

PHOTOLUMINESCENCE: A SURPRISINGLY SENSITIVE LIFETIME TECHNIQUE

T. Trupke and R.A. Bardos
Centre of Excellence for Advanced Silicon Photovoltaics and Photonics,
The University of New South Wales, Sydney, N.S.W. 2052, Australia,
Telephone: 61 02 9385 4054, Facsimile: 61 02 9662 4240,
E-mail : thorsten@trupke.de

ABSTRACT

Photoluminescence (PL) measurements in transient, quasi steady state and in an intermediate mode are used to determine the injection level dependent effective excess carrier lifetime $\tau_{\text{eff}}(\Delta n)$ in silicon wafers. The effective lifetime is measured over a wide dynamic range and down to very small injection levels $\Delta n < 10^9 \text{ cm}^{-3}$, demonstrating that PL is a convenient and also a surprisingly sensitive lifetime technique. We show experimentally that PL measurements are not significantly affected by excess carriers accumulated in space charge regions in contrast to other lifetime techniques such as photoconductance (PC). With PL measurements on bifacial silicon solar cells it is also demonstrated experimentally that simultaneous measurements of PL and of the incident light intensity yield the equivalent of Suns- V_{OC} measurements, but in contact less mode and without the need for a solar cell structure.

INTRODUCTION

The determination of the injection level dependent effective excess carrier lifetime $\tau_{\text{eff}}(\Delta n)$ by photoconductance (PC) measurements is an important technique that is widely used in photovoltaics for the characterization of silicon samples [1]. Recently, however, it has been established theoretically and experimentally that excess charges accumulated in space charge regions can lead to a dramatic overestimation of the lifetime in PC measurements [2-4]. Another unwanted effect in PC measurements could be caused by temperature variations. If the variations in the excess carrier concentrations under illumination are small (such as in low quality samples) even small changes in the temperature of the illuminated sample can have a larger effect on variations in the conductivity than changes of the minority carrier concentration. These effects can be so dominant, that PC measurements have been claimed to be unsuitable for the characterization of the effective lifetime e.g. in thin film silicon samples [4]. Open circuit voltage measurements on solar cell structures [5] are used as an alternative technique that is more robust against this type of experimental artifacts [4]. In combination with theoretical modeling they allow the calculation of $\tau_{\text{eff}}(\Delta n)$ and they can also be used to predict the I-V curve of finished devices. Such measurements however, cannot be performed in a

contact-less mode and more importantly, a solar cell structure (e.g. a pn-junction) is required. The main aim of this paper is to demonstrate that PL actually combines the advantages of PC and of Suns- V_{OC} measurements, i.e. that it is a contact-less and sensitive lifetime technique that is *not* significantly affected by excess carriers accumulated in space charge regions.

THEORY

The theory for the determination of the excess carrier concentration Δn and of the effective lifetime τ_{eff} from PL has been outlined in Ref. [6]. The measured relative PL signal $I_{\text{PL,rel}}$ is given as

$$I_{\text{PL,rel}} = A_i \cdot B \cdot n_e \cdot n_h = A_i \cdot B \cdot n_i^2 \cdot \exp(\Delta h / kT) \quad (1)$$

with $\Delta \eta$ the separation of the quasi-Fermi energies within the sample, B the radiative recombination coefficient and A_i a scaling factor by which we take into account that in most cases PL signals are measured in relative units only. All quantities in Eq.1 are defined as independent on the position within the sample. This may be a fairly inaccurate assumption in some cases, in particular if the diffusion length is smaller than the thickness or in the case of laterally inhomogeneous samples such as multicrystalline wafers. The analysis of PL data then gives information only about the effective lifetime as an average quantity in the same way as typical PC measurements. Eq.1 can be written

$$I_{\text{PL,rel}} = A_i \cdot B \cdot (N_{\text{D/A}} + \Delta n) \cdot \Delta n \quad , \quad (2)$$

where $N_{\text{D/A}}$ denotes the bulk doping concentration. Eq.2 simplifies to $I_{\text{PL,rel}} = A_i \cdot B \cdot \Delta n^2$ for high injection conditions and to $I_{\text{PL,rel}} = A_i \cdot B \cdot \Delta n \cdot N_{\text{D/A}}$ for low-injection conditions. The PL-signal thus depends linearly on Δn under low-injection conditions but quadratically on Δn under high injection conditions.

