Australian Government
Australian Renewable Energy Agency

ARENA

Advanced Recombination-based Loss Analysis Methods for Silicon Wafer and Silicon Solar Cells

Project results and lessons learnt

Lead organisation:	University of New South Wales (UNSW)
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Executive Summary

The improvement of solar cell efficiency requires the ability to identify and quantify loss mechanisms, many of which are recombination related.

Effective lifetime measurements are widely used to characterise recombination; however, commercially-available systems are relatively basic and provide only part of the obtainable information. For example, most of the commercially-available systems do not support temperature-dependent measurements and are limited to room-temperature operation, despite the fact the valuable recombination-related information can be only obtained by lifetime measurements performed at different temperatures (and light-intensities). Furthermore, measurement at room-temperature does not represent the field-operation conditions of most solar cells (such as those installed in the Australian deserts).

The aim of this research project was to develop a novel effective lifetime measurement system to investigate recombination processes, mainly in the silicon bulk, at wafer surfaces and at silicon-metal interfaces, over a wide range of temperatures.

The developed system is considered one of the best systems in the world and it has been heavily used by Australian researchers, but also by international visitors (from the Massachusetts Institute of Technology, Arizona State University and the University of Agder), to investigate defects in silicon. The knowledge gained during the project led to development of other novel characterisation methods for photovoltaic modules and for a new type of solar cells (perovskite-based).

Project Overview

Project summary

The improvement of solar cell efficiency requires the ability to identify and quantify loss mechanisms, many of which are recombination related.

Effective lifetime measurements are widely used to characterise recombination; however, commercially-available systems are relatively basic and provide only part of the obtainable information. For example, most of the commercially-available systems do not support temperature-dependent measurements and are limited to room-temperature operation, despite the fact the valuable recombination-related information can be only obtained by lifetime measurements performed at different temperatures (and light-intensities). Furthermore, measurement at room-temperature does not represent the field-operation conditions of most solar cells (such as those installed in the Australian deserts).

In this project we developed a novel effective lifetime measurement system. The system was then used to investigate recombination processes in the silicon bulk, at wafer surfaces and at silicon-metal interfaces.

During the project we also developed new characterisation methods to identify loss mechanisms in solar cells and modules. An exciting (and unexpected) result of this project is the development of luminescence-based imaging methods for perovskite solar cell.

Project scope

Solar photovoltaic energy has major potential to provide increasingly large fractions of the world's electricity needs but further cost reduction is imperative. Key technological paths to reduce costs are: (i) increasing solar cell efficiency and (ii) extending durability and reliability of photovoltaic modules; without significantly increasing manufacturing cost. Both of these paths can be addressed by improving silicon material quality. Defects within the bulk of the silicon wafer, **present in parts-per-trillion levels**, are centres for carrier recombination, limiting the obtained efficiency. Activation of these defects can occur during the expected 25 years of operation of the photovoltaic system (due to light, temperature or electrical potentials) which significantly affects its long term performance. Long-term efficiency and reliability can therefore be improved by identifying and understanding bulk defects.

The goal of the project was to investigate recombination processes **using an innovative measurement system**. The project overcame the limitations of commercial lifetime measurement systems, especially those related to measurements under low illumination, at elevated temperatures and of metallised samples. The project developed an innovative approach that combines a set of measurements at various conditions with powerful algorithms and simulation tools. This approach is very different from common ones where the measurement conditions are typically limited to room temperature.

The innovative system design of including both front and rear sensors significantly extends the measurement range to metallised samples that cannot be investigated by the standard systems.

The novelty of the developed system led to a large number of scientific publications in leading journals and conferences. It also led to strong collaboration with leading research groups across the world.

Outcomes

Development of advanced lifetime measurement system:

- **Development of advanced lifetime measurement system:** The system is based on three sensors [one photoconductance (PC) detector and two photoluminescence (PL) ones]. An advanced temperature control stage allows measurement in a temperature range of 100–670 K with an accuracy of 0.1 K. The illumination is based on a light-emitting diode (LED) array and high intensity flash; this illumination allows measurements of excess carrier concentration in the range of 10^{10}–5×10^{16} cm^{-3}. Software was developed in Python to take and analyse the measurements. As part of the Knowledge Sharing Plan, the software was uploaded to an open-to-public software-hosting website – GitHub. The software includes the most up-to-date temperature-dependent models of various silicon properties.
- **International visitors:** Strong evidence to the success of this project is the visits of a senior professor and three PhD students, arriving especially to use the developed system:
  - Ms. Mallory Jensen from the Massachusetts Institute of Technology (MIT, USA) visited our laboratory between beginning of July and the end of September 2016.
  - Mr. Simone Bernardini from Arizona State University (ASU, USA) arrived in January 2017 and stayed until the end of April 2017.
  - Ms. Sissel Sondergaard from the University of Agder (Norway) arrived in January 2018 for five months stay.
  - Professor Juan Carlos Jimeno from the University of Basque Country (Spain) arrived in January 2018 for three months stay.
- The systems developed in this project were also used to investigate an interesting observation of negative photoconductance. The paper describes this investigation was accepted ‘as is’ with supportive comment from the reviewers such as “***This is an interesting paper with a comprehensive analysis of a somewhat surprising observation***”.

