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### **Organic Solar Cell: It's future prospect**

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#### **Abstract**

Organic solar cells (OSCs) are emerging as a promising frontier in renewable energy technology, distinguished by their lightweight, flexible composition, cost-effective manufacturing processes, and potential for large-scale deployment. Unlike their silicon-based counterparts, which rely on inorganic materials, OSCs harness organic molecules or polymers to convert sunlight into electricity. Their adaptability in design and production is a key strength, facilitated by the ease with which organic materials can be synthesized and processed into thin films through methods like solution casting or printing. This versatility paves the way for a diverse array of applications, from integrating solar panels into wearable electronics to incorporating them seamlessly into building structures and powering portable devices. Moreover, the customizable properties of organic materials enable researchers to fine-tune the optical and electronic characteristics of OSCs to suit specific needs. Through adjustments in molecular structure or composition, they can optimize factors like light absorption, charge transport, and device stability, ultimately enhancing overall efficiency and performance. A major obstacle is their relatively lower efficiency compared to silicon-based solar cells. While strides have been made in enhancing the power conversion efficiency of OSCs, further advancements are essential to rival conventional solar technologies. Additionally, the stability and durability of OSCs pose concerns, particularly in adverse environmental conditions such as exposure to moisture, heat, and light. Organic materials are inherently more prone to degradation than their inorganic counterparts, leading to performance deterioration over time. Developing robust encapsulation techniques and stable

organic materials is imperative to extend the operational lifespan of OSCs and ensure their long-term reliability. The organic solar cells remains promising, propelled by ongoing research endeavors aimed at enhancing efficiency, stability, and scalability. Anticipated advancements in material design, device architecture, and manufacturing processes are expected to enhance efficiency and reduce costs. Moreover, the increasing demand for sustainable energy solutions and the global adoption of renewable energy policies create a conducive environment for the commercialization of OSCs. As the world shifts towards sustainable energy, organic solar cells are set to play a crucial role in meeting the growing energy needs. With sustained innovation and investment, OSCs hold the potential to emerge as a competitive alternative to traditional solar technologies, contributing significantly to a cleaner, greener energy future.

**Keywords:** Organic solar cells, Tunable properties, Photovoltaics, Efficiency, Charge transport, Sustainable energy,

## 1. Introduction

### 1.1 History:

The field of photovoltaics has seen remarkable progress from the early 19<sup>th</sup> century to the present day, enriched by both theoretical insights and practical advancements. Alexandre Edmond Becquerel, a French physicist, made a pivotal discovery in 1839 with the identification of the photovoltaic effect [1]. This foundational research was followed by significant contributions from Willoughby Smith in 1873, who investigated the conductivity of selenium, and Charles Fritz in 1883, credited with creating the world's first selenium-based module. Subsequently, in 1887, German physicist Heinrich Rudolf Hertz discovered the "external photoelectric effect," further expanding the understanding of light-electricity interactions. Alexander G. Stoletov's work from 1888 to 1891 further advanced research in this domain. The theoretical underpinning of the photoelectric effect was provided by Albert Einstein in 1907, paving the way for deeper exploration into semiconductor materials [2].

The demand for semiconductor cells drove intensified research efforts in engineering and photovoltaics. In 1916, Polish scientist Jan Czochralski made a significant breakthrough by discovering the process of crystal formation through the growth of single crystals from a melt. This discovery laid the groundwork for subsequent developments in crystallography and semiconductor technology. Further experiments in the 1930s and 1940s, involving thin films of copper oxide and silicon-based samples, led to the discovery of the p-n junction in semiconductors [3]. William Bradford Shockley's theoretical model of the p-n junction provided a crucial framework for the advancement of modern solar cell technology. These efforts reached a significant milestone in 1953 when Daryl Chapin, Calvin Fuller, and Gerald Pearson introduced crystalline silicon solar cells, marking a pivotal moment in the history of photovoltaics.

The origins of solar cell technology date back to the 19<sup>th</sup> century, beginning with French physicist Alexandre-Edmond Becquerel's discovery of the photovoltaic effect in 1839. He observed that certain materials generate electric current when exposed to light. However, early experiments did not lead to practical applications due to low efficiency and limited understanding of semiconductor physics. In 1883, American inventor Charles Fritts developed the first practical solar cell by applying a thin layer of gold onto selenium to create a junction. This device achieved a mere 1-2% efficiency. Despite its low efficiency, Fritts' invention laid the groundwork for future developments in solar cell technology [5].

The modern era of solar cells commenced in the 1950s when Bell Laboratories developed silicon photovoltaic (PV) cells. In 1954, scientists Daryl Chapin, Calvin Fuller, and Gerald Pearson showcased the first silicon solar cell that could convert sufficient sunlight into electricity to power everyday electrical devices. This breakthrough marked a significant advancement in solar technology and paved the way for commercial production. Solar cells gained prominence in space exploration during the 1960s as NASA employed PV technology to power satellites and spacecraft. Notably, the Vanguard 1 satellite, launched in 1958, was the first spacecraft to generate power using solar cells. Subsequent missions, including the Apollo lunar missions, further demonstrated the reliability and effectiveness of solar cells in space. During the 1970s and 1980s, advancements in solar cell technology resulted in higher efficiency and lower production costs. Government incentives and growing environmental awareness spurred the adoption of solar energy for terrestrial applications, such as remote power systems and telecommunications. The development of amorphous silicon and thin-film solar cells offered alternative materials and manufacturing processes, expanding the market for solar energy.

