



## ORGANIC AND INORGANIC SOLAR CELL: A COMPARATIVE ANALYSIS

LOKESH DIWAN<sup>1</sup>, MANISH GUPTA<sup>2</sup>, SAKSHI AGARWAL<sup>3</sup>

<sup>1</sup>M.Tech Scholar

<sup>2,3</sup>Assistant Professor, GSCE Sagar, M.P., India

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LOKESH DIWAN

### ABSTRACT

In the last decade, the highest efficiency attained from organic photovoltaic (OPVs), for instance bulk heterojunction polymer: fullerene solar cells, has risen from 2.5 to 11 % [1]. The inconsistent worth of energy, due to a diversity of motives ranging from geo-political constraints to national and international economic subjects, and the fact that these energy resources are finite, can be seen as the main incentives to make a transition to a clean energy society. The paper deals with utilization possibilities of solar energy (photovoltaic systems) and with transformation of this energy to chemical energy. Although solar energy has been harnessed for centuries, the recent slant has been to construct solar cells and solar module arrays. Herein, we review organic and inorganic solar cells. Organic solar cells a potential solution to energy problems. The ultimate goal of energy production is that it should be environment friendly, cost effective and user responsive. The organic solar cell is a promising way to meet all these three requirements.

Keywords— Solar Energy, Organic Solar Cells, Inorganic Solar Cells.

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### INTRODUCTION

Power is the most challenging and vibrant part for mankind today. Almost 15 TW ( $1\text{TW} = 10^{12}\text{W}$ ) is the global power consumption where the massive share of it is accomplished by the combustion of fossils fuels. Practice of these anthropogenic source of fossil fuels lead to catastrophic consequences in atmosphere by discharging  $\text{CO}_2$ ,  $\text{SO}_x$ ,  $\text{NO}_x$  etc. Man-made climate change is one of the greatest threats our world faces. The terawatt challenge is the effort to supply up to 30 TW of carbon-free power by the mid-21<sup>st</sup> century [2].

Respectable thought by Newton that there is no Action without any Reaction: we believed that the attainment of power demand by non-renewable source of energy is not the right way as it radically contaminates the atmosphere and this approach forced the researchers to move towards the Renewable Energy. Renewable energies issued from our natural environment, such as wind power, solar thermal, photovoltaic, geothermal heat, marine and hydro power etc. and logically usage of these can assist to lessen our consumption of fossil fuels. Solar energy is the key prerequisite of the lifecycle on the Globe. The current appraisal is devoted to photovoltaic energy and certain specific

photovoltaic devices grounded on organic materials. A French experimental physicist, Edmund Becquerel in the year 1839 discovered the influence of photovoltaic in his experiment. He discovered that two brass plates immersed in a liquid produce a continuous current when exposed to light. In the 1870's, English investigators, W. G. Adams and R. E. Day, observed that it was conceivable to generate and uphold an electrical current in selenium using candlelight. At that year, many researchers fingered the production of energy without the consumption of matter was a violation of the laws of physics and the effort was not pursued.

In 1905, Einstein clarified the photoelectric effect, which established the groundwork for a hypothetical understanding of the photovoltaic effect. When photons in the UV range are illuminated on a metal surface, free electrons escape from the metal surface due to excitation energy from the incident light. They are then ejected into the atmosphere. In most cases, when absorbed photons in a material pump ground state electrons to the excited state, the excited electrons promptly relax to the ground state. However, in photovoltaic devices, the excited electrons and the produced hole in the ground state should be collected separately to produce power [3].

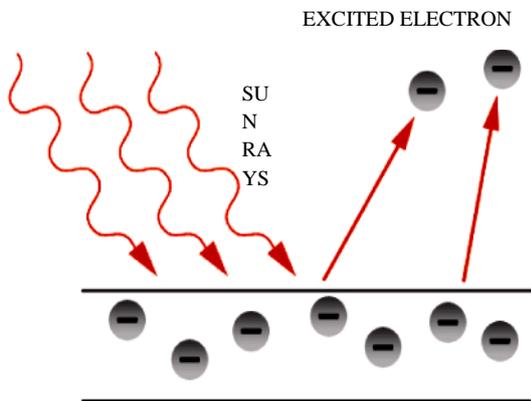


Fig 1.1: Photoelectric effect

Photovoltaic systems act in an unanticipated and useful manner: They respond to light by transforming portion of it into electricity. Additionally this translation is innovative and exclusive, since photovoltaic: have no moving parts (in the classical mechanical sense) to wear out, contain no fluids or gases (except in hybrid systems) that can escape out, as do some solar-thermal systems. Consume no fuel to operate. Have a rapid retort, attaining full output promptly. Be able to

operate at modest temperatures. Yield no pollution while producing electricity. Necessitate slight upkeep if properly manufactured and installed. Can be made from silicon, the succeeding most abundant element in the earth's crust. Are modular permitting a wide range of solar-electric applications such as - Small scale for remote applications and residential use - Intermediate scale for business and neighborhood supplementary power - Large scale for centralized energy farms of square kilometers size. Have a relatively high conversion efficiency giving the highest overall conversion efficiency from sunlight to electricity yet measured. Have wide power-handling capabilities, from microwatts to megawatts. Have a high power-to-weight ratio making them suitable for roof application. Are amenable to on-site installation, i.e., decentralized or dispersed power.

