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MAULIDIANI Siti Winny Adya

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Fabrication and Characterization of Organic Solar Cells

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Directeur de l'option : Pere Roca I Cabarrocas
Directeur de stage : Joaquim Puigdollers
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Nom et adresse de l'organisme :
Universitat Politecnica de Catalunya
The Nanoengineering Research Centre
Campus Diagonal Sud, Building C' (C Prima). C. Pascual i Vila, 15 08028
Barcelona, Spain
SUMMARY

Increasing total population in the world is leading to increase demand of energy. On the other hand, the availability of fossil fuels is limited. In order to solve the energy crisis, renewable energy especially energy solar photovoltaic have been developed. On the other hand, the commercial photovoltaic based on Silicon are expensive. Therefore, low cost organic solar cells have been researched. It has been a challenge to improve the performance of organic solar cell for commercialization purpose.

In this project, the structure of organic solar cells is ITO/MoO$_3$(3nm)/DBP:C70(1:1)(x nm)/BCP(8nm)/Al(150nm). The effect of bulk heterojunction layer thickness and degradation of bulk heterojunction have been studied. The thickness of bulk heterojunction can influence the performance of organic solar cells. Increasing the thickness of bulk heterojunction can increasing in efficiency, however, after some points, increasing the thickness will reduce the efficiency of organic solar cells. The best efficiency achieved in this project is 3.12% with 60 nm of thickness.

Furthermore, the performance of organic solar cell was decreasing gradually in the period of time. It occurs because of contamination of oxygen and or water vapor. Consequently, the efficiency, fill factor, and short circuit current were declining gradually. Moreover, the mobility and life time of bulk heterojunction also was decreasing. On the other hand, the parallel resistance and the series resistance of bulk heterojunction organic solar cells were increasing in period of time.
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1. Introduction

1.1 General Context of the Study

Increasing total population in the world is leading to increase demand of energy. On the other hand, the availability of fossil fuels is limited. It is necessary to find substitution of fossil fuels with clean and safe energy in order to provide energy for all citizens and also to protect environment. Availability of safe and renewable energy to all citizens is prerequisite of sustainable society.

![World Population Growth](image)

**Figure 1.1 - World population growth [1]**

Figure 1.1 shows that since 1750, total world population both in developing country and industrialized religion has increased rapidly. It is also predicted that total world population will keep growing continuously until 2050. Comparing with Figure 1.2, the total demand of energy is estimated will keep increasing along with growing of population. Presently, almost one thirds of the world population does not have access to electricity especially population in the develop countries [2]. It has been a serious problem in the meantime. If the population growth and energy security are uncontrollable, then world would face big crisis in energy.

Therefore, it is necessary to diversify the energy sources, mainly the renewable energies. Renewable energy is energy derived from natural processes (e.g. sunlight and wind) that are replenished at a faster rate than they are consumed [3]. One of the sources of renewable energy is solar. In solar photovoltaic (PV) technology, using photovoltaic modules as a device, solar energy from the sun could be converted directly into electricity. This technology is one of future energy with promising prospective.
Literally, photovoltaics mean light-electricity; photo comes from the Greek phos, meaning lights and volt from the Italian scientist Alessandro Volta; a pioneer in the study of electricity [4]. The advantages of PV technology are clean, easy to maintain, and can be installed for remote areas. The electricity generated by PV systems can be used directly, stored locally, or fed into an existing electricity grid.

![Projected Future Demand of Energy](image)

Figure 1.2 - Projected Future Demand of Energy [6]

The global total of solar PV was roughly 67 GW at the end of 2011, to be compared with just 1.5 GW in 2000. Over the past five years, solar PV has averaged an annual growth rate of over 50% [2]. Figure 1.3 shows the potential of solar energy in European Countries. South of Europe has the highest global irradiation which means that they have huge potential for solar technology application. Furthermore, some countries on west, center, and east Europe also have potential for generating power from solar energy. It means that solar photovoltaic in Europe Countries is feasible to be implemented as an alternative energy resources.
On the other hand, total energy consumption from solar energy is still not maximized. Figure 1.4 shows share of renewable energy in gross electricity consumption of EU countries in 2011. It can be seen that the consumption of energy from solar power is about 6.9%. Comparing with wind power which is about 26.5% and hydraulic power which is about 46%, the total consumption of energy from solar power is still less. It is not proportional with solar resources which are abundant.

One of the causes of this problem is the price of PV cells. The cost for installation of PV cells is not proportional with the cost of power generated by PV cells. In order to solve this problem, PV cells with low cost are being developed. In Germany, for instances, PV system prices has decreased significantly since 2006 until 2013. It is shown on Figure 1.5. Germany,
as one of the leader of PV industry in Europe, has proved that the price of PV systems can be reduced gradually and become feasible for being implemented.

![Figure 1.5 - PV system prices in Germany [8]](image)

Commercialization of solar photovoltaic is dominated by crystalline silicon. Even though the efficiency of photovoltaic based on Silicon is quite high, the production cost of Silicon photovoltaic is very expensive. The photovoltaic cells based on Silicon are called as first generation of solar cells. The highest efficiency of crystalline silicone is up to 25%. It is
shown on Figure 1.6. So far, the highest efficiency of all type solar cells is achieved by multijunction cells which are about 44% of efficiency.

Second generation is thin-film solar technology. The materials which are being used for this technology are CdTe, CI(G)s, and a-Si or micromorph PV. However, some fabrication uses toxic manufacturing processes, and various panels contain harmful materials, which can make the recycling of these green energy suppliers considerably more difficult and expensive [5]. Some of the vital raw materials for this technology generation are quite rare, leaving production costs susceptible to long-term price increases [5].

Third generation is organic solar technology. Organic photovoltaic (OPV) has low cost production. It could be one of solution for energy problem. The most attractive potential of OPVs is the capability for high-speed manufacturing in roll-to-roll coating and/or printing production. In addition, OPVs are light-weight, thin, and flexible to significantly reduce balance of systems costs and enable solar cells to be placed anywhere [2].

However, the efficiency levels are low, despite the fact that the active semiconductor can be synthesised from many different molecular and polymeric materials. The lifetime is in the order of days if the device is exposed to ambient conditions and existing commercial encapsulants can extend it only to 2-3 years [2].

Improving the efficiency of OPV cells has become the biggest issue. The existing inorganic photovoltaic cells have efficiency around 20%, conversely, OPV only has efficiency lower than silicon. The best efficiency of OPV until now is 12% from Heliatek Company. It has become a challenge to make a significant progress of OPV cells for commercialization.

