Trapping artifacts in quasi-steady-state photoluminescence and photoconductance lifetime measurements on silicon wafers

R. A. Bardos[a] and T. Trupke
Centre of Excellence for Advanced Silicon Photovoltaics and Photonics, University of New South Wales, Sydney 2052, Australia

M. C. Schubert and T. Roth
Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, D-79110 Freiburg, Germany

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Photoluminescence and photoconductance lifetime measurements on multicrystalline silicon wafers are presented. It is demonstrated experimentally that the large overestimation of the lifetime at low carrier concentrations due to trapping that is observed in photoconductance measurements is not found in photoluminescence data. This is explained theoretically by the dependence of photoluminescence and photoconductance on the product and the sum, respectively, of the minority and majority carrier densities. Based on this analysis, it is shown that photoluminescence lifetime measurements are not significantly affected by minority carrier trapping in most practical cases while implied current-voltage curves obtained from photoluminescence are completely unaffected. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2165274]

Anomalously high lifetimes have been observed in photoconductance (PC) measurements on multicrystalline silicon (mc-Si) samples[1,2] and also in monocrystalline silicon[3,4] at relatively low injection levels. Apart from this trapping-related artifact at low injection, PC suffers from another serious low injection level problem; the depletion region modulation (DRM) effect.[5–7] Where a space-charge layer exists in the sample (from a p-n junction or fixed surface charges), the DRM effect results in a dramatic increase in the apparent lifetime, τ_{app}, that is unrelated to the recombination lifetime, τ_r, at low injection levels. Note that the quantity τ_r is also referred to in the literature as the effective lifetime, which is determined by both surface and bulk recombination.

The photoluminescence (PL) method for lifetime measurements has been described in detail elsewhere.[8–10] In contrast to PC, which measures the sum of excess electron (Δn) and hole (Δp) concentrations, the measured PL intensity (I_{PL}) is proportional to the product of the total electron, n, and hole, p, concentrations.[8] This results in quasi-steady-state (QSS) PL being unaffected by the DRM effect, as has been demonstrated elsewhere.[9] In this work, we show that for doping densities corresponding to resistivities of $\sim 1\ \Omega\,\mathrm{cm}$, as typically used in photovoltaic cells, QSS-PL lifetime measurements are negligibly affected by trapping artifacts at trap densities typically existing in multicrystalline wafers.

Macdonald and Cuevas[2] obtained good agreement between experimental PC data and a simple model proposed by Fan,[11] and by Hornbeck and Haynes.[12] A defect level may be considered a minority carrier trap rather than a recombination center when a captured minority carrier is much more likely to be emitted to the band from which it was captured than to recombine with a majority carrier. For instance, considering trapping in p-type silicon, an electron captured from the conduction band into a trap state has a much higher probability of being released back into the conduction band than of recombining with a hole from the valence band. In the Hornbeck and Haynes model, recombination and trapping are considered to occur at separate defect centers; no recombination occurs at traps and no trapping at recombination centers. The case considered here is a p-type mc-Si wafer where the only electrically active states considered are dopant states, recombination centers and electron traps. The trapped electron density, n_t, and Δn are given by the following coupled differential equations:[2]

$$\frac{d\Delta n}{dt} = g_e - \frac{\Delta n}{\tau_r} + \frac{n_t}{\tau_g} - \frac{\Delta n\left(1 - \frac{n_t}{N_t}\right)}{\tau_t}, \tag{1}$$

$$\frac{dn_t}{dt} = \frac{\Delta n\left(1 - \frac{n_t}{N_t}\right)}{\tau_t} - \frac{n_t}{\tau_g}, \tag{2}$$

where g_e is the optical generation rate, τ_r is the recombination lifetime, τ_t is the mean time before a free electron is trapped (with all the traps empty), τ_g is the mean electron trapped time (independent of trap occupancy), and N_t is the trap density.

In steady state, the left-hand side of both Eqs. (1) and (2) is zero. Adding Eqs. (1) and (2) then yields $\Delta n = g_e \tau_r$ as in the case without trapping. Minority carrier trapping thus has no effect on the density of minority carriers (electrons in this case) in steady state.[2] This makes simple physical sense because under steady-state conditions, the trapping and detrapping rates balance each other. The same does not apply to the majority carriers (holes in this case), since charge neutrality requires that an equal density of holes must accompany the trapped electrons. The excess hole density, Δp, is therefore given by $\Delta p = \Delta n + n_t$. The excess QSS conductance, $\Delta\sigma$, is given by

$$\Delta\sigma = q(\mu_n \Delta n + \mu_p \Delta p), \tag{3}$$

where μ_n and μ_p are the electron and hole mobilities, respectively, and q is the elementary charge. The standard conversion of $\Delta\sigma$ into τ_{app} is given for QSS conditions by[13]

