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Compressed Sensing Current Mapping Spatial Characterisation of Photovoltaic Devices

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Abstract—A new photovoltaic (PV) device current mapping method has been developed, combining the recently introduced Compressed Sensing (CS) sampling theory with Light Beam Induced Current (LBIC) measurements. Instead of a raster scan, compressive sampling is applied using a Digital Micro-mirror Device (DMD). The aim is to significantly reduce the time required to produce a current map, compared to conventional LBIC measurements. This is achieved by acquiring fewer measurements than a full raster scan and by utilizing the fast response of the micro-mirror device to modulate measurement conditions. The method has been implemented on an optical current mapping setup built at the National Physical Laboratory (NPL) in the UK. Measurements with two different PV cells are presented in this work and an analytical description for realisation of an optimised CS current mapping system is provided. The experimental results illustrate the feasibility of the method and its potential to significantly reduce measurement time of current mapping of PV devices.

Index Terms—Light Beam Induced Current measurements, Solar Cells, Compressed Sensing, Spatial Characterisation.

I. INTRODUCTION

Spatial characterization of PV devices leads to an increase in product quality through detection and prevention of production induced defects and better understanding of material and degradation properties of PV devices. Characterisation techniques such as Light Beam Induced Current measurements (LBIC) [1], luminescence methods as Electroluminescence (EL) [2] and Photoluminescence (PL) [3] and Lock-in Thermography [4] are necessary for research into new PV materials and designs and for optimization of manufacturing methods. Electronic properties of solar cells, such as the diffusion length of minority charge carriers, are usually extracted from quantum efficiency (QE) data. The values of these properties are typically measured in an energy range slightly above the band-gap energy, where the QE is still close to its maximum [5]. For this reason, quantitative current mapping provided by LBIC measurements is essential for directly assessing the electronic, optical and material properties of PV devices.

LBIC imaging is a non-invasive characterisation technique which is used for current mapping of PV devices. It can be applied to deliver current maps of PV cells [6][7] and modules [8]. For its realization, a light beam scans a PV device and the induced current is measured for every point. Significant cell parameters can be mapped when measuring the local current response, such as diffusion length of minority charge carriers [9], external and internal quantum efficiency [10] or back surface recombination [11]. The main advantage is that the same principles that generate current in real applications of solar cells are applied in LBIC measurements. A well-known drawback of this measurement technique is that it lacks speed. The small laser spot, usually of a diameter in the micrometre scale, needs to scan the entire area of the cell for a complete current map. This means the smaller the laser spot size or the bigger the sample under test, the lengthier the measurements. Thus, measuring entire PV modules or full wafer cells at useful spatial resolutions is time-consuming.

The LBIC measurement speed can be significantly increased by applying compressed sensing (CS) theory [12][13]. According to the CS theory, one can reconstruct a signal from highly incomplete or inaccurate information. Image compression techniques with loss of information are widely used in everyday life. For instance, JPEG compression is used for image files. Compression techniques such as JPEG use transforms, such as the Discrete Cosine transform or the wavelet transform, to represent the image data in a sparse form. Only the largest basis coefficients for an accurate representation are kept. When reconstructing the signal, the non-stored coefficients are simply set to zero. This means that in most cases a large part of the information is simply thrown away without degrading the data/image significantly.

The question that arises is whether one can acquire the compressed version of the signal more directly, by taking only a small number of measurements of the signal in the first instance. Compressed sensing provides a way of acquiring a compressed version of the original signal. This is achieved by taking only a small number of linear measurements and then reconstructing an almost exact approximation of this signal. More precisely, using compressed imaging, an N pixel image can be reconstructed from M<<N observations. Compressed imaging applications have already been reported in the literature. An initial example of a CS imaging system was the single pixel camera, developed by Duarte et al [14]. In that setup a single detector is used to capture an image while a Digital Micro-mirror Device (DMD) chip was introduced as a pattern generator for implementing compressive sampling [15]. A large number of compressed sensing imaging applications have already been proposed and exhibited, such as the CS Magnetic Resonance Tomography (MRI) for reducing patient scan time and improving resolution [16].

