Charge carrier mobility dependent open-circuit voltage in organic and hybrid solar cells

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Abstract

A better understanding of the open-circuit voltage ($V_{oc}$) related losses in organic solar cells (OSCs) is desirable in order to assess their photovoltaic performance. We have derived $V_{oc}$ as a function of charge carrier mobilities ($\mu_e$ and $\mu_h$) for organic and hybrid solar cells by optimizing the drift-diffusion current density. The $V_{oc}$ thus obtained depends on the energy difference between the highest occupied molecular orbital (HOMO) level and the quasi-Fermi level of holes of the donor material and on the ratio of the electron ($\mu_e$) and hole ($\mu_h$) mobilities in the blend. It is found that the $V_{oc}$ increases with the increase of the mobility ratio $\mu_e/\mu_h$. The most loss in $V_{oc}$ is contributed by the energetics of the donor and acceptor materials.

Introduction

Research interest in organic solar cells (OSCs) is currently on the increase mainly because of their cost effectiveness, flexibility, easy fabrication techniques, large scale production and the potential integration of OSCs into a wide variety of devices [1-4]. The development of new materials for photovoltaic applications coupled with device optimization has led to a dramatic increase in OSCs’ performance in recent years [5]. A major research focus now lies in finding ways for further optimization of the power conversion efficiency (PCE), guided by a deeper understanding of the fundamental processes that influence the photovoltaic properties of OSCs [6]. The following four processes of OSCs and organic hybrid solar cells (OHSCs) make them remarkably different from their inorganic counterparts: i) photon absorption and exciton generation; ii) diffusion of excitons to the donor acceptor (DA) interface; iii) dissociation and charge separation at the interface; and iv) carrier collection by the electrodes [1,2]. These four processes have to be sufficiently efficient to reduce or eliminate energy losses leading to reduction in the short-circuit current density $J_{sc}$ and open-circuit voltage $V_{oc}$, and hence, reduction in the power conversion efficiency of OSCs and OHSCs.

The current density $J$ in the drift-diffusion model is a function of both the electrical and chemical potentials gradients, denoted by $\nabla U$ and $\nabla C$, respectively. In OSCs, $\nabla U$ is negligible because there is no built-in electric field like the one in inorganic solar cells due to the property of p-n junction [7]. Therefore, in OSCs and OHSCs $J$ depends mainly on the gradient of the chemical potential which is a function of $V_{oc}$ as shown below. Thus, $J$ becomes a function of $V_{oc}$ and by optimizing $J$ with respect to $V_{oc}$ one can determine the optimal value of $J$ corresponding to $V_{oc}$.

It is established that the $V_{oc}$ of OSCs [8-11] depends on the energy difference between the highest occupied molecular orbital (HOMO) of the donor material and lowest unoccupied molecular orbital (LUMO) of the acceptor material or the conduction band of the inorganic nanoparticle in the case of OHSCs [12]. In addition, simulation [5,6] and experimental [13-15] works show that charge transport have effect on PCE of OSCs and a detailed analysis of bulk heterojunction organic solar cells reveals that low $V_{oc}$ is the main factor limiting this efficiency [9]. This implies that the $V_{oc}$ of an OSC depends on the transport properties of the charge carrier in the material, which has not yet been studied adequately.

In this work, we have derived an analytical expression for $V_{oc}$ by optimizing the drift-diffusion current density $J$. The $V_{oc}$ thus obtained depends explicitly on the electron and hole mobilities and donor and acceptor HOMO and LUMO energy levels. In a previous study [5], the effective carrier mobility $\mu_{eff} = \sqrt{\mu_e\mu_h}$ is used to define the external voltage applied across an OSC, however in our approach the concept of the effective mobility is not used. Instead, it is found that the $V_{oc}$ depends on the ratio of the electron ($\mu_e$) to hole ($\mu_h$) mobility such that if the ratio ($\mu_e/\mu_h$) increases, the $V_{oc}$ also increases.

