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## **Solar Panel Optimization Based on Graphene-Silicon-Droplet Integration for Hybrid Solar-RF Energy Harvesting System**

Dr. Ahmed Kabeel

**26-28 January 2025**

The Ritz-Carlton Jeddah, Kingdom of Saudi Arabia

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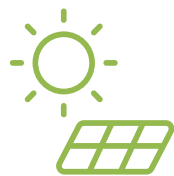
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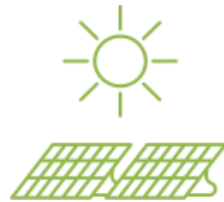
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# Our Agenda



**Solar Energy**



**Solar Panel Optimization**



**Research Direction.**



**Proposed System.**  
Hybrid Solar-RF EH System



**Results And Discussion .**



**Conclusion & Future work.**

# Solar Energy

- ✓ **Solar energy is crucial for sustainable and clean energy**
- ✓ **Reliable and lasting energy source but also a very cost-effective and efficient.**
- ✓ **Techniques to generate, use, and store the sun's energy by using different types of solar panels.**

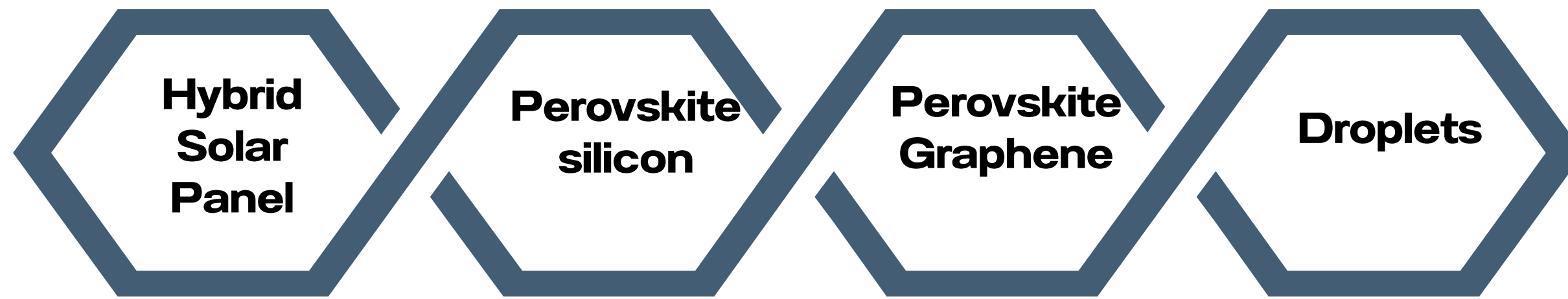
**Note:** A solar cell is an electrical device that converts the energy of light directly into electricity by the photovoltaic effect.



# Solar Panel Optimization

Ongoing research focuses on “**Hybrid Solar Panels**” with perovskite, silicon, graphene, and raindrop energy, where:

- Hybrid panels hold promise for reshaping the energy landscape towards sustainability.
- Raindrop energy is an innovative addition for diversified energy sources.



# Research Directions

✓ **Perovskite-silicon hybrid cells:**  
Combine light absorption of perovskite and silicon efficiency.

✓ **Perovskite Solar Cell Development:**  
Encompasses materials discovery, synthesis, fabrication, optimization, and integration.

✓ **High-Efficiency Breakthrough:**  
Scientists at KAUST achieve 33.7% efficiency in perovskite-silicon solar cell.



# Research Directions



## Graphene-perovskite solar cell

Graphene enhances conductivity, improving charge transport and panel efficiency.

Graphene-perovskite solar cell achieved 20.3% efficiency.

**Joule** | Article

**Mechanically Stacked, Two-Terminal Graphene-Based Perovskite/Silicon Tandem Solar Cell with Efficiency over 26%**

Enrico Lamanna,<sup>1</sup> Fabio Matteocci,<sup>1</sup> Emanuele Calabrò,<sup>1</sup> Luca Serenelli,<sup>2</sup> Enrico Salza,<sup>2</sup> Luca Marti, Francesca Menchini,<sup>2</sup> Massimo Izzi,<sup>2</sup> Antonio Agresti,<sup>1</sup> Sara Pescetelli,<sup>1</sup> Sebastiano Bellani,<sup>4</sup> Antonio Esau Del Rio Castillo,<sup>1</sup> Francesco Bonaccorso,<sup>1,5</sup> Mario Tucci,<sup>2,6\*</sup> and Aldo Di Carlo<sup>1,4,7,\*</sup>

**SUMMARY**  
Perovskite/silicon tandem solar cells grade the market-leading crystalline silicon. Two-terminal architectures resist four-terminal ones. However, it is challenging to directly stack the perovskite onto the silicon surface of record-high efficiency amorphous silicon solar cells. To overcome these hurdles, we present a mechanically stacked, two-terminal perovskite/silicon tandem solar cell, with the perovskite and silicon cells directly stacked, and subsequently coupled by an optical perovskite top cell with the textured silicon bottom cell. By minimizing optical loss, we demonstrate a 26.3% efficiency (1.43 cm<sup>2</sup>).

**INTRODUCTION**  
The current cost of commercially available and the power conversion efficiency (PCE) (PV) technology<sup>1</sup> is gradually approaching 29.4%.<sup>2</sup> The up-to-date record PCE of 26.1% using an interdigitated back contacts (IBC) structure is very close to the predicted 30%. This result is very close to the predicted performance. In fact, bulk recombination due to surface defects, lateral transport loss, front surface optical loss, and resistive loss.<sup>3,4</sup> Cu technology is related to the area-dependent average total utility-scale system (inverters, mounting systems, inverters, and positioning system (GPS) solar tracker, and irradiance sensors). It is, therefore, pivotal to reduce the cost of electricity of photovoltaic (PV) technology. One approach to upgrading the PCE of silicon-based tandem solar cells, in which

**Energy & Environmental Science** | PAPER

**Efficient stable graphene-based perovskite solar cells with high flexibility in device assembling via modular architecture design†**

Nang,<sup>1</sup> Hong Zhang,<sup>1</sup> Yulin Feng,<sup>2</sup> Wenming Tian,<sup>3</sup> Yuchen Wang,<sup>4</sup> Shengye Jin,<sup>5</sup> Yuhang Yin,<sup>6</sup> Michael Grätzel<sup>1</sup> and Yantao Shi<sup>1,4,\*</sup>

**Efficient stable graphene-based perovskite solar cells with high flexibility in device assembling via modular architecture design†**

Perovskite solar cells (PSCs) are emerging as low-cost stable photovoltaics. However, PSCs still lag behind that of devices based on Au or Ag as the current collector. To address this issue, we present an innovative modular PSC design using a carbon back electrode, whose cost is greatly reduced by covering it with another carbon-coated FTO substrate. Moreover, among the various commercial carbon sources (carbon black, graphite, carbon nanotubes, carbon fibers, and carbon nanofibers), graphene exhibited the best overall performance, showing the highest PCE of 18.65% as a charge collector. Power conversion efficiency (PCE) of 18.65% was achieved for IG-PSCs, which was among the highest efficiency reported so far for perovskite solar cells. Remarkably, G-PSCs showed significant structural stability in PCE after repeated disassembling and assembling for more than 1000 cycles. This work provides a promising prospect for the facile repair and maintenance of PSCs via modular architecture design.

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**The roles of graphene and its derivatives in perovskite solar cells: A review**

Kaiwen Gong<sup>a,b</sup>, Jichao Hu<sup>c</sup>, Nan Cui<sup>a,\*</sup>, Yunzhou Xue<sup>d</sup>, Lianbi Li<sup>a,b,e</sup>, Gen Long<sup>a,\*</sup>, Shenghuang Lin<sup>a,\*</sup>

**HIGHLIGHTS**

- PSCs is considered to be the most promising energy conversion candidate for carbon-free energy production in the next few years.
- How to keep PSCs high-performance and good stability is still a key issue.
- Graphene and its derivatives have revealed their advantages in the field of PSCs.
- Future challenges and opportunities for development of graphene and its derivatives in PSCs in the future are discussed.

**GRAPHICAL ABSTRACT**

**ARTICLE INFO**

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**ABSTRACT**

With the rapid demand growth of green energy technologies, solar cell has been considered as a very promising technology to address current energy and environmental issues. Among them, perovskite solar cells (PSCs) have attracted much research interest in recent years due to the prominent advantages of high weight, good flexibility, low cost, and comparable power conversion efficiency (PCE) to that of traditional commercial solar cells (i.e. amorphous silicon, GaAs, and CdTe). Meanwhile, elemental two-dimensional (2D) graphene and its derivatives, which possess the outstanding advantages of abundant functional groups, good environmental stability, and good compactness, have been extensively studied on the integration with PSC devices. The review introduces the properties and preparation methods of graphene and its derivatives, and the applications in PSC are summarized in detail. Ultimately, the critical challenges and prospects for the further development of graphene and its derivatives in PSCs are discussed.

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**1. Introduction**

Global energy consumption has reached 16 terawatts in 2006 and is predicted to increase to ~30 terawatts by 2050 [1]. However, traditional energy sources such as fossil fuels usually increase

# Research Directions

## ✓ Droplet Layer:

Transistor-inspired structure introduced new coplanar-electrode which overcomes issues related to parasitic capacitance. Strip-like droplet energy harvesting panel overcomes challenges, achieving high output voltage.

## ✓ Raindrop energy harvesting:

Raindrop impact's kinetic energy can supplement solar energy, especially in rainy regions.

## ✓ Radio Frequency Energy harvesting

energy conversion technique employed for converting energy from the electromagnetic (EM) field into the electrical domain.

**Joule** | Article

**Mechanically Stacked, Two-Terminal Graphene-Based Perovskite/Silicon Tandem Solar Cell with Efficiency over 26%**

Enrico Lamanna,<sup>1</sup> Fabio Matteocci,<sup>1</sup> Emanuele Calabrò,<sup>1</sup> Luca Serenelli,<sup>2</sup> Enrico Salza,<sup>2</sup> Luca Martir Francesca Menchini,<sup>2</sup> Massimo Izzi,<sup>2</sup> Antonio Agresti,<sup>1</sup> Sara Pescetelli,<sup>1</sup> Sebastiano Bellani,<sup>4</sup> Antonio Esau Del Rio Castillo,<sup>4</sup> Francesco Bonaccorso,<sup>4,5</sup> Mario Tucci,<sup>2,\*</sup> and Aldo Di Carlo<sup>1,4,7,\*</sup>

**SUMMARY**  
Perovskite/silicon tandem solar cells upgrade the market-leading crystalline silicon limit. Two-terminal architectures reveal four-terminal ones. However, it is challenging to fabricate solar cells directly onto the micro face of record-high efficiency amorphous silicon which limits both high-temperature and tandem solar cells. To tackle these hurdles, we present a mixed silicon/silicon tandem solar cell, with the silicon and subsequently coupled by a microscopic perovskite top cell with the textured silicon bottom cell. By minimizing optical loss selective layer/near contact structure porous electron selective layer for the p device demonstrates a 26.3% efficiency 1.43 cm<sup>2</sup>.

**INTRODUCTION**  
The current cost of commercially available and the power conversion efficiency (PCE) (PV technology) is gradually approaching 29.4%. The up-to-date record PCE of 26.1% using an interdigitated back contacts (IBC) This result is very close to the predicted p into account practical loss mechanisms in effects include bulk recombination due to its edge loss, lateral transport loss, front surface optical loss, and resistive loss.<sup>1-3</sup> Cu technology is related to the area-dependent the average total utility-scale system switches, mounting systems, inverters, and positioning system (GPS) solar tracker, an irradiance sensors. It is, therefore, pivotal to upgrade the PCE of perovskite/silicon tandem solar cells, in which

**Energy & Environmental Science**

PAPER

**Droplet energy harvesting panel†**

Xiaote Xu, Pengyu Li, Yongtao Ding, Wanhui Xu, Shiyuan Liu, Zhuomin Zhang, Zuankai Wang and Zhengbao Yang\*

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**Harvesting energy from light and water droplets by covering photovoltaic cells with transparent polymers**

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**HIGHLIGHTS**

- Harvesting energy from light and water drops simultaneously using hidden or transparent front-electrode.
- Highest photovoltaic performance with surface charge transfer, losses with electrostatic induction electrode.
- Curved electrodes allow easy removal of water drops.

**GRAPHICAL ABSTRACT**

**ARTICLE INFO**

**Keywords:**  
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Contact electrification  
Renewable energy

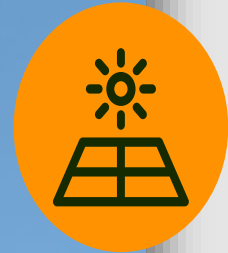
**ABSTRACT**  
Energy harvesting of sunlight is often done using photovoltaic cells covered by a protective layer of polymer or glass. Currently, this layer does not have any other function than being transparent and protective, but its functionality could be improved and in fact contribute to electrical energy harvesting from the environment. This work reports new findings on the integration of silicon-based photovoltaic solar with a water droplet energy harvesting device based on contact electrification using readily available materials. The water droplet energy harvesting device utilizes hidden or transparent front electrodes in flat or curved geometries to increase the power output due to water droplets while at the same time minimizing the power loss from the photovoltaic cell. Three different designs are designed and tested, and the advantages and disadvantages are outlined. Particular emphasis is put on investigating the performance of the flat cell design that exhibited the largest electrical power output due to water droplet impact. The electrical energy harvesting efficiency of the commercial photovoltaic cell is about 4.6%, whereas for the water droplet energy harvesting device it is about 6.0%. The relative contributions of the two energy harvesting mechanisms are analyzed, and possible applications outlined.