The utilisation of DMD chips for PV characterisation has been described previously in reported cases. A PV cell spatial characterisation system using a DMD based projector has been demonstrated [17]. Tomographic current mapping using a DMD chip for realising line scans has also been reported [18]. Although not using CS, this was the first instance where fewer measurements were applied compared to the pixels of the final image. Tomographic reconstruction techniques were used to
successfully acquire the current map. Recently, a DMD chip has been used to significantly speed up quantum efficiency measurements for PV devices [19].

A primitive “proof of concept” for CS current mapping of PV devices has been introduced in previous work [20][21]. Instead of applying a raster scan, a series of patterns are projected on the PV sample using a DMD, acquiring fewer measurements (M) than the pixels of the final current map (N). The final reconstruction of the current map is achieved by means of an optimisation algorithm, exploiting the compressibility (sparse representation after a transform) of the measured signal [22].

In this work an analytical description for the realisation of a CS current mapping measurement system is provided, based on an optimised simple experimental setup for small area devices. This CS current mapping optical system has been built at NPL, using a DMD chip for implementing the measurements. The optimised system exhibits significantly better performance than previous reported implementations. Measurement speed is increased, higher optical resolution is achieved and a simpler experimental setup has been realised. Experimental results of CS current mapping for both crystalline silicon and thin film PV samples are presented. Undersampling and resolution limits are explored for this experimental layout.

II. CS CURRENT MAPPING SYSTEM LAYOUT

A. Compressive sampling

The real current map that is going to be measured is represented as an N×1 column vector in \( \mathbb{R}^N \) with N elements \( x[n], n = 1, 2, ..., N \). Any two dimensional signal, such as the patterns to be projected on the sample or current maps, can be represented as a long one-dimensional vector. For instance, an image of size \( \sqrt{N} \times \sqrt{N} \) will be described by an \( N \times 1 \) vector. Using compressive sampling, a compressed representation of a signal, \( x \), is acquired using \( M < N \) linear measurements between \( x \) and a set of test functions \( \{\phi_m\}_{m=1}^M \), forming \( y[m] = \langle x, \phi_m \rangle \). The actual acquired measurement vector. Expressing test functions \( \{\phi_m\}_{m=1}^M \) as rows in a \( M \times N \) matrix \( \Phi = [\phi_1, \phi_2, \phi_3, ..., \phi_m] \), the problem can be written as [14]:

\[
y = \Phi x
\]

In general there is loss of information as a result of the transform from \( x \) to \( y \), as \( y \) has significantly fewer dimensions than \( x \) due to undersampling. Since \( M < N \), there are infinitely many \( \{x, y = \Phi x\} \). However, a sensing matrix \( \Phi \) 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, although almost all of them are compressible, meaning that they can be well-approximated by a sparse signal, or are sparse after a transform [23].

The sensing matrix \( \Phi \), which contains the binary patterns to be projected on the sample, should have some specific properties so that a successful CS process can be achieved [24]. As mentioned above, real signals are compressible, which means they have a sparse representation after a transform, \( \Psi \).

When \( \Psi \in \mathbb{R}^{n \times n} \) is a representing basis (or dictionary), the sparse version of \( x \) is \( a \), satisfying

\[
x = \Psi a
\]

It has been shown that in order to achieve successful CS measurements, a matrix \( \Phi \) must be chosen having minimal coherence with \( \Psi \) [25]. In other words, a matrix \( B = \Phi \Psi \) is desired to have columns with the smallest possible correlations. A second important property is that \( \Phi \) must satisfy the Restricted Isometry Property (RIP) [26]. This is an important feature, as it ensures that \( \Phi \) approximately preserves the distance between any pair of sparse vectors. This is especially important for signal recovery when measurements are contaminated with noise. In practical applications it is difficult to test if a sensing matrix satisfies the aforementioned properties as for actual applications, \( \Phi \) would have thousands of rows and columns. However, both the RIP and incoherence can be achieved with high probability simply by selecting \( \Phi \) to be a random matrix [27]. Effectively, each row of \( \Phi \) contains a full random pattern to be projected on the sample, containing just values of ones or zeros.

