On the Effects of the Asymptotic Behavior of Local Ideality Factor for a Two-Diode Model in Silicon Solar Cells

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Abstract. Deviations from ideality on the behavior of solar cells can be studied by the local ideality factor defined as the inverse of the slope of the *I-V* characteristic curves. In this work the local ideality factor is used to characterize damaged cells from the point of view of a two-diode model. By means of the two-diode model, only what takes place in the depletion zone is analyzed. The asymptotic study of the local ideality factor outlines three behaviors depending on the values of the parameters in the model. Dismissing any of the parameters would involve an incorrect characterization and a misunderstanding in the relevance of the components from the damaging structure.

INTRODUCTION

Non-ideal behaviors on the ideality factor observed in the characterization of solar cells are due to defects in the different stages of the manufacturing of solar cells. Several theories have been developed to explain the high values of the ideality factor, greater than 2 [1-12]. If the damage is induced by localized defects and affects to the depletion region, two regions with ideality factor, m and x, and equal to 2 are electrically connected through a resistance, and the transition from one to the other induces the high ideality factor performance [4, 12].

If a single trap defect is considered, the electronic circuit proposed to model the damage is shown in Fig. 1 [6]. The defect is connected to the rest of the cell through an interconnection resistance, R_C. The n=1 diode is not considered in the circuit as the voltage range analyzed is restricted to voltages below its influence region.

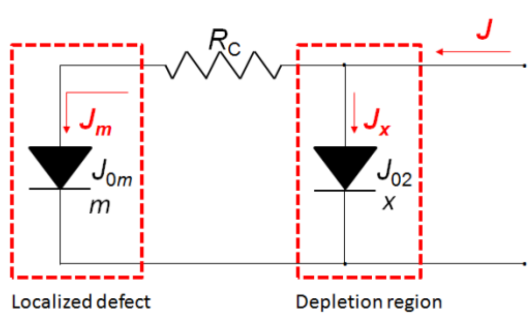

FIGURE 1. Electronic circuit for the localized defect and the depletion region behavior.

Deviations in the ideality on the *I-V* characteristic can be studied by the local ideality factor, n_{loc}, defined as the inverse of the slope of the *I-V* characteristic curve. The analytical expression of n_{loc} is expressed by equation (1) [13].

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$$n_{\text{loc}} = \frac{1}{V_{\text{T}} \frac{d(\text{Ln } J)}{dV}} \tag{1}$$

Depending on the damage the *I-V* characteristic curves vary and high values of n_{loc} are obtained; this leads to different interpretations of the phenomenon [9-12].

The aim of this work is to obtain the analytical expression of n_{loc} by means of the parameters of the two-diode model; in addition, the asymptotic analysis of the n_{loc} will help on outlining the relevance of every parameter concerning to the damage in the two-diode model.

THE LOCAL IDEALITY FACTOR FOR A TWO-DIODE MODEL

Solar cells with three different damage levels were manufactured in [12]. The damages induced were consistent with the modeling of a single defect trap, centered in E_{g} and $\zeta_{\text{n0}} = \zeta_{\text{p0}}$, with a defect small enough to have limited the spreading resistance. As a result, the damaged cells were characterized by the electronic circuit in Fig. 1. The induced electrical damage was characterized by a recombination diode and an interconnecting resistance, R_{C}, parallel connected to the rest of the circuit. The induced recombination term corresponded to m equal to 2, with a saturation current density, $J_{0\text{m}}$, in concordance with the range of the saturation current density for *p-n* junctions bordering the edge (SRH model). Moreover, this parameter seemed to be independent from the nature of the damage source. In that work R_{C}, was found to be higher than the geometrical resistance of the structure, so that its influence in the circuit should not be dismissed. The model proposed in Fig. 1 was validated by electroluminescence techniques in [14].