**1. Introduction**  
There is an increasing demand for local renewable electrical energy harvesting systems which do not need large scale investments or infrastructures. Photovoltaic solar cells are currently an important part of the strategy to fulfill these demands. However, an important question is

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# Proposed System



**01. Perovskite/Silicon Tandem Solar Cell**



**02. Graphene in Perovskite Solar Cells**



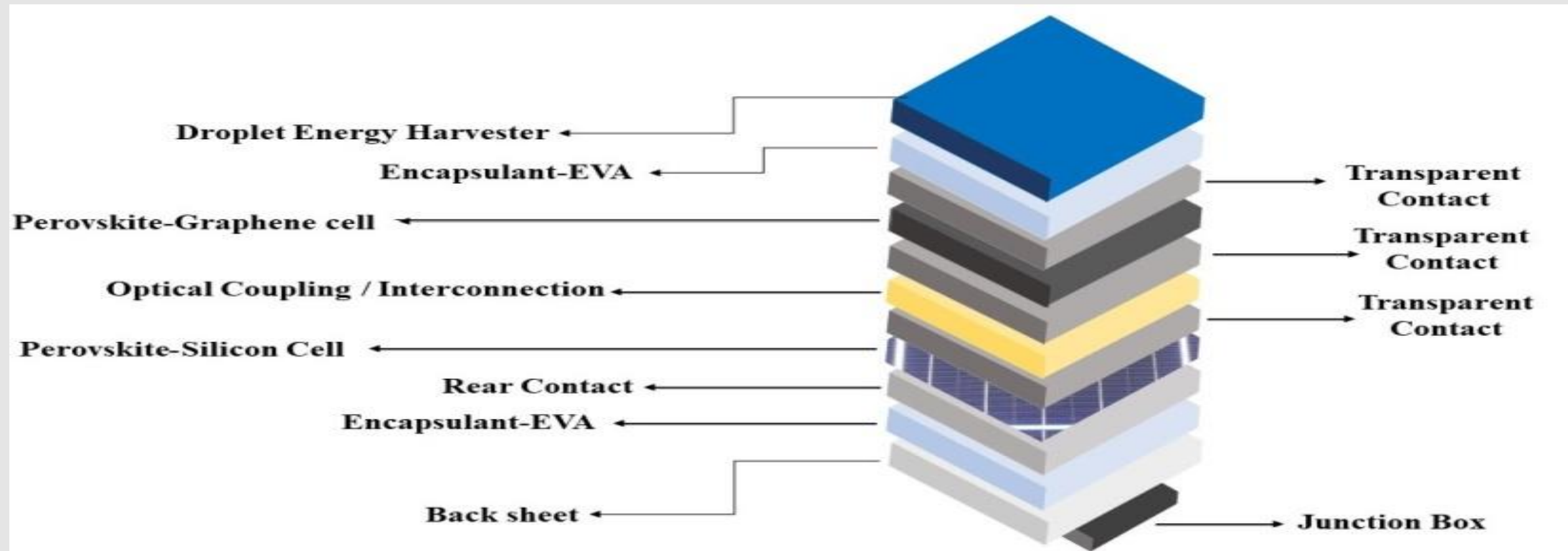
**03. Droplet Layer**



**04. Antenna**



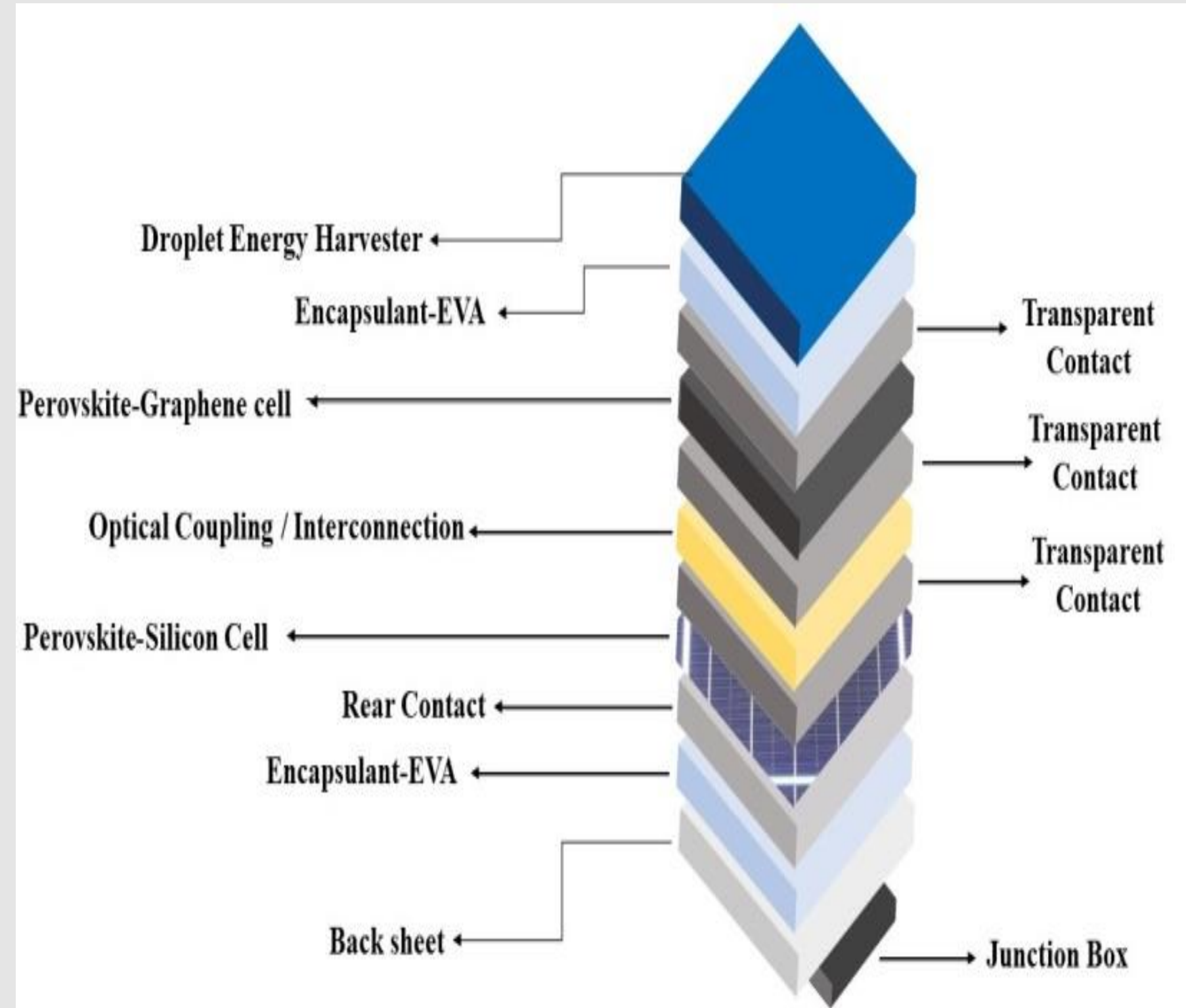
# Advanced Solar Panel Configuration



**Adaptive configuration captures sunlight and raindrop energy.**

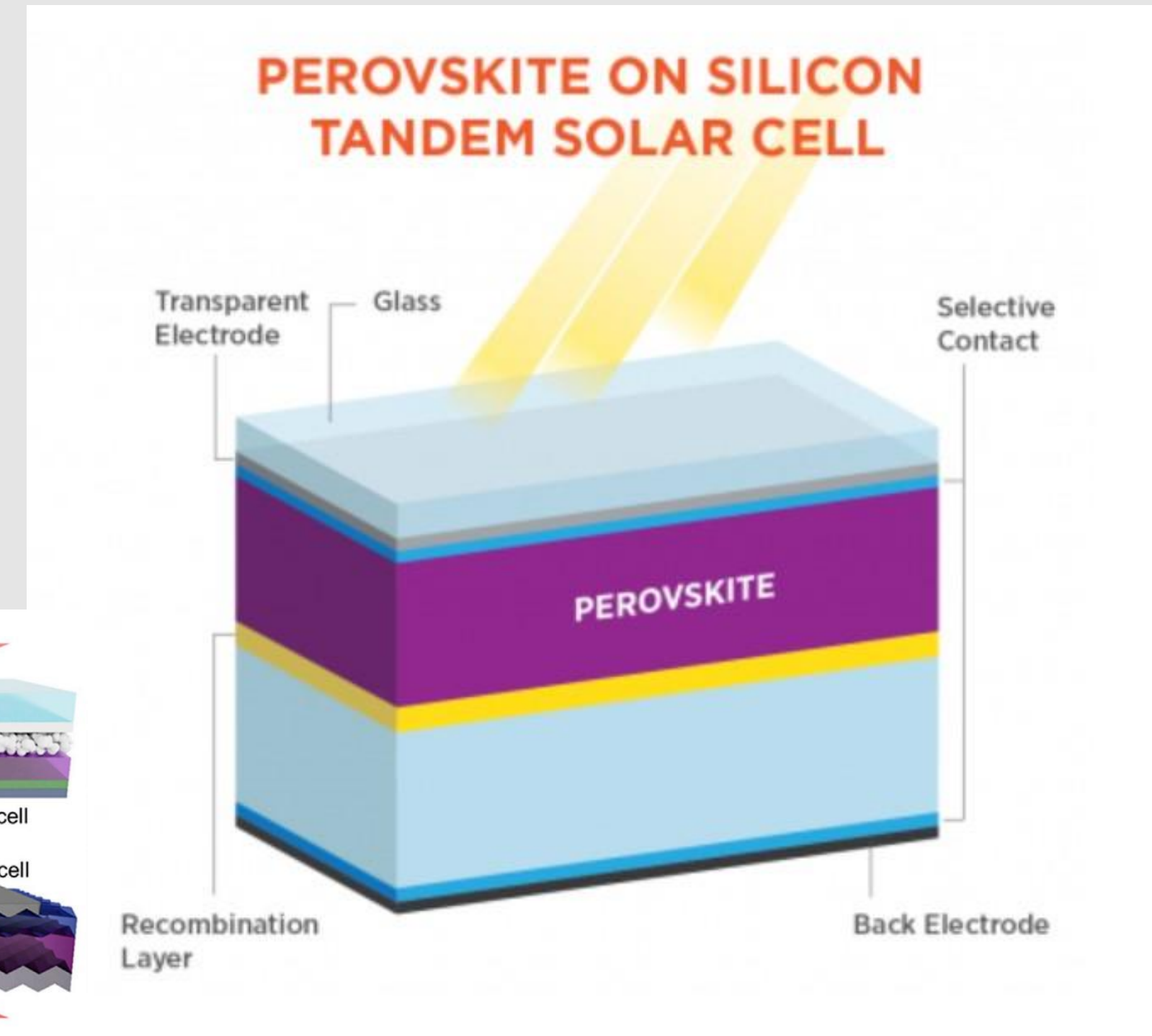
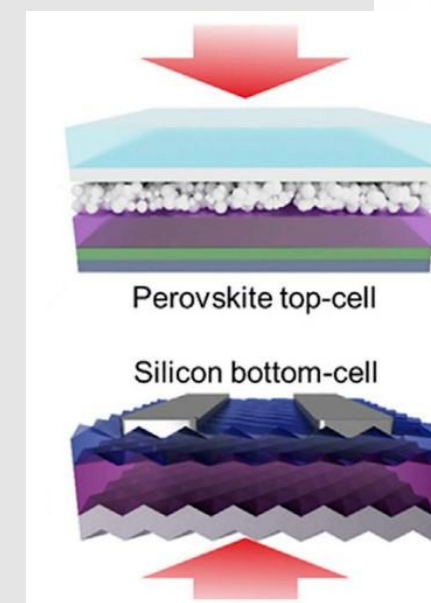
# Proposed System

- ✔ **Silicon layer:**  
Enhances charge separation and collection efficiency.
- ✔ **Perovskite layers:**  
Excel in light absorption, generating electron-hole pairs.
- ✔ **Graphene layer:**  
Acts as a superior conductor, amplifying charge transport.
- ✔ **Raindrop Energy Panel:**  
Raindrop impact generates electrical charge, adding to power generation.



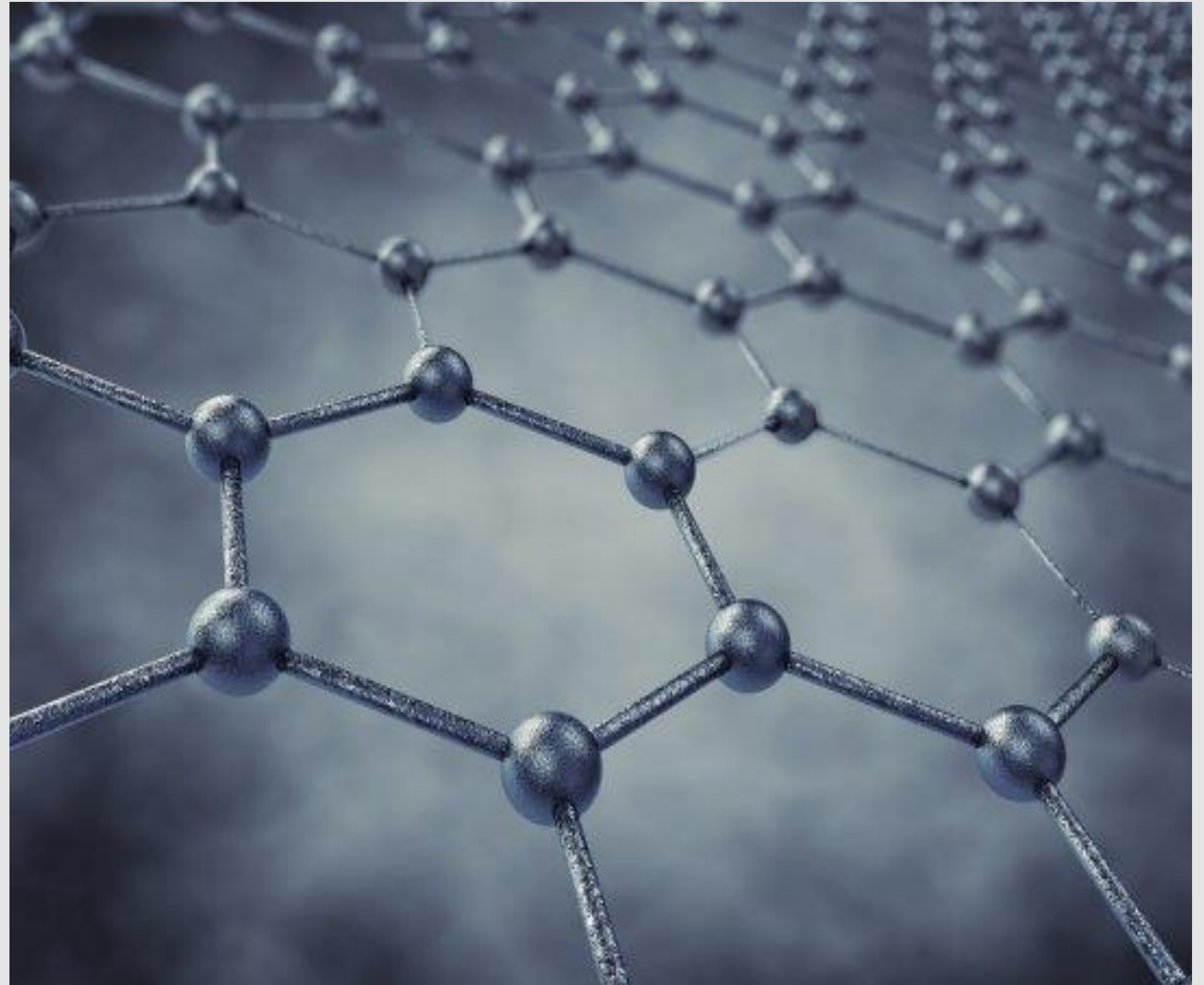
# Perovskite/Silicon Tandem Solar Cell Structure

- *Unified Solar Device Integration:*  
Merges perovskite and silicon technologies for enhanced solar spectrum capture and higher efficiency.
- *Perovskite Solar Cell Evolution:*  
Encompasses material discovery, synthesis, fabrication, optimization, and integration with other solar tech.

