

FPR – ORGANIC SOLAR CELL

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Abstract:

Solution processed organic solar cells offer the potential to produce power at low costs. Their mechanical flexibility, light weight and easy-to-use preparation methods make them suitable for a wide range of applications. Thus creating new organic materials and studying their properties and behavior in devices are subjects of current research. The overall goal is not only to achieve higher efficiencies, but also to obtain a fundamental understanding of the mechanisms occurring in these materials and at their interfaces.

The objective of this lab course is to impart a basic understanding of the principles and characteristics of organic solar cells. To achieve this, several organic solar cells will be prepared and characterized.

Keywords: photovoltaic cell, organic semiconductors, sp^2 -hybridization, excitons, fullerenes, polythiophenes.

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1 INTRODUCTION

Devices made of organic semiconductors are more and more becoming a part in our daily life. Organic light emitting diodes (OLEDs) used in TV-screens and smartphones are probably the best known example. But also wearable organic photovoltaic cells (OPVCs) for example integrated in bags or jackets are already commercially available. Soon printed electronics made of organic field effect transistors (OFETs) like radio-frequency identification (RFID) chips will become a normal part of our life like the (inorganic) transistor did with the introduction of the personal computer.

Although organic semiconductors are used in commercially available products, the mechanisms happening in them and at their interfaces to other organic and inorganic materials are not yet completely understood. Thus organic semiconductors still remain an interesting topic in current research.

The potential advantages of devices made of organic semiconductors to inorganic ones are vast. By easy-to-use, solution based preparation methods like roll-to-roll printing they offer low cost production methods. Also organic thin films can be processed on large areas via these preparation methods, while silicon based devices are limited to small wafers with a diameter of 300mm at best. Another advantage is their mechanical flexibility and light weight, which makes them suitable for mobile applications. Furthermore their electronic and optical properties can easily be tuned by the synthesis of different derivatives of organic molecules and polymers. All in all, these properties make them suitable for a wide range of applications and mass production.

Nevertheless there are also a few disadvantages. The efficiency of organic solar cells has undergone a huge acceleration in recent years, but cannot exceed 12% at the moment, while inorganic ones reach 30% and more. The main disadvantage though remains the very low charge carrier mobility of organic semiconductors compared to inorganic semiconductors. Thus organic semiconductors can never replace inorganic ones when it comes to fast electronics like processors, but are more than able to compete with inorganic semiconductors regarding slow electronics like the ones mentioned above.

The aim of this script and lab course is to teach you the basic principles of organic semiconductors and organic solar cells. During this lab course you will also learn how to handle organic semiconducting molecules and polymers and how to use basic preparation methods to produce organic devices.

2 PRINCIPLES OF ORGANIC SOLAR CELLS

2.1 ORGANIC SEMICONDUCTORS

Organic semiconductors are organic materials, meaning various materials containing hydrocarbon compounds, which have semiconducting properties. They are often divided into two classes: small molecules with a low molecular weight and polymers. The fundamental properties of both classes are in principle the same, the division mainly arises from the way they are processed. Small molecules are mostly thermally evaporated in vacuum, while polymers can only be processed from solution. The main characteristic of organic semiconductors is their conjugated π -electron system. The simplest case to understand π -bonding is ethene, a double bond carbon-carbon molecule with two hydrogens attached to each carbon atom, schematically shown in Figure 1.

Carbon consists of four valence electrons. In its ground state two of the valence electrons are in the 2s orbital and two in the 2p orbitals. For chemical bonds however it can be energetically favorable, if the atomic orbitals forming the bonds are hybridized. Hybridization means that the atomic orbitals are mixed to form new orbitals. In the case of carbon sp -, sp^2 - or sp^3 -hybridization is possible, where the s-orbital hybridizes with one, two or all three p-orbitals, respectively. For organic semiconductors sp^2 -hybridization is the most important case. Here the 2s-orbital is mixed with the $2p_x$ - and the $2p_y$ -orbital forming the three sp^2 -orbitals with the p_z -orbital remaining. The three sp^2 -orbitals are in-plane and oriented at 120° relative to each other and the p_z -orbital is standing perpendicular to the plane, as it is illustrated in Figure 1a.

In ethene two of the sp^2 -orbitals from the two carbon atoms form a covalent bond, which is called the σ -bond. As it is schematically shown in Figure 1b the two p_z -orbitals can overlap above and below the plane of the σ -bond, forming another covalent bond, the so called π -bond. The two halves of the π -orbital lie above and below the plane of the σ -bond and therefore the π -electrons are delocalized across the σ -bond (Figure 1c). As π -bonds are usually weaker than σ -bonds, optical excitation from the bonding π - to the antibonding π^* -orbital are possible without breaking the molecule (Figure 1d).

