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A new approach to study organic solar cell using Lambert W-function

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Abstract

Organic photovoltaic solar cells bear an important potential of development in the search for low-cost modules for the production of domestic electricity. One of the main differences between inorganic and organic solar cells is that photo-excitation in these materials does not automatically lead to the generation of free charge carriers, but to bind electron–hole pairs (exciton) with a binding energy of about 0.4 eV. Till now various numerical methods using approximations have been reported to study different aspects of organic solar cells. For the first time an accurate method using Lambert W-function is presented to study different parameters of organic solar cells.

Keywords: Organic solar cells; Lambert W-function; *I–V* characteristics

1. Introduction

Organic photovoltaic (OPV) solar cells are emerging as a potential alternative to existing inorganic solar cells. The key property, which makes OPV solar cells so attractive, is the potential of reel-to-reel processing on low-cost

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substrates with standard coating and printing processes. Up to now main efforts have focused on the improvement of the solar conversion efficiency which has seen a significant jump from a 1% yield 17 years ago [1] to a 5% yield [2]. This opens the perspective of seeing very soon, on a typical 5 yr time scale, OPV solar cells with solar efficiencies in excess of 10%.

Most organic semiconductors are intrinsic semiconductors and the primary excitation is coulomb-bound exciton [3–5]. Photovoltaic cells made from single organic semiconductors therefore achieve tiny power conversion efficiencies and low incident photon to current or external quantum efficiency (EQE). A high EQE does not guarantee good photovoltaic conversion, but it is a prerequisite. For OPV devices comprising a single polymeric semiconductor layer, EQE are typically below 1%. A solution was only found in 1995 when several groups independently showed that the EQE could be enhanced by several orders of magnitude upon blending two materials with relative preferences for positive and negative charges [6].

Three currently existing type of OPV solar cells are: (a) dye-sensitized solar cells [7] (DSSCs), (b) planar organic semiconductor cells [8–10] and (c) high surface area or bulk heterojunction cell [11–15].

Major problems associated with OPV solar cells are: (a) Spectral mismatch — most of the organic semiconductors investigated today absorb in visible range, while the sun has its maximum photon density around 700 nm. (b) Certain intrinsic limited durability of organic compound — when electrons are excited to higher orbitals, antibinding states arise and the probability for decomposition of compound increases. (c) Effective light harvesting in a blended photovoltaic device demands efficient charge separation and transport.

Advantages of organic materials for photovoltaic solar cell applications include: (a) they can be processed using spin coating or doctor blade techniques (wet-processing) or evaporation through a mask (dry-processing). (b) Amount of organic materials are relatively small (100 nm thick films) and large-scale production (chemistry) is easier than for inorganic materials. (c) They can be tuned chemically in order to adjust separately band gap, valence and conduction energies, charge transport, as well as solubility and several other structural properties. (d) The vast variety of possible chemical structures and functionalities of organic materials (polymers, oligomers, dendriomers, organo-minerals, dyes, pigments, liquid crystals, etc.) favor an active research for alternative competitive materials with desired photovoltaic properties.

In the present work an equivalent circuit for organic solar cell is taken from the literature [2]. The diode current equation for that circuit is derived, which is found to be transcendental in nature. The exact explicit solutions are determined using Lambert W-function [16–17]. Various parameters of organic solar cell are then derived using previously determined solutions.

2. Theory

The equivalent circuit diagram (ECD) for organic solar cell by Brabec [2] is given in Fig. 1. The voltage V across the cell is given by KVL and KCL equations:

$$V = I_{R\mathrm{sh}}\, R_{\mathrm{sh}} + IR_{\mathrm{S}}, \tag{1}$$

$$I = -I\mathrm{ph} + I_{R\mathrm{sh}} + I_{\mathrm{d}}, \tag{2}$$

$$I_{\mathrm{d}} = I_{\mathrm{o}}\, \mathrm{e}^{((V - iR_{\mathrm{s}})V_{\mathrm{th}}/n)}. \tag{3}$$

We are assuming $i = I$.

