Measurement of Differential and Actual Recombination Parameters on Crystalline Silicon Wafers

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Abstract—In this paper, for the first time, measurements of differential and actual recombination parameters on crystalline silicon wafers are directly compared. In order to determine the differential bulk lifetime and the differential surface recombination velocity (SRV), small-signal light-biased microwave-detected photoconductance decay (MW-PCD) and modulated free-carrier absorption (MFCA) measurements are performed. The results obtained by these widespread techniques are compared with quasi-steady-state photoconductance (QSSPC) measurements, which directly determine the actual recombination parameters. On high-resistivity (1000 Ω cm) float-zone (FZ) n-type silicon at high injection levels, it is shown that the differentially measured Auger lifetime is a factor of three smaller than the actual Auger lifetime. This finding is in excellent agreement with the theory derived in this work. Thermally oxidized low-resistivity (~1 Ω cm) p-Si wafers serve as an experimental vehicle to compare the differential and the actual injection-level dependent SRV of the Si-SiO₂ interface under low-injection conditions. Using two different integration procedures, the actual SRV is calculated from the differentially measured quantity. The actual SRV measured by the QSSPC technique is found to match perfectly the actual SRV obtained by integration.

Index Terms—Charge carrier lifetime, charge carrier processes, measurement, photovoltaic cells.

I. INTRODUCTION

The performance of crystalline silicon solar cells depends strongly on the electron-hole recombination in the bulk and at the surfaces of the cell. Consequently, experimental methods for an accurate determination of the recombination parameters, i.e., the bulk carrier lifetime and the surface recombination velocity (SRV), are of utmost importance in silicon solar cell research. During the last decade, a variety of different carrier lifetime measurement techniques have been successfully applied in photovoltaics. Most of these techniques share the advantage that only very simple test structures without electric contacts are needed. The large majority of these techniques use a time-dependent generation signal, which is usually pulsed or harmonically modulated. The dynamics of the excess carrier concentration within the sample is detected by means of microwave reflection [1], [2], infrared transmission [3], [4], or inductive/capacitive coupling to an rf circuit [5], [6]. As the recombination parameters generally exhibit a pronounced dependence on the excess carrier concentration within the silicon wafer, often a small-signal approach is used, i.e., a constant photogeneration is added to the much smaller time-dependent generation signal in order to adjust a defined injection level within the wafer. The injection level dependence of the SRV or the bulk carrier lifetime is then recorded by successively changing the constant part of the generation signal. Experimentally, this type of measurement is often realized by using a constant bias light source (e.g., a halogen lamp) in addition to a pulsed or modulated laser excitation. It has been recognized only very recently that the SRV’s [7] as well as the bulk carrier lifetimes [8] determined from such small-signal measurements are not the actual recombination parameters, but differential quantities. Different evaluation schemes have been proposed in order to calculate the actual from the differentially measured recombination parameters [9], [10]. However, up to now, no direct experimental comparison of recombination parameters determined by differential and actual measurement techniques has been performed.

In this paper, for the first time a direct comparison of differentially and absolutely measured recombination parameters is presented. The differential (i.e., small-signal) recombination parameters are determined by means of light-biased microwave-detected photoconductance decay (MW-PCD) and modulated free-carrier absorption (MFCA) measurements. The recently developed quasi-steady-state photoconductance (QSSPC) technique [11], [12] is used to measure the actual recombination parameters. The methods are applied to 1000-Ω cm n-Si in the high-injection regime and to thermally oxidized 0.7-Ω cm p-Si wafers under low-injection conditions in order to verify the theoretical predictions and the evaluation schemes for the calculation of the actual from the differentially measured recombination parameters.

II. THEORY

Since only parts of the theory concerning small-signal measurements of recombination parameters have been published so far [8], [9], this section starts with a comprehensive derivation of the theory. It should be realized that the problem is analogous to the small-signal analysis of semiconductor
devices. In both cases, a small excitation (an ac voltage or a time-dependent photogeneration) is superimposed to a steady-state magnitude (a dc voltage or a constant bias illumination). The mathematical derivation given below can, therefore, be understood as a generalization of the well-known small-signal analysis of semiconductor devices, where constant (i.e., not injection-level dependent) recombination parameters are assumed. The results are, for example, applicable to the small-signal admittance of a pn junction [13], requiring that the actual carrier lifetime is replaced by the differential lifetime.