Derivation of Open-Circuit Voltage ($V_{oc}$)

The open-circuit voltage is given by the energy difference between the electron and hole quasi-Fermi levels [7]

$$-qV_{oc} = E_{F,e} - E_{F,h},$$

(1)

In OSCs and OHSCs the open-circuit voltage is also related to the HOMO energy level of the donor ($E_{HOMO}^D$) and the LUMO energy level of the acceptor ($E_{LUMO}^A$) as [16]:

$$-qV_{oc} = E_{HOMO}^D - E_{LUMO}^A - \Delta E_{loss},$$

(2)

where $\Delta E_{loss}$ is an empirical value representing energy losses in transporting charge carriers to the electrodes.

According to the drift-diffusion model the total current density $J$ in a semiconductor under bias can be written as the sum of the electron and hole currents as follows:

$$J = J_e - J_h.$$
and hole current densities, given by [17]:

\[ J = J_0 + J_p = \mu_e n \nabla E_{F,\alpha} + \mu_h p \nabla E_{F,\beta}, \]

(3)

where \( J_0 = \mu_e n \nabla E_{F,\alpha} \) is the electron current density and \( J_p = \mu_h p \nabla E_{F,\beta} \) is the hole current density. Here \( n(P) \) is the electron (hole) density. \( \mu_e (\mu_h) \) is the electron (hole) mobility, and \( \nabla E_{F,\alpha} (\nabla E_{F,\beta}) \) is the gradient of the electron (hole) quasi-Fermi level.

The charge-carrier densities \( n \) and \( p \) of electrons and holes inside the active layer are, respectively, given as [18]

\[ n = N_c \exp[(E_{F,\alpha} - E_{LUMO}^D)/k_B T], \]

(4)

\[ p = N_c \exp[(E_{F,\beta} - E_{LUMO}^A)/k_B T], \]

(5)

where \( N_c (N_v) \) is the effective density of states for the LUMO (HOMO) of acceptor (donor) material and \( E_{F,\alpha} (E_{F,\beta}) \) is the energy of the corresponding Fermi levels. Using equations (1)-(5), the total current density in (3) can be written as a function of \( V_{oc} \) as:

\[ J = \mu_e N_c \nabla E_{F,\alpha} \exp[(-2qV_{oc} + E_{F,\alpha} - E_{LUMO}^D + \Delta E_{soc})/k_B T] \]

\[ + \mu_h N_v \nabla E_{F,\beta} \exp[(-2qV_{oc} + E_{F,\beta} - E_{LUMO}^A + \Delta E_{soc})/k_B T], \]

(6)

The total current density \( J \) in equation (6) can be optimized with respect to \( V_{oc} \) as \( \frac{dJ(V_{oc})}{dV_{oc}} = 0 \), which gives:

\[ \mu_e N_c \nabla E_{F,\alpha} \exp[(E_{F,\alpha} - E_{LUMO}^D)/k_B T] = -\mu_h N_v \nabla E_{F,\beta} \exp[(E_{F,\beta} - E_{LUMO}^A)/k_B T], \]

(7)

In OSCs the chemical potential energy gradient \( \nabla \mu \) drives the electrons and holes in the opposite direction [7], this explains the significance of the minus sign on the left hand side of equation (7); the minus sign is dropped from here onwards for convenience.

Multiplying both sides of equation (7) by \( \exp[(E_{F,\alpha} - E_{LUMO}^D)/k_B T] \) we get:

\[ \exp((-E_\alpha + qV_{oc})/k_B T) = \mu_e N_c \nabla E_{F,\alpha} / \mu_h N_v \nabla E_{F,\beta} \exp[2(E_{F,\beta} - E_{LUMO}^A)/k_B T], \]

(8)

where \( E = E_{HOMO}^D - E_{LUMO}^D \) is the effective band gap or the DA interface energy gap. Rearranging equation (8) we obtain \( V_{oc} \) as:

\[ V_{oc} = \frac{1}{q} \ln \left( \frac{\mu_e N_c \nabla E_{F,\alpha}}{\mu_h N_v \nabla E_{F,\beta}} \right) + \frac{\Delta + \Delta E_{soc}}{2}, \]

(9)

Following earlier works [5,18] we assume \( N_c = N_v \) and \( \nabla E_{F,\alpha} = \nabla E_{F,\beta} \) which gives:

\[ qV_{oc} = E - \Delta; \]

