Energy Losses in Small-Molecule Organic Photovoltaics

Theresa Linderl, Thomas Zechel, Michael Brendel, Daniel Moseguí González, Peter Müller-Buschbaum, Jens Pflaum, and Wolfgang Brütting*

Theresa Linderl, Thomas Zechel, Prof. Wolfgang Brütting
Institut für Physik, Universität Augsburg, 86135 Augsburg, Germany
*E-mail: wolfgang.bruetting@physik.uni-augsburg.de

Michael Brendel, Prof. Jens Pflaum
Lehrstuhl für Experimentelle Physik VI, Julius-Maximilians Universität Würzburg, 97074 Würzburg, Germany

Prof. Jens Pflaum
Bayerisches Zentrum für Angewandte Energieforschung (ZAE Bayern e.V.)
Magdalene-Schoch Str. 3, 97074 Würzburg, Germany

Daniel Moseguí González, Prof. P. Müller-Buschbaum
Lehrstuhl für Funktionelle Materialien, Physik Department
Technische Universität München
James-Franck-Str. 1, 85748 Garching, Germany

After intense research and development organic solar cells have matured among the family of thin-film photovoltaic technologies. On the laboratory scale they reach power conversion efficiencies in excess of 10%. Together with other attractive features, like transparency or the compatibility with low-cost, large area processing, they open reasonable perspectives for their commercialization. However, in order to close the gap to established inorganic technologies, primarily crystalline silicon, the fundamental understanding of loss processes has to be improved.

First and foremost, this concerns the energy loss between the optical gap for light absorption and the open-circuit voltage of the cell. In this Research News the scientific background for the different mechanisms of energy losses in organic photovoltaic cells together with current approaches toward their reduction are presented.

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1. Introduction

Organic photovoltaics (OPVs) have made tremendous progress over the last three decades. Starting with a power conversion efficiency (PCE) of only 1% in the first OPV cell using a heterojunction concept [1], this value has meanwhile exceeded 10% [2] and has encouraged the vision of low-cost, large-area applications of OPVs [3]. Nevertheless, they still lag behind crystalline inorganic solar cells based on silicon, which are presently dominating the market for photovoltaic (PV) applications [4]. Moreover, with the rapidly progressing hybrid organic-inorganic perovskite solar cells a very attractive candidate for solution processible PV technology has recently appeared as well [5].

Comparing the different technologies in terms of PCE, which is specified as the product of the short-circuit current density j_{SC}, the open-circuit voltage V_{OC} and the fill factor FF divided by the incoming light intensity under standard AM 1.5G illumination conditions, OPVs can well compete with their inorganic counterparts in terms of j_{SC} or, more precisely, the external quantum efficiency and also with minor trade-off in FF, but clearly suffer from lower V_{OC} at a given energy gap E_g of the light absorbing material. While this so-called bandgap-voltage offset can be as low as 0.3-0.4 eV in Si and GaAs [6] and only a little larger in perovskite cells [7], OPV cells exhibit energy losses of at least 0.6 eV – in many cases, however, this offset can approach and even exceed 1 eV [8]. This is currently one of the main bottlenecks toward making OPVs competitive with inorganic PV cells.

In this Research News we provide the required background information on the appearance of energy losses in OPV cells, by which we mean the difference between the equivalent of the optical gap and the measured open-circuit voltage that is frequently also denoted as voltage loss, and discuss recent progress toward better understanding their origin and strategies to reduce them. To keep focused, we will mainly address small molecules as active organic semiconductors, which are being processed into thin films by vacuum deposition techniques. Compared to frequently studied π-conjugated polymers, the synthesis of small molecules is more reproducible. Moreover, a rigorous purification of small molecules is easier, which gives the opportunity to reproducibly investigate well-defined systems. The application of vacuum deposition techniques prevents the use of solvents, which as a third component in wet chemical processing can strongly influence the morphology [9]. Thus, active layers of small molecules prepared by vacuum deposition methods mark a well-controlled model system for fundamental studies such as the origin of energy losses in OPV devices. However, we expect that most of the findings can be transferred to solution-processed OPVs as well, which have considerably higher complexity in terms of local morphology and phase behavior.

