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Improving Transient Photoconductance Lifetime Measurements on Ingots with Deeper Photogeneration

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Abstract. Transient PhotoConductance Decay (PCD) measurements on silicon ingots and blocks with different photogeneration profiles are simulated in this work. The results show that a deeper generation profile, achieved by using long-pass optical filters with longer cut off wavelengths, can improve the accuracy of the transient lifetime measurements by approximately 10% in the lifetime range above 150 μs under typical measurement conditions. This improvement is due to reduced recombination at the unpassivated surface as the carrier density profiles peak is moved deeper into the bulk. The simulation results are confirmed by comparison with experimental lifetime measurements using three different optical filters on a monocrystalline silicon block.

INTRODUCTION

The carrier lifetime is one of the key parameters for the performance of silicon solar cells and is invaluable for process control. The transient PhotoConductance Decay (PCD) and Quasi-Steady State PhotoConductance (QSSPC) techniques are widely used for bulk lifetime measurements on silicon wafers and ingots [1]. The effective lifetime itself is a critical factor in the choice of which lifetime measurement technique to apply [2, 3]. Transient PhotoConductance decay is difficult to use, in practice, in samples with low carrier lifetimes as the illumination source decay time is typically not fast enough to measure lifetimes below 100 μs. On the other hand, the steady-state assumption is less valid in the higher range of lifetime when using typical flash decay times, and so transient decay lifetime measurements are preferable techniques for silicon blocks with high minority carrier lifetimes [4]. In addition, for measurements on ingots or blocks, transient measurements are less prone to the effect of the high Surface Recombination Velocity (SRV) associated with the unpassivated surface, provided that the initial surface-dominated component is allowed to decay [3, 5].

Schuler et al. [6] demonstrated the improved accuracy of lifetime measurements by using a deeper generation profile in MDP (Microwave Detected PhotoConductance) as a method with steady state photogeneration, in comparison with μPCD (microwave detected PhotoConductance Decay) as a method with transient photogeneration, on thick silicon samples. Several studies (for example Mitchell et al. in [7-9], and [4, 10, 11] ) have also demonstrated the accuracy of PhotoLuminescence (PL) techniques for lifetime measurements on silicon blocks, such as PL Intensity Ratio (PLIR) methods, in which the ratio of PL intensities at two different detection wavelength ranges is used to determine the lifetime. More recently, Chung et al. [12], have demonstrated a PLIR technique in which two different excitation wavelengths of 915 and 1064nm are used to generate different carrier profiles with deep generation.

In this work, transient PCD lifetime measurements in silicon blocks are modeled, with an emphasis on the impact of deeper photo-generation profiles. A modeling tool is used to simulate PCD measurements performed using a "BCT-400" measurement system from Sinton Instruments. The impact of shifting the generation profile peak deeper in the sample, by using longer cut-off wavelength long-pass filters in front of the flash, is explored. The simulation results are confirmed by measurement on a Cz p-type monocrystalline silicon block using a BCT-400 tool with three different optical filters.
MODELING AND SIMULATION

For the transient mode simulations, the first stage is a QSS simulation, in order to build up the initial carrier concentration before the flash is terminated and the transient decay commences.

As explained in detail in [13, 14], the sample thickness was divided into intervals \( \Delta x \) small enough to ensure the electron current across the \( \Delta x \) thickness can be considered constant. Then, numerical analysis involves equating the total generation and total recombination rates of excess minority carriers across the sample thickness (W) as well as numerically solving the continuity equation in each element (\( \Delta x \) thick), including the diffusion of carriers into and out of the elements:

\[
-J_n(x + \Delta x) = -J_n(x) + qG(x)\Delta x - qU(x)\Delta x
\]  

(1)

where \( J_n \) is the electron current density (assuming p-type material) and \( G \) and \( U \) are the generation and the recombination rates respectively. Rearranging (1) results in [13]:

\[
\Delta n(x + \Delta x) = \Delta n(x) + \frac{J_n(x)}{q \text{Deff}} \Delta x - \frac{1}{q \text{Deff} \text{Neff}} n \text{Di} \Delta x
\]  

(2)

In which \( \Delta n(x) \) is the excess carrier density at the depth of \( x \), \( \text{Deff} \) is the effective diffusivity and \( \text{Di} \) and \( \text{Dp} \) are electron and hole diffusivities. As there is no output current in ingot measurements, \( J = 0 \), the last element of (2) is eliminated in the calculations. For the boundary condition at the surface (at \( x = 0 \)), we have:

\[
J_n(0) = \left[ \frac{\Delta n(0) \text{Neff}^2}{\Delta n(0) \text{Neff} \Delta n(0)} \right] \text{SRV}
\]  

(3)

where \( J_n(0) \) and \( \Delta n(0) \) are the current density and the excess carrier density at the surface, respectively. \( \text{Neff} \) is the sample doping and \( \text{SRV} \) is the surface recombination velocity which is assumed to be \( 10^6 \text{ cms}^{-1} \) in all simulations presented in this paper.