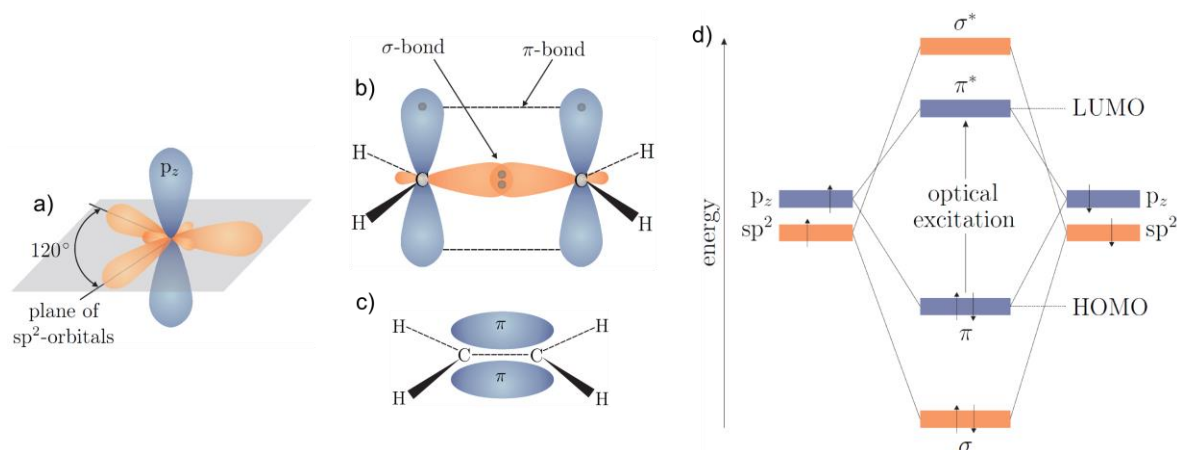


Figure 1: σ - and π -bonds. **a)** In a sp^2 -hybridized C-atom the s-, p_x - and p_y -orbitals form the three in-plane sp^2 -orbitals with the remaining p_z -orbital standing perpendicular to the plane. **b)** In ethene the σ -bond is formed by the overlap of two hybrid orbitals, whereas the π -bond is formed by the overlap of the two p_z -orbitals. **c)** The two halves of the π -orbital lie above and below the σ -bond, respectively. Therefore the two π -electrons are delocalized across the C-C bond. **d)** The energy level diagram of ethene shows that the energetic lowest electronic excitation is possible from the bonding π - to the antibonding π^* -orbital. Adapted from: Hörmann, U.: *Characterization of planar and diffuse heterojunction solar cells based on poly(3-hexylthiophene) and fullerenes*, University of Augsburg 2009.

In compounds with alternating single and double bonds the p_z -orbitals of σ -bonded carbon atoms are overlapping and can therefore form a conjugated system, where the π -electrons are delocalized throughout the whole system. The classic example for a conjugated π -system is the benzene ring shown in Figure 2. It has six π -electrons, which are delocalized throughout the whole ring. Many important organic semiconductors contain benzene rings as well as five-membered rings (see also Figure 10).

The energy gap of an organic semiconductor is an intrinsic property of the molecule or polymer, unlike the band gap in an inorganic semiconductor, which is a property of the crystal. Here the energy gap stems from the energy difference between the *highest occupied molecular orbital (HOMO)* and the *lowest unoccupied molecular orbital (LUMO)*. Typically the energy gap lies in the region of 1.5 to 3.0 eV, which is the region of visible light and therefore makes organic semiconductors suitable for optoelectronic devices. The energy gap depends on both the length of the conjugated system and on the influence of functional side groups. For that reason organic chemistry has the possibility to tailor the optical and electronic properties of organic semiconductors to specific needs.

In organic molecular solids the molecules are bound by weak van-der-Waals forces in contrast to inorganic materials, where the atoms form covalent or metallic bonds. As a consequence there is normally no formation of electronic bands in solids consisting of organic semiconductors, but localized molecular energy levels. Due to this, charges experience a strong coupling to the lattice and are usually described as polarons rather than free charge carriers. Charge transport therefore occurs via hopping (tunneling of charge carriers) between sites, which yields low charge carrier mobilities (10^{-4} to 10^{-1} cm^2/Vs) compared to mobilities in inorganic materials (10^2 to $10^4 \text{ cm}^2/\text{Vs}$).

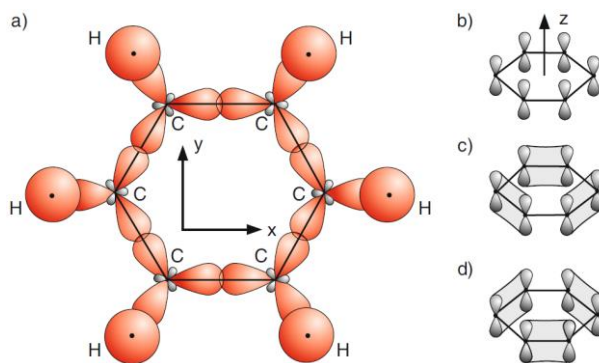


Figure 2: Benzene. a) The localized σ -bonds are lying in-plane. b) The p_z -orbitals standing perpendicular to the σ -bond plane are forming the π -electron system. c) and d) The two isomeric structures of benzene are indistinguishable leading to the π -electrons being delocalized throughout the whole ring. Source: Demtröder, W.: *Experimentalphysik 3* ©2010 Springer-Verlag, Berlin.

