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Introduction to Organic Solar Cells

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Abstract Polymer solar cells have many intrinsic advantages, such as their light weight, flexibility, and low material and manufacturing costs. Recently, polymer tandem solar cells have attracted significant attention due to their potential to achieve higher performance than single cells. Photovoltaic's deal with the conversion of sunlight into electrical energy. Classic photovoltaic solar cells based on inorganic semiconductors have developed considerably [1] since the first realization of a silicon solar cell in 1954 by Chapin, Fuller and Pearson in the Bell labs. [2] Today silicon is still the leading technology on the world market of photovoltaic solar cells, with power conversion efficiencies approaching 15 – 20% for mono-crystalline devices. Though the solar energy industry is heavily subsidized throughout many years, the prices of silicon solar cell based power plants or panels are still not competitive with other conventional combustion techniques – except for several niche products. An approach for lowering the manufacturing costs of solar cells is to use organic materials that can be processed under less demanding conditions. Organic photovoltaic's has been developed for more than 30 years, however, within the last decade the research field gained considerable in momentum [3,4]. The amount of solar energy lighting up Earth's land mass every year is nearly 3,000 times the total amount of annual human energy use. But to compete with energy from fossil fuels, photovoltaic devices must convert sunlight to electricity with a certain measure of efficiency. For polymer-based organic photovoltaic cells, which are far less expensive to manufacture than silicon-based solar cells, scientists have long believed that the key to high efficiencies rests in the purity of the polymer/organic cell's two domains -- acceptor and donor.

Keywords: *organic solar cells, solar energy, photovoltaic, polymer*

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1. Solar Energy

The amount of energy that the Earth receives from the sun is enormous: 1.75 × 1017 W. As the world energy consumption in 2003 amounted to 4.4 × 1020 J, Earth receives enough energy to fulfill the yearly world demand of energy in less than an hour. Not all of that energy reaches the Earth’s surface due to absorption and scattering, however, and the photovoltaic conversion of solar energy remains an important challenge. State-of-the-art inorganic solar cells have a record power conversion efficiency of close to 39%, [6] while commercially available solar panels, have a significantly lower efficiency of around 15–20%. Another approach to making solar cells is to use organic materials, such as conjugated polymers. Solar cells based on thin polymer films are particularly attractive because of their ease of processing, mechanical flexibility, and potential for low cost fabrication of large areas. Additionally, their material properties can be tailored by modifying their chemical makeup, resulting in greater customization than traditional solar cells allow. Although significant progress has been made, the efficiency of converting solar energy into electrical power obtained with plastic solar cells still does not warrant commercialization: the most efficient devices have an efficiency of 4-5%. [7] To improve the efficiency of plastic solar cells it is, therefore, crucial to understand what limits their performance.

2. Introduction

Organic solar cells can be distinguished by the production technique, the character of the materials and by the device design. The two main production techniques can be distinguished as either wet processing or thermal evaporation. Device architectures are single layer, bi layer hetero junction and bulk hetero junction, with the diffuse bi layer hetero junction as intermediate between the bi layer and the bulk hetero junction , Whereas the single layer comprises of only one active material, the other architectures are based on respectively two kinds of materials: electron donors (D) and electron acceptors (A). The difference of these architectures lays in the charge generation mechanism: single layer devices require generally a Scotty barrier at one contact, which allows separating photo excitations in the barrier field. The DA solar cells apply the photo induced electron transfer [5] to separate the electron from the hole. The photo induced electron transfer occurs from the excited state of the donor (lowest unoccupied molecular orbital, LUMO) to the LUMO of the acceptor, which therefore has to be a good electron acceptor with a stronger electron affinity. Subsequent to charge separation both the electron and the hole have to reach the opposite electrodes, the cathode and the anode, respectively. Thus a direct current can be delivered to an outer circuit. As the evidence of global warming continues to build-up, it is becoming clear that we will have to find ways to produce electricity without the release of carbon dioxide and other greenhouse gases. Fortunately, we have renewable energy sources which neither run out nor have any significant harmful effects on our environment. Harvesting energy directly from the sunlight using photovoltaic (PV) technology is being widely recognized as an essential component of future global energy production.