Solving the above equation we get

$$\ln\left(\frac{i + I_{\mathrm{ph}}}{I\mathrm{o}} - \frac{V - iR_{\mathrm{s}}}{I\mathrm{o}\; R_{\mathrm{sh}}} + 1\right) = \frac{V - iR_{\mathrm{s}}}{nV_{\mathrm{th}}}, \tag{4}$$

where i and V are terminal current and voltages, respectively, I_0, R_{s}, R_{sh}, n *and* V_{th} are the saturation current density, the serial and parallel resistivity, the diode ideality factor, and the temperature potential, respectively.

The processes associated with various blocks in ECD of organic solar cell are: The current source generates current I_{ph} upon illumination, which is equal to number of dissociated exciton/s, i.e., number of free electron/hole pairs immediately after generation — before any recombination takes place.

The shunt resistor R_{sh} is due to recombination of charge carriers near the dissociation site (e.g. donor/acceptor interface) and it may also include recombination farther away from the dissociation site (e.g. near electrode).

The series resistor R_{s} considers conductivity i.e. mobility of specific charge carrier in the respective transport medium, where the mobility is affected by space charges and traps or other barriers (hopping).

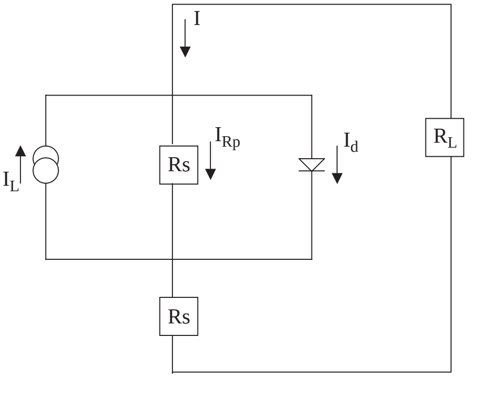

Fig. 1. Equivalent circuit for organic solar cell.

The ideal diode represents voltage-dependent resistor, that takes into account the asymmetry of conductivity .The diode is responsible for the nonlinear shape of the *I–V* curves. The diode characteristics are not necessarily Shockley type.

The cell can generate terminal voltage between 0 and V_{oc} depending on the size of load resistor. For obtaining voltages beyond this limit, an external voltage source is required. The voltage range between 0 and V_{oc} can be simulated by the same voltage source so that applying an external voltage can scan entire ranges. Since current for voltages beyond range $0 < V < V_{oc}$ is delivered from external voltage source so the external voltage source then acts as a current amplifier to boost the photosensitivity but the actual EQE of the cell remains same.

Some modifications in the ECD of the organic cell are inclusions of another diode, a capacitor and an extra shunt resistance. Here, diode accounts for the formation of extra blocking current, which can affect the *I–V* curves in the third quadrant. The capacitor takes into account, charging/discharging and other time-dependent effects that can be significant since the contact area can be large and distance between the electrodes is small. Extra shunt resistance considers the effects of recombination losses near the electrodes in addition to shorts due to pinholes or significant conductivity of bulk material.

The current–voltage equation of ECD of organic solar cell is transcendental in nature, hence current and voltage can be separated using Lambert W-function [ref]

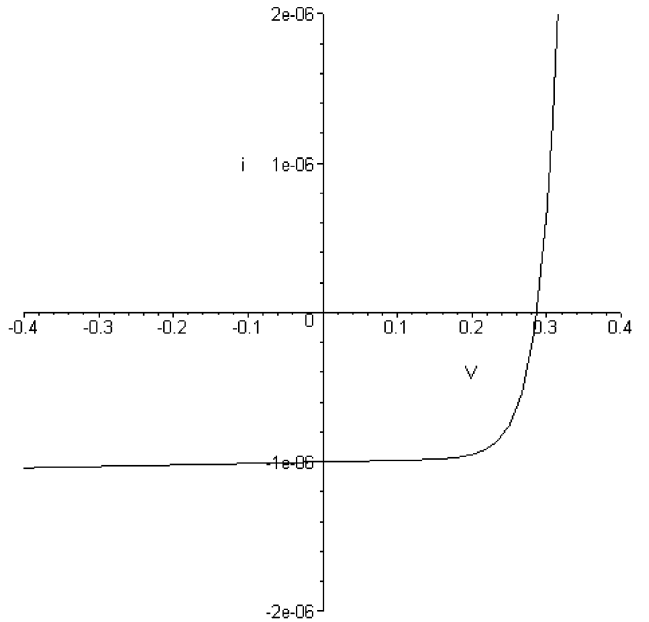

Fig. 2. Typical *I–V* characteristics of organic solar cell.