[a]Electronic mail: r.bardos@unsw.edu.au

$$\tau_{app} = \Delta\sigma / g_e q(\mu_n + \mu_p). \tag{4}$$

In the model considered here with N_t set to zero, $\Delta p = \Delta n$ and therefore the excess photoconductance related to τ_r, $\Delta\sigma_r$, is given from Eq. (3) by

$$\Delta\sigma_r = q\Delta n(\mu_n + \mu_p). \tag{5}$$

Equation (4) then reduces to $\tau_{app} = \tau_r$. In the presence of traps, Eq. (3) becomes

$$\Delta\sigma = q\Delta n\left(\mu_n + \mu_p\left(1 + \frac{n_t}{\Delta n}\right)\right),$$

$$= \Delta\sigma_r\left(1 + \frac{n_t}{\Delta n}\frac{\mu_p}{\mu_n + \mu_p}\right). \tag{6}$$

In steady state and for the case $\Delta n / N_t \ll \tau_t / \tau_g$, Eq. (2) yields $n_t / \Delta n = \tau_g / \tau_t$ which combined with Eqs. (4) and (6) gives

$$\tau_{app} = \tau_r\left(1 + \frac{\tau_g}{\tau_t}\frac{\mu_p}{\mu_n + \mu_p}\right). \tag{7}$$

Macdonald and Cuevas[2] find values of τ_g / τ_t typically of the order 10–100. Inserting $\tau_g / \tau_t = 100$ into Eq. (7) yields $\tau_{app} \approx 25\tau_r$. Conventional PC measurements cannot therefore be used to measure τ_r in the low injection limit, which is important for defect spectroscopy.[14] The same applies to all techniques which measure the sum of Δn and Δp, which includes infrared free-carrier emission[15] or infrared free-carrier absorption.

Analytical and experimental methods have been developed to try to solve the trap artifact problem. Sinton[16] and Macdonald[17] devised an approximate correction to the τ_{app} data, yielding corrected data above a certain injection level threshold. The technique makes it possible to lower by up to about one order of magnitude the minimum injection level at which τ_{app} is correct to within an error of $\sim 30\%$. It is not possible however to determine the low injection limit of τ_{app} with this method, since it relies on subtracting the trap-related photoconductance at low injection and cannot be used at injection levels below that at which the calculation is performed. Macdonald and Cuevas[2] used a fitting method, using the model described above, to extract τ_r from the τ_{app} data. In the case that τ_r varies significantly in the trap-dominated injection level range, both methods are problematic because the values of τ_r to be determined must be corrected for a much larger background related to trapping.[16] The infrared camera lifetime mapping (ILM) technique,[18] also known as carrier density imaging (CDI),[19] is based on infrared intraband absorption or emission and is therefore also subject to trapping artifacts at low injection levels as discussed above. It has recently been demonstrated that artifacts due to trapping in CDI measurements,[20] as well as in QSS-PC measurements,[21] can be suppressed by illumination with subband-gap light. The subband-gap light is absorbed predominantly by trapped minority carriers, emptying the traps thereby reducing the influence of trapping.

In the PL lifetime technique,[8] the measured PL intensity (I_{PL}) is proportional to the product of n and p giving

$$I_{PL} \propto \Delta n \cdot (\Delta p + N_A)$$

$$= \Delta n \cdot (\Delta n + n_t + N_A)$$

$$\approx \Delta n \cdot (n_t + N_A) \tag{8}$$

for the p-type wafer considered here, where N_A is the doping density and the last line holds for low level injection conditions (i.e., for $\Delta n \ll N_A$ and $\Delta n \ll n_t$). Importantly, I_{PL} is only affected by minority carrier trapping in proportion to the ratio of the np product with and without trapping, i.e., in proportion to $(n_t + N_A)/N_A$ under low injection conditions and an even smaller ratio for higher injection conditions. For typical solar cell wafers of $\sim 1\ \Omega\,\text{cm}$ resistivity ($N_A \sim 1.5 \times 10^{16}\ \text{cm}^{-3}$) and with $N_t = 1 \times 10^{14}\ \text{cm}^{-3}$, I_{PL} is thus only increased by a maximum of 0.7% by electron trapping if all traps are occupied. Consequently, $\tau_r < \tau_{app} < 1.007\tau_r$ representing an error of less than 1%. A larger relative impact of minority carrier trapping on QSS-PL measurements is expected for high-resistivity material (low background doping) with high trap density because the ratio $(n_t + N_A)/N_A$ then becomes larger. In practice this is not expected to be a problem, as the only relevant photovoltaic application for high-resistivity silicon is in high efficiency solar cells made from very pure float-zoned silicon, in which trap densities can be expected to be below the doping density.

