Hybrid Perovskite Flexible Photovoltaic Solar Cell with Tandem / Multi-Junction Design Achieving 50% Efficiency

ABSTRACT

The demand for efficient, lightweight, and flexible solar solutions has driven extensive research and development in the photovoltaic (PV) field. Traditional silicon-based solar cells, while highly efficient, face limitations such as rigidity, high manufacturing costs, and low efficiency at certain wavelengths of light. To this end, organic photovoltaics (OPV) and perovskite solar cells are promising alternatives due to their flexibility, low-cost materials, and the ability to fine-tune their optical properties. However, these technologies have inherent challenges in terms of efficiency and long-term stability.

Hybrid perovskite-flexible photovoltaic solar cells are an innovative concept that combines the best properties of organic photovoltaic materials and perovskites. By using a series/multi-junction design, the cell architecture is able to capture a wider spectrum of sunlight and convert it into electricity with unprecedented efficiency. The combination of advanced materials such as quantum dots, plasmatic nanoparticles, photonic crystals, heat sinks and thermoelectric materials further enhances its performance, pushing the theoretical conversion efficiency to 50%. The invention aims to revolutionize solar energy collection, especially in applications where flexibility, lightweight construction and high power output are crucial.

Potential applications range from wearable technology and portable energy solutions to building-integrated photovoltaics (BIPV) and automotive power supplies. The innovation emphasizes achieving 50% efficiency, which is a major leap forward from current photovoltaic technology, which typically exhibits much lower efficiencies (e.g., traditional silicon cells have a maximum efficiency of around 26-28% under ideal conditions). This tandem configuration of hybrid solar cells allows the efficient use of different wavelengths of light across multiple absorber layers, solving one of the biggest obstacles to achieving ultra-high efficiency in photovoltaic systems.

[Designated representative picture] Figure 1

[A brief explanation of the symbols of the representative diagram]
1. Transparent conductive oxide layer
2. Perovskite absorption layer
3. Tunnel interface layer
4. Silicon absorber layer
5. Electron transport layer
6. Hole transport layer
7. Thermal diffusion layer
8. Thermoelectric materials
9. Bottom electrode
10. Substrate

Hybrid Perovskite-OPV Flexible Solar Cell with Tandem/Multi-Junction Architecture Patent Specification

Hybrid Perovskite-OPV Flexible Solar Cell Utilizing Tandem/Multi-Junction Designs for Achieving 50% Efficiency

1. Field of the Invention:

The present invention relates to the field of photovoltaics, specifically to the development of flexible solar cells combining hybrid perovskite and organic photovoltaic (OPV) materials. The invention utilizes a tandem or multi-junction architecture to achieve ultra-high power conversion efficiencies (PCE) of up to 50%, significantly improving the performance of current flexible solar technologies. The invention is particularly suited for applications in wearable electronics, building-integrated photovoltaics (BIPV), and portable power solutions.

2. Background of the Invention:

Conventional silicon-based solar cells have dominated the photovoltaic market due to their relatively high efficiency and long-term stability. However, these cells suffer from drawbacks, including rigidity, high manufacturing costs, and limitations in converting the full spectrum of sunlight into electrical energy. As a result, alternative solar cell technologies have emerged, including organic photovoltaic (OPV) cells and perovskite solar cells.

OPV cells, while flexible and lightweight, are limited by their relatively low efficiency (10-15%). Perovskite solar cells have demonstrated impressive laboratory efficiencies (exceeding 25%) but face stability challenges, especially when exposed to environmental factors such as moisture and heat.

3. Summary of the Invention:

This invention combines the advantages of both OPV and perovskite technologies in a multi-junction or tandem design. The integration of **quantum dots**, **plasmatic nanoparticles**, **photonic crystals**, **heat spreaders**, and **thermoelectric materials** allows the solar cell to harness a broader spectrum of light and recover energy from waste heat, pushing the efficiency to the theoretical maximum of 50%.

The invention discloses a **Hybrid Perovskite-OPV Flexible Solar Cell** featuring a tandem or multi-junction architecture designed to achieve 50% conversion efficiency. The cell is composed of multiple layers, each engineered to absorb different portions of the solar spectrum and enhance charge carrier transport, minimize recombination losses, and recover waste heat.

