Trapping-related recombination of charge carriers in silicon

N. P. Harder,[1,2,a)] R. Gogolin,[1] and R. Brendel[1,3]
[1]*Institut für Solarenergieforschung Hameln (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany*
[2]*Institute of Electronic Materials and Devices, University of Hannover, Schneiderberg 32, 30167 Hannover, Germany*
[3]*Institute of Solid-State Physics, University of Hannover, Appelstrasse 2, 30167 Hannover, Germany*

(Received 6 July 2010; accepted 27 August 2010; published online 17 September 2010)

We present experimental evidence and theoretical explanation for simultaneous occurrence of trapping related increased apparent carrier lifetime and decreased actual recombination lifetime in low injection. This correlation is not describable by the common Hornbeck and Haynes [Phys. Rev. **97**, 311 (1955)] trapping model. McIntosh, Paudyal, and Macdonald [J. Appl. Phys. **104**, 084503 (2008)] recently used Shockley–Read–Hall (SRH) recombination statistics [Phys. Rev. **87**, 835 (1952)] for describing the temperature dependence of trapping. Our study shows that these SRH statistics for traps also explain a causal connection between trapping-related increased apparent charge carrier lifetime and reduced actual lifetime in low injection. © *2010 American Institute of Physics*. [doi:10.1063/1.3490240]

The description of trapping effects is traditionally done via the model of Hornbeck and Haynes (H&H),[1–3] which allows trap states to capture only minority charge carriers. However, McIntosh, Paudyal, and Macdonald[4] have shown that the temperature dependence of the trapping-effect in the apparent lifetime signal can be much more adequately described by allowing for nonzero, yet nevertheless very small, majority carrier capture cross sections. This is essentially equivalent to using the Shockley–Read–Hall (SRH, Refs. 5 and 6) recombination mechanism. In this case numerical equation solving is required for accounting for the concentration of trapped carriers, which give rise to the trapping effects in photoconductance-based lifetime determination, such as in quasisteady state photoconductance (QSSPC)-measurements.[7,8] We extend the approach of using SRH statistics for simultaneously describing both, trapping-related enhancement of the apparent lifetime in QSSPC-measurements and a pronounced decrease in the low injection carrier recombination lifetimes as observable in photoluminescence (PL) measurements. We thereby show that there is a causal relationship between the occurrence of trapping induced increased apparent carrier lifetime and a reduced carrier recombination lifetime in low injection.

We investigate the carrier lifetime in *p*-type multicrystalline (mc) silicon wafers with a resistivity of 1.7 Ω cm and a thickness of 265 μm. We passivate the surfaces with plasma-enhanced chemical-vapor deposition-SiN_x prior to measurements of the effective carrier lifetime. When applied to single-crystalline floating-zone silicon, this SiN_x passivation is sufficient to produce effective carrier lifetimes well beyond 1000 μs, which is about an order of magnitude larger than any of the effective carrier lifetimes measured on the mc wafers of our investigation. Hence, we are able to interpret the effective lifetime of our mc-Si samples as a good approximation to the carrier lifetime in the bulk. We performed QSSPC and PL measurements[9,10] for determining the carrier lifetime at 25 °C. Both measurements were performed for the same position on the wafers to assure comparability between the measurements. The results of such QSSPC (triangles) and PL (circles) lifetime measurements on one of the wafers are shown in Fig. 1. In low level injection the QSSPC method is prone to trapping induced effects which results in an overestimated lifetime.[8] In the following we therefore refer to such lifetime data that overestimates the actual recombination lifetime by the term "apparent lifetime" τ_{app}. In contrast to this, the lifetime data as obtained from PL intensity measurements is not prone to such trapping effects. Therefore the PL lifetime can be identified with the recombination lifetime τ_{r}.[9]