2. Excitonic organic solar cells

In order to properly address energy losses in OPVs it is useful to look at their working principles in more detail (see also [10]). Conceptually, they differ from inorganic cells by their quasi-Fermi-level splitting being inherent to the photo-generation of charge carriers as well as by the excitonic nature of photoexcitations in organic semiconductors. Thus, the primarily formed species after absorption of a photon in the absorber material (with an optical gap E_g) is a strongly bound electron-hole pair residing on one and the same molecule, i.e. a molecular exciton. With exciton binding energies of the order of 0.5 eV it is clear that this state cannot simply be dissociated by thermal energy as in inorganic PV materials. It requires a heterojunction between two materials, a donor (D) and an acceptor (A), with different ionization energies and electron affinities, so that an electron transfer from D to A can occur (see **Figure 1**(a)) or, vice versa, a hole transfer from A to D, if the photon is originally absorbed in the acceptor material. The electron on A and the hole on D are still Coulombically bound and form a so-called charge transfer (CT) exciton, which can either be separated into freely moving charge carriers or recombine at the D-A interface releasing its energy E_{CT} by emitting a photon or in a non-radiative process. As a consequence, the morphology of the active layers and the interface energetics will be of outmost importance for the PCE. Those carriers that do not recombine (either geminately at the D-A interface, if they stem from the same exciton, or non-geminately, if they recombine after splitting of the exciton on their way to the electrodes) can be extracted from the solar cell and deliver power to an external load. Thereby, $q \cdot V_{OC}$ (with q being the elementary charge) is an upper limit for the work delivered per absorbed photon.

According to this scenario, there are two main steps, where energy losses occur: (1) in the charge transfer process between E_g and E_{CT} to form the CT state, and, (2) in the process of charge separation and extraction between E_{CT} and V_{OC}. Thus, V_{OC} can be written as:

$$q \cdot V_{OC} = E_g - \Delta E_{CT} - \Delta E_{rec} \qquad (1)$$

with ΔE_{CT} being the so-called driving force for the formation of the CT state and ΔE_{rec} the recombination loss in its dissociation and conversion to free carriers performing work in the external circuit. Note that, strictly speaking, at V_{OC} the PV cell does not deliver any power at all, but it is generally accepted to take this value instead of the voltage at the maximum power point.

Due to their different physical origin it is common to treat both loss terms separately. In particular, the following expression is frequently used to quantify recombination losses only:

$$q \cdot V_{OC} = E_{CT} - \Delta E_{rec} \qquad (2)$$

Following the approach by Shockley and Queisser (SQ) [11], the schematic absorption spectrum displayed in Figure 1(b) can be used to calculate an upper limit for the PCE of an excitonic solar cell [12, 13]. Therein, the single step profile with an onset at the energy gap E_g (which has to be identified with the optical gap of the organic semiconductor having the smaller gap) and unity absorbance $\alpha_g \equiv 1$ has to be extended by a second step corresponding to the CT state, which is characterized by two parameters E_{CT} and α_{CT}. E_{CT} is lower than E_g by the driving force ΔE_{CT} and the absorption strength α_{CT} typically is of the order of 10^{-3} times the fundamental absorption across the optical gap. It is interesting to note that while the presence of the CT state in the subgap region has very little effect on the current j_{SC}, it has a significant impact on the voltage V_{OC}, as will be shown below.

Both parameters, E_{CT} and α_{CT}, have been used as variable input for calculating the modified SQ limit of an excitonic solar cell [13]. Figures 1(c) & (d) show the results for the PCE and the V_{OC} at different combinations of ΔE_{CT} and α_{CT}. As expected, the PCE as function of E_g (Figure 1(c)) decreases with increasing ΔE_{CT} and at the same time the position of its maximum is moving to slightly larger values. Importantly, α_{CT} has a pronounced effect on both the PCE and V_{OC} (Figure 1(d)). Especially, if α_{CT} is lowered from the typical value of 10^{-3} found in a bulk heterojunction, i.e. in a co-evaporated equimolar D:A mixture, toward extremely small values, V_{OC} increases by a few tenths of an eV and can even exceed E_{CT} and reach the value predicted by SQ theory for the given gap. Note that the dramatic increase in PCE for α_{CT} approaching 1 is due to the effect of a reduced energy gap $E_g = E_{CT}$, approaching the optimum gap of the SQ limit in this case.

While these simulations can provide an upper limit for the PCE of OPVs and nicely demonstrate the importance of both the energy level offsets at the D-A interface as well as the absorption strength of the resulting CT state for the total energy loss, they miss one important ingredient, viz. the presence of non-radiative recombination. Thus, the recombination loss term (ΔE_{rec}) in Equation (2) has to be extended to account for both contributions, leading to the following expression for V_{OC}:

$$q \cdot V_{OC} = E_{CT} - \Delta E^r_{rec} - \Delta E^{nr}_{rec} \qquad (3)$$

As shown in the literature, the radiative loss term (ΔE^r_{rec}) depends logarithmically on the absorption strength α_{CT} of the CT state, and the non-radiative loss (ΔE^{nr}_{rec}) can be written as $-\ln(\eta_{EL})$ with η_{EL} being the electroluminescence (EL) quantum efficiency for light emission from CT states [14]. Actually, as several authors have pointed out, because of the extremely