as follows:

$$i = \frac{-V + \left(-\mathrm{LambertW}\left(\frac{R_s\ I_o\ Rp\,\mathrm{e}^{\left(\frac{R_{sh}(R_s\ I_{ph}+R_s\ I_o+V)}{nV_{th}(R_s+R_{sh})}\right)}}{R_s\ n\ V_{th}+R_{sh}nV_{th}}\right) + \frac{R_{sh}(R_s\ I_{ph}+R_s\ I_o+V)}{nV_{th}(R_s+R_{sh})}\right)nV_{th}}{R_s}, \tag{5}$$

$$V = i\ R_s + \left(-\mathrm{LambertW}\left(\frac{I_o\ R_{sh}\,\mathrm{e}^{\left(\frac{R_{sh}(i+I_{ph}+I_o)}{nV_{th})}\right)}}{nV_{th}}\right) + \frac{R_{sh}(i+I_{ph}+I_o)}{nV_{th}}\right)nV_{th}. \tag{6}$$

The arguments of the W-function in Eqs. (5) and (6) only contains corresponding variable and the model's parameters.

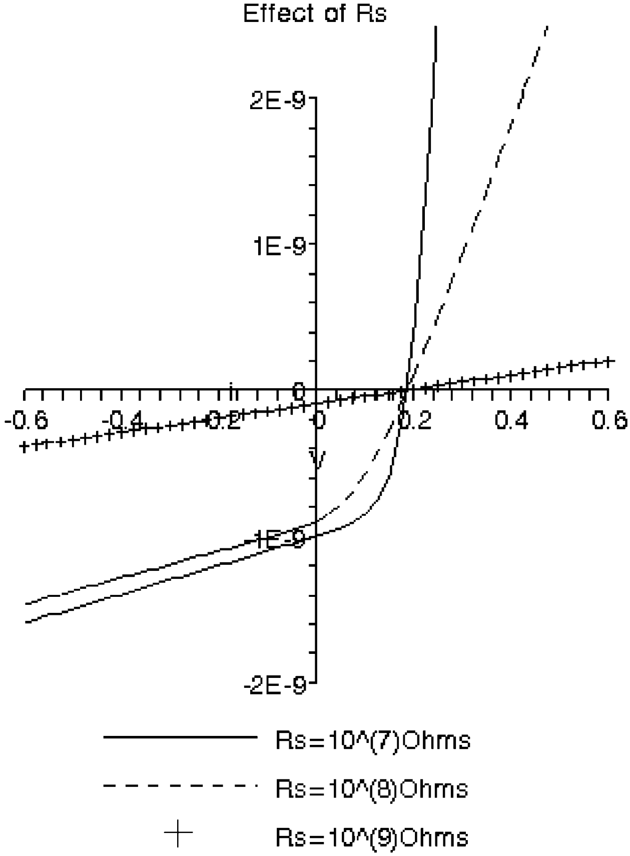

Fig. 3. Effect of R_s on I–V of organic solar cell.

Short circuit current (I_{sc}) can be obtained by substituting $V=0$ in Eq. (5) as follows:

$$I_{sc}=\frac{\left(-\mathrm{LambertW}\left(\dfrac{R_s\ I_o\ R_{sh}\ e^{\left(\frac{R_{sh}(R_s\ I_{ph}+R_s\ I_o)}{nV_{th}(R_s+R_p)}\right)}}{R_s\ nV_{th}+R_{sh}nV_{th}}\right)+\dfrac{R_{sh}(R_s\ I_{ph}+R_s\ I_o)}{nV_{th}(R_s+R_{sh})}\right)nV_{th}}{R_s}.$$

