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ScienceDirect

Energy Procedia 124 (2017) 47–52

Energy Procedia

www.elsevier.com/locate/procedia

7th International Conference on Silicon Photovoltaics, SiliconPV 2017

Temperature dependent photoluminescence imaging calibrated by photoconductance measurements

Halvard Haug[a,b]*, Rune Søndenå[a], Marie Syre Wiig[a] and Erik S. Marstein[a,b]

[a] *Institute for Energy technology, Solar Energy Department, Instituttveien 18, 2007 Kjeller, Norway*
[b] *University of Oslo, Institute for Technology Systems, Pb 70, 2027 Kjeller, Norway*

Abstract

In this paper we present a novel method for measuring temperature dependent lifetime images with high spatial resolution using photoconductance calibrated photoluminescence (PL) imaging. In order to achieve this, PL images are recorded at various temperatures by implementing a temperature stage into a commercial, steady state PL imaging setup. Carrier lifetime images are then calculated from the detected PL intensity, based on quasi-steady state photoconductance calibration measurements performed at the same temperatures that are used for the PL images. By analysing the carrier lifetime data as a function of injection level and temperature, this method allows for in-depth, spatially resolved defect characterization of Si wafers. Such temperature dependent lifetime data are also useful as input for device simulations of the temperature coefficient of solar cell efficiency. The uses of the method are illustrated with different examples based on commercial high performance multicrystalline Si wafers.

Peer review by the scientific conference committee of SiliconPV 2017 under responsibility of PSE AG.

Keywords: Carrier lifetime, temperature, photoluminescence, imaging, photoconductance

1. Introduction

Minority carrier lifetime measurements based on PL imaging has been a popular characterization method in Si solar cell research and engineering since it was introduced in 2006 [1]. In the latest years, there has been an increasing interest for using the method for temperature and injection dependent lifetime spectroscopy with spatial

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* Corresponding author. Tel.: +47 99486757
E-mail address: halvard.haug@ife.no

1876-6102
Peer review by the scientific conference committee of SiliconPV 2017 under responsibility of PSE AG.
10.1016/j.egypro.2017.09.338

resolution. Such measurements have normally been performed by so-called harmonically modulated PL measurements [2–4], where the carrier lifetime is calculated from the detected PL signal in a purely optical manner. This however requires expensive and often custom-built measurement setups with time resolved excitation and detection of the PL signal. Most PL imaging setups available in solar cell research laboratories today are based on steady state excitation and detection, and the PL intensity is therefore calibrated using an external QSSPC measurement [5,6]. However, the calibration constant is strongly temperature dependent, caused by a complex combination of the luminescence properties of the sample and the sensitivity of the camera at different wavelengths [7]. These effects can be taken into account theoretically [8], but the added complexity introduces several uncertainties in the quantification of the carrier lifetime from the measured luminescence signal. We therefore suggest a way to perform these measurements with individual QSSPC calibration measurements at each temperature. The advantage of this approach is that temperature dependent lifetime images can be obtained using relatively uncomplicated measurement setups with steady state detection systems (in contrast to the method used in Ref. [2]), and with few assumptions and possible sources for error (in contrast to the approach presented in Ref. [8]).

2. Experimental setup

Minority carrier lifetime curves were measured as a function of the excess carrier density at a range of temperatures using a Sinton WCT-120 TS lifetime tester. In this setup, the inductive coil used for photoconductance measurement is built into a temperature controlled sample stage, allowing for lifetime measurement in the temperature range from 25 to 200 °C [9]. Subsequently, uncalibrated PL intensity images were recorded as a function of temperature by building the WCT-120 TS heating stage into a LIS-R1 setup from BT imaging with an excitation wavelength of 808 nm. By using the same heating stage and temperature controller for both series of measurements, the error in the absolute wafer temperature for each pair of QSSPC and PL measurements was minimized. A constant photon flux of 1×10^{17} $cm^{-2}s^{-1}$ was used for the measurements presented below. The carrier lifetime images were finally calculated automatically based on similar algorithms used for room temperature measurements [10]. To ensure stable conditions and reduce the operator time needed each temperature series was measured automatically at set temperature intervals during cooling. The maximum temperature was set at a sufficiently low value in order to avoid permanent annealing effects, such as lifetime regeneration after light induced degradation (LID) related to boron-oxygen defects or iron-boron pairs. Such annealing effects were ruled out in each case by performing a reference QSSPC measurement at room temperature before and after each temperature scan.