Figure 1(a) shows by comparison with two SRH parameterized lifetime curves that it is not possible to reproduce the experimentally measured carrier lifetime in this mc-Si wafer by SRH recombination via a single type of defect. Regardless of the choice of the capture cross section parameters $(\sigma_{\mathrm{n}}, \sigma_{\mathrm{p}})$ and energy level of the trap (E_{T}) the data fit is not satisfactory. Moreover, it can be seen that the slope that connects the lifetime value plateaus of low injection and high injection occurs at a different excess carrier concentration than reproducible by SRH recombination via a single type of defect. However, this change from low-injection to high-injection is determined by the wafer doping, which has been independently confirmed to be 8.6×10^{15} cm^{-3} by four point probe measurements and also by inductively coupled conductivity measurements of the passivated wafer. We therefore conclude that at least a second SRH defect is necessary for adequately describing the measured lifetime curve in the trapping free region as shown in Fig. 1(b). Note that it has been reported before[11,12] that more than a single type of SRH defect is necessary to describe the lifetime data of even monocrystalline Si wafers grown by the Czochralski (Cz) method. It therefore appears plausible that our multicrystalline silicon wafers also accommodate a range of different types of defect states and require the assumption of more than a single type of SRH defect states.

The dashed lines in Fig. 1(b) are the lifetime limits imposed by each of the two types of SRH defects separately that we used to fit the experimental data. The solid line represents the modeled lifetime with both types of defects acting at the same time, together with Auger recombination as pa-

[a)]Electronic mail: harder@isfh.de.

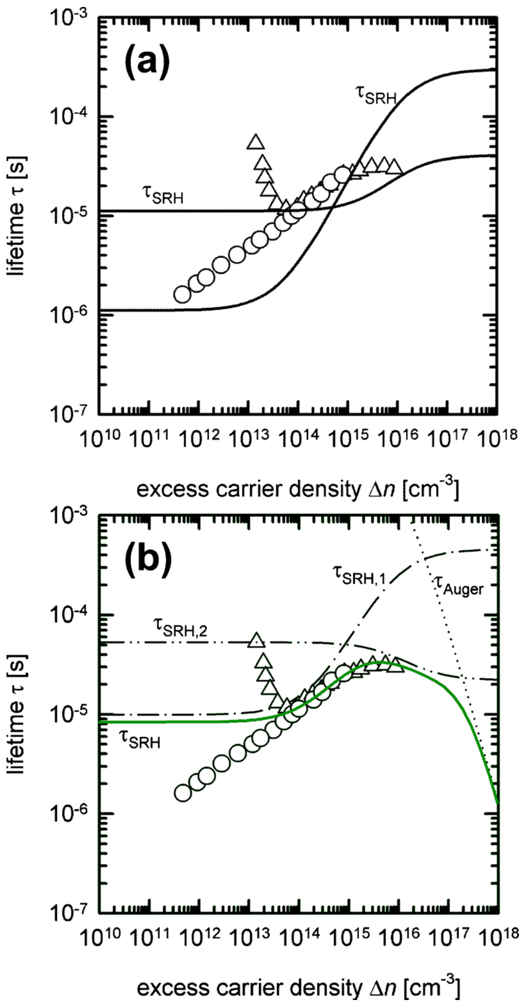

FIG. 1. (Color online) Carrier lifetime data from QSSPC (triangles) and PL (circles) measurements of SiN-passivated mc-Wafer. (a) The experimental data cannot be fitted adequately with SRH recombination model with only a single type of defect, as indicated by comparison with two SRH lifetime parameterization curves. (b) In the trapping free region (i.e., $\Delta n > 10^{14}$ cm^{3}) the lifetime data can be adequately described by simultaneous recombination via two different types of SRH defects. Dashed lines are the lifetime limits imposed by each of the two types of defects separately; the solid line represents the calculated lifetime with both types of defects acting at the same time.