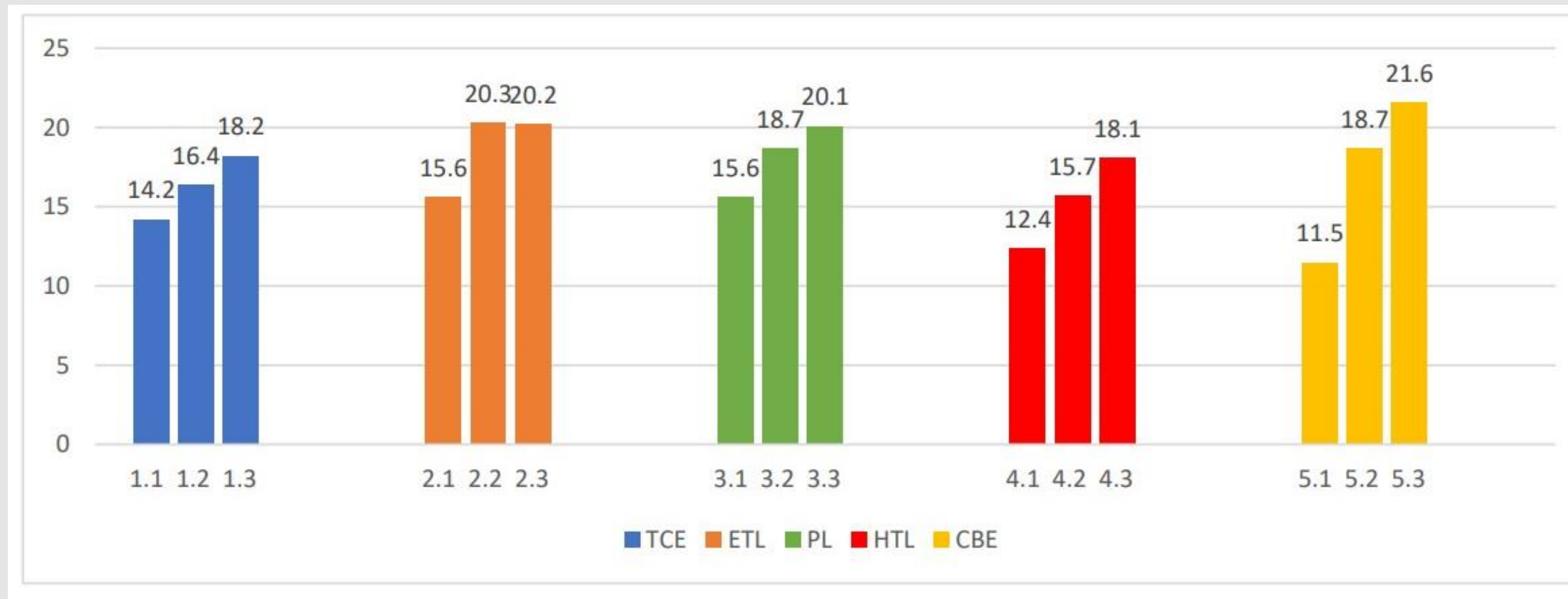


# Graphene Features

- *Two-dimensional (2D) material.*
- *Optical Transparency.*
- *Electrical Conductivity*
- *Carrier Transport Properties.*



# Graphene in Perovskite solar cells:



## Performance Impact of Graphene in Perovskite Solar Cell Layers

The position of graphene doping in one of the five layers significantly impacts the performance and efficiency of perovskite solar cells.

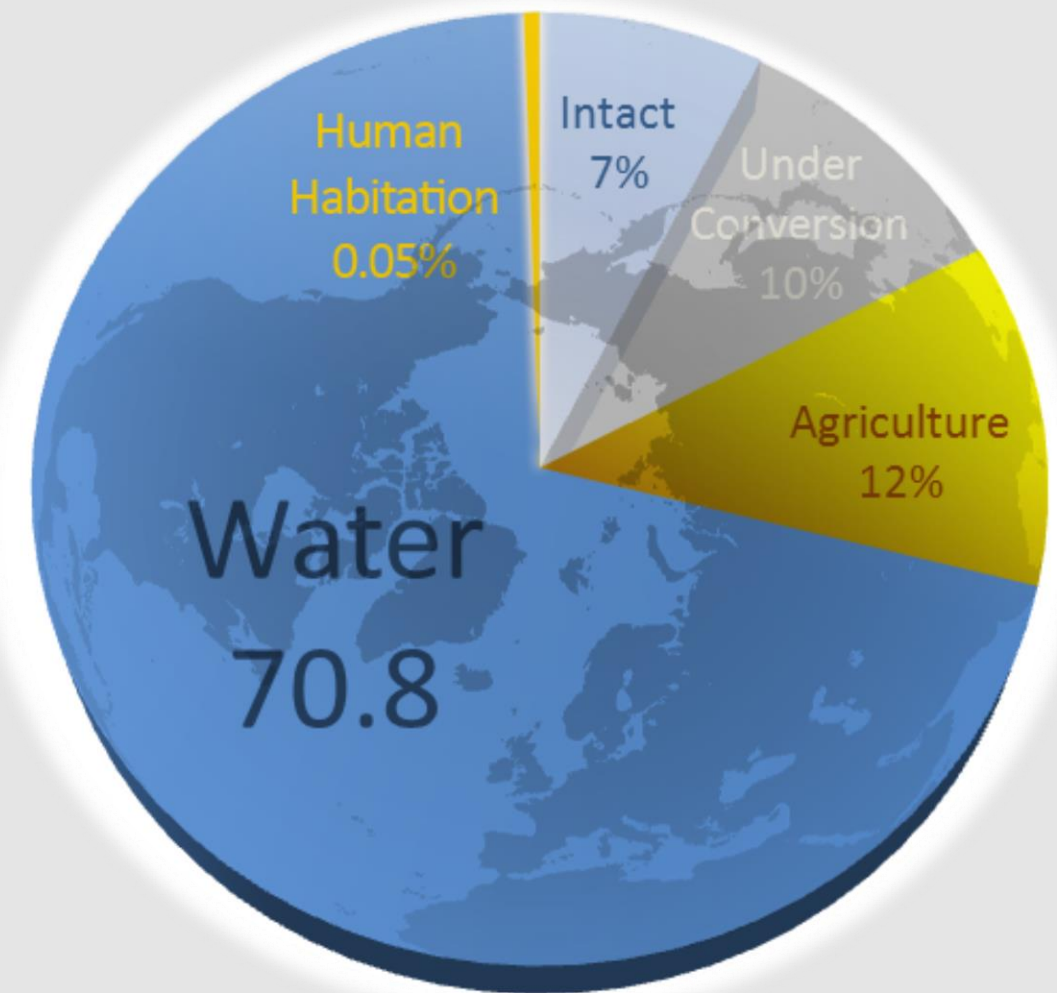
# Droplet Energy Harvesting

## Untapped Water Energy Potential:

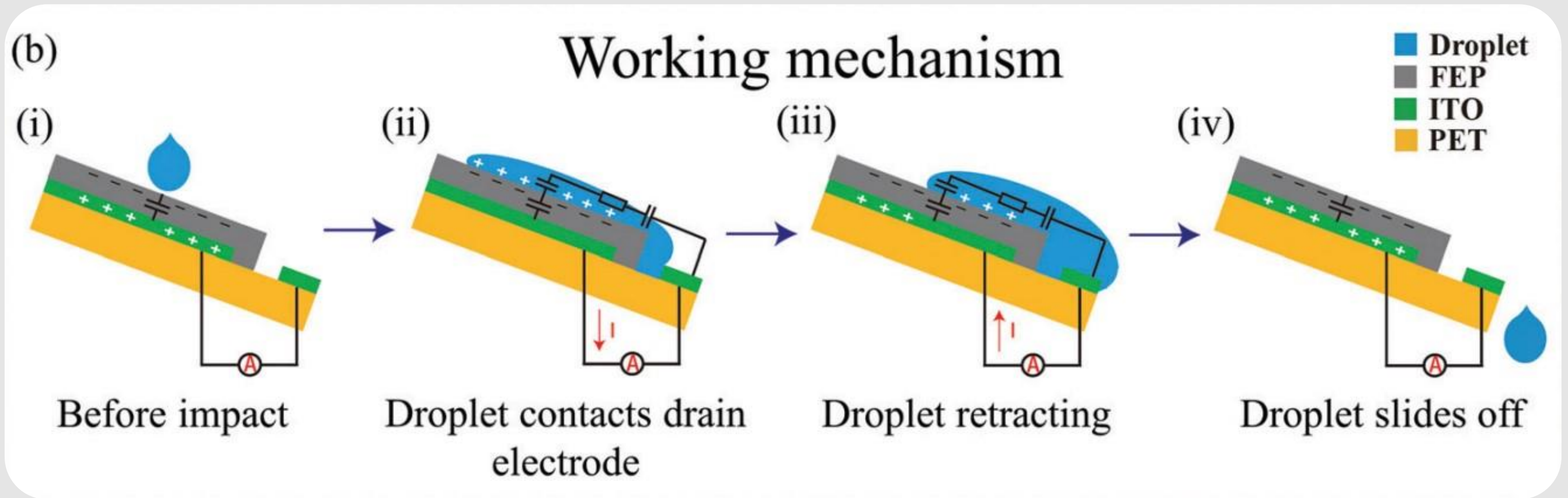
- 70% of the Earth's surface is covered by water.
- Earth's water holds substantial energy in various motion forms.
- Raindrops alone possess significant kinetic energy.
- An underutilized resource.

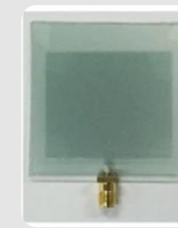
## Raindrops Energy Global Impact:

- Raindrops contribute substantial kinetic energy - 3000 TW h annually.
- This energy accounts for 5% of the world's yearly energy consumption.



# Droplet Mechanism



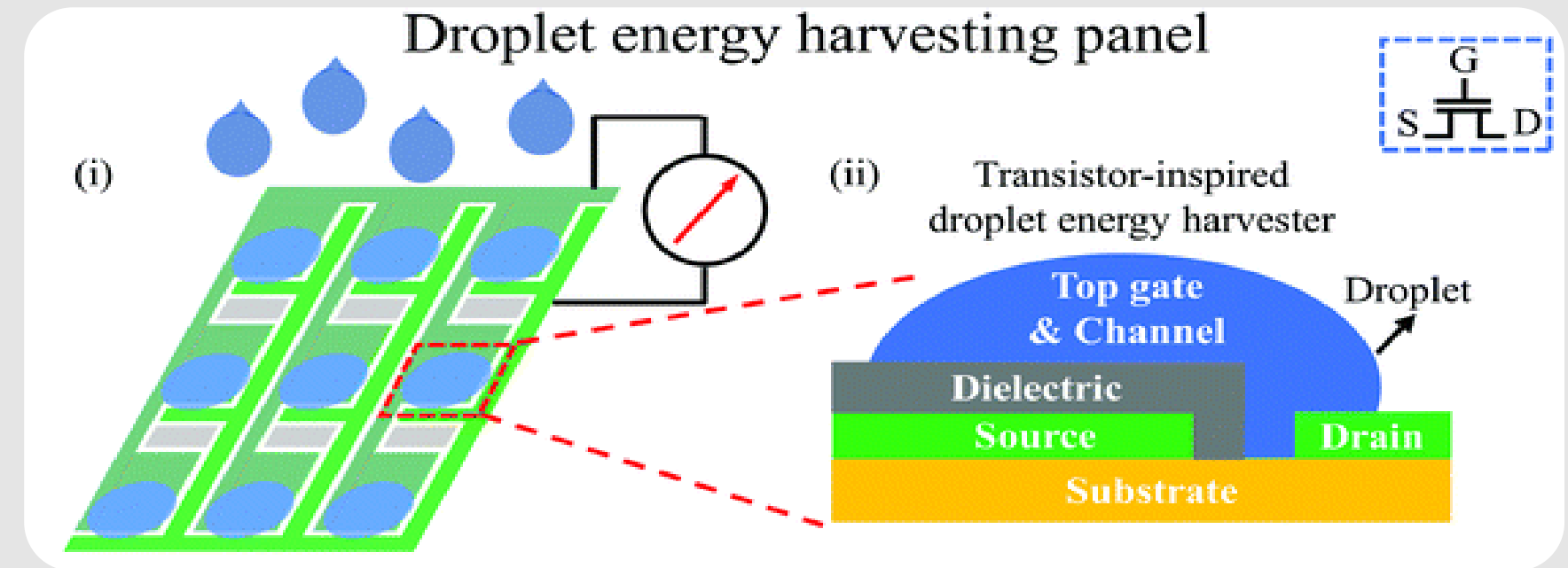


# Droplet Cell Structure

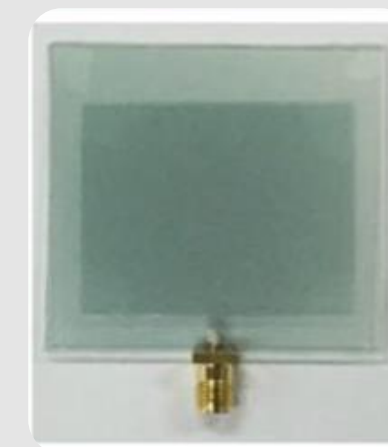
■	Droplet
■	FEP
■	ITO
■	PET

This transistor inspired structure DEH cell consists of 3 layers:

- **FEP:** Transparent Di-electric material, with strong electron-attraction ability.
- **ITO:** Transparent Conductor.
- **PET:** Transparent Hydrophobic Substance.



Transistor inspired structure DEH cell



ITO: Transparent Conductor.

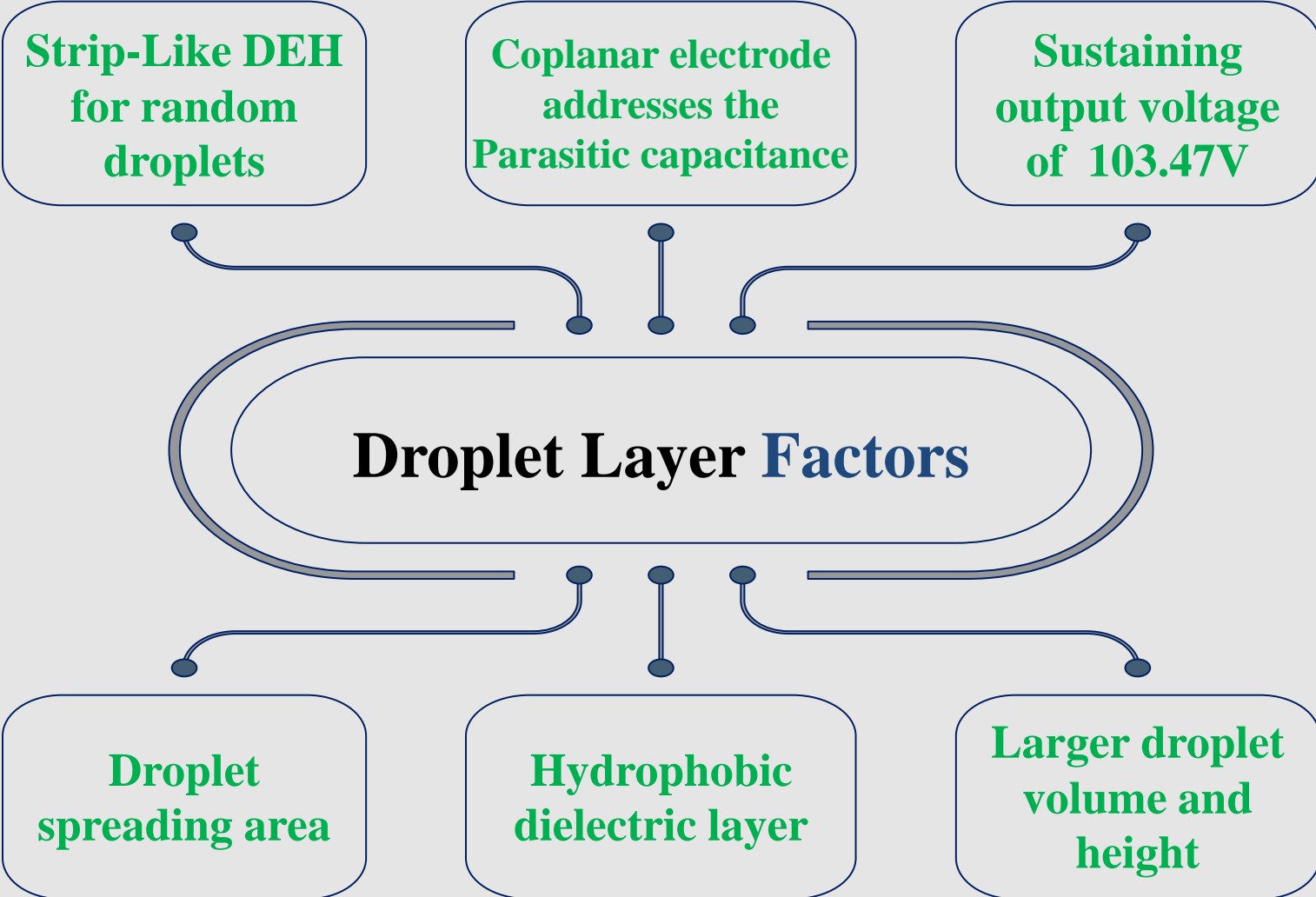
The coplanar **source** electrode and **drain** electrode were separated by etching a gap with a width of 1 mm on the ITO.



