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Improved evaluation of saturation currents and bulk lifetime in industrial Si solar cells by the quasi steady state photoconductance decay method

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ABSTRACT

For understanding and improving the performance of industrial Si solar cells, it helps to quantify the losses in the various device parts very precisely, because this enhances the predictive power of roadmaps deduced from such analysis. We show how the precision of commonly applied methods for measuring the saturation current density, J_0, can be noticeably improved. Firstly, two methods are compared for determining the optical properties of the samples specifically made for lifetime measurements. Secondly, it is evaluated, which excess carrier density level is best to choose for extracting J_0 of the various device regions. Thirdly, the bulk lifetime is extracted by a combination of measurements and modeling of the surface passivation.

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1. Introduction

For the improvement of the energy conversion efficiency of solar cells, it is crucial to know how the recombination losses are distributed among the emitter, base, and back-surface-field (BSF) region. This is so because reducing the recombination in the region with the highest recombination losses improves cell efficiency most effectively. The amount of recombination in the emitter and BSF regions is usually characterized by their saturation current density J_0. Commonly, J_0 is determined from measurements of the effective excess carrier lifetime, τ_{eff}, in dependence of the excess carrier density Δn, either via photo-conductance decay (PCD) applying the method of Kane and Swanson [1], or via quasi-steady-state photoconductance (QSSPC) as proposed by Sinton and Cuevas [2]. For samples with a high lifetime ($\tau_{\text{eff}} > 200\ \mu s$), the excess carrier decay is sufficiently slow so it can be monitored with PCD. For low lifetime samples, the flash duration is chosen to be longer than the excess carrier decay, so quasi-steady-state is reached where the rate of recombination, $\Delta n / \tau_{\text{eff}}$, is equal to the

rate of generation G. Such methods have been successfully applied to the characterization of crystalline silicon and solar cells [3–8].

In this paper, we improve the precision of these methods, particularly for mass-produced, standard Si solar cells, which have a full-area BSF and a locally higher doped region at the front contacts (selective emitter). For example, the determination of G is critical. Assessment of G via a PC1D simulation is suggested [9]. However, for samples with a non-uniform surface like the Al-doped BSF, an accurate optical simulation is difficult [10]. Therefore, we stop the flash in the QSSPC measurement abruptly so it turns into a PCD measurement, and G is obtained by matching the resulting lifetime from both decays [11,12]. We compare this method with direct measurements of the reflectance and transmittance of our samples, which is introduced in SEMI PV13 [13]. Secondly, the extracted J_0 generally depends on Δn where it is extracted from τ_{eff}. We evaluate the proposal of Ref. [14] on choosing the optimum Δn for determining J_0. We extract the bulk lifetime by a combination of lifetime measurements and modeling.

2. The saturation current under illumination

The amount of recombination of excess carriers in device regions is commonly characterized by the saturation current

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density J_0. It is helpful to elucidate the reasons for this in order to obtain meaningful values for J_0 under illumination. The definition of J_0 originates from the diode in the dark. There, recombination enables the external current flow and, hence, the total recombination in the diode is equal to its external current. This basic fact makes it possible to determine the amount of recombination from the I–V curve. The original definition of J_0 comes from Shockley's ideal diode equation [15, p. 314], which links the external current density J with the external voltage V:

$$J(V) = J_0(e^{V/V_{th}} - 1),$$ (1)

where J_0 is defined for the entire diode (not of a device region), V_{th} is the thermal voltage kT/q, with k being the Boltzmann's constant, T the absolute temperature, and q the elementary charge. Basically, J_0 is an equilibrium entity arising from the principle of detailed balance: it balances the drift current with the diffusion current in the device in thermal equilibrium (which is in the dark at zero applied bias). Nevertheless, J_0 is sometimes called 'reverse saturation current'. However, it bears ambiguities if J_0 is thought as originating from J at negative biases, because there no thermal equilibrium exists. The applied reverse bias merely forces the diffusion current toward zero so the drift current prevails with the size approximately equal to J_0, but in reality often deviates from J_0 obtained from the forward I–V curve. Therefore, it is only non-ambiguous to call J_0 the 'reverse saturation current' if it is indeed measured in the reverse bias range, which is rarely done.

