SPATIALLY RESOLVED DETERMINATION OF TRAPPING PARAMETERS IN P-DOPED SILICON BY MICROWAVE DETECTED PHOTOCONDUCTIVTY

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ABSTRACT: The novel method MDP (microwave detected photoconductivity) was applied to measure the injection dependent lifetime and photoconductivity. With these measurements and an evaluation algorithm based on the trapping model of Hornbeck and Haynes [1] a spatially resolved determination of trapping parameters in mc- and Cz-Si samples is possible. The possibility to map trapping parameters with a high resolution is investigated. First measurement results are presented for mc-Si and Cz-Si samples.
Keywords: lifetime, Silicon, defect density

1 INTRODUCTION

The contact less determination of the minority carrier lifetime is a widely used method to characterize semiconductor materials. Most of the destruction free lifetime measurement methods like µPCD (microwave detected photoconductivity decay), QSSPC (quasi steady state photo conductance) [2], CDI (Carrier density imaging) [3] or the here presented method MDP measure trapping effects at low injection levels. Especially in p-type mc-Si the trapping of electrons lead to an abnormally high apparent lifetime at low injections. This has to be taken into account for the correct interpretation of lifetime results.
The major advantage of MDP is, that it is possible to measure the minority carrier lifetime and photoconductivity at steady state simultaneously, over a wide range of injection levels and with a very high spatial resolution. Hence the trap density can be measured with a resolution that is only limited by the diffusion length of the carriers.
Although the relevance of traps for the device performance is known, it is still unclear what is the exact origin of traps especially in mc-Si. With the ability to measure the trap density with a high spatial resolution, it is possible to determine the exact location of high trap densities and to correlate them with other defect structures as dislocations.
The paper will show first measurement results at mc-Si and Cz-Si samples.

2 METHODICAL APPROACH

2.1 Microwave detected Photoconductivity

The novel method MDP was explained in detail in [4, 5]. With MDP it is possible to spatially resolve the minority carrier lifetime, along with the photoconductivity. It is predestined for the application in inline-measurement systems, since it has a high sensitivity and measurement speed. The apparent minority carrier lifetime is extracted from the transient of the photoconductivity and the injection can be computed at steady state conditions with $\Delta n = \tau \times G_{opt}$.

Several maps with different optical generation rates G_{opt} were measured and for every point of the map the minority carrier lifetime as a function of the injection and the photoconductivity as a function of the optical generation rate were computed.

2.2 Trapping model

The model of Hornbeck and Haynes was used [1]. The measurements were conducted at low injection levels and therefore the following assumptions were made:

i) the recombination lifetime, as described by the Shockley-Read-Hall mechanism [6] at low injection is constant
ii) the trap is only interacting with the conduction band and hence the capture cross section for holes $\sigma_p = 0$
iii) electrons are only reemitted from the traps by thermal generation

The following rate equation system describes this model:

$$\begin{aligned} \dot{n} &= G_{opt} - \frac{n}{\tau_{SRH}} + C - D \\ \dot{p} &= G_{opt} - \frac{p}{\tau_{SRH}} \\ \dot{n}_T &= G_{opt} - C + D \end{aligned} \quad (1)$$

Thereby C and D are describing the reemission and the trapping of electrons by:

$$\begin{aligned} C &= n_T \sigma_n v_{th} N_C \exp\left(\frac{-E_a}{kT}\right) \\ D &= n(t) \sigma_n v_{th} (N_T - n_T) \end{aligned} \quad (2)$$

with N_T absolute trap density, n_T number of currently trapped electrons, v_{th} thermal velocity, N_C effective density of states in the conduction band, σ_n electron capture cross section of the trap. If steady state conditions are assumed the occupied traps can be determined as follows:

$$n_T = \frac{\Delta n \cdot N_T}{\Delta n + N_C \cdot \exp\left(\frac{-E_a}{kT}\right)} \quad (3)$$

Hence the hole concentration no longer equals the electron concentration, but the sum of electrons in the conduction band plus electrons in the traps. The photoconductivity is then described by:

$$\Delta\sigma = e \cdot \left[\Delta n(\mu_n + \mu_p) + \mu_p n_T\right] \quad (4)$$

Figure 1 displays the influence of different parameters of the trap level on the photoconductivity.