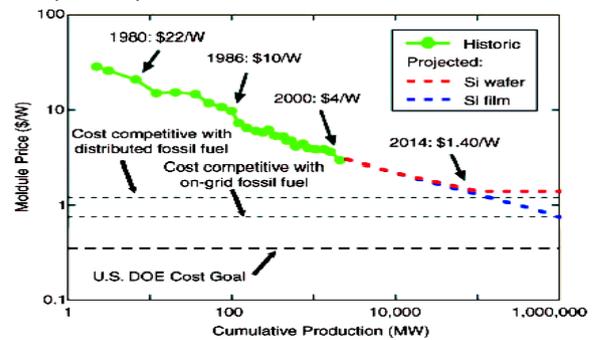


Fig 1.2: Solar Energy Production and Price

(4) **SCIENCE BEHIND PV's:**

Photovoltaic cells belong to the family of the optoelectronic devices. Two indispensable conditions must be gratify in order for a material to convert light into electrical energy. First, it needs to be intelligent to absorb incident photons through the promotion of electrons to higher energy levels. Second, it must encompass an internal electric field that accelerates the promoted electrons in a certain course, resulting in an electrical current. The most general view of the photovoltaic cells is illustrated in fig 2.1 below which can be thought of as any device when exposed to light that causes current to flow in an electrical circuit with a given load resistance. Here the magnitude of the electrical current is a function of intensity of the incoming light. But, in addition, the current also depends on the load resistance of the circuit.

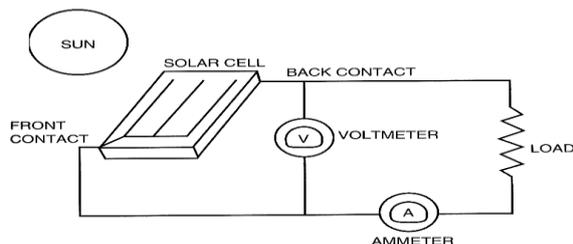


Fig 2.1: A photovoltaic cell placed in a simple circuit [4].

Photovoltaic cells produce valuable electrical energy from sunlight through manifold steps of energy conversion processes. Light is made up of packets of energy, called photons. Energy of these photons depends on the frequency, or color, of the light. The solar spectrum covers ultra violet to infrared wavelength ranges. Only 30% of incident light energy is in the visible light range, while in excess of 50% is in the infrared range. The photons in UV and visible range have adequate energy to pump electrons in semiconducting material, and this can be effectively used for charge generation. On the other hand IR waves are too weak to generate electricity using conventional PV technology.

Fundamentally the photovoltaic process is constituted of four steps: light absorption, charge generation, charge transport, and charge collection. [5]. Light absorption follows once the material has a semiconducting property that reacts to incident waves. The absorption characteristic is contingent on the bandgap of the semiconducting material and its intrinsic extinction coefficient. The next step is charge generation. When the incident photon hits electrons at the ground state, inorganic semiconductors produce free carriers.

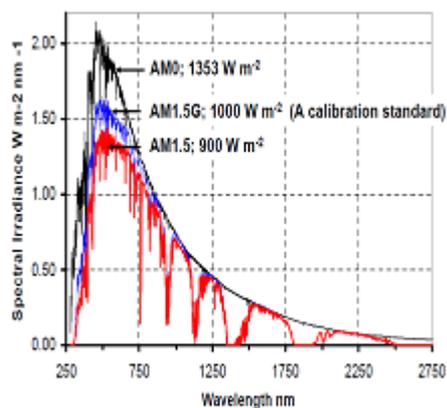


Fig 2.2: Solar spectrum

Though, in organic semiconductors, excited electrons slightly relax and then form an exciton, a bounded electron and hole pair. To make an efficient organic photovoltaic cell, effective dissociation of excitons is a key issue because the binding energy of the exciton is large [6].

After the detachment of excitons is the charge transport process instigates, concerning the transport of dissociated charges to electrodes through charge transporting pathways. During the charge transport, if the transporting medium has defects (charge traps or barriers), cell performance decreases. The charge collection is the finishing phase which arises when the transported charges are collected from the semiconductor to the cathode or anode at the interface. When the interface is not carefully optimized, it can cause a dissipating sink of the transported charges

#### (5) ORGANIC SOLAR CELL

The first organic solar cell was reported by Tang in 1986, with a power conversion efficiency of 1 per cent (Tang et al.) [7]. A fundamental difference between solar cells based on organic materials and conventional inorganic photovoltaic (IPV) cells is that light absorption results in the formation of excitons in molecular materials, rather than in free electrons and holes. An exciton in an organic semiconductor can be considered as a tightly coulombically bound electron hole pair. Due to its electrical neutrality and the strong binding energy between the hole and the electron it can be regarded as a mobile excited state. Due to this fundamental difference the processes involved in the conversion of photons into electrical energy are not the same as those occurring in IPV cells.

