Review Article

Organic Semiconductors: Exploring Principles and Advancements in OPV and OLED - A Review

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Abstract - This paper aims to recap the relatively new yet revolutionizing novel organic material technology thatis changing everyday life electronic applications. The primary objective of this review paper is to introduce this novel technology to new researchers, starting from the basics of differentiation between inorganic and organic semiconductors, working principles, and underlying fundamental theories like exciton theory, bandgap theory, electron spin theory, their applications and challenges. This will give the much-needed lead to the new researchers to pursue further work in this field. On the application aspect, this review focuses on Organic Light Emitting Diodes (OLEDs) and Organic Solar Cells in detail, from a brief historical outlook, developments, and discussions on the newest technologies along with their challenges and future potentials. More emphasis is given to organic solar cells since they address the wide issue of climate change and global warming. With this review paper, one can accumulate wide knowledge on organic semiconductors and their applications and can couple their research interest with the lead given by this paper to make their contribution in this particular domain, holding massive future potential. To summarize, this paper reviews in detail the basics of organic semiconductors, fundamental working principles and applications, comparing and compiling different research works to highlight the pain points and future research areas.

Keywords - Bandgap theory, Exciton theory, Organic semiconductor, Organic Light Emitting Diode, Organic photovoltaics, Spin theory.

1. Introduction

Energy is essential to our life. According to a reliable energy consumption report [1] energy consumption in 2050 is projected to increase to 760 exajoules due to various reasons such as population growth, urbanization, and industrialization, particularly in developing countries. Fossil fuels, which have traditionally met a large portion of this demand, are finite resources with detrimental environmental impacts.

By harnessing renewable energy, our world can significantly decrease its reliance on fossil fuels and mitigate the environmental damage caused by their extraction and combustion. As fossil fuel reserves deplete and their extraction becomes challenging, there is a need for sustainable and renewable energy sources to meet future energy demands. Figure 1. shows energy distribution details from major sources of energy supply from 2000-2050.

One key takeaway from the bar graph is the growth of the renewable energy sector, which, over the coming decade, is set to take over as the major contributor to energy supply. Organic semiconductor products offer a promising avenue for green energy generation and efficient energy utilization. Some of it includes Organic Light Emitting Diodes (OLEDs),

Organic Photovoltaics (OPVs), Organic batteries and storage devices, Organic Thermoelectric Generators (OTEGs) and a few more. The functionalities of OLEDs and OPVs are explained in this review, with a special focus on Organic Solar Cells. -Because, unlike traditional silicon-based solar cells, organic solar cells are lightweight, flexible, and can be manufactured using low-cost, environmentally friendly materials. They can be integrated into various surfaces and structures, making them suitable for a wide range of applications, including building-integrated photovoltaics and portable electronic devices.

Moreover, organic solar cells have the potential for high efficiency and scalability, making them a viable option for large-scale energy generation. Their flexibility and transparency also enable innovative design possibilities, such as solar windows and clothing embedded with solar cells. By investing in research and development to improve the efficiency, durability, and cost-effectiveness of organic solar cells, everyone can lend their hands to accelerate the transition towards clean and sustainable energy sources. Embracing organic solar cell technology not only reduces our dependence on fossil fuels but also stimulates innovation, creates new job opportunities, and promotes economic growth in the

renewable energy sector. Since it is a relatively nascent field, an enormous amount of research gap is prevalent, which includes new innovative and combinative photo-voltaic cell structures, integration of Artificial Intelligence (AI) and Machine Learning (ML), smart clothing, highly efficient wearable smart devices, foldable, & bendable light weight electronics and so on. Having a tight grasp on organic semiconductor fundamentals is essential to have an upper-hand in bringing up innovative solutions for a greener and brighter future.
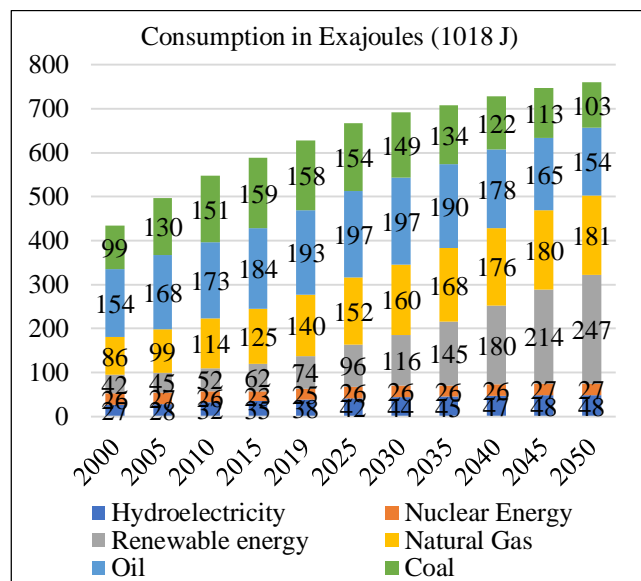

Fig. 1 Consumer consumption in exajoules vs energy source distribution [1]

2. Organic Semiconductors

The degree of conductivity decreases from metals to semiconductors to insulators. Metals have a very high conductivity of the order of 10^2 to 10^8 ohm per cm. In contrast, on the other hand, insulators have a very poor conductivity of orders lesser than 10^{-14} ohm per cm. The conductivity of semiconductors lies between these two extremes, ranging from 10^{-2} to 10^{-14} ohm per cm. The reason why most electronic devices are made of semiconductors but not metals or insulators is that it is easy to alter and control the flow of electrons through it to satisfy the respective needs of a specific device in design.

Roughly around 160 years back, in 1862, Henry Letheby, an English analytical chemist, laid the groundwork of 'Organic Semiconductors' by obtaining a partially conductive material (probably polyaniline when aniline was oxidized anodically in sulfuric acid [2]. It was not until 1954 when it was first indicated that current could be carried by organic compounds when in a perylene-iodine complex, that high conductivity (0.12 S/cm) was observed. With iodine acting as a hole injector, when a positively biased electrode containing it made in contact with an anthracene crystal, the flow of holes

through the crystal was observed for the first time in the 1960s. This result from Kallmann and Pope [3] was significant in proving that when electrodes eject charge carriers, the organic materials become semiconducting from bringing an insulator in principle. Organic Light Emitting Diodes (OLEDs), Organic Photovoltaics (OPVs), Organic Field Effect Transistors (OFETs), and a few more semiconducting electrical devices were made possible because of this discovery. The focus in this review will be on Organic Light Emitting Diodes (OLEDs) and a special focus on Organic Solar Cells, as briefly mentioned earlier

2.1. Fundamentals of Organic Semiconductors

A family of semiconductors known as "organic semiconductors" is made up of molecules that typically contain carbon and hydrogen. These molecules can be single molecules, short-chain oligomers, or long-chain polymers. Almost all organic solids are insulators, but the differentiating factor arises when the system has a π-conjugate structure, due to which transport of charge carriers is made possible. It is important to note that the significance difference between organic and inorganic materials arises from the fact that they vastly differ when it comes to their fundamental solid-state properties. While organic materials are characterized by van der Waals bonding that results in complex lattice structures such as monoclinic or triclinic, the inorganic counterparts are typically covalently bonded and crystallize in simple cubic lattices. A comprehensive comparison of organic and inorganic semiconductors is tabulated in Table 1.

Professor Heeger stated the following in his Nobel talk: "I am convinced that we are on the verge of a revolution in Plastic electronics". Our world is foreseeing rapid developments in the field of Organic Semiconductors (OSCs) as it is being extensively researched and implemented to incorporate organic material electronics into our daily lives. Organic semiconductors open many new application and integration perspectives due to their flexibility and their ability to be manufactured by roll-to-roll process which increases its ease of production [4]. Optoelectronic technology has reached new heights ever since the application of organic semiconductors in these devices. This dramatic increase in optoelectronic technology demonstrates the impressive potential of organic semiconductors as they introduce new functionality and devices to the world. To extract the best out of the massive potential it possesses, understanding organic semiconductors from the very basics is essential.

Organic Semiconductors are an innovative move towards flexible, large area and cost-efficient circuits and devices, providing us with more freedom of design, more compatibility and faster development iterations. When compared to their typical inorganic equivalents, organic counterpart caters variety of benefits, including low cost of manufacturing, low-temperature processing, mechanical flexibility, and wide availability.

