A comparison between quasi-steady state and transient photoconductance lifetimes in silicon ingots: simulations and measurements

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Abstract — We present and compare numerical simulations and experimental data for Quasi-Steady State (QSS) and transient photoconductance lifetime measurements on silicon ingots. The simulation results show that the QSS method is generally more accurate for lifetimes below 150 μs, whereas transient measurements are more accurate above this value. However, transient measurements require sufficient time to have elapsed after the flash is terminated, to ensure that the impact of the unpassivated ingot surface is reduced. The results also show that the surface recombination velocity has a slightly reduced impact on n-type material in comparison with p-type material, due to the reduced minority carrier mobility. The simulation results are also compared with measured QSS and transient lifetimes on a standard p-type monocrystalline block.

Index Terms — Carrier lifetime, QSSPC, Silicon ingot, Surface recombination, Transient lifetime.

I. 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 have been developed and are widely used for bulk lifetime measurements on silicon wafers and ingots [1]. However, the effective lifetimes measured on ingots with the QSS and transient methods may differ noticeably, depending on the carrier lifetime itself [2]. To investigate the reasons behind this discrepancy, we simulate the carrier dynamics of the QSS and the transient modes for both p-type and n-type ingot measurements. The p-type simulation results are compared to measurements with a BCT-400 boule tester from Sinton Instruments on a monocrystalline p-type Cz-grown silicon block.

II. SIMULATION AND EXPERIMENT DETAILS

The QSS and the transient modes are simulated in this work to compare the results measured by the two methods when applied to ingots. In both cases, the simulation of the excess carrier profiles is based on the continuity equation [3]:

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

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. The excess carrier density \( \Delta n(x, t) \) is then a function of both depth \( x \) and time \( t \). (1) was numerically solved for the QSS mode (when \( \frac{d\Delta n(t)}{dt} = 0 \)) and the transient mode (when \( G(t) = 0 \)). The simulations were based on a finite element 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 \( t \).

For both the QSS and transient modes, the simulated excess carrier densities are modulated by the depth sensitivity of the coil [2], and then used to calculate an average excess carrier density, \( \Delta n_{\text{avg}} \) (weighted average) as explained in detail in [4], where the effective thickness \( w_{\text{eff}} \) is also defined.

For the QSS mode, the effective QSS lifetime \( \tau_{\text{QSS-eff}} \) based on the average excess carrier density is then used to estimate the QSS bulk lifetime \( \tau_{\text{QSS-bulk}} \), via a transfer function, as proposed by Bowden and Sinton [4]. This transfer function is intended to remove the effect of surface recombination arising at the unpassivated ingot surface.

For the transient mode simulation, the first stage is a QSS mode simulation, in order to build up the initial carrier concentration before the flash is terminated and the transient decay commences. This results in a \( \Delta n_{\text{avg}}(t) \) 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. No transfer function is applied to the transient analysis.

In the simulations presented here, the true bulk lifetime \( \tau_{\text{bulk}} \) is defined as an input parameter, and is injection-independent, for simplicity.
To allow comparison with the simulation results, both QSSPC and transient lifetime measurements were performed with a BCT-400 boule tester from Sinton Instruments on a p-type monocrystalline block cut from the central region of a commercially grown Cz ingot. For the QSS mode, a standard flash decay time of 5 ms was used with an IR 1000 filter. In this work, measured QSS and transient lifetimes are reported at $\Delta n_{avg} = 10^{15}$ cm$^{-3}$.

III. RESULTS AND DISCUSSION

Fig. 1. shows the simulated excess carrier density profiles during a transient photoconductance decay, over a depth of 1 cm, at different times after the light source was turned off. In this case $\tau_{bulk} = 300 \mu$s and the peak flash intensity was 400 suns. It shows that the high surface recombination velocity significantly impacts the decay during the early parts of the measurement, which will cause the transient lifetime to be artificially low. However, this effect is reduced over time, and eventually the bulk recombination process becomes the major influence in the reduction of the excess carrier density.

![Image](image.png)

Fig. 1. Excess carrier density profile vs depth for different times after the light source is turned off, for p-type silicon. $\tau_{QSS-eff}$ is the simulated effective QSS lifetime and $\tau_{QSS-bulk}$ is the QSS lifetime after applying the transfer function. All lifetimes are determined at $\Delta n_{avg} = 10^{15}$ cm$^{-3}$.

Fig. 2 shows the simulated average excess carrier density as a function of time for transient measurements with different bulk lifetimes. The transient lifetimes extracted at $\Delta n_{avg} = 10^{15}$ cm$^{-3}$, are also shown, as are the corresponding QSS bulk lifetimes. In this case, which represents quite typical measurement conditions, the QSS results are closer to the true bulk lifetime values for lifetimes lower than 150 $\mu$s, whereas the transient lifetimes are more accurate above this value.

