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Open Circuit Voltage: An Overview

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Introduction

We know that when the solar cell is operated at open circuit, I = 0 and the voltage across the output terminals is defined as the open-circuit voltage VOC and conversion efficiency is –

$\eta = V_{OC} I_{SC} FF / P_{IN}$

This formula shows that conversion efficiency is directly related to open circuit voltage, a large value of open circuit voltage is necessary for improving the power conversion efficiency of the solar cells. In order to become viable alternative to inorganic solar cells, the power conversion efficiency of organic solar cells should be increased.

Review Literature

Amir Fallahpour (2014). The purpose of this study is to develop a model that is both consistent and capable of simulating organic photovoltaic cells (OPV). The model must have an accurate description of mobility, density of state, organic-metal contacts, and exciton. We model the photoconversion by combining the optical and electrical aspects of the process: the light absorption is modeled with a Transfer Matrix Model, and the charge transport is modeled with a Drift Diffusion method that takes into account the influence of energetically disordered materials. The majority of model parameters are derived directly from empirical data. This model is used to investigate the influence that energetically disordered materials have on the performance of the cell in terms of short circuit current, open circuit voltage, and fill factor. The model is studied using these metrics. On the basis of the findings of this model, it will be feasible to construct and make predictions regarding the ideal thickness of an OPV in order to achieve greater efficiencies.

Mohd Said, Nor, and Azlinda Suboh. (2016),Solar cells provide a photovoltaic effect, which is recognized as a kind of clean energy. Because of its reputation for being kind to the environment, organic photovoltaic cells have garnered a lot of interest in recent years. Organic solar cells are now being studied as a potential viable alternative to the more conventional silicon solar cells. Methods of generating solar cells by using organic materials offer a remarkable promise for the construction of vast areas at a reasonable cost. It was incredibly transparent and very thin, and it could be incorporated into other things. On the other hand, the efficiency of power conversion was just 17.3-5% about fifty years ago. For the purpose of increasing the conversion efficiency of organic photovoltaics, the structural design of organic photovoltaic cells as well as the material selection of organic photovoltaic cells are of critical importance. The goal of this research is to use simulation tools to develop the structure of bilayer solar cells that might be made from possible organic materials. The primary purpose of this analysis is to enhance the high fill factor as well as the conversion efficiency of bilayer organic solar cells. As a consequence of this, the bilayer structure of the organic solar cell (PEDOT:PSS/P3HT) discovered that the fill factor is 76.702998% and the efficiency reaches 8.914862% at a light intensity of 0.20. Lastly, it is appropriate for use in applications involving bilayer organic solar cells.

SOLAR CELL GENERATIONS

In 1839, Becquerel was the one who made the initial discovery of the photovoltaic effect in a junction that was established between an electrode and an electrolyte. He did this in a chamber that had been heated to a high temperature. Becquerel observed the effect in a connection that had been created between an electrode and an electrolyte. He was the first person to do so. Since that period in history, a significant amount of time and effort has been invested in the research and development of a wide range of alternative materials and the improvement of the efficiency of solar cells. Despite this, there was not a discernible rise in productivity until 1954, when a confluence of two key discoveries occurred at the same

time. Chapin and his coworkers at Bell Laboratories are credited with developing the first silicon solar cells that had an efficiency level that was well above average. On the other hand, Reynolds and his coworkers at the Aeronautical Research Laboratory presented cadmium sulfide cells that, when subjected to direct sunlight, exhibited open circuit voltages of 0.4 volts and short circuit currents of 15 milliamperes per square centimeter. These results were obtained when the cells were tested.
Davide Bartesaghi (2016). Simulations known as drift-diffusion (DD) and kinetic Monte Carlo (KMC) are two of the most prominent approaches taken when attempting to comprehend the physical workings of organic photovoltaic systems. While DD approaches have been effectively used to model and explain device features, KMC simulations bring up the prospect of investigating the basic processes involved in the functioning of solar cells. This is because KMC simulations provide a more accurate representation of how solar cells actually work. In this chapter, we will provide an explanation of DD and KMC simulations in both two- and three-dimensional formats (both 2D and 3D). Advancing beyond techniques of one-dimensional simulation enables a more accurate description of the operation of a device as well as a deeper comprehension of processes that are more basic. After providing a brief introduction to the fundamental processes that are involved in the functioning of organic photovoltaic devices, we will now provide an overview of DD and KMC methodologies. This will include a discussion of some of the technical problems that are associated with the execution of 2D and 3D simulations. In the end, we compare some of the results that were generated by DD and KMC simulations. While doing so, we place a special emphasis on the utilization of 2D and 3D simulations to shed light on how the active layer shape influences the efficiency of the device.