Table 1. Characteristics of organic and inorganic semiconductors

Characteristics	Organic Semiconductors	Inorganic Semiconductors
Chemical Structure	Carbon-based compounds consist of conjugated π-electron systems.	Covalently bonded elements such as silicon, gallium arsenide or germanium.
Structural Capabilities	Tunable energy bandgaps, electron delocalization	Strong and well-defined crystal structures
Charge Transport	Occurs through hopping and tunneling mechanism	Occurs through band conduction
Mobility and Resistivity	Disordered molecular structure, resulting in lower mobility and higher resistivity.	Due to bandgap energy difference resulting in higher carrier mobility and lower resistivity
Processing Complexity	Low-cost, low-temperature solution-based processes on flexible substrates	High-cost, high-temperature deposition-based processes on rigid substrates
Doping	Due to molecular irregularity, precise doping is challenging	Due to molecular regularity, precise doping is fairly easily achievable
Temperature Stability	Generally, less stable at high temperatures due to molecular decomposition	Generally, more stable at high temperatures due to structural rigidity.
Research Focus	Potential low-cost, flexible electronic applications, organic circuitry design, improving carrier mobility and stability	Improving the efficiency of existing techniques and exploring new materials for more advanced electronic devices.

Organic Light Emitting diodes (OLEDs) have been successfully commercialized for digital display in gadgets like computer displays, televisions, portable systems like mobile phones, and game consoles, showcasing the market's potential and adaptability to changes brought by efficient organic substitutes. Not just in display systems, organic semiconductors have proved to enhance the fabrication process of many electronic devices, such as solar cells, transistors, lasers, and photodetectors, just for a start. Their ability to be deposited as a thin layer over large areas widens their application and eases the manufacturing process. This is due to their capability of forming oligomer and polymer chains, unlike the inorganic counterpart, which takes only the single-crystalline form. The combination of excellent optical and electrical properties in organic materials mainly accounts for the boom of this field. Simple fabrication requirements and the compatibility of tuning the properties of organic materials as per requirements, there is no need to be highly ordered, unlike the inorganic substances, add up to efficient capital expenditure by reducing it by multiple folds [5].

Very efficient and comparatively simple manufacturing techniques based on printing in normal room temperatures are applied. Organic materials can be incorporated into inks and then deposited into a substrate by various techniques such as inkjet printing, silk-screen printing, engraving, flexography and a number of other printing techniques. These production methods are much simpler and cost-efficient than the conventional electron-beam lithography technique used in silicon-based electronics. Notably, this can be done on rigid substrates such as glass and on flexible substrates such as plastic, textiles and paper. It makes it practically possible for

wide scale integration of numerous electronic components in any desired shape, size and composition. It has unveiled a multitude of applications in real life, offering solutions to unsolved real-life problems in a much cheaper, much more efficient, a much greener way. Excellent progress is being accomplished in research and development sector of the 'printed organic electronics' domain. Evidently, in recent times, thin plastic film substrates have been used to build flexible displays, Radio-Frequency Identification (RFID) tags, smart labels, and a number of sensors based on Thin-Film Transistor (TFT) devices [6].

2.2. Working Principle of Organic Semiconductors
This section discusses the underlying principles of how organic semiconductors work. It is essential to have the basic structural and characteristic idea about these materials to have a tight grasp on fundamental understanding of the working principles, in order to apply it in real life. Discussions of molecular structure mobility, and then extending it to a few fundamental concepts like electron spin theory, bandgap theory, exciton generation and recombination theory, and a few more affecting the magnetic and, in turn, the optical properties of materials are very important to understand for effective design implementation and appropriate material selection to cater respective needs.

2.2.1. Molecular Structure and Stability
The selection of molecules used in Organic semiconductors is heavily dependent on the hybridization of the constituent carbon atom. The most important hybridization is sp^2, in which the angle between three orbitals (1s and 2p) is 120°, where two orbitals (p_x and p_y) lie on the same plane with

the remaining orbital (p_z) being perpendicular to them. Bonds that have rotational symmetry (σ-bonds) can be formed by the planar orbitals, whereas the perpendicular p_z orbital forms π-bonds above and below the plane of σ-bond. Figure 2 shows the pictorial representation of this hybridization. Here, planar yellow orbitals are p_x and p_y whereas the perpendicular p_z orbital is represented with blue colour.

The formation of a chain of carbon atoms can result in the development of alternate single and double bonds. This type of system typically has large dipole moments and strong coupling capacity with electromagnetic waves since they delocalize across the molecule. The above-formed conjugated p-orbital structure creates a one-dimensional electron band. While being partially emptied, the electrons in this band become mobile.

To demonstrate the above-stated phenomena, consider the case when the material is doped by oxidation, which results in the removal of certain delocalized electrons and allows the remaining electrons to flow across the so-called electronic band. In these delocalized orbitals, the electron mobility is high.
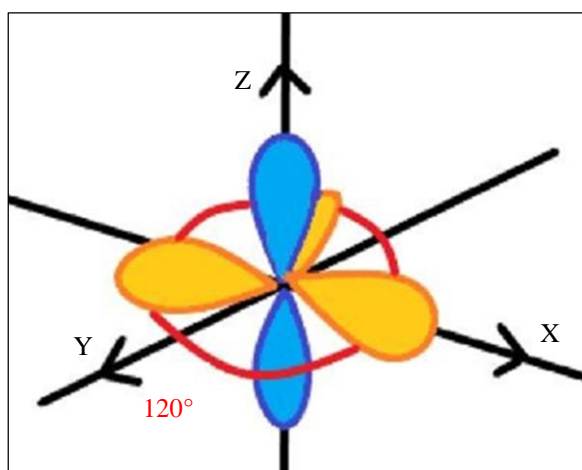

Fig. 2 Sp2 hybridization

In molecular solids, this mechanism of unsaturated compounds is ultimately vital for the carrier transport mechanism. Inorganic Light Emitting Diodes (OLEDs), Organic Thin-Film Transistors (OTFTs), Organic Photo-Voltaic Diodes (OPVDs), and organic lasers are just a few examples of the devices that use these unsaturated chains of compounds as active components [7]. They are particularly appealing as novel laser gain media since they have four-level systems in which the absorption and emission bands separate due to vibrational and structural relaxations.

Also, polymers such as Poly-Para- Phenylene (PPP), Poly-Para Phenylene-Vinylene (PPV), Poly-Thiophene, and others are popular candidates for practical purposes. Polyaniline is widely used as an organic conductive layer, and

polymers such as tris (8-hydroxyquinoline) aluminium, polyfluorene or triphenylamine are used as emissive layers in OLED architecture [8]. In most of the cases, only conjugated compounds are used which is explained by the delocalization factor. Figure 3 depicts the structure of polyaniline, polyfluorene and triphenylamine.
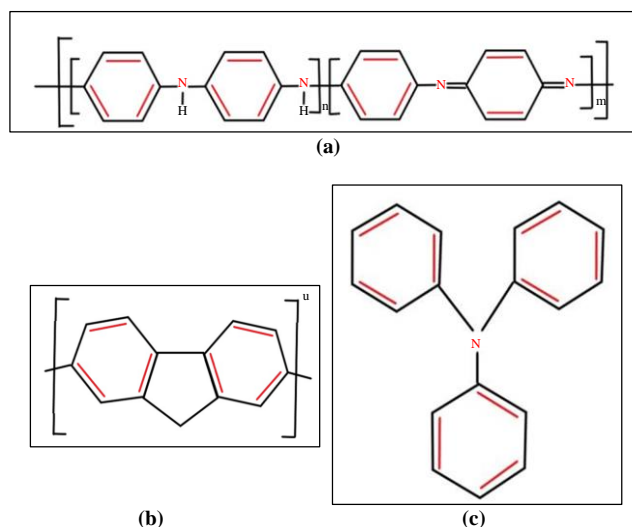

(a)

(b)   **(c)**
Fig. 3 (a) Alternate double bond structures of polyaniline,
(b) Polyfluorene, and (c) Triphenylamine.

2.2.2. Exciton Theory

The concept of 'exciton' plays an important role in the optical physics of organic semiconductors and interactions in organic materials [9], being the fundamental differentiating factor in the working principle of silicon-based photovoltaics and organic molecule-based photovoltaics. An exciton is a bound state of an electron and a hole which are attracted to each other by electrostatic Coulombic force. When an electron is stimulated into a higher energy state through any excitation method, leaving a hole in the lower energy level consequently results in the bound state of electron-hole, which is exciton (exciton formation is significantly dependent on band gap energy, which will be discussed in later sections).

