBIC prototype system

For the experimental implementation of CS-LBIC measurements a prototype setup was built in NPL. The setup is presented in figure 1. A 40mW 658nm wavelength laser is used as a light source, while a single mode fibre delivers the light to the optical system. The beam is expanded in order to overfill the micro-mirror array (DMD), which has a size of approximately 1cmx0.77cm and consists of 1024 by 768 square micromirrors of 10μm side size each. The DMD is the pattern generator used in this system. A mirror and a spatial filter are used to project fine generated light patterns on the sample. Instead of a pixel by pixel scan, a sequence of patterns is projected on the sample and the current response is measured every time, thus populating measurement matrix y. The pattern-test functions populate matrix Φ and the required current map is acquired by solving the optimization problem (2) as detailed in the previous section.
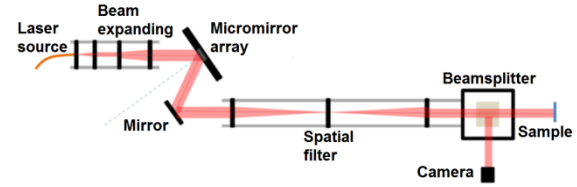

Figure 1: The experimental setup in NPL

Random binary matrices are used to produce the sensing matrix, while the discrete cosine transform is applied (basis Ψ) to provide the sparse representation of the image. Reconstruction of the final current map is implemented in MatLab, using the ℓ_1 MAGIC package by Candès and Romberg [12]. A significant advantage of using the DMD is that its response is shorter than 20μs. This increases measurement speed, which is only limited by the sampling rate and the number of samples taken for every pattern.
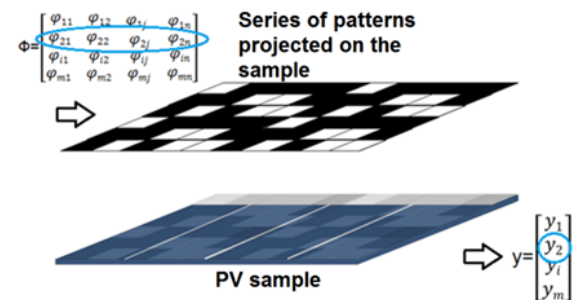

Figure 2: Compressed sensing measurement procedure; a series of random binary patterns are projected on the sample.

Using an x-y translation stage for a raster scan would require a couple of milliseconds to move from one point to the next. This setup virtually eliminates the control time between points, thus further reduces measurement time by almost an order of magnitude. Moreover, theoretically only 25% of measurements of

what a raster scan would require are enough for an almost exact reconstruction of the current map. Consequently, measurement time is reduced furthermore.

An initial issue of this first experimental prototype is that the light beam incident on the DMD does not have a completely uniform distribution. The output of the single mode fibre has a Gaussian distribution, the beam is expanded and the DMD area is overfilled with its central part. This configuration results in adequate uniformity for confirming the feasibility of CS LBIC measurements, although in the future a more accurate configuration will be implemented. Another factor that can create distortions in the final current map is the fineness of the projection on the sample. The focusing needs to be accurate and the projection needs to be on the plane of the sample, otherwise the current map will be blurry or distorted.

Results

8cm by 8cm ribbon mc-Si cells were encapsulated and characterised in CREST in order to be used as samples for CS-LBIC measurements with the experimental setup in NPL and be durable enough to be exchanged between the laboratories. Results with one of the samples are presented in this work. The sample contained a lot of defects, as can be seen from the EL image in *Figure 3*. Currently, the prototype setup can only scan a small area of the cell. The measured area is shown in figure 3.

**EL image**   **Measured area**
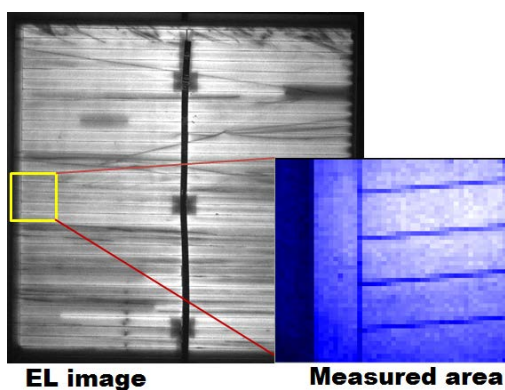
Figure 3: EL image of a mc-Si sample captured at CREST and a CS LBIC scan of a part of the sample with the experimental setup.