Open Circuit Condition

The representation of this scenario may be seen in figure, component c. Now, if light is made to fall on the apparatus while it is in this position, it will eventually lead to the formation of charges, which, due to diffusion, will flow towards the electrodes. If light is made to fall on the apparatus while it is in this position, it will lead to the generation of charges. As a direct consequence of this, there is an observable tendency for the diffusion current to go in a certain direction. However, a steady state current cannot flow since there is an open circuit between the two electrodes. This prevents the current from being able to flow. Because of this, the current that is being used for diffusion needs to be counterbalanced by a current that is drifting in the other direction but has the same amount of strength. This drift current is only able to flow if there is a finite field present inside the bulk of the material where it is flowing through. Therefore, there must be a voltage that is given from the outside source and that is traveling between the two electrodes in order for there to be an electrical current. This voltage is referred to as open circuit voltage (VOC), and it is an important feature that is used to assess the efficiency of the device. VOC stands for "voltage on the open circuit."

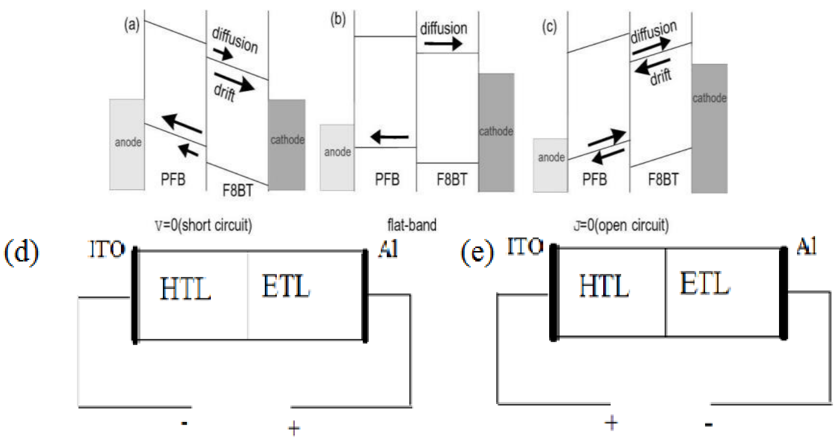

Fig.: The band diagram of a photovoltaic device is illustrated (a) when the device is in a short circuit (b) when the device is in a flat band (c) when the device is in an open circuit (d) when the device is in a reverse bias (e) when it is in a forward bias.

In figure, the diode is depicted with the bias in the other direction, which causes an increase in the electric field within the device. In the e representation depicted in figure, it can be seen that the diode has a forward bias. Even though the diode's internal field is being reversed and the charge injection is being increased, this causes an increase in the flow of the dark current. OPV devices create power by operating in the forward bias region; however, the photocurrent flows in the opposite direction of the dark forward bias current and is formed inside an environment with a lowered internal field. This is because the photocurrent is generated in an environment with a decreased internal field.

PARAMETERS

Solar cells may be examined for a wide variety of various characteristics due to their complex nature. On the other hand, the open circuit voltage, the short circuit current, the fill factor, and the efficiency are four essential features of the OSC. The V-I characteristic, as well as the factors that are connected with it, are shown in figure.

Open Circuit Voltage – When the solar cell is operated in open circuit, the current through the cell is equal to zero, and the voltage that is measured across the output terminals is referred to as the open-circuit voltage, or VOC. This reveals that the open-circuit voltage is the one that must be supplied in order to halt the flow of current, and it is this voltage that is required. In terms of mathematics, one may express it as follows:

$$V_{OC} = \frac{nkT}{q} \ln\left(\frac{I_{ph}}{I_0}\right)$$

Where the photocurrent is denoted by Iph and the reverse saturation current is denoted by I0 respectively.