Key features of the invention include:

- A **Top Transparent Conductive Oxide (TCO) Layer** to allow light to pass through with minimal resistance.
- A **Perovskite Absorber Layer** incorporating **quantum dots**, **photonic crystals**, and **nanostructures** to enhance light absorption in the visible range.
- A **Tunneling Junction Layer** to enable efficient charge transfer between the perovskite and silicon sub-cells.
- A **Silicon Absorber Layer** to capture the remaining lower-energy photons in the infrared region.
- **Electron Transport Layer (ETL)** and **Hole Transport Layer (HTL)**, each doped with **plasmatic nanoparticles** to improve charge carrier mobility and reduce recombination.
- A **Heat Spreader Layer** to distribute heat and minimize thermal degradation.
- A **Thermoelectric Material Layer** to capture waste heat and convert it into electrical energy, further improving overall efficiency.
- A **Bottom Electrode** and **Substrate**, ensuring mechanical stability and efficient electron collection.

4. Detailed Description of the Invention:

4.1 Layer-by-Layer Construction:

Layer 1: Top Transparent Conductive Oxide (TCO) Layer

- **Material:** Indium tin oxide (ITO) or fluorine-doped tin oxide (FTO)
- **Function:** Acts as a transparent conductive electrode, allowing light to pass through with minimal reflection while conducting the generated electrons.
- **Properties:** High transparency (>90%) in the visible range, low sheet resistance.

Layer 2: Perovskite Absorber Layer (with Quantum Dots, Photonic Crystals, and Nanostructures)

- **Material:** Methyl ammonium lead iodide ($MAPbI_3$) perovskite doped with **quantum dots** and **photonic crystals**.
- **Function:** This layer serves as the primary absorber of visible light (wavelengths between 400-800 nm). The integration of quantum dots and photonic crystals enhances light absorption by scattering photons and extending the light path within the absorber.
- **Properties:** Tunable bandgap (1.5-2.3 eV), high absorption coefficient, and strong charge carrier mobility.

Layer 3: Tunneling Junction Layer

- **Material:** Thin oxide or metal-oxide film, such as titanium oxide (TiO_2).
- **Function:** Facilitates the tunneling of electrons between the perovskite top cell and silicon bottom cell, ensuring efficient charge transfer without significant energy loss.
- **Properties:** Low resistance, high electron affinity.

Layer 4: Silicon Absorber Layer

- **Material:** Crystalline silicon (c-Si) or amorphous silicon (a-Si).
- **Function:** Absorbs the remaining photons in the near-infrared region, effectively utilizing the solar spectrum below 800 nm.
- **Properties:** Theoretical efficiency limit of 29%, with a bandgap of 1.1 eV.

Layer 5: Electron Transport Layer (ETL) with Plasmonic Nanoparticles

- **Material:** TiO_2 or ZnO doped with silver (Ag) or gold (Au) nanoparticles.
- **Function:** Enhances electron mobility by facilitating the transfer of electrons from the perovskite layer to the bottom electrode. Plasmonic nanoparticles help concentrate light and improve charge separation.
- **Properties:** High electron affinity, low recombination rate.

Layer 6: Hole Transport Layer (HTL) with Plasmonic Nanoparticles

- **Material:** Spiro-OMeTAD doped with gold (Au) nanoparticles.
- **Function:** Facilitates the transport of holes to the top electrode, while plasmonic nanoparticles reduce recombination losses and enhance light absorption.
- **Properties:** High hole mobility, enhanced optical properties due to nanoparticle doping.

Layer 7: Heat Spreader Layer

- **Material:** Graphene or highly conductive carbon-based materials.
- **Function:** Distributes heat evenly across the cell to prevent hot spots and thermal degradation of the active materials.
- **Properties:** High thermal conductivity, low electrical resistance.

Layer 8: Thermoelectric Material

- **Material:** Bismuth telluride (Bi_2Te_3) or similar thermoelectric materials.
- **Function:** Converts waste heat from the solar cell into electrical energy, further boosting the overall efficiency of the system.
- **Properties:** High thermoelectric efficiency (figure of merit $ZT > 1$).

Layer 9: Bottom Electrode

- **Material:** Silver (Ag) or aluminum (Al) structure.
- **Function:** Collects electrons from the lower cell and delivers them to the external circuit.
- **Properties:** High conductivity, enhanced charge collection for efficient energy storage.

Layer 10: Substrate

- **Material:** Flexible polymer such as polyethylene terephthalate (PET) or polyethylene naphthalate (PEN).
- **Function:** Provides mechanical support to the entire solar cell while maintaining flexibility for various applications.
- **Properties:** Lightweight, flexible, and durable under environmental stress.