In general however, the transient lifetime can always provide a more accurate result, if a sufficiently long time is elapsed before the slope is extracted. However, this is often not practical, as the peak sun intensity may need to be unreasonably high to allow the lifetime to be extracted at the desired excess carrier density after a sufficient elapsed time. Furthermore, the decay time constant of most flashes does not allow accurate transient measurements below 100 microseconds in any case.

As the bulk lifetime increases above 150 $\mu$s, the QSS-bulk lifetime is increasingly inaccurate in the simulation results presented here. This is due to the transfer function implemented in the Sinton Instruments tool being optimized for lower lifetimes. In a real QSS measurement, additional uncertainties arise in high lifetime samples in the QSS mode, due to dynamic effects occurring when the carrier lifetime becomes comparable to the flash decay time, meaning that the assumption of Quasi-Steady State conditions becomes increasingly invalid [5, 6].

![Image](image.png)

As mentioned above, and as discussed in [7], the unpassivated surface induces a large carrier diffusion current towards the surface, placing another constraint on the transient measurements. These surface recombination effects are largely removed from the carrier density decay over time. Consequently, the accuracy of the transient lifetime measurement depends on the time elapsed after which the decay rate is measured, as illustrated in Fig 3. The figure shows that if a sufficiently long time has elapsed, the transient method can in principle provide a very accurate result, at least for an injection-independent bulk lifetime, as assumed here. In practice, the achievable delay time is constrained by the initial flash intensity. Figure 3 also indicates the required delay time after the flash is terminated for the simulated bulk lifetime to approach the true bulk lifetime with 95% accuracy.

Fig. 3 also shows the elapsed time required for 95% accuracy of the transient lifetime with a peak flash intensity of 400 suns. For lower lifetimes, the delay time should be about 10 times the bulk lifetime, reducing to 6 times for lifetimes around 500 microseconds. In general, a conservative approach is to allow an elapsed time of at least ten times the
carrier lifetime, to ensure accurate results.

The surface recombination effect on both QSS and transient lifetimes also depends on the minority carrier mobility. The minority carrier electrons in p-type silicon material have significantly higher mobility (larger effective diffusion coefficient, $D_{eff}$) than the holes in n-type material. Consequently, minority carriers in n-type silicon diffuse towards the surface more slowly than electrons in p-type material, resulting in a higher excess carrier lifetime in n-type material with the same doping, lifetime and illumination intensity.

The Klaassen [8, 9] mobility model is used to calculate the effective diffusion coefficient in this work. The value of $D_{eff}$ is calculated as explained in ref [10] and is injection level dependent, resulting in a range of diffusion coefficients during the decays, as shown in Fig 4.

The initial excess carrier density in a sample directly depends on the illumination source intensity, as well as the carrier lifetime. Higher initial injection levels allow a longer delay time until the injection level decays to $\Delta n_{avg} = 10^{15}$ cm$^{-3}$. According to Fig. 3, a longer delay should result in a higher lifetime closer to the actual bulk lifetime. Fig. 5 shows the results for simulated transient lifetimes with different flash peak intensities, as well as the QSS-bulk lifetime, all reported at $\Delta n_{avg} = 10^{15}$ cm$^{-3}$. The transient lifetime values with 400 suns flash peak intensity are labeled (blue) in Fig. 5. This intensity is commonly used in the BCT-400 boule tester in transient mode.

As can be seen, the transient measurement results with the peak intensities below 200 suns report noticeably lower lifetimes than the bulk lifetime. In contrast, the reported lifetime with 500 and 600 suns are only slightly higher than the results with 400 suns peak intensity. Therefore, the flash with 400 suns peak intensity appears to be suitable for transient measurements at $\Delta n_{avg} = 10^{15}$ cm$^{-3}$ in this lifetime range.

Several transient measurements were performed on a monocrystalline p-type silicon block applying different flash peak intensities to find the peak at which the measured transient lifetime saturated. The results are shown in Fig. 6. The transient lifetime results are generally higher than the QSS-bulk results, as expected based on the simulations. There are significant increases between the measured transient lifetimes when the peak intensity increased from 180 to 413 suns. However, the lifetime is more stable when the peak intensity increased from 413 to 475 and 584 suns. This is also qualitatively consistent with the simulation results above.
Fig. 6. The lifetime measurement results on a standard p-type monocrystalline block at $\Delta n_{avg}=10^{15}$ cm$^{-3}$. The transient measurements were performed with flash peak intensities of 180, 413, 475 and 584 suns.

IV. CONCLUSIONS

Numerical simulations show that the QSSPC technique is accurate for measuring bulk lifetimes below 150 μs on ingots, for which the transfer function eliminates the surface recombination effects efficiently, resulting in good agreement with the actual bulk lifetime. However, above 150 μs, the transfer function is less accurate. Hence, the transient measurement is the preferred technique in this range, provided the lifetime is extracted after a sufficiently long time to ensure that the bulk recombination is the dominant recombination process in the carrier decay. A conservative approach to satisfying this requirement is to allow a delay time of 10 times the carrier lifetime. Measured lifetime data on a p-type monocrystalline silicon block were qualitatively consistent with these simulation results.

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REFERENCES


