Solar Energy Materials & Solar Cells 94 (2010) 1076–1080

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Theoretical and experimental comparison of contactless lifetime measurement methods for thick silicon samples

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ARTICLE INFO

Article history:
Received 24 August 2009
Received in revised form
18 January 2010
Accepted 10 February 2010
Available online 6 March 2010

Keywords:
Silicon
Lifetime
Ingot
μPCD
MDP

ABSTRACT

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 photoconductance lifetime measurement methods. The simulations were performed using a partial differential equation system that allows computing also non-steady state conditions. The specific effective lifetimes for different measurement conditions can be extracted and compared. Simulation results and measurement results for μPCD (microwave detected photoconductivity decay), a non-steady state method and MDP (microwave detected photoconductivity), which operates typically with a steady state photo generation, 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 depths 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 or methods with a steady state photo generation in general are less prone to the surface impact and accordingly better suited for investigating the bulk properties of silicon samples.

1. 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 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 [1], quasi steady state photoconductance (QSSPC) [2], carrier density imaging (CDI) [3] or 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 of *as-grown* silicon. Since surface recombination of thin silicon wafers strongly influences the measured lifetimes, the best strategy is to measure the lifetime of 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, which needs to be cut off. Unfortunately the measurement results of different lifetime methods can vary strongly for thick samples and the reasons for that have so far not been 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 as a representative for methods using non-steady-state photo generation and MDP as a representative for a steady-state photo generation were already compared at thin samples [4]. This paper is dedicated to the comparison of non-steady-state and steady-state photo generation methods (e.g. μPCD and MDP) for thick samples, where a spatial dependence of the carrier concentration in the depth of the sample has to be taken into account.

2. 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 and mapping of wafers or even ingots for inline metrology [5,6]. MDP differs from commercial μPCD systems in terms of sensitivity, resolution and speed, which was shown in a recent publication of this group [7]. A full lifetime and

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doi:10.1016/j.solmat.2010.02.028

Table 1
Measurement properties for MDP and μPCD.

	MDP	μPCD
λ [nm]	978	904
Penetration depth [μm]	100	33
mw-frequency [GHz]	9.4	10.4
Skin depth [μm]	636	608
Photons/(cm^{2}s)	3×10^{20}	7×10^{21}
Pulse length	200 μs	200 ns

photoconductivity map with a resolution of 1 mm of two surfaces of an ingot is achieved in about 2 min.

Both lifetime measuring methods determine the minority carrier lifetime from photoconductivity measurements. The photoconductivity, which is closely related to the diffusion length, can be measured by either 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 with a steady or non-steady state photo generation. Table 1 summarizes the properties that were used for the measurements and simulations.

3. Simulations

The laser excitation of *thick* samples ($W>500\,\mu m$) 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, which is directly derived from the carrier transport equations:

$$\frac{\partial}{\partial t}n(x,t)=\frac{\partial}{\partial x}\left[-\mu_n n(x,t)\frac{\partial}{\partial x}\Psi(x,t)+D_n\frac{\partial}{\partial x}n(x,t)\right]+G^0(x,t)-U(x,t) \tag{1a}$$

$$\frac{\partial}{\partial t}p(x,t)=\frac{\partial}{\partial x}\left[\mu_p p(x,t)\frac{\partial}{\partial x}\Psi(x,t)+D_p\frac{\partial}{\partial x}p(x,t)\right]+G^0(x,t)-U(x,t) \tag{1b}$$

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

The equation system includes carrier diffusion, drift current, generation and recombination. An injection and doping concentration dependent mobility model was used [8]. The recombination term combines band to band recombination, Auger recombination and SRH recombination, and is defined by the resulting injection dependent bulk lifetime.

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

The dominant recombination center was assumed to be FeB with a concentration of $10^{12}\,cm^{-3}$ [9]. For a doping concentration of $10^{16}\,cm^{-3}$ and an injection of $10^{16}\,cm^{-3}$, this results in an approximate bulk lifetime of 170 μs and a diffusion length of 600 μm.

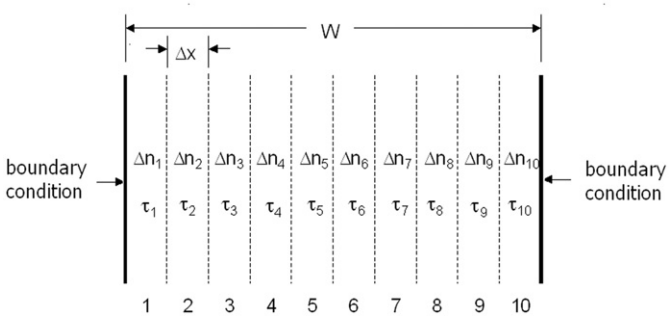

Fig. 1. Scheme of discretizing the *x* derivatives.