This attraction between electrons and holes causes their motion to be correlated, and the resultant electron-hole pair is called an exciton. It is an electrically neutral quasiparticle which is an elementary excitation of condensed matter that can transport energy without transporting net electric charge. Additionally, there are two limiting cases of excitonic studies like Frenkel Wannier-Mott excitons. To put it forward simply, excitons in semiconductors consist of a loosely coupled state of two Fermi particles- a hole and an electron. Using Bohr formulas for the hydrogen atom, the binding energy ε_0 and the exciton radius a_0 can be determined from the Equations (1) and (2).

$$\varepsilon_0 = \frac{1}{2}\frac{e^4 m}{\chi^2 h^2} \tag{1}$$

$$a_0 = \frac{\chi h^2}{m e^2} \tag{2}$$

Here, e is the charge of the electron, χ is the dielectric constant ($\chi = 10$ (approximate)), and m is the reduced effective mass of electrons and holes given by Equation (3).

$$m = \frac{m_e m_h}{m_e + n_h} \approx 10^{-28} g \tag{3}$$

Calculations result in ε_0 approximated to 10^{-2} eV and a_0 approximated to 10^{-6} cm. The average distance between these excitons will be $N^{-1/3}$ when the exciton concentration (N) is considered to be between 10^{17} and 10^{18} cm^{-3}, which is of the same order as their radius a_0. At $N^{-1/3} \sim a_0$, excitons deform each other by virtue of Pauli's principle, which proves that the Fermi particles with which excitons are made obey Pauli's principle. Different excitons containing two electrons/holes of parallel spins cannot come close to each other. Therefore, it is also proved that excitons are not regarded as structure less boson particles [10].

The energy required to dissociate an exciton into its constituent charge carrier particles, i.e., electrons and holes, is called the Exciton Binding Energy (BE). This parameter indicates the stability of an exciton. The higher the BE, the more stable the exciton is, with a longer lifetime. Various factors such as electron effective mass, hole effective mass, dielectric constant of the material and exciton's spatial confinement influence this energy. The value of this exciton binding energy is relatively low in most of the semiconductors due to the screening effect of inner electrons. A few examples are shown in Table 2.

Table 2. Binding energy of different semiconductor materials

Semiconductor	Exciton Binding Energy
GaAs	4.9 meV
CdTe	11 meV
ZnO	29 meV
Organic	0.1 – 1.0 eV
Perovskite	1 – 20 meV

Different types of excitons have also been discovered in carious materials in various molecular states. Exciton complexes such as 'Trions' and 'Biexcitons' were discovered while studies were ongoing for quantitative measurement of exciton binding energies. They were discovered in MX_2 compounds, which are heterostructures of Transition Metal Dichalcogenides (TMDs).

Fabrication of TMD heterostructures was made possible with the onset of Van der Waals (VdW) heterostructure. Week screening and extraordinarily strong coulombic interaction in TMDs and VdW heterostructures bring up a whole new model of exciton physics. This results in the formation of different

types of excitonic particles like optically allowed and forbidden dark excitons and spatially separated interlayer exciton states as well [11], which are shown in the following Figures 4(a) and 4(b). There are many challenges with design since the localized molecular bonds can degrade as a result of energy being dumped onto them during non-radiative recombination of excitons within the material [12].
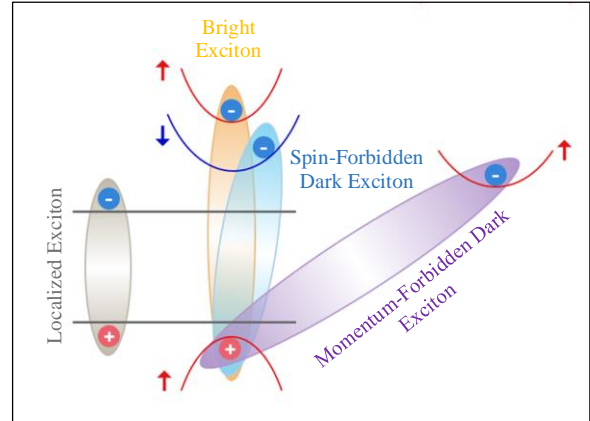

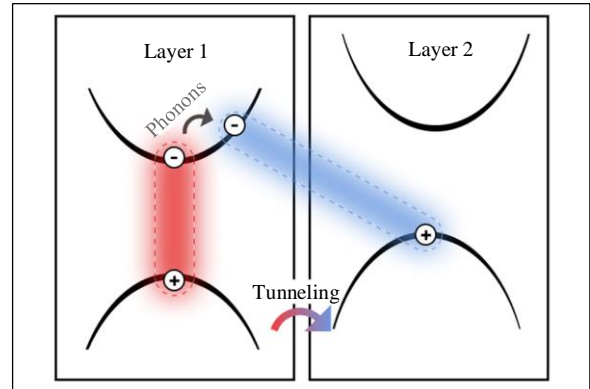**Fig. 4(a) Bright and dark exciton representation**

Fig. 4(b) Quantum tunneling phenomena in exciton formation

2.2.3. Electron Spin Theory

Quantization of electron spin took birth in 1926, when Wolfgang Pauli formulated Pauli's exclusion principle, through which it is inferred that, based on electron spin states, no two electrons of an atom can have the same combination of quantum numbers. Detailed research works led to its profound implications in various fields, including quantum mechanics, condensed matter physics, quantum computing and so on. Essential analytical techniques in physics and chemistry include the principles of Nuclear Magnetic Resonance (NMR) and Electron Spin Resonance (ESR), which are developed based on the electron spin theory [13].

The spin nature of electrons plays a crucial role in optoelectronics as they alter the magnetic and quantum properties of the material. 'Singlet exciton' is created due to the presence of an electron-hole pair with opposite spins, whereas the vice versa results in 'triplet excitons' or 'trions'

[14]. Excitons primarily determine the optical properties of organic semiconductor materials. In the case of inorganic semiconductors, the excitons are localized with weak binding energies. As a consequence of Coulombic screening differences, they need high binding energies for their dissociation. So, they delocalize over multiple bond lengths with significant binding energies, resulting in amplified coulomb interactions, due to which strongly bound excitons are formed upon optical excitation. This leads to the formation of strongly bound excitons upon optical excitation.

Opto-electronic devices are highly reliant on one property that is repeatedly used to explain many concepts- Exciton Binding Energy (BE). This is the reason why it garners so much attention. To demonstrate their impact with a simple example, charge separation phenomena, i.e., the movement of electrons and holes away from each other, forms the basis of the working principle in photo-voltaic devices. On the other hand, the presence of spatially confined electron-hole pairs is required in the case of photoluminescence quantum yield in Organic Light Emitting Diodes (OLEDs). These two contrast examples requiring low and high BE, respectively, demonstrate the need to choose appropriate BE according to the requirements of different applications [15].

2.2.4. Bandgap Theory

Organic Semiconductors, also called organic π-conjugated materials, are extensively used in hybrid electronic applications such as Organic Light Emitting Diodes (OLEDs), Organic Photovoltaics (OPVs) and Organic Thin Film Transistors (OTFTs) on account of their excellent charge transport and electroluminescent nature. The most fundamental concept on which material selection relies is the "band gap theory". Because of their impact on the evaluation of band gap energy of OSCs, recent research establishing the relationships between molecular and supramolecular structures and their semiconducting properties is grasping huge attention [20].

The band gap is essentially the energy difference between the Lowest Unoccupied Molecular Orbital (LUMO for electron transport) and the Highest Occupied Molecular Orbital (HOMO for hole transport). Knowledge of band theory has extreme fundamental relations to the domain of organic electronics, being decisive for material selection for the construction of efficient organic semiconductor-based devices. Band gap engineering has to be undertaken carefully and precisely because the band gap energy directly and heavily influences the mobility and behavior of charge carriers.

Spectroscopic methods such as reflectivity and absorptivity and some photoconductivity techniques are used to determine the HOMO-LUMO energy gap [16] experimentally. To accurately determine the band gap energies of thin films of OSCs, efficient, cost-effective, non-destructive, easy, versatile analytical techniques such as UV-Vis absorption spectroscopy are used. In this method, in comparison to a reference sample, the number of discrete wavelengths of Light (UV/Visible) are measured. Depending on the amount of light received by the analyte, the analyte quantity is measured. In different substances, the absorption of light occurs in different wavelengths. This is because electrons need a different specific amount of energy in different bonding environments to excite the electrons to a higher energy state.

Organic semiconductor-based devices heavily rely on various levels of bandgap energy properties. Tunable bandgap energy properties aid optoelectronic devices in precise and proper functioning due to their high dependency on the emission and absorption of photons of specific wavelengths [17]. Mobility of charge carriers is also dependent on the width of bandgap energy as D.M.de Leeuw et al. [18] have shown that narrow bandgap organic materials typically exhibit better charge carrier mobility than the ones with broader bandgap, resulting in enhancement in the performance of various organic devices.

2.3. Applications of Organic Semiconductors

Organic semiconductors have rooted their way into the modern electronic industry by marking their dominating presence with an increasing commercial application in consumer electronics. Organic Light Emitting Diodes (OLEDs), Organic Photovoltaics (OPVs), Organic Field Effect Transistors (OFETs), Organic Thin-Film Transistors (OTFTs), Organic sensors, and Organic memory devices are a number of its applications. Pioneering research, technologies and innovations are helping this industry to obtain significant growth down the lane. This section focuses on OLEDs and OPVs (organic solar cells). It discusses their history, working principles, current-day technologies and their future potentials so that upcoming researchers would be able to get a grasp on the path way of these trending applications.

