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Improving Photoluminescence Imaging using Non-uniform Illumination

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Due to its fast nature and in-depth results, photoluminescence (PL) imaging has been used not only as a characterisation method in research and development, but also as a critical quality control tool in production lines [1]. However, images of samples with a large spatial non-uniformity obtained from standard PL imaging systems are affected by lateral carrier flow upon uniform illumination due to the non-uniform local carrier effective lifetime and thus, excess carrier density [2]. This lateral carrier flow causes what is known as 'smearing', which can result in image blurring and loss of information, especially when quantitative results are required [3]. Zhu *et al.* have developed a method, based on non-uniform illumination, that mitigates the smearing, resulting in images that are not affected by lateral carrier flow [4]. Images produced using this method show a significant improvement in accuracy and sharpness when compared to the standard techniques [5]. However, this method requires significantly longer computing time compared to conventional methods. To compete with these standard methods, the non-uniform illumination technique should be as quick and accurate as possible. In this study, we improve this method by accelerating the analysis process and adding capabilities and functionality that will allow a more in-depth understanding of the obtained images.

Introduction

PL imaging is a fast and powerful characterisation method often used in photovoltaics (PV) research and production for the inspection of wafer, bricks and modules [1][6][7]. However, many PL images suffer from 'smearing'. Several methods have been proposed to mitigate smearing [3][4][9]. One method, outlined by Phang *et al.* [3][10], uses the continuity equation to 'de-smear' the PL image. While this method is capable of accurately removing smearing, it is limited to devices without a junction as it cannot account for the drift current [9]. Furthermore, it requires a high signal to noise ratio as the calculation is dependent on the estimation of the second derivative of the carrier recombination lifetime in the continuity equation [10]. Another method, outlined by Zhu *et al.* [4] and extended upon by Nie *et al.* [5], utilises a non-uniform illumination source during the PL imaging measurement [4][11]. A liquid-crystal-display (LCD) is used to control the light intensity at each pixel [5]. This method adaptively changes the illumination pattern to inversely match the PL pattern seen in the conventional PL image of a silicon sample using to the following expression:

$$\phi_{x,y}^{i} = \phi_{x,y}^{i-1}\left[\frac{PL_{o}^{i-1}}{PL_{x,y}^{i-1}}\,\varepsilon + (1-\varepsilon)\right] \tag{1}$$

where $\phi_{x,y}^{i}$ and $\phi_{x,y}^{i-1}$ are the light intensities at position (*x*,*y*) in the *i*th and (*i*-1)th iterations, respectively, $PL_{x,y}^{i-1}$ is the PL count at position (*x*,*y*) in the (*i*-1)th iteration, PL_{o}^{i-1} is the PL count at an arbitrary position that is chosen to stay with a constant light intensity throughout the iteration. ε is a damping factor between 0 and 1 that ensures convergence [4][5]. This results in a uniform excess carrier concentration across the sample and hence, no lateral carrier flow and no smearing [9]. For the system to adaptively change the illumination intensity to match the profile of the sample, a mapping step is required to correlate the camera's pixels to the LCD panel's pixels [5]. The mapping process requires the system to record the camera's response to each individual pixel in the LCD panel, saving an image each time. Due to the nature of this process, it is time-intensive as well as disk space-intensive. Furthermore, in the current state, the software can only be run through a string of different python scripts. This involves in-depth knowledge on what each script does, and what information and images each script depends on. A graphical user interface (GUI) is required to allow for the process to be run smoothly by users that may not be well versed in the actual operation of the system.

The non-uniform illumination method can be significantly improved by reducing the time required to conduct the mapping process, as well as reduce the disk space needed to perform the calibration step. Improvement of the method requires logical changes that create a more efficient overall process, both from time and resource point-of-views. Improving the non-uniform illumination method also involves automating specific tasks in addition to adding extra functions, such as image correction. These improvements will help the non-uniform illumination method become more viable in research institutes, as well as production companies, by allowing an easy and efficient way of obtaining high detailed PL images.

Method

The selected approach to improving the method is based on an iterative process using a repository on GitHub. Initially, the code has been improved to streamline the process to reduce inefficiencies. After this initial change, more improvements are produced by tracking the performance during any change to the system through the repository. If a change improved the system, it would be implemented into the next version of the software. As the system's initial mapping sequence involved a significant amount of time and human interaction, these inefficiencies are the focus of the first stage of modifications. Previously, this process was completed as a simple loop. Utilising multithreading in this work allowed the process to use more of the central processing units (CPU) cores and run multiple loops at the same time, rather than end-to-end. The CPU usage is recorded using the native Window's performance monitor.

Results

Testing this approach is performed on a system containing an Intel Core i7 - 9700K CPU @ 3.60 GHz, which contains eight logical processors and eight cores. From the implementation of the multithreading component in the software, the mapping process duration is reduced from an 80-minute task to a 16-minute task, resulting in a 500% improvement. From Figure 1, the process now utilises significantly more CPU processing power, with an average utilisation percentage of above 90%, compared to 26% seen in the original method.

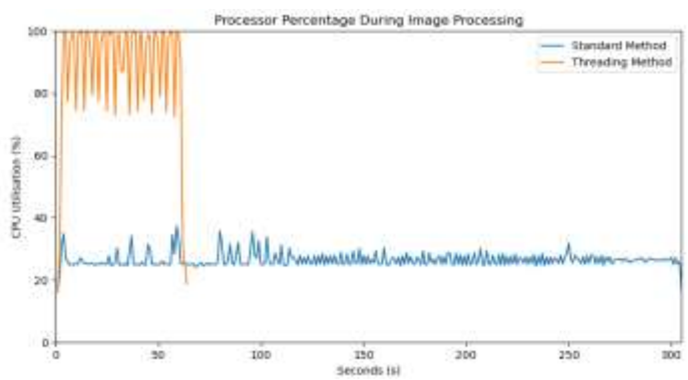

Figure 1. Processing percentage of the CPU during the image mapping step using the standard loop method and using the multithreading loop method. Note that the process was shortened from 256 image scans to 16 to show more detail.

Figure 2. A graphical user interface (GUI) was developed to allow for a secure, user-friendly method to map the hardware of the system.

Figure 2 shows the GUI developed for the method. This interface is developed to target the inefficiency of significant human interaction. The GUI allows a user to input specific initial parameters for the measurement, such as camera exposure time and hardware dimensions, as well as run the entire process while keeping track of the percentage completed and time remaining.

While there has been a significant improvement within the software, the system is still being further improved, including adding features and optimising other aspects of the code to reduce the processing time even further. These features include adding flat field image correction [12][13] and image deconvolution to counter the effect of the point spread function [14][15][16].

Conclusions

To summarise, PL imaging with non-uniform illumination offers the advantage of higher detailed images, which can lead to a deeper understanding of the sample being characterised. Accelerating the processing of the system allows the method to become commercially viable for research, as well as production lines. The system has been optimised to allow for quicker measurements with no cost to the quality of the resulting image.

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