SEPARATION OF BULK AND SURFACE RECOMBINATION BY STEADY STATE PHOTO CONDUCTANCE MEASUREMENTS

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ABSTRACT: A general approach for the evaluation of steady state photo conductance lifetime measurements is presented. Our evaluation technique explicitely includes the wavelength-dependent optical properties of the sample under test. We calculate the measured photoconductance from a solution of the one-dimensional steady state diffusion equation for the minority carriers. Performing two measurements under ultra violet light illumination and under infrared illumination we deduce the surface recombination velocity S and the bulk minority carrier lifetime τ_b of a non-passivated EFG-Si wafer.

Keywords: Evaluation – 1: Photoconductivity – 2: Lifetime – 3

1. INTRODUCTION

Developing novel solar cell processes requires the control and the measurement of the bulk minority carrier lifetime τ_b and the surface recombination velocity S. Monitoring the photo conductance decay after a short light pulse excitation by the transient microwave reflectance (*MWPCD*) is a well established technique to determine an effective lifetime τ_{eff} that depends on S and τ_b. However, *MWPCD* measurements yield differential recombination parameters rather than the actual recombination parameters [1, 2]. Injection level dependent determination of the actual S and τ_b is tedious and time consuming [2].

Recently Sinton and Cuevas introduced the quasi steady state photoconductance (*QSSPC*) lifetime measurement technique [3] that is becoming increasingly popular, because QSSPC yields information on the actual lifetimes and an injection dependency is analyzed with a single measurement. The principle of the QSSPC-technique is to determine the effective lifetime τ_{eff} from the balance of the total photo generation G and the total recombination rate $R = W \Delta n_{av} / \tau_{eff}$ under steady state conditions. Here W denotes the wafer thickness, n_{av} is the average excess minority carrier concentration in the wafer. The QSSPC technique determines $W n_{av}$ from the measured sheet conductivity of the wafer while G is assumed to be proportional to the short circuit current density j_B measured with a calibrated high-efficiency Si solar cell [3]. However the proportionality factor depends on the optical properties of the wafer under test and on the illuminating light spectrum. This dependence was not accounted for by previous analysis techniques.

The physical interpretation of the effective life time τ_{eff} measured under steady state conditions is obvious only if surface recombination vanishes and the photogeneration is constant throughout the wafer. Then it is $\tau_{eff} = \tau_b$ [3, 4]. For the more general condition of non-zero surface recombination and spatially non-homogeneous photogeneration the meaning of τ_{eff} was clarified only recently by Nagel et al. [5]. Neither of the previous evaluation schemes addressed the question how to derive the actual surface recombination velocity S and the bulk lifetime τ_b from a QSSPC-measurement.

This paper introduces an algorithm for the evaluation of *QSSPC* lifetime measurements under steady state conditions that minimizes the number of a priori assumptions. Accounting for the wavelength-dependent optical properties of the light source and the wafer under test we determine S and τ_b of non-passivated low-lifetime wafers from two *QSSPC* measurements performed under ultraviolet and infrared illumination.

2. THEORY

An analytical solution of the minority carrier diffusion equation

$$D\frac{\partial^2 n(z)}{\partial z^2} - \frac{n(z)}{\tau_b} = -g(z) \tag{1}$$

for the excess minority carrier concentration $n(z)$ under the boundary conditions

$$D\frac{\partial n(z)}{\partial z}\Big|_{z=0} = S_f\, n(0) \tag{2}$$

and

$$-D\frac{\partial n(z)}{\partial z}\Big|_{z=W} = S_b\, n(W) \tag{3}$$

requires an analytical expression for the carrier generation rate $g(z)$. Here z is the distance from the wafer surface, D denotes the electron diffusion constant assuming for p-type Si, W is the thickness of the sample, and $S_f = S_b = S$ are the surface recombination velocities of the front and back surface, respectively. In order to determine $g(z)$ we first calculate the photon flux

$$\Phi_B(\lambda) = \frac{j_B}{q} \cdot \frac{\Phi_{B0}(\lambda)}{\int \Phi_{B0}(\lambda')\ EQE(\lambda')\, d\lambda'} \tag{4}$$

illuminating the wafer from the current density j_B of the reference cell that has an external quantum efficiency EQE and the photon flux spectrum Φ_{B0} of the light source. The symbol q denotes the elementary charge. The carrier generation rate

$$g(z) = \int_0^\infty \left(c_1(\lambda)\, e^{\alpha(\lambda) z} + c_2(\lambda)\, e^{-\alpha(\lambda) z}\right) d\lambda \tag{5}$$

is then calculated from the absorption coefficient $\alpha(\lambda)$ of the semiconductor material and the constants

$$c_1 = \frac{\alpha(\lambda)(1-R_f(\lambda))R_b(\lambda)e^{-2\alpha(\lambda)W}}{1-R_f(\lambda)R_b(\lambda)e^{-2\alpha(\lambda)W}}\phi_B(\lambda) \quad (6)$$

and

$$c_2 = \frac{\alpha(\lambda)(1-R_f(\lambda))}{1-R_f(\lambda)R_b(\lambda)e^{-2\alpha(\lambda)W}}\phi_B(\lambda) \quad (7)$$

that depend on the front and back side reflectance $R_f(\lambda)$ and $R_b(\lambda)$, respectively.

