INJECTION DEPENDENT CARRIER DENSITY IMAGING MEASUREMENTS INCLUDING CORRECTION FOR TRAPPING EFFECTS

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ABSTRACT: Injection dependent lifetime measurements are often severely affected by trapping effects, resulting in an anomalous increase of lifetime under low-injection conditions. Carrier Density Imaging (CDI) measurements are presented where trapping effects are clearly present. Two different correction methods are proposed, based on the modeling of the injection dependent data. A model for CDI measurements, based on the Hornbeck-Haynes model is proposed as well as a bias-light correction adapted to CDI. Finally, a modification of the CDI setup is presented which allows to suppress trapping effects very efficiently. It is based on an additional irradiation with sub-bandgap light which is assumed to deplete trap levels resulting in trap-free lifetime measurements. A comparison of the carrier lifetimes resulting from these methods shows excellent correlation.

Keywords: Lifetime, Defects, Spectroscopy

1 INTRODUCTION

Measurement of recombination lifetime of free minority carriers on silicon at low-injection conditions are often severely interfered by trapping effects. An anomalous increase towards low-injection conditions can be observed. The recombination lifetime may not be accessible for realistic operating conditions of solar cells. In addition, the determination of the low-injection lifetime is of major interest for material characterization. The knowledge of the injection dependence of lifetime over a broad injection range is important for injection dependent lifetime spectroscopy. Many lifetime measurement techniques are sensitive to trapping effects, such as Quasi-Steady-State PhotoConductance QSSPC [1], MicroWave-detected PhotoConductance Decay MW-PCD [2] as well as Carrier Density Imaging CDI [3-5] (equally termed Infrared Lifetime Mapping ILM [6]). The injection level can be increased with a bias illumination to avoid an influence of trapping on lifetime measurements, but the low-injection lifetime may be inaccessible. Nevertheless the low-injection lifetime is a very important parameter for material characterization. For QSSPC measurements an empirical correction has been proposed in [7, 8].

In this paper we focus on the CDI technique which allows fast and contactless lifetime measurements with high spatial resolution. The CDI technique is based on the detection of infrared absorption or emission by free carriers. A CCD-camera, sensitive in the mid infrared, is used to detect the free carrier density simultaneously for all camera pixels. A Lock-in technique is used to reduce noise.

2 TRAPPING MODEL

In this paper, the Hornbeck-Haynes model [9] is used to describe the trapping effects. Other possible explanations for the anomalous increase of apparent lifetime can be found in [10,11]. More details may be found in [12]. In analogy to Shockley-Read-Hall (SRH) recombination [13, 14] trapping is assumed to be caused by defect levels. In contrast to recombination active defects, trap levels are thought to feature shallow energy levels and / or very asymmetric capture cross sections, i.e. the capture cross sections for the majority carriers σ_p are negligible compared to the capture cross sections for minority carriers σ_n. In the following a single trap level is assumed. Free minority carriers may be temporarily trapped with density n_T. Under steady-state conditions the excess free carrier density Δn is determined by generation and recombination and is hence independent from the amount of trapped carriers. Because of charge neutrality, the density of trapped minority carriers n_T has to be compensated by additional free majority carriers $\Delta p=\Delta n+n_T$. n_T can be expressed as [9]

$$n_T = \frac{N_T \Delta n}{\Delta n + N_T(\tau_t/\tau_g)}, \qquad (1)$$

where N_T is the total trap density and trap-escape ratio (τ_t/τ_g), i.e. τ_t is the mean time before a carrier is trapped under the condition that all traps are empty and τ_g is the mean time spent in the trap.