# Droplet Cell Features

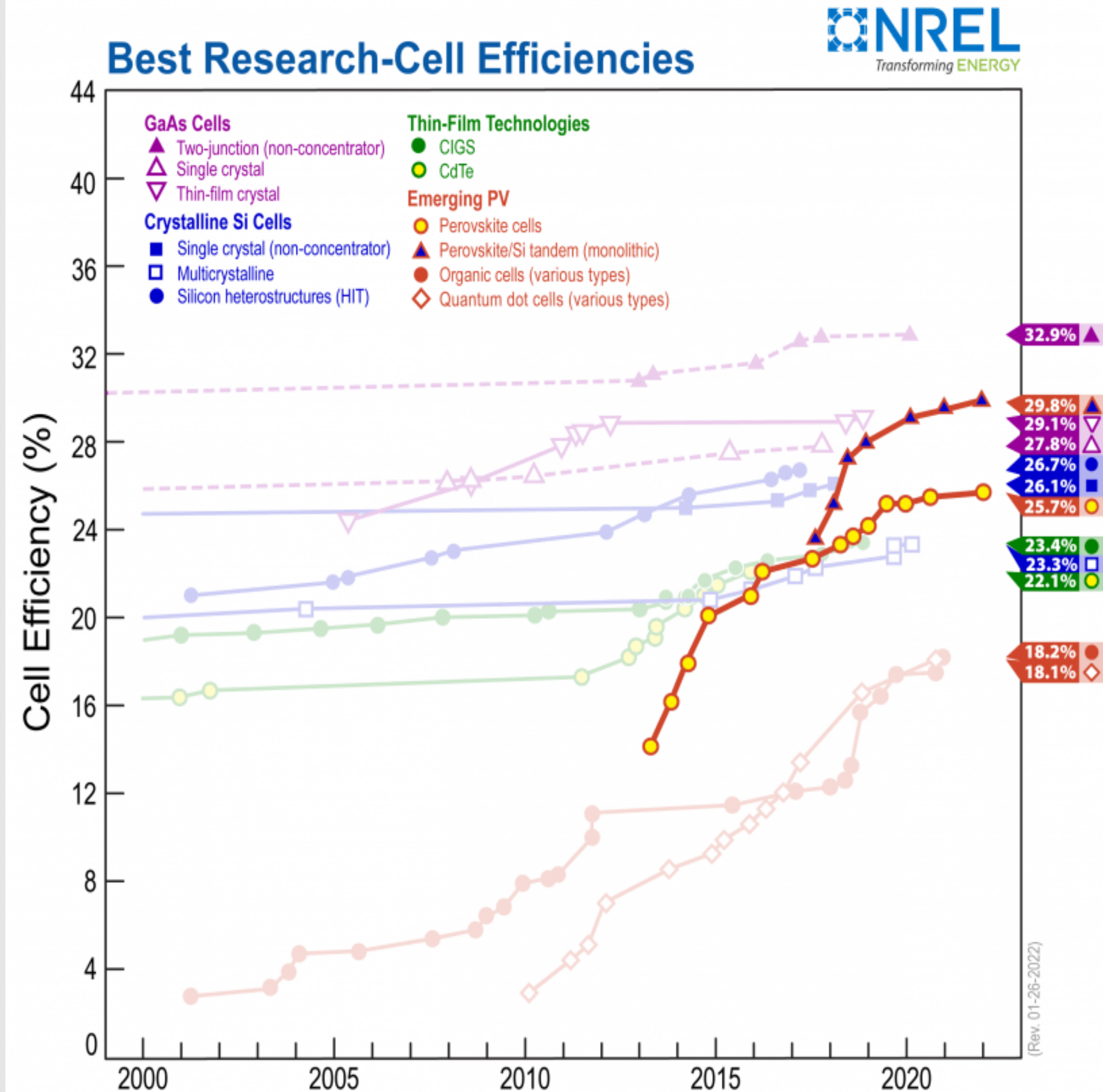
- Fully Transparent.
- High Performance.
- High-efficiency droplet energy harvesting under multi-position.
- **Robustness:**
  1. When the source–drain gap was covered by water, the output performance remained unchanged.
  2. After taking out from water, the output voltage gradually recovered and stabilized at about 220 V in 3 min.





# Simulation Results

- Perovskite/**Silicon Tandem** Solar Cell  
The expected theoretical PCE for such a solar cell is around 40%.
- **Up to now:**  
Scientists at KAUST achieved 33.7% efficiency in perovskite-silicon solar cell.



# Simulation Results

*By using the simulation software (COMSOL) yields the outcome:*

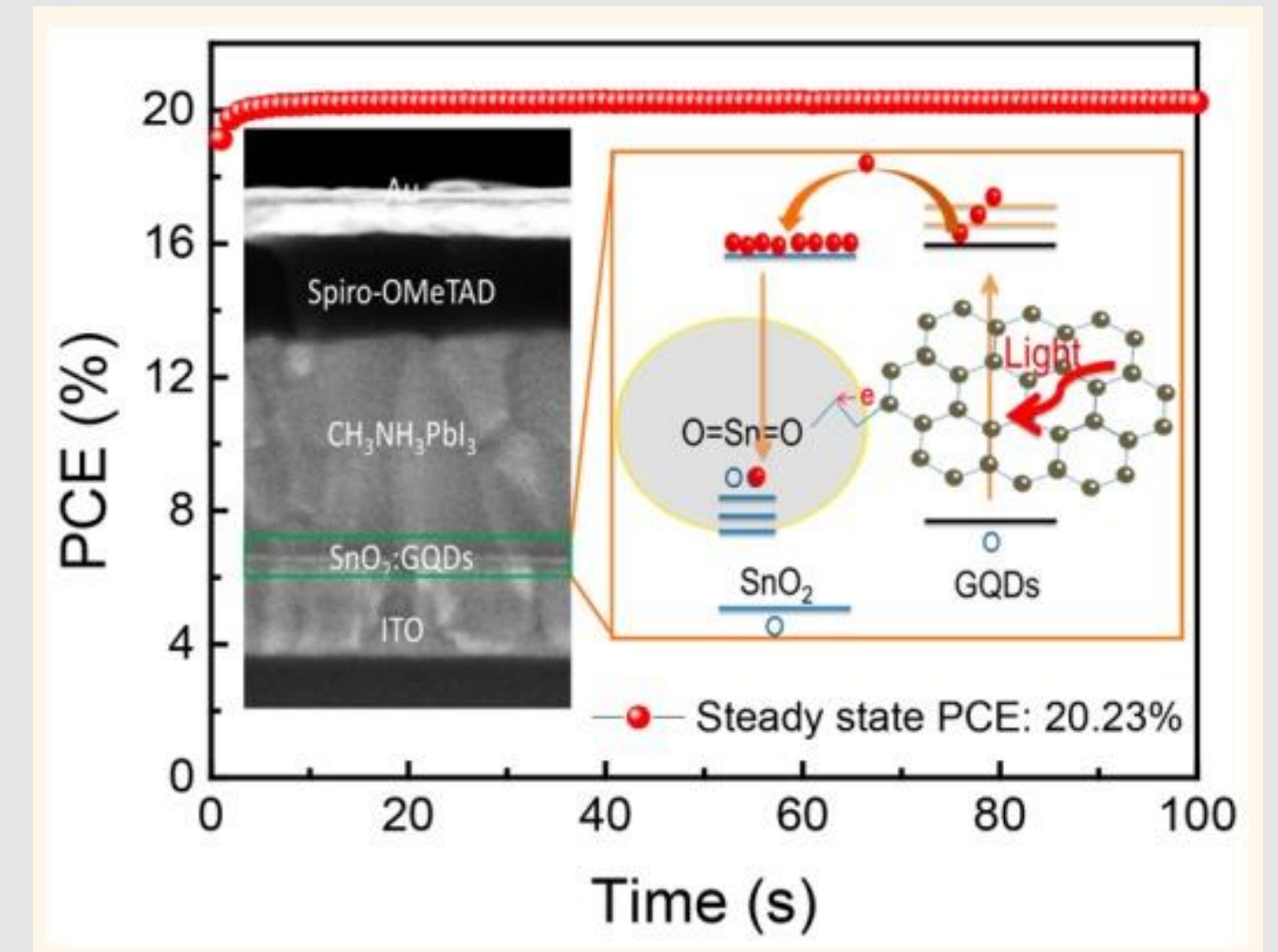
- Graphene in Perovskite solar cells

*Enhanced Device Performance with ( SnO<sub>2</sub>:GQDs):*

- Achieved average power conversion efficiency (PCE) of  $19.2 \pm 1.0\%$ .
- Peak steady-state PCE reached **20.23%** with minimal hysteresis.

*Method for Performance Enhancement:*

Enhancing electronic properties of SnO<sub>2</sub> effectively boosts cell performance.



**Result showcases improved perovskite solar cell performance**

# Simulation Results

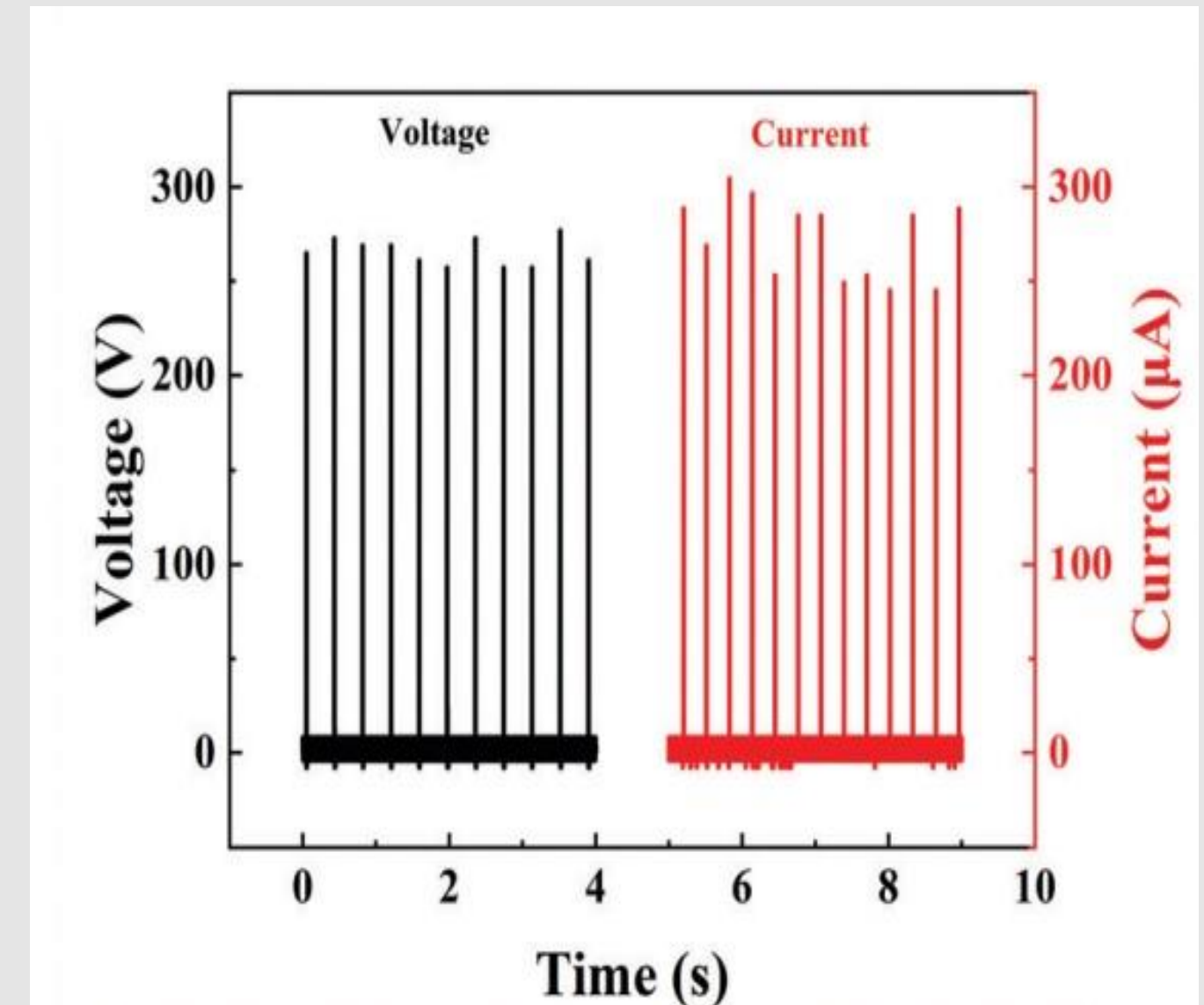
*By using the simulation software (COMSOL) yields the outcome:*

- **Droplet Energy Harvester:**

The latest achievement in DEH panel is a strip-like DEH panel to the coplanar-electrode DEH panel can delicately alleviates the parasitic capacitance issue.

Maintaining a high output voltage of 103.47V.

After taking out from water, the output voltage gradually recovered and stabilized at about 220 V in 3 min



Output voltage and current of the DEH cell

# RF Energy Harvesting

Radio frequency energy harvesting (RFEH) is an energy conversion technique employed for converting energy from the electromagnetic (EM) field into the electrical domain.

**In particular**, RF Energy Harvesting is a very appealing solution for use in body area networks as it allows low-power sensors and systems to be wirelessly powered in various application scenarios.



