Open-circuit voltage of organic photovoltaics: Implications of the generalized Einstein relation for disordered semiconductors

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A B S T R A C T
The open-circuit voltage dependence on light intensity and temperature is calculated for organic photovoltaics, taking into account the generalized Einstein relation for disordered semiconductors. The results show that open-circuit voltage losses in bulk-heterojunction organic solar cells are affected from the diffusion enhancement inherent to disordered semiconductors. The model is validated by the fitting to recently published experimental data.

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1. Introduction

Organic photovoltaics (OPV) are a promising alternative to conventional solar cells based on inorganic photovoltaics (PV) due to their low cost processability, light weight and flexibility. In particular, intense research has been devoted to the improvement of the bulk heterojunction (BHJ) OPV, in which a donor type conjugated polymer and an acceptor type fullerene (or fullerene derivatives, such as [6,6]-phenyl-C61-butyric acid methyl ester, PCBM) are mixed to form the photoactive layer [1,2]. Upon illumination, light is absorbed by the photoactive layer resulting in the formation of a neutral and stable excited state (an exciton). Free carriers can be generated by exciton dissociation at a donor–acceptor interface, leaving the electron on the acceptor’s (PCBM) lowest unoccupied molecular orbital (LUMO) energy level and the hole on the conjugated polymer highest occupied molecular level (HOMO), increasing the system’s electro-chemical potential.

Although major achievements have been made in increasing the BHJ OPV power conversion efficiency (PCE, which has the current record of 8.3% [3]), further improvement of efficiencies needs to be achieved in order to allow entry of these devices into the PV-market.

One of the most important factors controlling the cell PCE is the open-circuit voltage ($V_{OC}$), which reflects the amount of electro-chemical potential generated in the cell under illumination. Understanding of the $V_{OC}$ physical origin is critical for improvement of the BHJ concept. Though it has been known for decades for inorganic PV cells, it is still a matter of debate for the BHJ OPV devices. It has been accepted only recently that the origin of the $V_{OC}$ for BHJ OPV is the splitting of the electro-chemical potentials of holes and electrons, determined by the Fermionic nature of charge carriers [4,5], rather than the difference between the electrode’s working functions (in the metal–insulator–metal model [6,7]), or the HOMO–LUMO difference [8,9]. (The latter hypothesis was accompanied by the “missing 0.3 V” of unknown origin, eluding scientists in the OPV field for years.)

Although new models, which explain the $V_{OC}$ dependence upon light intensity and temperature, have been published [4,5,10], fundamental physics regarding the electro-chemical equilibrium in disordered organic semiconductors and, in particular, deviations from the usually accepted Einstein’s relation (known as the Generalized Einstein relation or GER) have yet to be implemented. The association of the GER to disordered organic semiconductor devices was first made by Roichman and Tessler [11] who relied on the Gaussian Disorder Model (GDM, presented by Bässler [12]), and applied its implications on OLEDS [11] and organic diodes [13]. Recently, more models incorporating the GDM and its implications have been used in the analysis of organic semiconductor devices [14,15], though with no reference to the GER effect on the properties of the open-circuit voltage in OPVs.

In this article, we review the relevant disordered semiconductor physics and relate it to a simple OPV BHJ model. Simulation results for the open-circuit voltage dependence on light intensity and temperature are presented and analyzed, shedding new light
on the BHJ ideality number and its generalization, and the open-circuit voltage temperature coefficient. The results are discussed in the context of recently published experimental findings regarding the open-circuit voltage behavior.

2. The GER for disordered semiconductors

The open-circuit voltage of any photovoltaic system is originated in its electro-chemical equilibrium, where the diffusion and drift currents are equal and opposite \cite{16}. This equality also yields the ratio between the diffusion coefficient \(D\) and the mobility \(\mu\), which is known as the Einstein relation for charge carriers. For non-degenerate semiconductors, this relation is usually taken to be \(KT/q\), which is a consequence of using the Maxwell–Boltzmann (MB) approximation for the calculation of electron/hole densities \cite{16}. As shown by Roichman et al. \cite{11}, for disordered semiconductors having allowed states in the bandgap (as a consequence of energetic disorder), this relation is multiplied by an “enhancement factor”—hence implying a change in the open-circuit electro chemical equilibrium.