With $g(z)$ from Eq. (4) the solution of Eqs. (1) to (3) yields the excess carrier density profile $n(z, S, \tau_b)$ that explicitly depends the bulk minority carrier lifetime τ_b and the surface recombination velocity S. Knowing $n(z, S, \tau_b)$ we calculate the sheet conductivity

$$\sigma(S,\tau_b) = q \cdot \int_{z=0}^{W} \mu \ \Delta n(z,S,\tau_b)dz \quad (8)$$

that is the quantity actually measured by the QSSPC-technique. Here μ denotes the (average) carrier mobility throughout the wafer. Our model calculates this conductivity as a function τ_b and S. Having implemented the optics into our model we are now able to analyze QSSPC measurements performed under various illumination conditions.

2. EXPERIMENTAL

We exemplify our analysis of QSSPC data for a p-type multicrystalline EFG (edge defined film growth) Si wafer that has a specific resistance of 3 Ωcm and a thickness W = 380 μm. The wafer is cut in two halfs. One half just sees a standard RCA cleaning (non-passivated sample). The other half receives an RCA cleaning plus a low temperature plasma silicon nitride passivation on both surfaces that provides a high-quality surface passivation (passivated sample) [6].

In order to separate surface and volume recombination we choose two different illuminations that are depicted in Fig. 1. These spectra result from placing filters in front of the Xe-flash lamp. Illumination with blue light favors surface recombination due to carrier generation close to the Si surface while illumination with (infra) red light favors volume recombination due to carrier generation deep in the waver.

Figure 2 shows the conductance transients measured for the non-passivated sample with a flash decay time of 2.5 ms. Extraction of recombination parameters requires an illumination level sufficiently strong to make the excess carrier concentration n larger than the trap concentration N_t [7]. Our sample satisfies this condition for σ > 1.4 mS. Therefore we analyze the passivated sample under blue and red illumination at two different times that both yield a measured conductivity of σ = 1.5 mS. This procedure also guarantees that the average minority carrier concentration n_{av} is identical under blue and red illumination. This is particularly important if the recombination is injection level dependent. For both points in time t(blue) and t(red) depicted in Fig. 2 the measured short circuit current densities j_b(blue) and j_b(red) permit

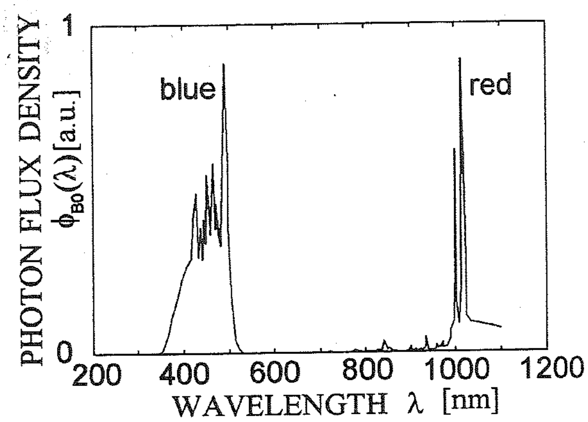

Figure 1: Spectral photon flux density distribution for the red and (infra) red light source.

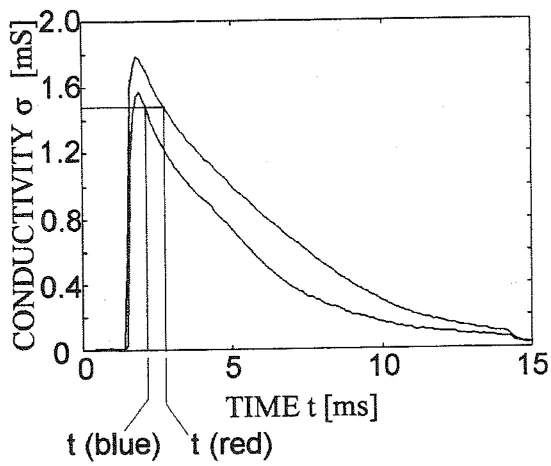

Figure 2: Measured photoconductance of the non-passivated sample for the illumination with red (upper curve) and blue (lower curve) light.

the determination of the illuminating spectra Φ_B (blue) and Φ_B (red) using Eq. (4).