##### A. Molecular materials

Organic molecules and polymers have the immense advantage of facile, chemical tailoring to alter their properties, such as the optical band gap. For example conjugated polymers (see Fig 1) combine the electronic properties known from the traditional semiconductors with the ease of processing and mechanical flexibility of plastics. The research on these kinds of organic materials was initiated by Heeger, MacDiarmid and Shirakawa, who discovered that the conductivity of polyacetylene (PA) could be increased by seven orders of magnitude. Since then, this new class of materials has attracted considerable attention owing to its potential of

providing environmentally safe, flexible, lightweight, and inexpensive electronics.

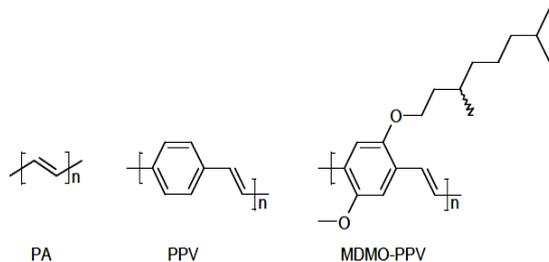


Fig 3.1: Molecular structures of the conjugated polymers trans-polyacetylene (PA), polyphenylene vinylene (PPV), and a substituted PPV (MDMO-PPV). Molecular materials that have a low ionization potential and thus can easily donate an electron are denoted as electron donors. Materials that have a high electron affinity and thus can easily take up an electron are denoted as electron acceptors. If a molecule is an electron donor or an electron acceptor is an intrinsic property of the compound. The energy levels in molecular materials can be related to the energy levels of inorganic semiconductors (see Fig 3.2). As already discussed in previous chapters the energy needed to release an electron from the valence band of an inorganic semiconductor to the vacuum level is denoted as the ionisation potential, while the electron affinity denotes the energy gained when an electron is transferred from the vacuum level to the conduction band edge. In molecular materials also electrons can be liberated from the so-called highest occupied molecular orbital (HOMO) to the vacuum. Excitons in organic materials have a binding energy [8] of 0.5 – 1 eV, due to their low dielectric permittivity [9] (= 3 – 4). The energy involved can roughly be estimated on basis of the electrochemical oxidation potential (vs. NHE) of the molecules using the relation:  $E_{\text{HOMO}} \approx E_{\text{NHE}} - V_{\text{ox}}$  with  $E_{\text{NHE}} = -4.5 \text{ V vs. vac.}$  In a similar way the electron affinity can be estimated from the reduction potential of the molecules using:  $E_{\text{LUMO}} \approx E_{\text{NHE}} - V_{\text{red}}$ . The difference between both energy levels corresponds to the optical bandgap of the molecules.

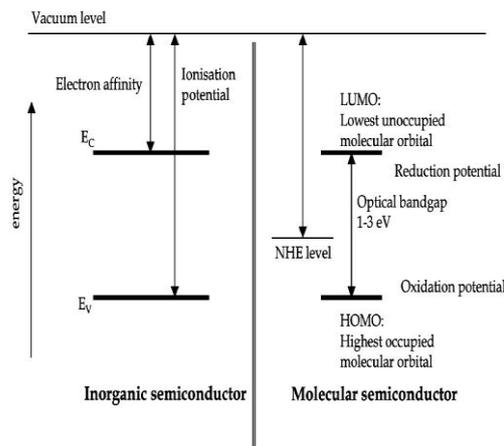


Fig 3.2: Overview of energy levels in inorganic semiconductors (left) and molecular semiconductors (right).

### B. Basic processes in organic solar cells

In general, for a successful organic photovoltaic cell five important processes have to be optimized to obtain a high conversion efficiency of solar energy into electrical energy:

1. Absorption of light and generation of excitons
2. Diffusion of excitons to an active interface
3. Charge separation
4. Charge transport
5. Charge collection

To create a working photovoltaic cell, the two photoactive materials are sandwiched between two (metallic) electrodes (of which one is transparent), to collect the photogenerated charges (see Fig 3.3). After the charge separation process, the charge carriers have to be transported to these electrodes without recombination. Finally, it is important that the charges can enter the external circuit at the electrodes without interface problems.

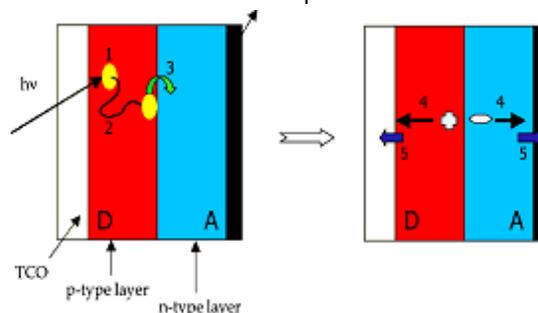


Fig 3.3: Schematic drawing of the working principle of an organic photovoltaic cell [donor material (in red) and acceptor material (in blue)].