The \( \Delta n_{\text{avg}}(t) \) (weighted average minority carrier density, \( \Delta n_{\text{avg}} \) and other parameters as explained in detail in [15] and [14]) at time \( t \) elapsed after terminating the light source, with the transient lifetime \( \tau_{\text{transient}} \) calculated from the slope of the average excess carrier density decay. This can be expressed with the continuity equation as [16]:

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

(4)

where \( G \) and \( U \) are the generation and the recombination rates respectively, and the last term is a diffusion term caused by non-uniform carrier densities. Equation (4) is numerically solved for the QSS mode (when \( \frac{\Delta n(t)}{dt} = 0 \)) as explained above and in detail in [14]. Then the light source is terminated at \( t = 0 \) and the transient mode (when \( G(t) = 0 \)) is simulated after that. The simulations were based on a finite elements approach, with the depth and time intervals \( \Delta x \) and \( \Delta t \) chosen to be small enough to ensure the local changes in the excess carrier density are approximately linear in \( x \) and \( t \). The excess carrier density within a depth interval constantly changes over time (\( \frac{\Delta n(t)}{dt} \neq 0 \)) as there is no photogeneration. This means the excess carrier density within an element \( \Delta x \) varies not only due to recombination but also because of a diffusion current to and from the adjacent depth intervals.

Therefore, \( \Delta t \) must be chosen to be very small in comparison with the lifetime to ensure the change due to recombination is insignificant within the time interval (on the order of 10 ns) while the diffusion current element is calculated. In practice \( \tau_{\text{transient}} \) is limited by surface recombination and Shockley–Read–Hall (SRH) recombination centers in the bulk, in addition to intrinsic recombination due to Auger and radiative recombination [17]:

\[
\frac{1}{\tau_{\text{transient}}} = \frac{1}{\tau_{\text{Auger}}} + \frac{1}{\tau_{\text{rad}}} + \frac{1}{\tau_{\text{SRH–bulk}}} + \frac{1}{\tau_{\text{surface}}}
\]  

or

\[
\frac{1}{\tau_{\text{transient}}} = \frac{1}{\tau_{\text{bulk}}} + \frac{1}{\tau_{\text{surface}}}
\]

(5)
As a Sinton Instruments BCT-400 tool is used in this work, the assumptions for the light source and the filter transmission in the simulations are adapted from the tool setup. In this case we assume a pre-filter peak photon flux of 1.27×10^{21} \text{ cm}^{-2}\text{s}^{-1}, equivalent to 5500 suns intensity, which is a typical peak intensity for the X5dR Q-flash from Quantum Instruments used in a Sinton Instruments BCT-400 tool. Inserting a standard 1000-nm IR-Pass Schott glass RG1000 filter in place, further reduces the on-sample photon flux to 2.3×10^{20} \text{ cm}^{-2}\text{s}^{-1}. The xenon flash spectrum and the measured transmission function for the standard RG1000 filter are shown in yellow and black lines respectively in FIGURE 1.

Figure 2.a) shows the excess carrier density profiles as a function of depth at various elapsed times after turning the light source off. The results are for a case of p-type silicon with a bulk lifetime of 300 \mu s. Note that the peak of the excess carrier density profiles moves deeper into the bulk as a function of time. Therefore, the effect of the high SRV of an as-cut unpassivated surface on the calculated lifetime is reduced and, consequently, \( \tau_{\text{transient}} \) will become closer to \( \tau_{\text{bulk}} \).

It should be noted here that all simulated lifetimes in this paper are calculated with the coil depth sensitivity function taken into the account for the excess carrier density that is sensed by the tool:
\[
\Delta n_{sensed}(x) = \Delta n(x) \times \exp \left( \frac{-x}{0.25} \right)
\]  
(6)

which is described in detail in [14, 18]. This is to enable simulations under realistic measurement conditions, thereby allowing comparison with measured lifetimes.

Figure 1.b) illustrates the continuous decay of the weighted average minority carrier density, \( \Delta n_{avg} \), over time after the light source was terminated for different bulk lifetimes (\( \tau_{bulk} \)). The simulated transient lifetime at any specific injection level is then determined by the slope of the minority carrier profiles [19]:

\[
\tau_{Transient} = \frac{\Delta n_{avg}}{\Delta n} 
\]

(7)

Simulations were also performed using optical filters with longer wavelengths to obtain deeper photogeneration. Two high-performance OD 4 long-pass filters from Edmund Optics with a sharp cut-off wavelength at 1050 nm (EO-1050) and 1100 nm (EO-1100) respectively are used to generate such deep photogenerations. Figure 1 shows the measured transmission function for these two filters and the standard RG1000 filter, along with the xenon flash spectrum. The longer and very sharp cut-off wavelengths of the EO filters move the carrier density profile peak deeper in the bulk. Figure 3 presents the tool reference cell QE and the filtered spectra for the three filters which hit the sample surface. As can be seen, the total photon flux will be reduced as the filters cut-off wavelength increases. This means that, in practice, there is a trade-off between achieving a deeper generation profile and maintaining a sufficiently large generation rate, or excess carrier density.