Figure 3 shows the measured hemispherical reflectance R of the non-passivated EFG wafer under test. In the visible spectral range the measured reflectance is identical to the front surface reflectance R_f of the wafer. In the near-infrared range we determine the front surface reflectance by extrapolation as indicated by the dashed line. In addition we measure the hemispherical absorption A of the Si wafer by mounting the wafer in the center of the integration sphere. Using standard formulas for the optical absorption A in a sheet of Si with surface reflectance values R_f and R_b we calculate the back reflectance R_b that yields the measured data A and R_f.

3. DATA ANALYSIS

Knowing the front and back surface reflectance R_f and R_b we calculate the carrier generation rate $g(z)$ in the Si wafer using Eqs. (5) - (7). The mathematically simple form of $g(z)$ permits an analytical solution of the steady

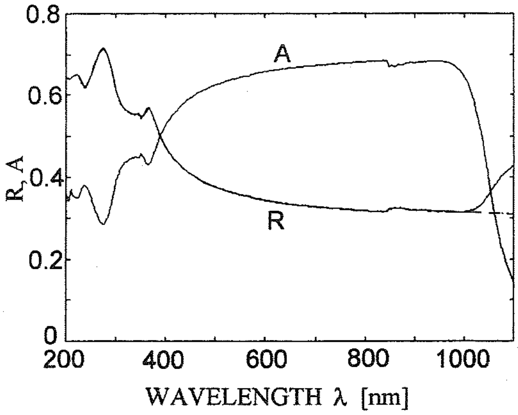

Figure 3: Measured hemispherical reflection R and absorption A of the non-passivated sample.

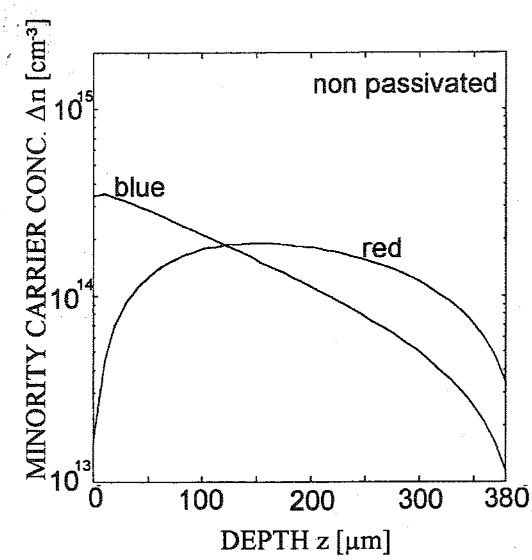

Figure 4: Minority carrier profiles for S = 560 m/s and τ_b = 7 μs. These are the recombination parameters of the non-passivated sample.

state diffusion equation (1) under boundary conditions (2) and (3). The minority carrier concentrations are plotted in Fig. 4 for blue and red illumination assuming a particular pair of values $S = 5.6\text{x } 10^3$ m/s and $\tau_b = 7$ μs. We will later show that these values are the actual recombination parameters of the non-passivated sample. The average carrier concentration is 10^{14} cm^{-3} and the base doping is $5 \text{ x } 10^{15}$ cm^{-3}. The wafer almost leaves the range of low injection.

For blue illumination the carrier density at the front surface is more than one order of magnitude higher than for red illumination. Under blue light the surface recombination rate

$$R_s = n(0)\, S_f + n(W)\, S_b \tag{9}$$

is 24 times larger than the bulk recombination rate

$$R_b = \int_0^W \frac{n(z)}{\tau_b} dz \tag{10}$$

In contrast, for red light illumination the surface recombination rate R_S is only 4 times higher than the bulk recombination rate R_b. The different weighting of bulk and surface recombination under blue and red illumination facilitates the determination of the recombination parameters.

Figure 5 shows hatched regions in the S-τ_b -space that are marked as blue and red. All points in the hatched regions yield the measured conductivity σ= 1.5 mS ± 0.15 mS under red and blue illumination, respectively. Equation (8) is used to calculate σ as a function of S and τ_b. Note that a *single* measurements yields already information on both, *S and* τ_b. The measurement using blue excitation light yields an upper limit $S < 10^3$ m/s and a lower limit $\tau_b > 0.25$ μs. In contrast, the measurement under red illumination gives no information on the surface recombination but a lower and an upper bound on τ_b is inferred. The information that we are able to deduce from a single measurement reflects the relative significance of surface and volume recombination under the respective illumination spectra.