1) Light absorption: For an efficient collection of photons (process 1), 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. Generally the optical absorption coefficient ( $\alpha$ ) of organic materials is much higher than that of crystalline or multicrystalline silicon as shown in Fig 8.5. For the conjugated polymers MDMO-PPV and P3HT and for the molecular dye, zinc phthalocyanine (ZnPc)  $\alpha$  exceeds  $1 \times 10^5 \text{ cm}^{-1}$  in the major part of the visible spectrum. 100 nm thick organic layers is sufficient to reduce the light intensity to  $1/e$  times its original value. For comparison, to obtain a similar decrease of the light intensity the crystalline silicon layer should be two orders magnitude thicker.

The absorption coefficient spectra show that of MDMO-PPV and P3HT, lack absorption in the red and NIR part of the spectrum. As discussed previously for a photovoltaic cell based on a single light absorbing medium a band-gap of approximately 1.1 eV is optimal. By lowering the band gap of the organic material it is possible to harvest more sunlight and therefore an increase in the photocurrent can be expected. For this reason much research effort is presently devoted to obtain organic polymers with an optical band in the NIR, so called small band-gap polymers. Though increasing the layer thickness is often advantageous for light absorption, charge transport might be hampered. This results in a lower the fill factor.

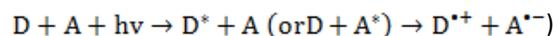
2) Exciton transport: For realization of an efficient organic solar cell all excitons formed due to light absorption should lead to the formation of free charge carriers. However exciton transport is in competition with other decay processes such as luminescence or radiative recombination to the ground state. The exponential lifetime of an exciton ( $\tau_{\text{EXC}}$ ) is determined by the reciprocal value of all radiative and non radiative decay rates together. For an efficient solar cell all excitons have to reach the photo-active interface within  $\tau_{\text{EXC}}$ . Transport of the excitons occurs by diffusion and the distance an exciton is able to cross,  $L_{\text{EXC}}$ , is given by:

$$L_{\text{EXC}} = \sqrt{D_{\text{EXC}} \tau_{\text{EXC}}}$$

In which  $D_{\text{EXC}}$  is the diffusion coefficient of the excitons. Since for molecular materials  $\tau_{\text{EXC}}$  is often

only several nanoseconds at most,  $L_{\text{EXC}}$  is generally limited to 10 nm. In practice this implies that only those excitons formed within a distance of  $L_{\text{EXC}}$  from the interface will contribute to charge separation. To avoid this problem, research has been devoted to increase the diffusion coefficient of excitons or to make the interfacial area much larger, so that each generated exciton is always nearby to an interface.

3) Charge separation: Creation of charges is one of the key steps in the conversion of solar light into electrical energy. In most organic solar cells, charges are created by photo-induced electron transfer. In this process an electron is transferred from an electron donor (D) material to an electron acceptor (A) material with the aid of the additional input energy of an absorbed photon with energy  $h\nu$ . An electron donor is characterized by a molecular material with a small electron affinity. Vice versa an electron acceptor is a material with a high electron affinity. The difference between both electron affinity levels is the driving force required for the exciton dissociation. In the photoinduced electron transfer process an exciton at the D/A interface decays by creation of the charge-separated state consisting of the radical cation of the donor ( $D^{\bullet+}$ ) and the radical anion of the acceptor ( $A^{\bullet-}$ ).



For an efficient charge generation, it is essential that the charge-separated state is the thermodynamically and kinetically most favorite pathway for the exciton. Therefore, it is important that the energy of the absorbed photon is used for generation of the charge separated state and is not lost via competitive processes like fluorescence or non-radiative decay. In addition, the charge-separated state should be stabilized, so that the photogenerated charges can migrate to one of the electrodes. Therefore, the back electron transfer or recombination should be slowed down as much as possible. In a homojunction between a p-type and an n-type silicon semiconductor under illumination electrons flow from the p-type to the n-type semiconductor. In a heterojunction based on an electron donor layer D and an electron accepting layer A, under illumination electrons flow from the D to the A layer as illustrated in Fig 3.3. Therefore the D layer is also denoted as the p-type layer and the A

layer as the n-type layer in analogy with a silicon p-n junction. Therefore molecular materials with a low ionisation potential are commonly p-type and materials with a high electron affinity n-type.