(10)

where \( \Delta \) is the energy loss contributed by the energetic (first term) and charge transport (second term)

**Results**

We have used equation (10) to calculate \( V_{oc} \) in several donor-acceptor (DA) materials listed in Table 1. The input parameters required for each DA in the calculations are also listed in Table 1. In addition, for calculating \( V_{oc} \) from equation (10) we need the values of the energy of the donor HOMO (\( E_{HOMO}^D \)) and acceptor LUMO (\( E_{LUMO}^A \)) which are listed in Table 2. It may be noted that following [18] we have used \( (E_{F,\beta} - E_{HOMO}^D) \approx 0.2 \text{eV} \) in equation (10) for all DA materials used in Tables 1 and 2. Using these input parameters the calculated values of \( V_{oc} \) are listed in Table 2 along with their experimental values obtained for these materials. According to Table 2, the calculated \( V_{oc} \) values are in reasonable agreement with those obtained experimentally.

According to equation (10) the \( V_{oc} \) increases if the ratio \( P > 1 \), that is, when the electron mobility is higher than the hole mobility as shown in Figure 1. In a material with equal mobility of electrons and holes, the contribution of the transport term to the \( V_{oc} \) vanishes.

Multiplying both sides of equation (7) by \( \exp[(E_{F,\beta} - E_{LUMO}^A)/k_B T] \) we get:

**Table 1.** Input values for calculating \( V_{oc} \) with donor-acceptor materials forming the active layer, electron mobility \( \mu_e \), hole \( \mu_h \), mobility and mobility ratio ratio \( P \).

| Entry | Active Layer | \( \mu_e \) \( \text{(cm}^2\text{V}^{-1}\text{s}^{-1}) \) | \( \mu_h \) \( \text{(cm}^2\text{V}^{-1}\text{s}^{-1}) \) | \( P = \mu_h/\mu_e \) | Ref. |
|-------|--------------|----------------------------------|----------------------------------|----------------|-----|
| OSC   | PTh7:PCBM    | \( 1.0 \times 10^4 \)            | \( 2.0 \times 10^4 \)            | 5.0            | [20]|
| OSC   | PCDTBT:PCBM  | \( 2.9 \times 10^4 \)            | \( 3.0 \times 10^4 \)            | 96.7           | [21]|
| OSC   | P3HT:PCBM    | \( x10^3 \)                      | \( x10^4 \)                      | 10.0           | [19]|
| OSC   | MDMOPPV:PCBM | \( x10^3 \)                      | \( x10^4 \)                      | 10.0           | [19]|
| OSC   | PBDBTBB:Bi:PCBM | \( 9.6 \times 10^4 \)           | \( 1.3 \times 10^4 \)            | 0.7            | [10]|
| OSC   | PBDBTBB:PCBM | \( 8.8 \times 10^4 \)            | \( 1.4 \times 10^4 \)            | 0.6            | [10]|
| OSC   | P3HT:Bi:PCBM | \( 9.6 \times 10^4 \)            | \( 1.0 \times 10^4 \)            | 1.0            | [10]|
| OSC   | MEHPPV:PCBM  | \( x10^3 \)                      | \( x10^4 \)                      | 1000.0         | [25]|
| OSC   | Si-PCPDTBTB:PCBM | \( 2.5 \times 10^4 \)           | \( 3.0 \times 10^4 \)            | 8.3            | [22]|
| OHSC  | MDMOPPV:nc-ZnO | \( 2.8 \times 10^4 \)           | \( 5.5 \times 10^4 \)            | 5.1            | [23]|
| OHSC  | P3HT:Si:NCs  | \( x10^3 \)                      | \( x10^4 \)                      | 1.0            | [24]|

