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Citation: [Applied Physics Letters](#) **104**, 073506 (2014); doi: 10.1063/1.4865804

View online: <http://dx.doi.org/10.1063/1.4865804>

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Contactless determination of the carrier mobility sum in silicon wafers using combined photoluminescence and photoconductance measurements

Ziv Hameiri,¹ Fiacre Rougieux,² Ron Sinton,³ and Thorsten Trupke⁴

¹Solar Energy Research Institute of Singapore, National University of Singapore, Singapore 117574

²Australian National University, Canberra 0200, Australia

³Sinton Consulting, 4720 Walnut Street, Suite 102, Boulder, Colorado 80301, USA

⁴The University of New South Wales 2052, Sydney, Australia

(Received 18 November 2013; accepted 1 February 2014; published online 19 February 2014)

A contactless method to determine the carrier mobility sum in silicon wafers, based on a comparison between photoluminescence and photoconductance measurements is presented. The method is applied to monocrystalline silicon wafers and the results are found to be in good agreement with well-established mobility models and another measurement method. The potential of the proposed method to determine the carrier mobility sum of multicrystalline and compensated silicon wafers is then demonstrated. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4865804>]

Carrier mobility is an important electrical parameter which significantly influences the performance of crystalline silicon (Si) solar cells, as it impacts parameters such as the diffusion length and the series resistance (the latter via the lateral transport to the contacts). Accurate data for carrier mobility are also required for other measurements, such as the photoconductance-based effective lifetime measurements. Models of carrier mobility in monocrystalline Si are well-established and include the effects of doping density,^{1,2} injection level,^{3–6} and temperature^{7–9} on the mobility. However, the effects of compensating dopants and grain boundaries have been less studied^{10–14} and there is yet to emerge a coherent model that accounts for these effects. More generally, there is a lack of data regarding the impact of injection level on carrier mobility. Some information can be found in the literature;^{3,4} however, so far, this data has been mainly obtained from high-resistivity Si wafers. The few measurements on low-resistivity substrates^{15,16} were limited to a relatively narrow injection range. Hence, there is a need for an injection-dependent mobility measurement technique to allow development of new injection-dependent mobility models that can be used for device characterization and simulation.

A wide variety of methods were employed in the past to measure the mobility. For example, Dannhauser and Krausse used combined infrared radiation and voltage measurements,^{3,4} while Neuhaus *et al.* used a combination of quasi-steady-state (QSS) photoconductance (PC) and QSS open-circuit voltage measurements.¹⁵ Note that both methods require contacts and a relatively complicated device structures. Recently, a contactless method to measure the carrier mobility sum μ_{sum} ($\mu_{sum} = \mu_e + \mu_h$, where μ_e and μ_h are the electron and hole mobility, respectively) was introduced by Rougieux *et al.*¹⁶ This method is based on combining transient and QSS PC measurements and required only a basic sample preparation (it will be referred here as the “PC-based method”). In this Letter, we present a method based on a comparison between photoluminescence (PL) and PC measurements (“PL-PC method”)¹⁷ and compare it with the PC-based one. We also analyze the uncertainty associated with the PL-PC method and demonstrate its ability to measure μ_{sum} of

multicrystalline Si (multi-Si) wafers and compensated Si wafers over a wide range of injection levels.

In the PL-PC method, the excess carrier concentrations Δn obtained by PL and PC measurements are compared in order to extract μ_{sum} . First, the PL signal I_{pl} is converted into Δn_{pl} using the well-known expression¹⁸

$$\Delta n_{pl} = -\frac{N_{net}}{2} + \sqrt{\left(\frac{N_{net}}{2}\right)^2 + \frac{I_{pl}}{A_i B}}, \quad (1)$$

where A_i is a scaling factor, B is the radiative recombination coefficient, and N_{net} is the net bulk doping density ($N_{net} = |N_A - N_D|$, with N_D and N_A the donor and acceptor concentrations, respectively) and where it is assumed that $\Delta n_{pl} \gg n_i^2/N_{net}$ which is valid for all practical measurements at room temperature (n_i is the intrinsic carrier concentration). Note that B itself depends on both the bulk doping density and Δn . In this study, B is modeled according to the expression of Refs. 19 and 20, where the sum of carrier concentrations is defined as $(n + p) = N_{net} + 2\Delta n$. The scaling factor A_i takes into account the fact that I_{pl} is measured only in relative units.¹⁸ It is influenced by the experimental system’s design, for example, the spectral sensitivity of the detection system, but it also accounts for the sample’s optical properties. Therefore, this constant needs to be determined for each sample. Various calibration methods have been suggested.^{21,22} In the present study, the self-consistent method²¹ was used. Note that A_i is not affected by the sample’s effective lifetime, only by its optical parameters, which are not altered by illumination.