low values of η_{EL} of the order of 10^{-6} (as compared to 10^{-3}-10^{-2} in GaAs, Si or perovskites) the non-radiative loss term is the dominant one in OPVs [7, 15]. Though the microscopic origin for the low EL quantum efficiencies has not been clarified yet, empirically, a linear relationship $q \cdot V_{OC} = E_{CT} - 0.6$ eV was obtained over a wide range of energies covered by both polymeric as well as molecular materials [14, 16, 17]. Compared to the bandgap-voltage offset in Si or GaAs solar cells (0.3-0.4 eV) the recombination loss between V_{OC} and E_{CT} in OPVs is significantly higher. Moreover, one has to be aware that in many cases an additional loss comes from the fact that the driving force ΔE_{CT} is non-negligible. Therefore, other authors have considered the performance of OPVs with respect to the total energy loss, i.e. $E_{loss}^{tot} = E_g - q \cdot V_{OC}$. However, they arrived at a similar conclusion that at least 0.6 eV energy losses are involved in efficient charge generation in OPVs [18, 19].

Beyond the simple model presented above, more complex and realistic models for the density of CT and transport states have been applied (see e.g. [20]). In particular, the recent work by Burke et al. [21] gives an expression that relates V_{OC} losses to the degree of disorder of CT states, their volume fraction of the cell and their lifetime. Taking typical values for these parameters the authors could well reproduce energy losses in the above mentioned range. Moreover, these and other authors have pointed out that the CT manifold can be more complex than one single band due to the coexistence of mixed and aggregated phases, which may be amorphous or crystalline as well [22, 23, 24]. This can have multiple consequences, such as energetic shifts of CT states or energy relaxation to the lowest CT band, to name just a few of them, which in turn has an impact on the V_{OC}.

3. Strategies to reduce energy losses

According to the different sources of energy losses in OPVs one can follow miscellaneous strategies to reduce them: (1) by reducing the CT strength α_{CT}, (2) by reducing the driving force ΔE_{CT}, and (3) by reducing non-radiative recombination.

3.1. Reducing the CT strength

As predicted by the above described simulations, one approach consists in changing the absorption strength of the CT state. As explained in detail in the literature, α_{CT} contains two contributions: one is the density of CT states per unit volume and the second is given by the electronic coupling strength between donor and acceptor [14]. **Figure 2**(a) schematically shows how both properties can be controlled, either by changing the morphology or by varying the relative molecular orientation. However, in a bulk heterojunction (BHJ) donor and

acceptor can exhibit a rich variety of phases, including neat phases of both of them on different length scales together with mixed phases of various compositions. Control over the BHJ morphology can be difficult as it requires also a precise determination of the morphology from the molecular to the mesoscopic scale. By contrast, a so-called planar heterojunction (PHJ) may still not have a perfectly flat D-A interface, but the contact area of both components is drastically reduced. Such an interface is well suited to study the effect of molecular orientation, provided that one is able to grow both materials in a reliable highly ordered, crystalline fashion on top of each other. However, recent work has shown that even in the case of prototypical "model systems" the interface can exhibit non-idealities, like intermixing or disorder, such that it is no longer an abrupt clean interface [25]. This is schematically shown in the right part of Figure 2(a) and should be kept in mind for the discussion below.

In both cases, BHJ and PHJ, the use of advanced x-ray scattering techniques such as grazing incidence small angle x-ray scattering (GISAXS) and grazing incidence wide angle x-ray scattering (GIWAXS) have proven to be very powerful to access the relevant structural information [26]. With GIWAXS the crystalline part is probed and crystal structure as well as crystal orientation with respect to the electrodes can be determined. With GISAXS the mesoscopic domain morphology can be comprehensively characterized. In addition, with polarized resonant soft X-ray scattering (P-SoXS) the orientation of molecules at interfaces can be determined also in case of non-planar interfaces and for non-crystalline interfaces [27]. Figure 2(b) exemplarily shows chemical structures of molecular materials that allow studying such effects (for further information we refer to [28-30]). In the first example (Figure 2(c)), we compare PHJ and BHJ solar cells consisting of DIP as donor and the fullerene C_{60} as acceptor. Detailed x-ray scattering and optical studies have revealed that DIP grows crystalline with almost upright standing orientation of its long axis in both cases of PHJ and BHJ configuration – leading to exceptional excitonic transport properties – and that the main absorber is the fullerene (which also has the smaller gap of both $E_g \approx 1.9$ eV) [28, 31]. While the PHJ has a smooth D-A interface, phase separation is observed in the BHJ; in both cases domain sizes depend on the details of the preparation conditions, particularly the temperature of the substrate during film growth. The current density-voltage (j-V) characteristics in Figure 2(c) show obvious differences between both configurations. While j_{SC} is higher in the BHJ, V_{OC} and FF are larger in the PHJ case. These distinctions are a consequence of the different D-A interfacial area in the two device architectures. Owing to a short exciton diffusion length of only 10-20 nm in C_{60}, the BHJ generates more current due to a larger interface but also

