

# Self-consistent calibration of photoluminescence and photoconductance lifetime measurements

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An experimental method is introduced by which relative photoluminescence or photoconductance signals can be converted into an absolute excess carrier concentration. This method is demonstrated by comparison of self-consistently calibrated quasi-steady-state photoluminescence measurements with transient photoluminescence and with transient and quasi-steady-state photoconductance measurements on silicon samples. The method simplifies photoluminescence lifetime measurements and the recently introduced Suns-photoluminescence technique as it allows these techniques to be used in a self-contained way, without the previous requirement for a separate experimental technique for calibration. Important experimental observations regarding photoconductance lifetime measurements are also discussed. © 2005 American Institute of Physics. [DOI: 10.1063/1.2119411]

The conversion of a measured photoluminescence (PL) signal into a spatially averaged absolute excess carrier concentration  $\Delta n$  is an essential step in quasi-steady-state photoluminescence (QSS-PL) lifetime measurements<sup>1</sup> and also in the recently introduced Suns-photoluminescence (Suns-PL) technique.<sup>2</sup> In recent applications this calibration has been carried out by comparison of relative PL measurements with calibrated photoconductance (PC) measurements taken under identical illumination conditions.<sup>1</sup> Here we describe a new experimental and analytical method by which the conversion of relative PL signals into absolute  $\Delta n$  is greatly simplified. The only quantities that must be known accurately in absolute units for this method to be applied are the incident light intensity and the reflectance of the sample. This methodology, which is discussed here mainly for PL, can also be applied to calibrate relative PC measurements, which, as will be discussed later, is necessary for the most accurate determination of the effective lifetime.

Assuming homogeneous carrier concentrations within a sample at all times, the evolution of the average excess carrier concentration under illumination as a function of time is determined by the generation rate  $G(t)$  and by the total recombination rate

$$\frac{d\Delta n(t)}{dt} = G(t) - \frac{\Delta n(t)}{\tau_{\text{eff}}[\Delta n(t)]}. \quad (1)$$

In Eq. (1) the recombination rate is expressed in terms of an effective minority carrier lifetime  $\tau_{\text{eff}}(\Delta n)$ , which itself depends on  $\Delta n$ . From Eq. (1) the effective lifetime is given as<sup>3</sup>

$$\tau_{\text{eff}} = \frac{\Delta n(t)}{G(t) - \frac{d\Delta n(t)}{dt}}. \quad (2)$$

We have recently described a self-consistent method that allows a calibration of  $G(t)$  in PL or PC lifetime measurements.<sup>4</sup> In that case the measured relative generation rate  $G_{\text{rel}}(t)$  is linked to the absolute generation rate by a scaling factor  $f_s$ , i.e.,  $G(t) = f_s G_{\text{rel}}(t)$ . With suitably chosen illumination pulse profiles the analysis of experimental

$\tau_{\text{eff}}(\Delta n)$  data (with  $\Delta n$  measured in absolute units) has been shown to yield a hysteresis loop unless this scaling factor  $f_s$  is chosen correctly. The method described here for converting relative PL (or PC) signals into absolute  $\Delta n$  is very similar to this procedure. As has been described elsewhere<sup>1</sup> the conversion of experimental relative PL intensities into absolute  $\Delta n$  consists in the determination of a single calibration factor  $A_i$ :

$$A_i \cdot I_{\text{PL,rel}} = B \cdot (N_D + \Delta n) \cdot \Delta n, \quad (3)$$

where  $B$  is the radiative recombination coefficient and  $N_D$  is the doping density. Hysteresis effects are also expected in  $\tau_{\text{eff}}(\Delta n)$  curves if the correct absolute generation rate  $G(t)$  but wrong calibration factors  $A_i$  are used for the analysis of experimental PL data. The conversion of relative PL intensities into absolute  $\Delta n$  is thereby reduced to the measurement of the absolute generation rate  $G(t)$  and subsequent variation of  $A_i$  during the analysis of experimental PL data until hysteresis effects in resulting  $\tau_{\text{eff}}(\Delta n)$  curves are either eliminated or minimized. It should be noted that a non linear dependence of the PL intensity on the product of electron-hole concentrations is expected at high excess carrier concentrations due to the reduced Coulomb attraction between electron and holes.<sup>5</sup> This effect can either be explicitly taken into account in the analysis by using an analytical expression for the relative variation of  $B$  with injection level<sup>5</sup> or the calibration can be restricted to excess carrier concentrations  $< 10^{15} \text{ cm}^{-3}$ , where  $B$  is constant.