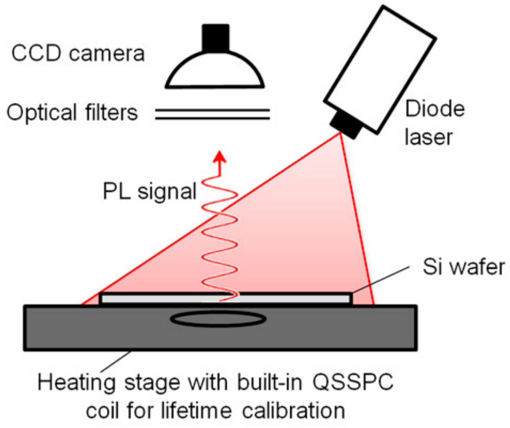

Fig. 1. Schematic illustration of the measurement setup. The wafer is placed on a heating stage during the PL imaging measurement, and the PL images are calibrated in post processing based on QSSPC measurements performed at each temperature.

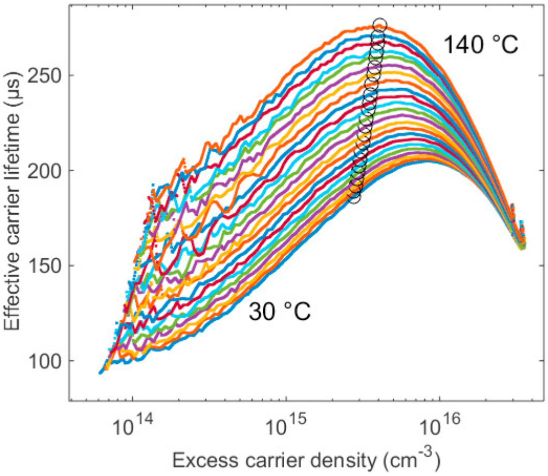

Fig. 2. Example of QSSPC measurements at a range of different temperatures. The data were measured on a HPMC wafer from the bottom of the block, after PDG and hydrogen passivation during contact firing, in 5 °C intervals from 140 °C to 30 °C. The points for each curve used for calibration of the corresponding PL image are shown in black circles.

3. Sample preparation and results

Carrier lifetime images for four different HPMC Si wafers are presented in Figs 3 and 4 below. The lifetime images are chosen to illustrate the effect of both position in the block and different processing steps. The first set of images (left) are acquired after phosphorus diffusion gettering (PDG) whereas the second set is measured on a neighboring wafer after PDG and subsequent hydrogen passivation obtained by passivating the wafers by PECVD a-SiO_xN_y:H on both sides and performing a belt furnace annealing equivalent to the process used for contact firing. The sample thickness and optical properties were kept equal for all wafers by etching away all surface layers and diffused regions using diluted HF and CP5 solutions. Before lifetime measurements, all surfaces were passivated using 40 nm PECVD a-Si:H layers on both sides. This process provides a low surface recombination velocity (SRV) below 5 cm/s at room temperature. Even though the SRV is also temperature dependent, the relative contribution from surface recombination on the effective lifetime is assumed to be low at all the temperatures used. The measured lifetime can therefore be considered equal to the bulk lifetime without introducing any significant errors.

As shown in the temperature coefficient maps and the lifetime vs temperature curves at selected spots, the defect behavior is both qualitatively and quantitatively different at different grains and at grain boundaries, and the behavior is strongly dependent on the wafer processing. For example, notice the difference in the temperature behavior of the lifetime in the grains marked (a) and (b) in the third image in Fig. 3, and how the grain boundaries are clearly visible in the temperature coefficient map. These observed differences arise from variations in the distribution of lifetime-limiting defects and impurities, and the addition of temperature dependence therefore gives an added value of the measurements.

