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Reporting effective lifetimes at solar cell relevant injection densities

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Abstract

Precise quantitative assessment of c-Si wafer quality is of crucial importance for the development and manufacturing of high efficiency solar cells. For this purpose, lifetime samples are typically fabricated with very well cleaned and passivated surfaces. Under those conditions the measured effective lifetime τ_{eff} is almost equal to the silicon bulk wafer lifetime τ_{wafer}, i.e. a material related quality parameter. Those lifetime measurements are typically carried out with a photo-conductance decay method (PCM) e.g. with a Sinton-WCT tool. The measurement result is an effective excess carrier lifetime τ_{eff} which typically exhibits a strong dependence on the excess carrier injection density Δn within the wafer. Stating τ_{eff} –values thus necessitates to specifiy Δn. The PV community typically reports at a fixed Δn in the range of $1\times10^{14}\,\text{cm}^{-3}$ to $1\times10^{16}\,\text{cm}^{-3}$ or for varying wafer doping density N_{dop} at $\Delta n = N_{\text{dop}}/10$. The latter allows for a comparison from the point of view of the Shockley-Read-Hall (SRH) formalism. Unfortunately, the impact of a certain lifetime for device performance changes with N_{dop}, due to the law of mass action. In this paper a wafer doping density dependent Δn which is relevant for the injection density at maximum power point (MPP) is derived. This Δn@MPP shows a contrary behaviour compared to the often used and accepted reporting method to set $\Delta n = N_{\text{dop}}/10$. Additionally, a wafer doping density independent material quality parameter, called material saturation current density $j_{0,\text{mat}}$ at MPP, is proposed to improve the comparability of measured effective lifetimes of differently doped wafers .

Keywords: Carrier lifetime; Effective lifetime; Lifetime measurement; Saturation current

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1. Introduction

Reporting carrier lifetime is done very often to describe the quality of silicon wafers for solar cell application. For this purpose, lifetime samples are typically fabricated with very well cleaned and passivated surfaces. Under those conditions the measured effective lifetime τ_{eff} is almost equal to the silicon bulk wafer lifetime τ_{wafer}, i.e. a material related quality parameter. Those lifetime measurements are typically carried out with a photo-conductance decay method (PCM) with e.g. a Sinton-WCT tool. The measurement result is an effective excess carrier lifetime τ_{eff} which typically exhibits a strong dependence on the excess carrier injection density Δn within the wafer. Example lifetime curves are analytically calculated and shown in Fig. 1, where a SRH defect and intrinsic, i.e. Auger and radiative, recombination [1] is assumed.

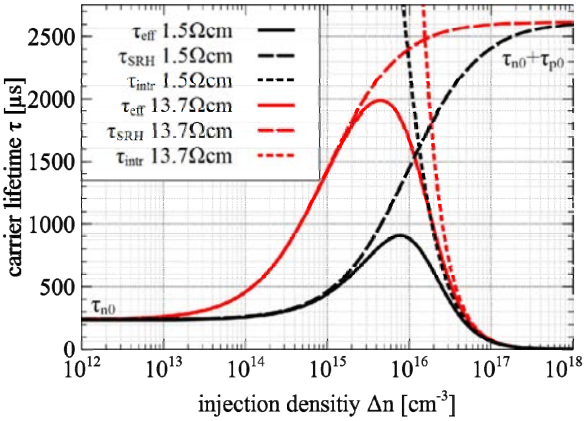

Fig. 1. Analytical calculations of two effective carrier lifetime curves for a 1.5Ωcm ($N_{\mathrm{A}}=1\times10^{16}\mathrm{cm}^{-3}$) and a 13.7Ωcm ($N_{\mathrm{A}}=1\times10^{15}\mathrm{cm}^{-3}$) substrate with the same SRH lifetime parameters τ_{n0} = 238.1µs and τ_{po} = 2381µs.

Stating τ_{eff} –values thus necessitates to specifiy Δn. The PV community typically reports at a fixed Δn in the range of $1\times10^{14}\,\mathrm{cm}^{-3}$ to $1\times10^{16}\,\mathrm{cm}^{-3}$ or for varying wafer doping density N_{dop} at $\Delta n = N_{\mathrm{dop}}/10$. Reading out τ_{eff} e.g. for $\Delta n = 5\times10^{14}\,\mathrm{cm}^{-3}$ in Fig. 1, two different values τ_{eff} = 345µs and τ_{eff} = 437µs for $N_{\mathrm{A}}=1\times10^{16}\mathrm{cm}^{-3}$ and $N_{\mathrm{A}}=1\times10^{15}\mathrm{cm}^{-3}$, respectively, are derived, whereas almost the same τ_{eff} is derived using $\Delta n = N_{\mathrm{dop}}/10$ (τ_{eff} = 437µs and τ_{eff} = 455µs for $N_{\mathrm{A}}=1\times10^{16}\mathrm{cm}^{-3}$ and $N_{\mathrm{A}}=1\times10^{15}\mathrm{cm}^{-3}$, respectively). The latter reporting of constant lifetimes can be expected from SRH theory and is meaningful for defect characterization when doing lifetime spectroscopy.

It will be shown that the injection density at maximum power point (MPP) of silicon solar cells shows a different behavior and decreases with increasing doping density. Furthermore, a wafer doping density independent material quality parameter, called material saturation current density $j_{0,\mathrm{mat}}$ at MPP, is proposed to make measured effective lifetimes of differently doped wafers comparable from the solar cell point of view.

2. Derivation of a solar cell relevant injection density at MPP

For the determination of a solar cell relevant τ_{eff} which considers injection- and doping-dependent effects, it is possible to estimate Δn@MPP using the single diode model. The law of mass action at all dopant and injection conditions is assumed:

$$n\,p = (N_D + \Delta n)\,(N_A + \Delta n) = n_{i,eff}^2\;e^{\left(\frac{qV}{k_B T}\right)} \qquad (1),$$

where V is the local voltage at the pn-junction without series resistance influence, n is the electron density, p is the hole density, N_{A} is the acceptor concentration, N_{D} is the donor concentration, k_{B} is the Boltzmann constant, T is the temperature, q is the elementary charge, $n_{\mathrm{i,eff}}$ is the effective intrinsic carrier concentration considering band-gap-