DOI 10.5162/SMSI2023/D5.4

Compressed Sensing Time Resolved Photoluminescence Imaging for Semiconductor Characterisation

Aidas Baltušis[1,2], George Koutsourakis[2], Sebastian Wood[2], Stephen Sweeney [3]
[1]Advanced Technology Institute, University of Surrey, Guildford, GU2 7XH, UK
[2]National Physical Laboratory, Hampton Road, Teddington, Middlesex, TW11 0LW, UK
[3]James Watt School of Engineering, University of Glasgow, Glasgow, G12 8LT, UK
aidas.baltusis@npl.co.uk

Summary:
Compressed sensing has been applied to time-resolved photoluminescence measurements for semiconductor device and material characterisation. This novel approach has the potential to achieve charge carrier lifetime imaging of semiconductor samples with shorter measurement times, higher repeatability and increased signal to noise ratio. The feasibility of the approach is investigated through simulations and an order of magnitude improvement in measurement acquisition speed over scanning approaches is demonstrated in this work. A proof-of-concept experimental system is presented, with initial measurements confirming the feasibility of this method.

Keywords: Compressed sensing, photoluminescence, semiconductor characterisation, signal processing, TCSPC

Introduction

The recent emergence of single pixel imaging techniques via compressed sensing [1] has led to implementations in various types of measurements. It is particularly useful in novel imaging applications where standard CMOS/CCD sensors cannot be used. It allows for images to be accurately acquired using a single-point detector, such as a photomultiplier tube (PMT) without requiring any mechanical movement of samples. Instead, digital light processing with a series of measurement patterns is used, and the image information is later reconstructed.

For semiconductor devices, this approach has been reported in the past for photocurrent mapping [2]. Another established but more complex measurement technique in semiconductor material and device characterisation is time-resolved photoluminescence (TRPL) [3]. The optical nature of the measurement is particularly useful because no contacts are required, and the method is non-destructive. The sample is excited using a laser pulse, resulting in photoluminescence (PL) emission. PL emission is detected with a single pixel detector such as a PMT, with high temporal resolution, allowing determination of the decay time of the signal and the charge carrier lifetimes. The lifetime probes the radiative and non-radiative recombination processes happening within the material [4].

In this work, a time correlated single photon counting (TCSPC) prototype system is demonstrated which can acquire maps of TRPL signal across a sample by applying compressed sensing methods. The process of the method is presented, along with feasibility experimental results and limitations of the prototype system.

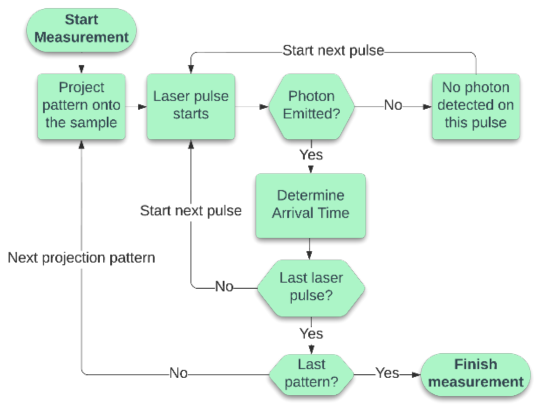

Figure 1. A diagram of the compressed sensing TRPL process. After projecting each pattern, the TRPL response is gathered from the excited area. The final measurements are TRPL responses for each pattern.

Methodology

In previous work, we have demonstrated the computational model for implementing compressed sensing TRPL imaging. Based on that, a proof-of-concept experimental setup has been developed. The measurement system is built similarly to a standard time-resolved photoluminescence setup. A digital micromirror device (DMD) [5] was added into the optical path and

DOI 10.5162/SMSI2023/D5.4

the laser beam expanded to overfill the DMD area. This allows for compressed sensing patterns to be projected onto the measured sample. A typical measurement process is shown in Figure 1. After projecting each sampling pattern onto the sample, the combined TRPL response of the excited area is acquired. PL images for each bin of the decay curve are then reconstructed using a modified convex optimization algorithm SPGL1 (spectral projection gradient L1 minimisation algorithm) [6].

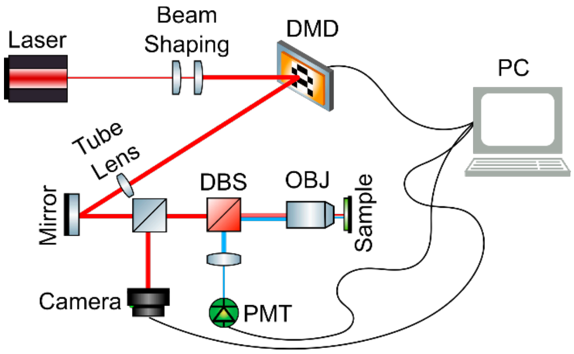

Figure 2. Schematic of the compressed sensing TRPL system of this work.