The signal reconstruction algorithm must take the measured \( y \) in the vector \( y \), the random measurement matrix \( \Phi \), the basis \( \Psi \) (transform) and reconstruct the N-length signal \( x \) or, equivalently, its sparse coefficient vector \( a \), as \( x = \Psi a \) and \( y = \Phi x = \Phi \Psi a \). It has been shown that using the \( \ell_1 \) optimization one can accurately reconstruct sparse vectors and closely approximate compressible vectors stably with high probability using a small number of random measurements [12]. In other words the solution to the underdetermined problem is the \( x \) vector (or more precisely the \( a \) vector) with the minimum \( \ell_1 \) norm [28]:

\[
\hat{x} = \text{argmin} \|x\|_1 \quad \text{subject to} \quad \Phi x = y
\]

Or

\[
\hat{a} = \text{argmin} \|a\|_1 \quad \text{subject to} \quad \Phi \Psi a = y
\]

This is a convex optimization problem that can be reduced to a linear program known as basis pursuit [12][25]. In this work, the \( \ell_1 \) minimisation algorithm is used for acquiring the solution [22]. There are a large number of reconstruction algorithms, sensing matrix types and even transforms available in the literature and the ones in this work were selected for their simplicity and straightforward application.

B. Measurement System Layout

The experimental setup is presented in figure 1. Two laser sources are available, a 40mW laser at 658nm wavelength and a 100mW laser at 785nm. A single mode fibre delivers the light to the optical system in both cases. The beam is expanded and collimated in order to overfill the micro-mirror array (DMD), which has a size of approximately 1.4cm x 1.0cm and consists of a 1024 by 768 array of square micro-mirrors each of 13.7μm x 13.7μm size. The DMD is the most significant part of this system, as it plays the role of the pattern generator. The output of the single mode fibre creates a beam with a Gaussian profile. Overfilling the DMD with the central part of the beam results
in a quasi-top-hat beam profile, which means it is not perfectly uniform but sufficient for this series of experiments. The maximum difference of intensity due to this non-uniformity is below 10%.

The angle of incidence of the collimated beam on the DMD has to be the “blaze” angle, so that diffraction from the micromirror array is minimised [29]. The blaze angle is wavelength dependent and within a very small range, so careful alignment is necessary to achieve it. 2-lens systems with spatial filters are used for rejecting out of focus, diffracted beams and cleaning the image to be projected. This is necessary as diffraction may be minimised but is still present. These 2-lens systems also create the projection of the pattern on the sample. However, the pinhole should not be extremely small, as it has to include the first order high frequencies, or else the projection will lack sharpness and the reconstructed current map will appear more blurred. A mirror is used for projecting each pattern created by the DMD onto the sample, which is placed horizontally on a z-stage platform. A National Instruments PXIe-4139 system source measure unit (SMU) is used for measuring the current response under each pattern.

Using an x-y translation stage for a raster scan, some milliseconds would be required to move from one point to the next. A significant advantage of using the DMD is that its response time is under 20μs, a property that can result in increased measurement speed, which would be only limited by the sampling rate and the number of samples taken for each pattern. The current speed of the system in this series of experiments is 10 samples (patterns) per second. Thus, when taking half the measurements a point by point scanning system would need (50%) and considering a 100x100 pixel image (10000 pixels) is acquired, measurements last approximately 8 minutes. This sampling speed is currently lower than the speed of a good LBIC system utilising lock-in techniques. Higher sampling speed can be achieved with optimisation of the control software. A reference measurement is also acquired for monitoring laser light intensity. The maximum laser intensity on the sample that can be achieved is approximately 100W/m² for the 658nm laser and 300W/m² for the 785nm one, considering the illuminated areas of the sample. The experimental results presented in this work are all acquired with these irradiance levels on the sample, for an illuminated pixel. Although the laser sources have relatively high power and could theoretically provide higher irradiance on the sample, there are a lot of losses due to the expansion of the beam and the optical elements included. All measurements are normalised with the reference measurement, in order to correct for any laser instability.

The compressive sampling procedure is presented in figure 2. The projected binary patterns that apply compressive sampling are physically projected on the sample with the utilisation of the DMD device. The current response of the PV device is measured for each pattern, thus populating measurement vector \( y \). The patterns-test functions populate sensing matrix \( \Phi \) and the required current map in vector form \( x \) is acquired by solving the resulting underdetermined optimization problem. The discrete cosine transform is applied as a basis \( \Psi \) to provide the sparse representation of the signal. Reconstruction of the final current map is implemented in MatLab, using the \( \ell_1 \) MAGIC package [30].