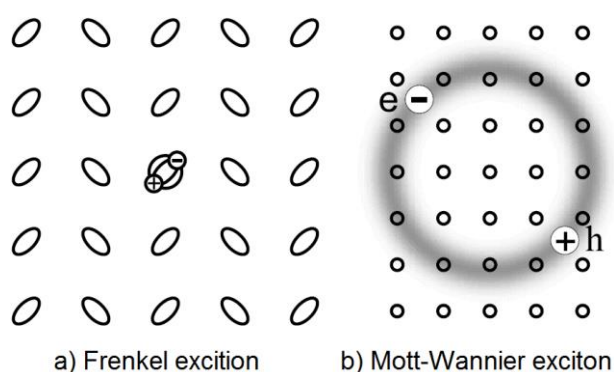


Figure 3: Excitons. a) A Frenkel exciton describes the case, where the electron and hole are localized on the same lattice site or molecule. Therefore it has a high binding energy in the order of 0.1 to 1 eV. This is the case for organic semiconductors. b) The radius of a Mott-Wannier exciton is larger than the lattice spacing and the binding energy of it is low in the order of 10 meV. It is typical for inorganic semiconductors. Source: Schwörer, M. & Wolf, H.C.: *Organic Molecular Solids* ©2007 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Light absorption in an organic semiconductor leads to the formation of an exciton. An exciton is a quasiparticle consisting in this case of an electron in the LUMO and a hole in the HOMO, which are bound through their coulombic attraction called the exciton binding energy. The excitons in organic semiconductors, called *Frenkel excitons*, are located on the same molecule and have a high binding energy in the order of 0.1 to 1 eV, in contrast to the so-called *Mott-Wannier excitons* in inorganic semiconductors, which have a low binding energy in the order of 10 meV and a radius typically much larger than the lattice spacing of the inorganic crystal. Both types of excitons are shown in Figure 3. Due to their high binding energy Frenkel excitons cannot be dissociated by

thermal energy (approx. 25meV at room temperature) and therefore a driving force is needed to generate free charge carriers. This is in contrast to inorganic semi-conductors, where nearly every absorbed photon immediately generates free charge carriers. The migration of excitons through the organic solid is dispersive and occurs via hopping. The mean free path of a Frenkel exciton is called the exciton diffusion length and is in the order of 5 to 20nm.

2.2 DEVICE OPERATION

Organic photovoltaic devices are normally prepared in a configuration, where the photoactive layer is sandwiched between two electrodes. In order to get light to the photoactive layer, one of the electrodes has to be transparent, which is typically the anode. Commonly transparent conductive oxides (TCOs) like indium tin oxide (ITO) are used as anode materials, which have to have a high work function to extract holes. As cathode materials low work function metals like calcium, magnesium or aluminum are used.

As it was discussed in chapter 2.1 a driving force is needed to dissociate electrons and generate mobile charge carriers. In a *homojunction* solar cell only one organic material is used as photoactive layer, thus charge separation can only occur at the interfaces of the organic materials and the electrodes. Therefore homojunction solar cells are very ineffective. One approach to increase the efficiency is to use *heterojunction* solar cells, where the photoactive layer consists of two different organic materials with one acting as an electron donor and the other as an electron acceptor. The concept is shown in Figure 4. When the offset of the frontier energy levels of both materials is larger than the exciton binding energy, the exciton can dissociate at the donor/acceptor interface and mobile charge carriers are generated. The hole is transferred into the HOMO of the donor and the electron into the LUMO of the acceptor material.

The energy levels of the involved materials and the alignment at their interfaces play a crucial role in the performance of the solar cell. Due to the exciton binding energy the optical gap in the materials is lower than the transport gap, which is the energy difference between LUMO and HOMO. The optical gap defines the range of the light, which can be absorbed by the material. Lowering of the optical gap therefore leads to an expansion of the usable light spectrum for charge generation, which leads to an increase in the produced photocurrent. The *open-circuit voltage* V_{OC} , described in chapter 2.3, is defined by the photovoltaic gap at the donor/acceptor interface. A general approximation of the open-circuit voltage V_{OC} is given by

$$eV_{OC} = E_{EA}^A - E_{IE}^D - 0.3 \dots 0.7,$$

where E_{EA}^A is the electron affinity of the acceptor and E_{IE}^D the ionization energy of the donor material.

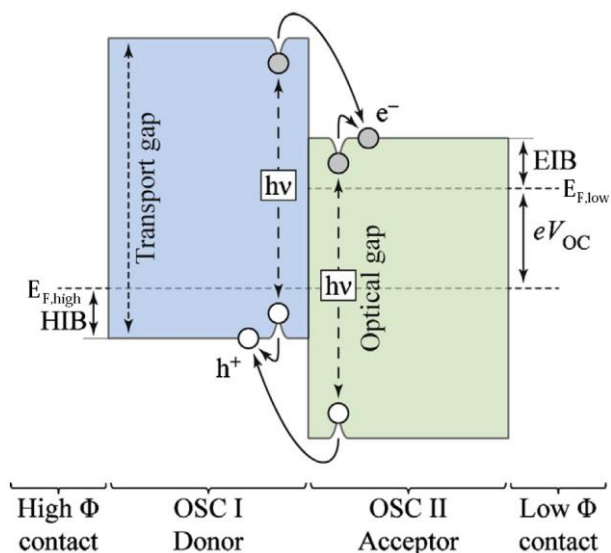


Figure 4: Energy level diagram of a heterojunction solar cell under open-circuit condition. Excitons are created by absorption of light in one of the two organic materials and can only dissociate at the donor/acceptor interface, which is possible due to the offset of the frontier energy levels of the donor and the acceptor being larger than the exciton binding energy. Adapted from: Opitz, A. et al., *J. Electron Spec.* **190**, 12–24 (2013).