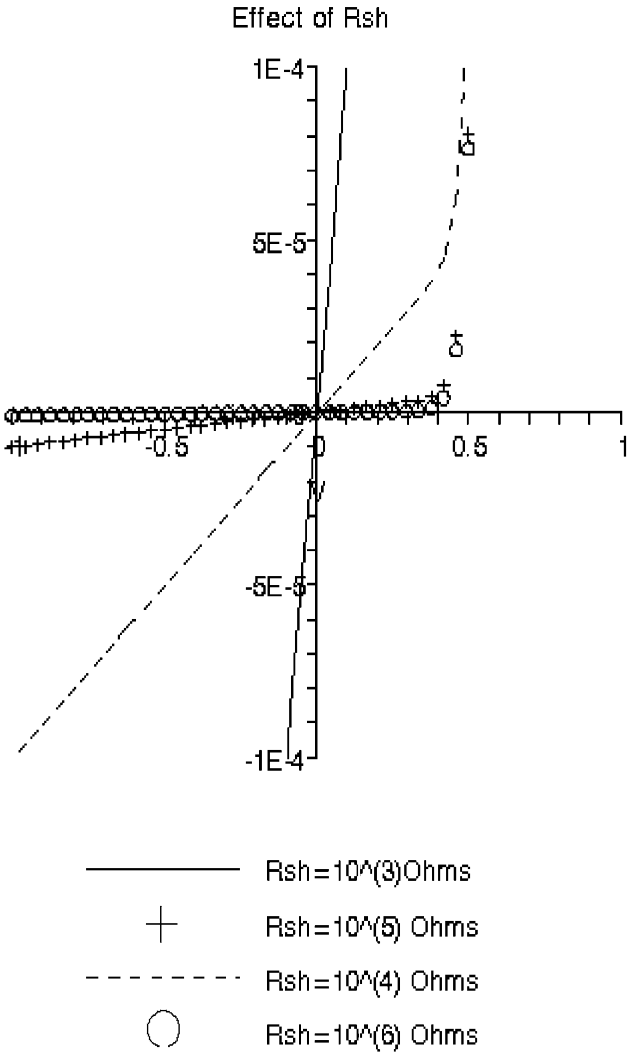

Fig. 4. Effect of R_{sh} on I–V of organic solar cell.

Open circuit voltage (V_{oc}) can be obtained by substituting $i = 0$ in Eq. (6) as follows:

$$V_{oc} = \left(-\mathrm{LambertW}\left(\frac{I_o\ R_{sh}\,\mathrm{e}^{\left(\frac{R_{sh}(I_{ph}+I_o)}{nV_{th}}\right)}}{nV_{th}} \right) + \frac{R_{sh}(I_{ph}+I_o)}{nV_{th}} \right) nV_{th}.$$

Organic solar cells usually have lower mobilities and smaller charge carrier concentration in comparison with their silicon counterpart. This leads to considerably smaller currents in most organic solar cells. In fact both the dark and light currents are about 1000 times smaller ($I_o \approx 1\,\mathrm{pA}andI_{sc} = 1\,\mathrm{nA}$) so that light current in these devices is as big as dark current in silicon devices, while the dark current is still about 1000 times smaller.

Organic solar cells very often suffers from high series resistance and in addition, relatively small R_{sh} values(R_{sh} is typically more than 3 orders of magnitude larger than R_s). As a consequence, losses due to both resistors are higher than in silicon cells.

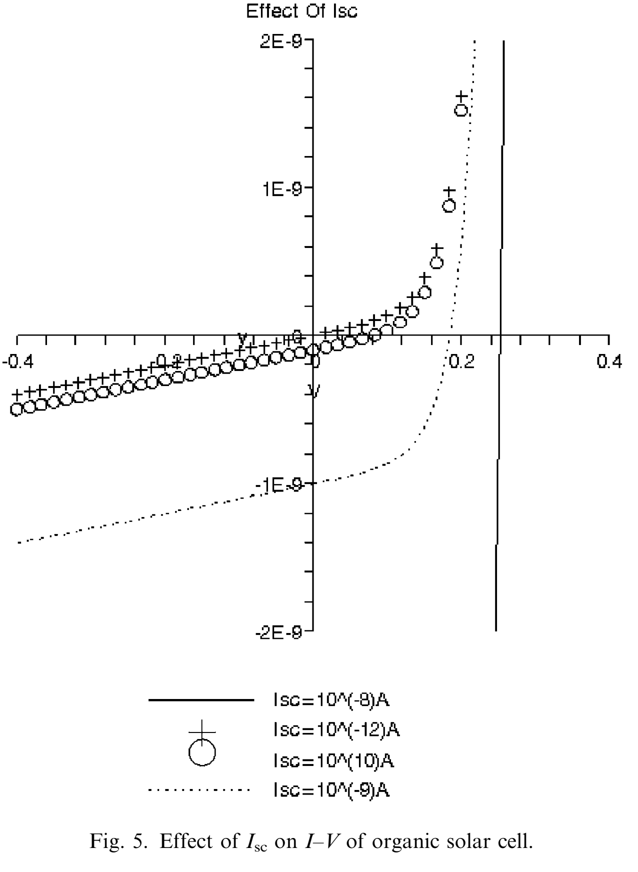

Fig. 5. Effect of I_{sc} on I–V of organic solar cell.