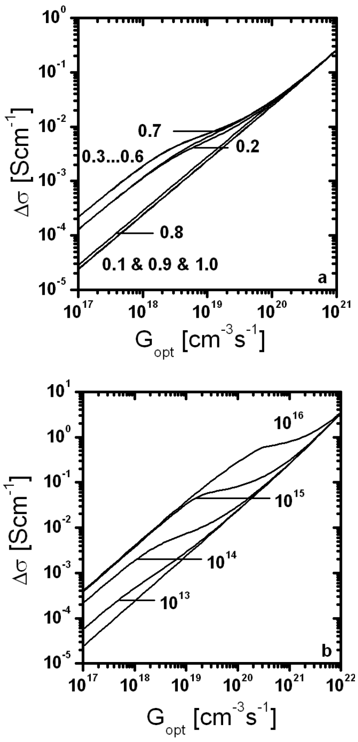


fig. 1:photoconductivity versus optical generation rate for p-type silicon with $N_{dot} = 10^{16}$ cm^{-3}; he parameters of the recombination center are N_{rc}=10^{14} cm^{-3}, $\sigma_n = \sigma_p$=10^{-15} cm^2, and E_{rc}–E_i=0 eV; Trap parameters: N_{trap} =10^{14} cm^{-3}, σ_n=10^{-15} cm^2, σ_p=10^{-19} cm^2, and E_{trap}=0.3 eV; trap parameters are consecutively changed to show the impact of different trap parameters on the photoconductivity; photoconductivity is depicted for (a) different trap activation energies, (b) a varying trap density

2.3 Determination of trap parameters

The determination of trapping parameters is possible by fitting a measured photoconductivity curve as a function of the optical generation rate. The fitting function is obtained by inserting equation (3) into equation (4), with the fitting parameters E_a and N_T. Additionally a mobility model [7] , the constant recombination lifetime at low injections τ_{LLI} and the injection Δn is needed. The injection is determined by the following equation, which is only valid for steady state measurements:

$$\Delta n = \tau_{LLI} \cdot G_{Gopt} \quad (5)$$

The recombination lifetime at low injections is not known exactly, because of the trapping effect, which apparently increases the measured lifetime. Instead the minimal measured lifetime is used, which can be too high for very high trap densities (see figure 2). This can lead to a smaller trap density and an error of approximately 10 % [8].

Figure 3 (a) shows an exemplary injection dependent lifetime curve, where the used τ_{LLI} is marked. In figure 3 (b) the measured photoconductivity versus the optical generation rate is displayed, along with the fitting curve.

3 EXPERIMENTALS

156x156 mm mc-Si and Cz-Si samples were investigated. They were passivated with SiN on both sides, so that a measurement of the bulk properties of the sample was ensured. A MDPmap measurement system by Freiberg Instruments was used for all measurements. First of all detailed injection dependent measurements of at least two points of each wafer were conducted to evaluate the proper laser power that should be used, in order to reach a low injection level, where the trapping effect is dominating. Additionally the activation energy and the trap density were fitted as described above. Maps with at least 20 different optical generation rates in this low injection range were conducted with a resolution of 1mm (mc-Si) or 500 µm (Cz-Si). One map takes about 2 min measurement time, so that a whole investigation of the trap density takes approximately 60 min.