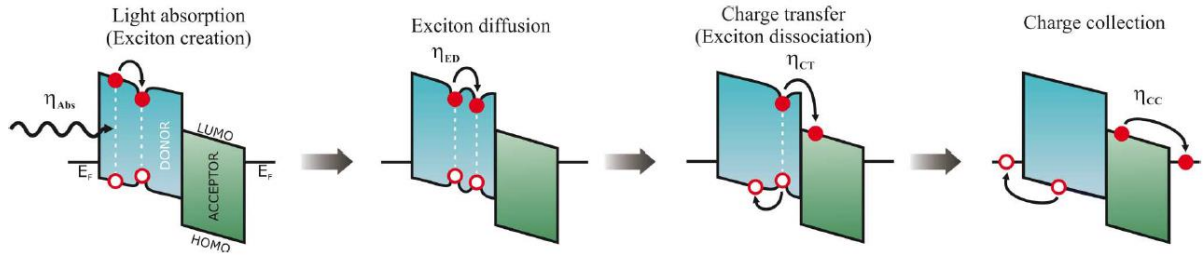


Figure 5: Four step process of charge generation in a heterojunction solar cell. First light is absorbed in the active layer of the solar cell forming a strongly bound exciton. This exciton diffuses throughout the layer until it reaches the donor/acceptor interface, where it dissociates and the electron and hole are separated. The charge carriers are then transported to the electrodes, where they are collected. Adapted from: Opitz, A. et al., *IEEE J. Sel. Top. Quant.* **16**, 6, 1707-1717 (2010).

The difference in energy between the HOMO of the donor and Fermi level E_F of the anode is called the *hole injection barrier (HIB)* and the one between the LUMO of the acceptor and the Fermi level of the cathode *electron injection barrier (EIB)*. High injection barriers lead to a reduced fill factor, therefore they need to be kept as small as possible.

The process of charge generation can be separated into four steps, like it is shown in Figure 5:

1. Light is absorbed in either of the two layers, which make up the active layer, and a strongly bound exciton is formed.
2. The exciton diffuses through the layer until it reaches the donor/acceptor interface.
3. There it dissociates and mobile charge carriers are generated.
4. The mobile charge carriers are then transported to the electrodes, where they are collected.

With each of the four steps there is a correlated efficiency and the whole process is quantified by the internal quantum efficiency

$$\eta_{IQE} = \eta_{Abs} \cdot \eta_{ED} \cdot \eta_{CT} \cdot \eta_{CC},$$

which is the product of all four single step efficiencies. To account for reflection losses, the external quantum efficiency is defined as

$$\eta_{EQE} = (1 - R) \cdot \eta_{IQE},$$

where R is the reflectivity of the device. The external quantum efficiency is basically the ratio of generated charge carriers to the number of incident photons. How to determine the external quantum efficiency experimentally is described in chapter 2.3.

To allow good light absorption in the active region of the heterojunction solar cell, the prepared layers commonly have a thickness of some hundred nanometers. As it was described in chapter 2.1 the exciton diffusion length is only in the order of a few ten nanometers. In a planar heterojunction geometry like it is illustrated in Figure 6a most of the created excitons decay before reaching the donor/acceptor interface and therefore don't generate mobile charge carriers. To get a larger interface area, bulk heterojunctions (illustrated in Figure 6b) are used. They can be prepared via solution processing by simply

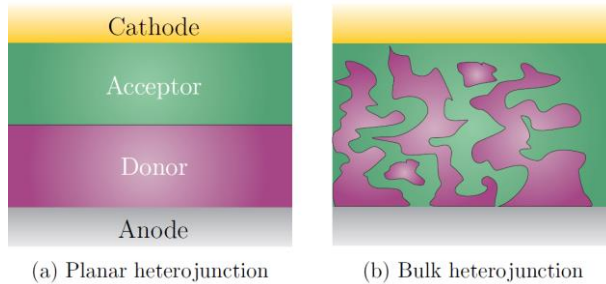


Figure 6: Different types of heterojunctions. a) Planar heterojunction. b) Bulk heterojunction. Adapted from: Hörmann, U.: *Characterization of planar and diffuse heterojunction solar cells based on poly(3-hexylthiophene) and fullerenes*, University of Augsburg 2009.

mixing the solutions of the two organic materials and spin-coating the mixture. The disadvantage of a bulk heterojunction is the possible formation of closed-off domains of either organic material, so that a generated charge carrier is trapped inside these domains. In contrast the planar heterojunction ensures closed paths to the electrodes. Therefore a trade-off between charge transport and exciton diffusion is unavoidable, while using these two simple-to-prepare heterojunction geometries.

2.3 DEVICE CHARACTERISTICS

Solar cells in general are characterized by a few key parameters obtained from their current-voltage curves under illumination. The typical I-V curves of a solar cell with and without illumination are shown in Figure 7. While the I-V curve without illumination resembles a typical diode behavior, the I-V curve with illumination is shifted towards the negative current regime due to the produced photocurrent.

The current measured in the short-circuit condition (zero voltage applied) is called the short-circuit current I_{SC} . To allow better comparison between different solar cells, it is convenient to refer to the *short-circuit current density* J_{SC} , which is independent of the size A of the solar cell. Due to the field dependence of the charge separation, the short-circuit current is not equal to the maximum of the photocurrent I_{sat} , which is often only reached in the negative voltage regime. At the *open-circuit voltage* V_{oc} the photocurrent completely compensates the dark current, thus the net current reaches zero. The point where the product of current and voltage reaches its maximum is called the *maximum-power-point (MPP)* and defines the operating point of the solar cell. The ratio between the maximum power output (orange area in Figure 7) and the product of the short-circuit current and the open-circuit voltage (grey area) is called the *fill factor FF*, which is an important parameter to characterize the performance of a solar cell.

