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Evaluation of recombination processes using the local ideality factor of carrier lifetime measurements

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ABSTRACT

The mechanisms that limit the performance of a solar cell can be often identified by an assessment of the solar cell's local ideality factor m. Typically, m is extracted from the current–voltage curve of a completed solar cell and plotted as a function of voltage. In this study, m is extracted from photoluminescence measurements of the effective carrier lifetime and plotted against the excess carrier concentration Δn or the implied open-circuit voltage V_{oci}. It is shown that a plot of $m(\Delta n)$ or $m(V_{oci})$ is a powerful way to analyse recombination processes within a silicon wafer, where its main advantage is that it can be determined from wafers that have neither metal contacts nor a p–n junction. With an $m(\Delta n)$ plot, one can readily identify a range of Δn (or voltage) that is dominated by a single recombination mechanism, or that constitutes a transition from one dominant mechanism to another. One can also identify the dominating recombination mechanisms at a cell's maximum power point. In this paper we demonstrate the application of extracting an $m(\Delta n)$ curve, and we show how it is affected by Shockley–Read–Hall and Auger recombination in the bulk, and by fixed charge in a dielectric coating.

1. Introduction

The mechanisms that limit the performance of a solar cell can be often identified by an assessment of the solar cell's local ideality factor m [1,2]. Typically, m is extracted from the current–voltage curve of a completed solar cell and plotted as a function of voltage [1–4]. In this study, m is extracted from a measurement of the effective carrier lifetime τ_{eff} and plotted against the excess carrier concentration Δn or the implied open-circuit voltage V_{oci} [5]. It is shown that a plot of $m(\Delta n)$ or $m(V_{oci})$ is a powerful contactless method to analyse recombination processes within a silicon wafer.

The local ideality factor can be defined as [1]

$$U \propto (n \times p)^{1/m}, \tag{1}$$

where U is the recombination rate, and n and p are the concentrations of free electrons and holes. The local ideality factor is therefore readily determined by photoconductance (PC) or photoluminescence (PL), which measure U as a function of either $(n+p)$ or $(n \times p)$. Appendix A shows how Eq. (1) relates to the common definition used for completed solar cells, which also incorporates the effects of shunting, series resistance and 2D effects.

By taking the derivative of Eq. (1) with respect to Δn and assuming that (i) the excess electron and hole concentrations are both equal to Δn, and (ii) $\Delta n » n_i^2/N$, (where N is the bulk doping concentration and n_i is the intrinsic carrier concentration), m can be expressed as a function of Δn:

$$m = \left(\frac{1}{n} + \frac{1}{p}\right) U \frac{d\Delta n}{dU} = \frac{2\Delta n + N}{\Delta n(\Delta n + N)} U \frac{d\Delta n}{dU}. \tag{2}$$

Note that Eq. (2) holds for wafers only; it is not necessarily accurate for completed solar cells, where m is affected by other effects, such as series resistance, 2D effects etc.

Alternatively, m can be expressed as a function of V_{oci}, which is equivalent to the separation of the quasi-Fermi levels and therefore given by

$$V_{oci} = \frac{kT}{q} \ln\left(\frac{n \times p}{n_i^2}\right), \tag{3}$$

where q is the elementary charge, k Boltzmann's constant and T the absolute temperature [6]. Combining this definition of V_{oci} with Eq. (1) gives

$$m = \frac{q}{kT} \left(\frac{d(\ln(U))}{dV_{oci}}\right)^{-1} = \frac{q}{kT} U \frac{dV_{oci}}{dU}. \tag{4}$$

In this work, our experiments are in steady-state or near steady-state, whereby the generation rate G equals U. Under these conditions, m can be expressed as either:

$$m = \frac{2\Delta n + N}{\Delta n(\Delta n + N)} G \frac{d\Delta n}{dG}, \tag{5}$$

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or

$$m = \frac{q}{kT}\left(\frac{d(\ln(G))}{dV_{oci}}\right)^{-1} = \frac{q}{kT}G\frac{dV_{oci}}{dG}. \tag{6}$$

Thus, $m(\Delta n)$ and $m(V_{oci})$ can be determined with Eqs. (5) and (6) using either PC or PL-based measurements. The resulting plots provide information that is not immediately apparent from the standard analysis of $\tau_{eff}(\Delta n)$, such as range of Δn that is dominated by a single recombination mechanism, or that constitutes a transition from one dominant mechanism to another.

The main advantage of using PC or PL to determine m is that it can be performed on wafers that do not have metal contacts or even a p–n junction. The local ideality factor is therefore unaffected by the shunting or series resistance related to metal contacts, which frequently prevent an assessment of recombination processes at low and high voltages in solar cells. By studying m before and after the formation of metal contacts, one can evaluate how they influence the dominant recombination mechanisms. One can also assess how the various recombination processes influence the fill factor FF of the resulting solar cell.