gives rise to higher non-geminate recombination losses, reducing the *FF*. The difference in V_{OC} can be ascribed to the effect of α_{CT}, which is of the order of 10^{-3} in the BHJ with phase separation on 10-100 nm length scale, while it is about an order of magnitude lower in the PHJ [13]. Actually, in the BHJ part of the V_{OC} loss is compensated by the higher photocurrent, since V_{OC} depends logarithmically on j_{SC}. Thus, the difference under equal carrier densities is even slightly larger than apparent from Figure 2(c) at first glance.

In a similar manner, the density of interfacial CT states can be varied by dilution. Vandewal et al. have reduced the donor content in a matrix of C_{60} from 10% down to only 1% and observed a continuous increase in V_{OC} by up to 150 mV [32]. Because the CT energy, as detected by optical spectroscopy, did not change, the effect could unambiguously be ascribed to a reduction in α_{CT}.

Another approach to modify α_{CT} consists in changing the relative orientation of D and A molecules at the interface of a PHJ. In particular, the face-on orientation (lying molecules) vs. the edge-on orientation (standing molecules) – see Figure 2(a) – are expected to yield significantly different electronic couplings, because the conjugated π-system of the donor molecule is strongly exposed to the acceptor in the former case, while it is shielded in the latter case [33]. This effect is even more pronounced, if two rod-like molecules like 6T and DIP are used as donor and acceptor, respectively, because the orientation of molecules in the donor layer templates the alignment of molecules in the acceptor layer as well.

As shown in Figure 2(d), it is therefore possible to grow films with both lying and standing orientation on a non-heated substrate, while a heated substrate yields standing only orientation of both species. This results in a significant difference of V_{OC} of almost 0.2 eV at room temperature [29]. As verified by independent photoelectron and optical spectroscopy measurements the CT energetics are not affected by molecular orientation [29, 34]. Thus, the increase in V_{OC} has to be ascribed to the weaker electronic coupling in the edge-on configuration. Quantitative simulations of the temperature dependence of V_{OC} in both devices indeed confirm this notion and yield a difference in α_{CT} of about three orders of magnitude [34].

Similar observations have been reported by other groups as well [35]. However, as demonstrated in these publications, care has to be taken to disentangle the effect of orientation dependent ionization energies and electron affinities on the one hand, and the actual differences in electronic couplings on the other hand [17]. Moreover, the importance of long-range electrostatic interactions should not be underestimated as well [36].

As already mentioned, D-A interfaces can be more complex than discussed above. There is evidence for intermixing in related systems like Pentacene/C_{60} or Zn-Phthalocyanine/C_{60} [25]. Furthermore, the coexistence of crystalline and amorphous phases of one or both partners at the D-A interface can have a significant influence on V_{OC} as well, as has been shown for Rubrene/C_{60} and Squaraine/C_{60} [24, 37].

3.2. Reducing the driving force

The most obvious approach for reducing energy losses is to minimize the driving force for CT formation. This can be achieved by varying the relative energy level positions at the D-A interface, e.g. by systematically changing the redox energies of a family of donor materials while keeping the acceptor fixed, or vice versa [38]. As already mentioned above, Li et al. have followed this approach and observed that the total energy loss cannot be reduced below 0.6 eV – otherwise the incident photon-to-current conversion efficiency (IPCE) starts to drop significantly [19].

At this point, we want to add that the energetics, i.e. the ionization energies and electron affinities as well as the CT state energy itself, can shift significantly by the presence of intermixing leading to the coexistence of multiple phases at the D-A boundary, which can cause changes in V_{OC} by several 100 mV as compared to an ideal, molecularly sharp interface. Recent examples are again Pentacene/C_{60} and 6T/C_{60} [22, 39].

A common way to quantify the charge transfer energy loss ΔE_{CT} directly is to detect the position of the CT band relative to the optical gap. Several authors have shown that ΔE_{CT} can approach zero for suitably chosen D-A pairs, which means that sensitive detection of the photocurrent as well as the EL spectra do no longer exhibit a distinct signature of CT states but only show absorption and emission across the fundamental gap of the absorber [34, 40]. However, only few of these cells still have high IPCE and PCE [41].

Another means of increasing the V_{OC} of OPVs is the implementation of interlayers. Instead of a single D-A heterojunction one or more additional layers are inserted between donor and acceptor so that the lowest unoccupied and the highest occupied molecular orbitals (LUMO / HOMO) of all materials form an energy cascade [42]. Thus, instead of a single-step charge transfer, which would be accompanied by a large energy loss, the CT process is split into several steps – so to speak – with much smaller overall loss. This concept is of general applicability and, in many cases, the interlayer can comprise even a derivative of the donor or acceptor compound, thereby, facilitating the morphological compatibility [42].