Development of advanced characterisation methods:

- **Development of photoluminescence imaging at high temperature:** A novel method to determine the energy levels of recombination centers (defects) relative to the conduction/valance band edges (Et), based on photoluminescence imaging at high temperature, was developed and tested. According to our knowledge, these were the first published PL-based spatially resolved Et maps.

- **Investigation of metal-silicon interfaces:** The project developed a front-detection system to investigate metal-silicon interfaces. We highlighted the limitations of current analysis methods and developed a new method based on Quokka modelling.
- **Luminescence imaging of perovskite solar cells:** A surprising output of this project is the development of luminescence-based characterisation methods for perovskite solar cells. A luminescence-based investigation of this exciting organic–inorganic material has been published in a high impact-factor journal at the end of 2015. The resulting images are believed to be the first ever published luminescence images of perovskite solar cells. The importance of this research was recognised by its selection as an 'accelerated publication', a selection that is usually reserved only for world records. The developed method has been heavily used in the last few years. We published three papers in *Advanced Energy Materials* (impact factor 16.72) and assisted the Perovskites Groups at UNSW to develop high efficiency large-area perovskite solar cells.
    - **Development of advanced photoluminescence imaging method based on non-uniform illumination:** Photoluminescence imaging is a fast and powerful spatially resolved characterisation technique, commonly used for silicon wafers and solar cells. In conventional measurements homogeneous illumination is used across the wafer. As part of this project, we developed a photoluminescence imaging setup that enables inhomogeneous illumination with arbitrary illumination patterns to determine various parameters of solar cells and solar cell precursors. To demonstrate the strength of the proposed inhomogeneous illumination imaging method, a set of proof-of-concept measurements have been conducted; these measurements include contactless series resistance (R_s) imaging, emitter sheet resistance and diffusion length measurements. The results indicate that the use of inhomogeneous illumination significantly extends the application range of photoluminescence imaging for the characterisation of silicon wafers and solar cells. This system has attracted significant attention in a conference last year. This attention led to a fruitful collaboration with the research group at Fraunhofer ISE (Germany).
    - **Outdoor photoluminescence imaging for photovoltaic (PV) modules**: An exciting output of this project is the development of outdoor photoluminescence imaging system for PV modules. This is the first ever contactless measurement system for modules in the field.

Investigation of bulk defects:

The developed system was used to investigate a wide range of bulk defects:

- We have identified the recombination parameters of the bulk defect that responsible for carrier induced degradation (CID) in multicrystalline silicon (mc-Si) wafers. Further information regarding these parameters was published as a part of collaboration with the research group at MIT. Our study was the first to correlate between hydrogen and this type of degradation.
- We investigated bulk defects in n-type wafers. As part of the n-type wafers investigation we developed a new micro-photoluminescence system.
- We also investigated cupper-related light induced degradation.

Transferability

Several methods have been used to transfer the knowledge gained in this project to the wider research community and to the public:

