Theoretical and experimental comparison of contact less lifetime measurement methods at thick silicon samples

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Simulations of time dependent carrier profiles for thick as-grown silicon samples (e.g. ingots) were computed for the excitation conditions of two different transient photo conductance lifetime measurement methods. The simulations were performed using a partial differential equation systems, that contrary to the widely used simulation tool PC1D, allows to compute also non steady state conditions. The specific effective lifetimes for different measurement conditions can be extracted and compared. Simulation results as well as measurement result for µPCD (microwave detected photoconductivity decay), a non-steady state method and MDP (microwave detected photoconductivity), which operates typically at steady state, were simulated and measured. It was found that the effective lifetimes measured at thick samples with each method may differ strongly. This discrepancy can be attributed to the different penetration depth of the laser light and microwave, but first and foremost to a varying light pulse length and its influence on the developing carrier profile. Altogether the MDP measurements are less prone to the surface impact and accordingly better suited for investigating the bulk properties of silicon samples.

I. INTRODUCTION

The minority carrier lifetime is one of the key parameters for the performance of semiconductor devices and is very valuable for process control especially in photovoltaic applications. In order to compare the quality of, e.g. multicrystalline silicon of different producers it is vital to obtain comparable results in lifetime measurements. To achieve this standard it is important to understand the deviating minority carrier lifetime measurements performed by commonly used non destructive methods like µPCD and MDP.

One main goal of inline metrology in production processes is to identify and sort out low quality material as early as possible. Hence it is vital to obtain significant measurement results at *as-grown* silicon. Because surface recombination at thin silicon wafers strongly influence the measured lifetimes, the best strategy is to measure the lifetime at thick ingots. Accordingly lifetime ingot measurement systems become more and more important and are currently used to determine the low quality ingot fraction at the top and bottom, that needs to be cut off. Unfortunately the measurement results of different lifetime methods can vary strongly at thick samples and the reasons for that are so far not investigated.

By a generalized rate equation system which describes all possible transitions between defect levels and bands in the forbidden gap of a semiconductor µPCD and MDP were already compared at thin samples [1]. This paper is dedicated to the comparison of µPCD and MDP at thick samples, were a spatial dependence of the carrier concentration in the depth of the sample has to be taken into account.

II. EXPERIMENTAL METHODS

Several as-grown mc-Si ingots were measured by µPCD and MDP.

The novel method MDP is well suited for both, defect investigation by e.g. injection dependent minority carrier lifetime measurements, as well as mapping of wafers or even ingots for inline metrology [2, 3]. MDP differs from µPCD in terms of sensitivity, resolution and speed.

Both lifetime measuring methods determine the minority carrier lifetime from photoconductivity measurements. The photoconductivity, which is closely related to the diffusion length can either be measured by microwave absorption (MDP) or microwave reflection (µPCD). Generally the sample is excited with a rectangular laser pulse. The effective minority carrier lifetime is extracted from the transient decay of the photoconductivity signal. Besides slight differences in laser wavelength and microwave frequency, the essential difference of both methods is the length of the exciting laser pulse. While µPCD uses a very short and intensive light pulse with only 200 ns duration, the high detection sensitivity of MDP enables the application also of weak laser pulses with unlimited duration facilitating experiments in steady or non steady state. Table 1 summarizes the properties, that where used for the measurements and simulations.

TABLE 1. measurement properties for MDP and µPCD

	MDP	**µPCD**
λ [nm]	978	904
mw-frequency [GHz]	9,4	10,381
Skin depth [µm]	636	608
G_{opt} [cm^{-3}]	$3*10^{21}$	$5*10^{22}$
pulse length	200 µs	200 ns

III. SIMULATIONS

The laser excitation of *thick* samples (W > 500 µm) with a short light pulse results in an inhomogeneous carrier profile and hence the carrier density depends strongly on the sample depth. This has a great impact on lifetime measurements and needs to be taken into account to correctly interpret the measured lifetime. It is necessary to simulate the carrier density as a function of time and space as correctly as possible.

This is achieved with a partial differential equation system, that is directly derived from the carrier transport equations.

$$\frac{\partial}{\partial t}n(x,t)=\frac{\partial}{\partial x}\left[-\mu_n n(x,t)\frac{\partial}{\partial x}\Psi(x,t)+D_n\frac{\partial}{\partial x}n(x,t)\right]+G^o(x,t)-U(x,t) \qquad (1a)$$

$$\frac{\partial}{\partial t}p(x,t)=\frac{\partial}{\partial x}\left[\mu_p p(x,t)\frac{\partial}{\partial x}\Psi(x,t)+D_p\frac{\partial}{\partial x}p(x,t)\right]+G^o(x,t)-U(x,t) \qquad (1b)$$

$$\frac{\partial^2}{\partial x^2}\Psi(x,t)=-\frac{q}{\varepsilon_0\varepsilon_r}\left[-n(x,t)+p(x,t)\pm N_{dot}\right] \qquad (1c)$$

The equation system includes carrier diffusion, drift current, generation and recombination. The recombination term combines band to band recombination, Auger recombination and SRH recombination and is defined by the resulting injection dependent bulk lifetime.

$$U(x,t)=\frac{\Delta n(x,t)}{\tau_{bulk}(\Delta n(x,t))} \qquad (2)$$

The dominant recombination center was assumed to be FeB with a concentration of 10^{12} cm^{-3} [3].