Figure 2(e) shows j-V characteristics of a 6T/C_{60} cell as an example, where the insertion of a thin DIP layer between both materials leads to a steady increase of V_{OC} with increasing DIP thickness. In this case, the effect of the DIP interlayer is twofold. It reduces the large energy loss for an electron transferred from 6T directly to C_{60} (V_{OC} = 0.42 eV) by providing an intermediate energy level on DIP. However, as the corresponding 6T/DIP and DIP/C_{60} cells exhibit much higher V_{OC}'s (1.22 eV and 0.91 eV, respectively), the main effect probably comes from suppressed recombination between 6T and C_{60} by the interlayer, similar to the application of wide-gap insulating interlayers as reported in literature [43].

An alternative mechanism to the formation of an energy cascade has recently been suggested in polymer-fullerene bulk hetero-junctions [44]. These authors have proposed that the presence of an intermixed interface with locally enhanced CT energy creates a driving force for charge separation without loss in V_{OC}.

Much stronger effects have been reported by Cnops et al. for a three-layer structure of 6T/subNc/subPc showing a V_{OC} = 0.96 eV, where the subPc layer provides an additional contribution to the photocurrent by transferring excitons to subNc [45]. This structure has recently been improved further by introducing an additional DBP layer – a derivative of the above discussed DIP – between 6T and subNc, yielding a V_{OC} = 1.18 eV [46]. The authors have shown that the CT state energy in this four-layer cascaded cell is equal to the smallest gap (E_{CT} = E_{subNc} = 1.73 eV) and, thus, that the total energy loss is 0.55 eV only.

In another work, the Janssen group has correlated IPCE and energy losses of polymer:fullerene BHJ cells, where the excitation was either on the polymer or on the fullerene [47]. Surprisingly, they found that excitation of the fullerene is accompanied by a substantially larger energy loss (at least 0.85 eV), while the threshold for efficient cells after excitation of the donor polymer can be slightly less than 0.6 eV. Although the microscopic origin for this significant difference is not clear yet, other groups have reported further examples of remarkably small energy losses using non-fullerene acceptors [48].

3.3. Reducing the non-radiative recombination

The least attention, so far, has been paid to the third loss term in Equation (3), which is actually the most important one: the non-radiative recombination losses. As Vandewal and Tvingstedt et al. have pointed out, those can be as large as 0.35-0.40 eV in polymer:fullerene BHJ cells, where the radiative loss is 0.24 eV only [7, 14]. As discussed in the context of Equation (3), the magnitude of non-radiative losses is related to the overall very low quantum

efficiency of EL from CT states. However, the exact origin of the low η_{EL} remained elusive for a long time.

Only recently, Benduhn et al. [49] have suggested to apply "the energy gap law for radiationless transitions" reported by Englman and Jortner in 1970 [50] to CT emission. They observed that the empirical relation $q \cdot V_{OC} = E_{CT} - 0.6$ eV is not strictly valid when data over a large range of CT energies are analyzed. Actually, the slope between V_{OC} and E_{CT} is slightly larger than 1, indicating that there is an energy dependence of the non-radiative loss term, as predicted by Englman and Jortner. In simple words, the non-radiative decay rate k_{nr} depends on the energy of the excited state, because the higher the latter is the more vibrational quanta $\hbar\omega$ are needed for dissipation and, thus, the lower is k_{nr}: $k_{nr} \propto \exp\left(-\frac{E_{CT}}{\hbar\omega}\right)$. As demonstrated by Benduhn et al., the effect of non-radiative recombination losses in OPVs is quite dramatic, because ΔE_{rec}^{nr} can be as large as 0.55 eV for an E_{CT} of 0.6 eV, while it is only about half as large for $E_{CT} = 1.6$ eV [49].

This mechanistic suggestion is a big step forward. Though it does not directly solve the problem of non-radiative losses, it could provide the necessary insights to guide materials science to tune CT states toward higher radiative decay efficiency. However, the challenge is not to increase the second loss term in Equation (3) – the radiative one – too much at the same time [51].

3.4. Overview of selected small molecule OPV cells

At the end of this section, we would like to give a brief overview of the materials and the progress that has been made over recent years in our groups. **Figure 3** shows a compilation of data for energy losses in small molecule OPVs. All of these cells have comparable (optical) energy gaps between 1.9 and 2.1 eV (in all cells with C_{60} or DBP as absorber the gap is 1.9 eV; with DIP as absorber it is 2.1 eV). The diagram shows that the energy loss is particularly large in the case of 6T/C_{60}, because almost 1 eV of energy is lost in the primary charge transfer step. This can be drastically reduced by choosing D-A pairs with better energy level matching, especially for the non-fullerene acceptors on the right-hand side, where a 6T/DBP cell has a CT loss of only 0.13 eV.