In the 1990s and beyond, the solar photovoltaics experienced a rapid growth and integration into the electricity grid. Advances in cell efficiency, module design, and manufacturing techniques contributed to the widespread adoption of solar energy for residential, commercial, and utility-scale applications. Government incentives, feed-in tariffs, and declining costs further accelerated the deployment of solar power systems worldwide. The 21st century witnessed significant technological advancements in solar cell efficiency, materials, and system integration. Innovations such as PERC (Passivated Emitter Rear Cell) and bifacial solar cells have pushed the efficiency boundaries, while research into next-generation materials like perovskite and organic solar cells holds promise for further improvements. Moreover, energy storage solutions and smart grid technologies are improving the reliability and flexibility of solar energy systems.

## **1.2 Literature Review**

The work investigates the optimization of organic solar cells (OSCs) through the development of a fast-growth film casting method to achieve a homogeneous donor-acceptor morphology in the bulk-heterojunction (BHJ) active layer. This approach seeks to tackle challenges like uneven material distribution and segregation at the interface. These issues can impede the flow of charges and the dynamics of recombination, ultimately constraining the performance of the device. The study demonstrates that the conventional spin-coating method often leads to an unbalanced donor-acceptor ratio, resulting in reduced device efficiency. In contrast, the fast-growth method facilitates rapid film formation, preventing the accumulation of acceptor material at the interface and promoting a more uniform morphology throughout the BHJ layer. Characterization techniques, including TEM microscopy and AFM measurements, confirm the effectiveness of the fast-growth method in achieving a homogeneous morphology with improved surface smoothness. Device performance evaluations, including current-voltage characteristics and internal quantum efficiency measurements, demonstrate that OSCs fabricated using the fast-growth method exhibit higher fill factors and increased short-circuit currents, leading to enhanced power conversion efficiencies. The study concludes that introducing a homogeneous morphology through the fast-growth method can overcome limitations associated with non-uniform donor-acceptor distributions, thereby improving the overall performance of OSCs.

The study delves into creating and analyzing zinc oxide nanoparticles (ZnO NPs) utilizing eco-friendly solvents sourced from renewable or recycled materials. Traditional methods for ZnO NP synthesis often involve the use of solvents like methanol (MeOH), which has limitations in terms of environmental impact and sustainability. Therefore, this study investigates the use of recycled methanol (r-MeOH) and bioethanol (b-EtOH) as potential alternative solvents. The synthesis process involves the dropwise addition of a potassium hydroxide (KOH) solution to a solution of zinc acetate dihydrate in the respective solvent. After purification, the resulting ZnO NPs are dispersed in alcohol-based solvents to form inks suitable for thin-film deposition. The optical, morphological, and electronic attributes of the resulting ZnO nanoparticles and thin films are thoroughly examined and contrasted with those achieved through conventional methanol usage. The optical transparency of the ZnO thin films prepared using the alternative solvents is confirmed, with minor variations observed in the transmission spectra compared to films prepared using methanol. Morphological analysis reveals homogeneous distribution of ZnO NPs on the thin films, with variations in NP size attributed to the choice of solvent. Kelvin Probe Force Microscopy (KPFM) measurements show comparable surface potential values for all ZnO NP thin films. Additionally, the electrical efficacy of the ZnO NP thin films is assessed by constructing inverted bulk heterojunction (BHJ) solar cells. Despite minor variations, the photovoltaic responses of the devices using ZnO NPs synthesized with alternative solvents are comparable to those using traditional methanol. This suggests that the alternative synthesis methods yield ZnO NPs with properties suitable for photovoltaic applications. Overall, the study demonstrates the feasibility of using recycled methanol and bioethanol as alternative solvents for the synthesis of ZnO NPs, offering potential benefits in terms of environmental sustainability without compromising material performance.