- **Invited talks:**
  - Initial results from the project were presented in the *Optics and Photonics Taiwan, International Conference* (*OPTIC*), (Taiwan, November 2015).
  - The developed system and initial results from the investigation of the bulk defect in mc-Si were presented in the *9th International Workshop on Crystalline Silicon for Solar Cells and the 3rd Silicon Materials Workshop* (Arizona, USA; September 2016).
  - Overview regarding the project and the obtained results were presented in the *3rd International Conference on Emerging Electronics* (Mumbai, India; December 2016).
  - The developed system for outdoor PL imaging of PV modules was presented in the *Photovoltaic Reliability Workshop* (Denver, USA; February 2018).
  - Overview regarding the project and the obtained results will be presented in the *European Advanced Energy Materials and Technology Congress* (Stockholm, Sweden; March 2018).
- **Journal publications:** 22 journal papers were published as part of this project.
- **Conference publications:** 40 conference papers were published as part of this project.
- **Public talks:**
  - In April 2015, Prof. Stuart Wenham (UNSW) hosted a workshop for the industrial partners of his ARENA's hydrogenation project. Prof. Wenham invited Dr Hameiri to present results from this project in this workshop. This was a great opportunity to expose the project, its goals and its results to some of the major photovoltaic companies.
  - In November 2016, as part of another ARENA grant (2014/RND009), a workshop between the research groups of UNSW and ANU was held. As part of this workshop, three presentations were given by Dr. Hameiri and the two PhD students hired by the project (Mr Robert Dumbrell and Mr. Yan Zhu). The workshop included researchers from both universities, but also representatives of companies (Sinton Instruments and BT Imaging).
  - In October 2017, as part of another ARENA grant (2014/RND009), a workshop between the research groups of UNSW and ANU was held. As part of this workshop, four presentations were given by Dr. Hameiri and the two PhD students hired by the project (Mr Robert Dumbrell and Mr. Yan Zhu). The workshop included researchers from both universities, but also representatives of an inspection company (BT Imaging).
  - In November 2017 Dr. Hameiri gave a two-hour public talk at the Solar Energy Research Institute of Singapore (SERIS) summarises the main output of this project.
  - In March 2018 Mr Robert Dumbrell gave a public talk (as part of SPREE seminar) regarding his work in this project.
- **Open source codes:** All the codes developed by this project were uploaded to an open-to-public software-hosting website – GitHub

An interesting output of this project is the development of luminescence-based characterisation methods for perovskite solar cells:

In the last few years solar cells based on mixed organic-inorganic hybrid perovskites have stunned the photovoltaic community. Although the first efficiency of a solid-state perovskite solar cell of 9.7% was reported only in 2012, rapid progress by several research groups has improved this efficiency to an independently confirmed value above 21% earlier last year.

One key challenge for this technology associated with perovskite-based solar cells, which is common to all thin film solar cell approaches, is the process uniformity. To date, perovskite solar cells have been fabricated mostly on relatively small substrates (generally smaller than 10 × 10 mm^2); however, commercial applications require scaling-up the process to a much larger substrate area (on the order of at least 156 × 156 mm^2). This scaling-up requires the ability to monitor the uniformity of the fabrication process. Lateral process variations can be expected particularly for solution spreading techniques that are commonly used for the fabrication of perovskite solar cells. As part of this project, fast camera based luminescence imaging measurements on perovskite solar cells were developed. During the project we published a few journal papers regarding the developed method; three of them in the very high impact *Advanced Energy Materials*.

Publications

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J2. Soufiani AM, Hameiri Z, Meyer S, Lim S, Tayebjee MJY, Sung J, Ho-Baillie A, Conibeer GJ, Spiccia L, Green MA. 'Lessons learnt from spatially-resolved electro- and photo-luminescence imaging: Interfacial delamination in $CH_3NH_3PbI_3$ planar perovskite solar cells upon illumination', *Advanced Energy Materials.* 2017; 7: 1602111.

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J12. Z. Hameiri, N. Borojevic, L. Mai, N. Nandakumar, K. Kim, S. Winderbaum, 'Low-absorbing and thermally stable industrial silicon nitride films with very low surface recombination', IEEE Journal of Photovoltaic, 2017, 7, 996-1003.

J13. H. Li, F. J. Ma, Z. Hameiri, S. Wenham, M. Abbott, 'On elimination of inactive phosphorus in industrial $POCl_3$ diffused emitters for high efficiency silicon solar cells', Solar Energy Materials and Solar Cells, 2017, 171, 213-221.

J14. R. Dumbrell, M.K. Juhl, T. Trupke, Z. Hameiri, 'Comparison of terminal and implied open circuit voltage measurements', IEEE Journal of Photovoltaic, 2017, 7, 1376-1383.

J15. H. Li, F. J. Ma, Z. Hameiri, S. Wenham, M. Abbott, 'An advanced qualitative model regarding the role of oxygen during $POCl_3$ diffusion', Physica Status Solidi - Rapid Research Letters, 2017, 11, 1700046.

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J22. X. Liu, Y. Zhang, L. Shi, Z. Liu, J. Huang, J.S. Yun, Y. Zeng, A. Pu, K. Sun, Z. Hameiri, J.A. Stride, J. Seidel, M.A. Green, X. Hao, 'Exploring inorganic binary alkaline halide to passivate defects in low-temperature-processed planar-structure hybrid perovskite solar cells', Advanced Energy Materials (accepted 9/3/2018).