3 STRATEGIES TO OBTAIN LIFETIME FREE OF TRAPPING EFFECTS

3.1 Modeling of trapping parameters and lifetime

CDI measurements are based on the detection of both, the minority and majority carriers. $\Delta n=\Delta p$ is assumed when the absorption or the emission signal is converted to minority carrier lifetime. This assumption fails if trapping effects are present under low-level conditions. We therefore propose a model for injection dependent CDI measurements which accounts for the difference of Δn and Δp and enables to describe analytically the apparent lifetime τ_{app}. We follow the argumentation used by Macdonald [15] in the development of his model to describe trapping influence in QSSPC measurements. A detailed description of the model may be found in [16]. The apparent minority carrier density Δn_{app} depends on the absorption coefficients for minority carriers α_n and majority carriers α_p (these are equal to the corresponding emission coefficients):

$$\Delta n_{app} = const(\alpha_n \Delta n + \alpha_p \Delta p) \qquad (2)$$

With $\Delta p=\Delta n+n_T$ and the determination of the constant considering the case without trapping we may write this as:

$$\Delta n_{app}(\Delta n) = \frac{1}{\alpha_n + \alpha_p} \Delta n \left[\alpha_n + \alpha_p \left(1 + \frac{n_T(\Delta n)}{\Delta n} \right) \right] \qquad (3)$$

The apparent lifetime τ_{app} is calculated from

$$\tau_{app}(\Delta n) = \frac{\Delta n}{G} = \frac{1}{\alpha_n + \alpha_p} \tau_{rec} \left[\alpha_n + \alpha_p \left(1 + \frac{n_T(\Delta n)}{\Delta n} \right) \right], \qquad (4)$$

where G is the optical generation rate of free carriers and τ_{rec} is the recombination lifetime without trapping effects. Using equations (3) and (4) an analytical expression for $\tau_{app}(\Delta n_{app})$ can be found by eliminating the true minority carrier density which is experimentally inaccessible. This expression can be fitted to injection dependent CDI measurement results in order to extract the trapping parameters N_T and τ_t/τ_g as well as the low-injection lifetime. The lifetime is assumed to be dominated by SRH recombination, thus is constant for low-injection conditions.

3.2 Bias-light correction adapted for CDI measurements

Injection dependent CDI measurements may be corrected by a method which is very similar to the "bias-light correction" for QSSPC measurements [7, 8]. The idea of this empirical correction is to subtract out the influence of the trap-induced additional majority carriers on the photoconductance by assuming a virtual bias-generation. The determination of lifetime is then performed relative to the trap-induced photoconductance.

We adapted the formulas deduced by Macdonald et al. [8] for the case of QSSPC to the case of CDI:

$$\tau_{corr}(\Delta n_{app}) = \frac{\Delta n_{app} - \Delta n_{app,bias}}{G - G_{bias}}, \qquad (5)$$

$$\Delta n_{corr}(\Delta n_{app}) = \Delta n_{app} - \Delta n_{app,trap}, \qquad (6)$$

where G_{bias} is the assumed virtual bias generation rate, $\Delta n_{app,bias}$ is the corresponding value for the apparent excess carrier density. $\Delta n_{app,trap}$ is the extrapolated value for the carrier density at G=0 and represents the influence of trapping (see Fig. 1). $\tau_{corr}(\Delta n_{corr})$ is the corrected injection dependent lifetime.

The trick is now to find the best value for the virtual bias generation G_{bias} which gives the best correction. This is achieved by following the instructions of Macdonald et al.: The bias generation is increased until a minimum for $\tau_{corr}(\Delta n_{corr})$ is found for the lower carrier densities (see Fig. 2). As in the case of QSSPC [12] this guideline shall assure that just enough virtual bias generation is used to perform the calculations.

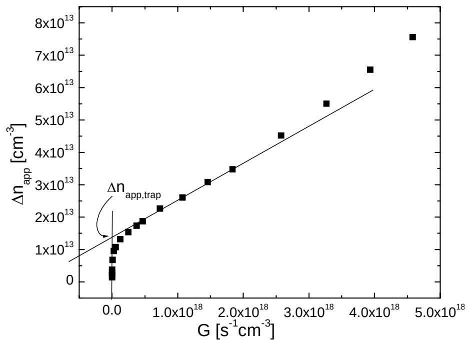

Figure 1: Generation rate G versus measured apparent excess carrier density Δn_{app}. Due to trapping a strong increase of Δn_{app} can be observed for low generation. When traps are filled, the curve becomes linear. At high generation rates the curve deviates from the linear behavior due to the injection dependence of the recombination lifetime. $\Delta n_{app,trap}$ is considered as the contribution of trapping effects on Δn_{app}.