Organic Devices

Certain organic devices have been shown to have the capability of achieving external quantum efficiencies of up to fifty percent, as was indicated in the previous sentence. The term "internal quantum efficiency," which is abbreviated as IQE and stands for "internal quantum efficiency," does not take into account any substrate reflections or the partial absorption of light that occurs within the polymer itself. Instead, IQE is abbreviated as "internal quantum efficiency." The result is referred to as the external quantum efficiency, abbreviated EQE for convenience, and is determined after all of these losses have been considered. This suggests that the amount of photons that are soaked in is directly proportional to the amount of electrons that are amassed in the system.

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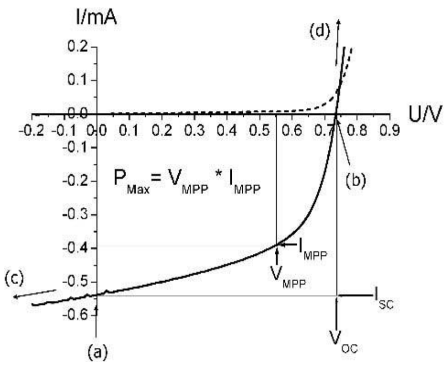

Fig.: Current-voltage (IV) curves of an organic solar cell (dark, dashed; illuminated, full line).

Ideal Open Circuit Voltage Analytical Model-

Figure (a) depicts a photovoltaic device having a hole transport layer (HTL) and an electron transport layer (ETL). Figure (b) of the same figure depicts the energy diagram of the device after it has reached equilibrium. It shall be assumed that the gadget in question has a symmetrical construction both for ease of explanation and for the purpose of simplicity. inside the context of this architecture, the heights of the electron and hole injection barriers will be equivalent, and it will be expected that the electron mobility and hole mobility will be equivalent and comparable inside both organic layers. Excitons that are created in the organic films as a result of the absorption of light ultimately find their way to the hetero-junction, where they dissociate to generate polaron pairs. This process takes place when the excitons arrive at the hetero-junction. The dissociation of polaron pairs, which can be induced by thermal energy or the auto ionization that takes place in an electric field, is what leads to the release of free electrons and holes in the ETL and HTL layers, respectively. This release takes place as a result of the dissociation of polaron pairs. After then, the free carriers will start to wander and scatter, which will ultimately lead to the creation of photocurrent and photovoltage. When there is a short circuit, the voltage that is already there in the device causes the internal field to become very robust.(V_{bi}) generates a short circuit current by sweeping the photo-generated electrons and holes to produce it. In the case of a flat band state, the internal field cancels out to zero, yet charge separation at the organic-organic interface ensures that the flow of current is not interrupted. Because electrons and holes are physically separated from one another, recombination is reduced, and charge carriers are able to diffuse to the electrodes that correspond to them. This results in a nonzero current flowing through the device..

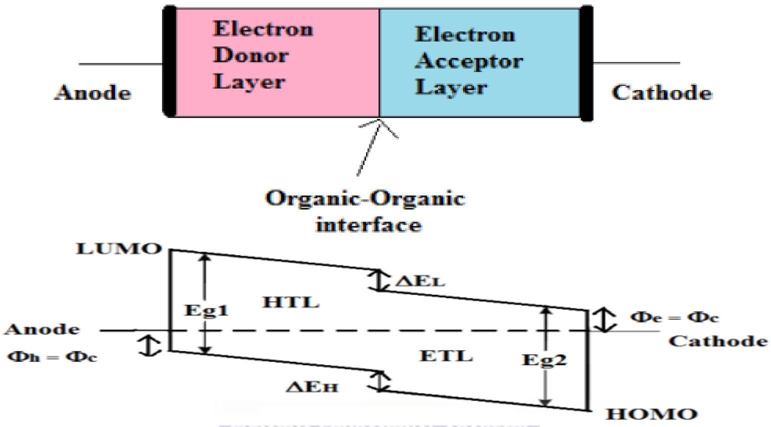

Fig.: (a) Diagram of a Single hetero-junction solar cell, (b) Energy level diagram at equilibrium, showing the relevant energy levels $\emptyset_c$ .represents electron and hole injection barrier heights taken to be equal. E_{g1} and E_{g2} .are energy gaps of hole and electron transfer layers respectively. ΔE_L and ΔE_H represent discontinuity in LUMO and HOMO levels respectively at the hetero-junction.