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

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 $2\times10^5\,cms^{-1}$ was assumed.

From the gained simulated carrier profiles a sensor-weighted average carrier density for every determined time can be evaluated as follows: [11]:

$$\Delta n_{sensor}=\frac{\int_0^W \Delta n(x)w(x)dx}{\int_0^W w(x)dx} \tag{3}$$

$$\text{with}\quad w(x)=e^{-x/\delta},\quad \text{and}\quad \delta=\sqrt{\frac{\rho}{\pi\nu\mu_0\mu_r}} \tag{4}$$

where δ is the skin depth of the microwave, ν is the frequency of the microwave, and μ_0 and μ_r are the permeability of vacuum and the sample, respectively. From the transient of this sensor-weighted carrier density the effective lifetime can be extracted, which should agree closely with the measured lifetimes.

4. Results

Fig. 2 displays the simulation results for the carrier profiles of MDP (a) and μPCD (b) measurements. 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. On the contrary, there is not enough time for diffusion during the very short light pulse of μPCD measurement and a very surface near carrier profile develops.

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 affect the results strongly.

For better comparison of the time dependent behavior Fig. 3 shows the development of the carrier profiles after the light was switched off for $t=0,\ldots,200\,\mu s$. For μPCD measurements the penetration depth of the carrier profile at $t=0\,\mu s$ is about 70 μs, which is in the range of the penetration depth of the laser light. The carrier profile of a typical MDP carrier profile is about 740 μm deep, which approximately equals the penetration depth of the

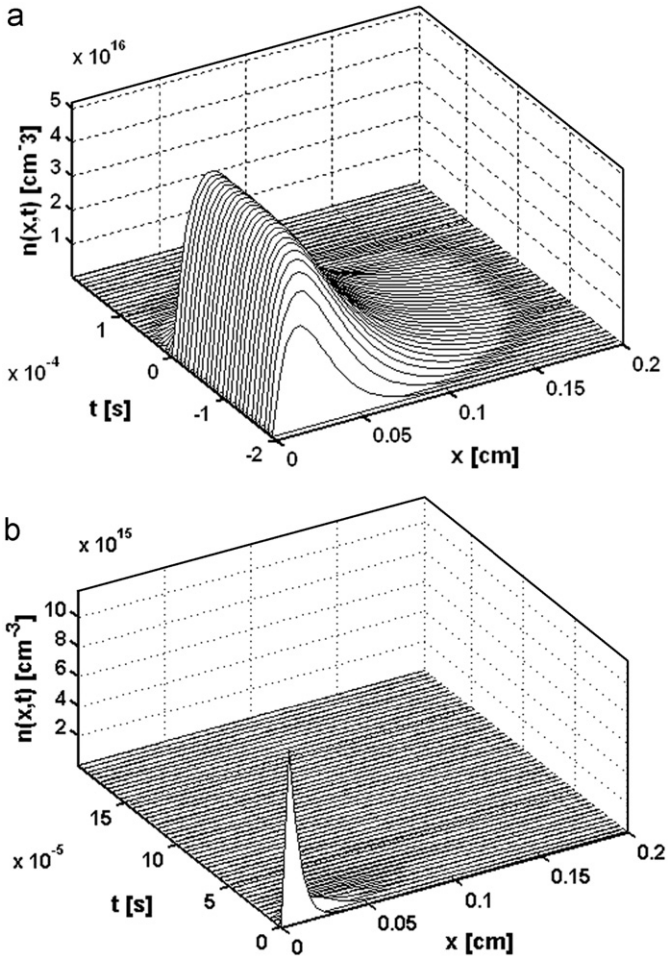

Fig. 2. Carrier profile in a 2 mm thick sample with $N_{dot}=10^{16}$ cm^{-3} at 300 K for a typical MDP (a) defined by light pulse duration of 200 μs, λ=978 nm, microwave frequency ν=9.4 GHz and a μPCD (b) measurement defined by light pulse duration of 200 ns, λ=904 nm, ν=10.4 GHz, for both cases FeB was used as the recombination center as defined in [9].