Due to the lower QE (dashed line in Fig.3) of the reference cell at longer wavelengths, the detected light intensity displayed by the tool will be less than the real intensity of the light which hits the sample surface. Hence, the mismatch factors for the reference cell QE at each wavelength applied to simulate the actual photon flux that hits the sample.

Figure 4 shows the initial excess carrier densities (solid lines) and photogeneration (dashed lines) profiles in a p-type silicon block created by the RG1000, EO1050 and EO1100 filters generated with a light source with the peak equivalent of 5500 suns. These carrier profiles are the steady-state profiles generated during the initial flash, before the flash is terminated and the transient decay is commenced. The carrier density profiles peak for each filter are displayed by an arrow. It can be clearly seen that the profile peak moves deeper inside the bulk by increasing the filter cut-off wavelength [6].

Figure 5 shows the subsequent simulated transient lifetimes calculated as a function of injection level after the flash is terminated. This simulates a typical transient PCD measurement. The reported transient lifetime is shown for \( \tau_{bulk} = 150, 300 \) and 500 \( \mu \)s for comparison.

![FIGURE 3. Filtered light spectrum with 3 filters and reference cell QE as functions of wavelength. The total light intensity is reduced as the cut-off wavelength increases.](#)
The improvement in the accuracy of the reported transient lifetime is approximately 10% when the longer cut-off wavelength filters are used. The excess carrier density profiles during the transient decay for the three filters are shown in Fig. 6 when $\Delta n_{avg}$ decayed from their initial values in Fig. 3 to $10^{15}$ cm$^{-3}$ for a bulk lifetime of 300 microseconds. As can be observed, the carrier profiles from the three filters are still noticeably different, including the profile peak position, leading to the more accurate reported lifetimes for the longer cut-off filters, despite the significant time elapsed after flash termination.

**FIGURE 4.** Generation (dashed lines) and excess carrier density (solid lines) profiles at $t = 0$ under steady-state conditions when the pre-filtered photon flux = $1.27 \times 10^{21}$ cm$^{-2}$s$^{-1}$ (generating different initial injection levels as labeled) as functions of sample depth for the three different filters.

**FIGURE 5.** Simulated transient lifetime as functions of injection levels for three different filters for bulk lifetime of 150, 300 and 500 $\mu$s.

**EXPERIMENTAL RESULTS AND DISCUSSION**

Three sets of transient measurements on a Cz block were performed with a BCT-400 measurement system from Sinton Instruments in transient mode with a RG1000 filter and the EO 1050 and EO 1100 filters respectively. The sample was a rectangular block cut from a standard industrial Cz p-type monocrystalline silicon ingot, with a square base of 156x156 mm and a height of 320 mm. Initially, transient lifetime measurements were performed at one fixed point on the block with different filters to compare the lifetime as a function of injection level for the three filters.
The measurement results are shown in Fig. 7 revealing that the filters which create deeper generation profiles result in higher $\tau_{\text{transient}}$ values at any specific $\Delta n_{\text{avg}}$.

The next step was to measure $\tau_{\text{transient}}$ along the sample with the different filters and compare the values. This is shown in Fig. 8 for 24 points on one side of the block, starting at 10 mm from the bottom up to 10 mm from the top with a 13 mm (the sensor width) gap between each point.

The measurement results show around 7% and 9% higher reported lifetimes at $\Delta n_{\text{avg}} = 10^{15}$ cm$^{-3}$ along the block when the EO-1050 and EO-1100 filters are used respectively, compared to the RG1000 filter.

This shows that the number of photons with long wavelengths in the photon flux is more important than the flux intensity. As shown in Fig. 3), although the RG1000 passes a much higher light intensity, the attenuation of the photons with wavelengths longer than 1100 nm causes a shallower generation peak close to the surface and subsequently lower reported lifetime.
CONCLUSIONS

Transient PhotoConductance decay lifetime measurements on silicon ingots are simulated in this paper. The accuracy of the results depends on the time elapsed after the light source is terminated due to the reducing impact of the high SRV as the carrier density profile peak moves deeper into the bulk. Different optical filters are used to create deeper photogeneration, resulting in increased measurement accuracy of around 10% in the lifetime range from 150-500 μs, as confirmed with measurements on a p-type Cz monocrystalline silicon block.

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REFERENCES