1.2 Context and Objectives
Since it is important to produce OPV with higher efficiency and also understand its characteristic, a project in Laboratory of Organic Solar Cells has been developed to fabricate Organic Solar Cells with bulk heterojunctions structures. In this project, current (I), voltage (V), external quantum efficiency (EQE), absorption, and transmittance are measured in order to know bulk heterojunction Organic Solar Cells performance. In collaboration with University of Barcelona, data of Variable Light Intensity Measurement (VIM) are also available.
The aim of this study is to fabricate and characterize organic solar cells in order to achieve higher efficiency and to understand its behavior.

In this context, the objectives of this project are:

1. Fabrication of bulk heterojunction Organic Solar Cells
2. Characterization of bulk heterojunction Organic Solar Cells
3. Study the effect of bulk heterojunction layer thickness
4. Study the degradation of bulk heterojunction Organic Solar Cells
2. **Background**

### 2.1 History of Organic Solar Cells [2] [9] [10]

Organic chemistry has significant development and remarkable progress. Chemical Abstracts Service (CAS) has been registering the number of known chemical substances since 1965. Firstly, in 1965, the number of chemical substances was 211,934 and lastly, in February 2005, it was 80,000,000 [2]. The discovery of single molecule or new group molecule is very important for organic solar cells in order to achieve organic solar cells with high performance.

In 1839, Becquerel discovered the photovoltaic effect. He observed a photocurrent when platinum electrodes, covered with silver halogen were illuminated in aqueous solution (photoelectrochemical effect) [2].

Photoconductivity in selenium was reported by Smith in 1873. The first observation of photoconductivity in organic compound (anthracene) was reported in 1906 by Pochettino. Photoconductivity in the poly(N-vinyl-carbazole) (PVK) polymers was put in evidence in 1957. During the same period the first inorganic photovoltaic cells were developed at Bell laboratories. These cells were based on crystalline silicon, their efficiency was 6%.

Thereafter, technology of solar cells based on Silicon has developed significantly and has reached efficiency about 25%. However, even if the price of these cells has been dramatically reduced, it is still too expensive and photovoltaic energy account for less than 0.1% of the total world energy production [2].

![Flexible organic solar cells](image-url)
Organic semiconductor is less expensive and more flexible. It is believed as an alternative of silicon based technology. The most important aspect of organic semiconductor is the cost of fabrication. It needs lower cost than silicon. During 1970s and 1980s, organic solar cells were fabricated, but they still have low efficiency due to their low concentration and mobility of free charge carriers [2]. On the other hand, during the last decade, the research of organic solar cells has been devoted. As a result, it has been discovered that the quantum efficiency of the electron transfer from an excited polymer to C\(_{60}\) is very high and the transfer is very fast, which is promising for charge carrier separation in PV cells. Moreover, the development of efficient organic displays based on organic light emitting devices (OLEDs) has proved that the organic components are feasible. Few years ago, Shaheen and co-workers have reported solar cells from MDMO-PPV blended with PCBM with 2.5% efficiency [2]. Moreover, CuPc/C60 bi-layer cell, with an exciton-blocking layer, yields a 3.6% efficiency [2]. Recently, organic solar cells with 11% of efficiency have already fabricated. In several years, it is estimated that organic solar cells would have stable and higher performance, therefore, it could be commercialized.

2.2 Basic of Organic Solar Cells

In order to investigate the performance of Organic Solar Cells, it is important to know first about the basic of organic semiconductor and working principle of Organic Solar Cells. In this subchapter, the organic semiconductor and working principle will be explained.

2.2.1 Organic Semiconductor [10][13]

![Figure 2.2 – Examples of organic semiconductor - polymers (left), and small molecules (right)]

The term “organic semiconductors” is used to describe organic materials which possess the ability of conducting electrons. The electronic conductivity of these materials lies between...
that of metals and insulators, spanning a broad range of $10^{-9}$ to $10^{3}$ $\Omega^{-1}$ cm$^{-1}$. Organic semiconductor can be divided into polymers and small molecules. Polymer is molecule composed by large number of monomers. Conversely, small molecules or oligomer is molecule that consists of few numbers of monomers.

Polymers are useful materials for semiconductors because they are easy to form thin films with large surface area. In addition, they have poor solubility in organic solvents and loss mobility during functionalization to enhance solubility. The advantage of small molecules is more facile to control charge transport by modification of various molecular. Polymers could be solution processed, for instances, being spin-coated from a solution of appropriate organic solvents, while little molecule materials mostly must be thermally evaporated and in some cases can be solution processed.

Mostly, organic materials are carbon-based compounds, with other atoms such as hydrogen, nitrogen, and oxygen. Each carbon atom is covalently bonded to other carbon atoms. They also have partially ionic interactions to atom of other elements.

![Figure 2.3 - Chemical structure and schematic drawing of ethylene](image)

In ground states, carbon atom has four valence electrons which are 2 in 2s and 2 in 2p orbitals. When a carbon atom receives an external excitation, an electron from the 2s orbital goes to 2p orbital. It creates mixture of 2s 2p orbitals which generates hybrid orbitals sp. The 2s orbital is hybridized with two 2p orbitals (2p$_x$, 2p$_y$) to form three sp$^2$ orbitals and one 2p orbital (2p$_z$) is left. The $\sigma$-bond between two carbons is formed by formation of an orbital overlap of two sp$^2$-orbitals. Therefore three $\sigma$-bonds are formed, two with neighboring carbon atoms and one with a hydrogen atom. In the sp$^2$-hybridisation, the p$_z$-orbitals form additionally $\pi$-bonds. These bonds have much smaller energetic than $\sigma$-bonds. The overlap of p$_z$ orbitals forms two molecular orbitals, a bonding $\pi$-orbital which is the highest occupied molecular orbital (HOMO) and an antibonding $\pi^*$-orbital which is the lowest unoccupied orbital (LUMO). HOMO and LUMO are equivalent with valence band and conduction band of an inorganic semiconductor. The difference of HOMO and LUMO is called band gap of
the organic material which is determined the optical and electrical properties of an organic material.