As noted, J_0 as 'saturation current' has its well defined meaning in detailed balance, and this is so regardless whether an ideal diode model is applied (such as Shockley's) or more sophisticated models (e.g. beyond the drift-diffusion or depletion region approximation [16], or including photon recycling [17], and others). However, photovoltaic action does not occur in thermal equilibrium but under illumination. In order to still use the Shockley equation to relate J with V under illumination, it is common to simply subtract the short-circuit current density J_{sc} from Eq. (1):

$$J = J_0(e^{V/V_{th}} - 1) - J_{sc}.$$ (2)

This approximation is commonly called the 'shifting approximation' or the superposition principle (because linearity in the semiconductor equations is assumed). It implies as if there were no recombination occurring at zero bias under illumination – while obviously the amount of $J_{rec}(0) = |J_{gen}| - |J_{sc}|$ of the photo-generated current density J_{gen} is recombining. Therefore, it is important to be aware that J_0 can only be related to J and V under illumination if the amount of recombination due to the forward bias is significantly larger than the recombination due to illumination:

$$|J(V)| - |J_{sc}| >> |J_{gen}| - |J_{sc}|.$$ (3)

Under 1-sun illumination, this condition is most often, but not always, fulfilled at the maximum power point (MPP) of the I–V curve of c-Si solar cells [18], but not of some other cell types [19].

Despite of these restrictions under illumination, the concept of J_0 is very useful for characterizing recombination in the various device parts of solar cells mainly because the concept can also be applied locally in the device: the external V lowers the built-in potential of the device, and a local voltage V_{loc} may be assigned to any position in the device. Because V_{loc} is equal to the separation of the quasi-Fermi energies, V_{loc} increases the product of the hole density p with the electron density n in an exponential manner according to the mass action law:

$$pn = n_{i,eff}^2 e^{V_{loc}/V_{th}}.$$ (4)

where $n_{i,eff}$ is the effective intrinsic carrier density, which is the intrinsic carrier density n_i affected by gap narrowing ΔE_g:

$$n_{i,eff}^2 = n_i^2 e^{\Delta E_g/V_{th}}.$$ (5)

Assigning Eq. (4) locally in Eq. (1) then yields:

$$J_{loc} = J_{0,loc}\left(\frac{pn}{n_{i,eff}^2} - 1\right),$$ (6)

and after algebraic manipulation:

$$J_{0,loc} = J_{loc}\frac{n_{i,eff}^2}{pn - n_{i,eff}^2}$$ (7)

Generally speaking, $J_{0,loc}$ is a measure for recombination in a device region because it is equal to the local current density J_{loc} that supplies the charge carriers for recombination in that device region, scaled by the quotient part of the formula where the excess carrier density Δn is involved, as is necessary when considering recombination rates of excess carriers. The term $pn - n_{i,eff}^2$ is only equal to Δn in a quasi-neutral region (not in a space-charge region), therefore, p, n, $n_{i,eff}^2$, and J_{loc} must be probed in the quasi-neutral region at the border of the local device region of interest. The 'loc' in $J_{0,loc}$ of the emitter or BSF is commonly replaced by 'em', 'e', or BSF, or more generally by n^+ or p^+.

Please note that the derivation of Eq. (7) is very general, because it makes use of only two basic entities: the built-in potential, which is necessary for photovoltaic action [20], and the mass action law, which is valid for the magnitudes of the built-in voltage, regardless whether device parts are doped so highly that they are degenerated and Fermi-Dirac statistics needs to be applied. Because Eq. (7) is so general, it serves as a definition of $J_{0,loc}$ in a similar manner as Eq. (1) serves as a definition of J_0: in thermal equilibrium, we again have a balance of currents obeying the principle of detailed balance. Therefore, it in unnecessary to name $J_{0,loc}$ differently than the original J_0 (the name 'recombination pre-factor' was suggested in Ref. [21,22] but apparently has not been used in the PV community).

Unfortunately, the local p, n, and J_{loc} cannot be directly measured in the device, so Eq. (7) serves mainly for evaluating $J_{0,loc}$ by means of simulations. However, $J_{0,loc}$ can be indirectly extracted from measurements. For doing this, it has proven useful to prepare the sample such that the region of interest is confined near the surface of the sample. Then, the total recombination in the sample can be taken as the sum of bulk recombination and surface recombination, which is approximately:

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_b} + \frac{2S_{eff}}{W},$$ (8)

where τ_{eff} is the measured lifetime ('effective' because it is usually influenced by various recombination mechanisms), τ_b is the bulk lifetime, W the thickness of the sample, and for two equal surfaces, a factor of 2 is inserted in front of S_{eff}. The effective surface recombination velocity S_{eff} is defined via its recombination current $J_{surf} = q\, S_{eff}\, \Delta n$, where Δn is assumed to be equal to the excess carrier density involved in τ_{eff} and τ_b. It is called 'effective' because surfaces are usually charged, so no quasi-neutrality exists. Hence, Δn must again be taken at a location where quasi-neutrality exists (e.g. in the quasi-neutral region of the sample just outside of the p–n junction or high–low junction). The last term of Eq. (8) is valid if S_{eff} is rather small [23], otherwise other expressions in Ref. [21] need be used. Because J_{surf} is a local current, we can now insert it in Eq. (6) and obtain:

$$S_{eff} = \frac{J_{0,loc}}{q\Delta n}\left(\frac{pn}{n_{i,eff}^2} - 1\right).$$ (9)