3. Organic Light Emitting Diodes (OLED)

Light Emitting Diodes (LEDs) have been around for over a century, and several modifications took place over time. LED has shown tremendous advantages over conventional fluorescent and incandescent lighting, such as much higher efficiency, longer lifecycle, flexibility of colour availability, environmental friendliness and so on. The development of LEDs to date is the result of extensive growth of LED technology over decades. The path of development from being very expensive to replace traditional lights to the period of domination of markets in numerous fields, LEDs have come a long way. Due to its high efficacy, smaller size, better Colour Rendering Index (CRI), colour control, higher life-efficacy, and other factors, it is now used almost everywhere, including biomedical/healthcare facilities, traffic lights, smart displays, detector systems, data transfer applications, indoor framing, etc. [19]. The introduction of Organic Light Emitting Diodes

(OLEDs) has had humungous advantages that paved the way for many modern-day devices, such as smart watches, transparent displays and much more. The advantages offered by OLEDs over conventional LEDs are as follows:

- Compared to ordinary LEDs, which only provide a 120 to 140-degree field of vision, OLEDs provide a greater viewing angle of roughly 170 degrees.
- The flexible nature of the substrate in OLED opens the gate to the application of display devices in the flexible and stretchable electronics domain.
- Organic layers are much thinner and lighter than the conventional crystalline layer used in LEDs.
- Minimal temperature effect on OLED performance, lower power consumption, and inhibition of better contrast play key roles in the rising domination of OLEDs in the market.
- OLEDs also massively reduce the screen thickness since it is easy to produce large and thin sheets dueto the thin organic layer.

Challenges remain in the production of low-cost OLEDs for commercial purposes, on which widespreadresearches are undertaken to cut costs with more efficient technologies.

OLED is a monolithic, thin-film, semiconductive device that emits light when voltage is applied to it. To achieve this, organic material is placed between the two electrodes, out of which at least one electrode is kept transparent for the light to emit. This optical process is called Electroluminescence in which radiative recombination of holes and electrons leads to the generation of photons when electric current is passed through the material.

Taking a peek at its history, in the 1960s, the discovery of Anthracene ($C_{14}H_{10}$) single crystals emit light with proper electrodes and external bias was the starting point in the scientific world to make use of organic materials for light emission [20]. Still, it was not practically applicable since anthracene-based devices required very high operating voltages. When Tang and Slyke published their landmark article [21] in 1987 describing a two-layer organic thin film structure based on an effective electron and hole transport medium, it marked a significant advancement.

Tris(8-hydroxyquinoline) Aluminium (AlQ3) was developed, which increased the half-time operation to hundreds of hours, many orders of magnitude larger than the previously reported devices. Another crucial discovery of the application of polymers was put forward by Burroughs et al. [22] in which they observed Electroluminescence in a single-layered device made of Polyphenylenevinylene (PPV). Since then, the growth of the polymer- and small-molecule-based OLEDs has been parallel. There are two main classes of OLED devices such as small organic molecule-based devices and organic polymer-based devices [23]. OLEDs have a thickness of just 100 to 500 nanometres. However, it has superior advantages such as excellent image efficiency (high contrast ratio, large viewing angle, bright colours), mechanical flexibility and stability, chemical versatility, easier fabrication, the ability of self-illumination, removing the need for backlighting, also having ultra-thin and lighter nature over conventional LCD and LED displays as well.

3.1. Types of LED
Different types of OLEDs are available in the market: Passive-Matrix OLED (PMOLED), Active-Matrix OLED (AMOLED), Transparent OLED (TOLED), White OLED, and Foldable OLED (FOLED).

1. Organic layers and perpendicularly aligned strips of anode and cathode comprise the pixels in PMOLEDs where Light is emitted with the assistance of external circuitry for the current supply. The SiNx layers, polyimide layers, and Indium Tin Oxide (ITO) lines are transferred to a plastic substrate after being photolithographically produced conventionally on a glass substrate.
2. AMOLED consists of anode, organic layer, and cathode. Additionally, a matrix of Thin-Film Transistors (TFTs) is layered over the anode layer, which is suitable for big display devices because it consumes less power in comparison.
3. A translucent substrate, cathode, and anode are components of a TOLED. You can achieve up to 85% transparency when you turn on a clean OLED monitor display. Their matrix displays could be active or passive.
4. Compared to fluorescent lights and bulbs, white OLEDs give forth a practically brighter white light. They actually provide the actual color of incandescent lamps. For incandescent and fluorescent lights, they are thought to be a more consistent, brighter, and energy-efficient alternative.
5. Flexible OLEDs are particularly gaining significant attention in the market due to their obvious flexibility, durability and their light weighted nature. This is due to the components used in manufacturing FOLEDs-Very flexible plastic or metallic substrates. Various applications such as foldable phones, watches and other electronics are expected to be in the market very soon considering the pace of research works [24].

3.2. Components of LED and Functionalities
The structure of present OLED technology shown in Figure 5 is made up of 8 layers, from top to bottom, that include the cathode, Electron Transport Layer (ETL), blocking layer, emissive layer, Hole Transport Layer (HTL), hole injection layer, anode, and substrate. On a substrate, two electrodes-the cathode and the anode are sandwiched with emissive and conducting layers. Organic plastic molecules make up the conducting/hole transport layer, while an organic compound film makes up the emissive layer that carries

electrons from the cathode. When an electric current passes through this layer, light is produced. As previously established, conjugation-induced delocalization of electrons facilitates conduction in organic layers.

The light emitting reaction due to current takes place when a potential difference is applied between anode and cathode, due to which electron moves from the cathode to the emissive layer through an electron transport layer and blocking layer, which controls the flow of electrons. Holes move from the anode to the emissive layer through a hole injection and a hole transport layer. This results in the formation of previously discussed exciton particles in the emissive layer, which in turn relaxes via a photo emissive mechanism either by a radioactive means or a non-radioactive means. Clear and crisp visuals are produced via recombination, which releases energy in the form of light.
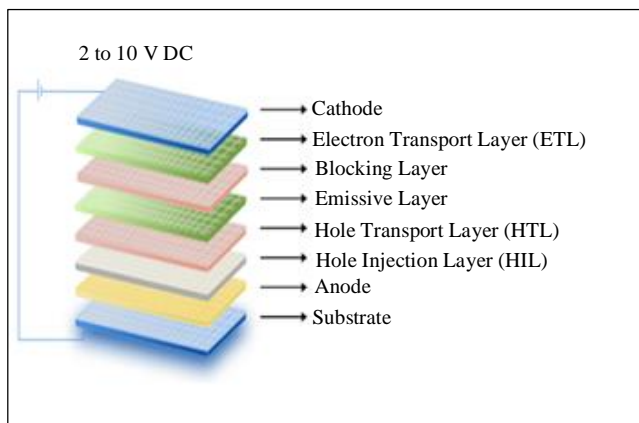

Fig. 5 Structural layers of OLED

3.3. Materials of LED

The existence of multiple functional layers in OLEDs needs multiple varieties of materials for its complete fabrication. Among the structural layers, the recombination and light emission take place in the emissive layer, which makes it the most important layer of all. Tiny organic compounds, conjugated oligomers and polymers generally make up the bright and low-power driving organic material-based electroluminescent systems [25].

Emissive efficiencies are defined by light extraction efficiency, power efficiency [26], recombination efficiency and luminous efficiency. According to whether they employ small molecules or polymers, emissive materials are divided into two more categories. Usually, high aqueous solubility and crystalline structure are found in small molecule materials. Though they offer an advantage in terms of manufacturing due to simple synthesis and purification processes, polymers, especially conducting polymers, offer more compact, lighter and less expensive OLEDs [27]. After plenty of research and experimentation, these small molecule compounds were widely used in OLED applications:

- AlQ3- Emitter and electron transport material.
- N,N'-Diphenyl-N,N'-bis(3-methylphenyl)-1,1-biphenyl-4,4'-Diamine) (TPD) and N,N'-di(naphthalene-1-yl)-N,N'-Diphenyl-Benzidine (NPB)- Hole transport materials
- Indium Tin Oxide (ITO)- Hole injecting anode
- Mg: Ag alloy (9:1 by volume)- Electron injecting cathode

It is worth noting that polymer OLEDs provide a high contrast ratio, large viewing angle, slim device physique, film forming capacity, low power consumption and high-speed image switching, which collectively results in this being more efficient than the small molecule-based device. Numerous emitting polymers have been discovered and synthesized to be used as active photo layers in organic optoelectronics.

In recent research, polymers, specifically conducting polymers, are becoming more preferred due to the wide range of advantages they cater such as solubility, film forming capacity, easier processability, lower manufacturing costs and much more. Tuning of polymers can be done by adding various electron donating/withdrawing groups that can influence the electron or hole injection/transportation capacities. This tuning can be used to bring out emissions in the required brightness range [28].