The *power conversion efficiency* η_{PCE} is defined as the ratio between the electrical power output P_{max} and the power of the incident light P_{in} , which can be expressed as

$$\eta_{PCE} = \frac{P_{max}}{P_{in}} = \frac{I_{MPP} \cdot V_{MPP}}{P_{in}} = \frac{FF \cdot J_{SC} \cdot V_{OC}}{P_{in}/A}.$$

Therefore the fill factor, the short-circuit current density and the open-circuit voltage are the key parameters to describe the performance of a solar cell. For an efficient solar cell they need to be as large as possible. For organic heterojunction solar cells power conversion efficiencies of 10% and more have been reached.

The power conversion efficiency accounts for the overall performance of the solar cell under illumination with a specific spectrum. A second measure of the conversion efficiency is the *incident photon to converted electron efficiency* η_{IPCE} or *external quantum efficiency* η_{EQE} , which is specific for

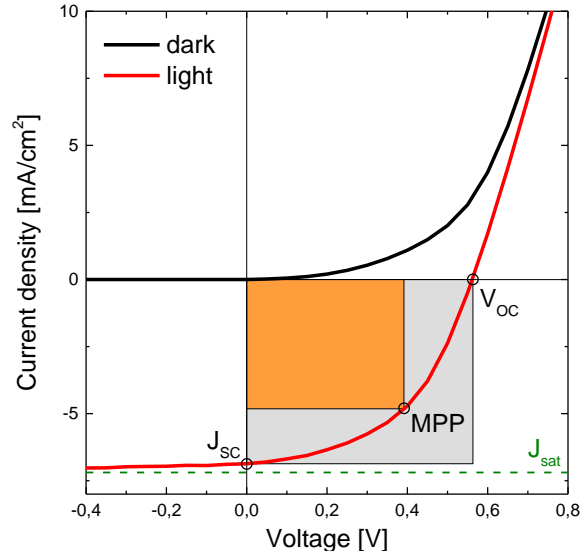


Figure 7: Current density-voltage characteristics of a solar cell in dark and under illumination. The fill factor is the ratio between the maximum power output (maximal-power-point MPP – orange area) and the product of the short-circuit current density J_{SC} and the open-circuit voltage V_{OC} (grey area). The maximal photocurrent density J_{sat} is only reached in the negative voltage regime and is therefore larger than the short-circuit current density J_{SC} .

the wavelength λ of the incident light. It is defined as the ratio of the number of generated charge carries to the number of photons with a specific wavelength and is expressed as

$$\eta_{EQE} = \frac{\text{\#electrons}}{\text{\#photons}} = \frac{hc}{e\lambda} \cdot \frac{J_{SC}}{E_e},$$

where h is Planck's constant, c the speed of light, e the elementary charge and E_e the irradiance of the incident light.

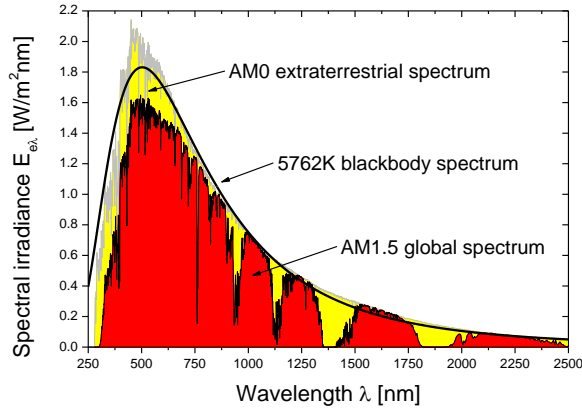


Figure 8: Solar Radiation Spectra. The AM0 extraterrestrial spectrum corresponds to the radiation of the sun at the top of the atmosphere. It matches the spectrum of a blackbody radiator at 5762K. The AM1.5 global spectrum corresponds to the radiation of the sun at sea level for a solar zenith angle of 48.2°. Data from *ASTM G173-03 Reference Spectra*, American Society for Testing and Materials.

The materials used in different solar cells usually have a different spectral sensitivity, therefore the power conversion efficiency depends strongly on the spectral distribution of the incoming light. For this reason and due to the fact that most of the major cities and therefore the main industry and solar plants across Europe, China and the US lie in temperate latitudes, a standard global reference spectrum has been defined, which simulates the radiation of the sun at sea level for an air mass (AM) of 1.5 (corresponding to a solar zenith angle of 48.2°). The AM 1.5 global reference spectrum shown in Figure 8 has an integrated power density of 100mW/cm².

3 EXPERIMENTAL METHODS AND MATERIALS

3.1 SPIN-COATING

Spin-coating is one of the most applied procedures to deposit uniform thin films of solution processable materials on flat surfaces. Its simplicity and easy usability makes it a widely used technique to achieve thin films with nanoscale thicknesses in applications in industry and research.