3. Organic Solar Cells

Organic materials bear the potential to develop a long-term technology that is economically viable for large-scale power generation based on environmentally safe materials with unlimited availability. Organic semiconductors are a less expensive alternative to inorganic semiconductors like Si; they can have extremely high optical absorption coefficients which offer the possibility for the production of very thin solar cells. Additional attractive features of organic PVs are the possibilities for thin flexible devices which can be fabricated using high throughput, low temperature approaches that employ well established printing techniques in a roll-to-roll process [8,9]. This possibility of using flexible plastic substrates in an easily scalable high-speed printing process can reduce the balance of system cost for organic PVs, resulting in a shorter energetic pay-back time. The electronic structure of all organic semiconductors is based on conjugated π-electrons. A conjugated organic system is made of an alternation between single and double carbon-carbon bonds. Single bonds are known as σ-bonds and are associated with localized electrons, and double bonds contain a σ-bond and a π-bond. The π-electrons are much more mobile than the σ-electrons; they can jump from site to site between carbon atoms thanks to the mutual overlap of π orbital's along the conjugation path, which causes the wave functions to delocalize over the conjugated backbone. The π-bands are either empty (called the Lowest Unoccupied Molecular Orbital - LUMO) or filled with electrons (called the Highest Occupied Molecular Orbital - HOMO). The band gap of these materials ranges from 1 to 4 eV. This π-electron system has all the essential electronic features of organic materials: light absorption and emission, charge generation and transport.

3.1. Structure of Organic Solar Cell

For organic solar cells based on polymer: fullerene bulk heterojunctions, the magnitude of JSC, VOC, and FF depends on parameters such as: light intensity [10], temperature [11,12], composition of the components [13], thickness of the active layer [14], the choice of electrodes used [15,16], as well as the solid state morphology of the film [17]. Their optimization and maximization require a clear understanding of the device operation and photocurrent, Jph, generation and its limitations in these devices. The relation between the experimental Jph and material parameters (i.e., charge-carrier mobility, band gap, molecular energy levels, or relative dielectric constant) needs to be understood and controlled in order to allow for further design of new materials that can improve the efficiency of this type of solar cells.