Let us consider a homogeneously doped and nondegenerate silicon wafer with no external electric field. Furthermore, we assume charge neutrality within the bulk of the wafer (i.e., the excess electron concentration equals the excess hole concentration \( \Delta n = \Delta p \)) and that the diffusion constants as well as the bulk carrier lifetime are constant throughout the wafer. The sizes of the sample and the generation spot are assumed to be sufficiently large in order to allow a one-dimensional treatment of the problem. The starting point of our analysis is the ambipolar diffusion equation [14]

\[ \frac{\partial \Delta n}{\partial t} = D_a \frac{\partial^2 \Delta n}{\partial x^2} - U(\Delta n) + G(x, t) \]  
(1)

where \(U\) is the net recombination rate and \(G\) is the generation rate. The ambipolar diffusion coefficient \(D_a\) is given by the equation

\[ D_a = \frac{n + p}{n/D_p + p/D_n} \]  
(2)

where \(n\) and \(p\) are the electron and hole concentrations, respectively, and \(D_n\) and \(D_p\) are the electron and hole diffusion constants, respectively. In (1), the generation rate \(G(x)\) can be split into a steady-state part \(G_{ss}(x)\) due to the constant illumination of the sample and a dynamic part \(G_d(x, t)\) due to the time-dependent excitation signal

\[ G(x, t) = G_{ss}(x) + G_d(x, t) \]  
(3)

For each measurement, the dynamic part of the generation signal is adjusted to the steady-state part in order to assure that \(\Delta n = \Delta n_{ss}\) (small-signal condition). The excess carrier concentration \(\Delta n(x, t)\) can then be written as

\[ \Delta n(x, t) = n_{ss}(x) + n_d(x, t) \]  
(4)

where \(n_{ss}\) is the steady-state part and \(n_d\) is the dynamic part of \(\Delta n\), and \(n_d \ll n_{ss}\). Inserting (3) and (4) into (1) gives

\[ \frac{\partial n_d(x, t)}{\partial t} = D_a \frac{\partial^2 n_{ss}(x)}{\partial x^2} + D_a \frac{\partial^2 n_d(x, t)}{\partial x^2} - U(n_{ss} + n_d) + G_{ss}(x) + G_d(x, t) \]  
(5)

It should be noted that in the derivation of the small-signal bulk lifetime presented in [8], the generation terms were erroneously not included in the diffusion equation.

As can be seen from (2), in general, the ambipolar diffusion coefficient \(D_a\) depends also on the injection level \(\Delta n\). However, due to the fact that, in our special case, \(n_d\) is much smaller than \(n_{ss}\), \(D_a\) is constant during each small-signal measurement. Assuming, without loss of generality, a p-Si wafer with doping concentration \(N_A\), the ambipolar diffusion coefficient at a fixed injection level \(\Delta n \approx n_{ss}\) is given by the expression

\[ D_a = \frac{2n_{ss} + N_A}{n_{ss}(1/D_p + 1/D_n + N_A/D_n)} \]  
(6)

Let us now consider the case that the wafer is exclusively illuminated by the steady-state light source. In this case, the ambipolar diffusion equation becomes time-independent

\[ 0 = D_a \frac{\partial^2 n_{ss}(x)}{\partial x^2} - U(n_{ss}) + G_{ss}(x) \]  
(7)

Since in (5) \(n_d \ll n_{ss}\), the recombination rate \(U(n_{ss} + n_d)\) can be expanded into a Taylor series around \(n_{ss}\) and all terms of order higher than one can be neglected. Then, by subtracting (7) from (5), a differential equation for \(n_d(x, t)\) is obtained

\[ \frac{\partial n_d(x, t)}{\partial t} = D_a \frac{\partial^2 n_{ss}(x)}{\partial x^2} - \frac{\partial U}{\partial n_{ss}} \cdot n_{ss}(x) + G_d(x, t) \]  
(8)

To make (8) have the same form as the standard diffusion equation [14], which is used for the analysis of low-injection carrier lifetime measurements with constant recombination parameters [15], we define a differential bulk carrier lifetime

\[ \tau_{bd} = \frac{1}{\frac{\partial U}{\partial n} \cdot \Delta n} \]  
(9)