The GER is calculated from the electro-chemical equilibrium, following Ref. \cite{17}. The drift and diffusion currents are derived for electrons, for simplicity:

\[
J_{\text{diff}} = -qDn\nabla\phi = \mu_n n \nabla(\bar{\mu} - \mu),
\]

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\]

\[
\bar{\mu}_{\text{en}} = \mu_{\text{en}} + \frac{q\phi_{\text{en}}}{kT},
\]

where \(n\) is the electron density, \(\bar{\mu}\) is the electro-chemical potential (quasi-Fermi level), \(\mu\) is the chemical potential (Fermi level), \(\phi\) is the electric potential, \(\mu_{\text{en}}\) is the electron mobility and \(q\) is the electron's fundamental charge. In electro-chemical equilibrium, \(J = 0\), \nabla \bar{\mu} = 0\)

and

\[
J = \mu_n n \nabla(\bar{\mu} - \mu) = \mu_n n \nabla(\bar{\mu}) - \mu_n n \nabla \mu (q \frac{\nabla \phi}{kT} + \frac{q\mu_n}{kT}) = 0.
\]

The last term in brackets must vanish, giving

\[
\frac{D}{\mu_n} = \frac{1}{q \frac{n}{\nabla \mu}}.
\]

The enhancement factor \(\eta\) is defined as

\[
\eta = \frac{1}{kT \frac{n}{\nabla \mu}} = \frac{1}{kT} \left( \frac{\nabla \mu}{\nabla \mu} \right)^{-1},
\]

so that the Einstein relation is

\[
\frac{D}{\mu_n} = \frac{\eta}{q} kT,
\]

where \(\eta\) is usually 1 for non-degenerate semiconductors, and can be greater than 1 for disordered organic semiconductors \cite{11}, meaning that the diffusion/mobility ratio can be greater than the usual value of \(KT/q\). This causes the enhancement of the diffusion over the drift current and the change in the electro-chemical equilibrium, affecting the \(V_{OC}\) as will be shown below.

For the calculation of \(\eta\), \(n\) must be calculated by the full Fermi–Dirac integral

\[
m(E_f) = \int g(E)f_{\text{dir}}(E,E_f)dE,
\]

where \(g(E)\) is the density of states (DOS) function. Here, we use the GDM \cite{11,12}, which approximates the existence of localized states (in space and energy) due to disorder as a Gaussian distribution around the mean energy \(E_0\):

\[
g(E) = \frac{N_e}{\sqrt{2\pi}\sigma} e^{-\frac{(E-E_0)^2}{2\sigma^2}},
\]

where \(N_e\) is the effective number of states and \(\sigma\) is the Gaussian variance, which reflects the DOS amount of disorder.

3. BHJ OPV model

In order to simulate the OPV cell open-circuit voltage behavior, we employ a simple model of BHJ cells. On the microscopic level, our BHJ consists of a P3HT:PCBM mixture, which is assumed to be intrinsic and homogenous. This enables us to treat it as an effective medium, with the P3HT HOMO level and the PCBM LUMO level \(E_0 = 1\) \text{eV}, Fig. 1a demonstrates the energy levels and the corresponding Gaussian DOS locations.

On the cell level, our cell has the structure of a p-i-n device, with the intrinsic BHJ as the absorbing medium between the two selective membranes. In open-circuit, the two quasi Fermi levels are constant, yielding the open-circuit voltage as their difference (Fig. 1b).

In order to analyze the \(V_{OC}\) dependence on illumination and temperature, one must first calculate it as a function of the varying electron/hole densities. Since the difference in the electrons/holes quasi-Fermi levels are constant, we only need to calculate it for one point in the cell’s active layer. For simplicity, this point is chosen to be the cell’s middle, where the \(V_{OC}\) is evenly distributed between the two quasi-Fermi levels, making it possible to treat only the electron side, with the basic assumption that \(n = p\) for an intrinsic absorber.

The open-circuit voltage is calculated from the quasi Fermi level dependence on charge density, as follows:

\[
V_{OC}(n,T) = \frac{1}{q} (E_{\text{fHOMO}}(n,T) - E_{\text{fLUMO}}(n,T)) = \frac{\eta}{q} (E_{\text{fHOMO}}(n,T) - E_i),
\]

where the energy levels are \(E_{\text{fLUMO}} = -4.3\) \text{eV}, \(E_{\text{fHOMO}} = -5.3\) \text{eV} and \(E_i = -4.8\) \text{eV} (as shown in Fig. 1a). The disorder level \(\sigma\) was varied between 0.05 \text{eV} and 0.15 \text{eV} (typical values for disordered organic semiconductors \cite{11,14,15}) in order to obtain the \(V_{OC}\) response to different disorder levels.