Fig.1. RF Waves Sources

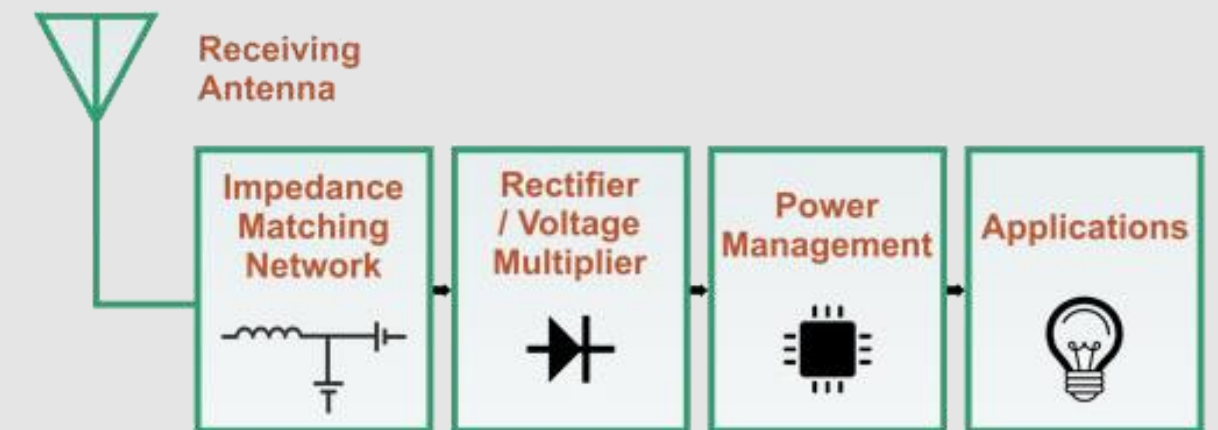


Fig.2. RF Energy Harvesting Block Diagram

# RF Energy Harvesting Design Procedure



## Band selection

- Local Survey for used bands and frequencies
- Band Usage and Allocation



## Circuit Design

- Combiner circuit design (only for antenna array)
- Rectifier Circuit design
- Matching network design



## Design of Antenna

- Patch Shape Selection and Analysis
- Design and Simulation
- Antenna Array Design

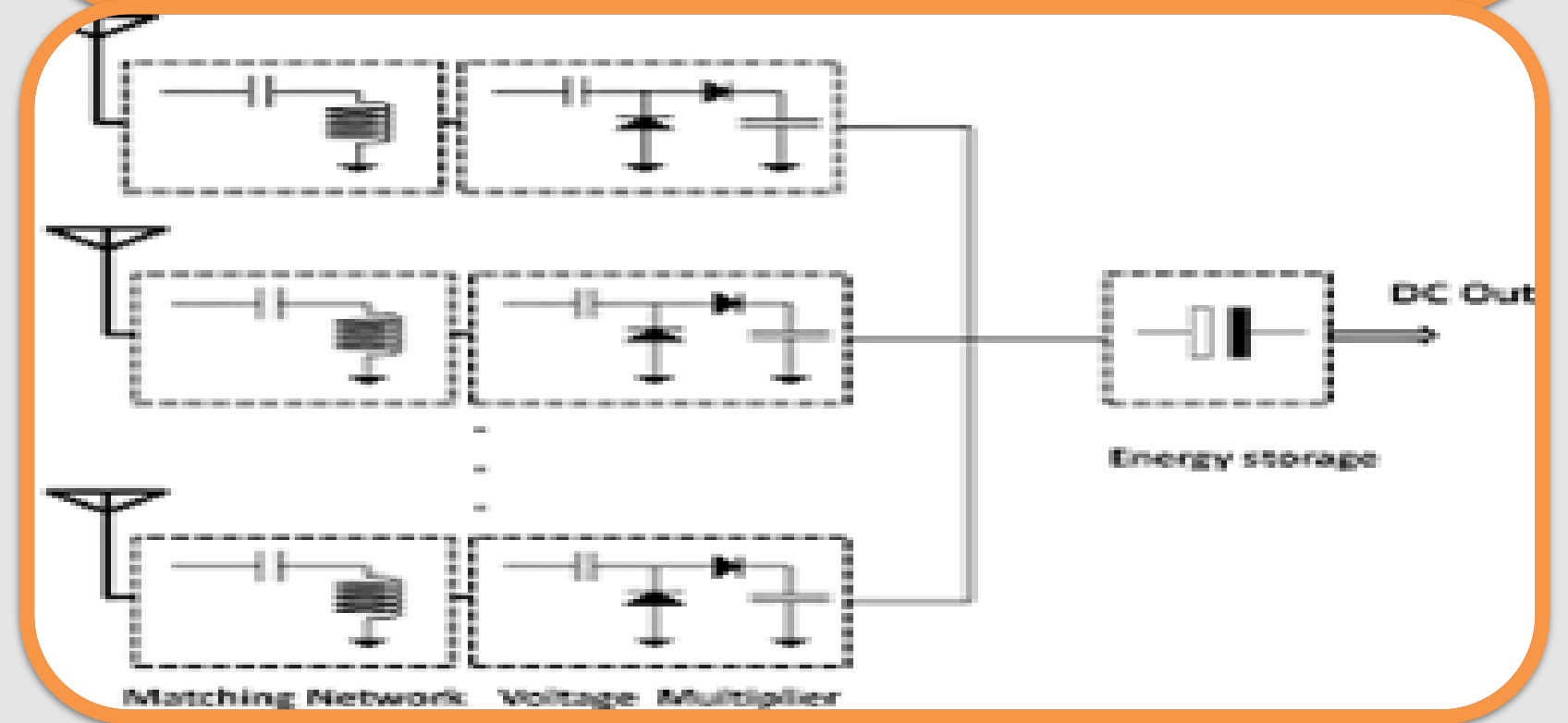
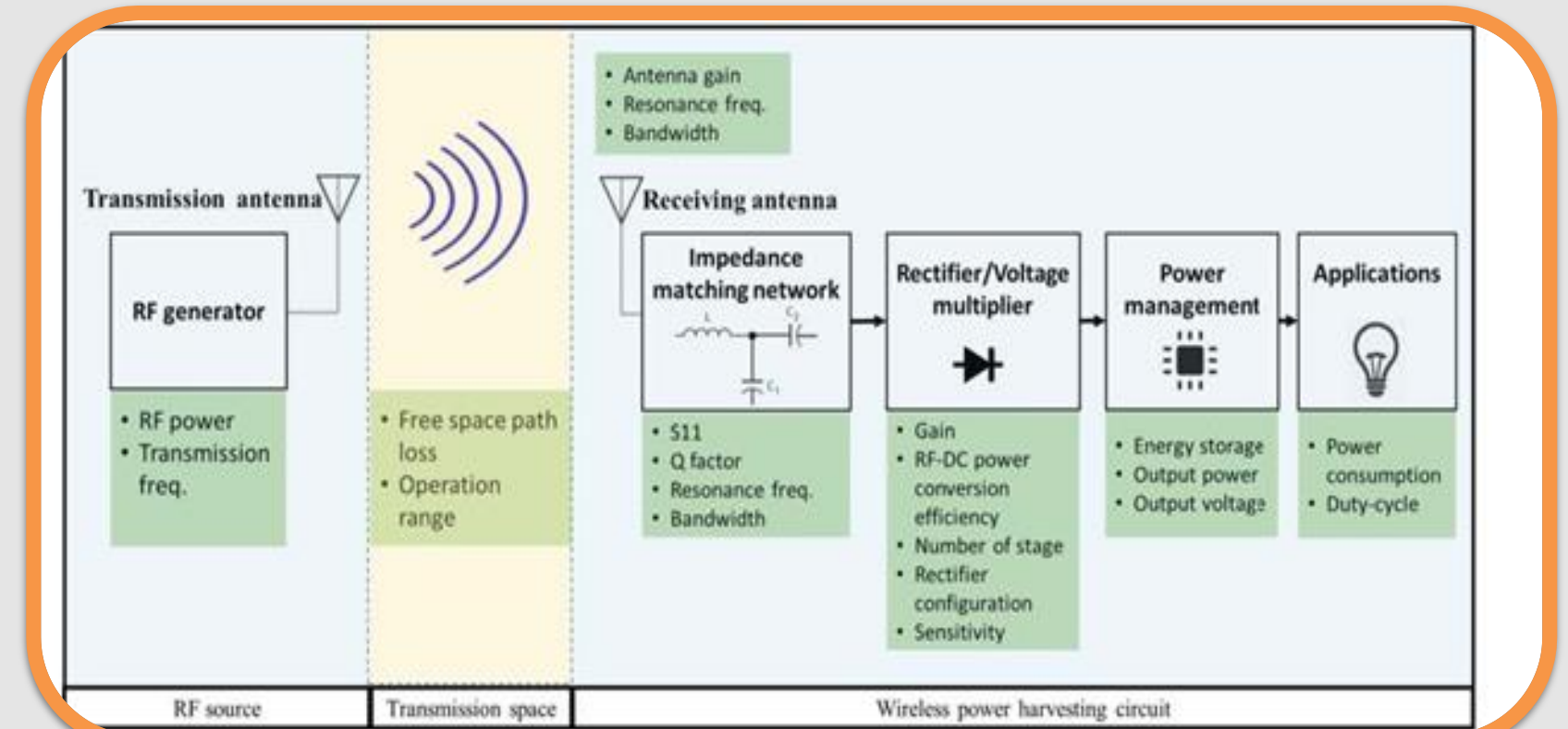


## Final Steps

- Fabrication
- Testing
- Assembly

# Using Antennas for Energy Harvesting

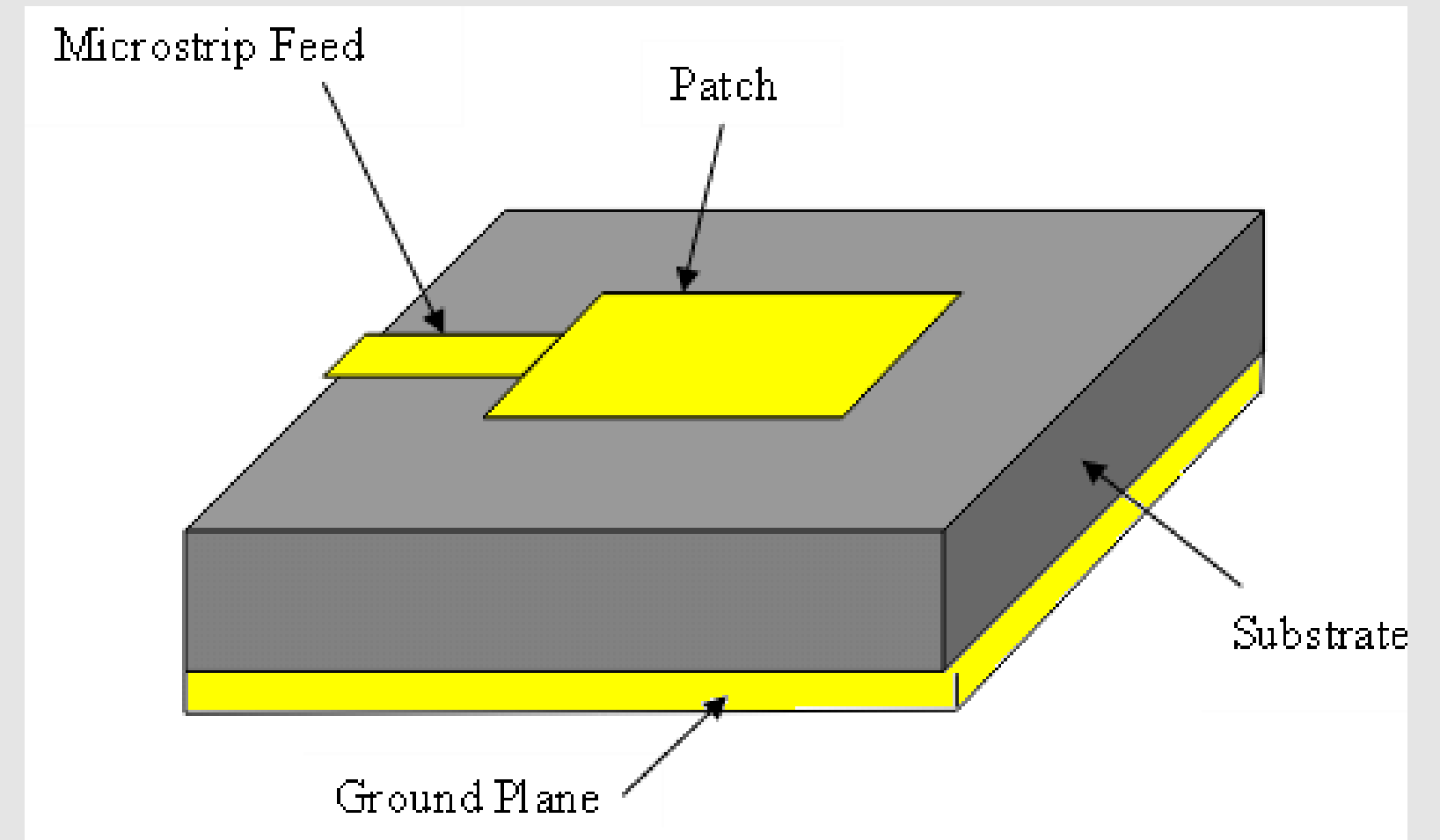
- Nowadays we are surrounded by a lot of electromagnetic waves from different sources such as WIFI, Bluetooth, telecommunication towers, etc. which makes a feasible source for energy harvesting.
- We can use antennas to harvest RF energy from the electromagnetic waves





# Microstrip Antenna

- ❖ A **microstrip patch antenna** is a type of low-profile antenna commonly used in modern wireless communication systems, such as mobile phones, satellites, and Wi-Fi routers.
- ❖ **Structure:**
  - A thin metallic patch (radiating element) on a dielectric substrate.
  - A ground plane on the other side of the substrate.
- **Key Features:**
  - Compact size, lightweight, and easy to integrate into devices.
  - Supports applications with frequencies ranging from MHz to several GHz.
  - Low cost and easy to manufacture.