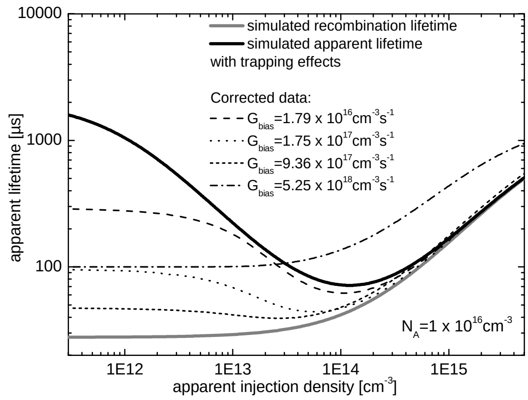

Figure 2: Exemplary calculated injection dependence of apparent lifetime including trapping effects for CDI measurements. Corrections for various virtual bias generation are displayed.

3.3 Detrapping by application of sub-bandgap light

In the following the case for p-silicon is discussed. The case of n-silicon can be treated analogously. In this approach the trapping effects are suppressed instead of correcting the trap-affected lifetime data. The suppression is achieved by the application of sub-bandgap light to effectively deplete the trap levels. Details can be found in [12, 17]. The depletion and thus reduction of n_T can be understood with the help of a modified SRH theory, where radiative transitions are included [18]. The capture cross sections for electrons and holes, $\sigma_{n,p}$, introduced in SRH theory are interpreted as describing thermal transitions and are termed (picking up the terminology of [18]) E_r^{th}, E_g^{th}, H_r^{th}, H_g^{th}, see Fig. 3. Optical capture cross sections, $\sigma_{n,p}^{opt}$, are introduced in [18] in order to describe the radiation related transitions (E_r^{rad}, E_g^{rad}, H_r^{rad}, H_g^{rad}). These transitions depend additionally on photon flux densities.

It is shown in [18] that the recombination processes depend on the black-body photon flux density at wafer temperature $\phi_{blackbody}$, whereas the generation processes depend in addition on the external photon flux density ϕ_{ext}. Note that generation and recombination indicates transition processes between trap level and conduction /

valence band where the energy of a carrier is increased or decreased, respectively.

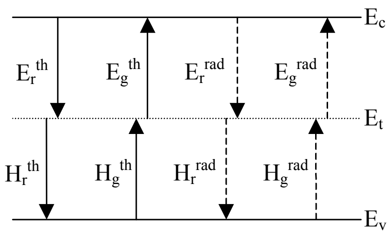

Figure 3: Thermal and radiative transitions between a defect state and valence-/conduction band. The arrows indicate the electron transitions. From Ref. [18].

The transitions between defect level and conduction band for example can be written as

$$E_g^{rad} = n_t \int_0^{\lambda_{max}} \sigma_n^{opt}(\lambda)(\phi_{blackbody}(\lambda) + \phi_{sub}(\lambda))d\lambda, \quad (7)$$

$$E_r^{rad} = n(N_t - n_t)\frac{1}{n_1}\int_0^{\lambda_{max}} \sigma_n^{opt}(\lambda)\phi_{blackbody}(\lambda)d\lambda. \quad (8)$$

where λ_{max} is the maximum wavelength permitting transitions and n_1 is the SRH density for electrons. Irradiation with photons of sufficient energy enhances the transition processes E_g^{rad} and H_g^{rad} but not E_r^{rad} and H_r^{rad}. For a trap level, H_g^{th} and H_r^{th} are assumed to be negligible. If $\sigma_n^{opt} >> \sigma_p^{opt}$ is assumed additionally, E_g^{rad} exceeds H_g^{rad} and a depletion of trap levels may be achieved. We propose that sub-bandgap light is used for this purpose in order to inhibit additional free carrier generation. The energy of sub-bandgap photons is chosen such that free carrier generation from the valence band to the conduction band is impossible but with energies high enough to enable the transition process from the trap level to the conduction band.