4. Results and discussion

4.1. \(V_{OC}\)-charge density dependence

Fig. 2a presents the open-circuit voltage versus the quantity \(np\) (calculated for \(T = 298\) \text{K} and three disorder levels, as mentioned above), which was chosen due to considerations that will be

![Fig. 1. (a) The D/A interface: electrons in bold circles near the PCBM LUMO; holes in empty circles near the P3HT HOMO. (b) Device illustration in open-circuit. The double arrow marks the open-circuit voltage.](image)
discussed in the next section. The $V_{OC}$ decrease relative to $E_g/q$ is the result of two contributions, marked by $A_1$ and $A_2$, corresponding to the shift caused due to the MB statistics and due to the disorder effect, respectively. The expression for the reduced $V_{OC}$ is [4,10]

$$qV_{OC} = E_g - A_1 - A_2,$$

where,

$$A_1 = KT \ln \left( \frac{N_c^2}{np} \right)$$

and the approximated expression for $A_2$, as given in [10] is

$$A_2 = \frac{\sigma_n^2 + \sigma_p^2}{2KT} \, (\sigma_n = \sigma_p = \sigma).$$

In this description, $A_2$ is a lower limit for the possible voltage offset caused by the disorder [10] (independent of charge density), while $A_1$ depends on the charge density (i.e., light intensity) and originates directly from the MB statistics.

Fig. 2a shows that while the MB shift is fundamental and unchanging for different disorder levels, $A_2$ increases with $\sigma$ (as in Eq. (14)) and decreases with $np$—an effect not considered by Eq. (14). It points out that $A_2$ is not a lower limit; in fact, $A_2$ approaches zero for very high $np$ values, meaning that the maximal value attainable for $V_{OC}$ is $E_g/q$ (=1 V here). The reason for this $A_2$ decrease is the enhancement in the $V_{OC}$–$np$ slope, which is shown in Fig. 2b. Eq. (15) depicts the expression of this slope, where Eq. (7) is used for the last equality:

$$\frac{\partial V_{OC}}{\partial \ln(np)} \bigg|_T = \frac{\partial (E_{fn}(n,T) - E_i)}{q} \frac{\partial \ln(n^2)}{\partial \ln(n^2)} = \frac{2 \varepsilon(E_{fn})}{2q \varepsilon(n)} = 1 \cdot \frac{\eta}{q}. \frac{KT}{q}.$$

Thus, the $V_{OC}$–$np$ slope enhancement is identical to the GER $\eta$, which is 1 for the non-disorder case and increases with the GDM variance and charge density. The reason why this enhancement is not taken into account by Eq. (14) is that it relies on the mean energy of charge carriers to be constant and equal to $\sigma^2/KT$ [5], which only applies for low quasi-Fermi levels since it is derived for the MB approximation [12]. The origin of $A_2$ is illustrated in Fig. 3; the occupied states form a Gaussian energy, shifted from the DOS [12].

Comparing to the MB case, the electron quasi-Fermi level “needed” in order to achieve the same charge density is lower and thus is reduced by $A_2 = \sigma^2/KT$ in 3a (where Eq. (14) applies) and by $A_2 < \sigma^2/KT$ in 3b, where the $E_{fn}$ is relatively high and the MB approximation is not valid. $A_2$ can be fully formulated by

$$A_{2\eta~np} = \frac{E_g}{q} \frac{KT}{q} \ln \left( \frac{N_c^2}{np} \right) - \frac{KT}{q} \int_{np}^{np} \eta(np) \, d\ln(np).$$

The case analyzed in [10] is therefore a special case of this solution, in which $A_2$ is constant (when the GER is not taken into account and $\eta=1$), as shown by Eq. (17):

$$A_{2\eta} = \frac{E_g}{q} \frac{KT}{q} \ln \left( \frac{N_c^2}{np} \right) - \frac{KT}{q} \int_{np}^{np} \ln(np) \, d\ln(np) = \frac{E_g}{q} \frac{KT}{q} \ln \left( \frac{N_c^2}{np} \right) - \frac{KT}{q} \ln \left( \frac{np}{n_p} \right) = \frac{E_g}{q} \frac{KT}{q} \ln \left( \frac{N_c^2}{np} \right). \frac{\eta}{q}.$$

