REVIEW ON PEROVSKITE SOLAR CELLS ($PVSC_S$): SMART MATERIAL FOR RENEWABLE ENERGY

Abstract

The efficiency of perovskite solar cells (PSC) has increased from 3.8% to 25.5% since its first reported work by Miyasaka in 2009. These halide based perovskites have higher light absorption coefficient, charge carrier mobilities which results in increased efficiency. Therefore, as an alternate to the existing silicon based solar cells, perovskites are proven to be best in terms of efficiency than the other photovoltaic materials like dye sensitized solar cells, quantum dots based solar cells. Here, we have reviewed the ongoing developments in the domain of perovskite solar cells that have resulted in the higher efficiency. The focus of the review chapter is to put more emphasis on the working principle of the perovskite and the methods of increasing the efficiency and carrier lifetime of the metal halide perovskite structures. The importance of HTL and ETL materials have been discussed in detail as the efficient strategy to increase the charge carrier nature of the designed PVSC. We also focused on the research trends of this promising technology in terms of device modeling, cutting-edge methodologies, and innovative device topologies. Further we have discussed the challenges and prospects for PVSC research as a futuristic smart material in the renewable energy domain.

Keywords: Perovskite Solar cells, Donor, Acceptor, DFT, TDDFT, Metal-halide perovskites, HTL, ETL

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I. INTRODUCTION

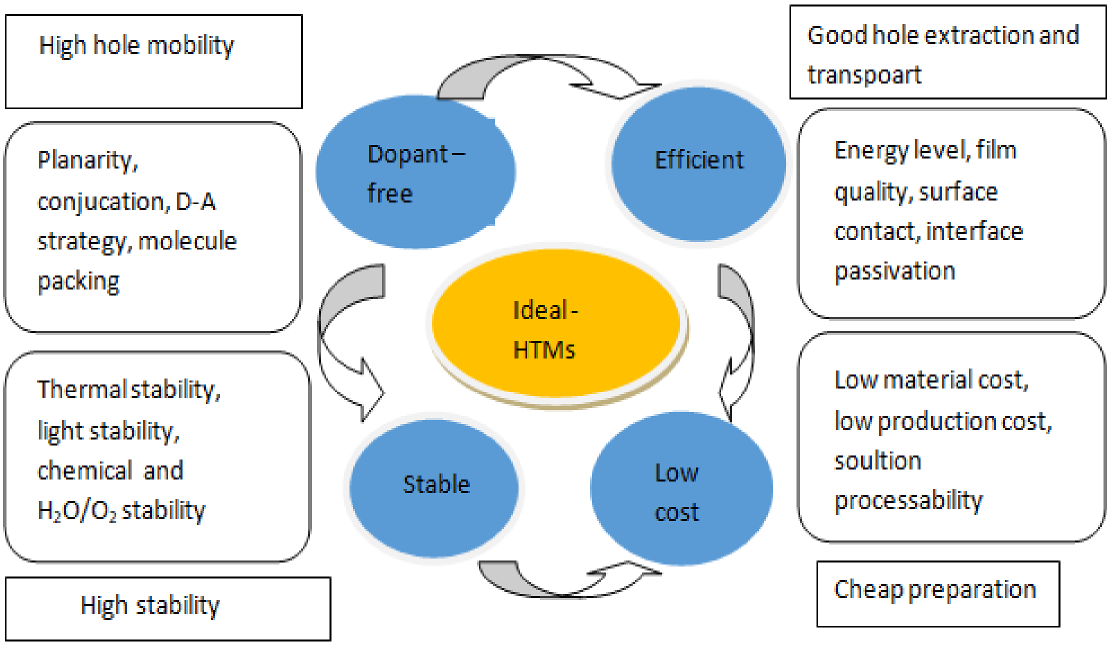
Energy is needed for many different applications such as transportation, industrial applications, agriculture, home and office applications. This can be in the forms such as wind energy, thermal energy, electrical energy, nuclear energy, light energy. Electricity is the most suitable form of energy that can be renewed into all another forms of energy. It is one of the most useful forms of energy in terms of transmission, distribution and control. Energy benefits play a very vital role in every person's daily routine. Availability of a sufficient amount of energy accelerates special and national development. In addition, it must be economical, environmentally friendly and socially acceptable. As fossil fuel consumption increases, greenhouse gas emissions increase proportionately. Thus, the use of renewable energy sources such as hydropower, wave, biomass, geothermal and solar energy is crucial for the sustainability of our planet. Therefore, the main concern of this century should be the development of clean, nontoxic, sustainable and affordable energy sources.