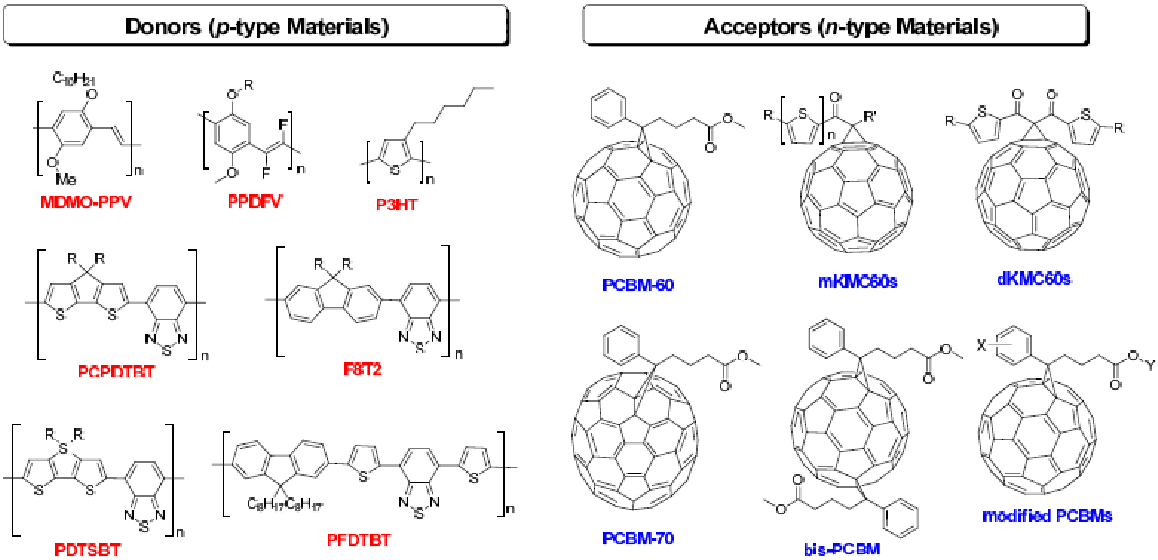

Figure 1. Chemical Structure of Organic solar cell Donor and Acceptor Materials

A first attempt to understand the physics behind the organic bulk hetero junction solar cells was done by using numerical models and concepts that are well established for inorganic solar cells, such as the p-n junction model. To improve the agreement of the classical p-n model with the experimental Jph of an organic bulk hetero junction cell, an expanded replacement circuit has been introduced [18,19,20]. This model replaces the photoactive layer by an ideal diode and a serial and a parallel resistance, which have an ambiguous physical meaning for an organic cell. However, different to classical p-n junction cells with spatially separated p- and n-type regions of doped semiconductors, bulk hetero junction cells consist of an intimate mixture of two un-doped (intrinsic) semiconductors that are nanoscopically mixed and that generate a randomly oriented interface. Moreover, due to the different charge generation, transport and recombination processes in bulk hetero junctions, the classical p-n junction model is not applicable to describe the Jph of these solar cells [21]. An alternative approach is to use the metal-insulator-metal (MIM) concept [22], where a homogenous blend of two unipolar semiconductors (donor/acceptor) is described as one semiconductor with properties derived from the two materials. This means that the photoactive layer is described as one 'virtual' semiconductor assuming that its conduction band is given by the LUMO of the acceptor and its valence band is determined by the HOMO of the donor-type material. Under PV operation mode, the potential difference available in the MIM device, that drives the photo generated charge carriers towards the collection electrodes, is caused by the difference between the work functions of the metal electrodes.

As shown in Figure 1, several donor and acceptor materials are being reported, but none of them allegedly obtains over 3% efficiency except for P3HT/PCBM or PCPDTBT/PCBM.

