Electronic Supplementary Information

Recombination kinetics in silicon solar cell under low-concentration: Electro-analytical characterization of space-charge and quasi-neutral regions

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THEORETICAL CONSIDERATION

The n$^+$- p junction located at x_j denoted by region 1 (see Fig. 1 of manuscript) have a total width of w_j where, w_j represents the total width of SCR. The acceptor and donor concentration of emitter and base depends on the depletion region width w_n and w_p respectively through the following equations (Eq. (1) & Eq. (2)):

$$w_n = N_a w_j / N_a + N_d \tag{1}$$

$$w_p = N_d w_j / N_a + N_d \tag{2}$$

Where N_a and N_d are the acceptor and donor concentrations, respectively. For n$^+$ emitters $(N_d \gg N_a)$, $w_n \ll w_p \approx w$.

The built in potential (V_{bi}) at n$^+$- p junction depends on acceptor (N_a), donor (N_d) and intrinsic carrier concentration (n_i); where, $n_i = (N_a n_{p0})^{1/2} = (N_d p_{n0})^{1/2}$, n_{p0} and p_{n0}denoting the minority carrier concentration in the base and emitter region, respectively [1, 2]. The built-in potential is given by Eq. (3):

$$V_{bi} = (k_B T/|e|)\ln\left(N_a N_d/n_i^{2}\right) \tag{3}$$

where, k_B and T represent the Boltzmann constant and cell temperature, respectively; e is the electron charge.

The hole-accumulation and hole-depletion at p-p$^+$ junction, located at x_0, sets up a back surface built-in voltage and is denoted by region 2 in Fig. 1 of manuscript. The magnitude of the built-in voltage is given as:

$$V_{b0} = (k_B T/|e|)\ln\left({N_a}^{+}/N_a\right) \tag{4}$$

An electric field associated with p-p$^+$ junction acts as a potential energy barrier to the minority electrons. This electric field repels electron back towards n$^+$-p region reducing the surface recombination and increasing the cells efficiency. The same polarity of V_{bi} and V_{b0} indicates that emitter-base and p-p$^+$ junction both are in series. The above discussed regions (region 1 and 2) along with a leaky Schottky barrier formed at the back contact of aluminum [3, 4] are incorporated in the single diode model of a mono-crystalline Si solar cell (Fig. S1) [4-7]. Assuming that electrons are effectively repelled by back surface field associated with p-p$^+$ junction, the resistance R_{SH} in Fig. S1 describes the main leakage path for electrons [8] across the n$^+$-p junction of the cell.

I_{PH}, I and I_{SH} are the light generated current, net output current and current flowing through R_{SH} of the cell respectively. The net output current (I), $= I_{PH} - I_d^{'}$. The current flowing through the p-p$^+$ junction, $I_d^{'} = I_d + I_{SH}$, where I_d is the diode current through n$^+$-p junction.