# Microstrip Antenna

## Basic Working Principle:

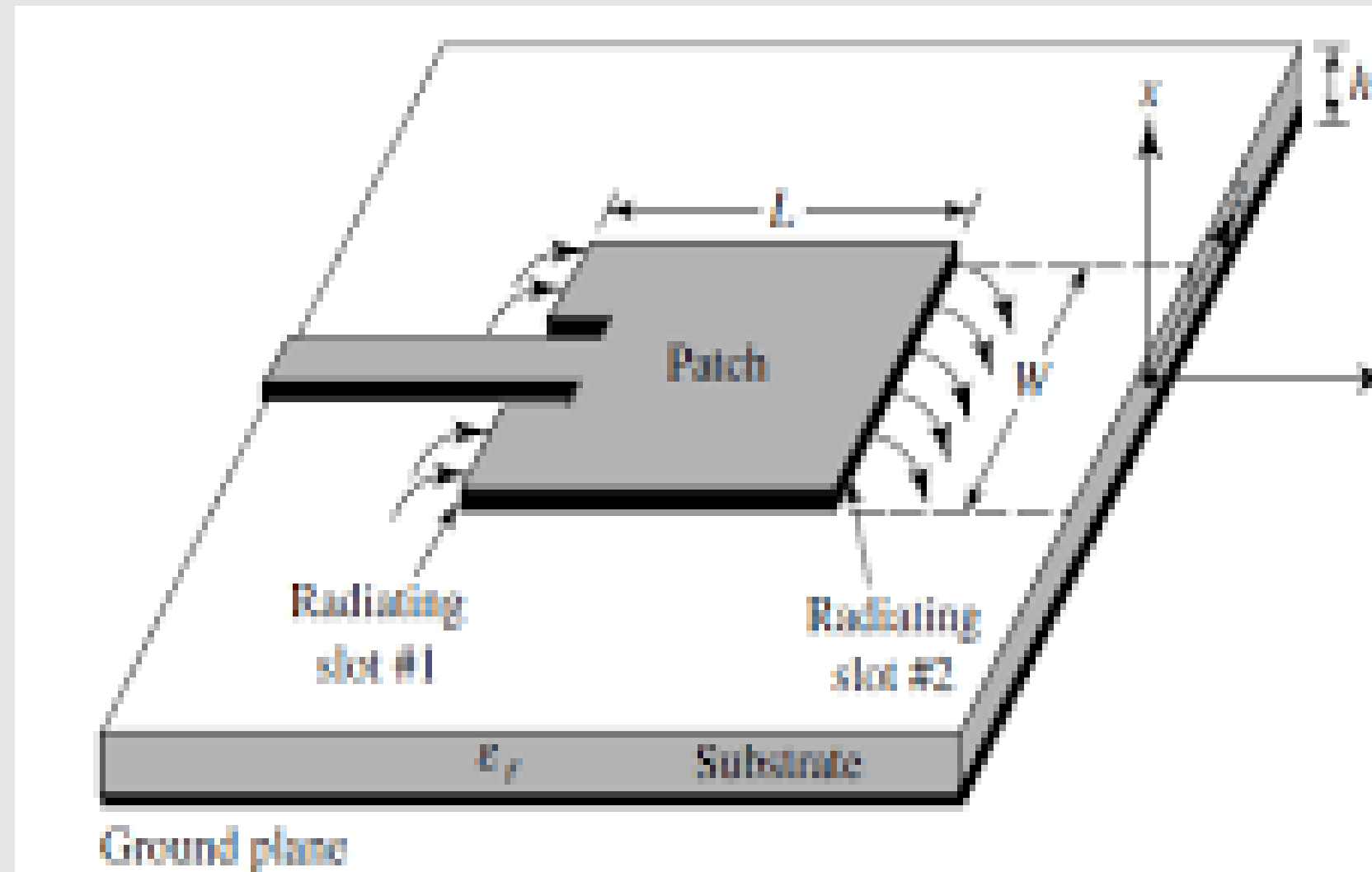
The metallic patch acts as a resonant cavity, radiating electromagnetic waves when fed with an RF signal. Radiation occurs due to the fringing fields at the edges of the patch.

## Modes of Operation:

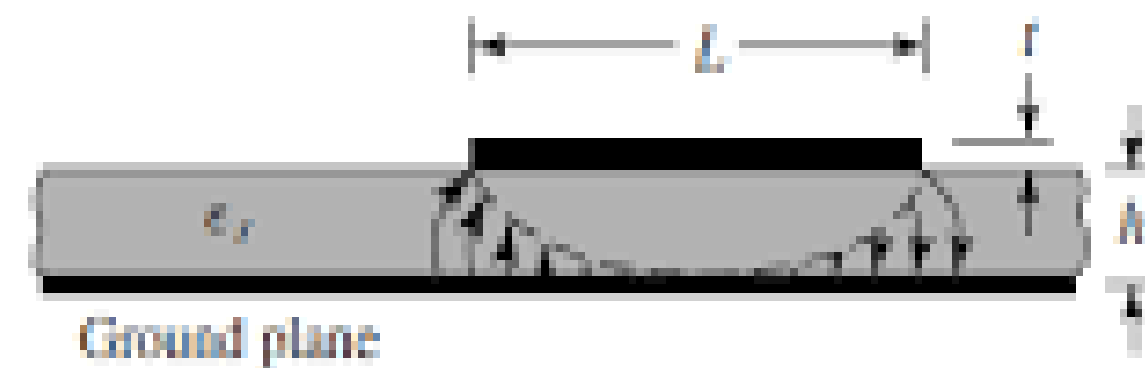
The dominant mode of operation is the  $TM_{1010}$  mode, where the electric field is maximum along one dimension of the patch.

## Feeding Methods:

Coaxial feed, microstrip line feed, aperture coupling, and proximity coupling.



(a) Microstrip antenna

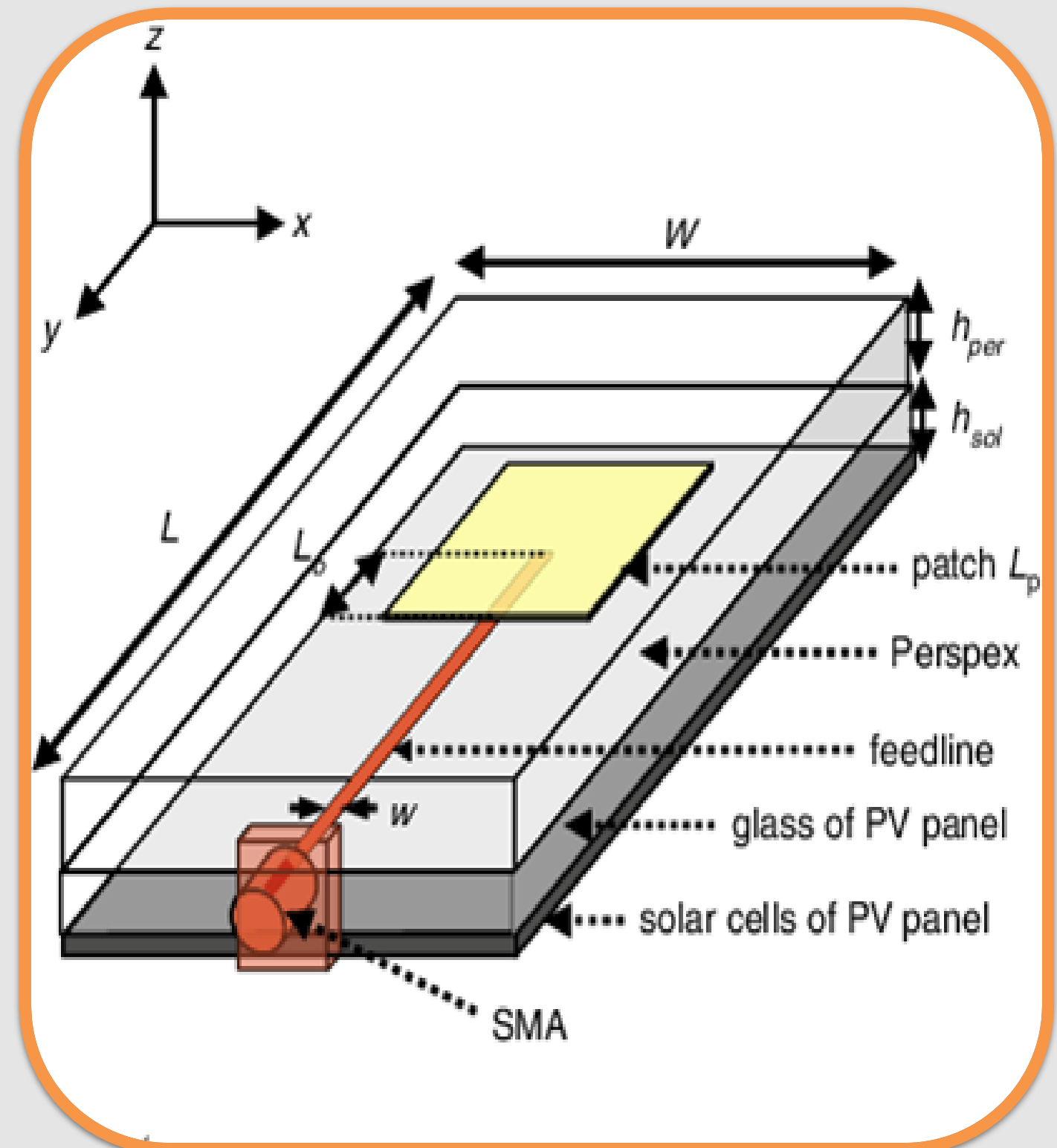


(b) Side view

# Construction of Antenna over Solar Cell for Hybrid system

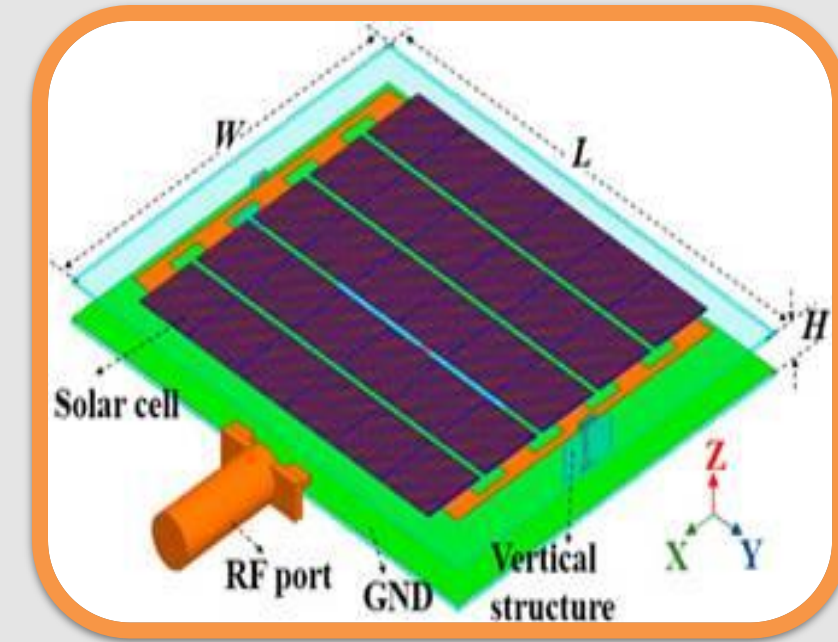
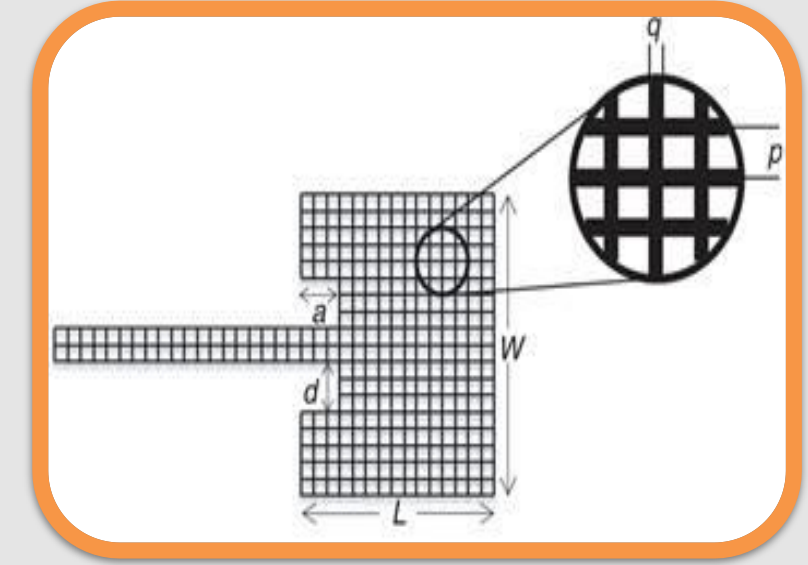
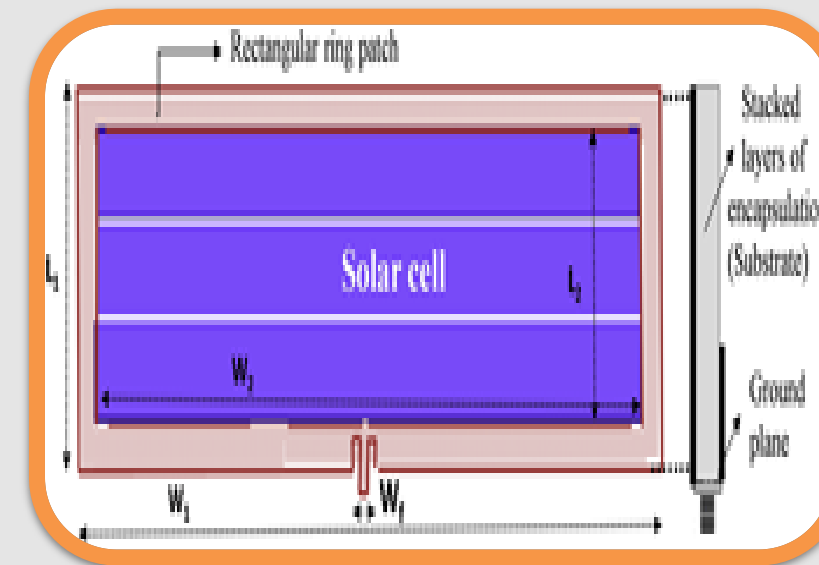
The whole system is constructed of the following parts:

- **Patch** acting as RF collector using conductive material
- **Perspex** acrylic substrate for RF Patch
- **Feedline** for transferring the collected RF power to the SMA connector for energy harvesting and matching the impedance with SMA connector.
- **Glass** for protecting the solar cell panel
- **Solar cell panel**
- **SMA** for terminating the antenna matching to 50ohm