EXPERIMENTAL

A *Sinton Consulting* PC system was modified to allow measurements of the incident light intensity, the PL- and PC signals, and if required of the open circuit voltage. The data acquisition was accomplished by a multichannel 16-bit data acquisition card, which allows parallel

acquisition of three or more channels. The PL and PC lifetime measurements presented here were carried out separately because the PC coil and the PL sensor are about 3cm apart from each other in the current setup.

A 1.5W / 870nm light emitting diode (LED) array was used as light source, which allows light intensities equivalent to about one sun to be generated over an area of $\sim 10 \text{ cm}^2$. Control of the LED output via a D/A port of the data acquisition card allowed arbitrary waveforms to be generated and automated repetitive signal averaging.

The PL signal was measured with a silicon diode, built into the experimental PC setup in combination with a low noise preamplifier. The investigated samples are illuminated from the front surface and the PL signal is detected from the rear surface. A combination of long and short pass filters was used to reduce the fraction of incident LED light that is transmitted by the sample and detected by the PL sensor. The relative variation of the incident light intensity was measured with a second silicon diode.

Calibration of PL lifetime measurements

Injection level dependent lifetime measurements require the determination of the excess carrier concentration Δn in absolute units. Absolute measurements of the PL intensity allow the determination of absolute values for Δn in principle, but are difficult in practice for various reasons. In our current setup the PL signal is therefore measured in relative units only. The relative PL signal $I_{PL,rel}$ is then converted into absolute values of Δn using [6]

$$\Delta n = -\frac{N_{D/A}}{2} + \sqrt{\left(\frac{N_{D/A}}{2}\right)^2 + \frac{I_{PL,rel}}{A_i \cdot B(T)}} \quad (3)$$

The calibration factor A_i is determined by comparison with a PC measurement on the same wafer under identical illumination conditions. This calibration of the PL signal is generally carried out at large injection levels, where the effect of space charge regions on PC data is expected to be minimal [2],

Another quantity that generally needs to be determined in lifetime measurements in absolute units is the generation rate $G(t)$. In all PL and PC experiments presented here we used a recently described self consistent method [7, 8] to determine the absolute generation rate within the sample from the measured relative incident light intensity.

Sensitivity of PL lifetime measurements

Using PL as a sensitive technique to determine small excess carrier concentrations (and thus lifetimes) in silicon may appear difficult given silicon's low radiative recombination coefficient. However, we have previously demonstrated that PL measurements on high resistivity (1000 Ωcm) float zone silicon samples allowed the determination of τ_{eff} down to injection levels $\Delta n < 10^{12} \text{ cm}^{-3}$ [6]. Eq.1 predicts that the same PL signal that is observed from a 1000 Ωcm wafer at an injection level of $\Delta n = 10^{12} \text{ cm}^{-3}$ is expected from a 1 Ωcm wafer at a much smaller minority carrier concentration of only $\Delta n \sim 10^9 \text{ cm}^{-3}$. The sensitivity of PL measurements to small minority carrier

concentrations is thus expected to increase linearly with the base doping.

Fig. 1 shows typical results from a PL lifetime measurement, performed on a 260 μm thick 1 Ωcm p-type wafer with phosphorous diffusions on both sides. The injection level dependence of the effective lifetime resulting from this measurement is shown in Fig.2 together with another PL measurement taken at lower light intensities. Fig.2 also shows the effective lifetime determined from a PC measurement on the same wafer taken under identical illumination conditions. Good qualitative agreement is observed between the lifetimes from PL and from PC at injection levels $\Delta n > 10^{13} \text{ cm}^{-3}$ with deviations smaller than 10%. The origin of these deviations is yet to be unambiguously clarified but seems to be related to a light soaking effect, which is observed in that wafer and which leads to variations in the effective lifetime depending on the previous illumination conditions.

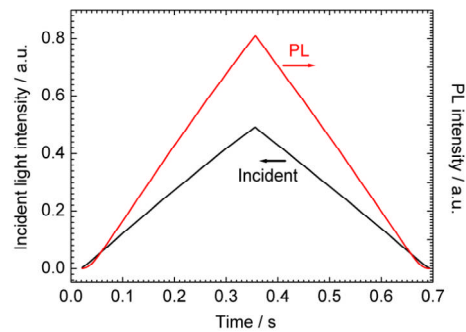


Fig.1 Incident light intensity (black) and PL signal (red) from a 260 mm thick 1 Wcm p-type wafer with phosphorous diffusions on both sides (both in arbitrary units).