This expression is independent of charge density and equals $\sigma^2/KT$ for a limited charge density and temperature ranges, as will be elaborated in the next section. Notice that $A_2$ increases with
Fig. 4 shows the difference between the general and the \( \eta = 1 \) cases. Indeed, in the latter case the \( V_{OC} \) is limited by the maximal value of \( (E_g - \Delta E_z)/q \), whereas for the general case when the GER is taken into account it is \( E_g/q \).

4.2. Ideality number generalization and enhancement

The open-circuit voltage dependence on light intensity is related to charge density through the fact that the recombination rate \( R \) equals the generation rate \( G \) everywhere throughout the device. The recombination rate is defined by the dominating recombination mechanism. We will consider the three possible types of recombination: trap-assisted monomolecular (first order), which is equivalent to Shockley–Read–Hall (SRH) recombination in inorganic photovoltaics [4,18]; bimolecular (second order), which is equivalent to band-to-band recombination [4]; trimolecular (third order), equivalent to Auger recombination [19]. It was shown that SRH recombination is the dominating type for ultra-low light intensities [17] where for light intensities of \( \sim 1 \text{sun} \) (1000 W/m\(^2\)) bimolecular recombination dominates [4].

The corresponding recombination rates are

\[
R_1 = \alpha n,
\]

\( n \eta \), which is strongly dependent on the disorder level \( \sigma \) and is known to limit \( V_{OC} \) in PV devices [16].

The ideality number \( n \) is defined by the derivative:

\[
\eta = \left( \frac{q}{kt \ln(V_{OC})} \right)_{T} = \left( \frac{q}{kt \ln(V_{OC})} \right)_{T} = \left( \frac{q}{kt \ln(n)} \right).
\]

For inorganic solar cells, this number is usually attained by replacing \( G \) with the short-circuit current density \( (J_{sc}) \), due to their linear correlation. For OPV, \( J_{sc} \) needs to be replaced with \( J_{rb} \) he maximal current obtained in reverse bias conditions, where all the charges are surely extracted from the device.

For non-disordered PV, where the MB approximation applies, Eq. (19) can be elaborated into

\[
n = \frac{\eta}{\eta} \frac{\eta}{\eta} \frac{\eta}{\eta} \frac{\eta}{\eta} = 2,
\]

where the subscript in \( n_1 \) marks the recombination order. In the same way, \( n_2 = 1 \) for bimolecular and \( n_3 = 2/3 \) for tri-molecular recombination, which gives the general expression \( n_i = 2/i \), where \( i \) is the recombination order.

For the disordered case, the MB approximation does not apply, and Eq. (7) will be used instead. For dominating monomolecular recombination,

\[
\eta = \left( \frac{q}{kt \ln(n)} \right) = \left( \frac{q}{kt \ln(n)} \right) = 2\eta = n_1\eta.
\]

Eq. (22) is the generalized ideality number for the disordered BHJ cell. In a similar way, the obtained generalized ideality numbers for bimolecular and trimolecular recombinations are

\[
\eta = \left( \frac{q}{kt \ln(n)} \right) = \left( \frac{q}{kt \ln(n)} \right) = 1\eta = n_2\eta.
\]

Eqs. (22)–(24) show that the “regular” ideality number is accompanied by the same diffusion enhancement coefficient \( \eta \), which was shown to increase the diffusion over the drift current, forcing the open-circuit voltage to increase in order to achieve electro-chemical equilibrium.