The work provides a comprehensive overview of solution-processed photovoltaic systems, focusing on the utilization of zinc oxide (ZnO) as an electron transport layer (ETL) in organic solar cells (OSCs). It discusses the challenges associated with conventional OSC configurations and highlights the advantages of using solution-based systems. The integration of ZnO, particularly in bilayer structures, is explored as a means to enhance device performance and stability. The experimental details include the materials used and the fabrication process for the OSC devices, emphasizing the deposition of ZnO and ZnO nanoparticles (NPs) to form the ETL. It describes the characterization techniques employed to assess the structural, optical, morphological, and elemental properties of the fabricated films. Techniques such as X-ray diffraction (XRD), UV-Vis-NIR spectrometry, atomic force microscopy (AFM), scanning electron microscopy (SEM), and X-ray photoelectron spectroscopy (XPS) are utilized to analyze the films' properties thoroughly. The results and discussion presented the findings from the structural, optical, morphological, and elemental analyses, demonstrating the improved crystallinity and morphology of the bilayer ZnO NP/ZnO films compared to single-layer ZnO. The photovoltaic performance of OSC devices with different active layers (PTB7-Th:IEICO-4F and PM6:Y6) and ETL configurations is thoroughly evaluated. The bilayer ZnO NP/ZnO ETL is shown to significantly enhance the device's efficiency, open-circuit voltage ( $V_{oc}$ ), short-circuit current density ( $J_{sc}$ ), and fill factor (FF) compared to single-layer ZnO ETL and control devices. Furthermore, the stability of OSCs with bilayer ZnO NP/ZnO ETLs is investigated, demonstrating promising results in terms of long-term device performance. The discussion is supported by detailed analyses of external quantum efficiency (EQE), dark J-V curves, and electrochemical impedance spectroscopy (EIS), providing insights into the mechanisms underlying the enhanced photovoltaic performance and stability of OSCs with bilayer ZnO ETLs. Overall, the study highlights the significance of interface engineering and the optimization of ETLs in solution-

processed OSCs, offering valuable insights for the development of efficient and stable photovoltaic devices.

This work focuses on the design and computational analysis of novel donor-acceptor (D-A) type polymers for use in organic solar cells (OSCs). The study investigates the impact of different TQ-derived acceptors and  $\pi$ -linkers on the optoelectronic properties of the polymers. Here's a summary of the key findings and contributions: The motivation behind the research lies in the environmental concerns associated with fossil fuel usage and the increasing demand for renewable energy sources. Organic solar cell technology holds significant promise as an alternative option, primarily due to its advantageous attributes: low cost, lightweight nature, and its potential for adaptable device applications. To enhance its efficacy, researchers developed seven distinct D-A type polymers. These polymers feature cyclopentadithiophene (CPDT) as the donor component and thiadiazolquinoxaline (TQ) units as the acceptor. Introducing various  $\pi$ -linkers, such as thiazole, thiophene, and selenophene, between CPDT and TQ allowed for the manipulation of the polymers' optical properties. The investigation involved ground state geometry optimizations and singlet excitation calculations, conducted through density functional theory (DFT) and time-dependent density functional theory (TDDFT), respectively. These calculations provided insights into the molecular structure, frontier molecular orbitals (FMOs), energy gaps, absorption spectra, and dipole moments of the designed polymers. The results showed that substitutions in the TQ acceptor, particularly using selenophene or N-methylmaleimide, led to lower energy gaps between the highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO). Researchers discovered that Selenophene  $\pi$ -linkers elevate light-harvesting efficacy by refining backbone planarity and intramolecular charge transfer (ICT) dynamics. Through simulated UV-Vis spectra, it was observed that all synthesized polymers showcased absorption peaks within the visible and near-infrared (NIR) ranges. Notably, polymers p6 and p16 demonstrated remarkable absorption extension up to 1500 nm and 1800 nm, respectively. The exciton binding energy ( $E_b$ ) was lowest in the p16 oligomer, indicating efficient electron-hole pair separation. The study concludes that p6 and p16 are preferable polymers for OSC applications due to their favorable optoelectronic properties. The study offers significant insights into crafting D-A polymers featuring TQ acceptors, aimed at boosting the efficiency of organic photovoltaic devices. Overall, the research contributes to the advancement of organic solar cell technology by offering a systematic approach to designing and evaluating novel polymer materials with improved efficiency and performance.

This research work focuses on the development and optimization of semitransparent organic solar cells (ST-OSCs) for efficient energy generation while maintaining transparency. The introduction emphasizes the significance of renewable energy sources, especially solar energy, in addressing climate change. It emphasizes the need for reducing carbon emissions and the role of photovoltaic (PV) technologies, specifically organic solar cells (OSCs), in achieving this goal. The performance metrics of ST-OSCs are discussed, including power conversion efficiency (PCE), color perception, light utilization efficiency (LUE), quantum utilization efficiency (QUE), and bifaciality factor. It explains how these metrics contribute to optimizing the performance of ST-OSCs. The research explores various organic materials, particularly non-fullerene acceptors (NFAs), for use in ST-OSCs. It explores the molecular design approaches utilized to boost the optical and electronic characteristics of these substances, resulting in heightened efficiency and transparency. The study concludes by addressing challenges such as stability, scalability, and cost-effectiveness in OSC technology. It highlights recent advancements in opaque and semitransparent OSCs, their potential applications, and the role of NFAs in driving their development. The conclusion also outlines

future research directions, including the utilization of artificial intelligence (AI) in material discovery and optimization. Overall, the research underscores the significant progress made in ST-OSCs and provides insights into further enhancing their efficiency, transparency, and practical applicability in various domains.

