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Photoconductance-calibrated photoluminescence lifetime imaging of crystalline silicon

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We use photoluminescence (PL) measurements by a silicon charge-coupled device camera to generate high-resolution lifetime images of multicrystalline silicon wafers. Absolute values of the excess carrier density are determined by calibrating the PL image by means of contactless photoconductance measurements. The photoconductance setup is integrated in the camera-based PL setup and therefore identical measurement conditions are realised. We demonstrate the validity of this method by comparison with microwave-detected photoconductance decay measurements.

1 Introduction Camera-based photoluminescence imaging is known as a relatively new, contactless and non-destructive measurement technique for the fast spatially resolved analysis of the quality of silicon (Si) wafers [1–3]. The luminescence signal from the Si sample under test is directly related to the separation of the quasi-Fermi levels and therefore to the implied open-circuit voltage of a corresponding solar cell. Due to its fastness and the fact that measurement conditions very close to solar cell operating conditions can be adjusted, camera-based PL imaging is a well-suited characterisation tool for photovoltaic applications. Importantly, it is possible to monitor the processing of solar cells at any stage of fabrication because no electrical contacts are required [3]. Another advantage of the PL imaging technique is the minor impact of measurement artefacts such as trapping [4, 5] or the depletion region modulation (DRM) [6]. This allows the lifetime mapping down to very low injection densities. Up to now, most PL images were published in arbitrary units. Recently, lifetime images were obtained by calibration with other lifetime measurement techniques such as infrared lifetime mapping/carrier density imaging (ILM/CDI) [7] or by quasi-steady-state photoconductance (QSSPC) measurements [8]. However, the comparison for the calibration in these methods is done at different excitation conditions and therefore for different carrier density profiles, leading to significant systematic errors. More recently, it was proposed that this problem could be solved by integrating a QSSPC system into a PL imaging setup [9]. However, no details of the measurement setup and the calibration procedure were presented.

In this letter, we demonstrate a fast and easy-to-apply method for the determination of the relation between the photoluminescence signal measured by a Si charge-coupled device (CCD) camera and the excess carrier density for identical excitation conditions. The PL image is calibrated by measuring the photoconductance of the Si wafer at a steady-state illumination of the sample. To obtain identical measurement conditions, we implement an inductively coupled photoconductance system into our PL imaging setup.

2 Experimental method The rate of radiative recombination R_{rad}, and therefore the PL signal I_{PL}, is proportional to the product of the electron and the hole carrier densities. For a p-type Si wafer of doping concentration N_A, a quadratic dependence on the excess carrier density Δn is expected for the PL signal I_{PL}:

$$I_{PL} \propto R_{rad} \approx B\,\Delta n\,(\Delta n + N_A)\,, \qquad (1)$$

where B is the radiative recombination coefficient.

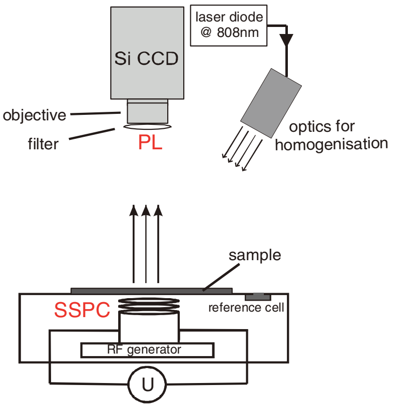

Figure 1 (online colour at: www.pss-rapid.com) Experimental setup for photoconductance-calibrated photoluminescence lifetime imaging (PC-PLI). The PL imaging is performed under the same excitation conditions as the photoconductance measurement.

The effective lifetime τ_{eff} of the charge carriers in a Si wafer under steady-state illumination conditions is calculated from the generation rate G and the excess carrier density Δn:

$$\tau_{\text{eff}} = \frac{\Delta n}{G}. \tag{2}$$

In our measurement setup shown in Fig. 1, we use a 30 W laser diode at a wavelength of $\lambda = 808$ nm for the illumination of the Si sample. For the optical excitation of the entire wafer area, the laser beam is widened and homogenised by an array of microlenses. We use a calibrated Si solar cell to measure the photon flux for excitation Φ. The generation rate for excess carriers G in the Si wafer of thickness W is then calculated using the expression