Although the charge densities needed for a significant enhancement are quite high (especially for low \( \sigma \) as shown in

\[
R_2 = \beta np = \beta n^2, \\
R_3 = \gamma (np^2 + n^2) \times \gamma n^3.
\]

Fig. 5 shows the ideality number dependence on the disorder level \( \sigma \) for \( np = 10^{23} \text{ cm}^{-6} \), with dominating bimolecular recombination. (b) The expected change in the generalized ideality number over 3 orders of magnitude in light intensity for \( \sigma = 0.0 \text{ eV} \).
Fig. 2b), the same effect can be observed for moderate charge densities. Fig. 5a shows the change in \( n \eta = \eta \) as the result of increased disorder. For charge densities of \( np \approx 10^{15} \text{ cm}^{-2} \), which correspond to an open-circuit voltage of \( \sim 0.6 \text{ V} \) (typical value for a P3HT:PCBM BHJ cell [20]) and generation rate of \( G \approx 10^{22} \text{ cm}^{-3} \text{ s}^{-1} \), equivalent to a cell generating \( \sim 10 \text{ mA cm}^{-2} \) of photo-current density under 1 sun illumination (0.1 W cm\(^{-2}\)). The bimolecular recombination rate was taken as \( \beta = 10^{-13} \text{ cm}^{3} \text{ s}^{-1} \), in accordance with [4].

As shown experimentally by numerous publications [4,18,21], bimolecular recombination is dominant in open-circuit conditions at this light intensity, leading to a universal \( \text{VOC}–\ln(G) \) slope of \( K T/q \) [4]. However, this observation is valid only for "excellent" devices: increase in the ideality number was observed for devices with varying disorder levels [22] and was attributed to enhanced trap-assisted (SRH) recombination. Here, we suggest that this deviation could be associated with \( \eta \), causing the BHJ generalized ideality number to be greater than 1, as shown by Fig. 5a.

Fig. 5b shows increase in \( \eta \) for a chosen \( \sigma \) value of 0.06 eV. It is clearly different from the observed \( \text{VOC}_\text{MB} \) behavior for inorganic PV at high intensities, where increased \( n \) has not been observed even for ultra-high intensities (up to \( 10^4 \) suns) [23]. Experimental observation of the increase in the ideality number with increasing light intensity (between 100 and 1000 suns) could serve as a direct check for the model prediction. However, published data on precise experimental characterization of OPV under high light intensity are absent. Such characterization becomes very complicated due to the necessity to keep the cell isothermal under high irradiance. Recently we suggested an experimental methodology for such precise measurements and checked it in the experiments with inorganic PV up to ultra-high irradiance (\( \sim 9000 \) suns) [24]. Similar methodology can be used in further experiments with BHJ OPV.

We also suggest that this characterization type could reflect the amount of material disorder and give an estimate of \( \sigma \). Another issue that is relevant to high intensity characterization is the cross over to tri-molecular recombination dominated regime. Experimental data on this recombination type in OPV is very limited—up to the best of our knowledge, only a single publication on this matter in BHJ OPV exists, which states a tri-molecular recombination coefficient of \( \gamma = 4 \times 10^{-28} \text{ cm}^6 \text{ s}^{-1} \) [19], corresponding to a cross over light intensity of \( \sim 1000 \) suns.

### 4.3. Temperature dependence of the open-circuit voltage

Fig. 6 depicts the change in the \( \text{VOC} \) dependence on \( np \) when the cell temperature is changed from 200 K to 300 K, for \( \sigma = 0.06 \) eV. While \( \Lambda_1 \) increases with temperature (following Eq. \( 13 \)), \( \Lambda_2 \) depends inversely on the temperature (Eq. \( 14 \)). The combination of both effects leads to a smaller change in the \( \text{VOC}–np \) dependence for the disordered material. This relative tolerance to temperature variation is characteristic of OPV devices, which exhibit lower temperature coefficient [10].

For a complete analysis of the \( \text{VOC} \) temperature dependence, five light intensities were chosen (from 0.1 to 1000 suns) and kept constant while varying the temperature from 0 to 1000 K. The results are plotted in Fig. 7a. The first observation is that for the MB case (shown in gray lines without symbols), \( \text{VOC} = E_g/q \) for all intensities at \( T = 0 \) K, as expected. For the disordered case, \( \text{VOC} \) values do not reach \( E_g/q \) even for \( T = 0 \) K, in contradiction to the common conception of the \( \text{VOC} \) temperature dependence in inorganic PV, adopted to the OPV case as in Refs. [4,26]. This means that for a given light intensity, the maximal obtainable \( \text{VOC} \) value is always under \( E_g/q \). Similar theoretical observation was made by Garcia-Belmonte [10], who calculated the \( \text{VOC}–T \) dependence down to 100 K, without analyzing the \( \text{VOC} \) near zero temperature.