The world receive huge quantity of Sun’s energy in the form of sunbeams[1]. The sunbeams can be transformed to the electric energy to accomplish our energy necessities[2]. The photovoltaic device can convert into electric energy[3]. A variety of photovoltaic technology were created in recent decades, with dye-sensitized solar cells(DSSCs),organic solar cell, quantum dot solar cell, and pervoskite solar cells[4-8]. The scientific community has become in these type of solar cells because of their straightforward manufacturing process and affordability [9]. Due to their high photovoltaic performance and inexpensive process and affordability[9]. Due to their high photovoltaic enactment and cost-effective, PSCs have attracted a lot of interest [10-15]. A perovskite light absorber layer is used in pervoskite solar cell(PSCs). The substance known as perovskite has the chemical formula ABO_3. The calcium titanate ($CaTiO_3$) was named perovskite. There is an another class of perovskite materials with the chemical formula ABX_3 (where A and B are cations and anion, X is halogen ions). Excellent absorption, charge carrier, and band gap properties characterize this class of perovskite materials. The usage of electrolyte/hole transport materials to be extremely important. The active layer, hole transporting materials (HTMs), electron transporting materials (ETMs), and electrodes set up the PSCs[16]. HTMs and ETMs are the vital components in PSCs.

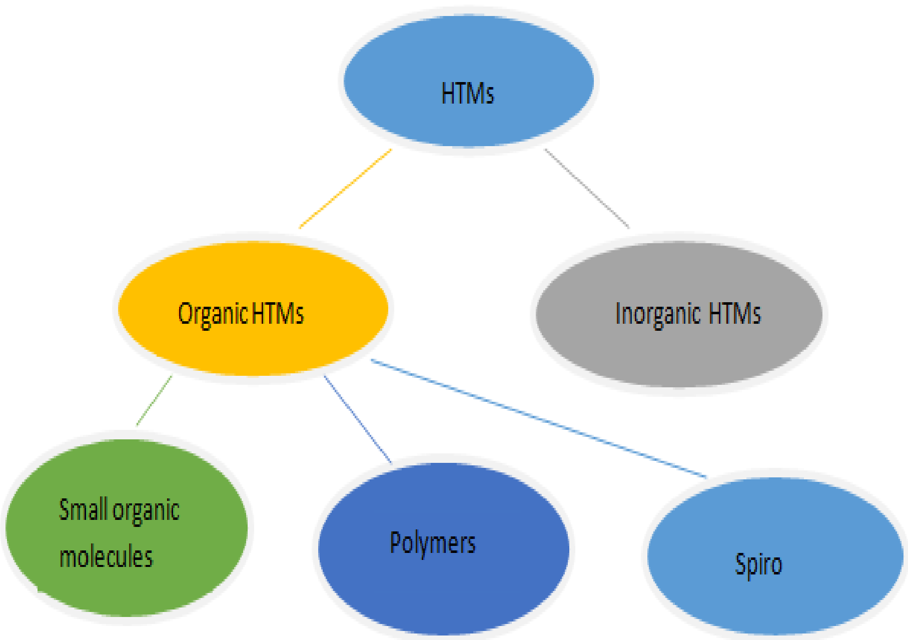
In this chapter, we have discussed the hole transport charge layer,electron transport layer and future prospective have also been discussed.

II. WHY HTL (HOLE TRANSPORT MATERIAL)

Outstanding photovoltaic performance is a result of HTL's role in the effective hole taking out the perovskite/HTL boundary, hole passage in the majority of HTL, and prevention of unwanted charge recombination processes. High hole mobility and conductivity hole transport materials (HTMs) and cascade energy level alignment of the HTL with perovskite are both necessary for high PCE. Additionally, HTMs employed in tandem and inverted structured PSCs are particularly desirable for having transparent windows in the viewable region. The HTL must be highly hydrophobic to prevent perovskite breakdown by oxygen and moisture, as well as thermally and photochemically stable. A perfect HTM candidate must also be easily created using straightforward synthetic methods and simple purifying techniques in order to realize low-cost device production[17]. Furthermore, the presence of HTL also ensures efficient charge separation and collection, resulting in improved photovoltaic performance.



Inorganic and organic molecule HTMs are the three primary divisions of solid-state hole transporters. These categories represent different approaches to designing efficient hole transporters, which can be used in a variety of applications, from displays to solar cells. Each of these categories has its own benefits and drawbacks dependent on the application. These categories are further differentiated by charge mobility, thermal stability, and solubility.



III. INORGANIC HOLE TRANSPORT MATERIAL

Inorganic hole transport materials (HTMs) are a class of resources that are used to facilitate the movement of positively charged "holes" in various electronic devices. Unlike organic HTMs, which are based on carbon-containing compounds, inorganic HTMs are composed of elements other than carbon. These materials are often used in electronic applications like solar cells, light-emitting diodes (LEDs), and other optoelectronic device.

Inorganic HTMs offer some unique advantages, such as higher hole mobilities, better stability, and often higher charge carrier concentrations[18]. Additionally, some inorganic HTMs can have energy levels that are better matched to the active layers of the device, leading to improved charge transport and device performance.

Some common inorganic hole transport materials used in electronic devices include:
Metal oxides: Inorganic metal oxides, such as NiO (nickel oxide), CuI (copper iodide), and CuSCN (copper thiocyanate), have been explored as hole transport materials in organic photovoltaic cells and other electronic devices.