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observation as well as with the numerical simulation [23]. In Figures 2a and 2b we have reproduced the J-V characteristics measured on P3HT:PCBM bulk heterojunction organic solar cells (BHJ OSCs) annealed at two different temperatures, 52°C and 70°C, respectively [23]. The measured mobility P3HT:PCBM of electrons and holes is found to be 

$$8 \times 10^5 \text{m}^2\text{V}^{-1}\text{s}^{-1},$$ 

$$12 \times 10^5 \text{m}^2\text{V}^{-1}\text{s}^{-1}$$  at 52°C (Figure 2a) and 

$$7 \times 10^5 \text{m}^2\text{V}^{-1}\text{s}^{-1},$$ 

$$10 \times 10^5 \text{m}^2\text{V}^{-1}\text{s}^{-1}$$  at 70°C (Figure 2b) [23]. Using these values, we find that the mobility ratio $P$ decreases from $8.3 \times 10^3$ to $1.0 \times 10^3$ when one anneals the sample at 52°C and 70°C. According to equation (10), this means that one should get a higher value of $V_{oc}$ at the annealing temperature of 52°C than at 70°C. This result is quite consistent with that shown in Figures 2a and 2b, where the measured and simulated $V_{oc}$ at 52°C is about 0.04 V higher than that at 70°C. Mobility dependent J-V characteristics have also been simulated by assuming $\mu_e = \mu_h$ [5]. The $V_{oc}$ is found to be independent of the charge carrier mobility in the range from 1 to $10^6 \text{cm}^2\text{V}^{-1}\text{s}$. According to equation (10) also, the mobility dependent term vanishes for $\mu_e = \mu_h$ and hence $V_{oc}$ becomes constant which is consistent with this result.

### Table 2. Donor-Acceptor materials, Donor HOMO level $E_{D}^{HOMO}$, Acceptor LUMO level $E_{A}^{LUMO}$, Effective band gap $E_g = E_{D}^{HOMO} - E_{A}^{LUMO}$, transport loss term $k_s T \ln(\mu_e/\mu_h)$ and $V_{calc}$ from equation (10).

| Donor material | $E_{D}^{HOMO}$ (eV) | Acceptor material | $E_{A}^{LUMO}$ (eV) | $E_g$ (eV) | $k_s T \ln(\mu_e/\mu_h)$ (eV) | $V_{calc}$ (V) | $V_{exp}$ (V) | Ref. |
|----------------|---------------------|-------------------|---------------------|-----------|-------------------------------|----------------|---------------|------|
| PTB7           | 5.15                | PCBM              | 4.06                | 1.09      | 0.04                          | 0.73           | 0.75          | [20] |
| PCDTBT         | 5.50                | PCBM              | 4.30 [26]           | 1.20      | 0.12                          | 0.92           | 0.85          | [21] |
| P3HT           | 5.10                | PCBM              | 4.06                | 1.04      | 0.06                          | 0.69           | 0.63          | [26] |
| MDMOPPV        | 5.36                | PCBM              | 4.06                | 1.30      | 0.06                          | 0.96           | 0.83          | [11] |
| PBHTBDD        | 5.23                | Big-PCBM          | 3.80                | 1.43      | -0.01                         | 0.97           | 1.00          | [10] |
| PBHTBDD        | 5.23                | PCBM              | 3.94                | 1.29      | -0.01                         | 0.88           | 0.86          | [10] |
| P3HT           | 5.10                | Big-PCBM          | 3.80                | 1.30      | 0.00                          | 0.89           | 0.74          | [10] |
| MEHPPV         | 5.20                | PCBM              | 3.95                | 1.00      | 0.18                          | 0.88           | 0.74          | [13] |
| Si-PCPDHBT     | 4.86                | PCBM              | 3.88                | 0.98      | 0.05                          | 0.63           | 0.59          | [22] |
| MDMOPPV        | 5.20                | nc-ZnO            | 4.20                | 1.00      | 0.04                          | 0.64           | 0.74          | [12] |
| P3HT           | 5.10                | Si-NcCs           | 3.95                | 1.15      | 0.00                          | 0.75           | 0.75          | [24] |

### Abbreviations

- PTB7: poly[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b’]dithiophene-2,6-diyli][3-fluoro-2-(2-ethylhexyl)carbonylthieno[3,4-b]thiophenediyl]]
- PCBM: 1-(3-methoxycarbonyl)-propyl-1-phenyl-(6,6)C
- PCDTBT: poly[N-9’-hepta-decanyl-2,7-carbazole-alt-5,5-(4’7’-di-2-thienyl-2’1,3’-benzothiadiazole)]
- P3HT: poly(3-hexylthiophene)
MDMOPPV:poly[2-methoxy-5-(3′,7′-dimethyloctyloxy)-1,4-phenylene vinylene]