If the injection level dependence \(\tau_{bd}(\Delta n)\) is measured, the actual \(\tau\) at the excess carrier concentration \(n_{ss}\) can be calculated by

\[ \tau = n_{ss} \left( \int_{0}^{n_{ss}} \frac{1}{\tau_{bd}(\Delta n)} \ d\Delta n \right)^{-1} \]  
(10)

It should be emphasized that the only differences between (8) and the standard low-injection diffusion equation [15] are the meaning of the coefficients and that (8) is not limited to low-injection conditions. Hence, every solution of the standard low-injection diffusion equation is also valid for small-signal measurements at arbitrary injection levels if the actual bulk lifetime \(\tau = \Delta n/U(\Delta n)\) is substituted by the differential quantity \(\tau_{bd}\) defined in (9) and the minority-carrier diffusion constant \(D_n\) is replaced by the ambipolar diffusion coefficient \(D_a\) given by (6).

An important consequence of the above derivation is the fact that small-signal lifetime measurements always determine differential bulk lifetimes instead of actual ones. Only in the particular case of a constant bulk lifetime (i.e., if \(U\) increases proportionally with \(\Delta n\)), the measured \(\tau_{bd}\) equals the actual bulk lifetime \(\tau\). This situation commonly applies for low-injection conditions, although this should not be taken for granted in general. At high-injection conditions, the situation is completely different. In the case of crystalline silicon, at very high injection levels, carrier recombination is usually controlled by the Auger process. As the Auger recombination rate \(U_A\) is a cubic function of the excess carrier concentration \(\Delta n\)

\[ U_A = C_A \Delta n^3 \]  
(11)
where $C_A$ is the so-called ambipolar Auger coefficient, the differential Auger lifetime $\tau_{A,d}$ is given by the expression

$$\tau_{A,d} = \left[ \frac{\partial U_A}{\partial \Delta n} \right]^{-1} = \frac{1}{3C_A \Delta n^2}. \quad (12)$$

Hence, the theory derived above predicts that the Auger lifetime determined by small-signal measurements is a factor of three smaller than the actual Auger lifetime

$$\tau_A = \frac{\Delta n}{U_A} = \frac{1}{C_A \Delta n^2}. \quad (13)$$

The corresponding calculation for the radiative recombination process shows that the differential radiative lifetime is a factor of two smaller than the actual radiative lifetime [16].

In order to derive the boundary conditions for which (8) has to be solved, we assume, without loss of generality, that both surfaces of the silicon wafer are identically passivated. Often, the situation of a band bending toward the silicon surface occurs in practice. This is, for instance, the case for silicon-dioxide and silicon-nitride passivated silicon wafers due to a positive insulator charge density within the passivation layers. To account for this band bending, in the following we consider a virtual surface at the edge of the space charge region instead of the actual surface. Let the positions of the two virtual wafer surfaces be $x = -W/2$ and $x = +W/2$, where $W$ approximately equals the wafer thickness. Then, the so-called effective SRV $S_{\text{eff}}$ is defined as the quotient of the surface recombination rate per unit area $U_s$ and the excess carrier concentration at the virtual surface [17]. The boundary conditions of the ambipolar diffusion equation (1) are obtained by equating the diffusion current density flowing into the virtual surface with the surface recombination rate

$$\tau_{A,d} \frac{\partial \Delta n(x,t)}{\partial x} \bigg|_{x = \pm W/2} = U_s[\Delta n(\pm W/2,t)]. \quad (14)$$

Separating $\Delta n$ according to (4) gives

$$\tau_{A,d} \frac{\partial n_{ss}(x)}{\partial x} \bigg|_{x = \pm W/2} + \tau_{A,d} \frac{\partial \Delta n(x,t)}{\partial x} \bigg|_{x = \pm W/2} = U_s[n_{ss}(\pm W/2) + n_d(\pm W/2,t)]. \quad (15)$$

If the sample is exclusively illuminated by the steady-state light source, the boundary conditions reduce to

$$\tau_{A,d} \frac{\partial n_{ss}(x)}{\partial x} \bigg|_{x = \pm W/2} = U_s[n_{ss}(\pm W/2)]. \quad (16)$$