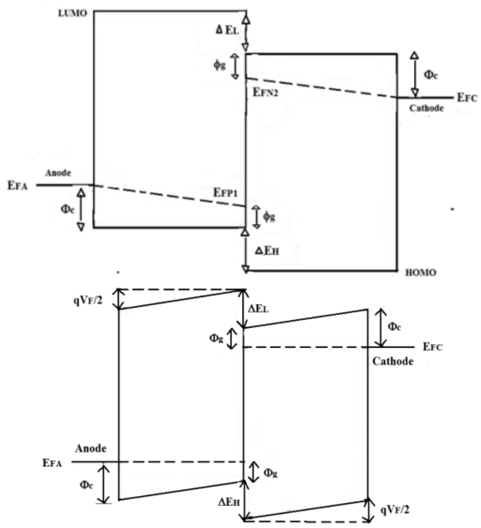

Fig.: Energy level diagram for the hetero-junction solar cell under (a) Flat band condition (b) Open circuit condition. E_{FN2} and E_{FP1} represent electron and hole quasiFermi levels in acceptor and donor layers respectively and $\emptyset_g$ represents their displacement from LUMO of

Open circuit voltage as a function of incident light

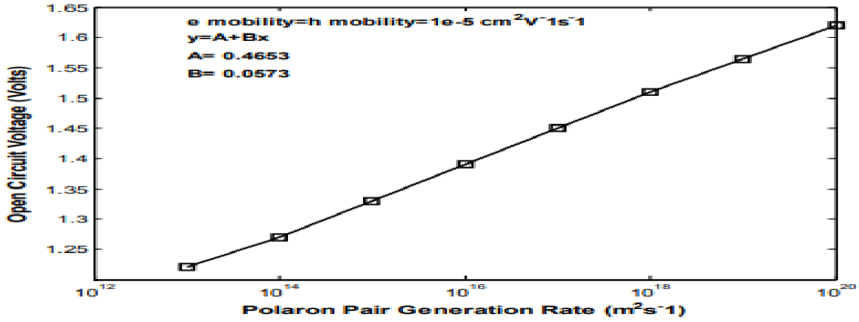

Fig.: Open circuit voltage as a function of incident light energy. μn and μp are electron and hole mobilities respectively $\emptyset_n$ and $\emptyset_p$ are electron and hole injection barriers. A linear fit is shown with the slope of 57mV/decade.

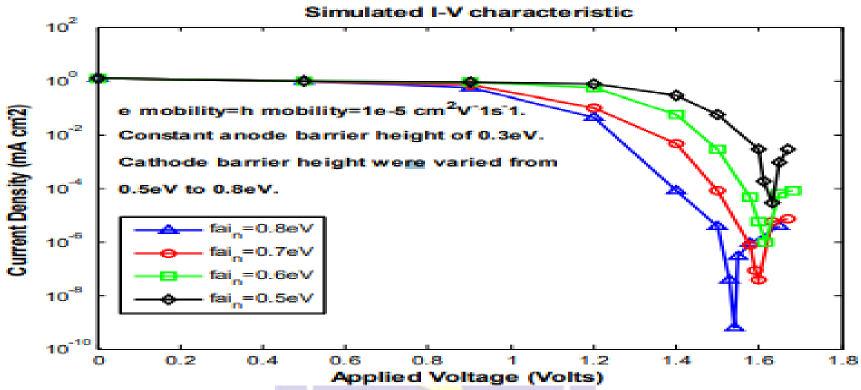

Fig.: Simulated I-V characteristic for a constant anode barrier height of 0.3eV. cathode barrier heights were varied from 0.5eV to 0.8eV. hole and electron mobility were taken to be $1 \times 10^{-5} cm^2 V^{-1} s^{-1}$. Open circuit voltages for different cathode barrier heights come out to be constant.