A number of experimental observations of \( \text{VOC} \) behavior at low temperatures has been published. The \( \text{VOC} \) tendency to saturate to a value lower than \( E_g/q \) was observed, but usually without supplying a rigorous analysis [25,26]. The most recent experimental studies on the \( \text{VOC}–T \) dependence were conducted both by Thakur et al. [27] and Rauh et al. [28], who measured the \( \text{VOC} \) down to 50 K. These results closely resemble the trend given by Fig. 7a. Rauh et al. explained this \( \text{VOC} \) behavior at low temperatures by the effect of energy barriers formed at the selective
contacts [28]. For the experimental validation of our model, we have fitted the experimental data given by Rauh et al. (see Fig. 2a in Ref. [28]) using the GDM approximation described above. Fig. 8 shows the results, where a good fitting is demonstrated using a disorder level $\sigma=0.05$ eV. The $E_g$ for this simulation was taken to be 1.1 eV in order to fit to Ref. [28] experimental details. This means that the $V_{OC}$ saturation could be explained by an inherent characteristic of the disordered active layer, without the external effect of the contacts. It should be noted here that correct determination of $V_{OC}$ at $T=0$ K is very important in the context of ongoing discussion about the $V_{OC}$ origin in BHJ OPV cells [4,5,8,10] and in particular for determination of the maximum $V_{OC}$ value obtainable for certain donor–acceptor systems in the OPV photoactive layers.

Fig. 7a also shows that $A_1(T=0)=0$ and $A_2(T=0)\neq 0$ for all light intensities. This in turn suggests that the decrease in $V_{OC}$ at zero temperature is originated only from $A_2$. Furthermore, it should be noted that Eq. (14) predicts that $A_2(T=0)\to \infty$, which gives a $V_{OC}$ value of zero, and therefore cannot be correct in this temperature regime.

Fig. 7b depicts the comparison between Eq. (14) result and the exact solution of $A_2(T=0)$, for the same light intensities. It is clear that the approximation given by the Eq. (14) is not valid for low temperatures and high charge densities where it overestimates $A_2$. On the other hand it underestimates $A_2$ for high temperatures. These two discrepancies origin from the fact that Eq. (14) is derived from the MB statistics, which is not applicable at these conditions. Fig. 9 shows that the $A_2$ behavior for low temperatures is a direct result of the increase in $\eta$ taking place for the same temperature regime, and therefore shows that the origin of the $V_{OC}$ deviation from the MB case is indeed the result of diffusion enhancement.

Another consequence of the increase in $A_2$ is the change in the $V_{OC}$ slope, or the temperature coefficient. While the MB case exhibits constant negative temperature coefficient $dV_{OC}/dT$, the disordered case temperature coefficient is constantly smaller (in agreement to experimental observations collected in Table 1 in Ref. [10]) and even approaches zero at very low temperatures. The complete expression for $dV_{OC}/dT$ is

$$
\frac{dV_{OC}}{dT} = \frac{V_{OC}}{q} - \frac{E_g}{q} \frac{d}{dT} \ln \left( \frac{Nc^2}{np} \right) - \frac{dA_2}{dT}.
$$

The first and second terms are responsible for the temperature dependence of the MB case [16]. The deviation from this behavior is the result of the third term. For moderate–high temperatures, Eq. (14) can be used as

$$
-\frac{dA_2}{dT} = \frac{\sigma}{KT^2}.
$$

This term approaches zero for high temperatures, leading to the parallel curves of the MB and the disordered cases at this temperature regime. For low temperatures, Eq. (16) must be used, and therefore an analytical solution could not be derived. However, it is clear that this term is greater than zero and even equals the first two terms (with an opposite sign), which leads to the almost temperature-independent behavior of $V_{OC}$ near $T=0$ K.

5. Conclusions

By accounting for the diffusion enhancement in disordered organic semiconductors in electro-chemical equilibrium and the resulting generalized Einstein relation, we have developed a model providing new insights regarding the open-circuit voltage properties of organic BHJ solar cells. The model predicts an anomalous behavior of the BHJ ideality number in high light intensities. Our results show that the Gaussian Disorder Model can successfully explain recently published experimental results dealing with temperature dependence of $V_{OC}$. From a practical point of view, the conclusion is that inherent disorder in the semiconductor materials leads to unavoidable losses and the alteration of $V_{OC}$ dynamics, which may be reduced by the employment of more ordered nano-structures in OPV.

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