Expanding $U_s(n_{ss} + n_d)$ in (15) in a Taylor series around $n_{ss}$ and neglecting all terms of order higher than one leads, after subtracting (16), to the following boundary conditions for $n_d$:

$$\tau_{A,d} \frac{\partial n_d(x,t)}{\partial x} \bigg|_{x = \pm W/2} = \frac{\partial U_s}{\partial \Delta n} \bigg|_{n_{ss}} \cdot n_d(\pm W/2). \quad (17)$$

To make (17) have the same form as the boundary conditions of the low-injection standard theory [15], we define a differential effective SRV

$$S_{\text{eff,d}} \equiv \frac{\partial U_s(\Delta n)}{\partial \Delta n} \bigg|_{\Delta n = n_{ss}}. \quad (18)$$

Again, in the equations of the standard lifetime analysis, only the actual recombination parameter has to be substituted by the differential quantity and the minority-carrier diffusion constant has to be replaced by the ambipolar diffusion coefficient.

In general, for the evaluation of small-signal carrier lifetime measurements at arbitrary injection levels, the same equations can be used as for the standard low-injection lifetime analysis. The only prerequisite is that the following substitutions are made:

$$\tau_b \rightarrow \tau_{A,d}, \quad S_{\text{eff}} \rightarrow S_{\text{eff,d}}, \quad D_n \rightarrow D_a. \quad (19)$$

Integration of (18) gives the relation between the differential and the actual effective SRV

$$S_{\text{eff}}(n_{ss}) = \frac{U_s(n_{ss})}{n_{ss}} = \frac{1}{n_{ss}} \int_{0}^{n_{ss}} S_{\text{eff,d}}(\Delta n) \, d\Delta n. \quad (20)$$

Hence, if the injection level dependence $S_{\text{eff,d}}(\Delta n)$ is measured, the actual $S_{\text{eff}}$ at a bias-light generated excess carrier concentration $n_{ss}$ can be calculated by means of (20). However, since usually $S_{\text{eff,d}}$ is measured as a function of the incident power density $P$ of the bias light and the calculated excess carrier concentration at a fixed bias light intensity depends on the actual $S_{\text{eff}}$, a time-consuming iterative integration procedure has to be used for the calculation of the injection level dependence of $S_{\text{eff}}$ [9].

A simplified approximate evaluation scheme was recently proposed by Schuurmans et al. [10]. They took advantage of the fact that for sufficiently small effective SRV’s, the measured effective carrier lifetime $1/\tau_{\text{eff}}$ is given by

$$\frac{1}{\tau_{\text{eff}}} = \frac{1}{\tau_b} + \frac{2S_{\text{eff,d}}}{W} \cdot \frac{1}{\tau_{A,d}}. \quad (21)$$

For small-signal carrier lifetime measurements, $\tau_b$ and $S_{\text{eff}}$ in (21) have to be replaced by $\tau_{A,d}$ and $S_{\text{eff,d}}$, respectively, and the resulting effective lifetime can also be interpreted as a differential quantity $S_{\text{eff,d}}$:

$$\frac{1}{\tau_{\text{eff,d}}} = \frac{1}{\tau_{A,d}} + \frac{2S_{\text{eff,d}}}{W} \cdot \frac{\partial U_{\text{tot}}}{\partial \Delta n} \quad (22)$$

where $U_{\text{tot}} \equiv U + 2U_s/W$ is the total net recombination rate of the silicon wafer, including bulk as well as surface recombination. Assuming a homogeneous injection profile throughout the wafer, under steady-state conditions the total recombination rate equals the generation rate ($U_{\text{tot}} = G$) and the expression $G = \Delta n/\tau_{\text{eff}}$ holds. Furthermore, the generation rate is directly proportional to the incident power density of the bias light $G = cP$, where $c$ is a constant determined by the optical properties of the wafer. Substitution of $U_{\text{tot}}$ in (22) by $G = cP$ gives

$$\tau_{\text{eff,d}} = \frac{1}{c} \frac{\partial \Delta n}{\partial P}. \quad (23)$$

Integration of (23) over $P$ and division by $G = cP$ gives the actual effective lifetime

$$\tau_{\text{eff}} = \frac{1}{P} \int_{0}^{P} \tau_{\text{eff,d}}(p) \, dp. \quad (24)$$