By grouping control of different elements of the micromirrors of the DMD together, current maps with several levels of display and optical resolution can be realised. Although the DMD consists of 1024x768 physical micromirrors, a maximum of 700x700 were used, creating a square projection of 100x100 ‘pixels’ for simpler sampling procedure, mathematical analysis and data processing. To realise this projection resolution, the micromirrors were controlled as binned groups of 7x7 (49 micromirrors per pixel), or smaller groups in the case of the thin film sample. The result is the projected patterns on the sample always have a projection resolution of 100x100, which gives the final reconstructed current maps always the same resolution.

Reconstruction time depends on the resolution selected: in our case, where the set resolution is 100x100, the reconstruction process with the specific algorithm used requires less than a minute. This does not include measurement time but only data processing when sampling has finished. The reconstruction
process is offline and a new set of measurements can start while processing of the previous measurement data is running. The CS current maps are not currently corrected with reflectivity measurements, as such measurements have not been integrated into the system. Direct reflection values can be measured in the future by utilising a beamsplitter and a photodiode after the last spatial filter, as the beam is collimated.

III. EXPERIMENTAL RESULTS

Measurement results with 2 different samples are presented here, so that the experimental setup is tested with different types (materials) of devices. One of them is an 8cm by 8cm encapsulated ribbon mc-Si cell, encapsulated at CREST. The second is a 2mm by 3mm solution processed CIGS cell [31] also produced at CREST. All the LBIC scans of the samples were realised at CREST with a newly developed 11 lasers system [32]. Results of two of the laser sources are presented in this work, with wavelengths 635nm and 780nm. The LBIC system’s sampling rate is approximately 7samples/s, which means that a 100 by 100 pixel scan takes approximately 23 minutes to be produced. Nevertheless, current maps of all the available laser wavelengths are acquired simultaneously, within this time.

The choices of sensing matrix type, reconstruction algorithm and basis \( \Psi \) all have a critical role on the reconstruction process. A qualitative and not quantitative comparison with the standard LBIC method is achieved in this work, in order to confirm that CS current mapping provides reliable results and is a viable approach for current mapping of PV devices.

Both laser sources were used for the mc-Si cell and a small 1cm x 1cm area of interest of the cell containing a crack and two very small spots was selected for measurements. The LBIC maps acquired at CREST are also presented for comparison. Penetration depth with these laser wavelengths is not more than a few micrometres, however it is adequate for validating that measurement results with the CS setup are in agreement with the standard LBIC scans.

In figure 3, the 100x100 pixel current maps acquired using the 658nm laser are presented. The two small spots are visible already when sampling 4000 measurements (40% of those needed for a full point-by-point scan). By acquiring more and more samples the current map becomes even sharper, although the improvement is small. Above 60% (6000 measurements) there is no further improvement and the reconstructed current maps are identical. An LBIC scan of the same area is included in the same figure. In all the current maps with this laser wavelength there is only a slight hint of the crack present in this area of the sample.

For the set of LBIC measurements presented here, signal to noise ratio (SNR) is approximately 300. For the compressive sampling case, the measured signal of each pattern is in the range of mA, as half of the measured area of the sample is illuminated. Measurement SNR\( \approx 6850 \) for the 658nm laser and SNR\( \approx 5100 \) for the 785nm laser. Nevertheless, since the sampling procedure is conceptually different, the final SNR of the reconstructed current maps will not be that high and it will also depend on the noise inserted by the reconstruction algorithm. In reality, initial sampling SNR is only one of the factors that influence the final SNR of the reconstructed image.
The same behaviour is also observed when using the 785nm laser source for CS current mapping, as can be observed from figure 4. The only difference is that in this case, the crack that is deeper in the device starts becoming visible. An LBIC map acquired with a 785nm laser source is also included in the same figure for comparison. Above 90% sampling, measurement noise starts having an impact on the optimisation algorithm that reconstructs the images. Thus, the reconstructed current map is contaminated with random noise. With 100% sampling, reconstruction fails completely due to this embedded noise in measurements. 100% sampling takes approximately 16 minutes. It is clear from the results in figure 4 that the highest quality images are delivered in the range of 40% to 80% of measurements. CS current mapping has very similar performance with LBIC measurements, but fewer measurements in absolute numbers are required for acquiring the current map.