The principle of the calibration method is now demonstrated using *numerically simulated* data. The excess carrier profile  $\Delta n(t)$  is calculated according to Eq. (1) for a generation profile with amplitude  $4.6 \times 10^{17} \text{ cm}^{-3} \text{ s}^{-1}$  and a frequency of 15.5 Hz. The effective lifetime is assumed to decrease linearly from 314  $\mu\text{s}$  at  $\Delta n=0$  to 309  $\mu\text{s}$  at  $\Delta n = 10^{14} \text{ cm}^{-3}$  similar to the experimentally observed lifetime data that will be discussed later. The doping density is assumed to be  $N_D = 5 \times 10^{15} \text{ cm}^{-3}$  (corresponding to 1  $\Omega \text{ cm}$   $n$ -type silicon). The absolute PL signal is calculated from Eq. (3) using the numerical data for  $\Delta n(t)$  and  $A_i=1$ . These numerically simulated PL data are then analyzed using Eqs. (2) and (3). The dotted lines in Fig. 1 show  $\tau_{\text{eff}}(\Delta n)$  curves cal-

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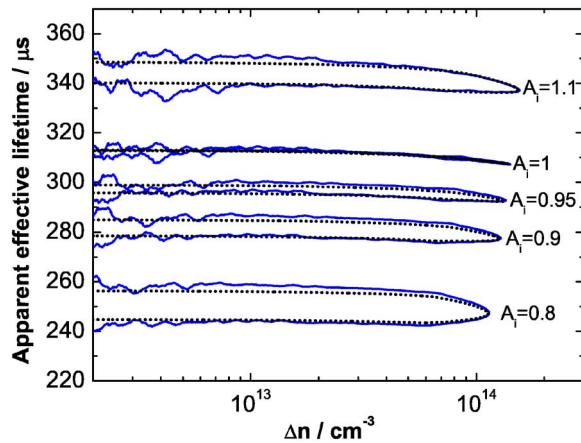


FIG. 1. (Color online) Numerical simulation (dotted lines) and experimental data (solid lines) for the injection level dependent lifetime  $\tau_{\text{eff}}(\Delta n)$  from a 1  $\Omega$  cm *n*-type silicon wafer determined from an intermediate mode PL experiment analysed with various trial values of the scaling factor  $A_i$ . The experimental data for  $A_i$  are normalized to the value that minimizes hysteresis effects in the curves.

culated from the numerically generated PL data for various trial values of  $A_i$ . Clear hysteresis effects are predicted even for deviations of  $A_i$  from unity of only a few percent (e.g., for  $A_i=0.95$ ). The minimization of such hysteresis effects in experimental  $\tau_{\text{eff}}(\Delta n)$  data allows the correct scaling factor  $A_i$  to be determined and thereby relative PL signals to be converted into absolute  $\Delta n$  as will be demonstrated experimentally later.

This method relies on an absolute measurement of the average generation rate  $G(t)$  within the sample. We use a solid state light source [light emitting diode (LED) array] with a narrow (30 nm full width at half maximum) spectrum centered at 870 nm. The penetration depth for this wavelength is much shorter than the thickness of a typical silicon wafer and the absorptance  $A(\hbar\omega)$  is therefore determined by the front surface reflectance  $R_f$ , i.e.,  $A(\hbar\omega)=1-R_f(\hbar\omega)$ . As the reflectance normally varies only marginally over a few nanometers wavelength in typical bulk samples, the determination of  $G(t)$  reduces to the measurement of the incident photon flux  $J_\gamma$  and of the front surface reflection, the latter measured at the peak emission wavelength, i.e.,

$$G(t) = \frac{1}{d} \cdot J_\gamma \cdot (1 - R_{f,870 \text{ nm}}), \quad (4)$$

where  $d$  is the thickness of the sample.