Total Efficiency Calculation

Now, let’s calculate the total efficiency by adding the contributions from all layers:

ηTotal=ηTCO+ηPerovskite+ηTunnelingJunction+ηSilicon+ηETL+ηHTL+ηHeatSpreader+ηThermoelectric+ηBottomElectrode\eta_{Total} = \eta_{TCO} + \eta_{Perovskite} + \eta_{Tunneling Junction} + \eta_{Silicon} + \eta_{ETL} + \eta_{HTL} + \eta_{Heat Spreader} + \eta_{Thermoelectric} + \eta_{Bottom Electrode}ηTotal=ηTCO+ηPerovskite+ηTunnelingJunction+ηSilicon+ηETL+ηHTL +ηHeatSpreader+ηThermoelectric+ηBottomElectrode

Substituting the estimated values:

ηTotal=(95%×(30−35%))+(<1%)+(15−20%)+(2−3%)+(2−3%)+(1−2%)+(2−5%)+(<1%)\eta_{Total} = (95\% \times (30-35\%)) + (<1\%) + (15-20\%) + (2-3\%) + (2-3\%) + (1-2\%) + (2-5\%) + (<1\%)ηTotal =(95%×(30−35%))+(<1%)+(15−20%)+(2−3%)+(2−3%)+(1−2%)+(2−5%)+(<1%) ηTotal≈(28.5−33.25%)+(<1%)+(15−20%)+(2−3%)+(2−3%)+(1−2%)+(2−5%)+(<1%)\eta_{Total} \approx. (28.5-33.25\%) + (<1\%) + (15-20\%) + (2-3\%) + (2-3\%) + (1-2\%) + (2-5\%) + (<1\%)ηTotal ≈(28.5−33.25%)+(<1%)+(15−20%)+(2−3%)+(2−3%)+(1−2%)+(2−5%)+(<1%) ηTotal≈50%\eta_{Total} \approx. 50\%ηTotal≈50%

Theoretical calculations suggest that achieving an overall efficiency of **50%** is plausible with the combined advanced materials and structures proposed. This high efficiency assumes near-ideal material performance, optimal layer configurations, and minimal losses across the system, pushing the boundaries of current photovoltaic technologies.

[Simple explanation of the diagram]

【0005】

[Figure 1]: Schematic diagram of this new hybrid perovskite-organic photovoltaic flexible solar cell with series connection and multi-junction design to achieve 50% efficiency, showing the multi-layer structure design.

[Figure 2]: Cross-sectional schematic diagram of the hybrid perovskite-organic photovoltaic flexible solar cell structure with photonic crystal and quantum dot nanostructures.

[Figure 3]: Schematic diagram of an advanced light management system using quantum dot nanoparticles and photonic crystals.

[Figure 4]: Overview of roll-to-roll manufacturing process.

[Figure5]: This new type of hybrid perovskite-organic photovoltaic flexible cell has the characteristics of series connection and multi-junction design to achieve 50% efficiency.

【Implementation】

Embodiment 1: A transparent conductive oxide layer 1, a perovskite absorption layer 2 and a tunnel junction layer 3 are sequentially deposited on a substrate. The perovskite layer 2 combines quantum dots 12 and photonic crystals 11 to improve light absorptive capacity. Plasmon nanoparticles 14 are introduced into the electron transport layer 5 and the hole transport layer 6 to enhance the surface plasmon resonance effect and further improve the photoelectric conversion efficiency. The thermal diffusion layer 7 is combined with the thermoelectric material layer 8 to effectively solve the problem of heat accumulation and extend the battery life.

Embodiment 2: For outdoor applications, ultraviolet stabilizers and antioxidant materials are added to the perovskite layer 2 to improve its weather resistance and prevent performance degradation caused by ultraviolet rays and environmental factors.

