

## A Simple Optical Setup for Current Mapping of Small Area PV Devices Using Different Sampling Strategies

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### Abstract

An optical setup for current mapping of photovoltaic devices is presented. It is based on a digital micro-mirror device (DMD) and a small number of additional optical elements making the implementation simple and cost effective. The specific properties of the DMD chip enable the application of two different sampling methods; point by point sampling and compressive sampling. Both sampling strategies are compared and cases when each one of them performs better are investigated. It is shown that compressive sampling can significantly enhance weak current signals and provide current maps in the cases when the point by point current signal is below the noise threshold.

### Introduction

Spatial non-uniformities can have a severe impact on the overall performance of a photovoltaic (PV) device. For this reason, the development of spatial characterisation methods is significant for the acquisition of local information on defects and inhomogeneities of solar cells. Light/Laser Beam Induced Current (LBIC) methods have been developed as a non-destructive characterisation technique which can be used for mapping the local current response of PV cells [1]. For its implementation, a light beam scans the PV sample and the induced current response is measured at each point. However, complicated experimental layouts are required for the realisation of such techniques. In addition, the method lacks speed, as the small size spot has to scan the entire area under measurement for a complete current map. On the other hand, the resolution that can be achieved with LBIC can reach sub-micrometre levels, which is difficult to be accomplished with other imaging methods of PV devices.

In this work a simple approach for realising an alternative type of current mapping system is demonstrated. The experimental

layout is based on a Digital Micromirror Device (DMD) [2]. Two different approaches are adopted for sampling; the standard point by point scan and compressive sampling (CS). Using a DMD to apply compressive sampling for current mapping of PV samples has been demonstrated in previous work [3]. By applying compressive sampling, one can measure a  $N$  element signal by only acquiring  $M \ll N$  linear measurements [4]. For solar cell current mapping applications, this is achieved by projecting a series of binary patterns on the sample and measuring the current response for each pattern. The current map is then reconstructed using an optimisation algorithm.

The aim of this work is twofold: the first is to introduce a simple and innovative current mapping setup for PV devices, based on a DMD chip. The setup is able to apply both point by point and compressive sampling. The second is to provide a pixel by pixel comparison between the two sampling strategies. Experimental results acquired with different samples show that each of these sampling methods has both advantages and drawbacks. Compressive sampling is preferable when high levels of noise are present, while raster scans can provide slightly better accuracy when noise levels are low, although measurements take more time.

### Experimental Setup

The experimental setup is presented in figure 1. The available laser sources are a 40mW laser at 658nm wavelength and a 100mW laser at 785nm. Both sources are single mode fibre coupled. The light output of the fibre is collimated at a size so that the beam overfills the micro-mirror array area of the DMD. The DMD is a V-7000 module, consisting of a 1024x768 pixel micromirror array, each micromirror having a pixel size of 13.7x13.7 $\mu\text{m}$ . The collimated beam is incident on the DMD at an angle and only the central region of the beam is used. The

plane of the micromirror area is perpendicular to the spatial filter system. A mirror is finally used for guiding the beam onto the sample, which is placed horizontally on a z-stage platform. The measurement area is 1cm by 1cm,

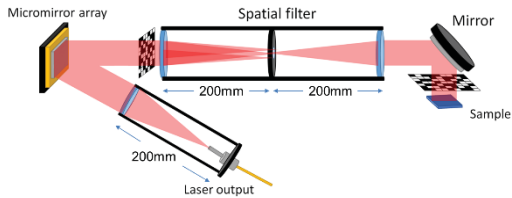


Figure 1: The optical setup of the current mapping system based on a DMD chip.

A National Instruments PXIe-4139 system source measure unit (SMU) is used for measuring the current response of the sample. As shown in figure 2, the experimental layout is kept as compact as possible, in order to demonstrate that the realisation of such a system is simple and a small amount of space and optical elements are required. A sampling rate of 10 measurements per second is achieved. The sample is placed at the focal plane of the last lens, so that the scanning spot or the patterns are actually projected on the sample. Nevertheless, a small misplacement from this plane has almost no effect on measurements due to spatial filtering. The optical setup is suitably enclosed for minimising external light contamination as well as for laser safety reasons.

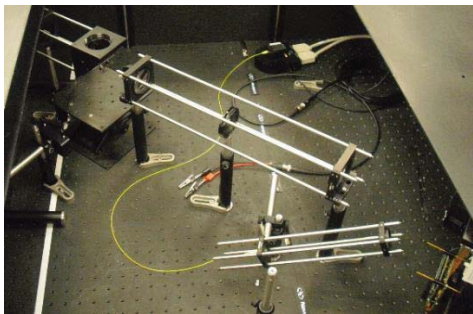


Figure 2. Picture of the current mapping setup at NPL based on the DMD device.