PBTDDB:D:poly(((4,8-Bis-(2-ethylhexyl)thiophen-2-yl)benzo[1,2-b:4,5-b′]dithiophene-2,6-diy]) bis(trimethyl)-co-(5,7-bis-(2-ethylhexyl)benzo[1,2-c:4,5-c′]dithiophene-4,8-dione))

Bis-PCBM: bisadduct of phenyl-C61-butyric acid methyl ester

MEHPVV:poly[2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene]

Si-PCDPTBT:poly[2,1,3-benzothiadiazole-4,7-diyl][4,4-bis(2-ethylhexyl)-4H-cyclopenta[2,1-b:3,4-b′]dithiophene-siloe 2,6-diy]]

cNC-ZnO: Zinc oxide nanoparticles

Si NCs: Silicon nanocrystals

Discussions

According to equation (10) the open-circuit voltage becomes equal to the effective band gap energy and hence independent of the charge carrier mobilities when the hole quasi-Fermi level is equal to the HOMO level of the donor molecule and the electron and hole mobilities are equal. It is to be noted that the $V_c$ derived in equation (10), depends on the electron and hole mobilities directly. The material with $\mu_e < \mu_h$ will have greater energy loss $\Delta$ and hence lower $V_c$ in comparison with materials with $\mu_e > \mu_h$, which will have lesser $\Delta$ and hence higher $V_c$. From this point of view, one may prefer to use materials with $\mu_e > \mu_h$ for obtaining higher $V_in$ in OSCs.

As stated above, in the calculation of $V_c$ from equation (10), we have assumed a constant value for $(E_{\text{HOMO}} - E_{\text{LUMO}}) = 0.2$ eV. As it is valid only if the charge carrier concentration remains constant and and that means the mobilities of charge carriers are not very high or very low. For example, in OSCs based on P3HT:PCBM, where a mobility ratio $\mu_e/\mu_h$ is considered [19], it is found that if both charge carrier mobilities at this ratio are high, then this will lead to the efficient extraction of charge carriers which reduces the charge carrier concentration. This reduction in carrier concentration is expected to draw the hole quasi-Fermi level away from the HOMO level of the donor material, which according to equation (10) will reduce the $V_c$. This will eventually reduce the PCE as found in [19]. Likewise, at low charge carrier mobilities at the same ratio, the recombination will be enhanced which will reduce the short circuit current [6,19], leading to reduction in PCE. In this view, the derived $V_c$ in equation (10) may be regarded as to be valid only at moderate electron and hole mobilities leading to high PCE.

For highlighting the role of the charge carrier mobility, it may be desirable to consider the two DA combination materials MDMOPPV:PCBM and P3HT:Bis-PCBM in Table 2. These two combinations have the same effective gap of 1.30 eV but the second term of $\Delta$ in equation (10) is 0.06 eV for the first combination and zero for the second (Table 2). As a result the value of $\Delta$ is less in the first combination than that in the second, producing higher $V_c$ (0.96 eV) in MDMOPPV:PCBM in comparison with that of 0.89 eV in P3HT:Bis-PCBM. It may be interesting to note that, using $(E_{\text{HOMO}} - E_{\text{LUMO}}) = 0.2$ eV in equation (10), we get, $\Delta = 0.4 - kT \ln(\mu_e/\mu_h)$ which shows that the loss of 0.4 eV due to the energy dependence is much bigger than the second term due to the charge transport whose calculated values are listed in column 6 of Table 2.

Conclusion

We have derived a mobility dependant expression for $V_c$ and OHS Cs and OSCs. We have shown that if the difference between the electron and hole mobilities is small, the $V_c$ derived here does not depend on the charge carrier mobilities significantly. According to our model, the $V_c$ of DA material depends on two terms; the first depends on the energetic and the second on the electron and hole mobility ratio. This may be expected to be useful in predicting the PCE of OSCs and OHS Cs prior to their fabrications from a combination of DA materials.

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