The spin-coating process consists of four steps, like it is shown in Figure 9. First a little amount of solution is dispensed onto the surface. The sample is then accelerated to high speed in order to spread the material across the sample and to throw off excess amount of fluid by centrifugal force. Following the film is thinned by spinning fluid off the edges of the sample. Simultaneously the solvent evaporates and therefore increases the viscosity of the solution, which counters the centrifugal force. The sample is rotated until the desired film thickness is reached or until the viscosity of the solution becomes so high, that no more material can be spun off. Afterwards the film is dried until only little residual solvent is left. Often this step is accelerated by applying heat to the sample. The resulting thickness t of the film can be empirically described by

$$t \propto \frac{c_0}{(1 - c_0)^{1/3}} \eta^{1/3} \omega^{-2/3},$$

where c_0 is the volume concentration of the material in the solution, η is the viscosity of the solution and ω is the angular spin velocity. For small concentrations c_0 the resulting film thickness increases linear with increasing concentration. Also the film thickness increases with decreasing spin speed. Normally it is best to have a high concentration and control the film thickness via the spin speed.

3.2 VACUUM THERMAL EVAPORATION

A common technique to deposit metal films is vacuum thermal evaporation. The material is put into a ceramic crucible or boat inside a vacuum chamber, which is then heated via a constant current flow. Depending on the used setup, currents in the range of 50A are needed to reach temperatures above 1000°C to evaporate the metal. The evaporation rate can be adjusted by varying the intensity of the current. The substrate is placed above the sample and is normally shielded via a shutter until the desired evaporation rate is reached. When the metal vapor reaches the substrate it condenses and therefore forms a thin film, which's thickness can be controlled on a sub ångstrom scale.

Evaporation rates are normally measured by a quartz crystal microbalance. It consists of a quartz crystal plate, which is driven to oscillate at its resonant frequency. When material is deposited on top of quartz plate, the change of the resonant frequency is proportional to the weight of the deposited material. This change in frequency can be measured very accurately, thus little changes in weight can be measured, which is used to calculate the evaporation rate. Typical evaporation rates are in the order of a few ångstroms per second.

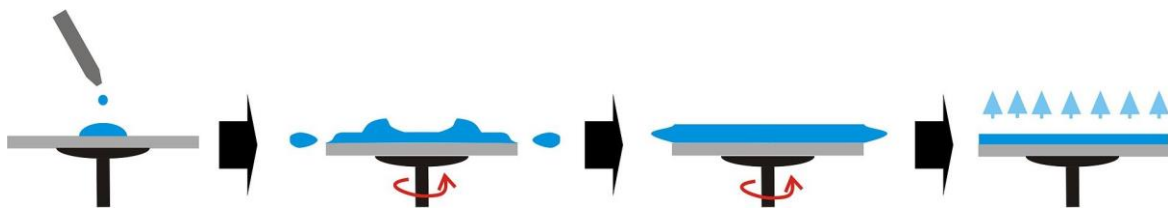


Figure 9: Spin-coating phases, which consist of dispensing a little amount of solution onto the sample, acceleration of the sample, film thinning and film drying. Source: *Solgel SpinCoating* by TyrionL 2008, Wikimedia Commons.

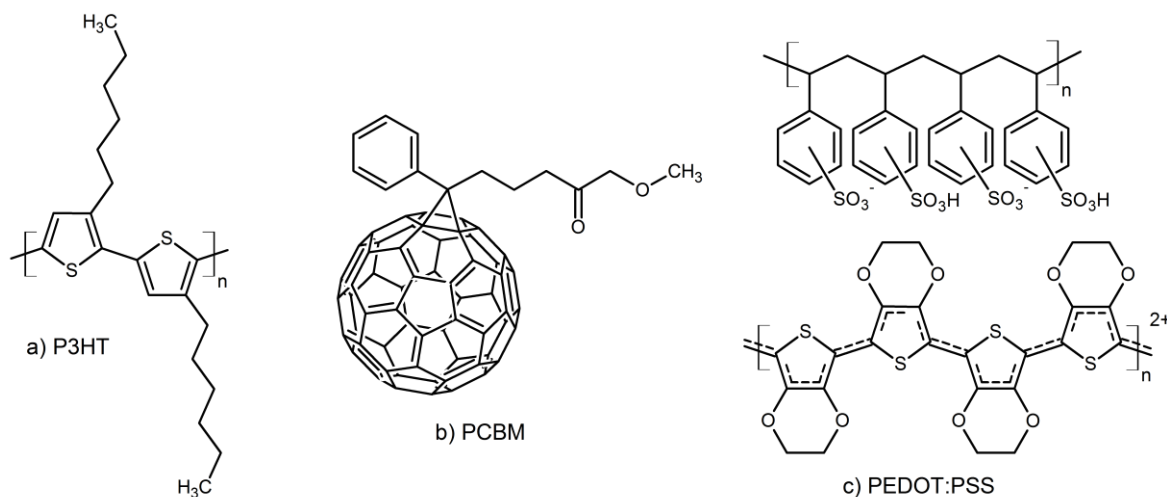


Figure 10: Structural formulas for the used organic materials. a) P3HT is used as a donor, whereas **b)** PCBM is used as an acceptor material. **c)** PEDOT:PSS is used as a hole extraction layer between the ITO and the active organic layer.

The base pressure inside the vacuum chamber should be lower than 10^{-7} mbar, to first lower the boiling point of the material, second provide a direct vapor beam, third avoid chemical reactions between metal and residual gas and fourth exclude doping with ambient gas molecules.

The thermal vacuum evaporation technique is also used to evaporate organic materials and is particular suited for materials, which are mostly insoluble and therefore cannot be processed from solution. Here the materials are commonly inserted into a quartz glass crucible. Also much lower temperatures and hence lower currents are needed to evaporate the materials.