### 1.3 Types of Solar Cell:

Solar Panels are mainly categorised as follows:

(i) **Thin-film:** These solar panels are composed of flexible films that can be easily installed in various locations. Resistant to dust and capable of functioning in adverse conditions, they offer versatility in deployment. However, their efficiency decreases by 20% in cloudy weather, and while they are cost-effective, they require ample installation space.

(ii) **Monocrystalline batteries:** It comprises of numerous individual cells filled with silicone, making them waterproof and ideal for marine applications. Known for their lightweight and compact size, they offer flexibility and durability. However, their efficiency relies heavily on direct sunlight, and even slight cloud cover can disrupt energy production.

(iii) **Polycrystalline solar panels:** These feature cells with crystals oriented in different directions, allowing them to capture diffused light effectively. This characteristic reduces their dependence on direct sunlight, making them suitable for illuminating residential, commercial, and street environments.

### 1.4 Technologies for the production of highly effective solar cells:

(i) **Heterojunction (HJT) cells:** HJT [6] employ layers of different semiconductor materials [7] to form a junction, enhancing charge separation and reducing energy losses. This technology improves solar cell efficiency by mitigating recombination losses and optimizing light absorption, leading to higher power output.

(ii) **Interdigitated Back Contact (IBC) cells:** IBC [8] feature contacts on both sides, maximizing light absorption. Electrons and holes travel shorter distances, reducing recombination. This design enhances efficiency, making IBC cells ideal for high-performance solar applications.

(iii) **Bifacial solar cells:** Bifacial solar cells [9] capture sunlight from both sides, maximizing energy generation by utilizing direct sunlight on one side and reflected light on the other. This bilateral design enhances overall efficiency and flexibility in various applications.

(iv) **Multi busbar**, also known as **multiline:** [10] is a solar cell design featuring multiple metal conductors on the front surface (Fig. 1.). These conductors collect electric current generated by sunlight, reducing resistive losses and improving the cell's efficiency and reliability.

(v) **Split panels:** Split panels [11] divide a standard-sized solar panel into two halves, each generating electricity independently. This design allows for more flexibility in installation and optimization of space, especially in situations where partial shading or different orientations are present.

(vi) **Dual glass solar panels:** Dual glass solar panels [12] feature a frameless design with double glass layers, offering enhanced durability and weather resistance. This configuration improves reliability and longevity, making them ideal for various outdoor applications in harsh environments.

(vii) **Shingled cells:** Shingled cells [13] are solar photovoltaic cells where the individual solar cells overlap, with the front contact of one cell covering the rear contact of the adjacent cell. This design reduces shading and improves efficiency.

