Solar Energy Materials & Solar Cells 119 (2013) 73–76

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

journal homepage: www.elsevier.com/locate/solmat

Polymer and organic solar cells viewed as thin film technologies: What it will take for them to become a success outside academia

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ARTICLE INFO

Available online 4 June 2013

Keywords:
Thin film solar cells
Polymer solar cells
CdTe
CIGS
a-Si
Q-function

ABSTRACT

The polymer and organic solar cell technology is critically presented in the context of other thin film technologies with a specific focus on what it will take to make them a commercial success. The academic success of polymer and organic solar cells far outweigh any other solar cell technology when judging by the number of scientific publications whereas the application of polymer and organic solar cells in real products is completely lacking. This aspect is viewed as a sign of the polymer and organic solar cell field as being more complex and less mature and it raises the question of whether an organic analog to a successful inorganic technology is forcibly needed and indeed whether it is at all worth exploring beyond academia.

1. Introduction

Crystalline photovoltaics are an established bulk energy producing technology and a consistent performer in today's energy systems. Even if solar electricity still accounts only for a fraction of the total electricity supply today the rise has been steep and the annual production of crystalline silicon based PV amounted to ~30 GW_p in 2012 with a total installed capacity of more than 100 GW_p [1]. Second to the indisputably successful crystalline PV technologies are the inorganic thin film technologies such as amorphous silicon [2], cadmium telluride [3], copper indium gallium diselenide [4] that in comparison to the crystalline PV efficiently address shorter energy pay-back time through lower processing temperature and use of less material in faster processes with a comparable to slightly lower performance. Amongst the thin film technologies are also the organic and polymer solar cells which are extreme in the sense that they potentially offer very fast modes of manufacture [5] using only abundant elements coupled to an extremely low embodied energy through very low processing temperatures using only ambient processing conditions on simple printing equipment enabling energy pay-back times as low as 2 months and potentially even of 1 day [6]. However, the practical performance currently achieved is too low to be useful in spite of the fact that academic reports promise in excess of 10% performance.

In this discussion we highlight some of the distinctions of polymer and organic solar cells when viewed as a thin film technology and also outline how the field should develop in an effort to progress beyond the art of scientific reporting towards a viable technical scientific discipline.

2. Discussion

Inorganic materials have consistently demonstrated excellent robustness within many areas of energy technology and electronics such as semiconductors, light emitting technologies, thermoelectrics, fuel cells and solar cells. The Achilles heel of inorganic materials from an industrial point of view is that they almost exclusively have a significant thermal budget and a rigid nature that inherently makes ultrafast manufacture of large areas impossible. This is of little significance for the semiconductor industry where one strives to make as much on as little an area as possible i.e. the central processing unit (CPU) of a personal computer. For solar cells however, large areas are implicitly needed to harvest solar energy that under the best circumstances presents an energy of around 1000 W m^{-2}. Crystalline silicon solar cells enable in best cases the harvesting of this energy and conversion into electrical energy with an efficiency of just above 20%. While this is quite a significant power conversion efficiency it does come with a significant thermal budget and the requirement for relatively large amounts of active semiconductor materials that are processed using slow methods (cutting and handling of discrete wafers). This is what has made room for inorganic thin film PV technologies and those in turn have led to the general interest in organic materials with potentially simpler and faster processing methods. This could be called the organic electronics revolution and while it does indeed promise properties and cost structures that could

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http://dx.doi.org/10.1016/j.solmat.2013.05.032

revolutionize many areas of technology within electronics the question is always if the motivation for an organic equivalent is simply the academic interest in creating an organic equivalent to an otherwise successful inorganic technology and more importantly if there are any advantages beyond the academic exercise.

2.1. Is the organic equivalent of inorganic PV justified and how is it distinct?

The answer to this question is most readily found by listing the distinctions of OPV as compared to inorganic PV and most notably the strengths. In the case of crystalline inorganic PV that almost exclusively employ a large thermal budget with prolonged heating steps and exist in a rigid or inflexible nature it is obvious that a thin flexible form that employ much less active material and lower thermal budgets are an advantage. In addition all the crystalline PV technologies employ relatively scarce components with low abundance except crystalline silicon which has been touted as the only environmentally friendly PV technology that is based on abundant elements that enable a scale comparable to the worlds energy needs. The polymer and organic solar cells in principle also enable this since carbon is highly abundant. Thus if the OPV was based entirely on carbon or abundant elements this would be an example of a thin film technology that also fulfilled this requirement. In contrast many of the inorganic thin film technologies i.e. a-Si, CIGS, CdTe also have a lower thermal budget, use of less material and enables faster production, the OPV technology however does the same to a more extreme degree. Many of the inorganic thin film technologies except a-Si suffer from use of toxic and/or scarce elements with CdTe being the "enfant terrible" by exhibiting environmental toxicity (from cadmium) and extremely low abundance (tellurium) [7]. The OPV technology is thus lacking significantly behind all other PV technologies in terms of efficiency and stability but it does efficiently answer the important question associated with any PV technology and represents the only example of a PV technology that is extremely scalable while being based on abundant elements with a low embodied energy. In fact OPV, as it can be manufactured today on a laboratory scale, already outperform all other energy technologies with an energy pay-back time as low as 60 days and the potential for an energy pay-back time of just 1 day [6]. The answer to the question that opened this section is thus, yes, provided that the abundant and environmentally friendly version of OPV is pursued. It is also likely that it is not prohibitive to be inferior in performance and stability if the manufacturing speed is exceptionally high and energy pay-back time is short.