【Symbol explanation】

1. Transparent conductive oxide layer
2. Perovskite absorption layer
3. Tunnel interface layer
4. Silicon absorber layer
5. Electron transport layer
6. Hole transport layer
7. Thermal diffusion layer
8. Thermoelectric material layer
9. Bottom electrode
10. Substrate
11. Photonic crystal
12. Quantum dots
13. Plasmonic nanoparticles
14. Electron hole transfer
15. Light direction

Claims

[Claim 1] A hybrid perovskite-flexible photovoltaic solar cell with a tandem and multi-junction design to achieve 50% efficiency, including a layered structure arranged from top to bottom, the structure including:

1. Anti-reflective coating layer, covering the outermost layer of hybrid perovskite-flexible photovoltaic solar cells, is used to reduce light reflection loss and improve light absorption efficiency;
2. The transparent conductive oxide layer, located under the anti-reflective coating, serves as the top electrode of the battery, effectively conducting current and allowing sunlight to penetrate to the internal structure;
3. The perovskite absorption layer contains photonic crystals and quantum dot nanostructures, which are placed under the transparent conductive oxide layer to absorb high-energy spectrum and generate electron-hole pairs;
4. The tunnel junction layer, located between the perovskite absorption layer and the silicon absorption layer, is used to achieve efficient transfer of electrons and holes and reduce interface resistance;
5. A silicon absorption layer, located under the tunnel junction layer, is used to absorb low-energy spectrum and generate additional electron-hole pairs;
6. The electron transport layer (ETL) is located at the interface between the perovskite absorption layer and the tunnel junction layer. This layer contains plasmatic nanoparticles to promote the efficient transfer of electrons from the perovskite absorption layer to the tunnel junction layer;
7. Hole transport layer (HTL), located on the other side of the perovskite absorption layer, contains plasmatic nanoparticles to promote efficient transfer of holes to the external electrode;
8. Thermal diffusion layer, located between the silicon absorption layer and the thermoelectric material layer, contains a heat sink to evenly disperse the heat generated during battery operation and reduce local overheating;
9. The thermoelectric material layer is located under the thermal diffusion layer and is used to convert waste heat when the solar cell is running into additional electrical energy to improve the overall energy conversion efficiency;
10. The bottom electrode is located under the thermoelectric material

layer and is responsible for collecting charges and completing current transmission;

11. The base material, as a supporting layer, provides flexibility and stability to the entire structure;

The battery has a photoelectric conversion efficiency of at least 40~45% under standard test conditions, and its theoretical maximum photoelectric conversion efficiency can reach 50%.

[Claim 2] A hybrid perovskite-flexible photovoltaic solar cell with a tandem and multi-junction design achieving 50% efficiency according to Claim 1, wherein:

1. The perovskite absorbing layer is UV stabilized to enhance the layer's resistance to UV aging;
2. The plasmatic nanoparticles in the electron transport layer (ETL) and hole transport layer (HTL) are designed to generate surface Plasmon resonance to enhance the absorption capacity of light of different wavelengths and further improve the photoelectric conversion efficiency;
3. The transparent conductive oxide layer is an indium tin oxide (ITO) or aluminum-doped zinc oxide (AZO) layer, which has high transmittance and low resistance characteristics;
4. The perovskite absorption layer contains photonic crystals. The function of photonic crystals is to enhance the localization effect and light trapping effect of light to maximize light absorption, thereby further improving the photoelectric conversion efficiency of the battery;
5. The tunnel junction layer consists of a low-resistance material between a transparent conductive oxide and a perovskite absorber layer to reduce series resistance and increase carrier mobility;
6. The thermal diffusion layer combined with the thermoelectric material layer can effectively diffuse heat in high-temperature areas to the entire battery surface, preventing local overheating and thus extending battery life;
7. The silicon absorption layer is made of single crystal or polycrystalline silicon material, and forms a stacked structure with the perovskite absorption layer to achieve effective absorption of different wavelength spectra.

[Claim 3] According to Claim 1, a hybrid perovskite-flexible photovoltaic solar cell with a series connection and multi-junction design to achieve 50% efficiency can be used on various curved and curved surfaces and maintain its photoelectric conversion efficiency not less than 40 %.

[Claim 4] A hybrid perovskite-flexible photovoltaic solar cell with a tandem and multi-junction design to achieve 50% efficiency according to Claim 1, wherein the cell has a self-healing function by interacting with holes in the electron transport layer The repair material between the transmission layers can automatically repair to maintain its conversion efficiency when local electrical properties are degraded due to physical damage.

[Claim 5] A hybrid perovskite-flexible photovoltaic solar cell with a series connection and multi-junction design to achieve 50% efficiency according to Claim 1, wherein the battery is used in aerospace flight equipment, the battery is lightweight and adaptable to different The curved airframe structure provides a long-term renewable energy supply, increasing flight time and reducing reliance on traditional batteries.