3.3 ELECTRICAL AND PHOTOVOLTAIC CHARACTERIZATION

To characterize the performance of a solar cell, I-V curves are measured in dark and under illumination. From these the key parameters can be obtained like it was described in chapter 2.3.

The measurement of the I-V curves is performed with a computer controlled Keithley 2602A Sourcemeter. For the illumination of the solar cells the solar simulator SUN 2000 from ABET Technologies is used, which simulates an AM1.5 global spectrum.

3.4 MATERIALS

The solar cell build during this lab course consists of a glass substrate with a layer of ITO as anode, a thin layer of PEDOT:PSS as hole extraction layer, a bulk heterojunction of P3HT as donor and PCBM as acceptor material and a top layer of Aluminum as cathode. The chemical structures of the organic materials are shown in Figure 10 and the materials are described in the following. The energy levels of the materials are shown in Figure 11.

3.4.1 Indium Tin Oxide

Indium Tin Oxide (ITO) is at the moment one of the most used transparent conducting oxides (TCOs) for applications such as OPVCs and OLEDs, where it serves as an anode contact. It provides the combination of high optical transparency and good electrical conductivity. It normally consists of 90% indium(III) oxide (In_2O_3) and 10% tin(IV) oxide (SnO_2). Due to its high doping with tin, ITO is a degenerate semiconductor, which acts more like a metal than a semiconductor. The main disadvantage of ITO is the high demand of indium, which is a rare earth element and therefore very

expensive. For that reason one main focus of current research is to find other TCOs, which provide the same performance as ITO.

3.4.2 Poly(3-Hexylthiophene)

Poly(3-hexylthiophene) (P3HT) is a hole conducting polythiophene, where each thiophene has an attached hexyl side chain. Since the double bonds along the chain are alternating, the polymer has a large conjugated π -orbital-system. The position of the side chains between to monomeric units can be in different configurations: head to head (hh), tail to tail (tt) and head to tail (ht).

Commonly P3HTs are used, where all monomeric units are aligned in the ht-configuration, like it is shown in **Figure 10a**. This conformation is called regio-regular and shows a higher charge carrier mobility than other conformations. P3HT is widely used as an electron donor material.

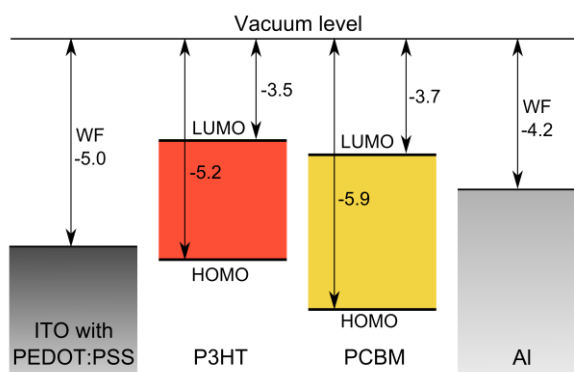


Figure 11: Energy levels of the used materials. All values in eV.

3.4.3 Phenyl-C61-Butyric Acid Methyl Ester

Phenyl-C₆₁-butyric acid methyl ester (PCBM) is a derivative of the buckminsterfullerene and is widely used as an electron acceptor material. Its side chain makes it soluble in conventional solvents, while preserving the electronic properties of the C₆₀ buckyball, thus it remains an excellent acceptor.

3.4.4 Poly(3,4-Ethylenedioxythiophene):Poly(Styrenesulfonate)

Poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) is a complex of two ionomers. The substituted polythiophene PEDOT is an intrinsically conductive polymer, which becomes highly conductive, when an electron is removed from its conjugated π -orbital-system. In the complex PSS acts as a polycounteranion to the PEDOT polycation. PEDOT:PSS has a very high conductivity of 1000S/cm. It's sold under the trade name CleviosTM as a water based dispersion and is widely used as an antistatic coating agent or like in this case as a hole extraction layer in organic solar cells.

3.4.5 Galinstan

Galinstan is a silvery eutectic alloy consisting of gallium, indium and tin, which is liquid at room temperature. Due to its non-toxic properties Galinstan is commonly used in applications previously employing the toxic, liquid mercury like for example thermometers. Since Galinstan has a good electrical conductivity, it can also be used as a replacement for evaporated aluminum top electrodes in organic solar cells by simply setting a drop of Galinstan on top of the organic film.

3.5 DEVICE FABRICATION

A sketch of the sample, which will be prepared during this lab course, is shown in Figure 12. The solar cells will be prepared on ITO-coated glass substrates. The substrates are patterned with two ITO stripes, each with a width of 1.6mm.

First the substrates need to be cleaned by rinsing with deionized water and afterwards sonication in acetone, isopropanol and highly pure isopropanol for 10min each time.