$$G = \Phi(1 - R_{\text{f,808nm}})\,\frac{1}{W}. \tag{3}$$

For the reflection of a planar silicon surface with an SiN coating ($W_{\text{SiN}} = 60$ nm, refractive index = 2.4) we use a fixed value of $R_{\text{f,808nm}} = 0.12$. Equation (3) is a valid approximation because the penetration depth at 808 nm is ~12.7 μm and thus less than a typical thickness of a Si wafer. For strongly inhomogeneous surfaces, a mapping of the surface reflectance is required. The PL signal is detected using a Si CCD camera which is mounted above the sample. We prevent the detection of laser reflections by a set of long-pass filters. In our setup shown in Fig. 1, the Si sample is placed directly on top of a radio-frequency (rf) coil, which is connected to a calibrated rf bridge circuit. The output voltage of this bridge is proportional to the photoconductance of the sample. Using a mobility model, the excess carrier concentration Δn in the wafer is extracted from the signal of the coil [10]. As the steady-state photoconductance (SSPC) measurement averages the signal approximately over the coil area (~18×18 mm^2), the PL signal has to be averaged as well over this area for the calibration. In order to demonstrate the applicability of the calibration method to solar-grade silicon, we investigate a

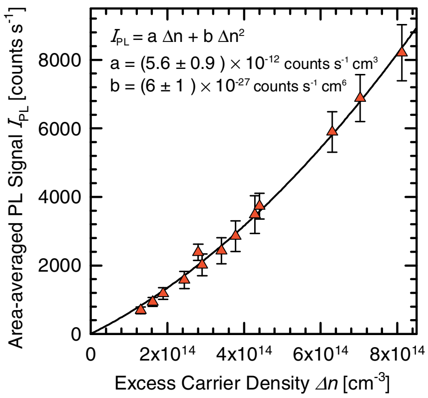

Figure 2 (online colour at: www.pss-rapid.com) Area-averaged PL signal I_{PL} as a function of the excess carrier density Δn as measured by the SSPC setup at $\lambda = 808$ nm.

p-type multicrystalline silicon (mc-Si) wafer with a doping concentration $N_{\text{A}} = 6.5 \times 10^{15}$ cm^{-3}. Sample preparation includes an acidic damage etching, an RCA cleaning and a PECVD silicon nitride (SiN) surface-passivation on both sides of the sample. Figure 2 shows the PL signal in counts of the Si CCD camera per second averaged over the coil detection area versus the excess carrier density obtained from the SSPC measurement under the same steady-state illumination conditions. The error bars stem from the error of the area which is taken for averaging the PL signal. In order to determine the relation between the PL signal and the excess carrier density, we assume a quadratic dependence in accordance with Eq. (1): $I_{\text{PL}} = a\,\Delta n + b\,\Delta n^2$. The values of the fit parameters are shown in Fig. 2. To avoid measurement artefacts such as trapping or DRM, which typically occur in photoconductance measurements [4–6], it is advisable to determine the calibration function at an injection level higher than the trap density. For our exemplary measurements shown here, the trap density is estimated to ~10^{14} cm^{-3} from the injection-dependent lifetime measurement shown in Fig. 3. Therefore, only excess carrier densities higher than $\Delta n = 10^{14}$ cm^{-3} were used to determine the calibration function in Fig. 2.

3 Measurements Figure 3 shows the injection dependence of the carrier lifetime for the investigated mc-Si sample that is measured using the PC-calibrated PLI method (red triangles) and the SSPC technique (open circles) under the same optical excitation conditions at $\lambda = 808$ nm. The PC-PLI lifetime values are the averaged means over the same effective area which is detected by the SSPC setup in the center of the sample. The setup achieves injection levels down to 10^{11} cm^{-3} for the investigated sample using the PL technique. A comparison of the PL lifetime image with a light-biased microwave-detected photoconductance decay (MW-PCD) lifetime mapping is shown in Fig. 4. Both lifetime distributions are recorded at a light intensity of ~0.3 suns. The average values over the entire wafer area are in good agreement: $\tau_{\text{mean, PC-PLI}} = (7.7 \pm 2.1)$ μs, $\tau_{\text{mean, MW-PCD}} = (7.8 \pm 1.2)$ μs.

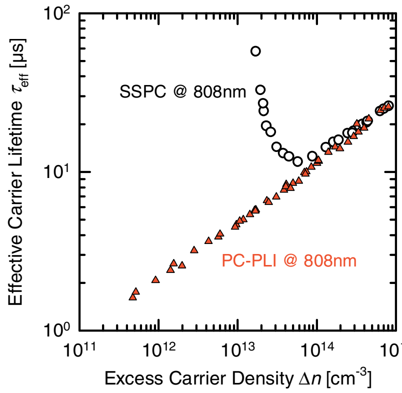

Figure 3 (online colour at: www.pss-rapid.com) Injection-dependent effective lifetime τ_{eff} measured with the PC-PLI setup (red triangles) and with the SSPC setup (at the same excitation conditons as the PL imaging) (open circles).