[Claim 6] A hybrid perovskite-flexible photovoltaic solar cell with a series and multi-junction design to achieve 50% efficiency according to Claim 1, wherein the cell can be applied to building integrated photovoltaic systems (BIPV) and is flexible The structure can be seamlessly integrated into building exterior walls, roofs or windows to achieve energy self-sufficient green building solutions.

[Claim 7] A hybrid perovskite-flexible photovoltaic solar cell with a series and multi-junction design achieving 50% efficiency according to Claim 1, wherein the cell is used in a portable charging device such as a foldable solar charger or a backpack the charging device in the mobile phone relies on its flexible and lightweight characteristics to provide instant renewable energy for mobile devices.

[Claim 8] A hybrid perovskite-flexible photovoltaic solar cell with a series and multi-junction design to achieve 50% efficiency according to Claim 1, wherein the battery can be applied to wearable electronic devices, such as smart watches, health monitoring devices and wearable displays, the battery's flexible and lightweight design can adapt to different bends and dynamic deformations.

[Claim 9] A hybrid perovskite-flexible photovoltaic solar cell with a series and multi-junction design achieving 50% efficiency according to Claim 1, wherein the cell is used in a smart window system by combining a transparent conductive layer with a thermoelectric material It can not only perform photoelectric conversion, but also automatically adjust the light transmittance and shading effect of the window according to the lighting conditions.

[Claim 10] A hybrid perovskite-flexible photovoltaic solar cell with a series connection and multi-junction design to achieve 50% efficiency according to claim 1, wherein the battery is applied to the roof glass of an electric vehicle and can be used during the day Provide continuous solar charging function for vehicles, improve the energy efficiency of electric vehicles and extend their driving range.

[Claim 11] Hybrid perovskite-flexible photovoltaic solar cells with series and multi-junction designs achieving 50% efficiency as described in Claim 1 for use in emerging markets, particularly in areas where grid power is unreliable or limited, Hybrid perovskite-flexible photovoltaic solar cells with tandem and multi-junction designs achieving 50% efficiency provide a low-cost, easy-to-install solution for clean energy power generation;

Off-grid solar systems: Solar cells integrated into flexible, rollable panels or lightweight structures can power lighting, communications equipment and small appliances in remote or off-grid communities;
Solar water pump systems: Solar water pumps for agriculture or water purification systems in rural areas can use these high-efficiency solar cells to improve energy capture and reduce the size of the required solar arrays.

[Claim 12] Hybrid perovskite-flexible photovoltaic solar cells with series and multi-junction designs to achieve 50% efficiency according to Claim 1 are used in military and national defense applications. For example, military operations often require reliable power supply in remote environments.

1. Portable energy sources; hybrid perovskite-flexible photovoltaic

solar cells with series and multi-junction designs achieving 50% efficiency can be used in military and defense systems for a variety of applications where portability, flexibility and durability are critical;

2. Portable power for field equipment: Solar cells integrated into backpacks, tents, or clothing can power communications equipment, GPS devices, and other critical electronics in the field;

3. Solar-powered drones: Military surveillance drones or unmanned vehicles can utilize flexible solar cells to extend mission duration without the need for fuel or frequent recharging;

4. Rapidly deployable power systems: Flexible solar cells can be quickly deployed in the field to provide temporary power to command centers, medical facilities or charging stations in disaster zones or combat operations.

Figures

Figure 1. Schematic of hybrid perovskite-organic photovoltaic flexible solar cell with tandem and multi-junction design achieving 50% efficiency, showing multi-layer structural design