For a typical organic solar cell ($n = 1.0$, $V_{th} = 25\,\mathrm{mV}$, $I_o = 1\,\mathrm{pA}$, $I_{ph} = 1\,\mu\mathrm{A}$, $R_s = 10\,\Omega$, $R_{sh} = 10\,\mathrm{K}\Omega$), the current–voltage characteristic using Eq. (5) (involving Lambert W-function) is shown in Fig. 2.

From the characteristic, it is clear that it is similar to that of inorganic solar cell with a difference that, value of short circuit current is reduced.

Effect of changes in series resistance(R_s) ,shunt resistance(R_{sh}) and short circuit current (I_{sc}) is also studied.

Fig. 3 Shows the effect of change in series resistance. From the plot it is clear that an increase in the series resistance decreases FF and the slope in the first quadrant. R_s is increased to the order of R_{sh}. This Plot also shows that an increase in R_s can decrease that short circuit current but not V_{oc}. R_{sh} dominates the slope in the third quadrant.

Fig. 4 Shows the effect of change in shunt resistance. It is more or less same as that for inorganic solar cell with a difference that, around 1000 times larger values are needed for the same response.

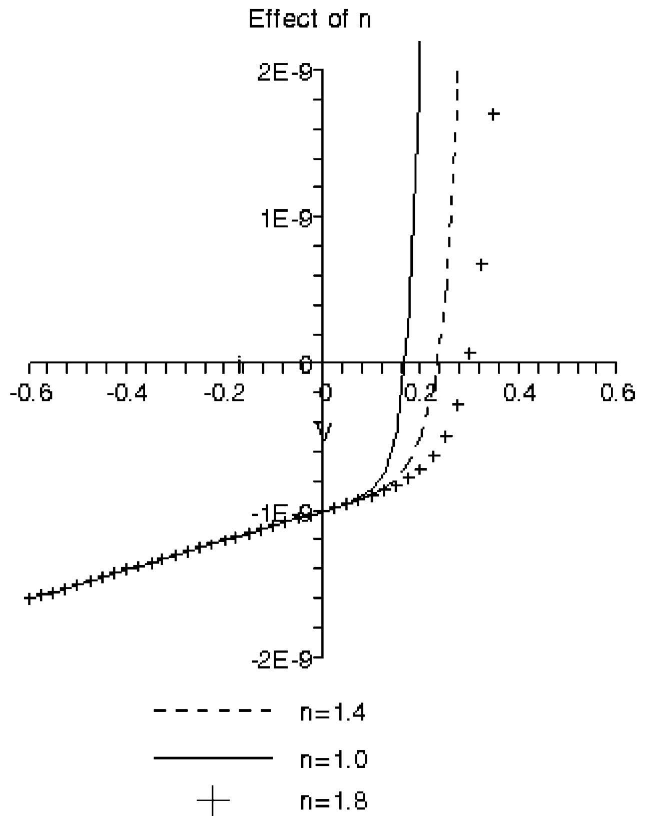

Fig. 6. Effect of ideality factor (n) on I–V of organic solar cell.

Fig. 5 Shows the effect of change in short circuit current (I_{sc}). It can be shown that low I_{sc} values can result in considerably small FF and lower V_{oc} values compared to higher I_{sc} values.

Fig. 6 Shows the effect of change in diode ideality factor (n). It is clear that I_{sc} remains same for different values of n but V_{oc} changes.

3. Conclusion

I–V Characteristics for different parameters are plotted using Lambert W-function. When compared with those plotted in Ref. [6] they are found to be better. This indicates that studies of organic solar cells using Lambert W-function, which provides exact explicit analytical solutions, is a better alternative to study the organic solar cells.

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