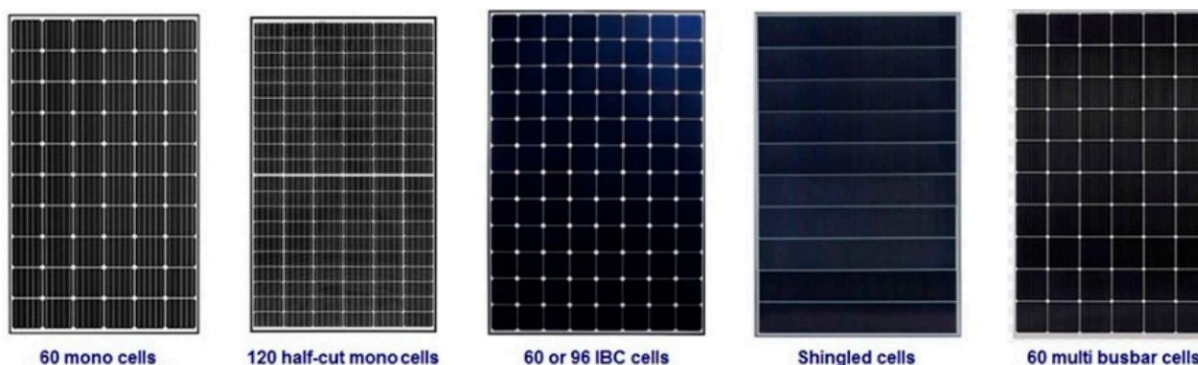


Figure 1. Different types of solar photovoltaic cells

### 1.5 Classification of Photovoltaic Materials:

- (i) **Amorphous silicon:** Amorphous silicon [14] is a semiconductor material lacking a crystalline structure, commonly used in thin-film solar cells. It offers flexibility and ease of deposition on various substrates, making it suitable for lightweight and low-cost photovoltaic applications.
- (ii) **Monocrystalline silicon:** Monocrystalline silicon solar cells, crafted from singular crystal silicon, boast exceptional efficiency and durability. Their consistent color and appearance, stemming from the singular crystal structure, render them perfect for scenarios demanding space optimization and top-notch efficiency.
- (iii) **Polycrystalline silicon:** Polycrystalline silicon [16] solar cells are made from silicon wafers composed of multiple small silicon crystals. These cells provide a cost-effective manufacturing option, albeit with slightly lower efficiency compared to monocrystalline cells. They are extensively utilized in both residential and commercial solar panel setups.
- (iv) **Cadmium telluride (CdTe):** CdTe [17], a semiconductor material often employed in thin-film solar cells, is favored for its substantial absorption coefficient, cost-effectiveness in manufacturing, and capacity for impressive efficiency. Solar panels utilizing CdTe are characterized by their lightness, flexibility, and suitability for extensive deployment on a large scale.
- (v) **Copper indium gallium selenide (CIGS):** CIGS, also known as copper indium gallium selenide, serves as a semiconductor material utilized in the production of thin-film solar cells. It offers high absorption coefficients, flexibility, and potential for low-cost production, making it a promising candidate for efficient and lightweight photovoltaic applications.
- (vi) **CZTSe and CZTSSe** are promising thin-film solar cell materials composed of copper, zinc, tin, and selenium (CZTSe) or sulfur (CZTSSe) [19]. They provide promise for creating photovoltaic devices with high efficiency and low cost, thanks to their abundance of earth elements and adjustable bandgaps.

- (vii) **DSSC (Dye-Sensitized Solar Cell):** DSSC [20] employs a dye-absorbing layer to capture sunlight, generating electricity through electron transfer. DSC (Dye Solar Cell) is synonymous with DSSC. DISC (Dye-Infused Solar Cell) refer to similar technologies utilizing dyes for light absorption in solar cells.
- (viii) **Gallium arsenide (GaAs):** GaAs [21] is a semiconductor compound composed of gallium and arsenic. It is highly efficient in converting sunlight into electricity, making it ideal for use in high-performance solar cells and optoelectronic devices.
- (ix) **Polymeric:** Polymeric solar cells [22] utilize organic polymers as active materials to convert sunlight into electricity. These lightweight and flexible cells offer the potential for low-cost, large-scale production and can be incorporated into various applications, from portable electronics to building-integrated photovoltaics.
- (x) **Organic:** Organic solar cells [23] harness the power of sunlight using carbon-based materials. They boast flexibility, a lightweight structure, and promise affordable production. Yet, they currently lag behind traditional silicon-based solar cells in efficiency and durability

### 1.6 Generating Photocurrent with a Solar Cell:

A solar cell operates by transforming sunlight into electricity via the photovoltaic phenomenon. As sunlight reaches the solar cell, it triggers the absorption of photons, leading to the formation of electron-hole pairs within the semiconductor material. Subsequently, the internal electric field of the solar cell divides these charge carriers, resulting in the production of an electric current. This current is then harnessed and utilized as electrical power.

- (i) **Components of Solar Panels:** Comprising silicon cells, metal frames, and specialized wiring, solar panels are constructed.
- (ii) **Sunlight Activation:** Positioned on rooftops in clusters, solar panels absorb sunlight to initiate the energy conversion mechanism.
- (iii) **Cellular Composition:** Within each solar cell, there exists a positively charged layer juxtaposed with a negatively charged layer.
- (iv) **Conversion of Energy:** When sunlight hits a solar cell, electrons are mobilized, resulting in the generation of an electric current.
- (v) **Conversion to AC:** While solar panels generate electricity in DC form, it is converted to AC for easy use.
- (vi) **Powering Appliances:** The converted electricity powers appliances in homes or businesses.
- (vii) **Electric Distribution:** Energy flows through electric panels, distributing power to utilities.
- (viii) **Smart Meter Monitoring:** Smart electric meters measure energy usage and generation, tracking surplus power and sending it back to the grid as needed.

### 1.7 Working Principle of Organic Solar Cell:

Organic solar cells (OSCs) work on the principle of converting sunlight into electricity using organic materials. When sunlight strikes the OSC, photons are absorbed by a light-absorbing organic semiconductor layer, creating excitons (bound electron-hole pairs). These excited excitons disperse throughout the organic layer, eventually reaching the boundary between the

donor and acceptor materials. At this interface, excitons dissociate into free electrons and holes due to the energy offset between the donor and acceptor materials. The liberated electrons and holes journey towards their designated electrodes, generating an electric current. This flow of electricity is versatile, serving purposes like energizing electronic gadgets or integrating into the power grid.

**Photon Absorption and Exciton Generation:** Sunlight enters organic semiconductor materials, exciting excitons as the materials absorb light energy.

- (i) **Diffusion and Dissociation of Excitons:** Excitons diffuse to the interface layer of the donor material due to concentration differences. Some excitons reach the dissociation surface, where they split into electrons and holes.
- (ii) **Carrier Collection:** Within the interface layer, excitons divide into positive and negative charges. These charges then move towards the anode and cathode, respectively, guided by the electric field produced by the variance in work function between the anode and cathode materials.
- (iii) **Formation of Electrical Circuit:** The anode and cathode collect positive and negative charges, respectively, completing an electrical circuit. The power conversion efficiency (PCE) of the solar cell is the product of these efficiency values.