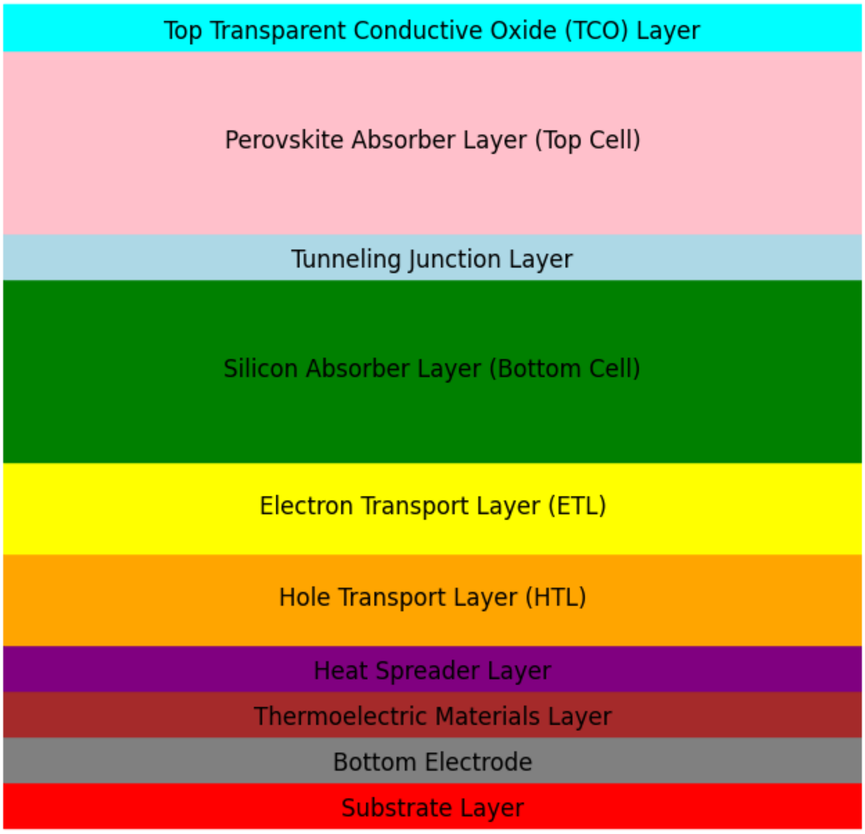

Figure 2. Cross-sectional schematic diagram of the hybrid perovskite-organic photovoltaic flexible solar cell structure with photonic crystal and quantum dot nanostructures.