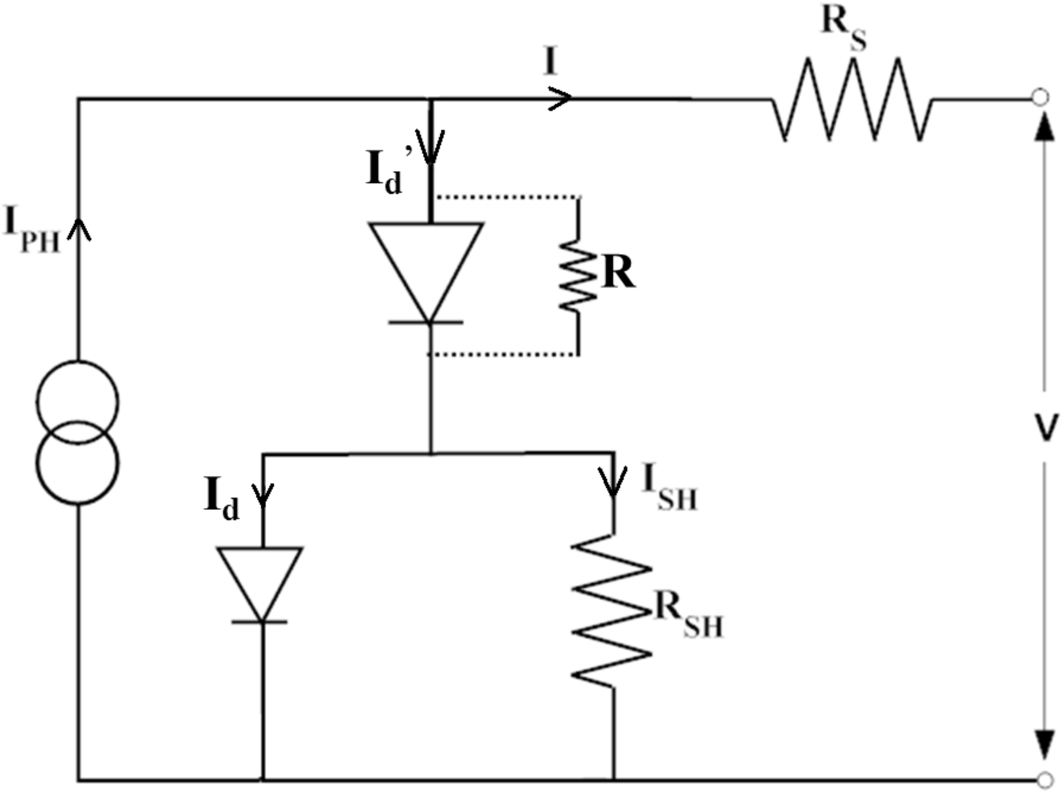

Fig. S1 The standard single diode model of a mono-crystalline silicon solar cell

Generally, for Si solar cells $I_{PH} \gg I_{SH}$, so in Eq. 1 (manuscript), the small diode and ground-leakage currents can be ignored under zero-terminal voltage. Therefore the short-circuit current is approximately equal to the photocurrent. The temperature and illumination dependent expression for I_{PH} is given by Eq. (5):

$$I_{PH} = \left[I_{SC} + K_I(T_C - T_{Ref})\right]\lambda \tag{5}$$

The saturation current of a solar cell varies with the cell temperature, which is described by Eq. (6):

$$I_0 = I_{RS}\left(\frac{T_C}{T_{Ref}}\right)^3 exp\left[\frac{q(E_{Fn} - E_{Fp})\left(\frac{1}{T_{Ref}} - \frac{1}{T_C}\right)}{mk_B}\right] \tag{6}$$

For the case of $q(E_{Fn} - E_{Fp}) \approx V_{OC}$ in Eq. (6), the conditions for QNR prevail and under these conditions, the ideality factor, $m = 1$, otherwise, for the case of $q(E_{Fn} - E_{Fp}) > V_{OC}$ the conditions of SCR prevail, that results in the ideality factor, $m = 2$. Reverse saturation current of the cell at reference temperature depends on the open-circuit voltage (V_{OC}) and can be approximately obtained by following equation as given by Tsai et al. [9]:

$$I_{RS} = I_{SC}/\left[exp\left(qV_{OC}/N_S k_B A T_C\right) - 1\right] \tag{7}$$

The maximum power output of LCPV cell is related to the I_{SC} and V_{OC} by following equation:

$$P_{MAX} = FF \times V_{OC} \times I_{SC} \tag{8}$$

The values of I_{SC}, V_{OC} and FF can be determined from the I-V characteristics. The efficiency of the solar cell in relation with the P_{MAX} is given by following equation:

$$\eta = P_{MAX}/(A \times \lambda) \tag{9}$$

A is the area of the solar cell and λ is the incident solar radiation (kW/m^2).

The capacitive components of Si solar cell are represented by emitter capacitance (C_{de}), transition capacitance (C_T) and the base capacitance (C_{db}). The resistive and capacitive components at p-p$^+$ interface are represented by R_{pp^+} and C_{pp^+} respectively. The total junction resistance at n$^+$-p junction (see Fig. 1 of manuscript) is given by Eq. (10).

$$R_j = \frac{R_d R_{SH}}{R_d + R_{SH}} \tag{10}$$

where R_d is the diffusion resistance of n$^+$-p junction. Analytical expression for diffusion resistance (R_d) is obtained by parallel combination of the resistances offered by emitter and base junction as given by Eq. (11).

