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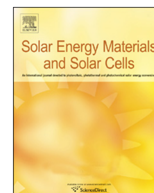

# An accurate method for calibrating photoluminescence-based lifetime images on multi-crystalline silicon wafers

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ABSTRACT

We present a method for converting photoluminescence images into carrier lifetime images for silicon wafers with inhomogeneous lifetime distributions, such as multi-crystalline silicon wafers, based on a calibration factor extracted from a separate, homogeneous, mono-crystalline calibration wafer and simple optical modelling of the photoluminescence signal from both the calibration wafer and the test wafer. The method is applicable to planar wafers with uniform carrier profiles depth-wise. A multi-crystalline wafer is used to demonstrate the difference between the conventional calibration approach, where the photoluminescence signal is calibrated against a quasi-steady-state photoconductance measurement on the test sample itself, and our proposed method. The lifetimes calibrated by our method are consistent, in contrast with the lifetime calibrated by the conventional approach, in which the magnitude and injection-dependence of the lifetime is observed to be sensitive to the choice of reference area. The error in the conventional calibration method mainly originates from measurement artifacts in the quasi-steady-state photoconductance measurements on multi-crystalline wafers, which we propose to be mainly due to minority carrier trapping, radial sensitivity of the quasi-steady-state photoconductance sensor coil and overestimation of the carrier mobility sum. We also show that the proposed new method is effectively insensitive to the lifetime, doping density, reflectance and wafer thickness of the calibration wafer (provided it is below 500 μm).

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## 1. Introduction

Photoluminescence (PL) imaging is a powerful tool for silicon wafer and solar cell characterisation. Given its rapid, contactless, non-destructive nature, and its ability to allow spatially resolved measurement, it is suitable for a variety of different applications such as carrier lifetime [1–3], series [4] and shunt resistance [5] imaging. Another advantage of PL measurements is that they are unaffected by measurement artifacts at low injection such as minority carrier trapping [6,7] and depletion region modulation (DRM) [8] effects, in contrast to the commonly used photoconductance-based lifetime techniques. This allows PL-based lifetime measurements to be performed at true low injection levels.

However, given that the PL intensity is usually measured only in relative units, a calibration procedure is required to convert the raw PL signal into carrier lifetime values. For arbitrary steady-state injection conditions and with a uniform carrier profile depth-wise, the measured relative PL intensity is given by

$$I_{PL,\ rel,\ measured} = C_{calibration}(p \times n) = C_{calibration}(N_{A/D} + \Delta n)\Delta n \qquad (1)$$

with $C_{calibration}$ being a calibration factor, $n$ and $p$ being the electron and hole concentrations respectively, and $N_{A/D}$ and $\Delta n$ being the background doping and the excess carrier concentrations. The relative PL signal has to be first converted into an absolute excess carrier concentration based on Eq. (1), from which the lifetime can then be calculated. This calibration procedure requires the determination of the calibration factor $C_{calibration}$, and it is most commonly done by performing a separate carrier lifetime measurement on an area of the test sample using the quasi-steady-state photoconductance (QSSPC) technique [2,9], and comparing the measured PL signal to the corresponding QSSPC data. This calibration procedure is typically performed at relatively high excitation levels in which the impact of trapping-like artefacts on the QSSPC data is usually negligible. This is based on the assumption that $C_{calibration}$, is injection level independent, an assumption which was shown to be valid only for injection level up to $1 \times 10^{15}\ cm^{-3}$ at room temperature [10].

In general, this standard calibration process is robust when the test sample is relatively homogeneous. It has the advantage that, since the calibration is performed on the test sample itself, there are usually negligible variations in doping, thickness, and optical properties of the calibration region compared to the rest of the test sample. However, as shown below, this approach is subject to

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significant uncertainty if the reference area chosen for the QSSPC measurement is highly inhomogeneous, as is often unavoidable for mc-Si samples in which large amounts of localised defects such as grain boundaries and dislocations exist. Moreover, the implicit extrapolation of the calibration factor to lower injection levels may also lead to quite large variations, as shown below.

Several studies have been performed on alternative techniques for self-consistent calibration of the PL signal, removing the reliance on the QSSPC data. Mitchell et al. [11] demonstrated a method to extract the bulk lifetime of silicon bricks through the ratio of two luminescence images taken with different spectral filters. However, this method is limited to samples with strongly non-uniform carrier density profiles depth-wise, such as bricks, and is not applicable to high lifetime wafers. Giesecke et al. [3] converted PL images into lifetime images based on a lifetime measurement on a part of the test wafer through time modulated quasi-steady-state photoluminescence (QSSPL). Herlufsen et al. [12] and Kiliani et al. [13] extracted carrier lifetime images based on a time dependent photoluminescence signal, captured either using an InGaAs camera or a silicon CCD camera with its signal modulated by a rotating shutter wheel. The advantage of the dynamic PL calibration techniques is that they do not require any prior knowledge of the wafer parameters. In this paper, we propose a steady-state method to convert PL images into calibrated lifetime images based on a calibration factor determined from a separate calibration wafer.

## 2. Theory

### 2.1. Conventional QSSPC calibration method

In the conventional calibration approach, the photoluminescence signal is calibrated against a QSSPC measurement on the test sample itself. Here, we discuss two commonly used approaches for averaging the PL data in the region over the QSSPC sensor, as required in the conventional calibration approach for determining $C_{calibration}$.