Additionally, the equation suggests that the open circuit voltage ought to be independent of the electrode work functions, which is a suggestion that is shared by the reference model. According to figure, the voltage in the open circuit remains the same for all of the different electrode work functions that are used as a reference. This, however, runs counter to the findings of the experiments, which demonstrate that the voltage across an open circuit shifts in a manner that is proportional to the change in the metal work function. The experimental data are obtained from reference and are presented in Table These results indicate how the open circuit voltage varies with the different work functions of the electrodes..

Table-The work function (Ø) of the anodes and cathodes used and the comparison between work function difference (ΔØ) and open circuit voltage (V_{OC})

Anode	Cathode	$\emptyset_{Cathode}(eV)$	$\Delta\emptyset(eV)$	Measured V_{OC} (V)	$V_{OC}-\Delta\emptyset$ (V)
ITO	Gold	5.1	-0.3	0.7	1.0
ITO	Copper	4.65	0.15	1.15	1.0
ITO	Chromium	4.5	0.3	1.35	1.05
ITO	Aluminum	4.3	0.5	1.5	1.0

It has been speculated that the limitations of the model that was used to describe the injection that took place at the contacts might be the root of this discrepancy. However, the open circuit voltage can be regarded to be independent of such a model, despite the fact that the injection model used for contacts could have an influence on the current that is flowing through the device. The fact that the derivation in the above sentence is true demonstrates this point. In this study, we suggest an alternative explanation that argues that although eq. properly reflects the open circuit voltage, this "ideal" value can only be observed if the parasitic leakage currents in the device are kept to a minimum. This explanation is based on our findings that the open circuit voltage is accurately reflected by the equation. Despite the fact that equation accurately depicts the open circuit voltage, this explanation is nonetheless supplied for your convenience. In the next part, it will be shown that including leakage currents in analysis makes it feasible to expect that the open circuit voltage of genuine organic solar cells may truly display reliance on electrode work functions, exactly as this dependence has been found experimentally. This demonstration will take place in accordance with the next section.

Voltage of an Open Circuit When Leakage Currents Are Present -

In order to compensate for leakage current, a shunt resistance must be connected in parallel with the photovoltaic device, as illustrated in figure. I represents the output current that will be obtained at this point in the figure. $V_{applied}$ voltage if no leakage is taken in to account. I_{net} is net output current under the influence of the leakage current. On x-axis we take internal voltage, not the total applied voltage