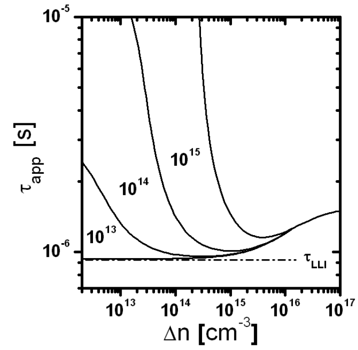


fig. 2: influence of the trap density on the measured lifetime minimum

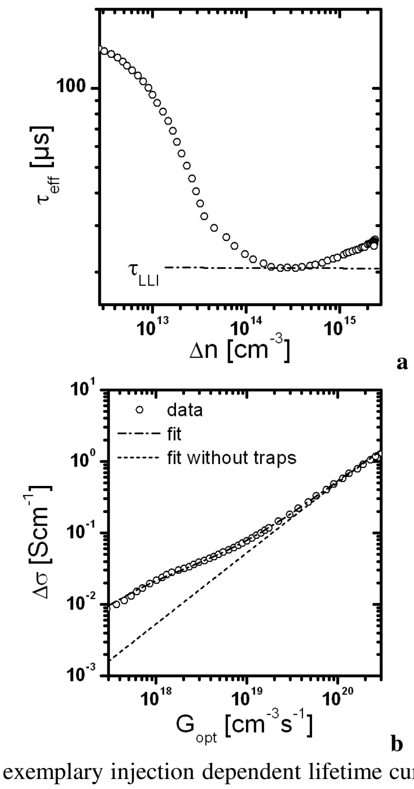


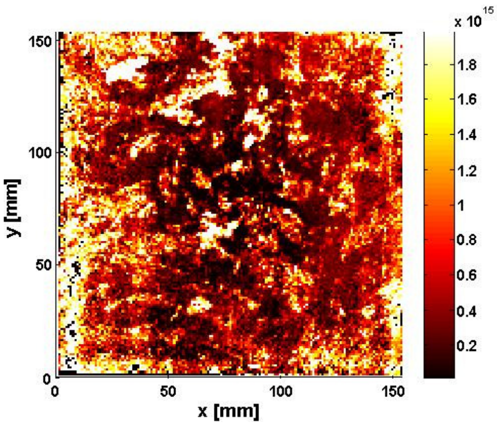
fig. 3: exemplary injection dependent lifetime curve with marked τ_{LLI} (a); photoconductivity versus optical generation rate, fitting curve with the following fitting parameters: N_T = 4.4 x 10^{14} cm^{-3}, E_A = 0.37 eV and fitting curve without traps

4 RESULTS

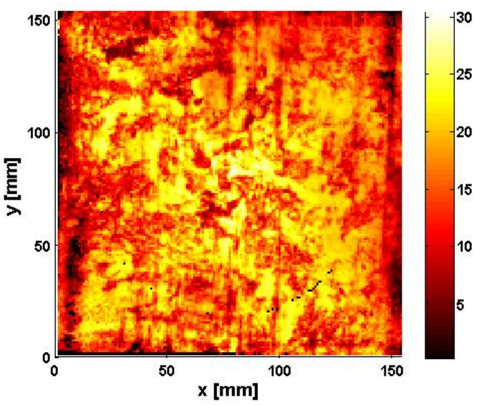
First measurement results of several different mc-Si samples resulted in a trap density in the range of $1x10^{14}…2x10^{15}$ cm^{-3}. The activation energy always ranges between 0.32…0.39 eV, independent of the ingot height as was already shown in [9]. It ought to be mentioned here that at room temperature only traps with an activation energy above approximately 0.25 eV can be determined.

Unfortunately it was not possible to gain an unambiguous fit for the activation energy in the performed mappings. Obviously at least 100 points are needed in the low injection range to gain an activation energy, so that based on the results of the detailed injection dependent measurements an activation energy of 0.35 eV was assumed. As can be seen in figure 1 (a) different activation energies can lead to a similar photoconductivity, hence temperature dependent measurements are better suited to gain accurate values. As shown in some other papers of this work group [10, 11] the method MD-PICTS (microwave detected photo induced current transient spectroscopy), which is based on the same measurement principle as MDP is very well suited for such measurements and will be compared with the here gained results in the future.

An exemplary trap density map of a mc-Si wafer is presented in figure 4 (a). An average density of $8.2x10^{14}cm^{-3}$ was determined, which is a typical value for a mc-Si wafer.



a



b

fig. 4: trap density map of a typical mc-Si wafer with an average density N_T = $8.2x10^{14}$ cm^{-3}, E_A = 0.35 eV (a); map of the determined τ_{LLI} (b)

In figure 4 (b) the lifetime at low injection τ_{LLI} is shown. Assuming that there is a constant doping concentration across the sample and only one dominant recombination center, τ_{LLI} is proportional to the recombination center density. As can be seen in figure 5 there is a clear correlation between the logarithmic trap density and τ_{LLI}. This suggests that the recombination center and the trap level have the same origin. The well known photoluminescence emission band D1 with an activation energy of E_C – 0.31 eV is known to correlate with dislocations and several different groups suggested the participation of an electron trap level with an activation energy of E_C 0.35 eV, which could be originating from oxygen segregations at dislocations [12, 13]. It was already postulated several times that oxygen and dislocations are necessary requirements for traps [14, 15].