Results

Results from Cadmium Indium Gallium Selenide (CIGS) solar cell sample are presented in this work. Figure 3 (a) shows a photocurrent map of the measured sample area. This is used as a reference image, against which reconstructed photoluminescence maps were compared, although we do not expect the photocurrent map to correspond directly to the PL images. In subfigure (b) the total reconstructed photoluminescence map is shown. PL map at the peak of TRPL decay and 1.2 ns after the peak are shown in (c) and (d) respectively. In (c) the PL illumination is more evenly distributed across the measured area, with a low-intensity corner remaining in the top-left part of the sample, where a contact is located. In (d) the recombination is more unevenly distributed, as carriers diffuse and recombine. The extended defects in the sample show up as darker areas in the image.

The current limitations of the prototype system are its sensitivity to any non-uniformities in the laser beam profile as well as noise sources in the measurements. The non-uniform beam profile of the laser used shows up as higher or lower intensity regions in the reconstructed images, convoluted with any variations of the sample structure. Furthermore, drift in the sample response and fluctuations in laser power result in the reconstruction algorithm being less efficient and so introduce random noise to the images.

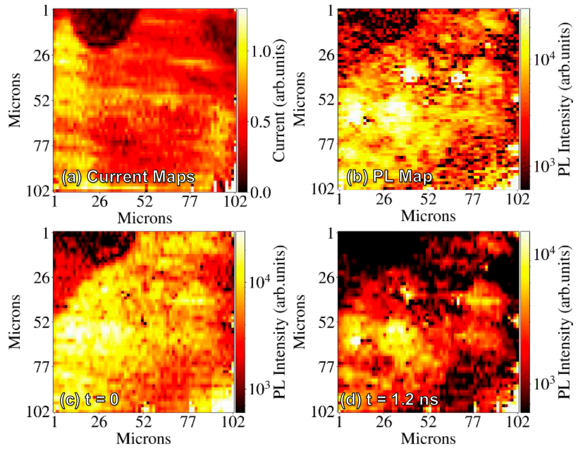

Figure 3. a) Photocurrent response map of a CIGS sample, 64x64 px resolution. The dark area in the top left is a piece of electrical contact, the rest is active material. (b) PL map after compressed sensing process of the same area. (c) and (d) present PL intensity maps at the peak of TRPL and 1.2 ns after the peak.

Conclusions

We have developed a prototype system and methodology for TRPL imaging without using a raster scanning approach. The use of projection patterns increases the measurement acquisition speed. The system can be further optimised by using a higher power laser with a uniform beam profile. Similar measurement methods can potentially be implemented to different types of measurements such as spectrally resolved photoluminescence.

References

[1] M. F. Duarte *et al.*, “Single-pixel imaging via compressive sampling” *IEEE Signal Process. Mag.*, vol. 25, no. 2, pp. 83–91, 2008, doi: 10.1109/MSP.2007.914730.

[2] G. Koutsourakis, A. Thompson, and J. C. Blakesley, “Toward Megapixel Resolution Compressed Sensing Current Mapping of Photovoltaic Devices Using Digital Light Processing,” *Sol. RRL*, vol. 2100467, pp. 1–8, 2021, doi: 10.1002/solr.202100467.

[3] T. Trupke, B. Mitchell, J. W. Weber, W. McMillan, R. A. Bardos, and R. Kroeze, “Photoluminescence imaging for photovoltaic applications,” *Energy Procedia*, vol. 15, no. 2011, pp. 135–146, Jan. 2012, doi: 10.1016/j.egypro.2012.02.016.

[4] M. Maiberg and R. Scheer, “Theoretical study of time-resolved luminescence in semiconductors. I. Decay from the steady state,” *J. Appl. Phys.*, vol. 116, no. 12, 2014, doi: 10.1063/1.4896483.

[5] L. J. Hornbeck, “The DMD™ Projection Display Chip: A MEMS-Based Technology,” *MRS Bull.*, vol. 26, no. 4, pp. 325–327, 2001, doi: 10.1557/mrs2001.72.

[6] E. van den Berg and M. P. Friedlander, “Probing the Pareto frontier for basis pursuit solutions,” *SIAM J. Sci. Comput.*, vol. 31, no. 2, pp. 890–912, 2008, doi: 10.1137/080714488.