The incident photon flux can be measured with a calibrated photodetector. It is important to note that the front surface reflectance has only a minor impact on the accuracy of the method especially in textured samples or in planar samples with antireflection coating in which the value of  $R_{f,870 \text{ nm}}$  is typically on the order of only a few percent. Because the generation rate is linear in  $1-R_f$  an absolute error in the reflectance of a few percent only results in a corresponding relative variation of  $G(t)$  allowing the self-consistent calibration to be carried out even if the reflectance  $R_f$  can only be estimated.

PL and PC measurements were carried out using an 870 nm LED array with 1.5 W cw optical output power for excitation. The incident light intensity was measured with a calibrated Si sensor and the reflectance of each investigated sample was measured with a Cary 500 spectrophotometer.

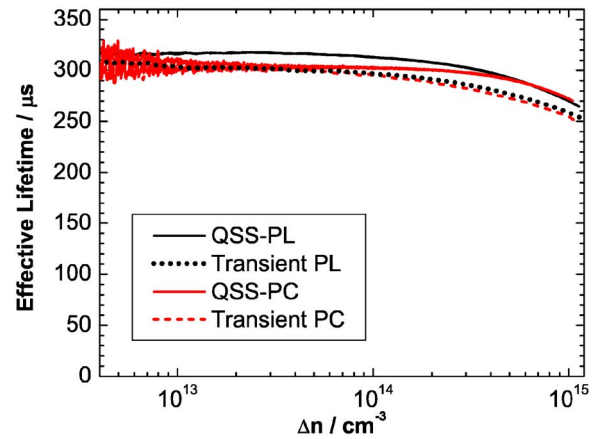


FIG. 2. (Color online) Effective lifetime of a 235- $\mu\text{m}$ -thick textured *n*-type silicon wafer obtained from QSS-PL (black solid line), from QSS-PC (solid red line), from transient photoluminescence (black dotted line) and from transient photoconductance (red dashed line).

The PL and PC setups used are described elsewhere.<sup>1</sup> Lifetime measurements were carried out on a textured 1  $\Omega$  cm *n*-type silicon sample with a thickness of 235  $\mu\text{m}$ , passivated with thermal oxides and a phosphorous diffusion on both sides. The relative PL signal from that sample was measured for a generation profile with frequency 15.5 Hz and a peak amplitude corresponding to an absolute generation rate of  $4.6 \times 10^{17} \text{ cm}^{-3}$ . The excess carrier concentration was determined from the relative PL data according to Eq. (3) with various trial values for  $A_i$ . The resulting  $\tau_{\text{eff}}(\Delta n)$  curves are plotted as a function of the injection level in Fig. 1 (solid lines). Only one value for  $A_i$  leads to consistent  $\tau_{\text{eff}}(\Delta n)$  data from the rising and the falling branches of the wave form, with significant hysteresis effects for all other scaling factors (note that the experimental trial values for  $A_i$  were normalized in Fig. 1 to the value of  $A_i$  that minimizes the hysteresis effects). The almost perfect agreement between the experimental and the theoretical data shown in Fig. 1 is a first strong indication of the viability and accuracy of our method.

An experimental check of the accuracy of the self-consistently calibrated PL lifetime measurement was carried out by comparison with transient PL experiments which have the advantage that they give the effective lifetime in absolute units independent of the calibration of the system, provided the latter is linear. The transient PL lifetime data are shown in Fig. 2 (black, dotted line) together with results from a self-consistently calibrated quasi-steady-state PL measurement in which the scaling factor  $A_i$  that was determined from the measurements shown in Fig. 1 was used (black, solid line). The transient and the self-consistently determined values for  $\tau_{\text{eff}}(\Delta n)$  agree to within 6% over the whole injection level range studied.

To confirm these results with an independent experimental method we measured photoconductance decay and QSS-PC (see Ref. 6) on the same sample using a calibrated PC setup (Sinton Consulting WCT-100). In PC measurements, the measured relative signal is converted into absolute excess conductivity  $\Delta\sigma$  using a linear ( $C_{\text{lin}}$ ) and a quadratic calibration factor. However, in typical PC setups this relation is to a very good approximation linear at low injection levels and the quadratic calibration factor can be neglected. Our commercial PC setup<sup>7</sup> was factory calibrated using a set of silicon wafers with variable resistivity. Figure 2 shows the