Internal voltage = $V\text{-}V_{bi}$

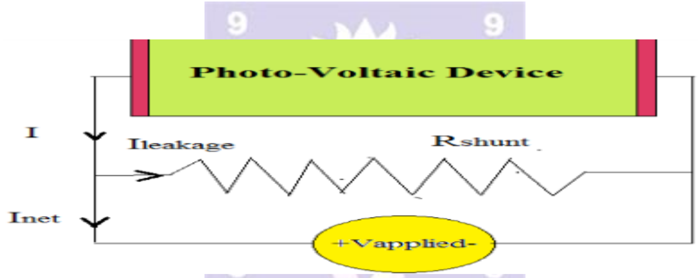

Fig.: Organic solar cell as a model with leakage current

I-V curves that were simulated can be shown in Fig.; these curves correspond to a polaron pair production rate of 1e20 m2 s-1 and a cathode barrier height of 0.8eV. On the x-axis, the measured value is the internal voltage rather than the total applied voltage. When we leave the cathode barrier height at its current value of 0.3 eV but adjust the anode barrier height, the built-in voltage responds appropriately. It is essential to take note of the fact that a proportionate change in open circuit voltage with rise in built-in voltage would present itself on the internal voltage axis by open circuit voltage seeming to be constant. This is the case even though the change would be proportional. According to figure, the open circuit voltage on the scale of the internal voltage is 0.64 volts when leakage is not taken into consideration. However, it is essential to take into account the fact that the current has dropped by more than several orders of magnitude relative to the level it was at while it was operating under the flat band condition at the built-in voltage as it gets closer to the open circuit voltage. In actual fact, because of the presence of leakage currents, the current would decrease to zero and change sign at a lower forward bias voltage. This behavior is caused by the inversion of the sign of the current. The outcome may be seen in Fig., which depicts what happens when a shunt resistance with a value of 10 Kohm-cm2 is connected in parallel with the device. In this particular scenario, current drops to zero when the internal voltage reaches 0.2 volts below its starting point. The fact that leakage current can make the contribution of internal voltage to the open circuit voltage independent of metal work functions is an important point to keep in mind in this context. Figure provides an illustration of the I-V characteristics for a cathode injection barrier height of 0.4 eV and an anode injection barrier height of 0.3 eV, respectively, with the rest of the circumstances being unaltered. However, because of leakage current, the contribution of internal voltage is only 0.18 volts, which is very near to the earlier estimate of 0.2 volts for 0.8eV cathode barrier height. Under these conditions, the internal voltage at which current falls to zero is 0.33 volts in the absence of leakage currents, but it is only 0.18 volts because of leakage current..

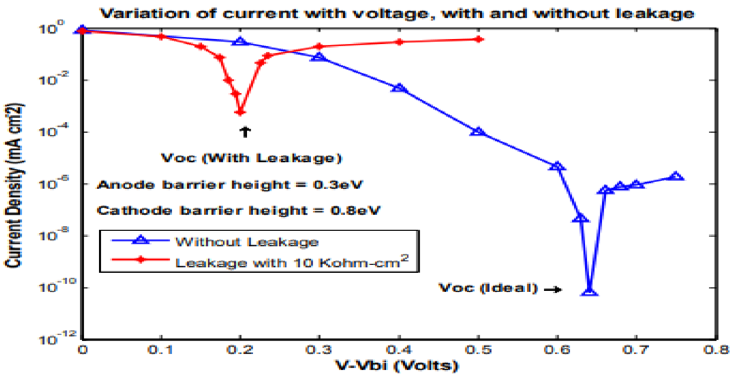

Fig.: Variation of current with voltage, with and without leakage. Cathode and anode injection barrier heights are 0.8eV and 0.3eV respectively $R_{shunt} = 10\text{Kohm-cm}^2$, $\Delta E_L = \Delta E_H = 0.5eV, \mu_n = \mu_p = 1 \times 10^{-5} cm^2 V^{-1} s^{-1}$.

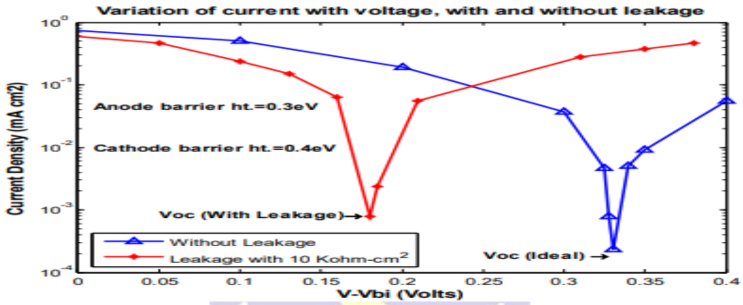

Fig. : Variation of current with voltage, with and without leakage. Cathode and anode injection barrier heights are 0.4eV and 0.3eV respectively $R_{shunt} =$ Kohm-cm^2 $\Delta E_L = \Delta E_H = 0.5eV, \mu_n = \mu_p = 1 \times 10^{-5} cm^2 V^{-1} s^{-1}$.

Figure illustrates how the open circuit voltage varies depending on the height of the cathode injection barrier. According to the conclusions we may draw from this graph, there is no substantial fluctuation in the open-circuit voltage associated with the cathode barrier height if there is no leakage. However, taking into account the leaky shunt resistance of 10Kohm-cm^2 and 100Kohm-cm^2, There is a linear relationship between the cathode barrier height and the variance in open circuit voltage.