Conferences:

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C5. Soufiani AM, Hameiri Z, Juhl MK, Jiang L, Cheng YB, Weber J, Ho-Baillie A, Trupke T, Green MA. 'Microscopic-scale characteristics of organic-inorganic perovskites: Full device photoluminescence and electroluminescence imaging', International Conference on Solution Processed Innovative Solar Cells, 2015.

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C13. Ma FJ, Li M, Hameiri Z. 'Advanced evaluation of surface passivation nonuniformity from photoluminescence imaging of undiffused lifetime samples', *26th International Photovoltaic Science and Engineering Conference*, 2016.

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C17. Borojevic N, Hameiri Z, Winderbaum S. 'Advanced optical characterization of industrial PECVD silicon nitride layers', *33rd European Photovoltaic Solar Energy Conference*, 2016: 519-522.

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C23. R. Dumbrell, M.K. Juhl, T. Trupke, Z. Hameiri, 'On the use of voltage measurements for determining carrier lifetime at high illumination intensity', 44th IEEE Photovoltaic Specialists Conference, 2017.

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C34. X. Yang, K. Weber, Z. Hameiri, S. De Wolf, 'Industrially feasible dopant-free, carrier-selective passivating contacts for high-efficiency crystalline silicon solar cells', 27th International Photovoltaic Science and Engineering Conference, 2017.

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C39. M.C. Schubert, F. Schindler, W. Kwapil, F.D. Heinz, T. Niewelt, R. Eberle, Y. Zhu, M.K. Juhl, Z. Hameiri, T. Trupke, F. Rougieux, D. Macdonald, 'Understanding the efficiency limitation of silicon material for solar cells', 10th International Workshop on Crystalline Silicon for Solar Cells, 2018.

C40. R. Lee Chin, Y. Zhu, G. Coletti, S. Binetti, M. Pollard, Z. Hameiri, 'Insights into striations in n-type Czochralski wafers investigated via low-temperature hyperspectral and temperature-dependent spectral photoluminescence', 10th International Workshop on Crystalline Silicon for Solar Cells, 2018.

Intellectual Property: Patents / Licences

1. Information regarding a novel method to detect cracks in modules has been provided to UNSW Innovations, to determine if a patent can be filed.
2. Information regarding a novel method to measure bulk lifetime in silicon bricks has been provided to UNSW Innovations, to determine if a patent can be filed.
3. Information regarding a novel method to improve diffusion of hydrogen atoms into the silicon wafer has been provided to UNSW Innovations, to determine if a patent can be filed.
4. Information regarding a novel method to detect an open-circuit voltage failure of a bypass diode has been provided to UNSW Innovations, to determine if a patent can be filed.

Awards

Invited talks:

1. Hameiri Z, Juhl MK, Trupke T. Spatially resolved lifetime spectroscopy from temperature-dependent photoluminescence imaging. **Optics and Photonics Taiwan, International Conference (OPTIC)**, November 2015.
2. Hameiri Z, Borojevic N, Mai L, Nandakumar N, Kim K, Winderbaum S. On the limitation of the refractive index at 633 nm to characterize silicon nitride films. **3rd International Conference on Emerging Electronics**, 2016.
3. Zhu Y, Castrillon C.V, Jensen M.A, Juhl M.K, Coletti G, Hameiri Z. Defect characterization via temperature and injection dependent lifetime spectroscopy**. 9th International Workshop on Crystalline Silicon for Solar Cells and the 3rd Silicon Materials Workshop**, 2016.
4. Hameiri Z. Outdoor and indoor luminescence imaging of photovoltaic modules. **Photovoltaic Reliability Workshop** (PVRW), 2018.
5. Hameiri Z. **European Advanced Energy Materials and Technology Congress**, 2018.

Awards:

Ziv Hameiri, ***International Association of Advanced Materials Scientist Medal***, 2018

Conclusion and next steps

The characterisation tools developed in this project will assist researchers in Australia and across the world to develop processes to eliminate defects in silicon wafers and solar cells.

The outcomes of this project will improve the durability and reliability of PV systems, reducing the price of Australian energy system.

The researchers involved in this project will continue their effort to improve the developed systems and to commercialise the outputs of this project.

Appendix

Keywords

Photovoltaic
Solar cells
Silicon
Characterisation
Luminescence
Photoluminescence
Perovskite
Modules
Defect
Loss mechanisms

Glossary of terms and acronyms

ASU - Arizona State University

CID - Carrier induced degradation

LED - Light-emitting diode

mc-Si - Multicrystalline silicon

MIT - Massachusetts Institute of Technology

PC - Photoconductance

PL - Photoluminescence

PV - Photovoltaic

R_s - Series resistance

Si - Silicon