lifetime from a transient photoconductance measurement (red, dashed line). It agrees very well with the transient PL results with deviations  $<2\%$ . We then measured the QSS-PC lifetime using the same wave form as for the self-consistent PL measurements from Fig. 1. Analyzing these data using the factory settings for  $C_{lin}$  yields a lifetime of only  $180\ \mu\text{s}$  and also produces pronounced hysteresis effects. We conclude from these data that the linear PC calibration factor  $C_{lin}$  has changed due to our modifications of the setup (the calibration is particularly sensitive to the distance between the wafer and the PC coil). Variation of  $C_{lin}$  in the analysis allowed these hysteresis effects to be eliminated in the same way as shown in Fig. 1 for PL. The lifetime curve for the value of  $C_{lin}$  that minimizes hysteresis in the PC (solid red line in Fig. 2) was found to be the one that also matches the transient PC and the PL data best, which gives another strong indication of the accuracy of our method. We investigated other silicon wafers with variable doping density, doping type, thickness, surface texture, and material quality and found similar good agreement between self-consistently calibrated QSS-PL data on one hand and transient PL, transient PC and self-consistently calibrated QSS-PC on the other hand. These experiments also showed that the calibration factor  $C_{lin}$  determined self-consistently for our PC setup varies by up to 30% from one wafer to the other. The cause of these variations is not clarified yet and will have to be investigated in more detail separately. The important point for PC users is that our measurements clearly demonstrate that a self-consistent calibration of the linear calibration factor  $C_{lin}$  is necessary for each type of sample in order to achieve the most accurate QSS-PC lifetime measurements.

It should be noted that in principle a comparison of a transient measurement with a quasi steady state measurement is sufficient to calibrate PL (or PC) measurements. However, especially on low lifetime samples transient PL measurements can be difficult in practice due to experimental limitations of the data acquisition rate or the bandwidth of the PL detection system, which typically consists of a photodetector and a low noise preamplifier. The self-consistent method is carried out in an intermediate regime between transient and QSS and can be carried out very close to quasi-steady-state conditions, i.e., with comparatively slow wave forms, thereby extending the range of lifetimes that it can be applied to. This important point is elucidated by the experimental data of the normalized  $\Delta n(t)$  and the normalized  $G(t)$  shown in Fig. 3. The small shift between  $G(t)$  and  $\Delta n(t)$  is sufficient to produce the pronounced hysteresis effects shown in Fig. 1, which in turn allowed  $A_i$  to be determined accurately as shown in Fig. 2.

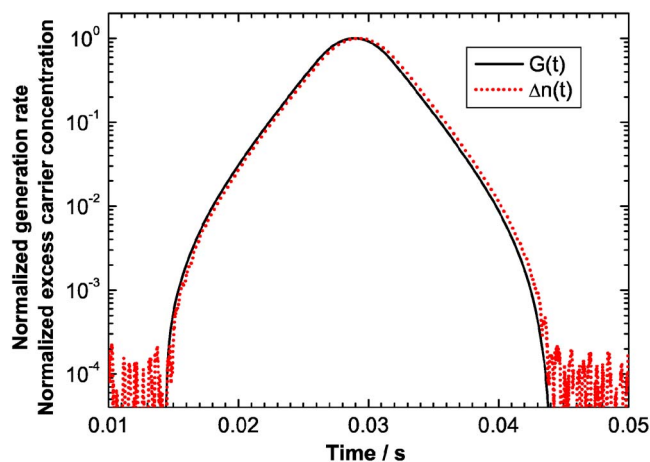


FIG. 3. (Color online) Experimental data of the normalized generation rate (solid line) and of the excess carrier concentration (dotted line) from an intermediate mode PL experiment carried out close to quasi-steady-state conditions.

Photoluminescence is an experimental technique that is ideally suited for sample characterisation in photovoltaics and that has some advantages (e.g., higher sensitivity, robustness against various artifacts) compared to other more widely used techniques. In the past the main obstacle to using PL measurements more routinely has been the perceived difficulty in the conversion of measured relative PL signals into absolute  $\Delta n$ . The experimental and analytical method described here represents a simple and very accurate solution to that problem, which will allow PL to be used as a stand-alone system for lifetime and Suns-PL measurements, without any additional system requirements and without the need for a separate calibration technique.

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