Polymers such as polyaniline, polypyrrole, polyacetylene, polythiophene, and polyphenylene vinylene are extensively used these days. Intensive researches are rolled out with the aim of synthesizing more polymers for advanced electronic applications.

The easier manufacturing process for OLEDs is a major factor in the uphill battle for their market share. The repeated mentioning of easier and less expensive manufacturing processes is because of its capability to be fabricated into complex designs and shapes through simple solution processes like spin-coating process, slot-dye coating, inkjet printing and screen printing.

A widely used polymer worth mentioning is PEDOT: PSS, shown in Figure 6, primarily employed as a Hole Transport Layer (HTL). They are typically fabricated using the mentioned spin coating process in which the PEDOT: PSS solution is spin-coated at 4500 rpm for 30 seconds. It is done on pre-patterned substrates to form layers of approximately 50 nm. Later, spin coating of emitting polymer solutions will be done on the top of PEDOT: PSS layers after undergoing a thermal annealing process at 120° for 5 minutes. The process is wrapped up with the thermal evaporation of the cathode layer, whose structure is depicted in Figure 6 [29].

Research is underway to enhance the performance of OLEDs. Several methods, such as doping organic metallic phosphorous [20] using fluorescent dyes to increase system effectiveness and colour purity [30] are currently under

development. OLEDs have massive potential with a lot of blank spots and challenges to work with, to increase efficiency, to expand wider application in flexible and foldable circuit design, lifetime and stability, device architecture and material choice, new technologies such as Perovskite-OLED hybrids [31], and so on.
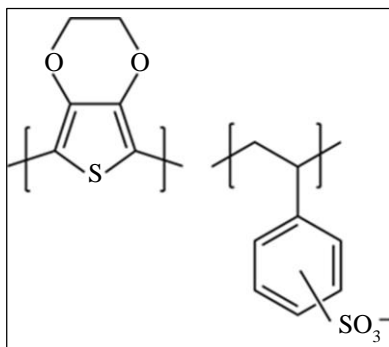

Fig. 6 Structure of PEDOT: PSS

3.4. Challenges and Research Gaps in OLED

The major challenges faced by the industry are in large-scale manufacturing and material lifetime and efficiency. OLEDs can be generally categorized as small-molecule or polymer-based types based on the materials that are utilized in them. Initially developed OLEDs were small-molecule ones, which come in fluorescent and phosphorescent varieties.

Small fluorescent molecules are frequently utilized and have a good lifetime and reliable manufacturability. Newer small-molecule OLEDs that are phosphorescent have a higher luminous efficiency than fluorescent ones. The sophisticated production process of small-molecule OLEDs is the main disadvantage of using them. To boost efficiency, they also need other elements like phosphorous as well.

The focus of recent research has been on OLEDs based on polymers, which are more affordable, effective, and appropriate for big displays. Since they are solution-based, manufacturing can be made simpler by using solution deposition methods like inkjet printing. Small-molecule OLEDs make up 99 percent of all OLEDs on the market right now. However, the success of polymer-based OLEDs is anticipated to open up new market potential, particularly if their efficiency and lifespan can be improved. Researchers are encouraged to conduct more comprehensive studies on existing material properties and to extend them by researching potential upgradations to smoothen the production issue.

4. Organic Photovoltaics (OPVs)

As the introduction stated, the world's energy consumption is growing at an average annual growth rate of 1.8%, and by 2030, the total world energy demand is expected to reach approximately 18.5 TW. Since almost all energy produced today originates from burning fossil fuels, and because of the threat posed by climate change and global warming, our civilization is using non-renewable energy sources to supply the expanding energy demand worldwide. Observing the growth in recent years in high-level international conferences aimed at combating climate change, such as COP28 (Dubai), which discussed measures to address climate change globally, making sure every nation is pushing towards fulfilling the demands of the Paris Agreement (2015). Among the various carbon-free options, using solar energy is a very alluring one. An average of 342 watts of solar energy fall on every square meter of Earth, according to NASA, over a year. This energy is immense; it is precisely 44 quadrillion (4.4×10^{16}) watts.

To put things into perspective, one billion (1×10^9) watts of power is produced by a sizable electric power plant. To match the energy emitted by the Sun, it would require 44 million of these power plants. It will be more than sufficient to meet the growing global energy demand by harnessing a small portion of the Sun's natural energy. The cost of a watt of solar cells is currently about US$1.3. The current cost of solar cells needs to be lowered by at least a factor of ten in order to meaningfully compete with the cost of producing electricity using fossil fuels. Once this is accomplished, solar cells will become generally accessible.

OPV devices have many known benefits, including an easy-to-fabricate structure, low weight, adaptability, and the capacity to produce vast quantities of solutions. These, along with the almost infinite variety of chemicals and designs, demonstrate extremely strong optical absorption. Added to it are the electrical and adjustable adaptive absorption capabilities, which would make them an appealing alternative to existing sources of energy.

4.1. Classification of Solar Cells

The broad classification of solar cells [32] is shown in Figure 7.

First-generation solar cells: These solar cells use either mono or poly-crystalline silicon. Continuous distribution of silicon crystal is found in mono-crystalline silicon, whereas random distribution of lattice structure is found in the latter. Sometimes, amorphous silicon is also used to boost the performance of solar cells.

Second-generation solar cells: Commercial thin film solar cell technologies such as CdTe, CIGS, etc., fall under this category. They use thin-film semiconductor substrates by doping one or more thin layers of silicon or gallium arsenide.

Third-generation solar cells: Present-day nascent stage solar cells, such as perovskite solar cells, dye-sensitized solar cells, and quantum dot-based solar cells, come under this category. This is one of the key areas to focus on in the research aspect due to the presence of a research gap and the lack of commercially viable structures and models.
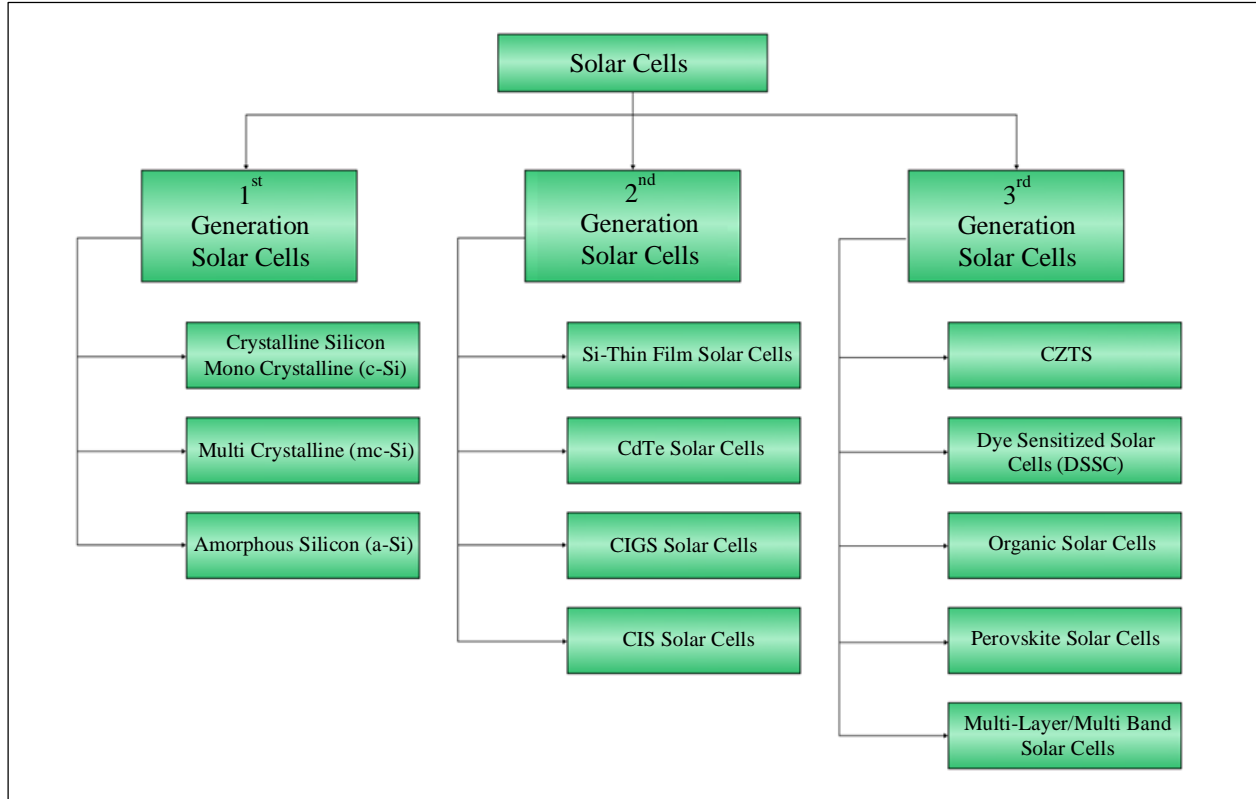
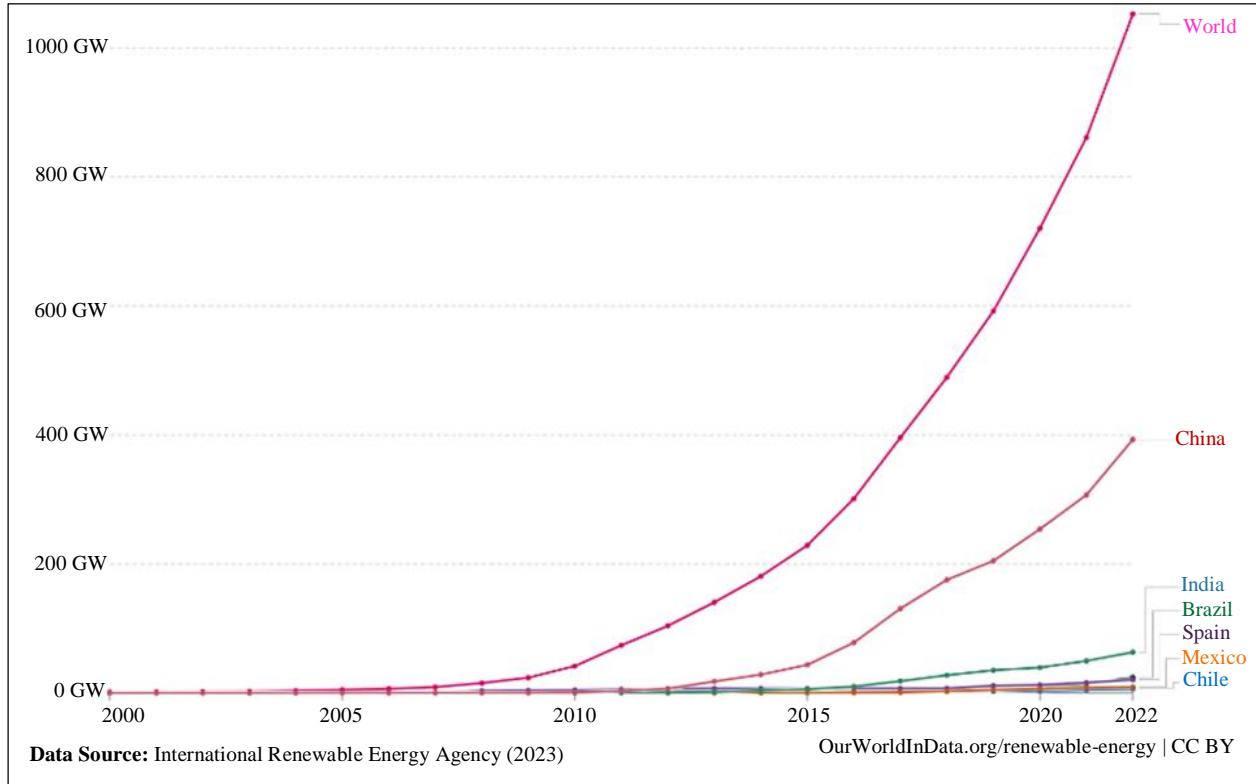**Fig. 7 Classification of solar cells**