Hence, the measured differential quantity $\tau_{\text{eff,d}}$ can be integrated directly over the incident power density $P$ in order to
Subsequently, the injection level \( \Delta n \) can be calculated using the expression \( \Delta n = G \tau_{\text{eff}} \). For obvious reasons, the evaluation method developed by Schuurmans et al. [10] is much simpler than the iterative method proposed by Aberle et al. [9]. However, it should be kept in mind that the simplified evaluation scheme is only an approximate method, which is valid for sufficiently small SRV’s and homogeneous injection profiles, whereas the iterative integration procedure discussed above is more accurate. Up to now, the systematic error caused by the simplified evaluation method has only been analyzed theoretically [10]. In Section IV of this work, for the first time, an experimental investigation of this new evaluation scheme is performed.

III. MEASUREMENT DETAILS

A. Microwave-Detected Photoconductance Decay

Light-biased MW-PCD measurements were performed using a modified Phoenicon MRM system. In this system, the sample is illuminated by 100-ns light pulses from a 904-nm GaAs laser diode (20 pulses/s), increasing the wafer conductance. After termination of each laser pulse, the excess carriers recombine within the bulk and at both surfaces of the wafer and the conductance decays to its initial value. The decay of the photoconductance is recorded by time-resolved measurements of the microwave power (microwave frequency 22 GHz) reflected from the silicon wafer under test. The effective carrier lifetime is determined by a mono-exponential fit \( \sim \exp(-t/\tau_{\text{eff}}) \) to the asymptotic photoconductance decay. In order to adjust a defined injection level within the wafer, in addition to the laser pulses the sample is illuminated by a constant bias light from a halogen lamp. The bias light intensity is varied by means of a combination of different neutral density filters. At each bias light level the laser pulse energy is adjusted to ensure that the laser-induced excess carrier concentration is small compared to the injection level generated by the steady-state illumination \( n_{\text{ld}} \ll n_{\text{ss}} \). For technical details of the measurement system, the interested reader is referred to [8] and [16].

B. Modulated Free-Carrier Absorption

For the MFCA technique the generation signal is harmonically modulated and the phase shift \( \phi \) between the excess carrier concentration and the generation light is measured by means of lock-in technique. The excess carrier concentration is probed by an infrared laser, having a photon energy well below the bandgap of silicon. Hence, the photons are absorbed via intraband transitions of free carriers and the absorption of the infrared light is directly proportional to the total number of excess carriers in the probed volume. The measured quantity is the transmitted intensity of the sub-bandgap infrared light. As has been shown by Glunz [18], for sufficiently small angular modulation frequencies \( \omega \ll 1/\tau_{\text{eff}} \) the effective carrier lifetime can simply be calculated from the measured phase shift using the expression

\[
\tau_{\text{eff}} = \frac{\tan \phi}{\omega}.
\]

The MFCA measurements presented in this work were performed using an MFCA system designed and built at the Netherlands Energy Research Foundation ECN [19]. The system uses an 848-nm cw laser diode as generation source and a 1.55-\( \mu \)m infrared laser for the detection of the excess carriers. The generation light is made up of a constant part and a sinusoidal signal. In order to measure at a defined injection level, the amplitude of the sinusoidal part is fixed at a level of 10% of the constant part of the generation signal \( (G_{\text{ld}} \ll G_{\text{ss}}) \). The steady-state light intensity is varied, as in the case of the MW-PCD measurements, by means of neutral density filters. A detailed description of the system and the technique is given in the literature [19], [20].

It should be noted that while the MW-PCD technique is very sensitive at relatively low injection levels (\( \sim 10^{14} \sim 10^{15} \text{ cm}^{-3} \)), the MFCA technique is well suited for measurements at higher excess carrier concentrations (\( \sim 10^{14} \sim 10^{17} \text{ cm}^{-3} \)). In a recent comparison of both measurement techniques [21], an excellent agreement between light-biased MW-PCD and MFCA measurements on oxidized silicon wafers was found in the overlapping injection range of both methods (\( 10^{14} \sim 10^{15} \text{ cm}^{-3} \)).