A Copper indium gallium selenide (CIGS) and a mc-Si PV samples (see Figure 3) are used for measurements. The patterns projected on the PV cells are also visible in the picture. The CIGS cell used for measurements had a size of 1cm by 1cm and is contacted with probes. The mc-Si sample has a size of 8cm by 8cm and only a small 1cm by 1cm area is measured.

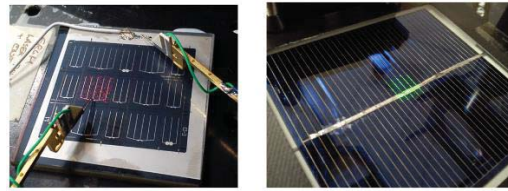


Figure 3. The CIGS sample on the left and the mc-Si sample on the right, which are used for measurements in this work.

## Sampling Methods

In order to apply a point by point scan, a number of micro-mirrors are grouped together depending on the desired optical resolution. When only one pixel of the micromirror array is used for the scan, the signal is rather low, which results in very noisy measurements. For this reason, the minimum group of pixels used in this series of measurements is 9 pixels (3x3), which results in an optical resolution of 41.1 $\mu$ m and the maximum is 49 (7x7), which gives a resolution of 96 $\mu$ m. 100x100 pixel current maps were acquired in the case of CS current mapping, in order to achieve a straightforward performance analysis of the measurement system.

During compressive sampling, a series of test functions  $\Phi = \{\phi_m\}_{m=1}^M$  are projected onto the PV device. Random binary matrices of ones and zeroes can be used as patterns, as they are easy to implement and satisfy the requirements for compressive sampling [5]. For every projected pattern the current response of the PV device is measured, populating the measurement vector  $\mathbf{y}$ . Since the projected patterns are known, constructing sensing matrix  $\Phi$ , the solution to the underdetermined problem is the  $\mathbf{x}$  vector with the minimum  $\ell_1$  norm [6].

$$\hat{\mathbf{x}} = \text{argmin} \|\mathbf{x}\|_1 \text{ subject to } \Phi \mathbf{x} = \mathbf{y} \quad (1)$$

With this method, current maps can be acquired with much fewer measurements than what a raster scan would require.

## Results

In Figure 4, two current maps of the CIGS PV cell are presented, using a different optical resolution each time, acquired with a point by point scan. It is clear that by grouping different number of micromirrors together one can focus on different areas of a sample with different levels of resolution. This is a very convenient feature of a DMD based system, as it allows much more freedom of settings, such as changing the

size of the spot that realizes the scan or selecting specific areas of interest. In Figure 4, the PV cell's current response appears to be rather uniform, apart from local tiny spots. The probe used for contacting the cell is also visible. A slight general non-uniformity of approximately 10% is due to the initial non-uniformity of the Gaussian collimated beam that overfills the DMD.

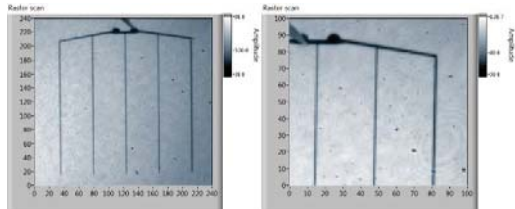


Figure 4: On the left 3x3 groups of micro-mirrors are used for the point by point scan, measuring the whole cell. On the right 4x4 groups are used for measuring a smaller area of the sample.

For the compressive sampling case 7x7 groups of micro-mirrors were used and 100x100 pixel current maps were produced, imaging the whole PV cell. As the aim of compressive sampling is to apply fewer measurements in order to reconstruct the final current map, different levels of undersampling were investigated. The unique property of this experimental layout is that it can apply both point and CS current mapping. This means that a pixel by pixel comparison can be realised, for a more accurate experimental optimisation and evaluation of CS current mapping.

In Figure 5, the reconstructed current maps are expressed as percentages, expressing the ratio of samples (projected patterns) acquired for reconstruction by the total number of pixels or equivalently, the ratio of CS measurements taken by the number of measurements a point by point would need. The total number of pixels of the current maps is 10000. The contacting grid pattern of the PV cell start becoming visible from 3000 measurements (30%) while current maps including all the features are acquired above 50%. By adding more measurements the reconstructed map converges to the actual current map.