Fig. 8 Cumulative installed PV (GWh) vs Timeline, data provided by the International Renewable Energy Agency [34]

4.2. Brief History of Organic Solar Cells

The conversion of solar energy from the sun to electrical energy by means of solar cells is regarded as one of the greenest alternatives for energy production. Due to the use of silicon, cadmium, and cadmium sulfide in commercially available inorganic solar cells, the production process is linked to the release of dangerous chemicals into the environment. Organic photovoltaics are a great option even in this regard. The current day market is hugely dominated by more than 80% silicon-based solar cells after so many modifications since the 1950's when the first silicon solar cell was developed by Bell Labs [30].

Passivated Emitter Rear Localized (PERL) structured solar cells were created in the 1990s by Australia's University of New South Wales [31]. Though it holds the highest record of efficiency (24%), it involves too many complicated manufacturing processes, making it inefficient for mass production. Solar cells available in current markets generally have efficiencies of around 17-20%. These solar cells had a very healthy and steady market growth through the initial years before it took a huge dip in the infamous 2009 crisis when the price of poly silicon dropped by 4 folds. It is worth noting that it is a crucial material needed to make poly-crystalline silicon solar cells.

However, then, continuous technological changes and adaptation of efficient technologies helped the industry get back on foot. At present, especially due to the increasing worldwide reaction to climate change, the solar industry has big potential for brand-new advancements to tackle global warming issues. Figure 8 is a demographic distribution data from the International Renewable Energy Agency (2023) indicating the total installed solar energy capacity in the world [33].

Commenting on the improvement of efficient technology, it is dependent on a few solar cell characteristics such as fill factor, quantum efficiencies, and power conversion efficiencies. In order to remove areas of shade, Panasonic moved the front contacts to the back of the screen in 2014, resulting in an efficiency of 25.6%. These days, it is common to focus on multi-junction solar cells; triple-junction solar cells set a record efficiency of 35.9% [34]. Over time multiple technologies were developed like thin film technology, multi-junction technology, heterojunction technology, solar cell models involving various contact technologies and much more [35].

Currently, intensive research is underway for next-generation solar cell technologies like Perovskitesolar cells, Bifacial solar cells, Intermediate band photovoltaics, Dye-sensitized solar cells, Quantum Dot solar cells, Organic/polymer solar cells and a few more. Efficiency records of various classifications of solar cells are mentioned in table 3 [36].

Table 3. Maximum efficiencies of different types of solar cells according to NREL [36]

PV Technology		Conversion Efficiency (%)	
		Cell	Module
Crystalline	Mono-Crystalline Si	27.6	24.4
	Multicrystalline Si	23.3	20.4
	Multi-Junction GaAs	47.6	38.9
Thin Film	CdTe	22.3	19.5
	CIGS	23.6	19.2
Emerging	Perovskite /Si Tandem	33.7	-
	Perovskite	26.0	17.9
	Organic	19.2	13.1

4.3. Working Principle of Organic Photovoltaics

Two photoactive organic materials, or so-called "donor-acceptor" systems, are typically found in OPV devices sandwiched between two conducting electrodes. When exposed to light, excitons are created in the photoactive layers, and at the donor-acceptor hetero-interfaces, some of them split into electrons and holes. Alternatively, some excitons would diffuse to the electrode, where they would be quenched and release energy as heat in the form of a phonon, leading to a non-radiative decay. The collection of these charge carriers then aids the photocurrent at the appropriate electrodes [37]. It is interesting to note that the process of photocurrent generation by an OPV device and the fundamental operating principle of an OLED are similar. Exciton creation by light absorption, diffusion of exciton, dissociation of exciton, and carrier collection are the four steps that make up the photocurrent generation process in OPVs [38]. Step by step process is shown in Figure 9.

To dig deeper, Highest Occupied Molecular Orbital (HOMO)-Lowest Unoccupied Molecular Orbital (LUMO) energetics in material design acts as the foundation in the working of this technology. To briefly describe its dependency, in order to increase the Open-Circuit Voltage (V_{OC}), the energy of the HOMO of the electron donor polymer should be lowered.

However, the lowering of HOMO without lowering of LUMO will increase the band gap of the polymer, which will have a negative effect on the Short Circuit Current (I_{SC}) of Organic Photovoltaics (OPVs) [39]. For improving power conversion efficiencies, effective material design is essential, and so far, creating a donor-acceptor copolymer by combining an electron-rich donor segment and an electron-deficient acceptor segment has worked out fairly well. In addition, it is required to consider the material's degree of solar light absorption, mix of morphology and microstructure, and transport characteristics [40].
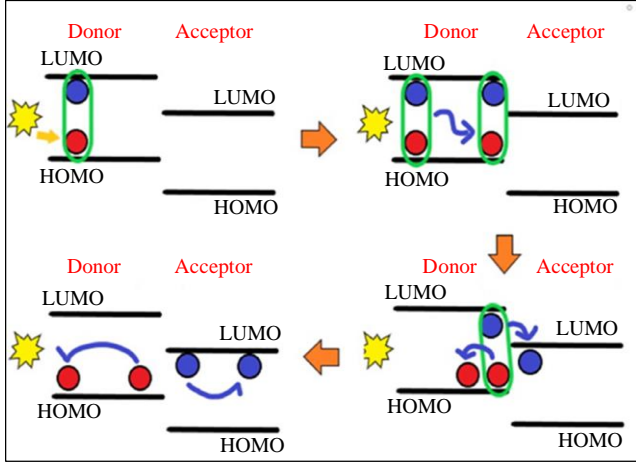
Fig. 9 Steps involved in photocurrent generation in OPVs: light absorption -> exciton diffusion -> exciton dissociation -> carrier collection