2. Modelling

A model following the approach of Girisch et al. [7] was developed using the software package Mathematica 8 (Wolfram Research). The inputs of this model are the sample parameters (N and thickness), the surface defect parameters (surface state density D_{it}, capture cross section of electrons σ_n and holes σ_p) and the fixed charge density within the dielectric Q_f. The surface potential ψ_s is determined as a function of Δn assuming charge neutrality [7]. Using ψ_s, the electron and hole concentrations at the surface are calculated. Based on these concentrations, the surface recombination is computed by the Shockley–Read–Hall (SRH) equation [8,9]. More information regarding these calculations can be found in Refs. [7,10].

The bulk recombination rate U_b is determined as the sum of the SRH (using inputs regarding defects in the bulk, such as energy level and the electron and hole lifetime parameters τ_{n0} and τ_{p0}), Auger and radiative [11] recombination terms:

$$U_{bi} = \Sigma U_{b\_i} = U_{b,SRH} + U_{b,Auger} + U_{b,Radiative}, \tag{7}$$

where U_{b_i} represents the different bulk recombination rates. At steady state G is equal to the sum of the different recombination processes and therefore can be expressed as:

$$G = \Sigma U_i = U_s\left(\frac{2}{W}\right) + (U_{b,SRH} + U_{b,Auger} + U_{b,Radiative}), \tag{8}$$

where U_i represents the different recombination mechanisms, U_s is the surface recombination and W is the sample thickness. The simulated m can then be extracted using Eq. (5) or Eq. (6).

3. Experimental

3.1. Sample preparation

Four float-zone (FZ) 1 Ω cm p-type (100) and four Czochralski (Cz) 1.7 Ω cm n-type (100) wafers were used in this study. The wafer thickness after an alkali saw damage etch was 210–220 μm. After a full RCA clean [12] and HF (hydrofluoric) dip, amorphous silicon nitride (SiN_x) was deposited onto both surfaces using a plasma-enhanced chemical vapour deposition (PECVD) system manufactured by Roth & Rau (AK-400). The refractive index and the film thickness were measured by a dual-mode ellipsometer at a single wavelength of 632.8 nm, using a single-side polished wafers, and found to be 2.4 and 75 nm, respectively. The effective lifetime was measured as a function of Δn using a PL-based system under near steady-state conditions and using the generalized analysis [13]. The local ideality factor was then calculated using Eq. (5) or Eq. (6).

Table 1
Effective lifetime and calculated S_{eff_ul} and τ_{b,SRH_ll} at Δn of 1×10^{15} cm^{-3}.

	τ_{eff} [μs]	S_{eff_ul} [cm/s]	τ_{b,SRH_ll} [μs]
p-type (1 Ω cm)	1611	1.1	2800
n-type (1.7 Ω cm)	489	19.2	504

In order to evaluate the passivation quality, the surface recombination velocity S_{eff} was extracted from τ_{eff} at Δn of 1×10^{15} cm^{-3}, using the following relationships:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{1}{\tau_s}, \tag{9}$$

$$\tau_s = \frac{W}{2S_{eff}}, \tag{10}$$

which combined to give

$$S_{eff} = \frac{W}{2}\left(\frac{1}{\tau_{eff}} - \frac{1}{\tau_b}\right), \tag{11}$$

where τ_b is the bulk lifetime and τ_s is the surface lifetime. Note that Eq. (10) can only be used when S_{eff} is relatively small [14]. As the limiting value for the samples presented in this study was calculated to be 470 cm/s, this expression contains negligible error.

The upper limit of S_{eff} (S_{eff_ul}) was calculated using the intrinsic limit [11] on τ_b, while the lower limit of the bulk SRH lifetime τ_{b,SRH_ll} was calculated under the assumption of no surface recombination using:

$$\frac{1}{\tau_{b,SRH\_ll}} = \frac{1}{\tau_{eff}} - \left(\frac{1}{\tau_{b,Auger}} + \frac{1}{\tau_{b,Rad}}\right), \tag{12}$$

where $\tau_{b,Auger}$ and $\tau_{b,Rad}$ are the Auger lifetime and the radiative lifetime, respectively.

Table 1 presents τ_{eff} and the calculated S_{eff_ul} and τ_{b,SRH_ll} at Δn of 1×10^{15} cm^{-3}. The very low S_{eff} obtained for both wafer polarities indicates that τ_{eff} is not dominated by surface recombination in either sample at this Δn. Furthermore, the high τ_{b,SRH_ll} (particularly that of the p-type sample) suggests that the bulk lifetime of these samples is relatively high.

3.2. Measurement system

In order to measure τ_{eff} at very low Δn, a PL-based lifetime system [15] was employed since it is minimally affected by artifacts such as trapping [16–18] and depletion region modulation [19–22].

The PL system is a modified Sinton Consulting WCT-120 instrument [23]. An additional silicon diode ('PL sensor') was integrated to detect the spontaneous emission. The signal is fed into a low-noise preamplifier before being analysed. The illumination source was either a 1.5 W array of 810 nm light emitting diodes (LEDs) or a high-power xenon flash. The control of the light source is accomplished by a digital-analogue port of a data acquisition card. The software allows the user to design a wide range of waveforms, to choose the number of repetitions, the number of data points and the desired signal averaging. More details on the system can be found in Refs. [15,20,24].