The determination of implied current-voltage characteristics from photoluminescence in so-called Suns-PL measurements,[10] in which a measured photoluminescence signal is interpreted in terms of an implied voltage, has recently been demonstrated. It may be expected that the argument used above for the validity of QSS-PL lifetime measurements would carry over to the Suns-PL case; that for samples where $(N_t + N_A)/N_A \sim 1$ the error is negligible at all injection levels, but that if this condition does not hold, the data may not be valid at relatively low injection levels. Surprisingly, Suns-PL measurements are unaffected by trapping regardless of the trap or doping density. The voltage of a solar cell and the PL signal are both directly related to the logarithm of the np product. The increase of the majority carrier concentration resulting from trapping discussed above, which could be defined as *light activated doping*, therefore leads to an increase of the cell voltage, which is correctly accounted for in the PL signal. Minority carrier trapping in high resistivity silicon can thus in principle yield an increased voltage. Some care has to be taken in this case in the conversion of the measured PL signal I_{PL} into an implied voltage U_i. As discussed in Ref. 10, this conversion must be carried out via $qU_i = kT \cdot \ln(I_{PL}) + C$, where C is a scaling factor that needs to be determined. A second conversion method demonstrated in Ref. 10, which involves conversion of I_{PL} into Δn via Eq. (8) followed by conversion of Δn into U_i leads to erroneous results at injection levels comparable to the trap density as the additional majority carrier concentration that balances the trapped minority carriers is not accounted for correctly. In contrast, at higher injection levels ($\Delta n \gg N_t$), this second conversion method can be used to accurately convert I_{PL} into U_i. The U_i values determined in this high injection range can then be utilized to determine the scaling factor C.

QSS-PL lifetime data were taken on a 302 μm thick, 1.2 Ωcm, mc-Si, boron-doped p-type silicon wafer with a SiN passivation layer deposited after chemical polishing. The wafer was made by the directional solidification method and supplied by Scanwafer. PL was detected from a 2 cm $\times$ 2 cm area of the sample using a similarly sized sensor located about 5 mm below the sample. Figure 1 compares the QSS-PL lifetime data with conventional QSS-PC data and with QSS-PC data taken with simultaneous subband-gap illumination. The sensitive region of the PC system is a disk 4

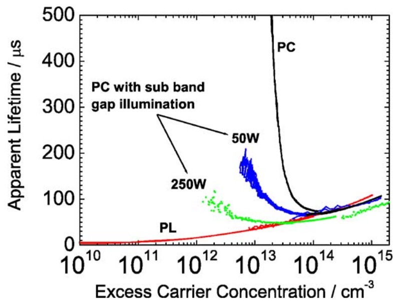

FIG. 1. (Color online) Effective minority carrier lifetime τ_{app} of a 1.2 Ω cm *p*-type mc-Si wafer as a function of Δn determined from QSS-PL, QSS-PC, and from QSS-PC with additional subband-gap illumination at two different intensities.

cm in diameter, with the PC coil (2.5 cm in diameter) located in the center. The subband-gap light was obtained by filtering light from either a 50 W quartz tungsten halogen (QTH) lamp, or a 250 W infrared filament (IF) lamp, through a 1 mm or 0.3 mm thick polished silicon wafer respectively. Three of the four data sets (QSS-PL, QSS-PC, QSS-PC with simultaneous subband-gap illumination from a 50 W QTH lamp) were calibrated using a recently introduced self-consistent method.[22] The illumination source for those three data sets was a 870 nm light-emitting diode (LED) array with 1.5 W optical power. The fourth data set (QSS-PC with simultaneous subband-gap illumination from a 250 W IF lamp) was carried out on a separate PC apparatus using a flash lamp light source and a conventional calibration of the PC bridge. Agreement between all four data sets is good at excess carrier concentrations $\Delta n > 1 \times 10^{14}$ cm^{-3}. The lifetime determined from PC increases rapidly at lower injection levels. In principle, this steep increase of the apparent lifetime could be caused by either minority carrier trapping or by the DRM effect, the latter as a result of a junction induced at the surfaces of the *p*-type wafer by the fixed positive charge in the SiN passivation layer. This increase of the apparent lifetime towards lower injection levels is still present in the subband-gap illuminated PC data, but the onset is shifted to lower injection levels with increasing subband-gap illumination. This clearly demonstrates that in this sample the low-injection behavior without subband-gap illumination is dominated by trapping, not by the DRM effect as the latter is not expected to vary with subband-gap illumination. Whether the residual rising behavior in the data taken with subband-gap illumination from the 250 W IF lamp is due to residual trapping or the DRM effect can only be determined by increasing the subband-gap illumination intensity further. In the PL data, the trend observed in all four data sets above $\Delta n = 1 \times 10^{14}$ cm^{-3} continues unaffected below this injection level, confirming the analysis presented above.

In previous publications, the minimum in the PC lifetime data has sometimes been taken as the approximate value of the lifetime in the low-injection limit. However, the large difference found here between the lifetime measured at $\Delta n = 1 \times 10^{11}$ cm^{-3} with PL and that at $\Delta n = 1 \times 10^{14}$ cm^{-3} (the lowest injection level at which PC data is valid) clearly demonstrates that this approximation can be highly inaccurate. This work shows that QSS-PL is an ideal tool for the accurate determination of the lifetime in the low-injection limit since it is affected by neither trapping nor by DRM.

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