The recombination losses of all material combinations are between 0.5 and 0.6 eV, which means roughly the same within the error bars, except for two cases. The high-temperature grown 6T/DIP cell has the highest $V_{OC} = 1.35$ eV and a recombination loss below 0.5 eV, most likely due to the upright standing orientation of both molecular species leading to reduced electronic coupling [29]. Also remarkable is the case of DBP/ZCl with a Zn-

chlorodipyrrin as acceptor having a recombination loss below 0.4 eV [40b]. This acceptor

molecule can exhibit an intramolecular symmetry-breaking CT in the excited state, which

might further reduce recombination losses.

4. Conclusion

Our understanding of energy losses in OPVs has made huge progress in recent years and

different strategies for reducing them have been developed. It has been demonstrated that the

driving force for the primary charge transfer step from a molecular exciton on the absorbing

species toward the formation of an interfacial CT state between donor and acceptor can be

basically reduced to zero. However, the overall energy loss from the optical gap to the open-

circuit voltage still has a lower bound of about 0.6 eV. In particular, non-radiative

recombination losses from CT states are still not very well understood, although they amount

for the largest loss term. Thus, the way to reduce energy losses in OPVs below this limit is by

no means obvious, but will require concerted efforts in materials design, device engineering

together with improving experimental detection techniques as well as theoretical modelling.