![Figure 2.4 – Energetic diagram of molecular orbitals](image)

2.2.2 Working Principle [9][10][11][12]
The most important difference between inorganic solar cells and organic semiconductors is in conversion of photons. In inorganic semiconductors, the photons are directly converted into free charge carries. The free charge carries would be collected by the corresponding electrodes. In organic semiconductors, photoexcitation of a molecule leads to creation of excitons. An exciton is a quasiparticle consisting of a boundstate of an electron and hole in semiconductors.

![Figure 2.5 – Diagram of process conversion from photon to free carriers in organic solar cell](image)

The process of converting light into electric current in an organic photovoltaic cell is illustrated in Figure 2.5. It is accomplished by six consecutive steps: (1) *Absorption* of a photon leading to the formation of an excited state, the electron-hole pair (exciton). (2) exciton creation within the photoactive layer. (3) *Exciton diffusion* to the interface of the two
different absorber layers. (4) charge transfer state where exciton gets separated. (5) Charge transport where charge free carriers are generated and transported through layer separately. (6) collection the charges at the electrodes, realized by Ohmic contacts.

**Light Absorption**

For an efficient collection of photons, the absorption spectrum of the photoactive organic layer should match the solar emission spectrum and the layer should be sufficiently thick to absorb most of the incident light. In organic devices, only a small portion of the light incident could be absorbed. It could be happen because the band gap of semiconductor is too high or the thickness of the layer is too thin. In general, the optical absorption coefficient (α) of organic materials is much higher than that of crystalline or multicrystalline silicon.

**Exciton Diffusion**

All exciton should reach dissociation site (interface between donor and acceptor). Exciton diffusion is in competition with other decay processes such as luminescence or radiative recombination to the ground state.

The average distance in a given material that an exciton can travel before annihilation is defined as the material-specific exciton diffusion length $L_D$, given by:

$$L_D = \sqrt{D\tau} \quad (1.1)$$

Where $\tau$ is the exciton lifetime and $D$ the diffusion coefficient. $L_D$ can vary from 1 nm to more than 50 nm, dependent on the material and structure. Only the excitons within a distance of $L_D$ from the interface will contribute to charge separation. In order to avoid this problem, research has been devoted to increase the diffusion coefficient of excitons or to the make the interfacial area much larger, so that each generated exciton is always close to an interface.

**Charge transfer state**

The dissociation happens via an intermediate state, a so-called charge transfer (CT) exciton. In this intermediate state the two charges are located on separate neighboring molecules. Exciton dissociation is favorable when energy of binding exciton ($E_x$) is larger than difference between ionization potential ($IP_D$) of donor and the electron affinity ($EA_A$) of acceptor.
\[ E_{\text{EX}} > IP_D - EA_A \] (1.2)

Exciton will recombine without contributing charges to the photocurrent if the difference is not sufficient.

**Charge Transport**

After separation process, charges have to be transported through the organic material to the electrodes to be collected. The loss mechanism occurs when there is recombination between electrons and holes while charges are transported to electrodes. The charge transport in organic materials can be described by a hopping mechanism, instead of band transport. Charge transport efficiency can be measured with mobility-lifetime ($\mu \tau$), which the average distance a charge carrier travels at a fixed electric field before it recombines.

**Charge Collection**

Electrons and holes which are able to leave the absorber layer are collected by electrodes. Electrons are collected on one side and holes are collected on other side. Transport layers let one kind of charge carriers go through and block the other one. The collection of charge carriers at the electrodes is regularly accomplished by a transparent conductive oxide (TCO) such as ITO or SnO2:F on one side and a metal contact such as Al or Ag on the other side.

### 2.3 Structure of Organic Solar Cells

Organic Solar Cells have been developed in the different structures. Firstly, the researchers established single layer structure. In order to obtain higher performance, the bilayer structure has been developed. Thereafter, bulk heterojunction structure has attracted attention to be fabricated and investigated further.

#### 2.3.1 Single Layer

![Sketch of Single Layer OPV](image)
The first organic solar cells consisted of a single layer of photoactive material between two electrodes of different work functions. However, due to the high binding energy of the excitons, the separation of the photogenerated charge carriers was so inefficient. Generally, single layer devices show high series resistance, low fill factor, and a field dependent charge carrier collection [5]. Since the recombination probability is proportional to the concentration of electrons and holes, the short circuit photocurrent dependence on the illumination intensity is sub linear.

2.3.2 Bilayer

![Diagram of Bilayer OPV]

The next breakthrough was achieved in 1986 by introducing the bilayer heterojunction concept, in which two organic layers with specific electron or hole transporting properties were sandwiched between the electrodes. The differing electron affinities between these two materials created an energy offset at their interface, thereby driving exciton dissociation.

In a bilayer device, the active layer is composed of two semiconductors, a donor and an acceptor. This device is based on the mechanism of the charge transfer from donor to acceptor. The photogenerated excitons have to move towards the interface where the potential drop between the energetic levels of two materials leads the breaking of the Coulombian interaction [10]. Consequently, the electrons accumulate in the acceptor and the holes in the donor. Once the charge carriers are separated in the two phases, their recombination only depends on defects concentration (traps) [10]. In addition, if the excitons fail to reach the interface, it leads to the loss of absorbed photons further away from the interface and results in low quantum efficiencies.

The efficiency of bilayer is limited by the charge generation 10-20 nm around the donor-acceptor interface [14]. Using thicker layers creates optical filter effects of the absorbing
material before the light gets to the interface. As a result, photocurrent is low at the maximum of the optical absorption spectrum. Furthermore, the thicknesses have to be optimized for the interference effects in the multiple structures [14].

2.3.3 Bulk Heterojunction

Bulk heterojunction photovoltaic cells were designed in 1995. The bulk heterojunction (BHJ) photovoltaic cells are using a blend of donor and acceptor materials. In this type of photovoltaic cell, the electron donor and acceptor are mixed together, forming a polymer blend, in order to obtain the maximum possible interface surface between the two materials. If the length scale of the blend is similar to the exciton diffusion length, most of the excitons generated in either material may reach the interface, where excitons break efficiently. Electrons move to the acceptor domains then were carried through the device and collected by one electrode, and holes were pulled in the opposite direction and collected at the other side.

2.4 Physics of Organic Solar Cells

The fundamental difference between OPV and inorganic PVs is that upon absorption of a photon by an inorganic material, free charge carriers are created, whereas in the case of organic materials, an excited electron-hole pair (or so-called exciton) is generated that needs to dissociate before free charge carriers are formed. The exciton is the bound state of an excited electron and positive charge carrier.
Current-Voltage Characteristics

In order to investigate the PV performance of a cell, the current density-voltage (J-V) characteristics in the dark and under illumination are considered.