The equation system can be solved by utilizing the method of lines [4] , discretizing the space derivatives. Figure 1 shows a scheme of this procedure. The sample of thickness W is divided into n section (in this case n = 10) and is solved with an ODE-solver for all sections with the according lifetime $\tau(\Delta n)$.

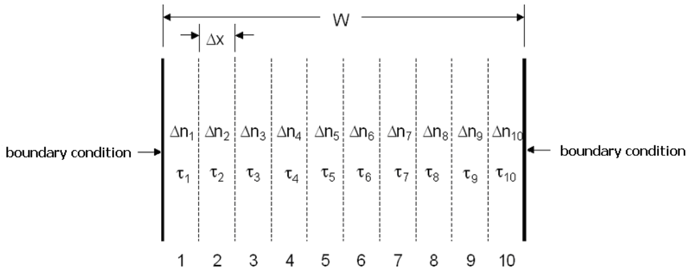

FIG. 1: scheme of discretizing the x derivatives

The initial conditions are the equilibrium carrier concentrations n_0 and p_0 and the boundary conditions are defined by the surface recombination velocity. For the here simulated as-grown silicon ingots a surface recombination velocity of 2 * 10^5 cms^{-1} was assumed.

From the gained simulated carrier profiles a weighted average carrier density for every determined time can be evaluated as follows [5]:

$$\Delta n_{avg}=\frac{\int_0^W \Delta n(x)\cdot w(x)dx}{\int_0^W w(x)dx} \qquad (3)$$

with $w(x)=e^{-\frac{x}{\delta}}$,

where δ is the skin depth of the microwave. From the transient of this average carrier density the effective lifetime can be extracted, which should agree closely to the measured lifetimes.

IV. RESULTS

Figure 2 displays the simulation results for the carrier profiles of a MDP (a) and µPCD (b) measurement. It becomes evident, that the MDP conditions generate carrier profiles, that are expanded much deeper into the sample. During the comparatively long light pulse a steady state is reached, where the carriers develop a stable diffusion profile. Contrary to that, there is not enough time for diffusion during the very short light pulse of a µPCD measurement and a very surface near carrier profile develops.

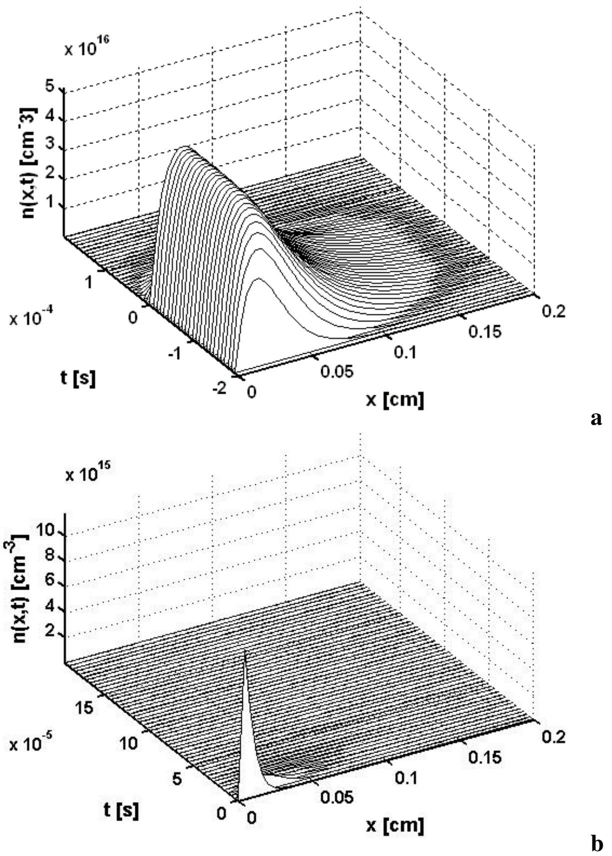

FIG. 2 Simulation of the carrier distribution in a 2 mm thick sample for typical MDP (a) and µPCD (b) conditions

Besides the differences in diffusion, there is also a slightly different injection. But since FeB was chosen as the dominant recombination center, the injection dependence of the bulk lifetime is not very distinct and should not effect the results strongly.

For better comparison of the time dependent behavior figure 3 shows the development of the carrier profiles after the light was switched off for t = 0…200 µs. The carrier density for µPCD decays a lot faster than under MDP conditions. This is also evident in figure 4, where the determined transient of the average carrier concentration is displayed.