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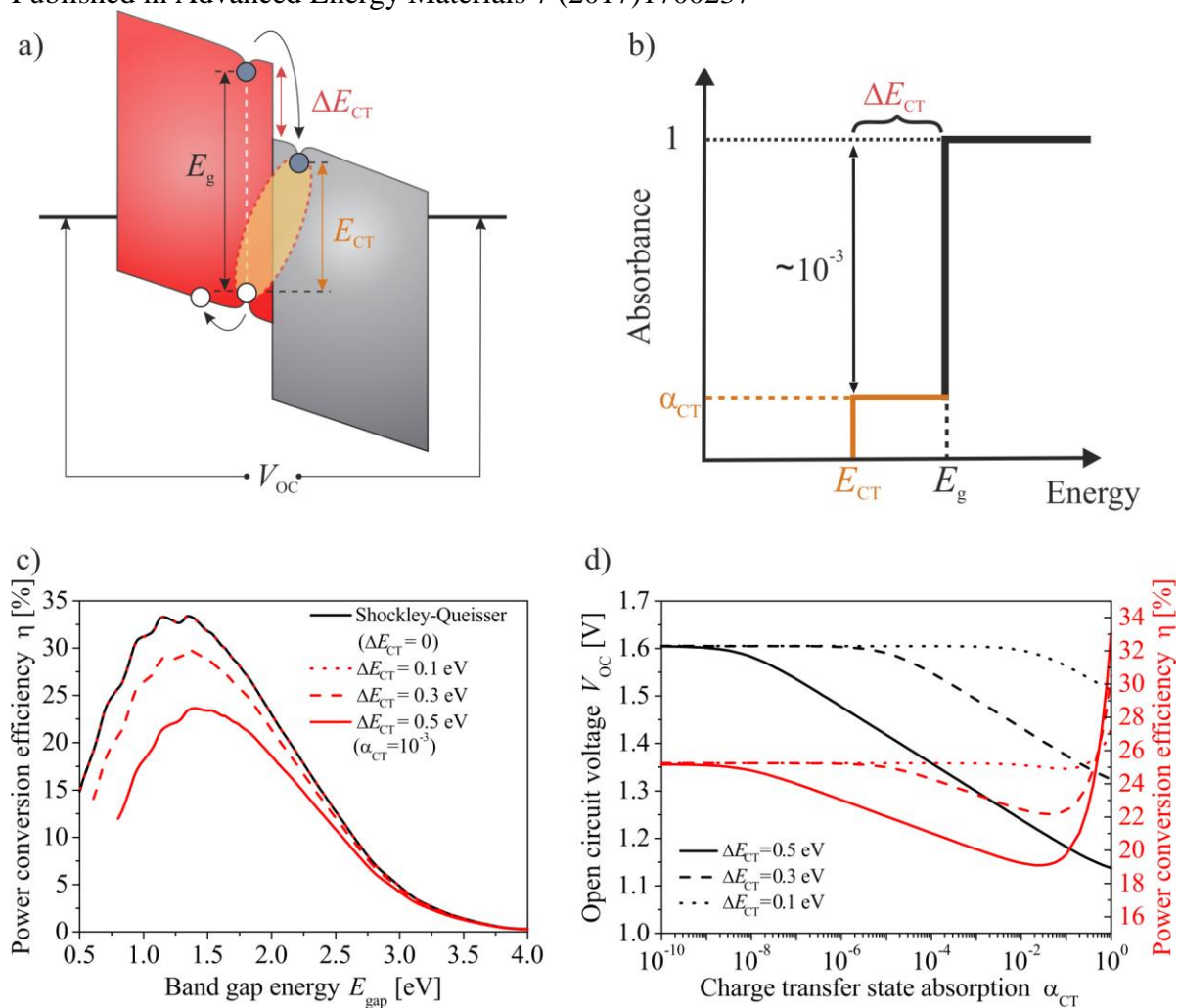
Figure 1. Working principle of an organic donor-acceptor (D-A) solar cell and predictions for their power conversion efficiency (PCE) as function of the energy and absorption strength of interfacial charge-transfer (CT) states. a) Schematic energy level diagram with photo-induced electron transfer from the donor at the left to the acceptor on the right. b) Simplified absorption spectrum with a subgap absorption step for CT states at the D-A interface. c) & d) Calculated PCE and V_{OC} following the modified Shockley-Queisser detailed balance approach with E_g = 1.9 eV and, both, E_{CT} and α_{CT} as variable parameters (for details see Ref. [13]). Reproduced with permission.[13] Copyright 2012, Wiley-VCH.
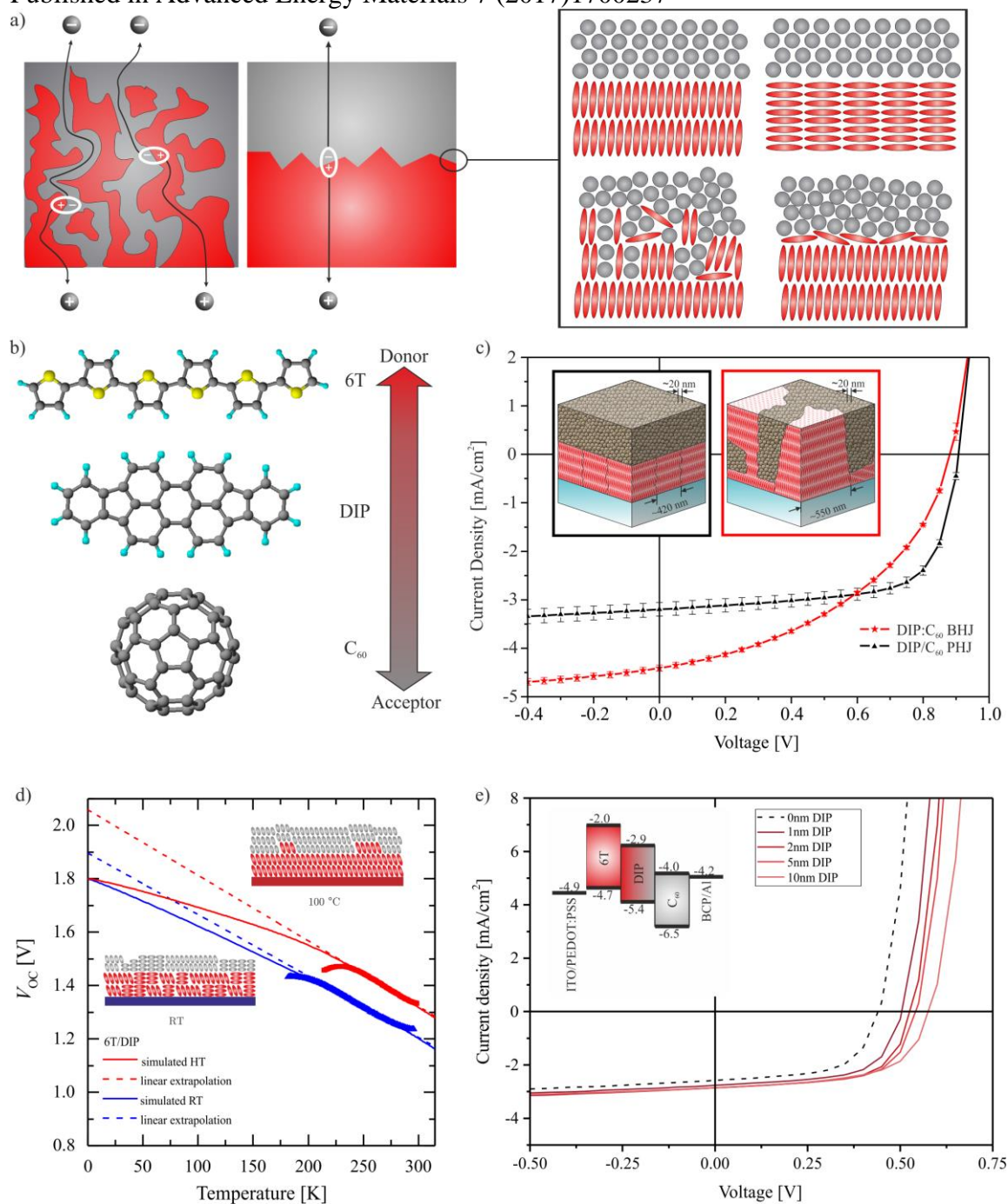
Figure 2. a) Schematic visualization of different interface morphologies in a bulk-heterojunction (BHJ) and a planar heterojunction (PHJ); for the latter, different molecular orientations can play a role as well, and the donor-acceptor interface can exhibit non-idealities such as intermixing or disorder. b) Chemical structures of some proto-typical small molecule semiconductors used for organic solar cells. c) Comparison of current-voltage characteristics and the corresponding morphology of DIP/C_{60} BHJ (red) and PHJ (black) solar cells (for details see Ref. [28]). d) Temperature