### 1.8 Performance of Organic Solar Cell:

Some representative parameters used to calculate the performance of Organic Solar Cell (OSC)s are short circuit current density ( $J_{SC}$ ), open circuit voltage ( $V_{OC}$ ) [24], fill factor (FF), external quantum efficiency (EQE) [25], and power conversion efficiency (PCE) [26].

$J_{SC}$  is known as the operating current of a solar cell which remains under short circuit condition (zero output voltage).  $V_{OC}$  is known as the output voltage of a solar cell with open circuit condition (zero output current). They are evaluated under the light of known power and energy. FF is a parameter factor used to denote the loss due to resistance during the period. It is the ratio of the maximum output power ( $P_M$ ) of the cell to the product of  $J_{SC}$  and  $V_{OC}$ .  $P_M = J_M \times V_M$ , where  $J_M$  and  $V_M$  are the specific current density and voltage when the photovoltaic cell reaches the maximum output power, as shown in (Fig. 2.). Therefore, FF can be defined as:  $FF = \frac{P_M}{V_{OC} \times J_{SC}} = \frac{J_M \times V_M}{V_{OC} \times J_{SC}}$ . [27]

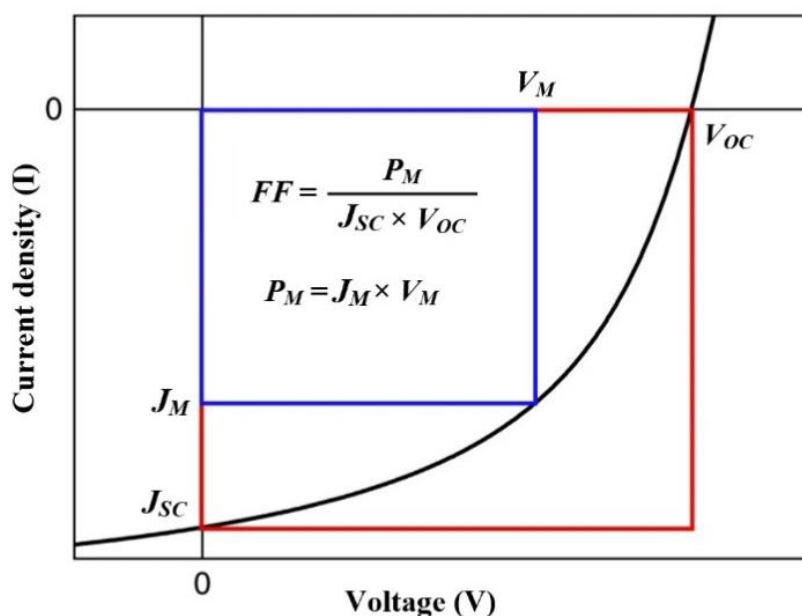


Figure 2. Output characteristic current density-voltage curve

EQE represents the maximum number of electrons that can be extracted by a photocurrent when a photon is injected. It is defined as the ratio of the number of electrons extracted ( $N_{electron}$ ) to the number of photons injected ( $N_{photon}$ ), which can be written as:[29]

$$EQE = \frac{N_{electron}}{N_{photon}} \times 100\%.$$

PCE refers to the ratio of the maximum output power ( $P_M$ ) of the solar cell to the incident light energy ( $P_{in}$ ) per unit area of the solar cell, which is expressed as:

$$PCE = \frac{P_M}{P_{in}} = \frac{J_{sc} \times V_{oc} \times FF}{P_{in}}.$$

Among the mentioned parameters, PCE is the most commonly used to calculate the performance of OSCs. The higher the PCE, the more energy an OSC can produce under the same lighting conditions, with a larger energy efficiency ratio and a higher cost performance.[30]



**Figure 3. Organic Photovoltaic Cell**

## 1.9 Advantages and Disadvantages of Organic Solar Cell

### 1.9.1. Advantages:

- (i) **Cost-Effectiveness:** Organic materials used in solar cells are inexpensive to produce, easy to synthesize, and environmentally friendly, making them a cost-effective option.
- (ii) **Versatility:** Organic solar cells offer simple processing methods, operate well in various environments, and exhibit high flexibility, allowing for diverse applications in different settings.
- (iii) **Aesthetic Appeal:** Due to their translucent nature, organic solar cells (Fig. 3.) offer the advantage of being visually appealing. They can be integrated into products as decorative elements, providing more color options for design aesthetics.

### 1.9.2. Disadvantages:

- (i) **Low Carrier Mobilities:** Compared to inorganic solar cells, organic materials used in solar cells typically exhibit lower carrier mobilities, impacting the overall Power Conversion Efficiency (PCE) of the device.