$$R_d = \frac{R_{db}R_{de}}{R_{db} + R_{de}} \tag{11}$$

Recombination properties of a solar cell can be explored by observing the variation of R_d with voltage or by comparing different solar cells having different morphology or energy band gaps. At low forward bias condition, R_j saturates to a value that might be due to the dominating shunt resistance (R_{SH}) as a consequence of unavoidable leakage currents. Under strong forward bias or in quasi-neutral region (QNR), the last term of the denominator in Eq. 4 (manuscript) can be neglected and the total D.C. resistance reduces to Eq. (12):

$$R_{dc} = \frac{\left(R_d + R_s + R_{pp^+}\right)}{\left[1 + I\left(\frac{\partial R_s}{\partial V}\right)\right]} \tag{12}$$

The net capacitance (C_j) for n$^+$-p junction is given by Eq. (13):

$$C_j = \left(C_T + C_d\right) \tag{13}$$

where, C_d represent the diffusion capacitance of n$^+$-p junction. The relation between C_d and diffusive component of base (C_{db}) and emitter (C_{de}) region (see Fig. 1 of manuscript) is given by Eq. (15):

$$C_d = \left(C_{db} + C_{de}\right) \tag{14}$$

$$C_d = \frac{e^2 n_i^{\,2}}{mk_BT}\left(\frac{L_p}{N_d} + \frac{L_n}{N_a}\right)\exp\left(\frac{|e|V_j}{mk_BT}\right) \tag{15}$$

where L_p and L_n represent the diffusion length of holes and electrons respectively.

In general, diffusion capacitance (also known as chemical capacitance, C_μ) is governed by excess carriers and related to the change in electron occupancy of density of states $\left(C_\mu = q^2 L g_n(V_F)\right)$ where L is the active thickness of Si solar cell. At higher forward bias, the electron occupancy of density of states progresses leading to an increase in the value of C_d. The transition capacitance, C_T (also known as depletion-region capacitance, shown in Fig. 1 of manuscript) decreases or remains constant with increasing reverse bias which is expected since the separation of charges increase with applied bias. The voltage dependence of C_T is utilized for the extraction of built-in potential and doping density of n$^+$-p junction. By measuring the junction capacitance (C_j) and junction resistance (R_j) over a voltage range, the values of C_T, and C_d as well as R_{SH} and R_d can be determined. The transition capacitance is given by Eq. (16) [10]:

$$C_T = \left(\frac{(\varepsilon|e|N_a)}{2\,(V_{bi} - V_j)}\right)^{1/2} \tag{16}$$

By combining these identities the minority carrier lifetime in emitter and base region of n$^+$-p junction is determined. The effective carrier lifetime τ_j can be given by Eq. (17):

$$\tau_j = 2\,R_j C_j \tag{17}$$

The net impedance (Z) of the equivalent circuit shown in Fig. 1 (manuscript) is a series combination of the impedances, Z_j and Z_{pp+} of the n$^+$-p and the p-p$^+$ junctions, respectively. The R_{pp^+} - C_{pp^+} loop will remain undetected in EIS as long as the following conditions are satisfied: (i) $Z'_j \gg Z'_{pp+}$, and (ii) $|Z''_j| \gg |Z''_{pp+}|$, where the primed and double primed terms represent real and imaginary impedance components respectively. Considering the individual impedance elements of Fig. 1 (manuscript), these two conditions can be written as follows [11]:

$$\frac{R_j}{1+\left(\frac{\omega}{\omega_j}\right)^2} \gg \frac{R_{pp+}}{1+\left(\frac{\omega}{\omega_p}\right)^2} \tag{18}$$

$$\frac{(R_j)^2 C_j}{1+\left(\frac{\omega}{\omega_j}\right)^2} \gg \frac{(R_{pp+})^2 C_{pp+}}{1+\left(\frac{\omega}{\omega_p}\right)^2} \tag{19}$$

$\omega_j = {}^1/2R_jC_j$ (for $\omega_j\tau \ll 1$) is the rate constant of recombination and equivalent to the reciprocal of the electron lifetime, ω is the angular frequency and $i = (-1)^{1/2}$. The carrier collection efficiency is governed by a key parameter known as diffusion length, L_n. The diffusion length is related to recombination characteristic angular frequency $(i.e.\ \omega_j = {}^{D_n}/{L_n}^2)$.

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