The PC signal is converted into Δn_{pc} using the measured excess conductivity $\Delta\sigma$ ²³

$$\Delta n_{pc} = \frac{a(\Delta V_{pc})^2 + b\Delta V_{pc}}{qW\mu_{sum}} = \frac{\Delta\sigma}{qW\mu_{sum}}, \quad (2)$$

where q is the elementary charge, W is the sample’s thickness, V_{pc} is the PC signal, and a and b are the PC system calibration constants which convert the measured V_{pc} into $\Delta\sigma$.

Experimentally, the measured PL and PC signals are converted into Δn for a wide range of illumination intensities. The injection level dependent μ_{sum} is then used as a fit parameter in order to achieve the best fit between Δn_{pc} and Δn_{pl}

$$\mu_{sum} = \frac{\Delta\sigma}{qW\Delta n_{pl}}. \quad (3)$$

Importantly, the method presented here does not require a conversion of the signals to effective lifetime. Hence, it is expected to work independently of the measurement conditions (i.e., transient versus steady state). Note that the method presented above is based on the equality of Δn_{pc} and Δn_{pl} , whereas the PC-based method relies on the equality of lifetime as measured from a transient and QSS flash.¹⁶ Hence, while the PC-based method is limited to a certain range of lifetimes, the PL-PC method is expected to work for wider measurement conditions (in terms of injection level and the wafer's effective lifetime).

The uncertainty associated with the measurement is calculated using a Monte Carlo²⁴ based program.²⁵ The inputs of this program are the measured raw data (I_{pl} and V_{pc}), the system calibration constants (a and b), the sample parameters (W , N_{net} and A_i), and the model used to determine B . Each input parameter is quantified by its estimated value and by its standard deviation (STD) to create its probability density function (PDF). As the parameters are independent and identically distributed, they are treated in the program as normally distributed, following the guidelines of Refs. 26 and 27. Note that as the system constants a and b are strongly correlated,²⁸ the sum $a(\Delta V_{pc})^2 + b\Delta V_{pc}$ (and not the individual parameters) is quantified. The program then samples the input PDFs to randomly generate a total of m values of each parameter (in this study $m = 200$). These values are used to calculate m values of μ_{sum} that are used to estimate the uncertainty associated with the measurement. Note that as both the PL and the PC signals are not converted to effective lifetime, the uncertainty associated with determination of the generation rate does not influence the measurement; this is contrary to the PC-based method.¹⁶

Measurements were done using a modified WCT-120 lifetime tester from Sinton Instruments. The instrument was modified to include an additional photodiode (a "PL sensor") inside the PC sensor to allow simultaneous measurement of PC and PL from the same area. The illumination is accomplished by either a 1.5 W, 810 nm light emitting diode (LED) array with a light intensity equivalent to about one sun or a xenon flash lamp with a light intensity equivalent to about 60 suns. More information regarding the system can be found in Refs. 18 and 29.

Prior to the measurements, the WCT-120 was calibrated with eight Si wafers of known resistivity, following the procedure of Ref. 30. We estimate the uncertainty associated with a second order polynomial fit of the conductance dependence on the voltage [$a(\Delta V_{pc})^2 + b\Delta V_{pc}$] to be 8%. The temperature was monitored during measurements and found to be extremely stable, provided a long-pass filter is used during measurements under high light intensities.

A variety of wafers were used in this study. Table I summarizes their main parameters, together with the uncertainty associated with each parameter. The thickness of each wafer was measured across 20 points with a Mitutoyo thickness probe (model ID-S112) with a rated accuracy of $\pm 1 \mu\text{m}$; here, the uncertainty represents the variation between 20 measurement points. The bulk doping density of the uncompensated wafers was determined by a dark conductance measurement performed using the calibrated PC coil of the WCT-120. The measured bulk conductance was then converted into bulk doping density using PC1D.³¹ The uncertainty associated with this measurement represents the variation between measurements (each wafer was measured 10 times) and the uncertainties associated with the thickness measurement and with the calibration process of the WCT-120. The bulk doping densities of the compensated Si wafers were measured by a dynamic SIMS (secondary ion mass spectrometry) with a rated accuracy of $\pm 5\%$.

Before measurements, the saw damage was etched from all wafers by an alkaline solution (KOH at 80 °C) followed by a chemical polishing ($\text{HNO}_3\text{:HF:H}_2\text{SO}_4$ at 6 °C). After a full RCA (Radio Corporation of America) clean,³² silicon nitride (SiN_x) was deposited onto both surfaces using a semi-remote plasma-enhanced chemical vapor deposition (PECVD) system from Roth&Rau (AK-400). Each measurement was performed 20 times as it was shown that sampling more than 10 times reduces the uncertainties associated with V_{pc} and I_{pl} to a level that makes them insignificant contributors to the total uncertainty.²⁸ In order to compare between the PL-PC and the PC-based methods, representative samples were sent to the Australian National University (ANU) to be measured according to the method of Ref. 16.