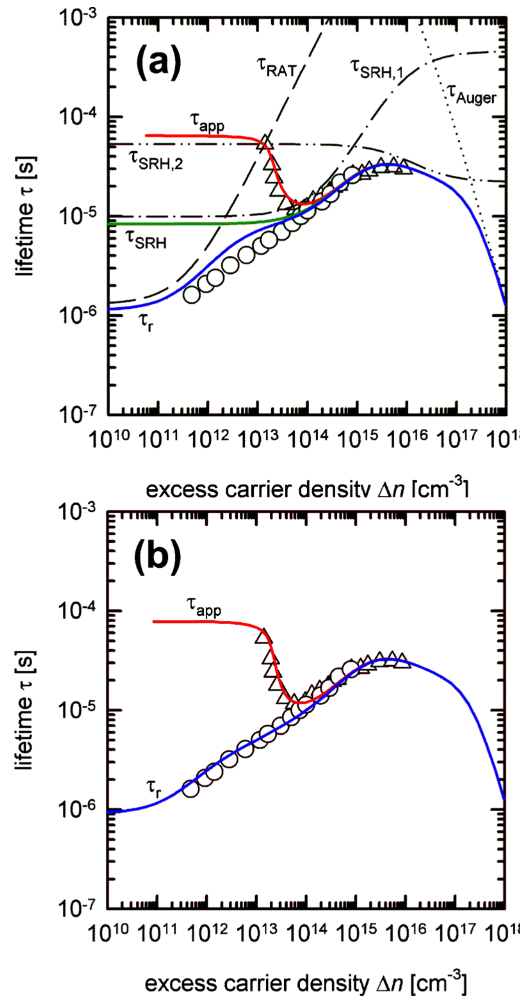

FIG. 2. (Color online) QSSPC (triangles) and PL lifetime data (circles) shown together with fits to the experimental data. (a) Inclusion of a single type of RAT splits up the carrier lifetime into an increased apparent lifetime and a decreased recombination lifetime in low injection. Trapping and reduced low injection lifetime is qualitatively well-described already by a single type of RAT state. (b) Improved fit of experimental data by *two* types of RATs.

rameterized by Kerr and Cuevas.[13] The parameters of the two SRH defect types are well defined by the measured lifetime curve and are listed in the first two columns of Table I.

The rapid increase in the apparent lifetime toward low injection can be well reproduced by using the model of H&H.[1–3,8] However, such H&H trapping does not alter at all the recombination lifetime and therefore does not explain the extraordinary decrease in the low-injection lifetime as measured by PL.

The assumption of the H&H model that traps do not capture majority charge carriers is highly idealizing and it appears rather unlikely that electronic transitions between any real trap state and the majority charge carrier band are completely forbidden. Ascribing nonzero capture cross sections σ_p and σ_n for both types of carriers, that is, for minorities and majorities, turns the H&H trap model into SRH recombination statistics. McIntosh, Paudyal, and Macdonald[4] improved the description of the temperature dependence of trapping effects by using SRH statistics for traps. We call such states "recombination active trap" (RAT). In this paper, we show that these RAT defects cause both; RAT states obscure in QSSPC measurements the recombination lifetime by an increased apparent (trapping) lifetime similarly to H&H traps, but additionally, the RAT defects also decrease the actual recombination lifetime at low injection.

TABLE I. Defect parameters for fit curves of Figs. 1 and 2.

Parameter	SRH 1	SRH 2	RAT 1	RAT 2
N_t (cm^{-3})	1×10^{12}	8.5×10^{11}	7×10^{13}	1×10^{13}
E_t-E_V (eV)	0.55	1.00	0.55	0.5
σ_n (cm^{-3})	9×10^{-15}	5×10^{-15}	1×10^{-15}	1×10^{-15}
σ_p (cm^{-3})	2×10^{-16}	1×10^{-13}	4×10^{-20}	1.5×10^{-18}

Figure 2 shows the result of including such RAT defects in the fits of the experimental data, whereby Fig. 2(a) includes the fit curves of Fig. 1(b). In order to fit the reduced PL carrier lifetime at low injection we have to introduce a type of third defect with long high-injection lifetime and very short low-injection lifetime. The lifetime limit imposed by this defect is indicated in Fig. 2(a) by the dashed line labeled with τ_{RAT}, with the respective defect parameters listed in Table I under "RAT 1." The ratio of $\sigma_{n,RAT}/\sigma_{p,RAT}$ determines the occupation probability of the density of trap states N_{RAT} and thus density of trapped excited carriers $n_{trapped}=\Delta n_{majority}-\Delta n_{minority}$. In low injection this difference can be much larger than the minority carrier concentration itself. However, the commonly used analytical expression for the SRH recombination is based on the assumption $\Delta n_{majority}=\Delta n_{minority}$, which causes calculating an artificially increased apparent lifetime from photoconductance based lifetime measurements.[4,8] We do not make this simplifying assumption of equal majority and minority excess carrier densities and solve the respective equations for the SRH capture and emission rates equations numerically for the RAT state, similarly to the procedure described in Ref. 4. This yields the recombination lifetime τ_r [blue solid line labeled by in Fig. 2(a)] as measured by PL. We now use the calculated minority and majority excess carrier concentrations and "reinterpret" these carrier densities by calculating an apparant excess carrier concentration Δn_{app} from the excess conductivity as follows: $\Delta\sigma=q(\mu_e\Delta n_e+\mu_h\Delta n_h) \equiv q(\mu_e+\mu_h)\Delta n_{app}$. This expression corresponds to the standard interpretation of photoconductance measurements and produces an overestimation of the minority excess carrier concentration and thus the overestimated (apparent) minority carrier lifetime τ_{app} as shown in Fig. 2(a).