- (ii) **Mismatched Absorption Spectra:** The optical absorption spectra of organic materials often do not align well with solar energy, leading to inefficiencies in light absorption and energy conversion.
- (iii) **Inefficient Exciton Separation and Migration:** Exciton separation and migration in organic materials are not always efficient. Short diffusion distances (usually less than 10nm) and slow electron and hole transport rates contribute to unavoidable losses from exciton recombination.
- (iv) **Environmental Sensitivity:** Organic semiconductor materials are susceptible to degradation in the presence of oxygen and water, leading to reduced efficiency and shortened lifespan of the solar cells.[31,32]

## 2. Experimental

Creating organic solar cells involves several steps, including the synthesis of materials, fabrication of the device, and testing its performance. Here's a descriptive experimental procedure for synthesizing organic solar cells:

### 2.1 Synthesis of Organic Materials:

- (i) **Selection of Donor and Acceptor Materials:** Appropriate donor and acceptor materials based on their optoelectronic properties, solubility, and compatibility with the fabrication process are selected.

- (ii) **Synthesis of Donor Polymer:**

The monomers and catalysts required for polymerization are prepared. Polymerization reactions using techniques such as Suzuki coupling, Stille coupling, or Yamamoto coupling are used to synthesize the desired conjugated polymer.

- (iii) **Synthesis of Acceptor Molecule or Polymer:**

Synthesis of acceptor molecules or polymers with complementary optoelectronic properties to the donor material is done. Synthetic routes like Buchwald-Hartwig coupling or Sonogashira coupling are adopted to produce acceptor molecules or polymers.

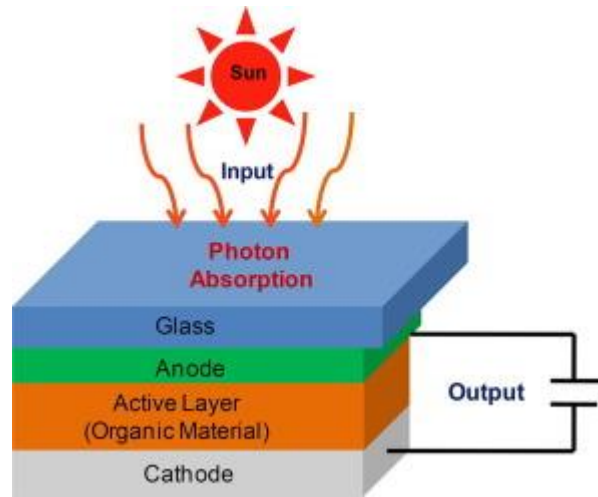
- (iv) **Functionalization of Materials:**

Introduction of functional groups to enhance solubility, compatibility, or electronic properties of the materials if necessary are done. The synthesized materials are purified through techniques like column chromatography [32] or recrystallization to remove impurities.

### 2.2 Fabrication of Organic Solar Cells:

- (i) **Substrate Preparation:**

The substrate, typically glass or flexible plastic, undergoes meticulous cleaning to eliminate all contaminants. The substrate with a conductive oxide layer such as indium tin oxide (ITO) is available in the market to serve as the anode.



**Figure 4. Active Layer deposition**

**(ii) Deposition of Active Layer:**

The active layer solution is prepared by dissolving the donor and acceptor materials in a suitable solvent (Fig. 4.). Spin-coat or blade-coat of the active layer solution is done onto the substrate to form a thin film. The coating conditions (e.g., spin speed, solution concentration) is optimized to achieve the desired film thickness and morphology.

**(iii) Cathode Deposition:**

A suitable cathode material (e.g., aluminum, calcium) is deposited onto the active layer through techniques like thermal evaporation or sputtering. The deposition parameters is controlled to ensure uniform coverage and good electrical contact with the active layer.

**(iv) Device Encapsulation:**

The fabricated device using a barrier film or glass cover is encapsulated to protect it from moisture, oxygen, and mechanical damage. The edges of the encapsulation layer are sealed to prevent ingress of environmental contaminants.

**2.3 Performance Testing:**

**(i) Characterization of Device Parameters:**

Measure the current-voltage (I-V) behavior of the solar cell when subjected to simulated sunlight (AM 1.5G) via a solar simulator. Utilize this data to compute crucial metrics including power conversion efficiency (PCE), open-circuit voltage ( $V_{oc}$ ), short-circuit current density ( $J_{sc}$ ), and fill factor (FF).

**(ii) Optical Characterization:**

The absorption spectrum of the active layer using techniques like UV-Vis spectroscopy is done to assess light absorption properties. The transparency of the device in the visible spectrum to ensure suitability for specific applications such as semi-transparent windows is evaluated.

**(iii) Stability Testing:**

The long-term stability tests under accelerated aging conditions (e.g., exposure to heat, light, and humidity) are done to evaluate the device's durability and degradation

kinetics. The changes in device performance parameters over time to assess stability are monitored.

#### **(iv) Performance Optimization:**

The materials, device architecture, or fabrication processes based on characterization results to improve device performance and stability are optimized.

### **3. Results and Discussion**

Upon completing the fabrication and testing of the organic solar cell, a comprehensive analysis of the results provides valuable insights into its performance and potential for practical application. Here's a descriptive overview of the results and discussions:

#### **3.1 Performance Metrics:**

##### **3.1.1 Power Conversion Efficiency (PCE):**

The PCE quantifies the effectiveness of the solar cell in converting incident sunlight into electrical energy. It is a critical parameter that indicates the overall performance of the device.