![Figure 2.9 - J-V characteristics of a solar cell under the dark and under illumination](image)

When the cell is illuminated, the J-V curve is shifted down by the amount of photocurrent (Jph) generated. The open-circuit voltage, $V_{OC}$, is the maximum photovoltage that can be generated in the cell and corresponds to the voltage where current under illumination is zero.

In organic solar cells, the open circuit voltage is found to be linearly dependent on the highest occupied molecular orbital HOMO level of the donor (p-type semiconductor quasi Fermi level) and lowest unoccupied molecular orbital LUMO level of the acceptor (n-type semiconductor quasi Fermi level) [5].

The maximum current that can run through the cell at zero applied voltage is called the short-circuit current, $J_{SC}$. Ideally, loss free contacts, the short circuit current, $J_{sc}$, is determined by the product of the photoinduced charge carrier density and the charge carrier mobility within the organic semiconductor[5]:

$$J_{SC} = ne\mu E$$

(2.1)

where $n$ is the density of charge carriers, $e$ is the elementary charge, $\mu$ is the mobility, and $E$ is the electric field.

The maximum of the obtained electrical power $P_{max}$ is located where the product of current density $J$ and voltage $V$ reaches its maximum value ($J_{max} \times V_{max}$; as seen in Figure 2.9). $P_{max}$ is
bigger when the J-V curve resembles a rectangular with the area $J_{SC} \times V_{OC}$. The ratio between (the rectangle of) $P_{max}$ and the product of (or a rectangle defined by) $J_{SC}$ and $V_{OC}$ measure the quality of the shape of the J-V characteristics, and is defined as the fill factor (FF):

$$FF \equiv \frac{J_{max}V_{max}}{J_{SC}V_{OC}}$$

Thus, $P_{max}$ is defined as below:

$$P_{max} = J_{SC} \times V_{OC} \times FF$$

(2.3)

The power conversion efficiency $\eta$ (or PCE) of a solar cell is the ratio between the maximum output power $P_{max}$ and the power of the incident light $P_{light}$:

$$\eta = \frac{P_{max}}{P_{light}} = \frac{J_{SC} \times V_{OC} \times FF}{P_{light}}$$

(2.4)

In order to increase $\eta$, for the same incident light power $P_{light}$, either $J_{SC}$, $V_{OC}$, or FF (or all) need to be increased. For organic solar cells, the magnitude of $J_{SC}$, $V_{OC}$, and FF depends on parameters such as light intensity, temperature, composition of the components, thickness of the active layer, the choice of electrodes used, as well as the solid state morphology of the film.

In order to compare efficiencies of solar cells, incident solar power density ($P_{light}$) standards have to be defined. $P_{light}$ is standardized at 1000 W/m$^2$. In the present time, the standard is the AM1.5 spectrum which can be approached by commercial solar simulators. AM or Air Mass is the path length which light takes through the atmosphere normalized to the shortest possible path length. The reduction in the power of light is quantified by the Air Mass as it passes through the atmosphere and is absorbed by air and dust. Air mass 1.5 atmosphere thickness, corresponds to a solar zenith angle of $z=48.19^\circ$. Therefore, AM1.5 is useful to represent the overall yearly average for mid-latitudes.

![Spectral irradiance of the AM 1.5G (red area) solar spectrum up to 2600nm](image)

Figure 2.10 – Spectral irradiance of the AM 1.5G (red area) solar spectrum up to 2600nm

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The I-V curve of a solar cell is the superposition of the I-V curve of the solar cell diode in the dark with the light-generated current [16]. The light has the effect of shifting the I-V curve down into the fourth quadrant where power can be extracted from the diode. In ideal solar cell, the current-voltage characteristic in dark condition can be expressed as the sum of the Shockley as below:

\[
J(V) = J_0 \left( e^{\frac{qV}{nk_BT}} - 1 \right) \quad (2.5)
\]

with an additional photocurrent term \( J_{ph} \), under illumination conditions:

\[
J(V) = -J_{ph} \quad (2.6)
\]

Assuming a generation rate of charge carriers independent of the applied voltage \( V \) and adding up Eq.2.5 and Eq.2.6, current density in the solar cell results in:

\[
J(V) = J_0 \left( e^{\frac{qV}{nk_BT}} - 1 \right) - J_{ph}
\]

where \( J \) is the current density, \( J_0 \) reverse bias saturation current density, \( n \) is the diode ideality factor, \( k_B \) the Boltzmann constant, and \( T \) the absolute temperature.
In solar cells, parallel resistance \( R_p \) and series resistance \( R_s \) are very important parameters related to power and current generated by solar cells. In organic solar cells, parallel resistance \( R_p \), known as shunt resistor \( R_{sb} \), can attribute to recombination of charge carriers near the donor-acceptor interface. Moreover, series resistance \( R_s \) expresses contact resistances such as ohmic losses in the front and rear contact. Ideally, the shunt resistance has high number and the series resistance has low number, therefore, all the current flows to the external circuit. In fact, there is possibility of currents flow back into internal circuit and lost through recombination. \( R_p \) and \( R_s \) can be expressed as below:

\[
\frac{1}{R_p} = (\frac{dJ}{dV})_{oc}
\]  

\[
\frac{1}{R_s} = (\frac{dJ}{dV})_{sc}
\]

where \( (\frac{dV}{dJ})_{oc} \) is the rate of change of voltage with current density at open circuit point and \( (\frac{dV}{dJ})_{sc} \) is the rate of change of voltage with current density at short circuit point.

The mobility and life time of the charge carriers

The mobility and life time of the charge carriers depends on the chemical composition and chemical properties of the molecules. It can be analyzed by applying biased voltage across the solar cell without illumination. Furthermore, the effective mobility-lifetime of carriers is the sum of the mobility and lifetime of the electrons and mobility and lifetime of the holes. The effective mobility-lifetime of the carriers is given as:

\[
\mu \tau_{eff} = \frac{l_{col}L}{V_{dwf}}
\]

where \( l_{col} \) is the effective collection length, \( L \) is the thickness of the photoactive layer, \( V_{dwf} \) is the difference in the work functions of the ITO and the electrode. The \( V_{dwf} \) is given by the difference in the work functions of the ITO and the Aluminium electrode as below:

\[
V_{dwf} = (Wf)_{electrode} - (Wf)_{ITO}
\]

The effective collection length on the other hand is given by the following equation:

\[
l_{col} = \frac{V_c + V_{dwf}}{V_{dwf}} \ast \frac{L}{2}
\]
where \( V_c \) is the ratio of the two parameters at the short circuit point of the solar cell.