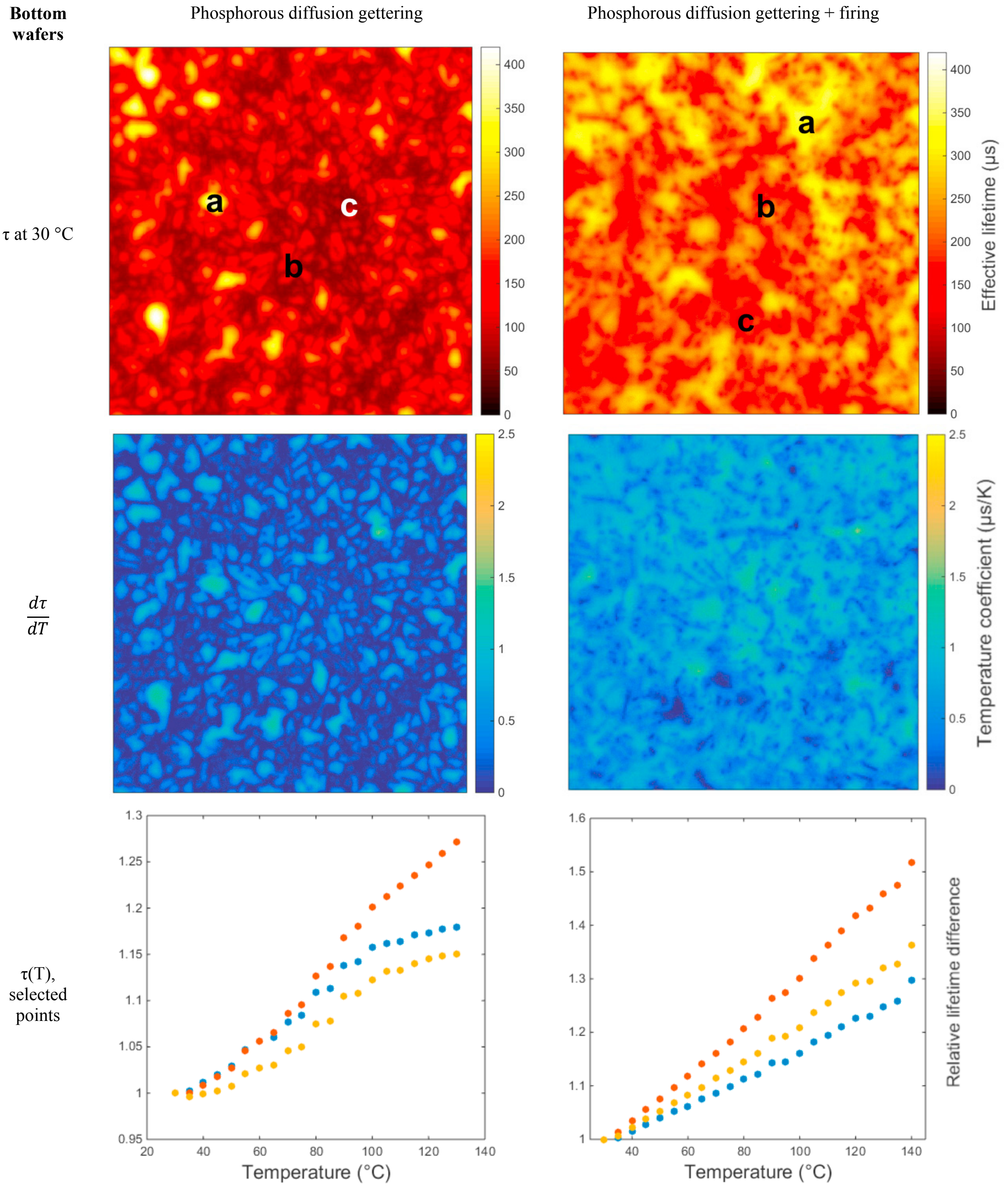

Fig. 3. Illustration of temperature dependent PL lifetime images, applied to a neighboring pair HPMC Si wafers taken from the *bottom* part of the block. Wafers were measured after PDG + etching + passivation (left) and after PDG + hydrogenation + etching + passivation (right). The top row shows the effective lifetime measured at 30 °C, on the same color scale. The middle row shows the average temperature coefficient of the lifetime in the range from 30 to 90 °C. The bottom row shows the relative change in the lifetime for three different positions of each wafer, as indicated in the top image.

