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The state of organic solar cells—A meta analysis

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ABSTRACT

Solar cells that convert sunlight into electrical power have demonstrated a large and consistent growth through several decades. The growth has spawned research on new technologies that potentially enable much faster, less costly and environmentally friendly manufacture from earth abundant materials. Here we review carbon based solar cells through a complete analysis of all the data that has been reported so far and we highlight what can be expected from carbon based technologies and draw scenarios of how it can be made of immediate use.

1. Introduction

Organic photovoltaic (OPV) research has been in an exponential growth phase since the early reports [1–6] as witnessed by the number of papers produced yearly and the number of new scientists joining the field. This is naturally due to the pressing problem of finding sustainable energy solutions for the future, but perhaps also because the OPV technology is actually not very mature and possess a rich complexity offering many opportunities for research. This also has consequences for commercial exploitation, seemingly representing an uphill battle for an inferior PV technology having to compete with superior and established PV technologies that when taken together have to compete with many high performing renewable technologies such as wind energy and hydropower [7,8]. The OPV technology is attracting because it promises to be very low cost, light weight, produced from abundant materials and easily manufactured at high speed in large scale on simple roll-to-roll printing machinery [9–11]. On the other hand there are some evident hurdles to overcome: the present power conversion efficiency (PCE) is very low (≤10%) while optimistic projections have been made [12,13] and the stability is also considered lacking [14,15]. Another problem that has not received much interest is the transition from square millimeter sized scientific devices arduously prepared in the laboratory to large scale technical production. In many ways it seems that the scientific pursuit of OPV has developed into a race for the best efficiency number through clever schemes of optimizing the chemistry and device fabrication rather than the more distant goal of producing practically useful solar cells. One of the reasons is perhaps that it is by no means settled which materials should be used and what the optimum construction of the OPV device is. It can thus be viewed as one of the attractions (and pitfalls) of OPV research that almost infinite variation is possible. The interesting question is whether research in OPV is indeed justified or whether it is simply an oversold scientific idea? If it is not what can we realistically expect from it? And finally, how would or could we make use of its distinctive features?

2. Seeing OPV “en large”

The progress of photovoltaic technologies is often summed up in a simple diagram of efficiency *versus* time and shows an impressive learning curve for OPV [13], but it is based on a few hero cells and does not reflect the overall status of the field. It would be far more interesting to have all the data to give a comprehensive overview and to be able to extract information on different types of OPV with respect to composition and fabrication. Unfortunately, PV device parameters are not directly accessible in a central database, but are distributed in the ca. 9000 individual

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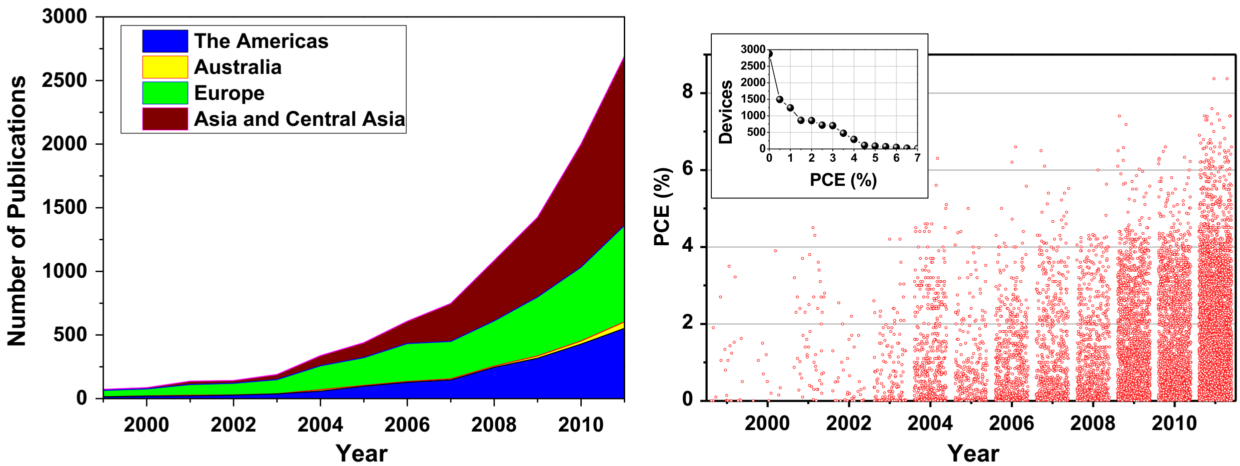