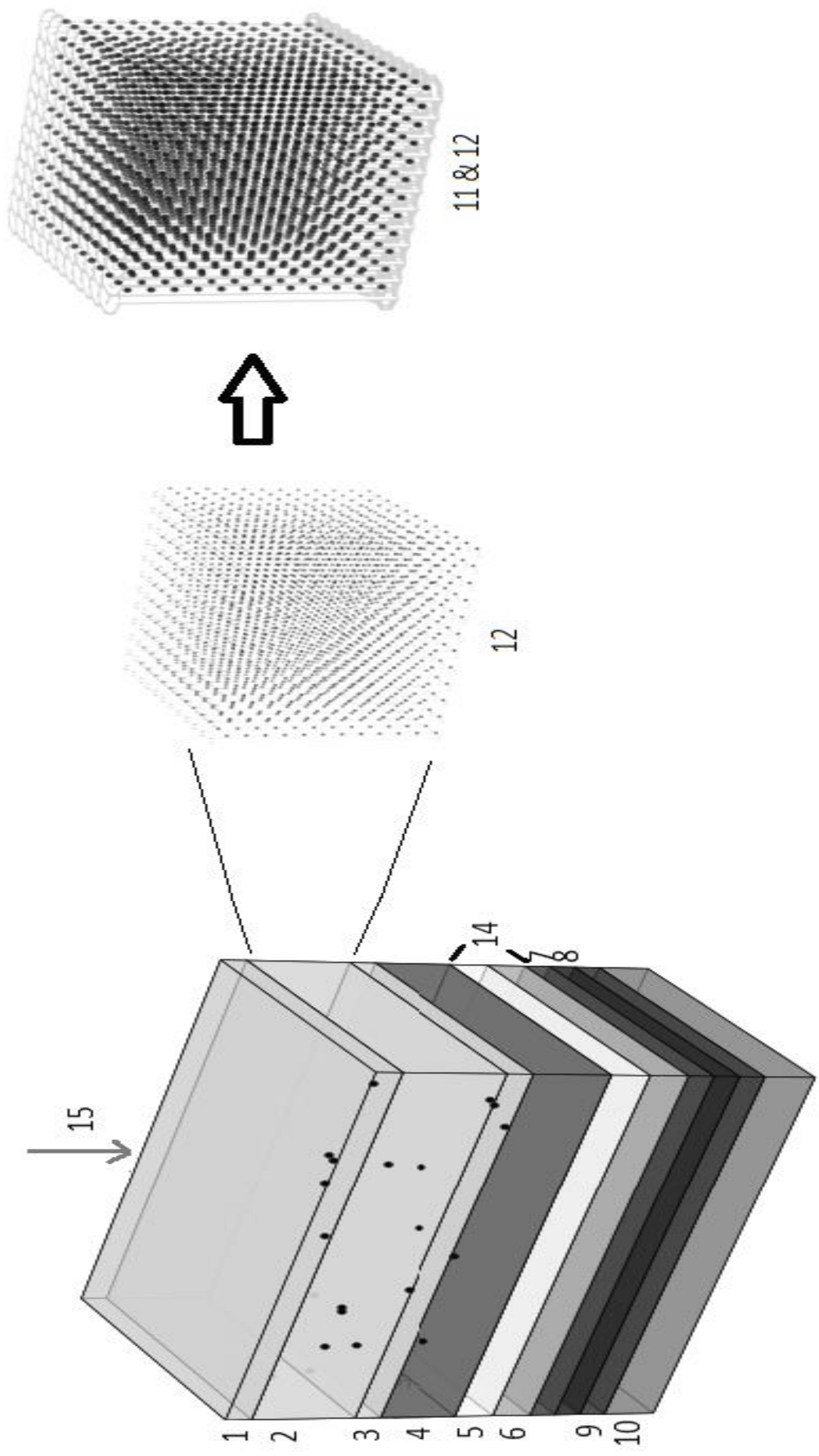

Figure 3. Schematic diagram of an advanced light management system using quantum dot nanoparticles and photonic crystals