The 658nm 40mW single mode fibre coupled laser was used for measuring the thin film sample. CS current mapping results are presented in figure 5, with an LBIC map of the same sample for comparison, acquired the LBIC system in CREST with a laser wavelength of 635nm [32]. The CS current maps have a display resolution of 100x100 (10000) pixels and different levels of optical resolution were realised. This can be achieved easily by grouping a smaller number of micromirrors of the DMD chip together and measuring a smaller area of interest on the sample. The different pixel resolutions in figure 5 were realized by binning 5x5, 3x3, and 2x2 pixels of the DMD together. 5000 (50%) measurements were acquired to produce the current maps of figure 5 as they provide a reliable reconstruction as shown in the above results. An optical resolution of 27μm is achieved without any demagnification optical elements. In the CS system, even if the sample is not placed exactly at the focal point of the last lens, the projection will be clear due to the spatial filter used. Measurements are made here on an area of interest with a large local defect on the top left area of the cell, to provide more information of current non-uniformities of that specific area.

The small device under test is produced in-house at CREST and consists of several different cells. However, the cells are not perfectly isolated and signal from adjacent cells is measured as can be seen by the CS current maps. The probes used for contacting are clearly seen on the top right corner of the CS map and at the top left corner of the LBIC map. As measurement points do not overlap each other when using compressive sampling, there is some pixelation in very uniform areas of the cell in the CS current maps.

CS current maps of the area with the defect with different numbers of measurements acquired are presented in figure 6. Acquiring more than 5000 (50%) measurements provides no further improvement of the current map, while even 4000 measurements provide a reliable current map of the sample. The performance of the method for this thin film device is similar to that for the mc-Si sample case, with the useful region of undersampling being in the range of 40% to 80%. These results confirm that the CS current mapping method has similar performance for different types of PV samples.

Fig. 5. 100x100 pixel CS current maps of the area of the sample where a pinhole is present. The percentages represent the ratio of the number of measurements to the total number of pixels of the image. An LBIC scan of the same sample is also presented for comparison (top left). The pixel size is also noted for each CS current map.

Fig. 6. 100x100 pixel CS current maps at the area of the thin film sample where a pinhole is present. The percentages represent the ratio of the number of measurements to the total number of pixels of the image.

IV. CONCLUSIONS

The LBIC technique for current mapping of PV devices is a significant tool in the research of new materials and designs for PV applications. In this work, an alternative experimental setup
that applies the CS sampling theory to LBIC measurements is analytically described and experimental validation results with different samples are presented. It is demonstrated that current mapping of PV devices can be potentially carried out significantly faster than using a standard LBIC system, due to the fewer measurements needed for reconstructing the final current map and the fast response of the micro-mirrors of the DMD. This is achieved by a simple experimental setup with no moving parts.

Accurate current maps were produced with only 40% of the measurements a point by point scan would need. The current setup can measure a small area of 1 cm by 1 cm, making it ideal for current mapping of small thin film research samples. The sampling area can be easily magnified in order to measure larger samples, by using simple optical elements. The significant signal amplification that is achieved by illuminating half of the sample also diminishes the use of lock-in techniques, which is an important feature for having a simple experimental layout. Current maps of an optical resolution up to 27 μm were acquired, without the use of any demagnification of the projected pattern that the DMD generated. Utilising a microscope objective lens in this system, can realistically push resolution to almost sub-micron levels. The addition of reflectivity measurements can also lead to IQE mapping of samples. Frequency modulation and lock in techniques can also be used for accelerating this method even further, achieving sampling speeds of the latest LBIC systems and further reducing measurement noise.

Further investigations are necessary regarding the compressed sensing related tools for this specific application. Different algorithms, sensing matrix types and transforms can be explored as other combinations than the ones used here may provide even better results.

Scaling up of this new current mapping method is plausible using Digital Light Processing (DLP) technology, which is based on DMD chips. This could potentially allow cell by cell straightforward current mapping of full sized PV modules. Utilising a projection system, the whole module could be light biased except the cell under measurement, on which CS current mapping measurements will be applied. Different combinations of light bias can be implemented to override bypass diodes in commercial PV modules. Further optimisation and development of this method could lead towards the implementation of a new accurate measurement system as a new state-of-the-art in the standard of LBIC systems for PV cells and modules.

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