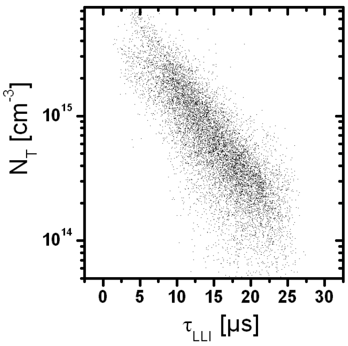
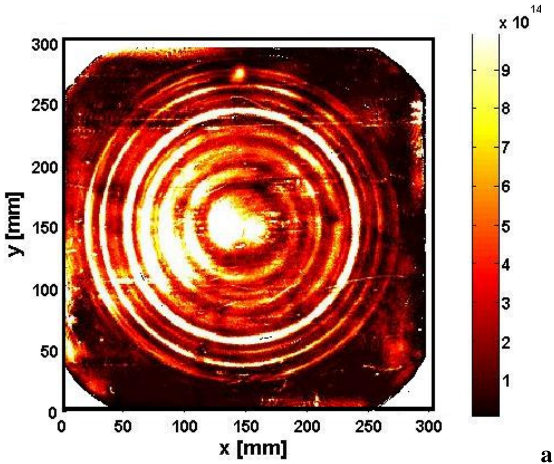


fig. 5: trap density versus τ_{LLI} for every point in a map of a mc-Si wafer

Figure 6 (a) shows the trap density map of a Cz-Si wafer with striations. The trap density is strongly increased compared to typical trap densities, which were measured at standard Cz-Si wafers. The trap density for typical Cz-material is in the range of $5x10^{12}…5x10^{13}$ cm^{-3}. The activation energy, which was gained by detailed injection dependent measurements, was slightly higher than for the mc-Si wafer and lay in the range between 0.45…0.52 eV. Again an activation energy of 0.48 eV had to be assumed for the trap density map.



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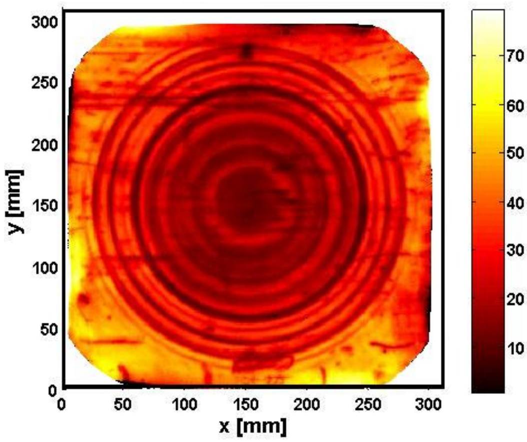

fig. 6: trap density map of a Cz-Si wafer with striations and an average density $N_T = 3.9x10^{14}$ cm^{-3}, $E_A = 0.48$ eV (a); map of the determined τ_{LLI} (b)

Again figure 6 (b) displays the determined τ_{LLI} and figure 7 the correlation between the trap density and τ_{LLI} for the Cz-Si wafer. Although there is a clear correlation between the observable striation in the τ_{LLI} map and the trap density map, the plot in figure 7 shows not a linear correlation between these two parameters, as observed for the mc-Si wafer. Obviously in this case there are different origins for the observed trap effects. By spatially resolved and temperature dependent MD-PICTS measurements, it is planned to figure out, if different trap levels exist at the striations and the rest of the sample.

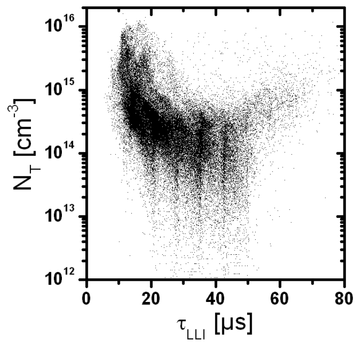

fig. 7: trap density versus τ_{LLI} for every point in a map of a Cz-Si wafer with striations

5 CONCLUSION

It was shown that it is possible to spatially determine the trap density of mc- and Cz-Si wafers. Furthermore first measurement results show that the trap density at striations of Cz-Si wafers is increased. First correlations of τ_{LLI} and the trap density in combination with the determined activation energy seem to confirm that there is a correlation between the traps and dislocations in mc-Si. Further investigations with the temperature dependent method MD-PICTS are planned to determine a more accurate activation energy and to separate different existing trap levels.

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