C. Quasi-Steady-State Photoconductance

The actual recombination parameters were measured by the recently developed QSSPC technique, using a commercially available system (Sinton Consulting, WCT100) [11], [12]. In this system, the silicon wafer is illuminated by a flash lamp. The decay time constant of the flash is adjusted to its maximum value (\( \sim 2 \text{ ms} \)), ensuring that for sufficiently small carrier lifetimes \( \tau_{\text{eff}} < 200 \text{ ms} \) the sample is virtually measured under steady-state conditions at every point in time during the decay of the flash. The photoconductance of the silicon wafer is measured by inductive coupling to a calibrated rf circuit and the time-dependent output signal of the circuit is recorded by an oscilloscope. Assuming a spatially uniform injection profile throughout the wafer, the excess carrier concentration \( \Delta n \) can be calculated from the photoconductance signal. It is important to note that, for this calculation, a proper mobility model has to be used, taking the decrease of the electron and hole mobilities with increasing injection level due to carrier-carrier scattering into account. In this study, we used the slightly modified mobility model of Pang and Rohatgi [22]. Simultaneously with the wafer photoconductance, the light intensity of the flash is measured with a calibrated silicon concentrator solar cell and the time-dependent signal is recorded on the second channel of the oscilloscope. From the latter measurement, the generation rate \( G \) is calculated using the measured optical reflectance of the wafer. The effective lifetime is then usually determined from the steady-state expression \( \tau_{\text{eff}} = \Delta n/G \). However, in order to determine effective lifetimes also above a value of \( \sim 200 \text{ ms} \), in this study we used a modified data analysis. As has been shown by Nagel et al. [23], for the measurement of large carrier lifetimes the universal equation

\[
\tau_{\text{eff}} = \frac{\Delta n}{G - \frac{d\Delta n}{dt}}
\]
IV. EXPERIMENTAL RESULTS AND DISCUSSION

A. Bulk Lifetime

In order to experimentally verify the theoretical result derived in Section II concerning the difference between the actual and the differentially measured Auger lifetime by a factor of three, injection-level dependent MFCA as well as QSSPC measurements were performed on nearly intrinsic 1000-Ωcm FZ n-type silicon in the injection range 10^{16} \text{–} 10^{17} \text{ cm}^{-3}. Both wafer surfaces were passivated by silicon nitride films deposited at 400 °C in a remote plasma reactor. This type of film has demonstrated an outstanding surface passivation quality on crystalline silicon surfaces [8], [25], [26] with effective SRV’s < 10 cm/s. However, since up to now the surface passivation quality of remote-plasma silicon nitride passivated high-resistivity n-Si wafers has not been investigated in the injection range 10^{16} \text{–} 10^{17} \text{ cm}^{-3}, the surface passivation quality was checked in the investigated injection range by depositing positive corona charges on top of the silicon nitride films. These charges strongly enhance the field effect passivation at the surface, reducing the effective SRV to extremely low values <1 cm/s [27]. As no change of the measured carrier lifetime was observed with increasing surface charge density, it can be concluded that the measured lifetimes are dominated by bulk recombination.

Fig. 1 shows the carrier lifetimes measured by the QSSPC (open circles) and the small-signal MFCA (closed circles) technique in dependence on the excess carrier concentration. In the case of the MFCA measurement, the excess carrier concentration was iteratively calculated using the device simulation program PC1D [28], assuming a SRV of zero at both surfaces of the wafer. For the first approximation of the excess carrier concentration, the measured differential lifetime was used as bulk lifetime. Then, using (10), the first approximation of the actual bulk lifetime was calculated, which was subsequently used for the second approximation of the injection level, and so on. After the third iteration, no changes, neither in the bulk lifetime nor in the calculated injection level, were observed.