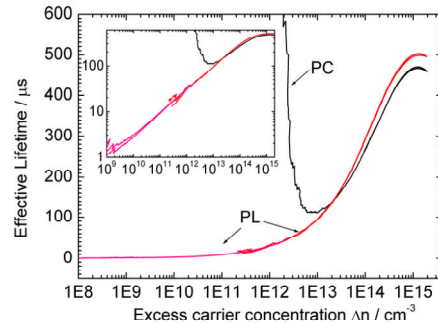


Fig.2 Effective lifetime from PL (red and pink) and from PC (black) for a 1 Wcm p-type wafer with phosphorous diffusions on both sides. The inset shows the same data on a logarithmic scale and highlights the sensitivity of the PL lifetime at low excess carrier concentrations.

The inset of Fig.2 shows that the PL data taken at low light intensity could be analyzed down to very small injection levels on the order 10^9 cm^{-3} with reasonable accuracy confirming the predicted higher sensitivity of PL for lower resistivity material. The PL data at lower light intensities were taken by averaging a very slow waveform (8s) ten times. Averaging a slightly shorter waveform 1000 times

(which took about one hour) allowed the determination of excess carrier concentrations on the order 10^8 cm^{-3} . Such long data acquisition times are certainly impractical for industrial applications of the PL technique but these results demonstrate the somewhat surprising sensitivity of the PL technique. For most applications the determination of carrier concentrations $> 10^{10} \text{ cm}^{-3}$ is sufficient. A very large injection level range can then be scanned without averaging and in fractions of a second.

Fig.2 also shows that PL lifetime measurements can be used to determine low effective lifetimes and are by no means restricted to highest quality float zone silicon wafers. The lowest lifetime detectable with our setup is limited by the light intensity achievable with the LED array and the lowest detectable PL signal. We can estimate that in quasi steady state mode lifetimes $< 1\text{ns}$ should be detectable with PL.

Reduced space charge accumulation effect

The effects of excess carriers accumulated in space charge regions on the results from photoconductance lifetime measurements have recently been analyzed [2] and shown to create dramatic artificial effects on the determined effective lifetime especially at small injection levels.

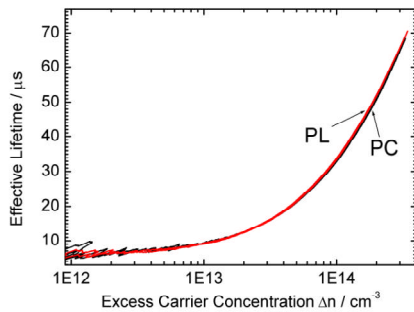


Fig.3 Effective lifetime from PL (red) and from PC (black) for a 1Wcm p-type wafer with Boron diffusions on both sides.

Using a simple PC1D simulation we have recently shown theoretically that PL lifetime measurements are much less strongly affected by these effects [6], because the PL signal is related to the *product* of minority and majority carriers and is directly linked to the separation of the quasi-Fermi levels and thus to the voltage of a solar cell. PL is therefore an ideal technique to be used for sample characterization in PV because the measured signal reflects exactly those properties of the material, which will eventually determine the device performance, i.e. the voltage. In contrast, the artificially high effective lifetimes at small injection levels from PC obtained on samples with a pn-junction contain no information at all about the expected device performance or the bulk properties of the material.

To demonstrate the robustness of PL against the effect of space charge regions experimentally we investigated two $1\Omega\text{cm}$ p-type wafers, one with a Phosphorous diffusion the other one with a Boron-diffusion on both sides. The

artifacts in PC described above are only expected for the Phosphorous-doped sample. Fig.3 shows the lifetimes of the Boron diffused sample determined from PC and from PL. Very good agreement is observed between PL and PC with no indication in both measurements of an influence of space charge regions. In contrast the PC lifetime from the Phosphorous doped sample shown in Fig.2 increases steeply at injection levels $< 5 \cdot 10^{12} \text{ cm}^{-3}$ (up to an apparent lifetime of 13ms, not shown in Fig.2). This increase is consistent with the theoretically predicted effects resulting from the space charge regions on both sides of the wafer [2]. As also predicted by the theory, the PL lifetime is obviously unaffected by these effects.

These results clearly indicate that whenever a space charge region is present within a wafer (as a result of doping or as in SiN passivated wafers) the PC technique cannot be used to determine the lifetime at small injection levels. Fig.2 also shows that using the lifetime minimum from the PC data as a measure for the low level injection Shockley Read Hall lifetime (as suggested in Ref.[9]) can be very inaccurate. Sophisticated lifetime techniques such as temperature dependent (TDLS) lifetime spectroscopy [10] however rely on accurate data for the lifetime at small injection levels. As we have shown here, the PL technique represents a convenient and sensitive experimental alternative to PC.