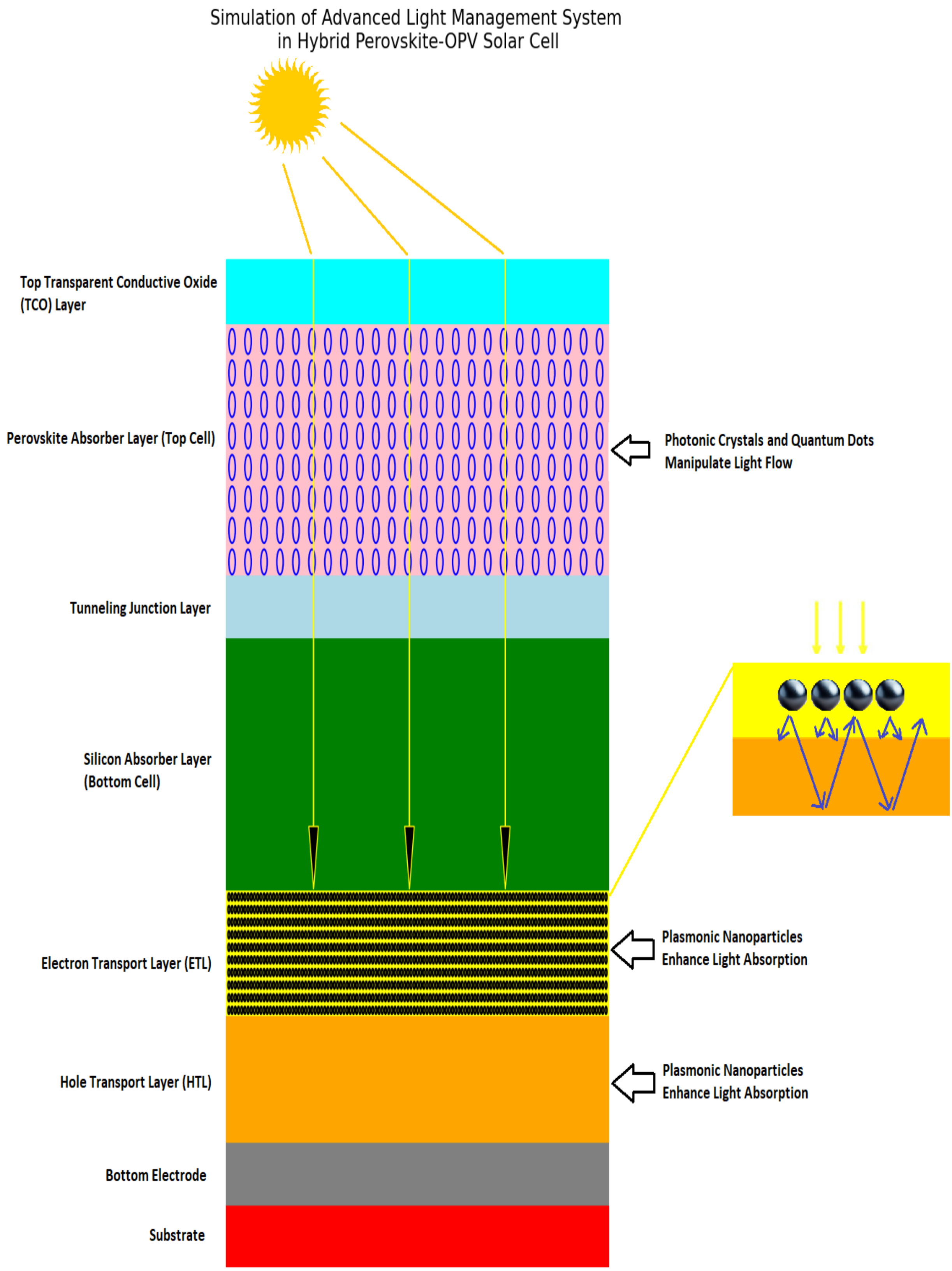

Figure 4. Overview of the roll-to-roll manufacturing process.

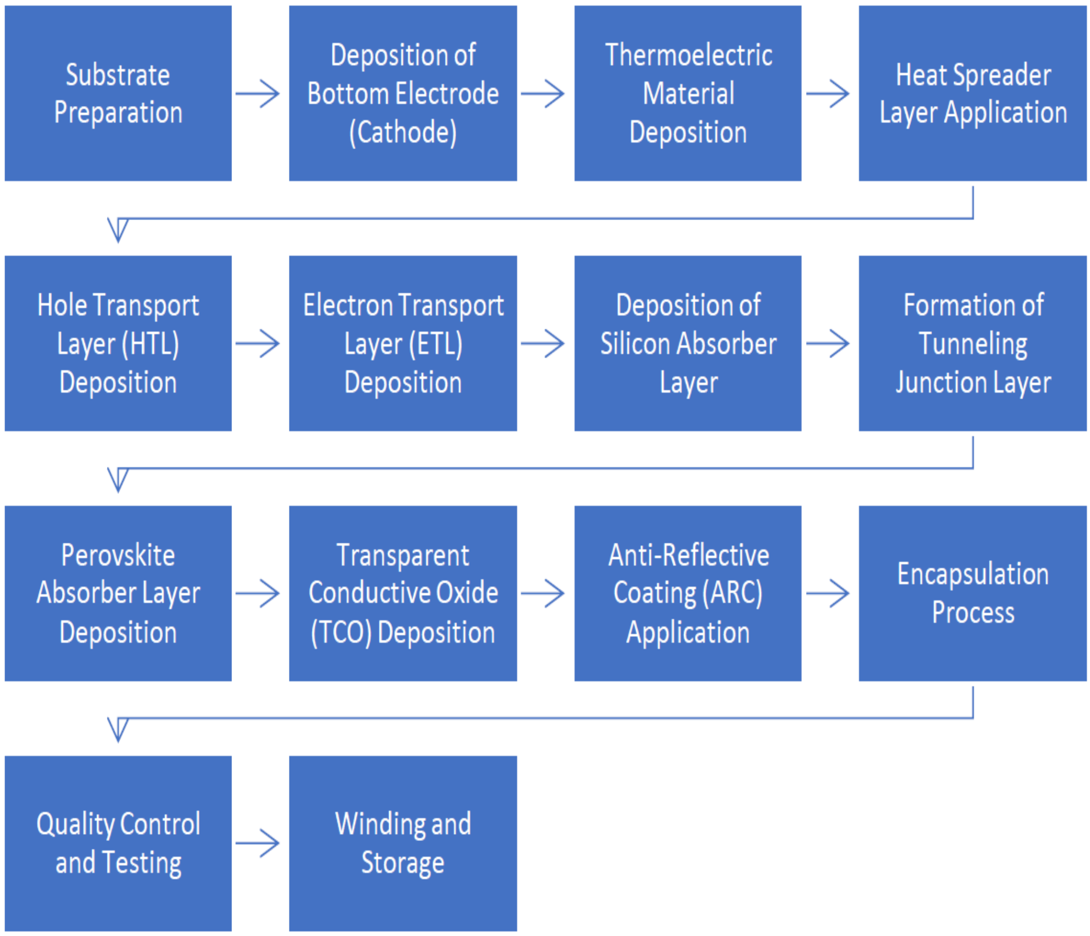

Figure 5. This new type of hybrid perovskite-organic photovoltaic flexible cell has the characteristics of series connection and multi-junction design to achieve 50% efficiency.