4 EXPERIMENTAL RESULTS

Injection dependent Emission-CDI measurements have been performed on a SiN_x-passivated multicrystalline silicon sample with irradiation levels from 3.6 µW/cm² to 36 mW/cm² at 939nm. A measurement of the apparent lifetime τ_{app} for a region of 13x13 mm² is displayed in Fig. 4 (a). The irradiation density was 1.9 mW/cm². A pronounced fine structure can be observed as well as very diffuse regions with different apparent lifetime. The fine structure is due to trapping effects which severely affect the measurement under the low-level injection conditions used. The correction methods proposed in chapter 3 have been used to correct the measurement in order to obtain recombination lifetime values which are no longer influenced by trapping. The extraction of the recombination lifetime from both, the fitting of the adapted Hornbeck-Haynes model (τ_{model}) and the bias-light correction (τ_{bias}) are based on the analysis of the injection dependent measurement data.

The determination of the recombination lifetime from the Hornbeck-Haynes model has been automated to be performed for all pixels of injection dependent CDI measurements (an example is shown below in Fig. 5, filled points). The model has been fitted to the data (solid line in Fig. 5) for each pixel, the recombination lifetime has been extracted and the resulting lifetime image plotted in Fig. 4 (b). The convergence of the automated procedure has been monitored.

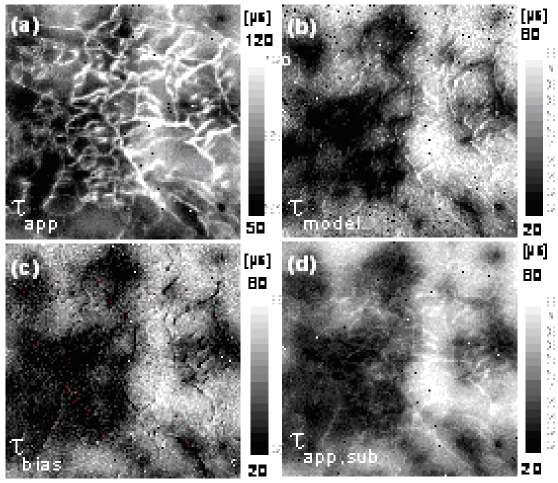

Figure 4: Apparent lifetime image with severe trapping effects (τ_{app}) at an illumination density of 1.9 mW/cm² in comparison with different correction methods. (τ_{bias}) and (τ_{model}) are models predicting the recombination lifetime under low level injection conditions from injection dependent measurements with the bias-light correction and the Hornbeck-Haynes model for CDI measurements (see eqs. (3), (4)), respectively. ($\tau_{app,sub}$) is the apparent lifetime image obtained with additional irradiation of sub-bandgap light. The measured area is 13 mm x 13 mm.

As a second method to obtain low injection recombination lifetimes the bias-light correction method for CDI measurements has been performed as described in chapter 3. In a first step, the automated procedure for each pixel estimates $\Delta n_{app,trap}$ from a plot of generation rate G versus apparent carrier density Δn_{app} (see Fig. 1). Then, corrections for the injection dependent lifetime with different virtual bias generation G_{bias} are calculated with equations (5) and (6). The most appropriate virtual bias generation for the correction is determined from the correction yielding the minimal corrected lifetime. The injection dependent lifetime data can then be displayed at any constant generation level or, if desired, at any constant injection level by linear interpolation of the injection dependent lifetime curves. In Fig. 4 (c) the corrected lifetime τ_{bias} is displayed at constant generation level which corresponds to the generation rate of the measurement in Fig. 4 (a) and is suitable for comparison.

In Fig. 4 (d) only one single measurement has been performed under the same conditions as for Fig. 4 (a), except that the sample has been irradiated with sub-bandgap light between 1.1 µm and 3.5 µm in addition. The fine structure interpreted as coming from trapping effects has almost vanished and mainly the underlying regions of different recombination lifetime remain visible.