Fig. 10 IV characteristics of solar cells depicting 'Short-circuit current density J$_{sc}$' & 'open circuit voltage V$_{oc}$'

Two criteria, namely internal/external quantum efficiency and Power Conversion Efficiency (PCE), are primarily used to assess the performance of PV cells. PCE is determined by plotting the current density output across a varied voltage bias while being stimulated by solar light. This process is known as the current density and voltage (J-V) plot shown in Figure 10. The parameter that determines the maximum power output from a solar cell is called 'fill factor (η)', which is calculated with short circuit current density (Jsc) and open circuit voltage (Voc), which are current density at zero bias and voltage measured at zero current respectively [41].

$$\eta = J_{sc} \ V_{oc} \ FF/ \ P_{in} \qquad (4)$$

The fill factor has been reported to depend on numerous internal factors of the cell. These include the bulk material properties, layer interfaces, electrode interfaces, exciton dissociation rate, which is field dependent, unbalanced charge carrier intensities and light intensity. Research by Yan et al. [41] demonstrates how the fill factor can be increased up to 76%. This is done by optimizing the active layer thickness, whose role can be correlated to the lifetime and diffusion lengths of excitons. The fill factor parameter is given utmost importance due to the amount of key information that can be extracted from it.

The following are also important parameters to consider: The difference between internal and external quantum efficiency is that the former refers to the amount of charge carriers gathered at the electrodes relative to the number of photons of a given energy radiator on the solar cell from the outside. At the same time, the latter measures the total amount of charge carriers gathered at the electrodes to the number of photons of a given energy that are absorbed by the cell. In the visible spectrum, the IQE is always greater than the EQE. Low IQE values indicate poor carrier collection of the solar cell.
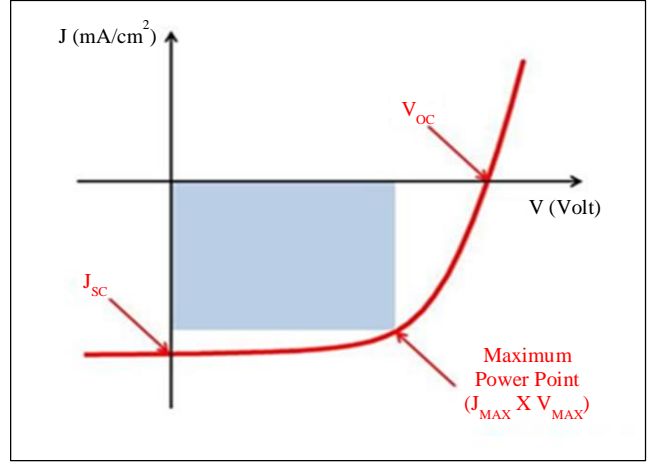
Avoiding electron-hole recombination afterits generation is very important because charge recombination causes a drop in EQE. The square shape of the ideal Quantum Efficiency (QE) graph depicts the constant nature of QE along the entire measured spectrum of wavelengths. Due to the effects of recombination, QE is decreased in the majority of solar cells, which prevents the charge carriers from moving into an external circuit [42].

$$\eta_{IQE} = \eta_{abs} \eta_d \ \eta_{cc} \qquad (5)$$

Where η_{IQE} is the internal quantum efficiency, η_{diff} is the exciton diffusion efficiency, η_{ed} represents the dissociation efficiency, η_{abs} indicates the photon absorption efficiency, and η_{CC} represents the charge collection efficiency. The expression for external quantum efficiency is given by Equation (6). Here, R denotes the reflectivity of the interface between substrate and air.

$$\eta_{EQE} = (1-R) \ \eta_{abs} \ \eta_{diff} \ \eta_{ed} \ \eta_{cc} \qquad (6)$$

It is also found that organics havemore than 10 times the absorption coefficient and also the ability of comparatively thinner active region layers of organic semiconductors, providing equivalent photon capturing abilities to that of the inorganics, enabling wider instalment application and compatibility. Nevertheless, this leads to another challenge of short diffusion length (5-20 nm) before recombination or separation, low lifetime in the order of nanoseconds, and low carrier mobility, impacting its working efficiency. The optimal thickness of Polymer Solar Cells (PSCs) is about 100 nm. Only at the donor-acceptor interface, where there are significant variances in electronegativity between the two, are the charges in an exciton forced to separate. The offset of LUMO energies between the donor and acceptor provides a force larger than the exciton BE, which is required for dissociation.

4.4. Device Architecture of Organic Photovoltaics

As previously mentioned, Tang [20] introduced the concept of bilayer heterojunction, in which two organic layers with particular electron or hole transporting properties were sandwiched between an Ag cathode and Indium Tin Oxide (ITO)-coated glass as the anode. This innovation was the catalyst for the exponential growth of the OPV field. Figure 11 depicts the general organic photo-voltaic cell's construction. Under simulated AM2 illumination with 75 mW cm^{-2} of light intensity, an extraordinarily high PCE of 0.95% was recorded, which is an order of magnitude greater than that for single-layer OPV devices. This was accomplished by employing a perylene tetracarboxylic derivative as the acceptor and Copper Phthalocyanine (CuPc) as the donor [43].
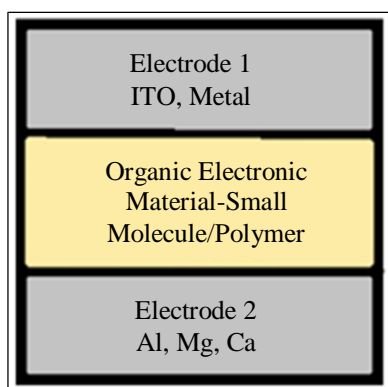

Fig. 11 Structure of Organic Photo-Voltaic cell

Recent studies have also been focusing on the promising effect of polymer-donor-molecular-acceptor Bulk Heterojunction (BHJ) based photo-voltaic cell technology. Power conversion efficiencies have been drastically increased in the recent past due to rigorous research undertaken by organic molecule scientists. They offer a wide range of advantages when compared with inorganic counterparts, such as very thin device structure, easier fabrication process, cost-effective and, most importantly flexible nature that makes wider practical application of solar cells possible.

By blending polymers or using co-evaporation techniques, donor and acceptor materials are intimately mixed to create bulk heterojunction. Scientists studying organic molecules have recently conducted rigorous research that has resulted in a dramatic rise in power conversion efficiencies. Throughout the bulk heterojunction, the mixed layer forms a spatially distributed donor-acceptor interface that enables the effective dissociation of all excitons produced into free-charge carriers.

They offer a wide range of advantages when compared with inorganic counterparts, such as very thin device structure, easier fabrication process, cost-effective and, most importantly flexible nature that makes wider practical application of solar cells possible. The bulk heterojunction produces higher short circuits and dark currents, hence thickening the photoactive layer and reducing the likelihood of charge carrier recombination. So far, the polymeric blend of electron donor with fullerene derivatives used as an electron acceptor in a single BHJ Organic Photo-Voltaic (OPV) has provided excellent power conversion efficiencies of up to 18%. One BHJ Organic Photo-Voltaic (OPV) has so far demonstrated excellent power conversion efficiencies of up to 18% using a polymeric blend of electron donor and fullerene derivatives as electron acceptors. In a typical BHJ OPV cell, the photoactive organic layer comprising of an n-type material, typically conjugated polymers or oligomers and a p-type fullerene (derivatives) or non-fullerene-based materials, is sandwiched between a high work function transparent Indium Tin Oxide (ITO) anode on the bottom and a low work function top metal cathode such as Aluminium or Calcium. To improve the functionality of the device, interfacial layers may be added to either the top or bottom of the sandwiched copolymer layer.

Here, the acceptor molecule is in charge of electron mobility, while the polymer donor acts as the primary solar light absorber and as the phase that transports holes. After a long time of research and experimentation, fullerenes were identified to be an excellent electron acceptor pair for polymeric conjugated donors because the presence of a thin fullerene layer on an organic cell's power-producing layer was found to form something called an 'energy well', which is a low energy area preventing the recombination of electrons with positively charged holes that are left behind in that layer. Prevention of charge carrier recombination/separation of hole and electron concentration is the most fundamental principle behind the working of solar cells, and this is satisfied by fullerene, which acts like a massive antenna that can collect an electron charge from anywhere in the device [44].

4.5. Materials for Organic Photovoltaics

Donor and acceptor materials that are generally used in OPVs are CuPc, buckminsterfullerene, PTCBI [45], pentacene [46], PCBM, PC70BM and P3HT [47]. The primary cause of the performance gain is the notable rise in exciton dissociation efficiency, which is made possible by the donor-acceptor interface's discontinuous HOMO and LUMO levels, which effectively dissociate bound electron-hole pairs into free charge carriers. Charge collection efficiency is also increased by the use of separated charge-transporting materials in bilayer device architecture.