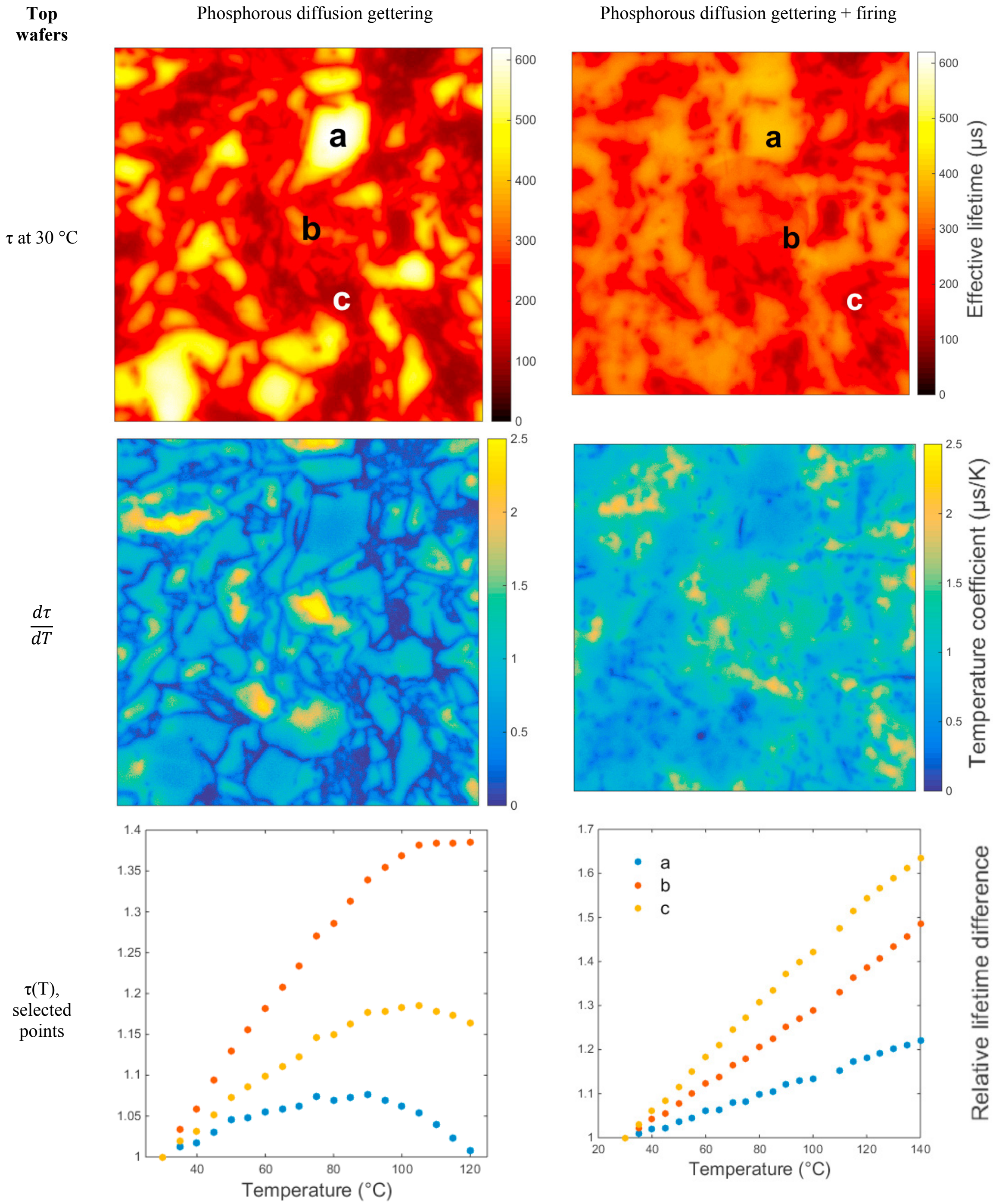

Fig. 4. Results from temperature dependent PL lifetime images, applied to a neighboring pair HPMC Si wafers taken from the *top* part of the block. Wafers were measured after PDG + etching + passivation (left) and after PDG + hydrogenation + etching + passivation (right). The top row shows the effective lifetime measured at 30 °C, on the same color scale. The middle row shows the average temperature coefficient of the lifetime in the range from 30 to 90 °C. The bottom row shows the relative change in the lifetime for three different positions of each wafer, as indicated in the top image.

4. Conclusion and further work

By performing a relatively simple experiment combining two commercially available measurement setups available in many solar cell laboratories (steady state PL imaging and QSSPC with heating stage) we have demonstrated a method for measuring temperature dependent lifetime images with few assumptions and sources for error. Initial experiments on commercial HMPC wafers reveal that clear temperature signatures from different grains and grain boundaries can be revealed with such measurements, and thus provide more information about the material than room temperature measurements only. We are currently working on a Shockley-Read Hall recombination analysis of the injection and temperature dependent images, which will be used for local impurity identification. Temperature dependent lifetime maps together with local J_0 simulations and lumped circuit full cell models [11,12] will hopefully also be useful for predictions and analysis of the temperature coefficient of solar cell efficiency.

Acknowledgements

Funding for this work was provided through the EnergiX programme of the Norwegian Research Council, project number 256271 - Performance and Reliability IN Compensated Elkem Solar Silicon.

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