Fig. 2 shows the performance of the n_{loc} for the damaged solar cells. From the curves, the maximum value of n_{loc} varies from 4.5 to 8 depending on the damage, classified here as low, medium and high. The higher value comes for the less damaged cell; however, this maximum value shifts to the left with higher damage and the slope from the maximum to $n_{\text{loc}} \approx 1$ region is much more pronounced for softer damaged cells. This performance agrees with the theoretical analysis of several n_{loc}-s made in [15].

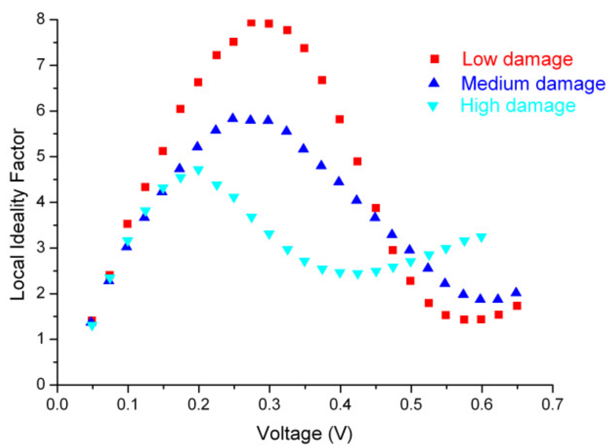

FIGURE 2. Local ideality factor of the dark *I-V* curves for three solar cells with different damage levels.

The variability in the values of the local ideality factor is such that carrying out a study of the asymptotic behavior for a two-diode model proposed in Fig. 1, would help on understanding the influence of the characteristic parameters of the damage, $J_{0\text{m}}$, m and R_{C} for limiting scenarios. The two-diode model involves only the depletion area, since in previous results the damage was characterized as p-n junction bordering the edge.

The expression of the local ideality factor for a two-diode model shown in Fig. 1 helps to analyze the variability of n_{loc} depending on the parameters affecting the depletion area. For that, based on a two-diode model and starting from equation (2), equation (3) shows the mathematical expression of n_{loc}.

$$J = J_x + J_m = J_{0x}\left[\exp\frac{V}{xV_{\text{T}}} - 1\right] + J_{0m}\left[\exp\frac{V - J_m R_{\text{C}}}{mV_{\text{T}}} - 1\right] \tag{2}$$

$$n_{\mathrm{loc}} = m\frac{\left[\left(\exp\frac{V-J_mR_C}{mV_T}-1\right)+\frac{J_{02}}{J_{0m}}\exp\frac{V}{xV_T}\right]\left[\frac{mV_T}{R_C}+J_{0m}\exp\frac{V-J_mR_C}{mV_T}\right]}{\exp\frac{V-J_mR_C}{mV_T}\cdot\left[\frac{mV_T}{R_C}\left(1+\frac{m}{x}\frac{J_{02}\exp\frac{V}{xV_T}}{J_{0m}\exp\frac{V-J_mR_C}{mV_T}}\right)+\frac{m}{x}J_{02}\exp\frac{V}{V_T}\right]} \tag{3}$$

Where J_{02} and J_{0m} are the saturation currents of the depletion region diode and the damage diode with ideality factors of x and m respectively; V_T corresponds to the thermal voltage.

ASYMPTOTIC BEHAVIOR

Based in the terms obtained in (3), and assuming that the damage itself is significantly higher than the depletion region diode of the solar cell (e. g. $J_m >> J_x$), the asymptotic behavior of the n_{loc} is obtained in order to analyze the influence of the localized defect into the two-diode set, and therefore its influence into the solar cell. Table 1 shows the relevant cases under study. For each case, the asymptotic conditions are specified and a simplified expression for n_{loc} is found.

TABLE 1. The simplified expressions for n_{loc} for the three relevant cases for asymptotic conditions.