The wavelength of the laser (658nm) implies that light is measuring the surface of the cell only and does not detect internal cracks, grain boundaries and defects of the cell that are visible in the EL image. After the optimization

of this prototype with such a visible laser, infra-red lasers will be used at a later stage to provide a deeper penetration into the sample so that more defects can be detected.

Experimental results are presented in figure 4. A 48 by 48 current map (2304 pixel image) was acquired with a different number of measurements every time, as a percent of what a raster scan would need. A current map acquired by a raster scan would need 2304 measurements. Using with CS-LBIC, already from as few as 692 measurements (30%), the features of the sample are clearly visible. Moreover, from 922 measurements (40%) and above no significant improvement of the image can be observed.
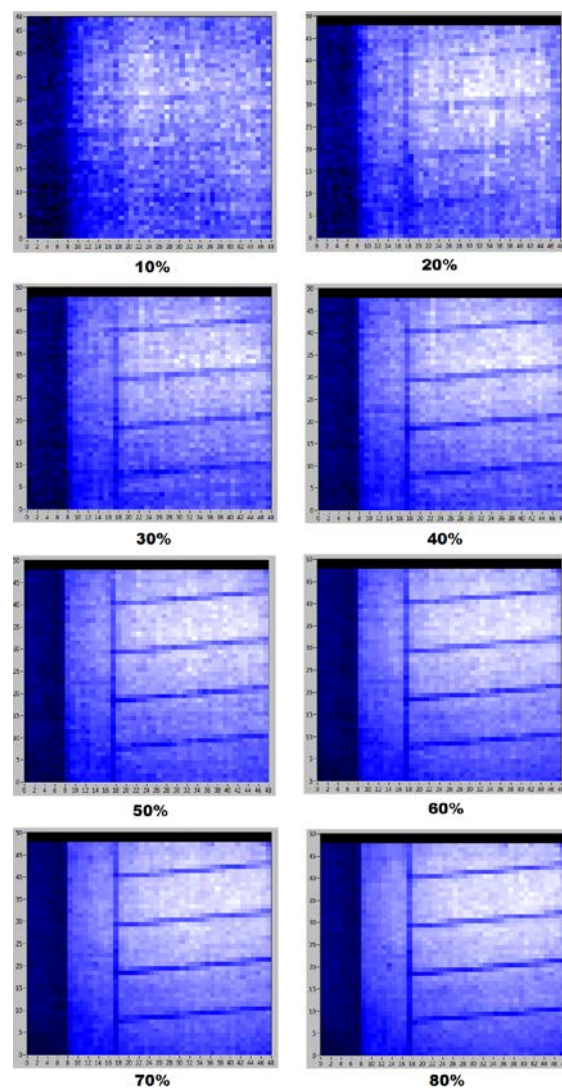
Figure 4: CS-LBIC measurements with the prototype setup in NPL. Different numbers of measurements are used every time for reconstruction of the image. The percentage presents the ratio of the number of measurements and the total pixels of the image.

The fingers of the sample do not appear perpendicular to the side finger as they should be, but seem to have an inclination. This is most likely because the projection plane does not exactly coincide with the plane of the sample, thus the image appears distorted as if it is observed at an angle. Such artefacts can be corrected by more precise focusing and alignment, which will bring the projection and the sample at the same plane. The non-uniformity of the illumination is also visible in the current maps, as the central area of the images appears slightly brighter.

These initial experimental results clearly indicate the method's feasibility and show that current maps with significantly fewer measurements compared to a raster scan. Correction of the aforementioned issues will result in more accurate results with even fewer numbers of measurements.

Conclusions

A novel application of the CS sampling theory for PV characterisation was presented. For the implementation of CS sampling, a DMD, integrated in an optical system, was utilised for generating the necessary pattern sequence. Current mapping of PV devices can be carried out significantly faster due to the fast response of the micromirror array of the DMD and the fewer measurements needed. An initial experimental setup has been built in NPL and the presented results illustrate the feasibility of the method. Further optimisation of the experimental setup and use of longer wavelengths will allow the detection of various defects of samples, for comparison with other spatial characterisation methods.

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