4) Charge transport: The charge transport mechanisms operating in IPV cells and organic solar cells to drive charge carriers towards the electrodes are again very different. Light absorption in IPV cells leads directly to the production of electrons and holes in the same material. Since the two carrier types have the same spatial distribution, the concentration gradient, which is the driving force for the transport by diffusion is identical (Fig 3.4). Therefore both charge carriers are driven in the same direction. Since this is a small driving force in IPV cells, the electrical potential gradient present at the interface of a p-n junction (the band bending) is able to separate the photo-induced electrons from the holes effectively. In contrast to IPV cells in organic solar cells after the charge transfer the electrons and holes are in close proximity. Therefore there is a large chemical potential gradient that drives the charge carriers away from the exciton dissociating interface.

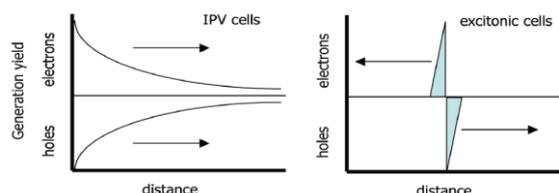


Fig 3.4: Schematic description showing the effect on the charge carrier distributions induced by the different charge carrier generation mechanisms in IPV cells (left) and organic solar cells (right).

Though for IPV cells the electric field is the main driving force for charge transport, it is not yet clear to what extent the internal electrical field contributes to the charge transport in organic solar cells. This is due to the differences in mobilities in molecular materials and inorganic semiconductors. The velocity charge carriers acquire under the influence of an electric field ( $\xi$ ) is given by the relation:

$$v_{di} = \mu_i \xi$$

in which  $\mu_i$  is the mobility. The mobility in molecular materials is relatively small ( $< 0.1 \text{ cm}^2/\text{Vs}$ ) as compared to inorganic semiconductors

( $100 - 10000 \text{ cm}^2/\text{Vs}$ ). In addition it is not yet clear if and how an electrostatic potential in an organic bilayer is formed. This is due to the fact that molecular materials contain only low densities of mobile charge carriers. In view of the above the rate kinetics for the various charge carrier recombination processes are important parameters in particular for organic solar cells. These processes should be sufficiently slow to allow the charge carriers to reach the electrodes.

5) Charge collection: The collection of charge carriers at the electrodes is regularly accomplished by a transparent conductive oxide (TCO) such as ITO or **SnO<sub>2</sub>: F** on one side and a metal contact on the other side. Care has to be taken that an ohmic contact between the electrodes and the molecular layers is formed. In practice special contact layers have been developed to obtain better performance of the solar cell. Examples of contact layers are a **PEDOT: PSS** layer, which is a charged conducting polymer layer at the TCO side and LiF layers at the metal contact. The exact reason how these layers improve the cells is unclear.

For IPV cells the  $V_{OC}$  is limited by the electrostatic potential at the junction. For organic solar cells reasonable open circuit voltages have been measured for cells build up by using a single photoactive molecular material and identical electrodes. From this observation it is evident that the  $V_{OC}$  is determined by other factors than for an IPV cell.

For an organic solar cell based on two molecular materials as depicted in Fig 3.3 optical excitation leads to the formation of an exciton in one of the layers. For the charge separation process part of the original energy of the photon is lost, yielding an electron in the n-type material and a positive charge carrier in the p-type material. In case there is no potential loss at the electrodes the maximum observed potential can be obtained by as shown schematically in Fig 3.5

$V_{OC}$  = Ionisation potential of the p-type material – electron affinity of the n-type layer. In practice a potential loss at the electrodes in the order of 0.2 V is often observed.

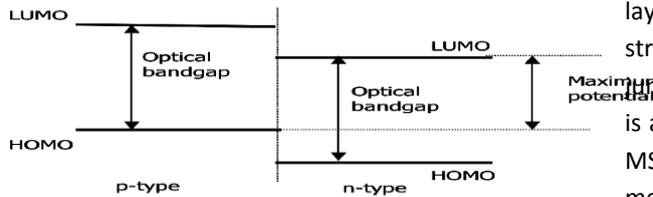


Fig 3.5: Energy levels involved in determining the maximum potential generated by an exciton solar cell.

**(6) INORGANIC SOLAR CELLS**

**A. The p-n junction**

At present, the most frequent example of the above-described solar cell structure is realized with crystalline silicon (c-Si) [10]. A typical structure of c-Si solar cell is illustrated below. A moderately-doped p-type c-Si with an acceptor concentration of  $10^{16} \text{ cm}^{-3}$  is used as the absorber. The upper side of the absorber a thin, of about  $1 \mu\text{m}$  thick, highly-doped n-type layer is molded as the electron membrane. Whereas the rear side of the absorber a highly-doped p-type assists the hole membrane. Regions are molded with an internal electric field, at the borders among the c-Si p-type absorber and the highly-doped n-type and p-type membranes. These regions are particularly significant for solar cells and are p-n junctions [11]. The existence of the internal electric field in the solar cell facilitates the separation of the photogenerated electron-hole pairs. When the charge carriers are not separated from each other in a relatively short time they will be annihilated in a process that is called recombination and thus will not contribute to the energy conversion. The easiest way to isolated charge carriers is to place them in an electric field. In the electric field the carriers having opposite charge are drifted from each other in opposite directions [12] and can reach the electrodes of the solar cell. The electrodes are the metal contacts that are attached to the membranes. The p-n junction fabricated in the same semiconductor material such as c-Si is an example of the p-n homojunction. There are also other types of a junction that result in the formation of the internal electric field in the junction. The p-n junction that is formed by two chemically different semiconductors is called the p-n heterojunction. In the p-i-n junctions, the region of the internal electric field is extended by inserting an intrinsic, i, layer between the p-type and the n-type