**Spectral response for solar cell** [16] [24]

The spectral response is conceptually similar to the quantum efficiency. The quantum efficiency describes the number of electrons output by the solar cell compared to the number of photons incident on the device, on the other hand, the spectral response is the ratio of the current generated by the solar cell to the power incident on the solar cell [16].

\[
SR(\lambda) = \frac{j_{ph}(\lambda)}{P(\lambda)} [A/W]
\]

\( EQE \equiv \frac{\text{number of electrons of external circuit}}{\text{number of incident photons}} \)

(2.12)

(2.13)

External quantum efficiency (EQE) is calculated from the spectral response \( SR(\lambda) \) of the device over a range of wavelengths with considering that the energy of a photon \( E_p = hc/\lambda \) with \( h \) being Planck’s constant, \( c \) the speed of light and \( q \) the elementary charge as below:

\[
EQE = SR(\lambda) \frac{hc}{q\lambda}
\]

(2.14)

EQE determines the conversion efficiency of an absorbed photon into a free charge carrier (extracted electron-hole pair). The EQE of organic photovoltaic can be expressed as the follow product of efficiencies, as below:

\[
EQE = \eta_A \times \eta_{ED} \times \eta_{CT} \times \eta_{CC}
\]

(2.15)

where \( \eta_A \) is the absorption efficiency, \( \eta_{ED} \) exciton diffusion efficiency to the donor acceptor interface, \( \eta_{CT} \) the charge transfer efficiency, and \( \eta_{CC} \) the carrier collection efficiency. From spectra of the EQE, the contribution of photocurrent of a definite wavelength can be evaluated, especially for bulk heterojunctions made of two different materials absorbing in different spectral regions. Hence, the contribution of each material to photocurrent can be obtained. If the absorption characteristics in thin films are known for the used materials, loss mechanism such as recombination of electron-hole pairs can be determined.
3. Methodology and Tools

3.1 Material
In this chapter, materials are used in the project will be discussed. There are Indium Tin Oxide (ITO), Molybdenum Trioxide (MoO₃), Fullerene (C₇₀), DBP, BCP, and Aluminum.

3.1.1 Glass and Indium Tin Oxide (ITO) [11]
In this study, all the devices were fabricated on the top of glass and Indium Tin Oxide (ITO, or tin-doped indium oxide). Glass is used as a substrate for depositing materials because of its flatness, rigidity, and transparency. Indium tin oxide is a solid solution of Indium (III) oxide (In₂O₃) and tin(IV) oxide (SnO₂), typically 90% In₂O₃, 10% SnO₂ by weight. ITO is one of the most widely used transparent conducting oxides because it has high electrical conductivity and high optical transparency. ITO has a high work function of ~4.8 eV, which makes it very reliable as a hole-extracting electrode. To achieve a better match between the energy levels of the anode and the HOMO of the hole conducting material, the commonly used indium tin oxide (ITO) anode can be modified by plasma etching or by coating with a higher work function organic hole transport layer.

3.1.2 Molybdenum Trioxide [18]

Fig 3.1 - MoO₃ structure
Molybdenum trioxide (MoO₃) with the work function is about 5.3 eV, is used as a hole transport layer in organic devices. It can effectively substitute PEDOT:PSS as the buffer layer in the organic PV cells. It can improve hole injection and operational stability in OLED applications. In small molecule solar cells, it can help to enhance the fill factor due to the reduction in the series resistance and also power conversion.
3.1.3 DBP [19]

Dibenzo tetraphenyl dindeno perylene or DBP is produced by the reaction of phthalic anhydride with n-butanol in the presence of concentrated sulphuric acid as a catalyst. Excess alcohol is recovered and recycled and the di-n-butyl phthalate is purified by vacuum distillation and/or activated charcoal. In organic solar cells, DBP is used as an electron donor. The molecular formula of DBP is C_{64}H_{36}. It has HOMO level about -5.5 eV and LUMO level about -3.5 eV. The molecular weight of DBP is 804.97.

3.1.4 Fullerene C_{70} [9]

C_{70} is the fullerene molecule which consists of 70 carbon atoms. It is made of 25 hexagons and 12 pentagons, with a carbon atom at the vertices of each polygon and a bond along each polygon edge. Each carbon atom on the structure is bonded covalently with 3 other atoms. In organic solar cells, C_{70} is used as an electron acceptor. It has HOMO level about -6.2 eV and LUMO level about -4 eV. The molecular weight of C_{70} is 840.75 and the density of C_{70} is 1.7 g/cm^3.

In the cost analysis of the fullerene, the high price of single component fullerenes C_{60} and C_{70} is due to the high price of separation and purification, which is clearly seen by comparing the cost of pure fullerene grades to the as-produced “raw” fullerene grades, which are mixtures
primarily of C\textsubscript{60} and C\textsubscript{70}. Since the composition of the active layer is typically at least half fullerene derivative for this type of organic solar cells, there is a large incentive in final device cost-savings to minimize fullerene purification as much as possible [9].

3.1.5 Bathocuproine (BCP) [20]

![Fig 3.4 - BCP structure](image)

In organic solar cells, Bathocuproine, 2,9-dimethyl-4,7-diphenyl-1,10-phenanthroline, also called BCP, is used as electron transport layer. Bathocuproine is soluble in organic solvents such as nitrobenzene and insoluble in water [21]. The appearance of BCP is white or yellow crystalline powder. It has HOMO level about -7 eV and LUMO level about -3.5 eV. Inserting BCP in organic solar cells layer enhances power conversion efficiency of organic solar cells. As BCP is a wide-band gap material, it acts as an exciton blocking barrier that prevents exciton diffusing toward Aluminum electrode. The optimal BCP thickness for application in organic solar cell is between 8 and 10 nm.