Figure 2(a) shows the important finding that already the inclusion of only a single type of RAT defects allows a qualitatively satisfactory simultaneous fit of the QSSPC and of the PL data as follows: the inclusion of a RAT defect splits up the lifetime data in an artificially increased apparent lifetime τ_{app} as measured by QSSPC (triangles), and a strongly reduced low-injection recombination lifetime τ_r as measured by PL (circles). The corresponding defect parameters are given in Table I.

The fit of the recombination lifetime τ_r (continuous line) in Fig. 2(a) still shows a slight deviation from the actual measured recombination lifetime (circles). This difference could be reduced by further increasing the minority carrier capture cross section $\sigma_{n,RAT}$ of the RAT state. Alternatively, it shall be mentioned that the assumption of only one type defect state that is causal for trapping (and additional recombination) is not compelling. In this experiment we examine a mc sample that is likely to harbor a comparatively high number of different types of crystal defects and impurities. Therefore it appears justified to take into account a second type of RAT defect to describe the measured data. In this manner we find an excellent agreement between the experimental data and our modeling as shown in Fig. 2(b). Table I summarizes the defect state parameters that were used for modeling the lifetime data in Figs. 1 and 2.

We have shown that the observation of both the diverging increased apparent lifetime (QSSPC) and the decreasing recombination lifetime (PL) can be explained by a single physical mechanism; i.e., by RAT states that cause trapping due to minority carrier capture and emission, and recombination by (much smaller but nonzero) majority carrier capture rates. This asymmetry gives rise to trapping effects that obscure the recombination lifetime by an increased apparent lifetime in, e.g., photoconductivity based lifetime measurements, similar to the trap states of the H&H model. However, the RAT states additionally decrease the recombination lifetime in low level injection as it can be observed by PL based lifetime measurements. This implies a causal relation between trapping and increased recombination activity. Such conclusion agrees well with the observation that regions of high trapping activity in mc-Si wafers turn out to be badly performing regions of final processed solar cells.[14]

Trapping as detected by photoconductivity measurements should therefore be considered as an indication for hidden, yet potentially strongly increased, low injection recombination activity.

[1] J. R. Haynes and J. A. Hornbeck, Phys. Rev. **90**, 152 (1953).
[2] J. A. Hornbeck and J. R. Haynes, Phys. Rev. **97**, 311 (1955).
[3] J. R. Haynes and J. A. Hornbeck, Phys. Rev. **100**, 606 (1955).
[4] K. R. McIntosh, B. B. Paudyal, and D. H. Macdonald, J. Appl. Phys. **104**, 084503 (2008).
[5] W. Shockley and W. T. Read, Phys. Rev. **87**, 835 (1952).
[6] R. N. Hall, Phys. Rev. **87**, 387 (1952).
[7] R. A. Sinton and A. Cuevas, Appl. Phys. Lett. **69**, 2510 (1996).
[8] D. Macdonald and A. Cuevas, Appl. Phys. Lett. **74**, 1710 (1999).
[9] R. A. Bardos, T. Trupke, M. C. Schubert, and T. Roth, Appl. Phys. Lett. **88**, 053504 (2006).
[10] S. Herlufsen, J. Schmidt, D. Hinken, K. Bothe, and R. Brendel, Phys. Status Solidi (RRL) **2**, 245 (2008).
[11] J. Schmidt and A. Cuevas, J. Appl. Phys. **86**, 3175 (1999).
[12] D. Macdonald, A. Cuevas, and J. Wong-Leung, J. Appl. Phys. **89**, 7932 (2001).
[13] M. J. Kerr and A. Cuevas, J. Appl. Phys. **91**, 2473 (2002).
[14] M. Schubert and W. Warta, Prog. Photovoltaics **15**, 331 (2007).