The first approach determines $C_{calibration}$ through comparing a simple arithmetic average of the PL signal in a defined region above the QSSPC sensor, $I_{PL,\ Avg}$, with the corresponding excess carrier density data measured by the QSSPC technique, $\Delta n_{QSSPC}$.

$$C_{calibration} = \frac{I_{PL,\ Avg}}{(N_{A/D} + \Delta n_{QSSPC})\Delta n_{QSSPC}} \tag{2}$$

Eq. (2) is simple, easily implemented, and is accurate for homogeneous samples. However, it becomes less accurate when the sample has significant lateral non-uniformities. Firstly, the non-linear relationship in high injection between the local values of $I_{PL,\ rel,\ measured}$ and $\Delta n$, as indicated in Eq. (1), leads to errors in the simple arithmetic averaging process. More importantly, in practise there are significant variations in the radial sensitivity of the radio frequency coil used in the QSSPC measurement [3,13], leading to further inaccuracies in the averaging process.

Accounting for both of these problems, a more accurate calibration can be performed by correlating the local PL intensity measured at each pixel to the QSSPC measured excess carrier density data [3] according to the following equation:

$$\Delta n_i = \frac{-N_{A/D} + \sqrt{N_{A/D}^2 + 4\frac{I_{PL,\ i}}{C_{calibration}}}}{2} \tag{3}$$

$$\Delta n_{QSSPC} = \sum_i^N \frac{\Delta n_i \times S_r(r_i)}{N} \tag{4}$$

with $I_{PL,\ i}$ and $\Delta n_i$ being the local PL intensity and excess carrier density at each pixel respectively, $S_r$ being the radial sensitivity of the QSSPC sensor and $N$ being the total number of pixels in the sensed area of the QSSPC measurement. Eq. (3) is derived through solving Eq. (1) for $\Delta n$. Fig. 1 shows the values of $S_r$ used in this work. It can be seen that the radial sensitivity of the sensor varies significantly, being most sensitive near the radio frequency coil. Note that we did not measure the radial sensitivity of the QSSPC sensor used in this work, but applied a sensitivity function measured by Giesecke [14]. This could lead to some errors as the sensitivity function of each QSSPC sensor may vary slightly. Despite this, the function is sufficient to demonstrate the errors induced by not accounting the radial sensitivity of the sensor coil, which is the main objective of the work. $C_{calibration}$ can be determined through solving Eqs. (3) and (4) by iteration. In this paper, we will compare both averaging algorithms mentioned above with our proposed calibration method, and discuss the possible causes of errors in applying the conventional calibration approach.

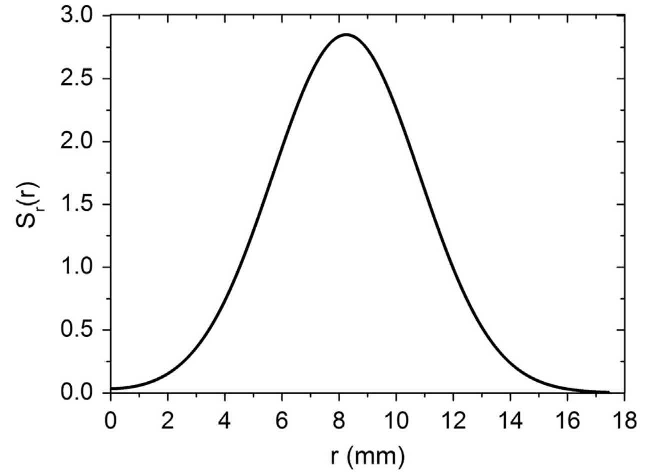


**Fig. 1.** Radial sensitivity function of the QSSPC sensor, extracted from Giesecke [14]. $r$ represents the distance from the centre of the sensor. Following Giesecke [14], the sensitivity values are normalised according to $2\pi \int_0^R r\, dr \Delta S_R(r) = \pi R^2$, with $R$ chosen to represent the radius of the active sensing region of the sensor.

### 2.2. Proposed calibration method

As mentioned above, the conventional QSSPC-based calibration method is robust on homogeneous samples, but is subject to significant uncertainty on highly inhomogeneous samples. Therefore, we propose extracting an accurate calibration factor using a monocrystalline silicon wafer with homogeneous lifetime, and then converting it for application to the mc-Si test sample. Since the calibration sample and the test sample may have different doping, thickness and optical properties, and since $C_{calibration}$ depends on these properties of the sample, a correction has to be applied to $C_{calibration}$ to account for these variations. This correction can be performed based on modelling of the photoluminescence signal. In general, this can be achieved with simulation packages such as Quokka [15], which allows the PL emission from silicon wafers to be accurately simulated. For the case of planar samples with uniform carrier profiles depth-wise, a simpler analytical approach can also be used, as outlined below.

Assuming a uniform carrier profile across the wafer thickness, the rate of spontaneous emission of electrons and holes via band-band transitions can be expressed by [16,17],

$$r_{sp}(\hbar\omega) = B(\hbar\omega) \times (pn) = \alpha(\hbar\omega)\frac{n_{Si}^2 \times (\hbar\omega)^2}{\pi^2 \hbar^3 c^2} \times \exp\left(\frac{-\hbar\omega}{kT}\right)\left(\frac{1}{n_i^2}\right)(pn) \tag{5}$$

where $\alpha$ is the absorption coefficient for band to band transitions [18], and $B(\hbar\omega)$ is the spectral radiative recombination coefficient. $n_{Si}$. $\hbar\omega$, $\hbar$, and $c$ denote the refractive index, photon energy, Reduced Planck's constant and velocity of light in vacuum respectively. Accounting for reabsorption and multiple reflections on

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