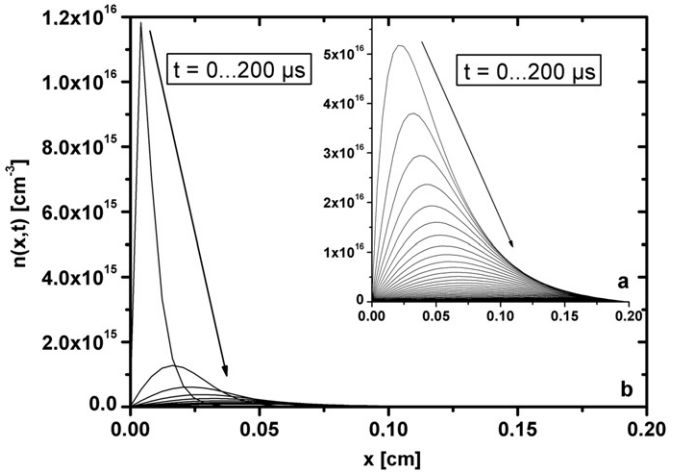

Fig. 3. Time dependent behavior of the carrier profiles of MDP (a) and μPCD (b) measurement with $N_{dot}=10^{16}$ cm^{-3}.

laser light plus the diffusion length of the carriers. The carrier density for μPCD decays a lot faster than under MDP conditions, because the carriers recombine at the front surface and diffuse into the bulk of the sample after the light is switched off.

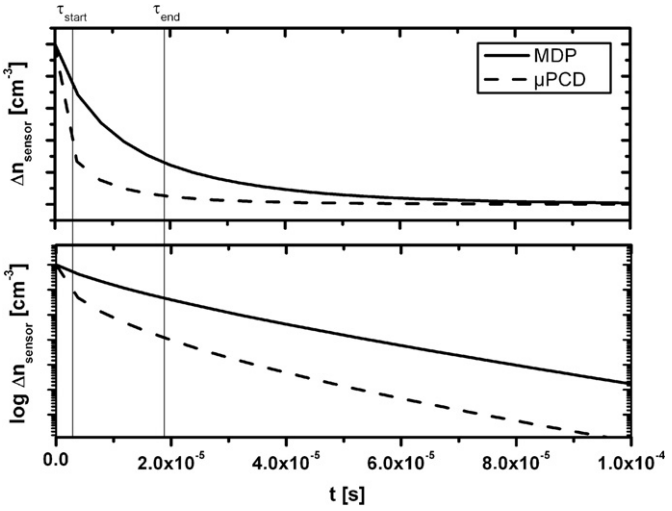

Fig. 4. Normalized transient of sensor-weighted carrier density for MDP and μPCD conditions.

This is also evident in Fig. 4, where the determined transient of the sensor-weighted carrier concentration is displayed. Hence the main reason for the difference in the shown transients is the influence of carrier diffusion and the strong surface effect on the profile of μPCD. All these effects lead to a lower effective lifetime for μPCD measurements. Obviously the MDP measurements are also affected by diffusion and 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. For the determination of the effective lifetimes the linear regression of the logarithmic transient was determined in the range of $\frac{3}{4}$ of the height of the signal (τ_{start}) to $\frac{1}{4}$ of the signal height (τ_{end}), which is indicated in Fig. 4. The results of this evaluation are shown in Fig. 5a.

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 increase in bulk lifetime. The measured effective lifetime depends also on the doping concentration, since the skin depth of the applied microwave varies with resistivity (Eq. (4)). For lower doping concentrations a higher effective lifetime is measured for both methods, since the skin depth is larger and vice versa. For very high bulk lifetimes the effective lifetime saturates at about 11 and 20 μs for μPCD and at 50 and 73 μs for MDP for a doping concentration of 10^{16} or 10^{15} cm^{-3}, respectively.

The influence of the used laser wavelength is shown in Fig. 5(b). With an increase in wavelength and hence an increase in penetration depths the effective lifetime increases strongly and approaches the bulk lifetime. Hence some work groups using μPCD switched to a laser wavelength of 1064 nm [1]. However at the same wavelength steady-state-photo generation methods promise to deliver better results than μPCD.