layers. The i-layer behaves like a capacitor and it stretches the electric field formed by the p-n junction across itself. Alternative sort of the junction is a junction between a metal and a semiconductor, MS junction. The Schottky barrier molded at the metal semiconductor boundary is a typical example of the MS junction.

**B. Formation of a space-charge region in the p-n junction**

Schematically isolated pieces of a p-type and an n-type semiconductor and their equivalent band diagrams are presented below. In both isolated pieces the charge neutrality is sustained. In the n-type semiconductor the large concentration of negatively charged free electrons is compensated by positively-charged ionized donor atoms. In the p-type semiconductor holes are the majority carriers and the positive charge of holes is compensated by negatively-charged ionized acceptor atoms. For the isolated n-type semiconductor [13] we can write:

$$n = n_{n0} \approx N_D$$

$$p = p_{n0} \approx \frac{n_i^2}{N_D}$$

For the isolated p-type semiconductor;

$$p = p_{p0} \approx N_A$$

$$n = n_{p0} \approx \frac{n_i^2}{N_A}$$

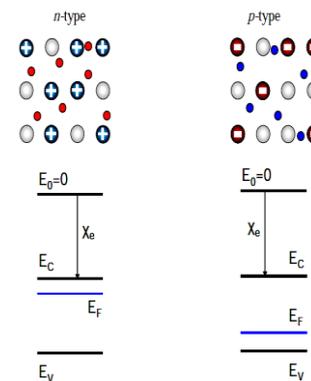


Fig 4.1: Schematic representation of an isolated p-type and n-type semiconductor and corresponding band diagrams.

When a p-type and an n-type semiconductor are brought together, a very large difference in electron concentration between n- and p-type semiconductors causes a diffusion current of electrons from the n-type material across the metallurgical junction into the p-type material.

Correspondingly, the difference in hole concentration causes a diffusion current of holes from the p- to the n-type material. Caused by this diffusion procedure the region nearby to the metallurgical junction becomes nearly depleted of mobile charge carriers. The gradual depletion of the charge carriers gives growth to a space charge created by the charge of the ionized donor and acceptor atoms that is not compensated by the mobile charges any more. This region of the space charge is called the space-charge region or depleted region and is schematically illustrated in Fig 4.2. Regions outside the depletion region, in which the charge neutrality is conserved, are denoted as the quasi-neutral regions.

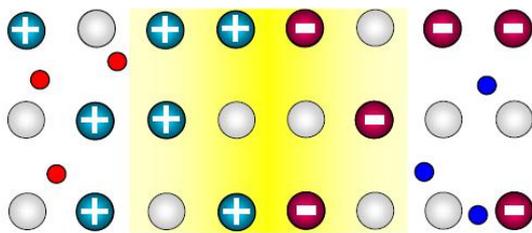


Fig 4.2: Creation of a space-charge region, when n-type and p-type semiconductors are brought together to form a junction. The colored part represents the space-charge region.

The space charge around the metallurgical junction results in the formation of an internal electric field which forces the charge carriers to move in the opposite direction than the concentration gradient. The diffusion currents continue to flow until the forces acting on the charge carriers, namely the concentration gradient and the internal electrical field, compensate each other. The driving force for the charge transport does not exist anymore and no net current flows through the p-n junction.

### C. p-n junction under equilibrium

The p-n junction signifies a system of charged particles in diffusive equilibrium in which the electrochemical potential is constant and liberated of position. The electrochemical potential define a typical energy of electrons and is characterized by the Fermi energy [14], [15]. It means that under equilibrium conditions the Fermi level has constant position in the band diagram of the p-n junction. The distance between the Fermi level and the valence and/or conduction bands does not change in the quasi-neutral regions and is the same as in the isolated n- and p-type semiconductors. Inside the

space-charge region, the conduction and valence bands are not represented by straight horizontal lines any more but they are curved. This designates the existence of an electric field in this region. Due to the electric field a difference in the electrostatic potential is created between the boundaries of the space-charge region. The electrostatic-potential profile is included in Fig 4.3.

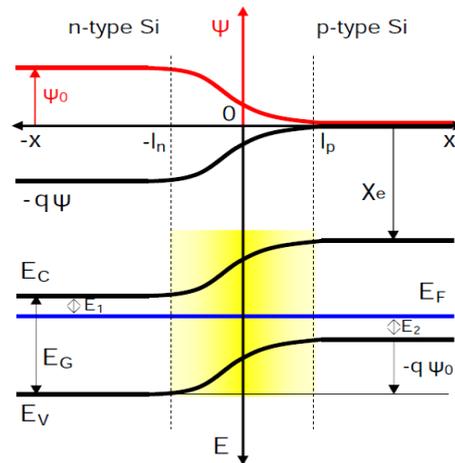


Fig 4.3: Energy-band diagram of the p-n junction. The electrostatic potential profile (red curve) is also presented in the fig.