Figure 1 presents $\mu_{sum}(\Delta n)$ of the Czochralski (Cz) wafers as obtained by both the PL-PC and the PC-based methods. For a comparison, Fig. 1 also presents $\mu_{sum}(\Delta n)$ as predicted by the mobility models for monocrystalline Si of Klaassen⁵ and of Dannhauser and Krauss.^{3,4} The error bars represent a one-STD range, as calculated by the Monte Carlo based program. This range represents a 68% confidence that the actual value lies within these boundaries.³³

First, note the wide measurement range of the PL-PC measurement (1×10^{13} – $5 \times 10^{16} \text{ cm}^{-3}$), which covers the

TABLE I. Tested wafers parameters.

Wafer ID	Type	W (μm)	N_A (cm^{-3})	N_D (cm^{-3})	A_i
Cz-p	p-type (Cz)	485 ± 6	$(1.4 \pm 0.1) \times 10^{16}$		$(3.3 \pm 0.3) \times 10^{16}$
Cz-n	n-type (Cz)	328 ± 3		$(4.3 \pm 0.4) \times 10^{15}$	$(3.6 \pm 0.4) \times 10^{16}$
multi-p	p-type (multi-Si)	161 ± 3	$(8.4 \pm 0.4) \times 10^{15}$		$(6.4 \pm 0.6) \times 10^{16}$
Comp-p	p-type (multi-Si)	160 ± 3	$(2.5 \pm 0.1) \times 10^{16}$	$(5.9 \pm 0.6) \times 10^{15}$	$(2.1 \pm 0.2) \times 10^{16}$

FIG. 1. Mobility sum as a function of minority carrier concentration of Cz *p*-type (a) and Cz *n*-type (b) samples, as obtained by the PL-PC and the PC-based methods.

full range relevant for one-sun solar cell applications. The lower limit ($1 \times 10^{13} \text{ cm}^{-3}$) is due to the sensitivity limit of the PC system. The PL system itself allows accurate measurements down to Δn of $1 \times 10^{10} \text{ cm}^{-3}$.

In contrast, the PC-based method is currently limited to a much narrower range ($1 \times 10^{15} - 3 \times 10^{16} \text{ cm}^{-3}$). At low Δn , the measurement becomes (in the PC-based method) quite inaccurate, as the derivatives of the quasi-static and transient conductance become very similar.¹⁶ At high Δn , the measurement accuracy is limited as the effective lifetime is reduced (due to Auger recombination), leading to difficulties in performing accurate transient measurements. Within the measurement range of the PC-based method, an excellent agreement between the two methods (within a maximum of

4% relative deviation) was achieved. Good agreement (in the range of 8%) was also achieved between the measurements and the theoretical mobility models, similar to the agreement obtained in Ref. 16. The agreement between the two methods and the agreement between the methods and the models confirm the capability of the PL-PC method to measure μ_{sum} over a wide Δn range.

In order to gain a knowledge regarding the uncertainty associated with the PL-PC method, the contribution of each input parameter to the measurement uncertainty was analyzed. Figure 2 presents these contributions to the measurement uncertainty of a representative sample [sample Cz-p of Fig. 1(a)] at low and high injection (for sample parameters see Table I). As N_{net} does not have an impact on the PL measurement at high injection,²⁹ the measurement uncertainty is lower under this measurement condition. The uncertainty associated with A_i dominates the measurement uncertainty in both injection levels, contributing around 70% of the total error. We estimate the measurement uncertainty to be between 8.5% (at high injection) and 12.6% (at low injection), which is similar to the PC-based method.