Fig. 1. Number of publications as a function of time with contributions from main countries (left). The PCE values obtained as a function of publication year (right). The inset show the distribution of PCE values.

scientific papers. We judged that this might be the last time that it would be feasible to collect these data by reading through each paper.[1] A search using the terms: "polymer solar cells" or "organic solar cells" were conducted in September 2011 using the Thomson Reuters Web of Knowledge database to compile a series of text files containing the bibliographic information including the digital object identifier (DOI) for each paper excluding review and conference proceeding papers; In total 8962 papers. An Excel database was constructed with a record for each solar cell device found in these papers. Each record has 26 fields comprising bibliographic information, materials used (polymers and acceptors), fabrication details and photovoltaic parameters of efficiency (PCE), open circuit voltage (V_{oc}), short circuit current density (J_{sc}), fill factor (FF), active area *etc.* The database was filled using a custom written program as a front to enter the data into the database read from each article. This resulted in a database of 10533 individual records of solar cells that are used as the basis for this paper. The process of reading papers and entering data took half a year with the help of a number of students and hired assistants. Recently, a smaller database study has been conducted on selected papers concerned with the P3HT:PCBM solar cell including 579 papers covering 2002–2010 [16]. Our aim was to construct a complete database covering all reports and we will in the following try to expose the actual state of OPV based on all publically available solar cell data rather than on single hero cells and also show that certain correlations appear some of which we believe are linked to PV based on carbon and others that may even reach beyond OPV to PV technologies at large.

3. The state of OPV

The search gave 8962 papers written by 15374 individual authors (by Jan 2012). Since year 2000 the growth has been exponential with over 2144 publications in 2011 from 6218 authors of which 5766 had not published in the previous years (in this field). In the beginning most of the contributions came from USA and European countries, but lately the Asia has taken lead. In this search the country of origin was taken from the address of the corresponding author. The exponential increase also means that about half of the authors have only contributed one paper and in the other end of the spectrum 169 (1%) authors have 25 or more papers and in total co-authored 4025 (45%) papers.

[1] A recent search (Aug 2012) resulted in 13151 papers.

In Fig. 1 the PCE value of the individual 10533 solar cells are plotted against the year of submission for the paper. In most OPV papers the term "state of the art solar cells" are equated with the best or "hero" cells produced and these are normally used to indicate the status of the research field. It is clear that substantial progress is being made, but also that hero cells account for a very small part of the population and that they are not representative. Instead, the bulk of PCE values fall far below suggesting that these coveted results are actually rare exceptions. Remarkably, when the number of OPV devices is plotted as a function of PCE one does not get a normal distribution, but rather one that is skewed heavily toward zero PCE. This is in stark contrast to the study by Dang et al. [16] which only considered the maximum PCE for the limited and selected subset for P3HT:PCBM in 579 publications. One of the reasons is of course that the OPV field has become very complex with a huge number of possible variations in structure, chemical composition, fabrication history, interfacial layers *etc.* [17,18]. As a consequence many less performing devices are reported describing non-ideal choices. Some are also due to comparative studies varying different factors and others may simply reflect less competent procedures. It must also be a testament to how poorly defined and documented OPV production is. Even skilled workers may have a hard time duplicating hero cells because it involves factors that are simply unknown or not made public.

The PCE is a function of the product of the open circuit voltage (V_{OC}), short circuit density (J_{SC}) and fill factor (FF) divided by the incident power of the light source (P_i):

$$PCE = \frac{V_{OC} J_{SC} FF}{P_i} \quad (1)$$

When the PCE is plotted as a function of J_{SC} it appears that almost all OPV fall below a diagonal line corresponding to $PCE^{max} \sim 0.55 \times J_{SC}$ (Fig. 2, top left). Remarkably, the best inorganic solar cells also obey this rule except for gallium arsenide (GaAs) cells which have V_{OC} values above 1 V [19]. This limit to the PCE can be derived from the definition (Eq. (1)). For bulk heterojunction type OPV the upper limit for V_{OC} is believed to be determined by the energy difference between the LUMO energy level of the polymer/organic molecule donor and the HOMO energy level of the acceptor material [20–22]. It is further reduced by the exciton binding energy and other factors. The fill factor of OPV devices vary greatly, but rarely exceeds 60%. It immediately follows that the factor of 0.55 is simply the product of V_{OC}^{max} and FF^{max}. It is not a strict physical limit that cannot be overcome, but as the results show it seems very hard to do so. The V_{OC}^{max} is also a linear function of the band gap which means that there is a trade-