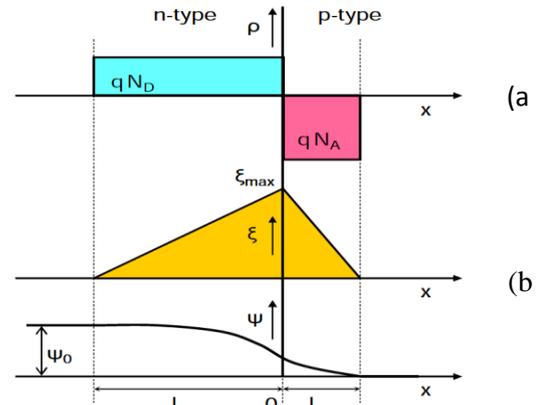


Fig 4.4: a) space-charge density  $\rho(x)$ ; b) electric field  $\xi(x)$ ; c) electrostatic potential  $\psi(x)$  across the depletion region of a p-n junction under equilibrium. The situation of the metallurgical junction is placed at zero shown in Fig 4.4, the width of the space-charge region in the n-type material is represented by  $I_n$  and the width of the space-charge region in the p-type material is symbolized as  $I_p$ . The space-charge density is described by following equations:

$$\rho(x) = qN_D \quad \text{for } -I_n \leq x \leq 0$$

$$\rho(x) = -qN_A \quad \text{for } 0 \leq x \leq I_p$$

$N_D$  and  $N_A$  is the concentration of donor and acceptor atoms, separately. Outside the space

charge region the space-charge density is zero. The electric field is can be calculated from the Poisson's equation, which has the following form for one dimensional analysis:

$$\frac{d^2\psi}{dx^2} = -\frac{d\xi}{dx} = -\frac{\rho}{\epsilon_r\epsilon_0}$$

In above equality  $\xi$  is the electric field,  $\rho$  is the space-charge density,  $\psi$  is the electrostatic potential,  $\epsilon_0$  is the permittivity of the vacuum and  $\epsilon_r$  is the semiconductor dielectric constant. For crystalline Si  $\epsilon_r = 11.7$  and the permittivity of the vacuum  $\epsilon_0 = 8.854 \times 10^{-14}$  F/cm. The electric field profile can be found by integrating the space-charge density across the space-charge region.

$$\xi = \frac{1}{\epsilon_r\epsilon_0} \int \rho dx$$

**D. p-n junction under applied voltage**

When an external voltage,  $V_a$  is applied to a p-n junction the potential difference between the n-type and p-type regions will change and the electrostatic potential across the space-charge region will become  $(\psi_0 - V_a)$ . Remember that under equilibrium the built-in potential is negative in the p-type region with respect to the n-type region. When the applied external voltage is negative with respect to the potential of the p-type region, the applied voltage will increase the potential difference across the p-n junction. We mention to this position as p-n junction under reverse-bias voltage. The potential barrier across the junction is increased under reverse-bias voltage, which results in a wider space-charge region. The band diagram of the p-n junction under reverse-biased voltage is shown in Fig 4.5 a. Under external voltage the p-n junction is not under equilibrium to any further extent and the concentrations of electrons and holes are described by the quasi-Fermi energy for electrons, EFC, and the quasi-Fermi energy holes, EFV, correspondingly. As soon as the applied external voltage is positive with respect to the potential of the p-type region, the applied voltage will decrease the potential difference across the p-n junction. Here let mention to this situation; as p-n junction under forward bias voltage. The band diagram of the p-n junction under forward-biased voltage is presented in Fig 4.5 b. The potential barrier across the junction is decreased under forward-bias voltage and the space charge

region becomes narrower. The balance between the forces responsible for diffusion (concentration gradient) and drift (electric field) is disturbed. The lowering of the electrostatic potential barrier leads to a higher concentration of minority carriers at the edges of the space-charge region compared to the situation in equilibrium. This process is referred to as minority-carrier injection. This gradient in concentration causes the diffusion of the minority carriers from the edge into the bulk of the quasi-neutral region.