The PL-PC method relies on fitting Δn_{pc} to Δn_{pi} ; it is thus based on the assumption that the detected conductivity is proportional to Δn_{pc} . The method is therefore expected to have difficulties in cases where the PC signal is affected by minority carrier trapping³⁴ or depletion region modulation (DRM).^{35,36} As trapping or the impact of the grain boundaries on the lateral mobility³⁷ can impact the measured conductance of multi-Si wafers at low injection level, it is expected that the method will be influenced by these artifacts in the range of $\Delta n_{pc} < 5 \times 10^{14} \text{ cm}^{-3}$. Although these limitations still allow determination of μ_{sum} for a large range of Δn ($5 \times 10^{14} - 5 \times 10^{16} \text{ cm}^{-3}$), the use of the light-bias method³⁸ can extend the reliable PC data to even a wider range ($\Delta n_{pc} > 1 \times 10^{13} \text{ cm}^{-3}$). In order to determine the magnitude of the required light-bias correction, the effective lifetime of the multi-Si wafers was measured by both PC and PL under QSS illumination conditions before the μ_{sum} measurement. It was found that the effective lifetime obtained by QSSPC increases sharply for $\Delta n < 2 \times 10^{14} \text{ cm}^{-3}$, which can be caused by trapping, by the potential barriers near the grain boundaries or by DRM (due to the positive charge within the SiN_x layer). On the contrary, the lifetime obtained by the QSSPL method is not influenced by these effects.³⁹ The influence of these artifacts was significantly removed by applying a light-bias correction of 0.05 suns; this correction

FIG. 2. The contribution of each input parameter to the measurement uncertainty at low and high injection.

FIG. 3. Mobility sum as a function of minority carrier concentration of a multi-Si *p*-type sample, as obtained by the PL-PC method.

extends the good agreement between effective lifetime measured by QSSPC and QSSPL down to Δn of $\sim 1 \times 10^{13} \text{ cm}^{-3}$. This value of the light-bias correction was then used in the μ_{sum} analysis.

Figure 3 presents the measured $\mu_{sum}(\Delta n)$ of a multi-Si wafer, as obtained by the PL-PC method, before and after a light-bias correction. The figure also includes the mobility models of monocrystalline Si wafer with the same N_A . Without the light-bias correction, a strong deviation from the expected trend of $\mu_{sum}(\Delta n)$ is observed at Δn below $2 \times 10^{14} \text{ cm}^{-3}$. The effectiveness of the light-bias correction is obvious, extending the measurement range down to $1 \times 10^{13} \text{ cm}^{-3}$. As a good agreement (within a maximum of 5% relative deviation) between the measurement and the models was obtained, it seems that grain boundaries and dislocations have only a minor effect on the mobility in the illuminated multi-Si wafers tested in this study, similar to previous findings.⁴⁰ Note that the relatively low effective lifetime of this sample does not allow a measurement under transient condition and therefore no comparison to the PC-based method is presented.

Several empirical modifications to Klaassen's model accounting for compensation effects have been suggested recently.^{12,41,42} However, there remains a lack of extended data regarding mobility in compensated silicon especially under injection. The PL-PC method and other newly developed techniques⁴³ can serve as useful tools for studying the impact of the compensation level on the carrier mobility. Figure 4 shows the PL-PC $\mu_{sum}(\Delta n)$ measurement of a partially doping compensated Si wafer. As Klaassen's model accounts for the presence of both acceptors and donors as scattering centers, Fig. 4 compares between the measurement and μ_{sum} predicted by this model. The donor and acceptor concentrations used in the model were the ones measured by SIMS. Here, we assumed a full dopant ionization, which is valid for these dopant levels.¹⁴ The compensation level (R_C) of the sample was calculated as $R_C = (N_A + N_D)/(N_A - N_D)$ and found to be 1.63. A good agreement (within a maximum of 8% relative deviation) between the measurement and the model is demonstrated for the entire range. Although mobilities in compensated Si were found to be lower than predicted by Klaassen's model, it was shown that for compensated

FIG. 4. Mobility sum as a function of minority carrier concentration of a compensated Si sample, as obtained by the PL-PC method.

levels below 4–5, the error associated with this model is smaller than 10%,⁴¹ similar to the results observed in this study.

In summary, we presented a contactless method, based on a comparison between PL and PC measurements, to determine the influence of injection level and dopant density on the carrier mobility sum in Si wafers. Importantly, this method allows measurements over a wide Δn range and therefore permits investigation of the influence of very high and very low injection levels on the mobility. Good agreement was observed between the method presented here with a PC-based method and also with well-established mobility models. The uncertainty associated with the method was analyzed and found to be in the range of 8%–13% and to be most strongly influenced by the calibration procedure of A_i . Current research focuses on methods to determine A_i more precisely. The potential of the method to determine the carrier mobility sum of multi-Si wafers and compensated Si wafers was demonstrated. The proposed method is expected to be of high value in developing and validating mobility models for various types of Si wafers under an extended range of dopant densities and injection levels.

The authors thank Mr. Heuer from Calisolar for his kind help providing the compensated Si samples and Mr. Peiting Zheng from ANU for assisting with the measurements. The Solar Energy Research Institute of Singapore (SERIS) is sponsored by the National University of Singapore (NUS) and Singapore's National Research Foundation (NRF) through the Singapore Economic Development Board (EDB). This work was sponsored by NRF Grant No. NRF2010EWT-CERP001-022.

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