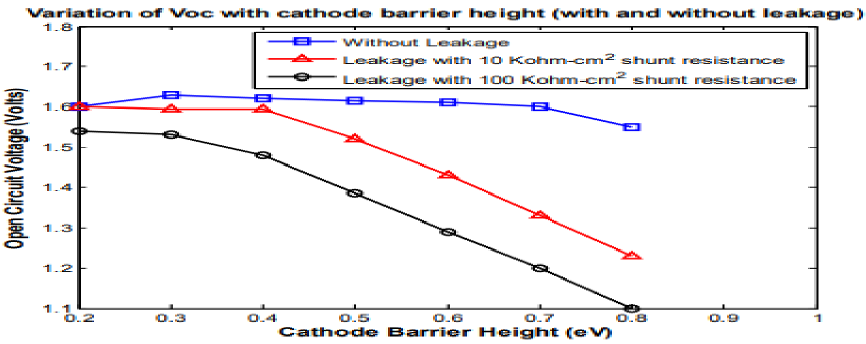

Fig.: Variation of open circuit voltage with cathode barrier heights. Three cases have been shown, without leakage, with shunt resistance 10 Kohm-cm 2 and with shunt resistance of 100 Kohm-cm 2 . Anode injection barrier height was taken to be 0.3eV. $\Delta E_L = \Delta E_H = 0.5eV, \mu_n = \mu_p = 1 \times 10^{-5} cm^2 V^{-1} s^{-1}$.

CONCLUSION

The utilization of MATLAB code within the framework of this simulator makes it possible to create each and every stage of the procedure for transforming light into energy by utilizing a

bilayer organic solar cell in an accurate and efficient manner. Within the low-voltage range that is necessary for solar activity to take place, this simulator functions remarkably well.
It has been shown that the open circuit voltage is reliant not only on the disparity in the work functions of the electrodes but also on the intensity and the charge densities that are present at the electrodes. This is the case even when the work functions of the electrodes are not directly related to one another. Either increasing the injection barrier in the polymer or reducing the charge densities at the electrodes can lead to an increase in the open circuit voltage. Both of these approaches are viable options. The increase in voltage across an open circuit is proportional to the light intensity, hence the relationship between the two is logarithmic.
The fact that the organic solar cell model developed by does not display any changes in open circuit voltage when the injection barrier height of the electrodes is altered is evidence that the model and the experimental results are at odds with one another. The results of the simulations that were carried out for the purpose of this studyreveal that if the leakage currents are accounted for in the OSC model, the open circuit voltage will begin to exhibit a dependency on the injection barrier height of the electrodes. This conclusion was reached as a result of the simulations that were carried out for the purpose of this thesis. The difference in open circuit voltage is related to the cathode barrier height in a way that may be described using a linear equation.
The conventional model of an organic solar cell has a few flaws, such as a photo-generated current that is not constant and is dependent on voltage, a virtually identical open circuit voltage regardless of the height of the carrier injection, and an open circuit voltage that is independent of the parasitic series resistance. However, a new model has been developed that addresses these issues. An innovative model for an organic solar cell takes into account the parasitic resistance that is present when the voltage is applied to the open circuit. In light of this, we may deduce that the circuit will, in addition to a voltage-independent constant photo-current, possess both internal and exterior resistances. The purpose of this investigation was to construct a model of a solar cell circuit that had a constant photocurrent. A recently created and noticeably more effective technique is described here in order to retrieve the model parameters from this particular model.
It has been proved that if dark characteristics are supposed to follow an exponential current-voltage relationship, with an open circuit voltage and light produced current treated as constant, then an increase in the value of ideality factor will result in a reduction in the value of fill factor. This is the case even when an open circuit voltage and light generated current are taken as constant. If, on the other hand, dark features are supposed to follow a polynomial current-voltage relationship while the light produced current remains constant, then a rise in m will increase fill factor, which will become closer and closer to the value of 1.
6. In addition to the shape of the dark characteristic, it has been established that the amplitude of the dark current measured at the open circuit voltage is an incredibly important component in estimating the fill factor of a device. This is the case even when the open circuit voltage is known. An increase in the dark current that is present when the open circuit voltage of a photovoltaic device occurs also leads in a rise in the fill factor of the photovoltaic device, as has been proved via the use of computer simulations. This relationship between the two variables has been established.

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