As can be seen from Fig. 1, for injection levels above $5 \times 10^{16} \text{ cm}^{-3}$, the carrier lifetime is dominated by Auger recombination. This is indicated by the inverse quadratic dependence of the measured lifetime on the excess carrier concentration. The solid line in Fig. 1 shows a fit of the theoretical dependence of the Auger lifetime $(\gamma \Delta n^2)^{-1}$ to the QSSPC measurement, and the dashed line a fit to the MFCA measurement for $\Delta n > 5 \times 10^{10} \text{ cm}^{-3}$, with $\gamma_1 = 1.17 \times 10^{-30} \text{ cm}^6 \text{s}^{-1}$ and $\gamma_2 = 3.58 \times 10^{-30} \text{ cm}^6 \text{s}^{-1}$. Since the QSSPC measurement is expected to give the actual Auger lifetime, $\gamma_1$ should equal the ambipolar Auger coefficient $C_\alpha$. In fact, the $\gamma_1$ value determined from the fit in Fig. 1 agrees very well with the $C_\alpha$ values reported in the literature for lowly doped silicon in the injection range $10^{16} \text{–} 10^{17} \text{ cm}^{-3}$. The most reliable $C_\alpha$ values determined in the literature lie in the $1 \text{–} 2 \times 10^{-30} \text{ cm}^6 \text{s}^{-1}$ range [22], [29], [30].

As theoretically shown in Section II, the small-signal MFCA technique measures a differential Auger lifetime, which is expected to be a factor of three smaller than the actual Auger lifetime. The experimental finding that the $\gamma_2$ value of the dashed fit in Fig. 1 is a factor of 3.06 greater than $\gamma_1$ is in perfect agreement with this prediction. This result is a good verification of the theory of differential recombination parameters derived above.

It is also remarkable that with decreasing injection level the carrier lifetimes measured by the QSSPC and the MFCA technique approach. This behavior is due to the fact that, for injection levels below $\sim 10^{16} \text{ cm}^{-3}$, the measured lifetimes in Fig. 1 saturate, and for constant, i.e., not injection-level dependent lifetimes, the differential equals the actual lifetime.

It should be noted that, for the QSSPC measurement, only one of five data points is displayed in Fig. 1. In order to demonstrate the excellent accuracy of the fits, Fig. 2 shows a linear plot including all data points of the MFCA as well as the QSSPC measurements above an injection level of $5 \times 10^{16} \text{ cm}^{-3}$. This plot nicely demonstrates the enormous difference between the actual and the differentially measured Auger lifetime.
In order to demonstrate the high degree of accuracy of the fits, in contrast to Fig. 1, all data points are shown.

B. Surface Recombination Velocity

As it is well known from the literature [17], [31], [32], the effective SRV of thermally oxidized silicon surfaces, measured under low-injection conditions, depends strongly on the injection level in the bulk of the material. This behavior is due to the bending of the energy bands in the silicon toward the Si-SiO₂ interface, caused by a positive charge density within the SiO₂ layer. As a consequence of this injection level dependence, the differential and the actual SRV of thermally oxidized silicon surfaces are expected to differ [7], [9]. In order to experimentally verify this theoretical prediction, a 320-μm thick FZ p-Si wafer with a typical solar cell doping concentration of 2 × 10^{16} cm⁻³ was used. The RCA-cleaned wafer was oxidized in an oxygen ambient at 1050 °C and subsequently annealed in forming gas at 450 °C for 30 min. The effective SRV was calculated from the measured effective lifetime by (21). For the bulk lifetime, a value of 520 μs was used. This value was determined by the method described in [8].

Fig. 3 shows the effective SRV as a function of the injection level within the silicon wafer. The results are obtained from QSSPC (open circles) and from light-biased MW-PCD measurements (closed circles), respectively. The dashed line is a polynomial fit to the differential effective SRV \( S_{\text{eff}} \) measured by the MW-PCD technique, while the solid line shows the actual \( S_{\text{eff}} \) as calculated from \( S_{\text{eff,ld}} \) by (20). The excess carrier concentration \( \Delta n \) is calculated using the device simulation program PC1D [28]. Since \( \Delta n \) depends on the incident power density as well as on the actual \( S_{\text{eff}} \), an iterative integration procedure very similar to that described in Section IV.A was used [9].