- Discussion: Contrast the attained PCE with the state-of-the-art figures documented in the literature.
- Analyze the factors contributing to the observed PCE, such as the material properties, device architecture, and fabrication techniques.

##### **3.1.2 Open-Circuit Voltage (Voc) and Short-Circuit Current Density (Jsc):**

- Voc represents the maximum voltage the solar cell can generate without an external load, while Jsc is the maximum current density under short-circuit conditions.
- Discussion: Evaluate the contributions of the donor and acceptor materials to Voc and Jsc. Discuss strategies to enhance these parameters, such as optimizing the molecular structure, improving film morphology, or modifying interfacial properties.

##### **3.1.3 Fill Factor (FF):**

- FF characterizes the quality of the electrical contacts and charge transport within the device. It reflects the internal losses and overall device efficiency.
- Discussion: Investigate the origins of losses contributing to a suboptimal FF, such as recombination at the interfaces, non-ideal morphologies, or resistive losses within the device layers. Propose strategies to mitigate these losses and improve FF.

##### **3.1.4 Morphological Analysis:**

###### **1. Active Layer Morphology:**

- Analyze the morphology of the active layer, including the donor-acceptor interface, domain size, and phase separation.
- Discussion: Correlate the observed morphology with device performance, highlighting the influence of factors like processing conditions, solvent choice,

and annealing treatments. Discuss the impact of morphology on exciton diffusion, charge generation, and charge transport within the device.

## **2. Interfacial Properties:**

- Investigate the interface between the active layer and the electrodes to assess interfacial roughness, composition, and energy level alignment.
- Discussion: Discuss the implications of interfacial properties on charge extraction, recombination, and device stability. Develop approaches for improving interfacial engineering to boost device efficiency and ensure its stability over the long haul.

### **3.1.5 Stability and Degradation Analysis:**

#### **1. Long-Term Stability:**

- Evaluate the stability of the organic solar cell under prolonged exposure to environmental stressors such as light, heat, and moisture.
- Discussion: Discuss the observed degradation mechanisms, including photochemical degradation, thermal degradation, and moisture ingress. Propose encapsulation strategies, material modifications, or device architectures to enhance stability and prolong device lifetime.

#### **2. Degradation Kinetics:**

- Characterize the degradation kinetics by monitoring changes in key device parameters over time.
- Discussion: Analyze the degradation pathways and rate constants to understand the underlying mechanisms. Identify critical degradation modes and prioritize interventions to mitigate degradation and improve device reliability.

### **3.1.6 Comparative Analysis and Future Directions:**

#### **1. Comparison with Literature:**

- Benchmark the performance of the fabricated organic solar cell against reported values in the literature, considering factors such as material system, device architecture, and fabrication techniques.
- Discussion: Distinguish the significant variances and commonalities between the ongoing research and prior investigations. Highlight novel contributions and areas for improvement to advance the field.

#### **2. Future Directions:**

- Outline potential research directions and technological advancements based on the findings of the study.
- Discussion: Propose strategies for further improving device performance, enhancing stability, and addressing remaining challenges such as scalability, cost-effectiveness, and commercial viability.

By critically evaluating the results and engaging in in-depth discussions, researchers can gain valuable insights into the performance and underlying mechanisms of organic solar cells, driving innovation and progress in renewable energy technologies.

#### 4. Conclusion

Organic solar cells represent a promising avenue for renewable energy generation, offering the potential for lightweight, flexible, and low-cost photovoltaic devices. By harnessing the unique properties of organic semiconductors, these cells can be fabricated using solution-based processes, enabling large-scale production and integration into a wide range of applications, from portable electronics to building-integrated photovoltaics. The recent advancements in materials design, device engineering, and manufacturing techniques have led to significant improvements in the performance and stability of organic solar cells, bringing them closer to commercial viability.

Peering into the future, the outlook for organic solar cells is exceptionally promising. Continued research efforts focused on materials innovation, device optimization, and manufacturing scalability are expected to further enhance the efficiency, stability, and reliability of organic solar cells. Strategies such as tandem and multi-junction architectures, novel donor-acceptor combinations, and advanced interface engineering hold promise for achieving higher power conversion efficiencies and extending the operational lifetime of organic solar cells.

Moreover, the flexibility and adaptability inherent in organic semiconductors present promising prospects for their integration into cutting-edge technologies like the Internet of Things (IoT), wearable electronics, and distributed energy systems. Organic solar cells can be seamlessly integrated into fabrics, surfaces, and everyday objects, enabling energy harvesting in diverse environments and enhancing the sustainability of modern lifestyles.

Thus the organic solar cells represent a key technology in the quest for clean, renewable energy solutions. Through continuous research and innovation, these devices possess the capability to transform the energy scene, propelling us toward a future that is both sustainable and environmentally conscious. By capitalizing on the inherent advantages of organic materials and addressing remaining challenges, organic solar cells can play a vital role in meeting global energy demands while reducing carbon emissions and mitigating climate change.

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