dependent V_{OC} of 6T/DIP solar cells with different relative orientation of the two compounds caused by different substrate temperature upon film growth (for details see Ref. [29, 34]). e) Current-voltage characteristics of cascaded solar cells with variable thickness of the DIP layer in between 6T and C_{60}.
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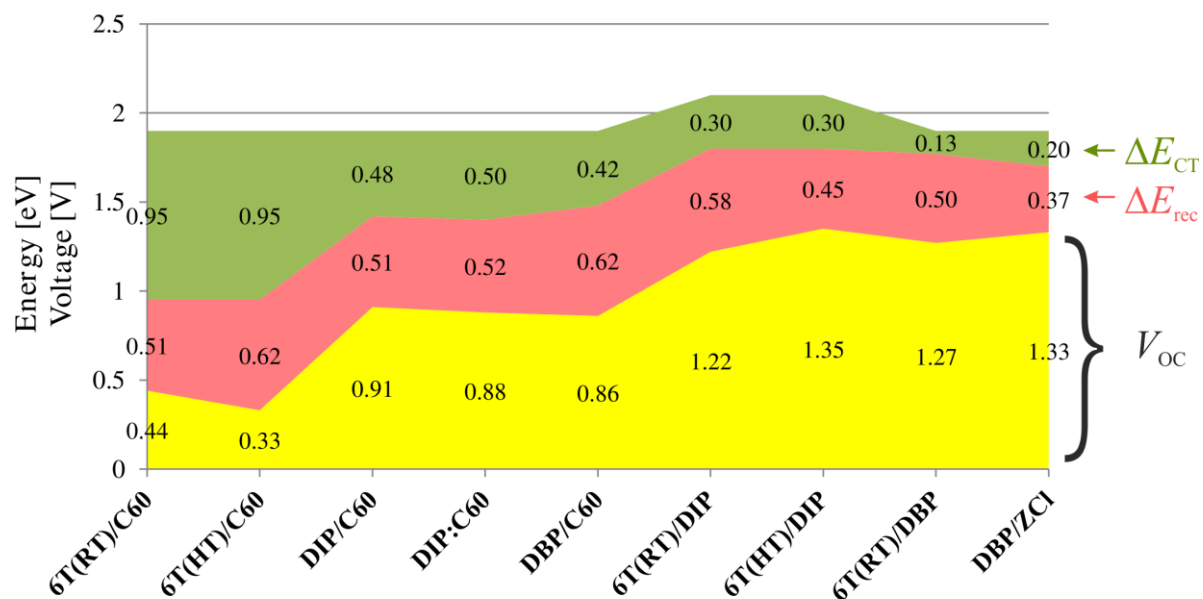
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Figure 3. Compilation of open-circuit voltages and the involved energy losses for selected small-molecule solar cells. The given numbers are taken from the following references: 6T/C_{60} [16a, 29], DIP/C_{60} [16b], DBP/C_{60} [40a], 6T/DIP [29], 6T/DBP [40a], DBP/ZCl [40b]. RT and HT denote film deposition with the substrate at room temperature or at 100°C, respectively. All cells except for DIP:C_{60}, which was a BHJ, were fabricated in PHJ architecture.

TOC entry:

The energy loss between the optical gap and the open-circuit-voltage is one of the primary reasons why the efficiency of organic photovoltaic cells lags behind their inorganic counterparts. This Research News highlights the scientific background and presents strategies to improve on this issue.

Theresa Linderl, Thomas Zechel, Michael Brendel, Daniel Moseguí González, Peter Müller-Buschbaum, Jens Pflaum, and Wolfgang Brütting*

Energy Losses in Small-Molecule Organic Photovoltaics