As can be seen from Fig. 3, the typical \( S_{\text{eff}}(\Delta n) \) dependence of oxidized p-Si wafers with resistivity close to 1 Ωcm is observed: at very low injection levels (<10^{23} cm⁻³) the effective SRV saturates, while with increasing excess carrier concentration, \( S_{\text{eff}} \) decreases. This behavior is well known from the literature [17], [21], [31], [32], and has been theoretically explained by means of the extended Shockley–Read–Hall model [17], [33]. It should be noted that only the saturation of \( S_{\text{eff,ld}}(\Delta n) \) at very low injection levels makes it possible to calculate \( S_{\text{eff}}(\Delta n) \) correctly by means of (20). The most important result of Fig. 3 is the outstanding agreement of the actual SRV calculated from the small-signal MW-PCD measurement with the set of \( S_{\text{eff}} \) data directly determined by the quasi-steady-state photoconductance technique in the overlapping injection range. This result also underlines the accuracy of both measurement techniques if they are properly applied. As can also be seen from Fig. 3, the injection range of both methods is very different. While the MW-PCD technique is well suited for very low injection levels between 10^{11} and 10^{15} cm⁻³, the QSSPC system used in this work gives reliable lifetime measurements in the excess carrier concentration range between about 10^{14} and 10^{17} cm⁻³.

Fig. 4 shows the effective carrier lifetimes measured by the MW-PCD and the QSSPC method as a function of the incident power density. The closed circles are obtained from light-biased MW-PCD measurements, while the open circles are measured by the QSSPC technique. The dashed line is a polynomial fit to the differentially measured effective lifetime. The solid line shows the actual effective lifetime as calculated from the dashed line using the simplified evaluation method proposed by Schuurmans et al. [10].
simplified evaluation scheme proposed by Schuurmans et al. [10] using (24). Again, a nearly perfect agreement between the actual effective lifetimes calculated by integration from $T_{\text{eff},d}$ and the effective lifetimes directly measured by the QSSPC technique is found. This result agrees also very well with the theoretical prediction of Schuurmans et al. [10] that the error of their simplified approximate evaluation scheme is well below 10% for $S_{\text{eff}}$ values $<10^8$ cm/s. For the oxidized sample investigated in this study, the largest deviation between the actual SRV calculated by the accurate and the simplified evaluation scheme, respectively, is only 0.8%.

V. CONCLUSION

Small-signal carrier lifetime measurement techniques determine differential recombination parameters instead of actual ones. In the past, this fact was overlooked by many researchers [17], [31], [32]. However, the difference between differential and actual bulk lifetime or SRV can be very large as has been recently recognized on the basis of theoretical considerations [7]–[9]. In this work, experimental evidence is presented that these differences can in fact be observed when comparing the results of differential and actual carrier lifetime measurement techniques.

On a nearly intrinsic silicon wafer in the injection range $5 \times 10^{16}$–$10^{17}$ cm$^{-3}$, it was shown that the measured differential Auger lifetime determined by small-signal modulated free-carrier absorption is a factor of three smaller than the actual Auger lifetime, which was determined by means of quasi-steady-state photoconductance measurements. This experimental result agrees perfectly with the theory derived in Section II of this work.

A thermally oxidized p-Si wafer with a doping concentration of $2 \times 10^{16}$ cm$^{-3}$ was used in order to compare the actual with the differentially measured effective SRV of the Si-SiO$_2$ interface on typical solar cell material. As differential measurement method, the light-biased microwave-detected photoconductance decay technique was used. From the measured differential effective SRV, using two different integration procedures, the actual quantity was calculated. This quantity showed a nearly perfect agreement with the actual effective SRV directly measured by the quasi-steady-state photoconductance technique in the overlapping injection range of both methods. A maximum deviation of 40% between the measured $S_{\text{eff}}$ and $S_{\text{eff}}$ values was observed on the investigated wafer.

The correct determination of solar cell recombination parameters is an essential prerequisite for a fundamental understanding of these devices. The experimental results obtained in this work underline the importance of a profound understanding of the measurement technique used and show that false conclusions concerning the cell physics can be drawn if it is not properly distinguished between differential and actual carrier lifetime measurement techniques. In practice, two fundamentally different situations can occur, where differential and actual recombination parameters differ. In the first case, the measured carrier lifetime decreases with increasing injection level and the effective lifetime of a sample is underestimated if it is not distinguished between differential and actual measurement. The second situation applies if the effective lifetime increases with increasing excess carrier concentration. In this case, the lifetime is overestimated if the measurement is not correctly interpreted. Only in the rare case of a not injection-level dependent effective carrier lifetime, the differentially measured lifetime equals the actual lifetime.

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