Effective exciton dissociation in bilayer organic photo-voltaic devices happens at the donor-acceptor heterojunction, provided that the exciton Binding Energy (EB) of the photoactive material is less than the HOMO or LUMO energy level offset [48]. To further note, the role of HOMO LUMO energy levels is observed in donor polymers like poly-3-hexyl thiophene-2, 5-diyl (P3HT), one of the most used substances in BHJ OPVs, fullerenes have received the most attention in recent years.

In light of their favourable LUMO energy level, electron transport properties, anisotropic charge transport, and especially their solubility in common solvents used for donor polymers, homologues like PC60BM and PC70BM fullerenes are frequently taken into consideration. This enables the concurrent casting of polymer and fullerene for the formation of an effective bulk heterojunction. Charge transfer from the LUMO of the donor to the LUMO of the acceptor must be on the order of the exciton binding energy once the exciton reaches the interface, which is dependent on the length of the exciton diffusion.

Another prerequisite for effective electron transfer is that the acceptor LUMO level should be lower than the donor LUMO level. This acceptor LUMO tuning process can be exceedingly delicate. Due to the heterogeneous junction between the donor and acceptor phases, the BHJ OSC efficiently promotes exciton dissociation in bulk [48]. As previously mentioned, the mixture of poly (3-hexylthiophene-2, 5-diyl) (P3HT) and [6, 6]-phenyl-C61-butyric- acid-methyl ester (PC61BM) is the most promising homogeneous blend. The optical combination of P3HT and PCBM is superior and is grasping much attention these days. Previous research experiences with different combinations, such as PPV: PCBM help us significantly improve the current day research based on P3HT: PCBM.
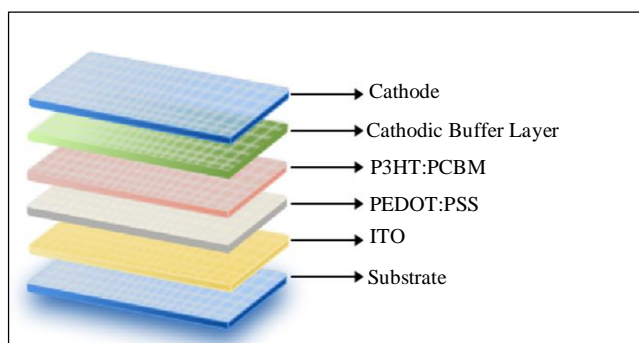

Fig. 12 Components of Organic Photo-Voltaic cell

The morphology of the P3HT: PCBM film in Figure 12 is seen to be improved by the thermal annealing procedure, which entails heating the material over its recrystallization temperature and then cooling after the proper period. The annealing temperature for P3HT is between the glass transition temperature (12°C) and the polymer's melting point (178°C). The deep experimental knowledge has led to a drastic improvement in the material selection process throughout the entire domain.

To get beyond the restrictions imposed by BHJ OPVs, tandem Photo-Voltaic Solar Cells (PSCs), which stack two or more single junction cells that absorb in various wavelength bands, are also being investigated. Power Conversion Efficiency (PCE) has climbed over 10% as of now. Even though that is pretty much a very low number when compared

with the PCE of inorganics, unique advantages and properties are expected to open up niche marketing opportunities.

4.6. Challenges and Research Gaps in OPVs
Despite having many promising properties, commercializing organic solar cells to displace the well-established conventional solar cells still presents numerous challenges. The poor carrier mobilities and short exciton diffusion lengths of OPV cells contribute to their low efficiencies. In the end, these two traits lead to the usage of thin active layers, which have an impact on the device's overall performance.

Additionally, compared to inorganic devices, the operational lifetime of OPV modules is still much shorter. One such challenge is that donor material (P3HT) with low surface energy forms vertical phase separation and travels toward the surface (i.e., cathode) as a result. Owing to the inadequate distribution of donor and acceptor materials inside the device, device stability is diminished. Active solutions to numerous challenges are being addressed. This specific problem can be resolved by using inverted organic semiconductors, where the bottom cathode layer is made up of a transparent conductive oxide and the top anode layer is made of a high work-function metal. Since the top electrode is the anode and not the cathode, vertical separation now favours the device's performance.

Another challenge is the effect of moisture and oxygen in the surroundings degrading their lifetime, which can be avoided again with the use of inverted organic semiconductors since the high work function metal layer on the top enhances the stability against moisture and oxygen. A further significant obstacle to achieving high PCE is the mismatch between photoactive organic material absorption and the terrestrial solar spectrum. Various research conducted around the globe calls for the need for new material choices to enhance the maximum PCE.

One of the thorough device models for small molecule-based OPV devices has been presented by Rand et al. [49]. It allows for the estimation of a maximum PCE of up to 12% for an optimized double heterostructure OPV device, where the donor and acceptor materials should have optical bandgaps of 1.5 and 1.8 eV. A systematic study on the dependence of open circuit voltage on the bandgap and HOMO levels are carried out by open Scharber et al. [51]. They found that, under the assumption that the fill-factor and the average EQE stay equal to 0.65, a PCE of 10% can be obtained for the PCBM-based polymeric OPV device with a bandgap less than 1.74 eV and a LUMO level less than -3.92 eV. Other recent research and findings include the work of Rehman et al. [52], where the usage of hollow TiO_2 spherical nanoparticles to ETL carbon nanoparticles to HTL enhanced the performance of perovskite solar cells, Ahmed et al. [53] presented performance analysis of a multi-junction solar cell with a mini-channel heat sink to reduce the cell temperature and a comprehensive review by

Baiju et al. [54] on the efficiency progress in multi-junction solar cells. Incorporating the usage of Bismuth in solar cells has also been comprehensively studied in recent times. It includes the development of low bandgap GaAsNBi solar cells, with pin heterostructure GaAasNbi i-layer by Puustinen et al. [55] and a work by Pham et al. [56] finding a Bismuth-based alternative to Pb-based perovskite cells that can be manufactured at approximately half the thickness of Pb-counterpart's active layer thickness. Researchers are encouraged to develop more comprehensive studies on Bismuth-based photo-voltaic cells, given that it is showing high potential in enhancing the performance of perovskite solar cells, in particular. Challenges are addressed every day, and the PCE of OPVs has steadily improved up to 18.2% (certified by NREL) with enhanced performance lifetime demonstrated potential for roll-to-roll manufacturing using solution processing. Even though numerous technological advancements have taken place, and serious research and development works are going on, this is still an emerging field. These are the areas of focus that need further attention:

- Enhancing power conversion efficiency.
- Material stability.
- Increasing absorption range.
- Developing scalability and manufacturing techniques.
- Efficient interface and charge transport.

Here are a few R&D areas that address key challenges:

- Finding new absorber materials.
- Novel materials for contact and barriers.
- Developing new electron and hole contact layers.
- Degradation mechanisms of devices and materials.
- Generating new driving forces and mechanisms underlying the charge transfer between donor and acceptor materials.
- Works on Tandem structures and Dye-sensitized solar cells.

4.6.1. Recent Tandem Structures

Tandem device architectures, a relatively new leading technology, are being developed for both OLEDs and OPVs and have been widely used to improve device performance. Kido et al. [57] created the first tandem structure, which is essentially made up of two or more separate electrically coupled subcells. During operation, charge carriers are created in the connecting unit and subsequently introduced into the nearby Electroluminescence (EL) elements. Theoretically, one can boost luminous efficiency and operation lifetime correspondingly by increasing the number of EL units. It is also possible to make white light with this method by combining two or more complementary colours. An ultrathin (~5 Å) discontinuous metallic film serves as an interlayer to connect two separate OPV cells in sequence in a tandem OPV structure, as demonstrated by Xue et al. [58]. Since then, there have been several changes.

Kim et al. [59] stacked two subcells together using a thin TiOx interlayer to achieve an astonishing PCE of 6.5%. However, due to the thickness-dependent optical characteristics of the thin interlayer and optical interference effects, each subcell's corresponding photoactive layer thickness needs to be carefully adjusted in order to execute the tandem structure.

5. Conclusion

In summary, this review paper discussed the fundamentals of organic semiconductors, underlying theories and 2 major applications- OLEDs and OPVs with the notion of recapping the progress made in this field so far, which will help new researchers in this field to gain a beginner's grasp to extend their researches to contribute to the scientific community striving hard for the betterment of humankind.

Further researches in this field hold massive potential since these ideas are revolutionary, given that our world is shifting towards more efficient and greener technologies. Pain points of research and key topics to research are discussed. Meeting global energy demands efficiently is of utmost importance due to the recent uprising of climate change and global warming issues reaching alarming states. Innovative uses of organic materials could pave the way for various much-needed new applications that can bring about a huge change that will have a significant impact on the lifestyle of future generations.

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