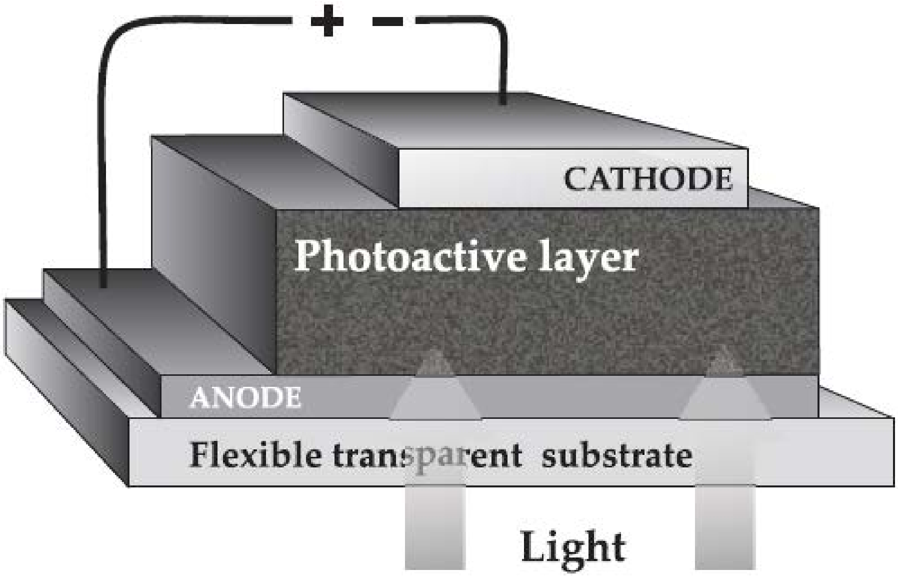

Figure 2. Schematic layout of an organic solar cell(Architecture of an organic photovoltaic device. The negative electrode is aluminum, indium tin oxide (ITO) is a common transparent electrode, and the substrate is glass. The schematic depicts a bulk heterojunction (BHJ) active layer where the donor and acceptor blend forms phase segregated domains within the active layer. The structure of the BHJ is critical to the performance of the solar device. - See more at: http://www-ssrl.slac.stanford.edu/content/science/highlight/2011-01-31/effects-thermal-annealing-morphology-polymer%E2%80%93fullerene-blends-organic#sthash.iE7FUkF8.dpuf)

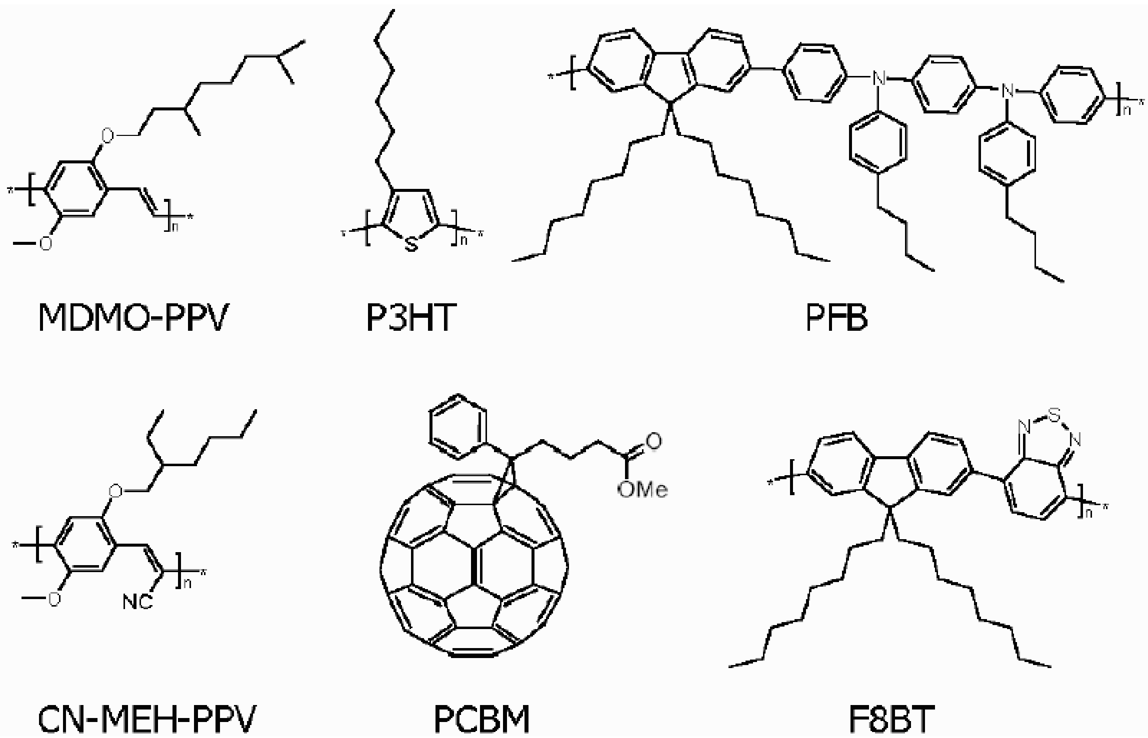

Figure 3. Several solution processible conjugated polymers and a fullerene derivative used in organic solar cells. Chemical structures and abbreviations of some conjugated organic molecules. From left: poly (acetylene) PA, poly(*para*-phenylene-vinylene) PPV, a substituted PPV (MDMO-PPV), poly(3-hexyl thiophene) P3HT, and a C60 derivative In each compound one can identify a sequence of alternating single and double bonds