These simulated differences in effective lifetime measurements for thick samples are in very good agreement with first experimental results. Fig. 6 shows exemplary μPCD and MDP measurements performed at two as-grown ingots with the measurement conditions summarized in Table 1. The measurements were not performed at the exact same injections, but at very similar injections. It is likely that FeB is the dominant recombination center in the shown samples, which yields in a bulk lifetime, that has no strong injection dependency. Hence the measured difference has

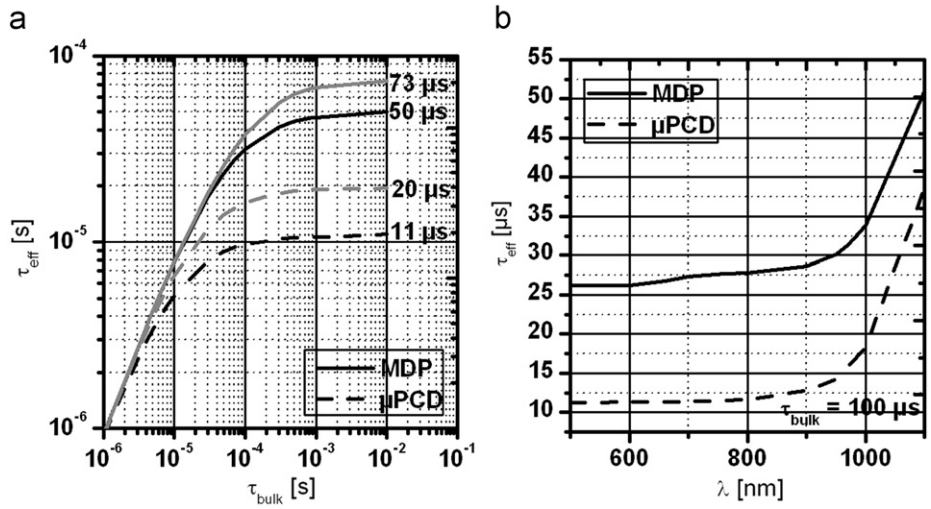

Fig. 5. Evaluated effective lifetimes as a function of bulk lifetime (a) for both methods and $N_{dot}=10^{16}$ cm^{-3} (black) and $N_{dot}=10^{15}$ cm^{-3} (gray); evaluated effective lifetimes as a function of the exciting laser wavelength (b).

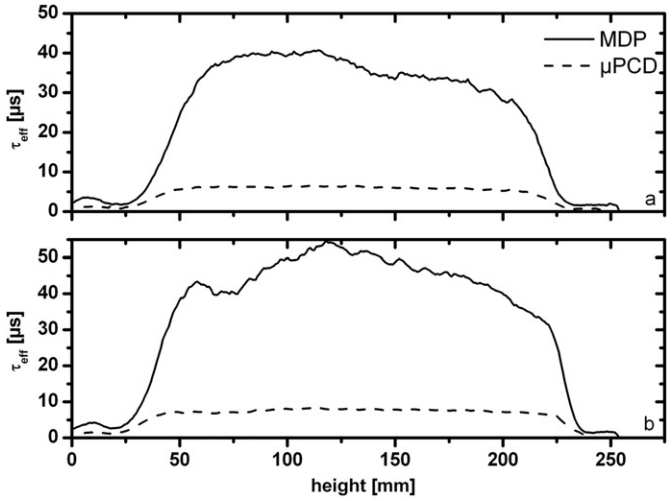

Fig. 6. Exemplary measurement results for two mc-Si ingots with $\rho=1.31\ \Omega$cm (a) and $\rho=0.92\ \Omega$cm (b).

to be due to the different carrier profiles and cannot be explained by injection differences.

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 and diffusion effect, and indicates onces more that the bulk lifetime and accordingly the quality of the material is determined more realistic with MDP or other steady state photo generation methods as QSSPC. Some measurement result and simulations of QSSPC at ingots, confirming the results in this paper, are described in [12].

5. Conclusions

Both simulations and first measurements demonstrate that for thick samples different effective lifetimes are achieved for methods using steady-state or non-steady-state photo generation conditions. Besides injection differences and differences in the penetration depth of the used micro- or radio-wave, 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 is very close to the surface and accordingly the effective lifetime measured by µPCD is much more affected by surface recombination. To achieve effective lifetimes, which are more strongly dominated by the bulk lifetime laser light with a high penetration depth has to be used.

Measurement methods, that use steady-state photo generation condition as MDP or QSSPC 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 these methods as an inline metrology tool for ingots leads to much better criteria for the evaluation of their quality.

Acknowledgement

This work has been supported by the Solar World Innovations GmbH.

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