3.1.6 Aluminum [22][23]

Aluminum is the third most abundant element in the Earth's crust after oxygen and silicon. The appearance of Aluminum is ranging from silvery to gray, depending on the surface roughness. Aluminum is soft, durable, lightweight, and ductile. The atoms arrangement of Aluminum is face centered cubic (FCC) structure. In organic solar cells, Aluminum acts as an electrode. Organic solar cells with aluminum (Al) cathode often suffer from degradation in air [22].
3.2 Fabrication Device

Substrate preparation

The substrate preparation is very important to prevent obstacle on organic substrate. In this project, all solar cells used glass coating with the transparent Indium Tin Oxide (ITO). ITO has been supplied by Luminescence Technology Corporation. Glass substrates with thick 1200~1600Å have a sheet resistance of 9~15 Ω/sq and the transmission is higher than 84% at 550nm.

The first step of substrate preparation was cleaning the substrate with acetone for 30 minutes. Thereafter, substrate was cleaned by isopropyl for 30 minutes. Isopropyl could dissolve all acetone left on substrate. The cleaning process was done in deionized water (Fig. 3.6). Using
nitrogen, the ITO glass was dried thereafter ITO glasses were put to an ultraviolet-ozone surface treatment during 30 minutes (Fig 3.7). This process is done to increase the work function and remove any remaining carbon residues.

**Hole Transport Layer Deposition**

MoO$_3$ was deposited by thermal evaporation at base pressure of $10^{-6}$ mbar. The evaporation rate is fixed at 0.05 Å/s. For depositing 3 nm of MoO$_3$, it needs about 15 – 20 minutes. The thickness of the film is estimated from the frequency of the quartz oscillator.

**Deposition of organic layers**
The fabrication of organic solar cells was carried out by thermal evaporation of small molecules in nitrogen atmosphere using the glove box MBraun200B (Fig. 3.8). Inside the glove box, there are two types of chamber; one is metal chamber for depositing metal such as MoO$_3$ and Aluminum, and the other one is organic chamber for depositing organic materials. Figure 3.9 shows schematic of organic chamber with temperature controllers. Organic chamber consists of 5 shutters for organic materials and one substrate shutter. Organic material is put inside the shutter and it will be evaporated into substrate shutter to create organic layers on cells. The rate of depositing organic layers was managed with controlling of temperature. There are three temperature controllers to establish specific substrate temperature during deposition of different organic materials. In this way, it is possible to control the thickness of the layers. If needed, two or more materials can be evaporated in sequence or at the same time. Bulk heterojunction was deposited by thermal evaporation under a base pressure of approximately $10^{-7}$mbar at a rate of 0.2 Å/s.

Figure 3.9 – Schematic of organic chamber with the relation between the three temperature controllers with five evaporation sources and substrate holder
In order to know the accurate thickness of organic solar cells, measurement of thickness is done by Veeco DEKTAK 150 profilometer (Figure 3.11). If in any case there is a difference result of thickness from deposition and thickness from measurement, the control of deposition will be calibrated. It is very important since in organic solar cells are very sensitive towards thickness. The thickness will affect the performance of organic solar cells.

**Metal contact deposition**

Metal contact deposition is critical process in small molecules solar cells. It has to be done in appropriate rate in order to prevent cells being shorts. In this project, Aluminum is used as a cathode. The rate of depositing Al is controlled below 0.1 Å/s in first 2nm, 0.2 Å/s in 20 nm, and 1 Å/s until required thickness. The metal was deposited on organic layers through shadow mask to give an active area of 0.075 cm². The metal was rotated at 30 rpm during evaporation process in order to achieve a uniform layer. After depositing Al finished, the substrates is annealing thermally for 30 seconds at 160 °C. Due to annealing, the OPV
crystallinity has improved and the hole mobility is increased. Annealing not only causes recrystallization but also reduces the free volume and the density of defects at the interfaces. Thermal annealing under chloroform vapor or simple thermal treatment leads to an overall increase in power conversion efficiency [14].

Figure 3.12 – Solar cell device before testing

3.3 Characterization Device

In order to characterize organic cells, the prototype in nitrogen ambient was used. The prototype was fabricated by microLIQUID. Four substrates with four cells in each substrate was placed inside the prototype, therefore the measurement of organic solar cells could be conducted in nitrogen atmosphere (Fig 3.13).

Figure 3.13 - Prototype holder by microLIQUID
Devices were measured at room temperature using a HP 4142B DC Source measurement unit and an AM1.5 solar simulator (Newport Oriel Instruments [52]) (Figure 3.14) at the light intensity of 100mW/cm$^2$ calibrated with a pyranometer. The schematic of measurement is shown on Figure 3.14(a). Solar illumination will illuminate OPV device, then in comparing with reference cell which is cell without illumination, the source meter obtain the result of measurement and transfer it into PC. From the PC, J-V curve of the cells can be analyze and also some parameters such as FF, efficiency, $J_{sc}$ and $V_{oc}$ can also be determined.

On the other hand, the schematic of EQE measurement is shown on Fig 3.14(b). Light source is connected to monochromator with chopper and filter wheel are inserted in between. An automated filter wheel with appropriate order sorting filters is incorporated to minimize second order artifacts and are specific to the wavelength range defined by the detectors in use. Furthermore, monochromator provides light of very narrow bandwidth (nearly monochromatic). The light will be illuminated into devices then lock in amplifier will carry out the signal and transfer it into PC. From PC, the EQE in definite wavelength can be seen.
EQE characterization of photovoltaic cells was carried out on a QEX10 integrated system by PV Measurements Co. under standard measurement conditions. Chopping frequency was fixed at 80 Hz to avoid any perturbation from light ambient.

**Optical Characterization**

UV-visible-NIR Spectrometer (Shimadzu 3600) with UV-probe software for photometric analysis of solid and liquid materials in the 185 to 3300 nm range has been used for optical measurements. Spectrometer is equipped with ISR 3100 Integrating Sphere. Absorption measurements were performed in air at ambient circumstance without device encapsulation.
Variable light intensity measurement (VIM) is a measurement with generating different light intensity in order to obtain different I-V curve in different illumination and also to determine some parameters of solar cells such as parallel resistance and series resistance. Furthermore, VIM also can help to evaluate degradation of solar cells in period of time. After some time, the external factors such as oxygen and water vapor can affect the performance of organic solar cells. It is possible to occur due to the cover of cells holder is not closed enough or the level of oxygen inside the glove box is quite high. As a result, the fill factor and efficiency will decrease. The schematic of VIM is shown on Figure 3.17.
4. Results and Discussion

4.1 Study the effect of bulk heterojunction layers thickness

In this study, the OPV fabricated with thermal vacuum deposition, has structure as shown on Figure 4.1. The detailed configuration was ITO/MoO$_3$(3nm)/DBP:C70(1:1)(x nm)/BCP(8nm)/Al(150nm). The donor was DBP and the acceptor was C70. In order to facilitate electrons and holes collection, MoO$_3$ as hole transport layer and BCP as electron transport layer were inserted between the active layers and electrodes.