The denoted range shows the inhomogeneity of the lifetime distribution of the investigated sample which is shown in Fig. 4. Both lifetime mappings are qualitatively in good agreement. However, in the poor lifetime regions, the PC-PLI lifetimes are generally smaller than the MW-PCD lifetimes. Main sources for these deviations are the fact that in the case of the MW-PCD mapping differential lifetimes are measured [11], while the PC-PLI determines actual lifetime values and that the injection level is generally less well-defined in MW-PCD measurements. The estimated difference between differential lifetime and actual lifetime for the injection dependence of our sample is ≤50%. The step width of the MW-PCD setup is set at 250 µm, which leads to a total acquisition time of 3 hours for the mapping, shown in Fig. 4b. For the PC-PLI setup the resolution is 150 µm (only restricted by the used objective and the size of the detected area, respectively) and an integration time of 0.6 s. To improve the signal-to-noise ratio, 100 images were averaged, resulting in a total measurement time of 60 s for the image shown in Fig. 4a.

4 Discussion In the following, we discuss possible error sources of the PC-PLI method: (i) Due to the temperature dependence of the lifetime, the temperature stability of the Si wafer is an important parameter for this measurement technique. During illumination with the laser diode up to several suns, a temperature increase of the investigated sample may possibly occur, especially for long integration times. At low illumination intensities and for small integration times as used in this study, the increase in temperature is negligible. (ii) For Si wafers with an injection-dependent lifetime, the PL signal is additionally influenced by reabsorption. The lifetime determines the depth-dependent profile of the excess carrier density and therefore the influence of reabsorption. For regions of low lifetimes, the effect of reabsorption on the PL signal is less pronounced [12]. We determine the calibration function for a certain injection level regime (>10^{14} cm^{-3}) and extrapolate down to injection levels of 10^{11} cm^{-3}. For Si wafers

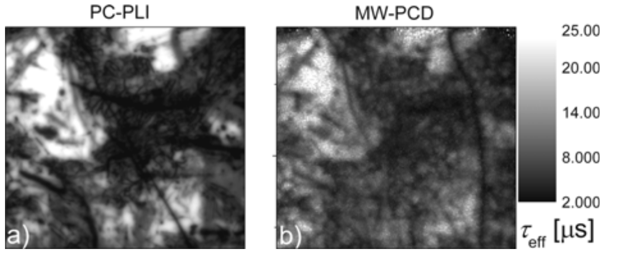

Figure 4 a) PC-calibrated PL lifetime image of a 50 × 50 mm^2 multicrystalline Si wafer and b) for comparison an MW-PCD lifetime measurement of the same wafer.

with strong injection dependence, the lifetime varies up to two orders of magnitude. This may lead to deviations of the actual lifetime from the value extracted from the calibration function for low injection densities. (iii) The size of the detection area of the rf coil in our SSPC setup is another possible source of uncertainty, because this area determines the averaged PL signal I_{PL}. The impact on the calibration function in Fig. 2 is especially important for wafers with a strongly inhomogeneous lifetime distribution. For the sample in this study this error was estimated by varying the averaging area and is in the order of 10%.

5 Conclusions In this letter, a fast and easy-to-apply method for lifetime imaging was presented, which is based on calibrating a photoluminescence image using a coil-detected photoconductance setup. Good agreement between PC-PLI and MW-PCD lifetime measurements were found on multicrystalline silicon. Using PC-PLI, it becomes possible to achieve high-resolution lifetime images down to injection levels of 10^{11} cm^{-3}. Compared to conventional point-by-point lifetime measurement tools, such as the MW-PCD technique, shorter measurement times (<1 s) are achievable. Furthermore, as PC-PLI is a steady-state technique, device-relevant absolute lifetime values are obtained.

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References

[1] T. Trupke et al., Appl. Phys. Lett. **89**, 044107 (2006).
[2] H. Sugimoto et al., Jpn. J. Appl. Phys. **46**, L339 (2007).
[3] M. D. Abbott et al., J. Appl. Phys. **100**, 114514 (2006).
[4] D. Macdonald et al., Appl. Phys. Lett. **74**, 1710 (1999).
[5] J. Schmidt et al., Appl. Phys. Lett. **80**, 4395 (2002).
[6] M. Bail et al., Appl. Phys. Lett. **82**, 757 (2003).
[7] M. The et al., Proc. 22nd EUPVSEC, 354 (2007).
[8] D. Macdonald et al., J. Appl. Phys. **103**, 073710 (2008).
[9] T. Trupke et al., in: Proceedings 18th Workshop on Cryst. Silicon Solar Cells & Modules (Vail, USA, 2008), unpublished.
[10] R. Sinton and A. Cuevas, Appl. Phys. Lett. **69**, 2510 (1996).
[11] J. Schmidt, IEEE Trans. Electron Devices **46**, 2018 (1999).
[12] T. Trupke, J. Appl. Phys. **100**, 063531 (2006).