Then the PEDOT:PSS (dissolved in water) is dispensed through a hydrophobic filter onto the substrate and spin-coated at 50rps for 30sec. This will result in a thin film of approximately 40nm thickness. Afterwards the sides of the sample are cleaned with a water soaked Q-tip. Subsequently the substrate

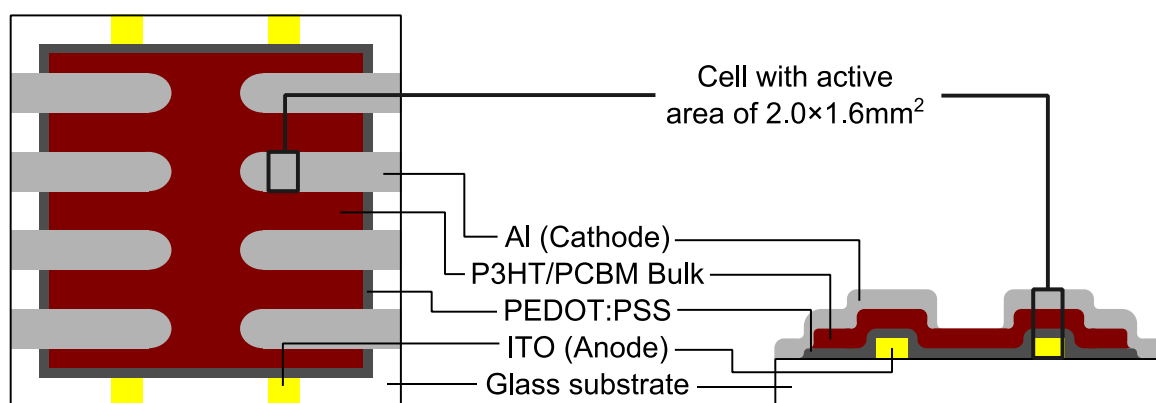


Figure 12: Schematic of a prepared sample. On the left-hand side the top-view of the sample is shown. The overlap between the ITO and the Al-strips defines eight solar cells, each having an active area of $2.0 \times 1.6 \text{ mm}^2$. On the right-hand side a cross-section of the sample shows the different organic and electrode layers building up the devices.

needs to be annealed on a hot plate at 150°C for 15min to remove residual water from the PEDOT:PSS film.

A solution mixture of P3HT and PCBM (1:1 by weight) with a concentration of 20mg/ml in dichlorobenzene is then spin-coated onto the PEDOT:PSS layer at 15rps for 2min. The thickness of the bulk layer is in the region of 80-100nm. Afterwards the sides of the sample are again cleaned with a chloroform soaked Q-tip. Following the sample is annealed at 75°C for 1h to improve the order of the P3HT/PCBM blend.

After the sample is cooled down, it is mounted in a sample holder with a mask on top of it and transferred into a vacuum chamber. When the base pressure of the chamber is below 10^{-7} mbar , a layer of aluminum is deposited via thermal vacuum evaporation onto the sample as top electrode. The geometry of the deposited Al-layer is shown in Figure 12. Each of the Al-strips has a width of 2mm. The overlap of the ITO and Al electrodes defines eight solar cell devices, each having an active area of $2 \times 1.6 \text{ mm}^2$.

4 TASKS

Before the lab course:

1. Read the following literature carefully as they will be discussed during the pretest. The literature is listed in order of importance. You can find the pdfs at <http://www-sms2.physik.hu-berlin.de/teaching.html> and receive the password from the supervisor.
 - a. Dennler, G., Scharber, M. C. & Brabec, C. J.: Polymer-Fullerene Bulk-Heterojunction Solar Cells, *Adv. Mater.* **21**, 1323–1338 (2009)
 - b. Dyer-Smith, C. & Nelson, J.: Organic Solar Cells in *Practical Handbook of Photovoltaics* 543–569 (Elsevier Ltd., 2012)
 - c. Deibel, C. & Dyakonov, V.: Sonnenstrom aus Plastik, *Physik Journal* **7**, 51–54 (2008)
 - d. Brütting, W. & Rieß, W.: Grundlagen der organischen Halbleiter, *Physik Journal* **7**, 33–38 (2008)
 - e. Du Pasquier, A., Miller, S. & Chhowalla, M.: On the use of Ga-In eutectic and halogen light source for testing P3HT-PCBM organic solar cells, *Sol. Energy Mater. Sol. Cells* **90**, 1828–1839 (2006)
2. Think about possible variations of the organic solar cell, how they can affect the performance of the cell and why (see task 3).

On the first day:

3. Prepare five different solar cell samples. The first one has to be prepared like it was described in chapter 3.5. For the second the layer of PEDOT:PSS is omitted. The third and fourth sample are likewise varied after discussion with the supervisor. For the fifth sample Galinstan is used as top electrode instead of aluminum.
4. Mount the samples into the vacuum chamber (except sample 5). The chamber needs to be pumped down over night to reach the desired pressure.

On the second day:

5. Evaporate an aluminum electrode on top of the four samples.
6. Now I-V curves of the prepared samples have to be obtained in dark and under illumination of a solar simulator. To get to know the solar simulator and the measurement setup, I-V curves of an inorganic solar cell are recorded as reference.
7. For the solar cell with the best performance also I-V curves have to be measured with different intensities of the incident light. To vary the intensity gray filters are used.

After the lab course:

8. Evaluate the obtained I-V curves and calculate the key parameters and the power conversion efficiencies of the solar cells with a sufficient accuracy.
9. Discuss your results focusing on the preparation dependent and intensity dependent performance of a P3HT:PCBM blend organic solar cell. How are the key parameters and the power conversion efficiency affected and why? Also, think about how your prepared solar cells can be further improved.

Please note: You are going to work in a chemistry lab. Therefore long pants (no shorts and skirts) and closed shoes are mandatory, even in summer! If you are not wearing appropriate clothing, you won't be allowed to continue with the lab course.