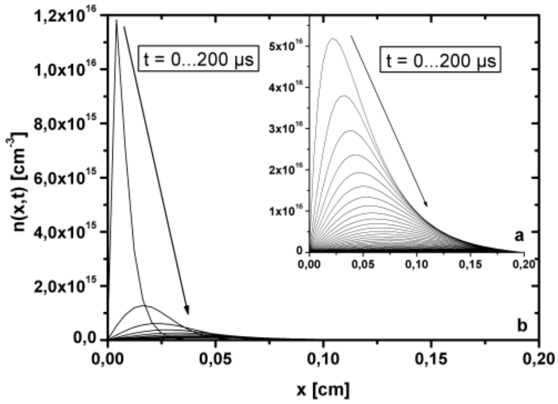

FIG. 3 Time dependent behavior of the carrier profiles of a MDP (a) and µPCD (b) measurement

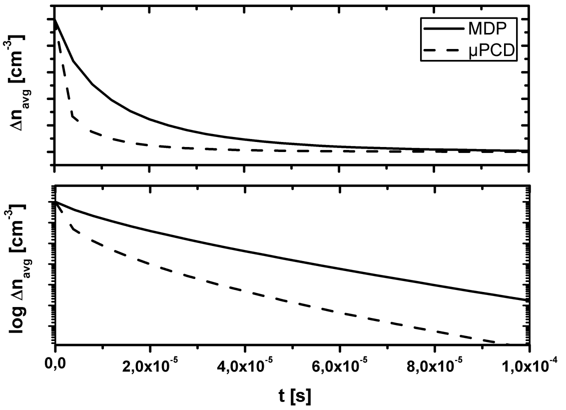

FIG. 4 Determined transient of average carrier density for MDP and μPCD conditions

The main reason for this difference is, that the surface near profile of μPCD is much more affected by the surface recombination and therefore results in a lower effective lifetime. Of course the MDP measurements are also affected by surface recombination and the measured lifetime is unfortunately not equal to the bulk lifetime. For a quantitative analysis of this effect, different bulk lifetimes were assumed and the effective lifetime was evaluated for both methods. The results are shown in figure 4.

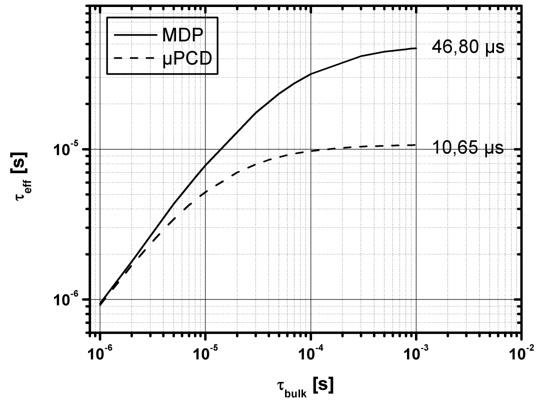

FIG. 5 Evaluated effective lifetimes as a function of bulk lifetime for both methods

As anticipated from the carrier profiles the surface effect strongly influences μPCD measurements. This leads to an increasing difference between effective lifetimes for MDP and μPCD with increasing bulk lifetime. For very high bulk lifetimes the effective lifetime saturates at about 11 μs for μPCD and 47 μs for MDP.

These simulated differences in effective lifetime measurements for thick samples are in very good agreement to first experimental results. Figure 5 shows exemplary μPCD and MDP measurements performed at two unpassivated ingots.

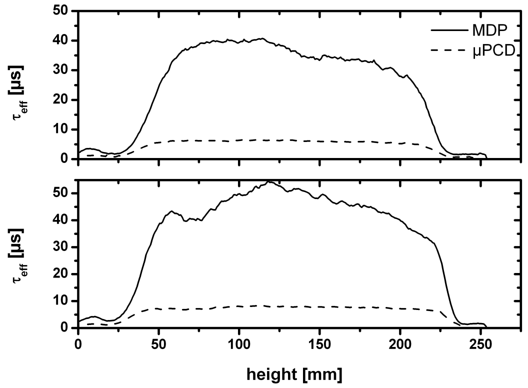

FIG. 6 Exemplary measurement results for two mc-Si ingots

As expected from the simulations, the measured lifetimes by MDP are higher, except for the poor quality parts at the ingots bottom and top, where the bulk lifetime is very low.

The lifetime measured by MDP decreases slightly with ingot height, which is caused by the very low segregation factor of metal impurities, especially iron. For μPCD measurements this behavior is masked by the strong surface effect and indicates ones more that the bulk lifetime and accordingly the quality of the material is determined more realistic with MDP. Of course this result also applies to other steady state methods, e.g. QSSPC (quasi steady state photo conductance).

VI. CONCLUSION

Both, simulations and first measurements, demonstrate that for thick samples different effective lifetimes are achieved from MDP and μPCD measurements. Besides injection differences, the main reason for that is the carrier profile, that develops after the excitation with different light pulses. The maximum of the carrier profiles of μPCD measurements are very close to the surface and accordingly the effective lifetime measured by μPCD is much more effected by surface recombination.

MDP measurements are less prone to surface effects and hence display the bulk properties of the sample much more accurately. With regard to process metrology these results indicate that the application of MDP as an inline metrology tool for ingots leads to much better criteria for evaluation of their quality.

Acknowledgement

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