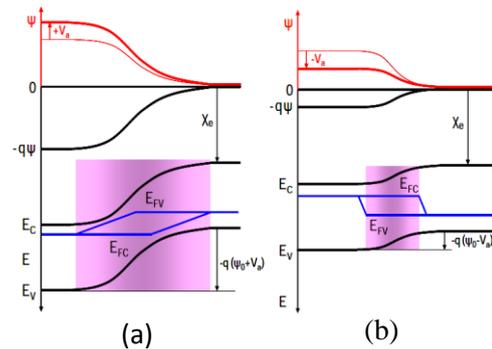


Fig 4.5: Energy band diagram and potential profile (in red) of p-n junction under (a) Reverse bias (b) Forward bias

The diffusion of minority carriers into the quasi-neutral region causes a so-called recombination current,  $J_{rec}$ , since the diffusing minority carriers recombine with the majority carriers in the bulk. The recombination current is compensated by the so-called thermal generation current,  $J_{gen}$ , which is caused by the drift of minority carriers, which are present in the corresponding doped regions (electrons in the p-type region and holes in the n-type region), across the junction. Both, the recombination and generation currents have contributions from electrons and holes. When no voltage is applied to the p-n junction, the situation inside the junction can be viewed as the balance between the recombination and generation currents.

$$J = J_{rec} - J_{gen} = 0 \quad \text{for } V_a = 0$$

It is supposed that when an adequate forward-bias voltage is applied to the junction the recombination current surges with the Boltzmann factor  $\exp\left(\frac{qV_a}{kT}\right)$  (the Boltzmann approximation) [16]:

$$J_{\text{rec}}(V_a) = J_{\text{rec}}(V_a = 0) \exp\left(\frac{qV_a}{kT}\right)$$

On the other hand, the generation current is nearly independent of the potential barrier across the junction and is determined by the availability of the thermally-generated minority carriers in the doped regions.

$$J_{\text{gen}}(V_a) \approx J_{\text{gen}}(V_a = 0)$$

The external net-current density can be expressed as

$$J(V_a) = J_{\text{rec}}(V_a) - J_{\text{gen}}(V_a) = J_0 \left[ \exp\left(\frac{qV_a}{kT}\right) - 1 \right]$$

where  $J_0$  is the saturation-current density of the p-n junction, given by

$$J_0 = J_{\text{gen}}(V_a = 0)$$

formerly equality for  $J(V_a)$  is recognized as the Shockley equation [11] that defines the current-voltage behavior of an ideal p-n diode. It is a central equation for microelectronics device physics.

The recombination of the majority carriers due to the diffusion of the injected minority carriers[17] into the bulk of the quasi-neutral regions results in a lowering of the concentration of the majority carriers compared to the one under equilibrium. The drop in the concentration of the majority carriers is balanced by the flow of the majority carriers from the electrodes into the bulk. In this way the net current flows through the p-n junction under forward-bias voltage. For high reverse-bias voltage, the Boltzmann factor in equality for  $J(V_a)$  becomes very small and can be neglected. The net current density is given by

$$J(V_a) = -J_0$$

and represents the flux of thermally created minority carriers across the junction. The current density-voltage (J-V) characteristic of an ideal p-n junction is schematically shown in fig:

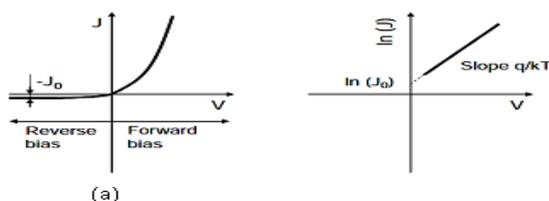


Fig 4.6: J-V characteristics of a p-n junction (a).Linear plot and (b).Semi-logarithmic plot.

## (7) CONCLUSION

A fundamental distinction between solar cells grounded on organic materials is that light

absorption results in the formation of excitons in molecular materials and conventional in an inorganic photovoltaic (IPV) cells by free electrons and holes. Inorganic semiconductors are superior matched in their band gap energies to the solar spectrum, however have inferior absorptivities than organic materials, requiring thicker absorbing layers, and high purities (and high costs) to insure proficient operation. Additional significant dissimilarity amid OPVs and conventional inorganic solar cells is in the exciton binding energy. In both systems excitons (excited states) are molded upon photon absorption. In inorganic semiconductors the energy requisite to dissociate these excitons into charge carriers is quite small (a few millielectron volts, easily achieved at room temperature). In organic semiconductors the "exciton binding energy" can be as high as 0.5 eV or higher, requiring the formation of a D/A heterojunction (see below) to provide the internal electrochemical driving force for exciton dissociation to occur. Inorganic solar cells can be very efficient because a single inorganic material can be used with an exciton binding energy is negligible at room temperature. The physics of organic solar cells very different because the exciton is strongly bound. We need to have an acceptor and donor component with as much interface as possible between them in order that the formed excitons can quickly reach the interface to disassociate. Once the excitons have disassociated into two separated species, the electron and the hole, they must move efficiently toward the electrodes. The pronounced evolution in OPVs in the last ten years can be accredited to advances in four fronts: (i) a better understanding of the fundamental mechanism of photon-to-electron conversion; (ii) advances in the molecular design of new materials with tailored energy levels and solubility; (iii) new processing approaches to induce the optimal microstructure in the active layer and new progress in the application of analytical tools; and (iv) new device architectures with developments in optimizing the interfacial layers.

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