![Figure 4.1 – Structure of solar cells studied](image)

![Figure 4.2 – J-V Curves for different DBP:C70 thickness](image)
In order to analyze optimum thickness of bulk heterojunction DBP:C70 (1:1), organic solar cells with thickness vary from 30 nm up to 70 nm have been fabricated. Figure 4.2 shows J-V curve of bulk heterojunctions with different thickness.

![Graph showing Jsc variation with thickness](image)

**Figure 4.3 – Variation of Jsc with DBP:C70 thickness**

It was found that the short current of bulk heterojunction was increasing while the thickness of bulk heterojunction is increasing up to 70 nm, indicating an efficient charge generation in this thickness. On the other hand, the thickness is higher than 70 nm, the short circuit current starts to decrease. The highest short current was achieved by bulk heterojunction with thickness about 70 nm and the lowest short current was reached by bulk heterojunction with thickness about 30 nm. The maximum short current is 17.84 mA/cm² and the lowest short current is about 6.19 mA/cm².

![Graph showing Fill Factor variation with thickness](image)

**Figure 4.4 – Variation of FF with DBP:C70 thickness**
In contrast, the fill factor of bulk heterojunctions is decreased while the thickness of bulk heterojunction was increasing (Figure 4.4). The maximum fill factor is about 39%, achieved by bulk heterojunction with thickness 30 nm, and the lowest fill factor is about 26.6%, reached by bulk heterojunction with thickness 70 nm. The FF is decreasing due to increasing recombination of charge carriers by increase of the mean distance. The charge carriers need to travel before they are extracted at the electrodes [5]. At thickness about 90 nm, the FF suddenly climbs up to 36.8% and the FF falls up to 27% at thickness about 100 nm. Overall, the tendency of FF is declining while the thickness is larger.

![Figure 4.5 – Variation of Voc with DBP:C70 thickness](image)

Furthermore, the tendency of $V_{oc}$ is declining while the thickness is increasing (Figure 4.5). The highest $V_{oc}$ occurs when the thickness is about 30 nm and the lowest is at 100 nm. Since the $V_{oc}$ of bulk heterojunction is linearly related to the HOMO donor and LUMO acceptor energy difference, the $V_{oc}$ is lower when the ionization potential of the donor is decreasing [5]. As a result, the $V_{oc}$ is lower in higher thickness. The higher thickness also implies higher recombination since the carrier needs more time to travel to interface. Therefore, the higher recombination implies the decreasing of $V_{oc}$. 

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The efficiency of bulk heterojunction has increased, until one point, it became diminished. From figure 4.6, it can be seen that the lowest efficiency occurs when the thickness is about 100 nm, and the highest thickness occurs when the thickness is 60 nm. When the thickness is higher than 60 nm, the efficiency falls down. The maximum efficiency is about 3.12% and the minimum is about 1.01%.

Efficiency of solar cells is influenced by fill factor, $V_{oc}$, and $J_{sc}$. The difference in power conversion efficiency is mainly determined by the difference of these parameters. At thickness 30 nm, for instances, even though the open circuit voltage and fill factor are very high, but the short circuit current is very low, consequently, the power conversion efficiency of bulk heterojunction at 30 nm of thickness, is quite low.

In contrast, bulk heterojunction with thickness is about 60 nm, the fill factor, short circuit current, and open circuit voltage are optimum, even though they are not the highest, but they lead to the highest power conversion efficiency. The summary of measurement can be seen on table 4.1.
Table 4.1 – Measurement results of the devices with various DBP:C70 thicknesses

<table>
<thead>
<tr>
<th>Thickness (nm)</th>
<th>Efficiency (%)</th>
<th>Fill Factor (%)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1.76</td>
<td>39</td>
<td>-6.19</td>
<td>0.73</td>
</tr>
<tr>
<td>50</td>
<td>2.82</td>
<td>36.8</td>
<td>-10.78</td>
<td>0.71</td>
</tr>
<tr>
<td>60</td>
<td>3.12</td>
<td>33.3</td>
<td>-14.12</td>
<td>0.65</td>
</tr>
<tr>
<td>70</td>
<td>2.9</td>
<td>26.6</td>
<td>-17.84</td>
<td>0.61</td>
</tr>
<tr>
<td>90</td>
<td>1.9</td>
<td>36.8</td>
<td>-8.44</td>
<td>0.61</td>
</tr>
<tr>
<td>100</td>
<td>1.01</td>
<td>27</td>
<td>-6.57</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Figure 4.7 – EQE curves for different DBP:C70 thicknesses

Figure 4.7 shows the External Quantum Efficiency (EQE) in definite length. EQE can show the highest and the lowest short circuit currents of bulk heterojunction. The highest area of EQE belongs to bulk heterojunction with 70 nm of thickness. Comparing with previous result of short circuit current, bulk heterojunction with 70 nm of thickness has also the highest short circuit current.

Conversely, the lowest area belongs to bulk heterojunction with 30 nm and 100 nm of thickness. The short circuit current of both cells are similar which are about 6.19 mA/cm² and 6.57 mA/cm².

Furthermore, the peak around 350 – 450 nm means the ability of C70 to absorbs and the peak around 500 – 650 nm belongs to DBP. Ideally, the curve of EQE is flat which means that the cells are absorbing in whole wavelength. The curve of bulk heterojunction with 60 nm of thickness has tendency almost linear comparing with other cells. It means that the cells with 60 nm can absorb more than other cells.
Comparing with absorption measurement result, the highest absorption is reached by bulk heterojunction with 60 nm of thickness. This result is correlated with the result of EQE. The principle of this measurement is that photons with energies higher than the band gap energy will be absorbed and electrons are excited from the valence band to the conduction band with the absorption of energy equal to the band gap of the material [5]. The rapid drop in the absorption coefficient on the high energy side of the absorption spectra leads to the band edge in semiconductors [14].

The absorption spectra of DBP:C$_{70}$ with varied thickness is shown on Figure 4.8. The increasing thickness from 30 nm to 60 nm has increased the ability of absorption of bulk heterojunctions, but if the thickness keeps increasing, the ability for absorbing falls down.