2.2. Why is the interest in OPV so large when it is the poorest performer?

Another question that arises after having responded yes to the above is why the research intensity is so much higher for OPV than it is for any of the other thin film technologies. In comparison a database search using Thompson Reuters Web-of-Science for respectively polymer solar cells (~12,000 documents), amorphous silicon solar cells (6000 documents), cadmium telluride solar cells (2500 documents) and copper indium gallium diselenide solar cells (1500 documents) reveals that the polymer solar cells are much more investigated than any of the other three in spite of the fact that polymer solar cells are not available in large volume whereas all other three are. We ascribe this observation to two possible reasons and also describe some of the implications in the following section. The first reason could be that polymer solar cells have an inherently large variation in materials because organic materials are molecular and in contrast to the other three subjects in this discussion where the number of elements are very limited and variation is mainly found in the deposition and processing methods. For polymer solar cells the variation is enormous and perhaps because of this a high performance has come along rather slowly in comparison with a-Si, CdTe and CIGS. The second reason could thus be that a-Si, CdTe and CIGS quite rapidly reached industrially relevant performance with a limited choice of materials and variability. The spread in observed performance has thus been smaller and both academic and industrial agreement has been quickly reached. This is far from the truth when it comes to polymer and organic solar cells and this must of course be rectified if polymer and organic solar cells are to be added to the list of industrially relevant thin film technologies.

2.3. Performance claims must be corroborated and on large scale

A clear driver for academic research is the achievement of high power conversion efficiency. A decade ago the benchmark was a PCE of 5% and until recently the benchmark has been a PCE of 10%. The benchmark has been claimed to be reached in both cases within academia and it would seem that when ambitious PCE goals are set forward they are reached. The number of experiments with new materials in new solar cell geometries have increased in recent years and reached levels exceeding many thousands. The statistical foundation for predicting when a certain efficiency will be reached is possible provided that one has knowledge on the statistical spread that is typically encountered when a competent research group studies and reports the efficiency of an organic solar cell. The typical praxis in the field is to report the efficiency of hero cells which when viewed positively represents the ultimate state-of-art with respect to a judicious choice of materials and morphology, etc. Another possibility is to view all polymer solar cells statistically. Measurements of the PCE for solar cells are subject to a fair variation as demonstrated by several inter-laboratory studies with standard deviations on the order of 10% or more (for large devices) [8–13]. Statistically speaking we may thus represent the PCE as a rather wide normal distribution. The implications of the standard praxis of reporting the values of hero cells rather than a mean value are thus severe. The reasoning is perhaps that these hero cells represent the ultimate state-of-the art. On the other hand they may also be considered statistical outliers that probe the farthest reaches of the normal distribution. This is aggravated by the fact that the sampling space – the number of OPV devices produced – increases exponentially with time. It means that even assuming a constant actual PCE value the reported maximum PCE values will grow over time simply because there is a larger statistical probability of reaching the extremes of the normal distribution when the sample space increases for a technology presenting a large standard error in efficiency. As an example we can investigate how the maximum reported PCE value would evolve over time. The sampling space (number of solar cell devices) can be estimated roughly from the number of scientific papers on OPV and the number of devices reported herein as shown in Fig. 1. An exponential fit was performed to extend the estimated number of solar cells produced each year until 2015. The probability of measuring a given maximum PCE can be calculated based on the normalized Q-function (the tail probability of the normal distribution) with a given mean PCE and standard deviation. In our case we have chosen to represent several mean PCE values from 3 to 6% with $\sigma = 20\%$.

The learning curve of polymer and organic solar cell efficiency can thus be drawn based on the number of experiments carried out or phrased differently, how many more experiments must be carried out before a certain efficiency is reached within the theoretical limits of power conversion efficiency for polymer and organic solar cells which currently is ~10% for single junctions and 12% for tandem solar cells. It should however be stressed that very few of the high PCE