Suns-PL measurements

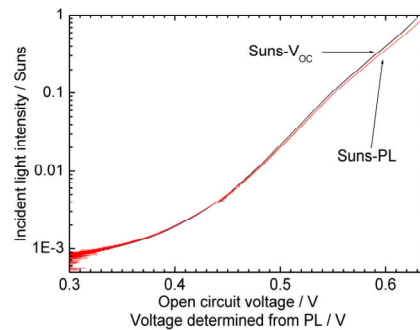


Fig.4 Suns-Voc (black) and Suns-PL (red) measured on a bifacial double-sided buried contact silicon solar cell.

According to Eq.1 the PL signal depends exponentially on $\Delta\mu$. On the other hand the voltage of an ideal solar cell is given as $eU = \Delta\mu$. PL measurements can thus be interpreted as contact less voltage measurements. In combination with measurements of the incident light intensity they can therefore in principle be utilized to predict the I-V-characteristics in analogy to Suns-Voc measurements [5] but with the advantage that no electrical contacts, not even a solar cell structure are required. Recently these by no means new ideas [11] have been demonstrated experimentally for the first time over a wide range of incident light intensities by simultaneous measurements of the open circuit voltage, the PL intensity and the incident light intensity on bifacial silicon solar cells [12]. As an example the Suns-Voc curve of a bifacial double sided buried contact silicon solar cell is plotted in Fig.4 together with the incident light intensity as a function

of the voltage that is determined from the PL signal emitted by that cell. The good agreement between the two curves demonstrated the feasibility of the PL technique for which we have suggested the terminology Suns-PL [12]. The measurements from Fig.4 also represent an alternative method to convert the measured relative PL signals into absolute units [12].

Transient PL measurements

The PL measurements described above were obtained in quasi steady state mode (QSSPL), while the self-consistent method to determine the generation rate was applied in an intermediate PL mode (IPL), i.e. intermediate between QSS and transient.

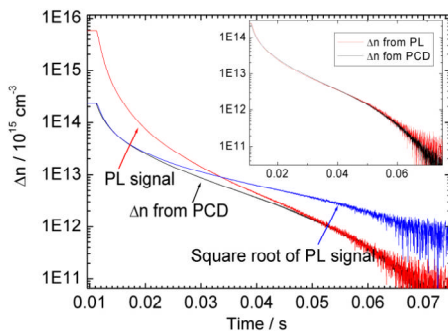


Fig.5 Transient excess carrier decay in a 300 Ωcm n-type float zone wafer from PCD (black) in comparison with the PL signal (red) and the square root of the PL signal (blue). The inset shows that Δn can be accurately calculated from the PL signal using Eq.2.

Fig.5 shows that PL measurements can also be performed in transient mode. It shows photoluminescence decay (PLD) and PCD data measured on a 4-inch 420 μm thick 300 Ωcm n-type float zone wafer. The analysis of PLD is slightly more complicated compared to PCD due to the square dependence of the PL signal on Δn at high injection conditions. As a result the measured PL decay time corresponds to *half* the excess carrier lifetime under high injection conditions.

Fig.5 shows exactly this theoretically predicted behavior i.e. good agreement between Δn from PCD and the square root of the PLD signal at high-injection level conditions and good agreement between PLD and Δn from PCD at low injection levels. If the bulk doping concentration is known, then Eq.3 allows Δn to be calculated from the PL signal and good agreement between Δn from PL and from PC is observed (inset of Fig.5). On the other hand, the comparison of Δn from PLD and PCD data shown in Fig.5 could be used to accurately determine the doping concentration within the wafer.

Conclusions

We have demonstrated experimentally that PL is an excellent alternative lifetime technique that is very sensitive to small excess carrier concentrations and that is

not significantly affected by excess carriers accumulated in space charge regions. Relative PL measurements must be calibrated to give the excess carrier concentration Δn in absolute units and we have shown that typical PC measurements or simultaneous PL and V_{oc} measurements on bifacial solar cells can be used for such calibration. Given the advantages of PL we are optimistic that in the future the PL lifetime technique will find applications in PV research and also in the PV industry.

Acknowledgement: The authors wish to thank Peter Cousins and Aihua Wang from our Centre for providing silicon samples and bifacial silicon solar cells. The Centre of Excellence for Advanced Silicon Photovoltaics and Photonics is supported under the Australian Research Council's Centres of Excellence Scheme.

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