3.2. Organic Solar Cell Application Field

We will summarize its application field by utilizing reports from Konarka and Plextronics. First, Konarka limits the application in 4 fields; 1) personal mobile phone charger, 2) small home electronics and mobile electronics attachment, 3) BIPV such as building's exterior wall, window, or blinder, and 4) power generation. Konarka predicts the market may be pioneered in each of these fields according to the module efficiency. In particular, the company predicts that the organic solar cell will be initially applied for special uses such as military market first due to low efficiency and high power generation unit cost.

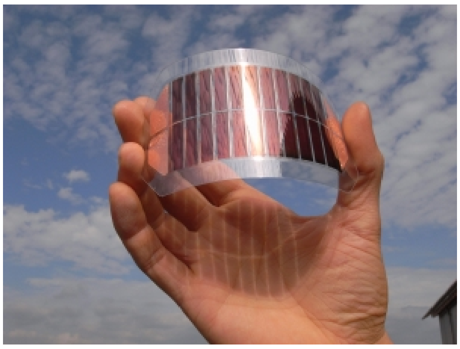

Figure 4. Organic Solar Cell

4. Conclusions

Latest advances have shown a great potential for organic solar cells compared to conventional silicon cells. Their versatility in production methods, properties and applications looks very promising for the future of solar energy.

4.1. Organic Solar or Photovoltaic Cells (OPVs)

Organic or plastic solar cells use organic materials (carbon-compound based) mostly in the form of small molecules, dendrimers and polymers, to convert solar energy into electric energy. These semi conductive organic molecules have the ability to absorb light and induce the transport of electrical charges between the conduction band of the absorber to the conduction band of the acceptor molecule. There are various types of organic photovoltaic cells (OPVs), including single layered and multilayered structured cells. Both types are currently used in research and small area applications and both have their respective advantages and disadvantages.

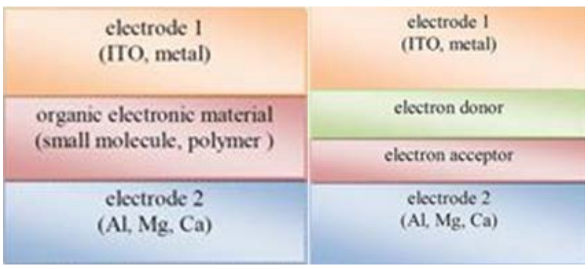

Figure 5. The Structure of a Single-Layer & a Multilayer Organic Solar Cell

4.2. Advantages of Flexible Organic Compared to Rigid Conventional Solar Cells

The latest advances in molecular engineering have uncovered a series of organic cell potential advantages that may eventually outbalance the benefits of silicon based solar cells. Although conventional solar cells currently dominate the existing market, the case may be quite different in the near future.

4.3. Manufacturing Process & Cost

Organic solar cells can be easily manufactured compared to silicon based cells, and this is due to the molecular nature of the materials used. Molecules are easier to work with and can be used with thin film substrates that are 1,000 times thinner than silicon cells (order of a few hundred nanometers). This fact by itself can reduce the cost production significantly.

Since organic materials are highly compatible with a wide range of substrates, they present versatility in their production methods. These methods include solution processes (inks or paints), high throughput printing techniques, roll-to-roll technology and many more, that enable organic solar cells to cover large thin film surfaces easily and cost-effectively. All above methods have low energy and temperature demands compared to conventional semi conductive cells and can reduce cost by a factor of 10 or 20.

4.4. Tailoring Molecular Properties

An important advantage of organic materials used in solar cell manufacturing is the ability to tailor the molecule properties in order to fit the application. Molecular engineering can change the molecular mass, bandgap, and ability to generate charges, by modifying e.g. the length and functional group of polymers. Moreover, new unique formulations can be developed with the combination of organic and inorganic molecules, making possible to print the organic solar cells in any desirable pattern or color.