The three different correction methods applied in order to remove trapping effects from the original measurement data yield very comparable results. Both, spatial distribution and absolute values of the determined lifetime correlate nicely. Only minor deviations in regions with very high trap density can be observed. The quality of the correction methods over the whole injection range is illustrated in Fig. 5. The apparent lifetime and the correction values averaged over a small region are displayed for an injection range from approx. 10^{12} to 10^{15} cm^{-3}. The injection dependent apparent lifetime without application of sub-bandgap light (black dots) coincides well with the fitting curve (solid line) from the adapted Hornbeck-Haynes model. The model does not include the injection dependence of SRH-lifetime and assumes a constant recombination lifetime. This assumption reflects the expected constant behavior of SRH-lifetime under low injection conditions. In the injection range from approx. 10^{14}-10^{15} cm^{-3} the lifetime increases according to SRH-lifetime behavior. The dashed line marks the low-injection recombination lifetime deduced from the fitting model. Calculations of corrected lifetime values with the bias-light correction at different injection levels are marked with a cross. They nicely coincide with the low-injection lifetime deduced from the fitting model. The increase of lifetime for higher injection conditions is correctly reproduced.

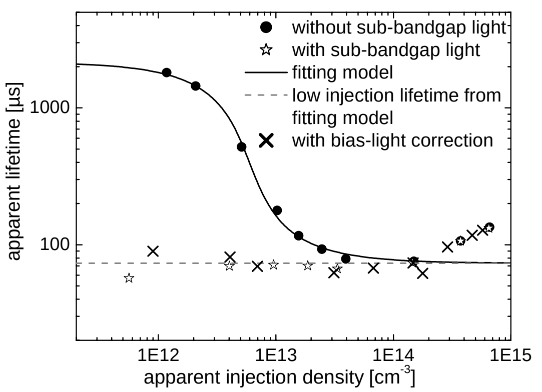

Figure 5: Measured injection dependent apparent lifetime in comparison with different correction methods on a spot of the wafer shown in Fig. 4. The fitting model used in this graph is obtained from equations (3) and (4).

Star symbols in Fig. 5 denote measurements taken with sub-bandgap light and otherwise under exactly the same conditions. The measurement correlates well with the data obtained without sub-bandgap light in the higher injection range, whereas a significant difference is obtained in the low-injection range. The measurement follows a SRH-lifetime behavior with high accuracy, i.e. on the one hand the low-injection part coincides with the constant recombination lifetime retrieved from the modeling, on the other hand in the region of higher injection an increase corresponding to the expected SRH-curve is obtained. Note that it is not necessary to perform injection dependent measurements to obtain lifetime images with strongly suppressed trapping influence, when sub-bandgap light is applied.

5 CONCLUSION

Injection-dependent lifetime measurements with Emission-CDI have been presented. It has been shown that trapping may severely affect the measurement results yielding apparent lifetimes that do not reflect the SRH-recombination behavior. Different correction methods have been proposed. The Hornbeck-Haynes model adapted to the CDI method fits the injection-dependent apparent lifetime values well. The low-injection recombination lifetime has been extracted from this model. The resulting values have been compared to corrected lifetime values calculated from the bias-light correction method adapted to CDI. Excellent correlation has been found.

Measurements taken with additional irradiation by sub-bandgap light nicely follow the lifetime behavior predicted from the Hornbeck-Haynes model and the bias-light corrected data. In contrast to these methods no assumptions on the expected lifetime behavior (i.e. constant low-injection lifetime) have to be made inorder to obtain values for the recombination lifetime free of trapping effects. Furthermore no injection dependent measurements are necessary. The application of sub-bandgap light is therefore a very powerful method to inhibit the negative influence of trapping on CDI measurements.

6 ACKNOWLEDGEMENT

We like to thank A. Dehnert for the help with the measurements and H. Lautenschlager for sample preparation. We gratefully acknowledge R. Sinton and M. Hermle for helpful discussions. This work was partly supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety within the framework of the “Netz Diagnostik” project.

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