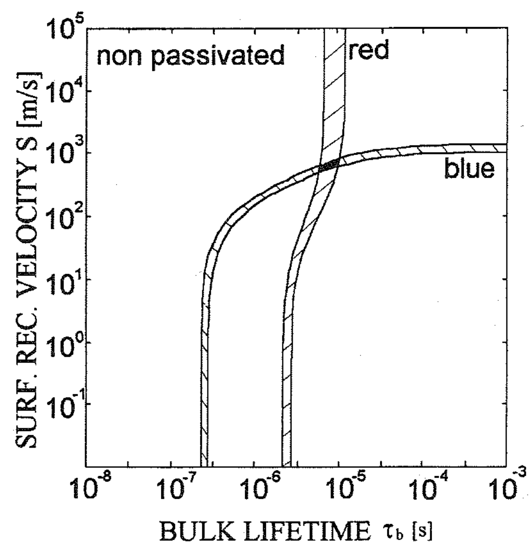

Figure 5: Conductivity σ-iso-lines in the S-τ_b-space for the non-passivated sample at a sheet conductivity of σ = 1.5 ·mS ± 0.15 mS.

Combining the two measurements, the region of intersection of the σ-iso-lines in the S-τ_b-space yields the actual surface recombination velocity S = (593 ± 167) m/s and the actual minority carrier bulk lifetime of τ_b = (7.7 ± 2.3) μs. The minority carrier profiles belonging to these parameters are shown in Figure 4. The lifetime τ_b = 7.7 μs is much shorter than the 2.5 μs-decay time of the flash light. This finding justifies the assumption of steady state conditions that underlies Eq. (1).

Figure 6 depicts the σ-iso-lines for the silicon nitride passivated sample. The conductivity value is again σ = 1.5 ·10^{-3} S. On the logarithmic sscale the intersection region is much wider in the S-direction than for the non-passivated sample. We are deduce a range range of S < 22 m/s for the recombination velocity. A recombination velocity S as small as 0.5 m/s that we expect from the excellent surface passivation [6] is also compatible with the measurement. The bulk life time we deduce for the passivated sample is τ_b = (5.4 ± 2.2) μs and yields the same value as the non-passivated sample within the measurement uncertainty.

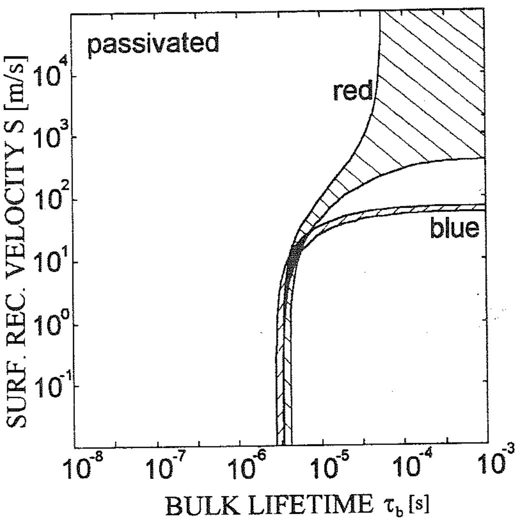

Figure 6: Conductivity σ-iso-lines in the S-τ_b-space for the nitride passivated sample at a sheet conductivity σ = 1.5 mS ± 0.15 mS.

5. CONCLUSIONS

An analytic approach for the evaluation of (quasi) steady state photoconductance measurements that accounts for the wavelength dependent optical properties of the Si wafer under test is presented. Our analysis technique extends the applicability of QSSPC-measurements to beyond the determination of effective lifetimes τ_{eff} and there by adds to the previous work on this technique [3,5,7].

We applied this model successfully to non-passivated and passivated Si wafers with a low-minority carrier lifetime. Using different illumination spectra we demonstrated that surface recombination velocity S and the bulk minority carrier lifetime τ_b are both determined without passivating the surfaces. This simplifies the sample processing necessary for lifetime measurements.

Our technique to determine the intersecting regions of iso-conductivity-lines in the S-τ_b-space yields a maximum of information with a minimum of apriori assumptions. A determination of S and τ_b is possible with good accuracy if the σ-iso-lines intersect close to normally. Whether this is the case or not depends on the recombination parameters and the illumination condition chosen. Therefore we do not expect that the lifetime of any wafer is measurable without surface passivation.

The price to pay for the decomposition of the effective lifetime τ_{eff} into its contributions from surface and volume recombination is extra experimental work on optical measurements. Our analysis should also be capable to handle textured wafers with light trapping because the model guarantees a total photogeneration than exactly corresponds to the measured absorption. The precise shape of the generation profile $g(z)$ is not modeled correctly. However, we expect this to be not critical for the analysis of QSSPC-measurements. Please note that the optical filters reduce the light intensity and thus limit the range of experimentally accessible injection levels.

We envisage several extensions of our analysis-technique. Samples having different front and back surface recombination velocities S_b and S_f could be analyzed performing a third measurement with blue-light shining on the back surface of the cell [4]. An extension to long lifetimes comparable to the decay time of the flash light [5] requires an analytical solution of the time-dependent diffusion equation that we discuss elsewhere [8].

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