4.5. Desirable Properties

The tailoring of molecular properties and the versatility of production methods described on the previous page enable organic polymer solar cells to present a series of desirable properties. These solar modules are amazingly lighter and more flexible compared to their heavy and rigid counterparts, and thus less prone to damage and failure. They can exist in various portable forms (e.g. rolled form) and their flexibility makes storage, installation, and transport much easier.

4.6. Environmental Impact

The energy consumed to manufacture a solar cell is less than the amount required for conventional inorganic cells. Consequently, the energy conversion efficiency doesn't have to be as high as the conventional cell's efficiency. An extensive use of organic solar cells could contribute to the increased use of solar power globally and make renewable energy sources friendlier to the average consumer.

4.7. Multiple Uses and Applications

The present situation indicates that organic solar cells cannot substitute for silicon cells in the energy conversion field. However their use seems to be more targeted towards specific applications such as recharging surfaces for laptops, phones, clothes, and packages, or to supply the power for small portable devices, such as cellphones and MP3 players.

Other than the domestic use, recent developments have shown a military application potential for organic solar modules. Research in the US (Konarka) has shown that organic cells can be used in soldier tents to generate electricity and supply power to other military equipment such as night vision scopes and GPS (global positioning system) receivers. This technology is thought to be extremely valuable for demanding missions.

4.8. The Current Situation

Organic Solar cells have certain disadvantages including their low efficiency (only 5% efficiency compared to the 15% of silicon cells) and short lifetime. Nonetheless, their numerous benefits can justify the current international investment and research in developing new polymeric materials, new combinations, and structures to enhance efficiency and achieve low-cost and large-scale production within the next years. A commercially viable organic solar cell production is the target of the next decade.

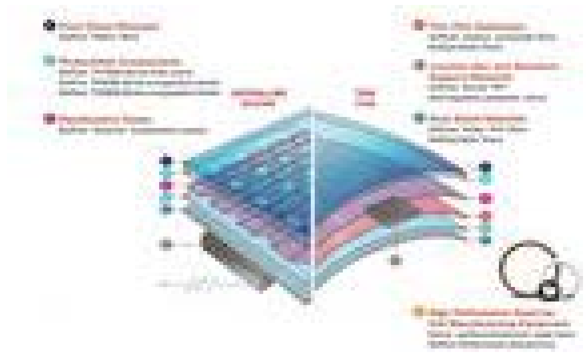

Figure 6. Schematic Comparison of a Rigid Crystalline Silicon to a Flexible Organic Solar Cell

Donor–acceptor based organic solar cells are currently showing power conversion efficiencies of more than 3.5%. Improving the nanoscale morphology together with the development of novel low band gap materials is expected to lead to power conversion efficiencies approaching 10%. The flexible, large-area applications of organic solar cells may open up new markets like “textile integration.” Organic semiconductor devices in general and organic solar cells in particular can be integrated into production lines of packaging materials, labels, and so forth. Because there is a strong development effort for organic electronics integration into different products worldwide, the solar powering of some of these products will be desired. The next generation of microelectronics is aiming for applications of “electronics everywhere,” and such organic semiconductors will play a major role in these future technologies. Combinations of organic solar cells with batteries, fuel cells, and so forth, will enhance their product integration. This inerrability of organic solar cells into many products will be their technological advantage.

The Si solar cell which has high manufacturing process expenses show delayed commercialization due to difficulties in overcoming its manufacturing cost limitation as Si wafer raw material supply shortage intensifies. On the other hand, the conjugated system organic/polymer material based organic solar cell is expected to reduce the manufacturing cost through new processes such as printing process. Therefore, the commercialization seems only possible by maximizing the energy conversion efficiency through a development of new conjugation system organic materials with reduced band gap.

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