![Figure 4.8 – Absorption spectra for different DBP:C70 thicknesses](image)

From figure 4.9, it is shown that bulk heterojunction with 60 nm of thickness has the lowest transmittance than other bulk heterojunctions. Comparing with glass as a reference, at 60 nm, the bulk heterojunction has a big gap with the transmittance of glass which means that at 60 nm, the bulk heterojunction absorbs more. As expected, the bulk heterojunction with 30 nm of thickness has the highest transmittance which means it allows the photon through the cells without absorbing.
4.2 Study the degradation of bulk heterojunctions organic solar cell

In this subchapter, the study of degradation of bulk heterojunction will be investigated by Variable Light Intensity Measurement (VIM). For this measurement, one of bulk heterojunction has chosen. It is bulk heterojunction which has 30 nm of thickness. From this measurement, parallel resistance and series resistance can be known at the short circuit point and open circuit point.

The organic solar cells can have degradation after some period times since they have finished fabrication process. The degradation can be caused by atmospheric condition which has more oxygen. The cells are supposed to be in nitrogen atmospheric, but sometime, there are some leakages coming through the holders. Therefore, the cells are contaminated with oxygen and water vapor. Consequently, they have lower performance than the first time of measurement. Table 4.2 shows comparison of some parameters for some period time. Firstly, the cell has 6.19% of efficiency, then it falls down to 2.5%, and lastly, it has declined up to 1.18% of efficiency. Figure 4.10 shows the tendency of some parameters of bulk heterojunction. For all parameters, they has tendency to decrease while the time is longer. It means that the contaminated of oxygen and water vapor has a big effect for decreasing performance of organic solar cells.
Table 4.2 – Comparison of photovoltaic parameters over time

<table>
<thead>
<tr>
<th>Time [hr]</th>
<th>Jsc [mA/cm²]</th>
<th>Voc [V]</th>
<th>FF [%]</th>
<th>η [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.19</td>
<td>0.75</td>
<td>39.0</td>
<td>1.76</td>
</tr>
<tr>
<td>1</td>
<td>2.57857</td>
<td>0.75656</td>
<td>32.5489</td>
<td>0.63498</td>
</tr>
<tr>
<td>6</td>
<td>2.25121</td>
<td>0.75553</td>
<td>31.5815</td>
<td>0.53716</td>
</tr>
<tr>
<td>11</td>
<td>2.04507</td>
<td>0.74364</td>
<td>30.6846</td>
<td>0.46665</td>
</tr>
<tr>
<td>16</td>
<td>1.77854</td>
<td>0.73723</td>
<td>30.7845</td>
<td>0.40364</td>
</tr>
<tr>
<td>21</td>
<td>1.4471</td>
<td>0.73142</td>
<td>29.9772</td>
<td>0.31729</td>
</tr>
<tr>
<td>26</td>
<td>1.30919</td>
<td>0.72582</td>
<td>29.9160</td>
<td>0.28427</td>
</tr>
<tr>
<td>31</td>
<td>1.18547</td>
<td>0.72907</td>
<td>29.2127</td>
<td>0.25248</td>
</tr>
</tbody>
</table>

Figure 4.10 – Evolution of photovoltaic parameters over time

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The open circuit voltage degrades slightly with time shows that contamination of oxygen and water vapor has a little impact to their HOMO-LUMO levels and density of states. Furthermore, the efficiency of bulk heterojunction has declined rapidly due to the short circuit current which is decreasing sharply in the period of time.

Other parameters can be investigated are parallel resistance and series resistance. Ideally in solar cells, the parallel resistance is needed to be high, conversely, the series resistance is needed to be low. From figure 4.11, it shows that both of parallel resistance and series resistance, the tendencies are increasing. High value of series resistance reduces the value of current output. Increasing of series resistance is related to degradation of electrodes. On the other hand, the increment of the parallel resistance restricts the flow of current back to the inside circuit of the diode while allowing the flow of current to the external circuit. It means with higher parallel resistance, the current will also be higher.

![Figure 4.11 – Evolution of $R_P$ (red) and $R_{SC}$ (blue) over time](image)

Figure 4.11 shows the decreasing of mobility lifetime product of the charge carrier in period of time. It is determined the behavior of charge carriers in the chemical structures of the photoactive materials. Declining the mobility lifetime is related to degradation of active layer. This degradation can be caused by contamination of oxygen and water vapor.
Figure 4.12 – Evolution of mobility lifetime product over time
5. Conclusion

The fabrication of Organic Solar Cells has been developed in several methods. One of the methods of fabrication of Organic Solar Cells is thermal evaporation deposition using glove box. Procedure has to be followed in sequence, starting from substrate preparation, hole transport deposition, organic layer deposition, and metal contact deposition. In order to investigate performance of organic solar cells, the characterization of organic solar cells in dark and under illumination condition has been established.

As a result, it is found that the thickness of bulk heterojunction can influence the performance of organic solar cells. Increasing the thickness of bulk heterojunction creates increasing in efficiency, however, after some points, increasing the thickness will reduce the efficiency of organic solar cells. In this project, the optimum thickness of bulk heterojunction DBP:C$_{70}$ (1:1) is 60 nm with efficiency 3.12%.

Furthermore, the degradation of bulk heterojunction organic solar cells has been investigated. After some period of time, the performance of organic solar cell was decreasing gradually. It occurs because the organic solar cell requires nitrogen atmosphere in order to perform well. On the other hand, sometime there is a leaking allowing oxygen and or water vapor coming inside and contaminating organic solar cells. Consequently, the efficiency, fill factor, and short circuit current were declining gradually. Furthermore, the mobility and life time of bulk heterojunction also was decreasing. On the other hand, the parallel resistance and the series resistance of bulk heterojunction organic solar cells were increasing in period of time.
6. Future Work

For the next project, instead vary the thickness of organic solar cells, vary the ratio of DBP:C$_{70}$ can be an interesting study in order to obtain the optimum ratio of bulk heterojunction. There is a possibility that the ratio 1:1 is not the optimum ratio of bulk heterojunction. Therefore, to get higher efficiency of organic solar cell, it is important to know the optimum ratio of bulk heterojunction.

Tandem organic solar cells also can be developed in order to obtain higher performance. Theoretically, in tandem structure, organic solar cells can absorbs more since it uses different kind of material with variation of absorption spectra. Consequently, it supposes to have better performance than organic solar cell which uses one type of donor and acceptor.
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