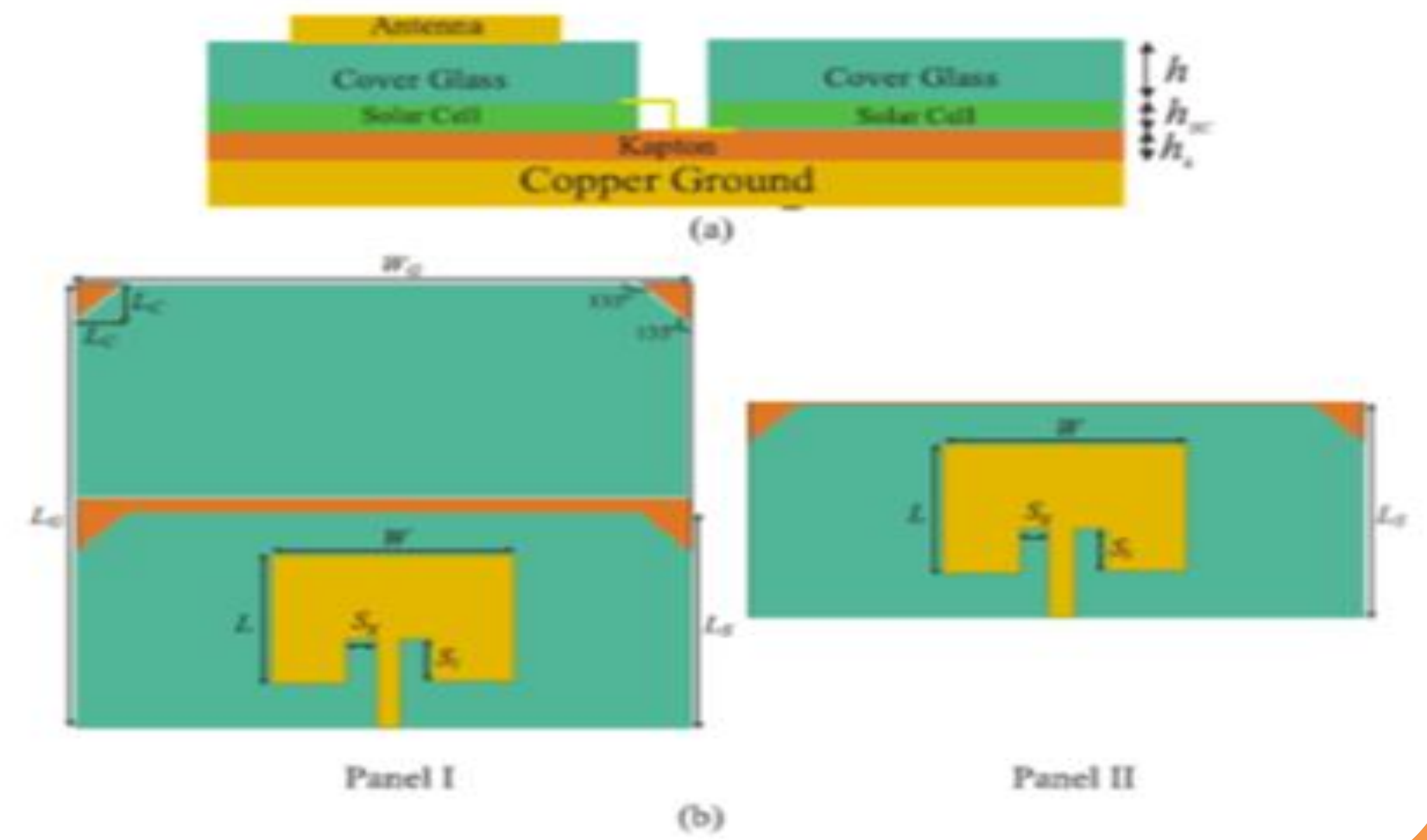
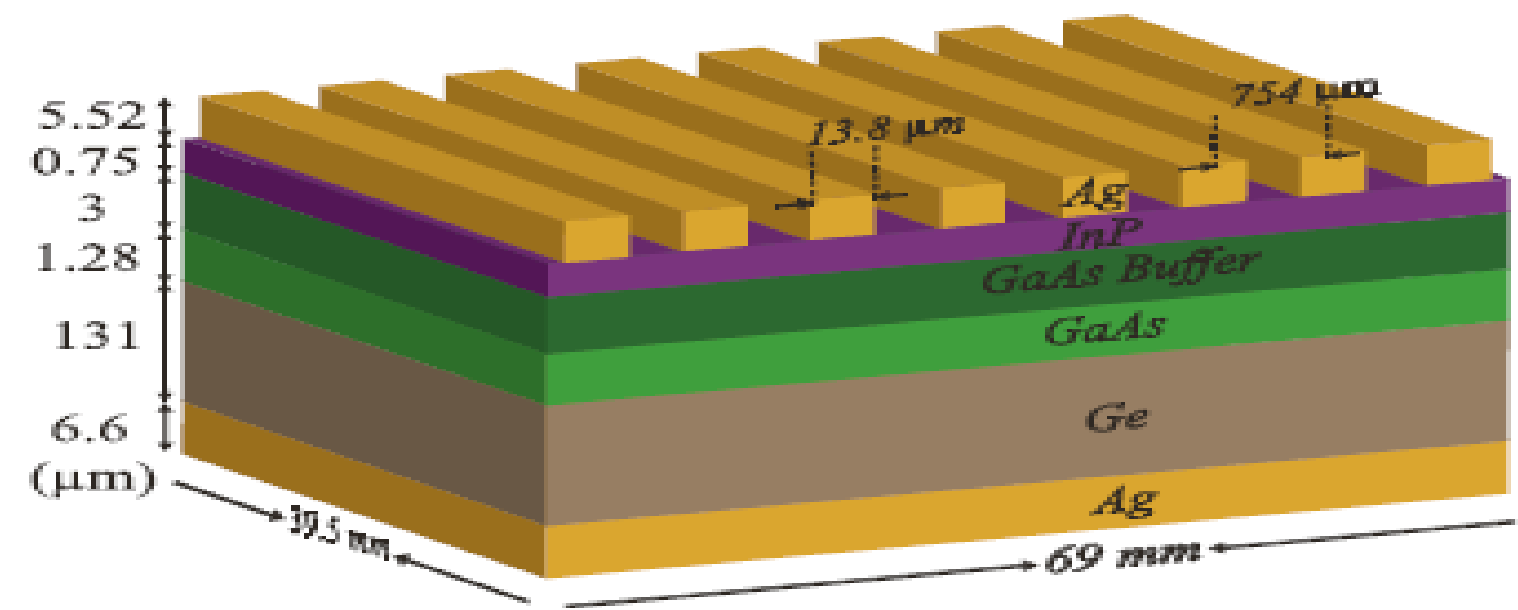
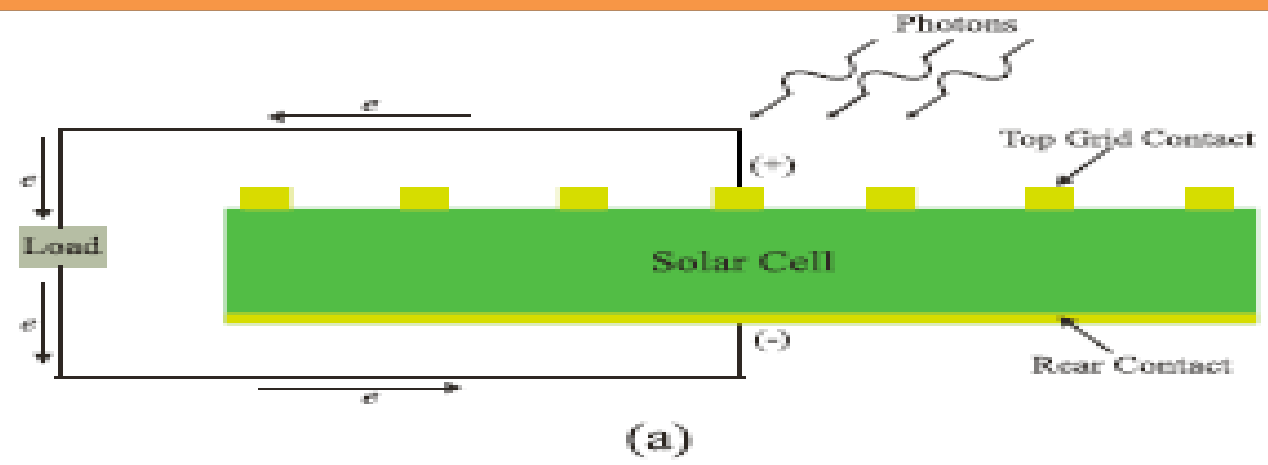
# Combining Solar Cell with Antenna

- Building antennas around solar cells
- Interdigitate the Antenna over the solar cells
  - Using Meshed Antenna
  - Using Transparent Conductors



The transparent antenna allows us to utilize the whole solar cell surface to build antenna and/or antenna arrays

# Combining Solar Cell with Antenna



# Transparent Antenna Concept

- ✓ **Transparent antenna could be achieved by:**

Using transparent material

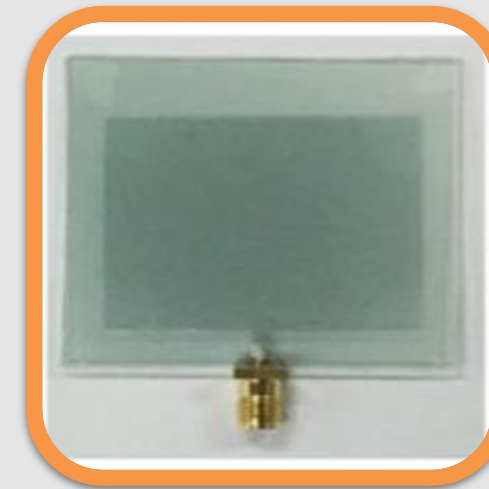
Meshing the Antenna Design by using very thin lines

- ✓ **Meshing line width effect the peak gain of antenna**



# Types of Transparent Conductors

- Nano Carbon
  1. Graphene
  2. Carbon Nano Tubes (CNT)
- Transparent Conductive Oxide (TCO)
- Conductive Polymer
- Nanowires



ITO



Carbon NanoTubes (CNT)

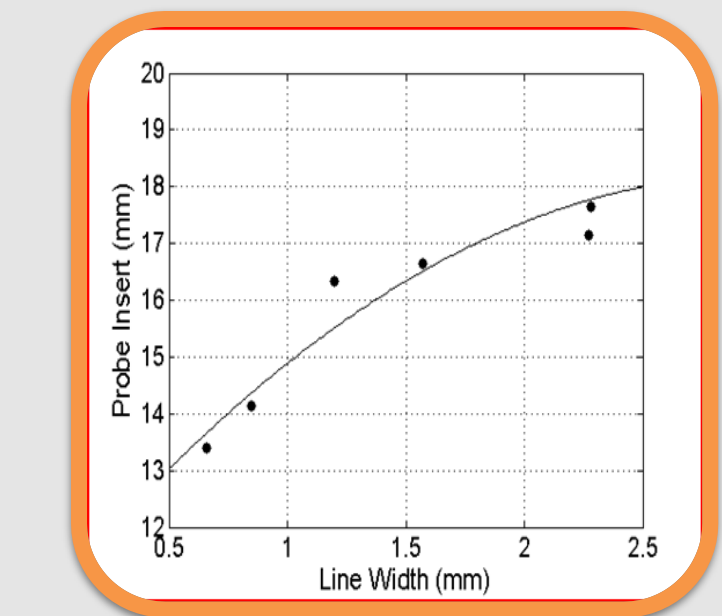
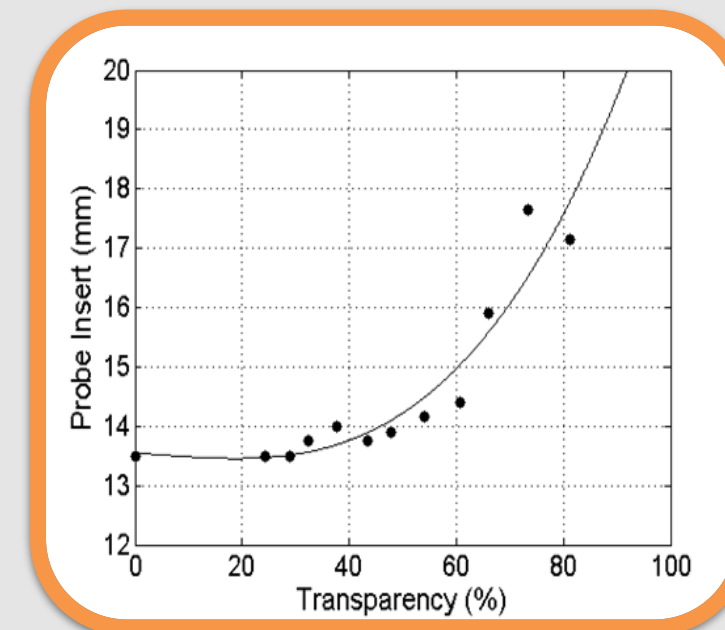
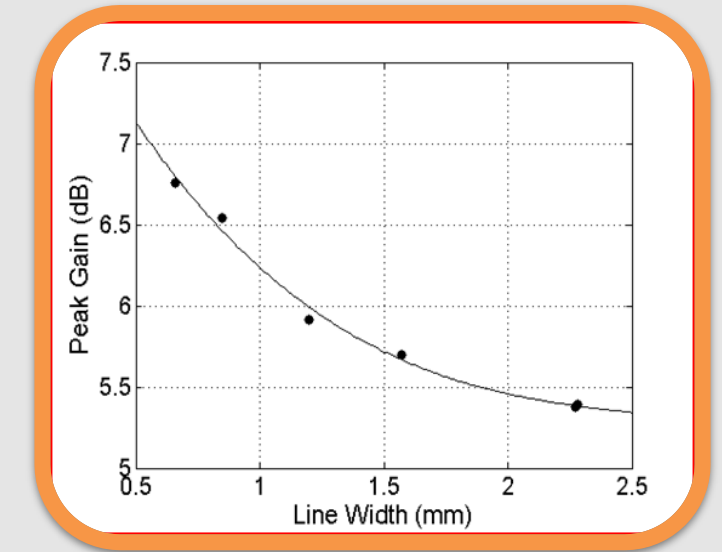
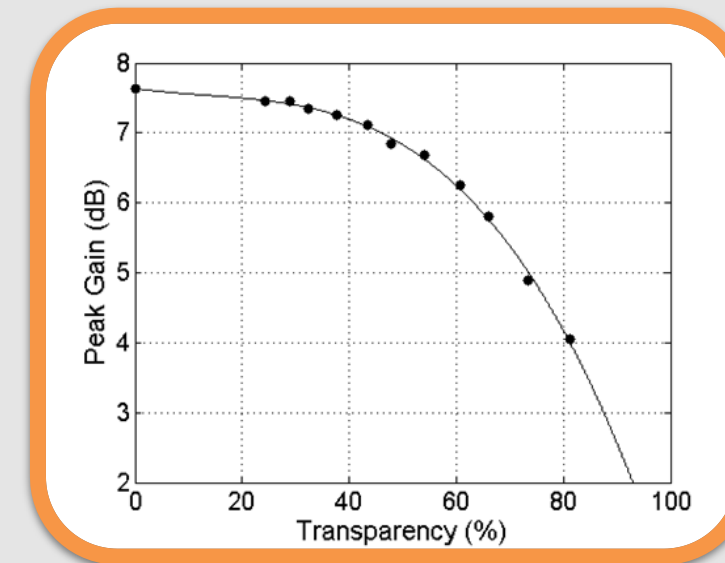