The curve of the correlation coefficient for is presented in Figure 6, as a function of number of measurements acquired. The small local decrease observed at 50% of measurements is thought to be due to the interaction of the DCT transform with the symmetry of the cell. Apart from the small

local spots and imperfections, the PV cell is rather symmetric, which has an influence when Fourier based transforms are used. The results confirm that compressive sampling is a reliable current mapping method that requires fewer measurements than a point by point scan.

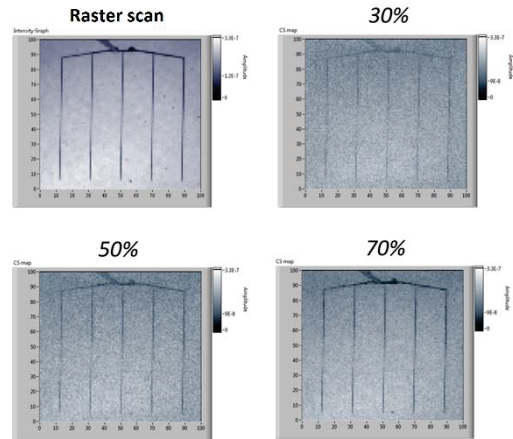


Figure 5. Reconstructed current maps of the PV cell using different number of measurements compared to the point by point scan.

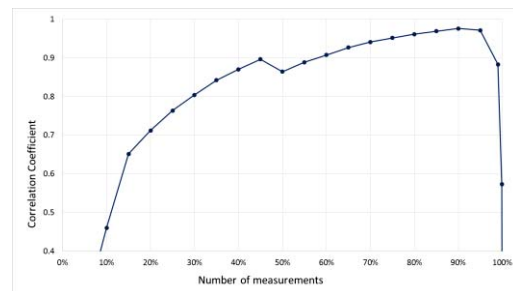


Figure 6. The correlation coefficient between the CS current maps and the LBIC map, as a function of number of measurements acquired.

In some cases compressive sampling is necessary because a point by point scan does not provide reliable results due to signal to noise issues. This is clear when the large 8cm by 8cm mc-Si PV cell is used and a small 1cm by 1cm area of the cell is measured, known to contain cracks and spots. A raster scan results in an extremely noisy current map, where even the sharpest features of the cell area are barely distinguishable. Since this is a large area sample, the noise levels are very high compared to the current signal of the point by point scan. Thus the very weak signal is lost within the background noise. A lock-in technique has not been applied during measurements, which could help reduce measurement noise. However, when using compressive sampling, the current signal is

greatly enhanced, since half the measured area is illuminated and not just a single spot. The reconstructed current maps are presented in figure 7. Both laser sources were used for measurements. Using the IR laser the crack starts becoming visible, although the light still doesn't penetrate deep enough into the cell to make this feature sharper. Current maps with the LBIC system in CREST [7] are presented in the same figure for confirming the validity of measurements.

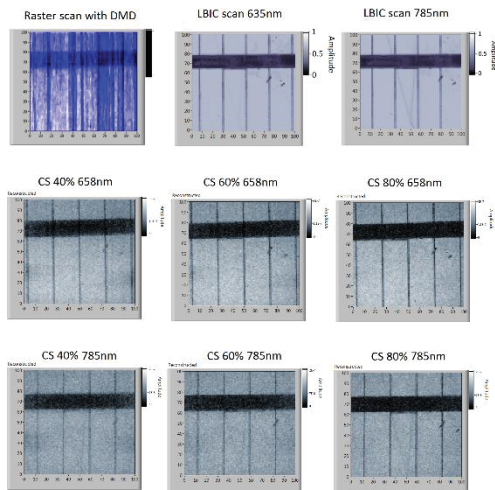


Figure 7. CS current mapping results using two different laser sources, for different levels of undersampling compared to the point by point scans using a DMD and from the CREST LBIC system.

## Conclusions

A current mapping optical system is realised in this work in a very simple and straightforward way without moving parts, complicated optical elements or lock-in methods to achieve high optical resolution and sampling rate. It also offers the unique opportunity for an experimental pixel by pixel comparison of LBIC and CS current mapping. It is shown that compressive sampling yields reliable results always with fewer acquired measurements than point by point sampling, although the difference sometimes can be small. On the other hand, the application of compressive sampling is necessary in cases with very high noise levels, where the signal levels must be enhanced for meaningful sampling above the noise threshold.

This simple DMD system can be utilized for reliable current mapping not only for PV devices, but also for photodiodes and other semiconductor devices. Such a setup can easily be realised at any PV research

laboratory to provide a useful tool for spatial characterisation of small area PV devices. Moreover, it offers the opportunity to investigate the performance of different algorithms and sensing matrices for compressive sampling, as a direct comparison with a raster scan is possible.

## Acknowledgements

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