	CASE A	CASE B	CASE C
ASYMPTOTIC CONDITIONS	$\exp\frac{V-J_mR_C}{mV_T}-1 \ll 1$	$\exp\frac{V-J_mR_C}{mV_T}-1 \gg 1$	$\exp\frac{V-J_mR_C}{mV_T}-1 \gg 1$
	$\exp\frac{V-J_mR_C}{mV_T} \ll \frac{mV_T}{J_{0m}R_C}$	$\exp\frac{V-J_mR_C}{mV_T} \ll \frac{mV_T}{J_{0m}R_C}$	$\exp\frac{V-J_mR_C}{mV_T} \gg \frac{mV_T}{J_{0m}R_C}$
	$\frac{J_{02}}{J_{0m}}\exp\frac{V}{xV_T} \ll \exp\frac{V-J_mR_C}{mV_T}$	$\frac{J_{02}}{J_{0m}}\exp\frac{V}{xV_T} \ll \exp\frac{V-J_mR_C}{mV_T}$	$\frac{J_{02}}{J_{0m}}\exp\frac{V}{xV_T} \ll \exp\frac{V-J_mR_C}{mV_T}$
LOCAL IDEALITY FACTOR	$\boldsymbol{n_{loc} \cong \frac{V}{V_T}}$	$\boldsymbol{n_{loc} \cong m}$	$\boldsymbol{n_{loc} \cong \frac{J_{0m}\exp\frac{V-J_mR_C}{mV_T}}{\frac{V_T}{R_C}+\frac{1}{x}J_{02}\exp\frac{V}{V_T}}}$

The expression for n_{loc} varies significantly depending on Case A, Case B and Case C. With some rough approximations, n_{loc} is mostly independent on the damage for Case A, but this does not happen for Case B and Case C. For Case B, indeed, n_{loc} could be simplified to the ideality factor of the damaging circuit, whereas in Case C, no clear correlation can be made without analyzing the asymptotic condition.

Case A studies the scenario in which the damage happens to be very little but the characteristic diode of the cell happens to be much little. Under this scenario, n_{loc} is mostly independent from the damage and depletion region diode influencing area. The local ideality factor corresponds to the inverse of the thermal voltage, as expected.

In an intermediate scenario, Case B, the main factor influencing the local ideality factor of the set is the damaging diode. As a result, n_{loc} can roughly be expressed by the ideality factor of this damaging-diode.

Case C deals with the scenario in which the induced damage is higher than the solar cell's second exponential term and higher than the mV_T/R_C term. Under this scenario, the local ideality factor of the diode set requires a thorough analysis as the relationship is not direct.

The transition from Case B and Case C depends merely on the value of R_C, which means that for lower values of R_C, the term mV_T/R_C will have a low value compared to high values of R_C. From [12] R_C took values from 10 to 1000 depending on the level of the damage. As a result, in that study it was said that the damaging diode was nearly the same in the cells but the difference stood in the isolation from the main structure due to the R_C value. This is to say that the scenario at which $n_{loc} \approx m$ is shorter for higher values of R_C.

CONCLUSIONS

In this work the analysis of a two-diode model for damaged solar cells has been introduced from the point of view of the local ideality factor. The mathematical expression for the local ideality factor has been obtained as a function of the characteristic parameters of a two diode model. The relevancy of every parameter in the two-diode model is outlined by means of the asymptotic expression of the local ideality factor for the model.

By the analysis of the asymptotic behavior of the local ideality factor, three different scenarios have been outlined. In Case A, no dependence on the damage is found so that the local ideality factor increases with a slope inverse to the thermal voltage. In Case B, the damage itself is the relevant factor and the local ideality factor of the set can be approximated to the local ideality factor of the recombination diode of the damage. However, for Case C, the expression of the local ideality factor is complex, dependent on both diodes and the connecting resistance. This case requires thorough analysis of the interdependence of the saturation currents of the two diodes in the two-diode model, J_{02}, J_{0m}, as well as their ideality factors, x and m, and the interconnecting resistance R_C.

The asymptotic study of the local ideality factor of a two-diode model reveals that all the parameters in the model are relevant; therefore, dismissing any of them could lead to misunderstand the effect of the damage in a solar cell. However, this analysis requires a more thorough approach in order to characterize in detail each of the three scenarios.

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