CNT-Silver Nano Tube -Hybrid

# Effect of transparency on antenna gain

For a fixed line width, higher transparency results in gain reduction,

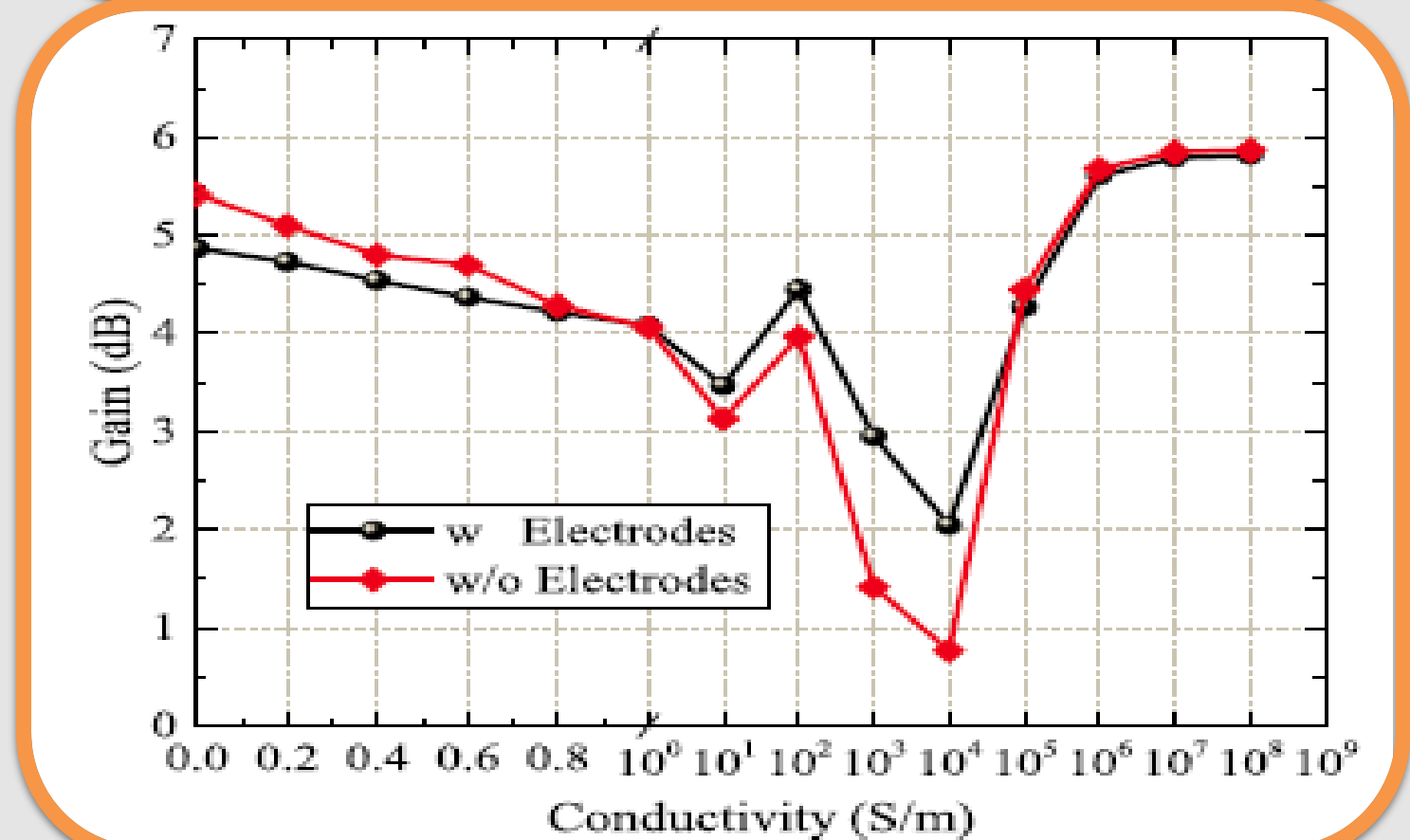
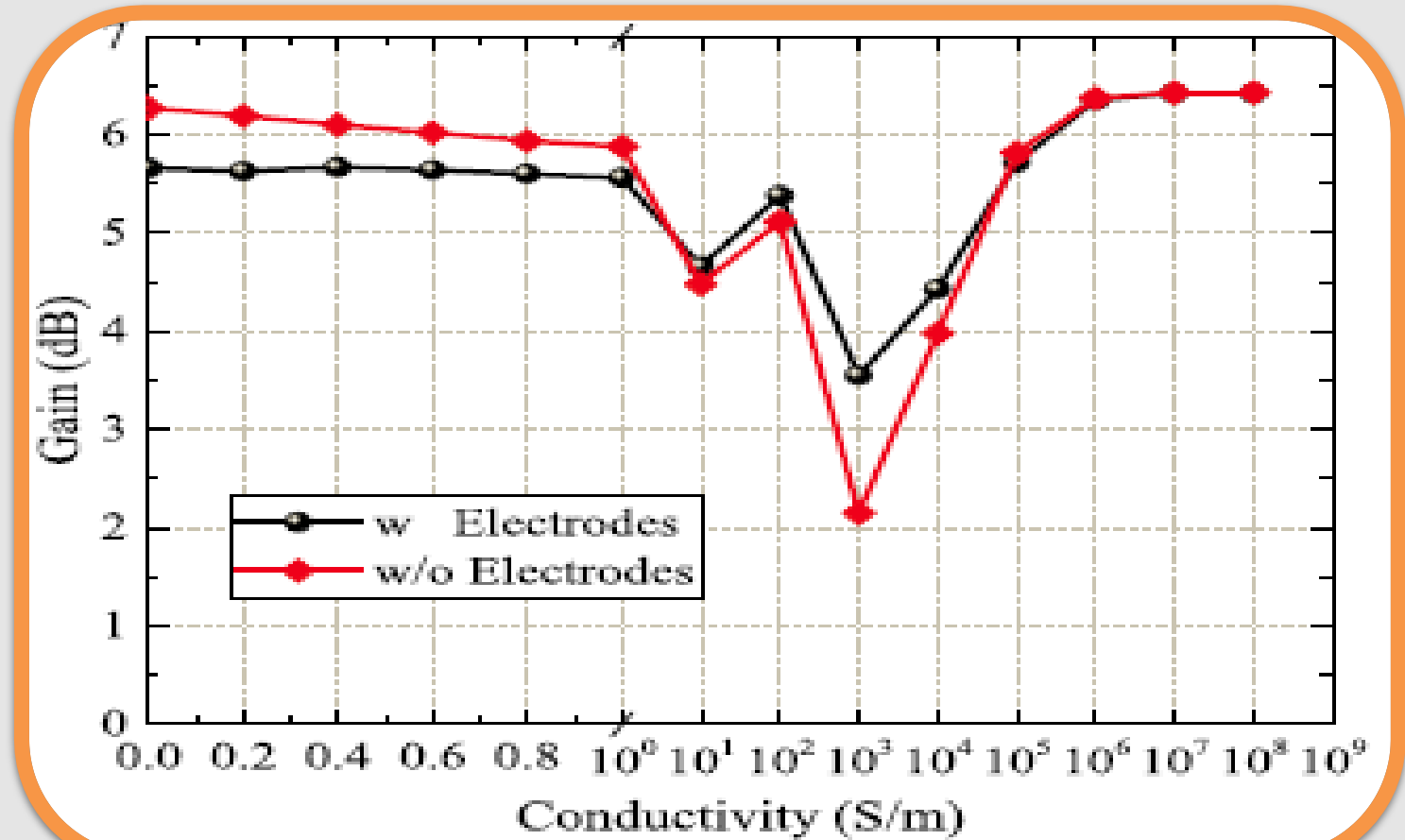
however, when fixing transparency and optimizing for line width, it is noticeable that the relation between antenna gain and line width is **inversely proportional** thus the thinner the line results in higher gain.





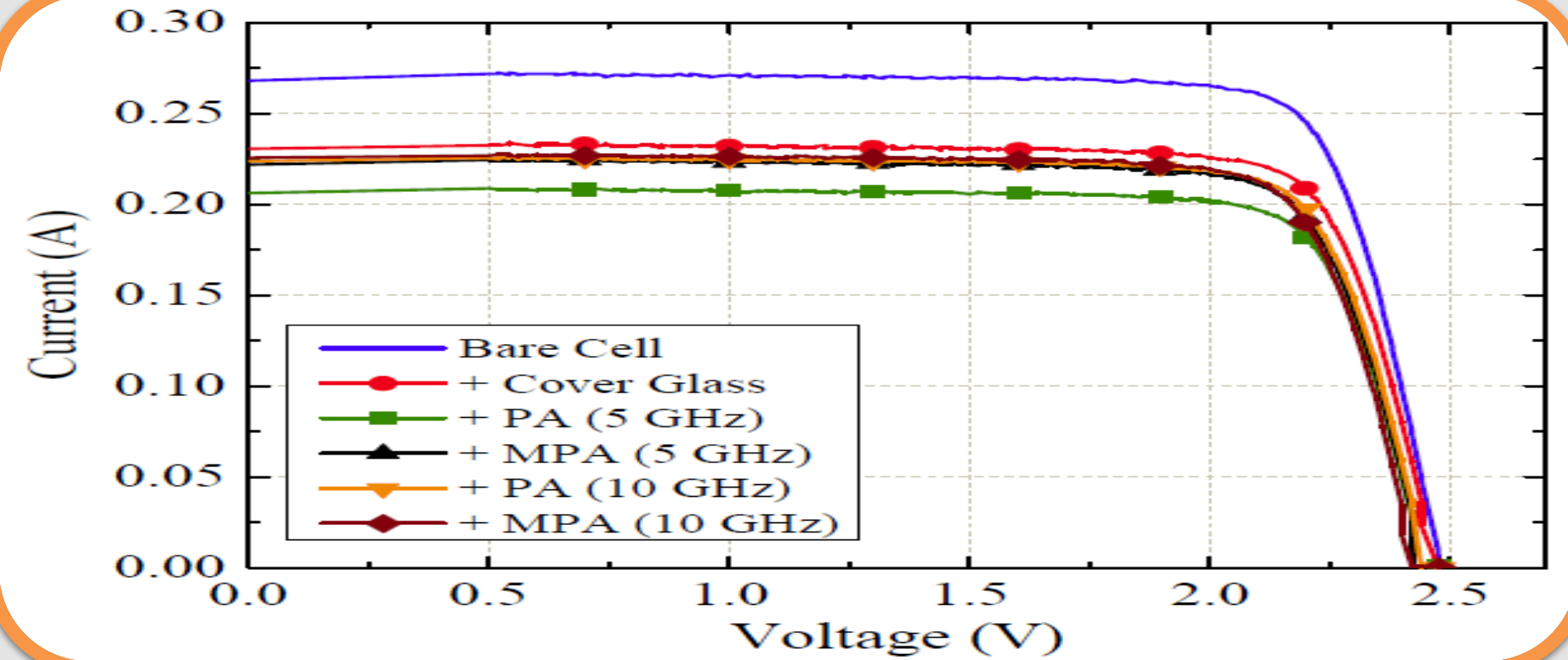
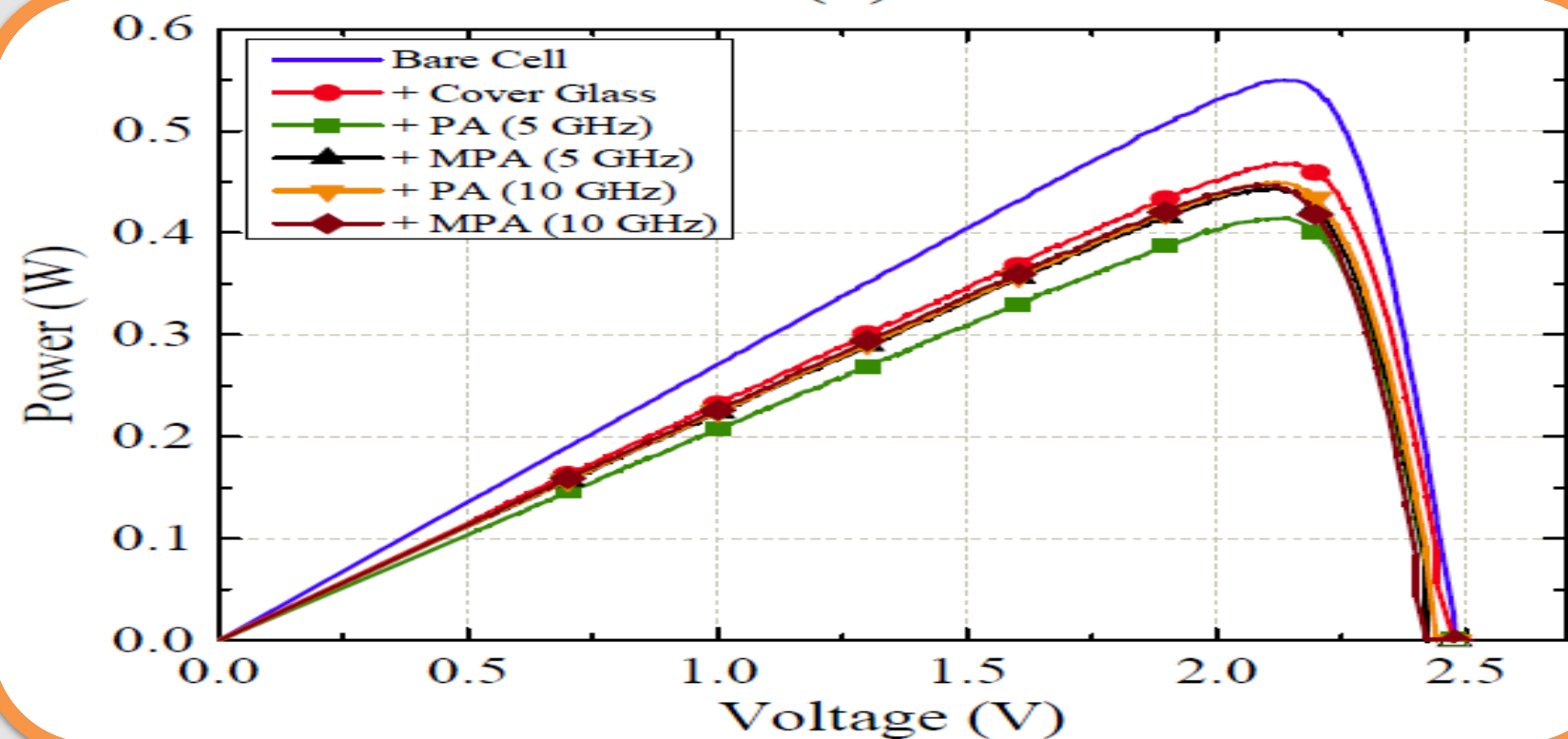
# Effect of solar cell on antenna

- When solar cells are placed near an antenna, they can cause interference and affect the performance of the antenna
- This interference effect the overall efficiency of the antenna
- The presence of solar cells can also lead to changes in the radiation pattern and polarization of the antenna
- The most noticeable reduction in antenna gain occurs at the conductivity level where solar panel junctions operate



# Effect of Antenna on Solar Cell

- Solar cells efficiency is very sensitive to the attenuation in solar energy
- Addition of any materials over the solar cell increase the attenuation
- Conductors easily block light due to it's nature



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# Conclusion

- ❖ Integration of perovskite, silicon, and graphene layers yields remarkable achievements.
- ❖ Efficacy of up to 33.7% (perovskite-silicon) and 23.1% (perovskite-graphene) realized
- ❖ Hybrid Energy Source: Combining transparent microstrip patch antennas with solar cells enables dual-mode energy harvesting from both RF and solar sources.
- ❖ Transparency Advantage: Transparent antennas offer practical benefits for applications requiring visibility, such as in windows or wearable devices.
- ❖ Nanomaterial Enhancements: Using nanomaterial substrates improves the efficiency and compactness of transparent antennas, optimizing energy harvesting.

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# Future Work

- Study the feasibility of transparent conductive materials suitable for antenna
- Development of suitable conductive ink with low resistivity and can sustained wear and tear.
- Testing more techniques for placing antenna over solar cells for better transparency results.
- Study the feasibility of using graphene solutions to print antenna using ink-jet material printers.
- Adding the new materials to simulation software and simulating the antenna structure using it.
- Study the impedance effect on matching transmission line due to different materials used in antenna and connector electrode.



# Thank you



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