Transition metal chalcogenides Some transition metal chalcogenides, like MoOx (molybdenum oxide) and WOx (tungsten oxide), have been investigated as hole transport materials in various optoelectronic devices.

IV. ORGANIC HOLE TRANSPORT MATERIALS

Organic hole transport materials (HTMs) are a class of organic compounds used in various electronic devices, particularly in organic photovoltaic cells (solar cells) and organic light-emitting diodes (OLEDs). These materials play aessential role in facilitating the movement of positively charged "holes" within the device, which is essential for generating an electric current or emitting light, depending on the device's functionality.
Organic HTMs possess specific characteristics that make them suitable for charge transport in organic electronic devices, including:

1. **Hole Mobility:** Organic HTMs have good charge carrier mobility, enabling efficient movement of holes within the device's active layers.[20]

2. **Suitable Energy Levels:** The energy levels of organic HTMs are designed to be well-matched with the adjacent layers, optimizing the charge transfer and minimizing energy losses.[21]

3. **Solution Processability:** Many organic HTMs can be easily processed from solution, allowing for low-cost, large-scale fabrication of devices using techniques like spin-coating or printing

4. **Stability and Compatibility:** Organic HTMs are designed to be stable under operating conditions and compatible with the other materials used in the device.[22]

V. POLYMERIC HOLE TRANSPORT MATERIAL

Polymeric HTMs are conjugated polymers that has significant role in enabling the movement of positive charge carriers (holes) within the active layers of organic electronic devices, such as organic photovoltaic cells and organic light-emitting diodes (OLEDs). They are in charge of effectively moving holes from the layer that absorbs light to the electrode, which is necessary for generating an electric current in solar cells or for emitting light in OLEDs.

Key characteristics and advantages of polymeric HTMs include:

1. **Charge Transport Efficiency:** Polymeric HTMs possess excellent charge transport properties, enabling efficient and rapid movement of holes through the active layer of the device. This is crucial for achieving high device efficiency.

2. **Film Formation and Processability:** Polymeric HTMs can be easily processed into thin films using various solution-based techniques, making them approachable with huge-scale manufacturing processes like roll-to-roll printing.

3. **Stability:** Many polymeric HTMs exhibit good environmental stability, which is important for the long-term performance and reliability of organic electronic devices.

4. **Tunability:** The chemical structure of polymeric HTMs can be tailored and modified to optimize their energy levels and charge transport properties, making them versatile materials for different device architectures.

5. **Low Cost:** Some polymeric HTMs can be synthesized from abundant and inexpensive raw materials, potentially reducing the overall cost of the device.

   Examples of polymeric hole transport materials include those mentioned in the previous response, such as PEDOT:PSS, polyfluorenes, polythiophenes, F8BT, P3HT, and poly(carbazole) derivatives. Researchers continually explore new polymeric materials and seek to enhance existing ones to improve the overall performance and stability of organic electronic devices.

   Some common polymeric hole transport materials used in organic electronic devices include:

   - **Polythiophenes:** Similar to polyfluorenes, polythiophenes are a class of polymers based on the thiophene unit and can be tailored for specific applications.[23]

   - **Poly(9,9-dioctylfluorene-co-benzothiadiazole) (F8BT):** This copolymer combines fluorene and benzothiadiazole units to improve charge transport and stability.[24]

   - **Poly(3-hexylthiophene) (P3HT):** This polymer is commonly used in organic photovoltaic devices due to its good charge transport properties and processability.[25]

   - **Poly(carbazole) Derivatives:** Carbazole-based polymers have been investigated for their potential as hole transport materials in OLEDs and other organic electronic devices.[26]

The selection of polymeric HTM depends on the necessities of the device, as charge transport efficiency, energy levels, film-forming properties, and environmental stability. Researchers continue to explore new polymeric materials and optimize existing ones to enhance the performance and commercial viability of organic electronic devices.

VI. SMALL ORGANIC MOLECULES

In these organic electronic devices, a hole transport material is a type of small organic molecule or polymer that facilitates the movement of positively charged "holes" within the device. When light is absorbed by the organic material, it creates electron-hole pairs. The electrons and holes thenneed to be separated and transported to their respective electrodes to generate an electric current or emit light, depending on the device's functionality.

Hole transport materials are typically used in the active layer of organic photovoltaic cells or in the emissive layer of OLEDs. They have good electrical conductivity and energy levels that allow them to efficiently transport holes while preventing recombination with electrons, which is essential for the optimal performance of these devices.
Some commonly used hole transport materials include:

OMeTPA-FA[27]
EDOT-OMeTPA[28]

VII. SPIRO

Spiro-OMeTAD(2,2',7,7'-Tetrakis(N,N-di-p-methoxyphenylamine)-9,9' spirobifluorene) [29]is a derivative of spirobifluorene, an organic compound that has proven to be an efficient hole transportmaterial in perovskite solar cells. The characteristics of Spiro-OMeTAD that make it suitable for use in perovskite solar cells include:

1. **High Hole Mobility**: Spiro-OMeTAD has excellent charge carrier mobility, allowing it to efficiently transport holes from the light-absorbing perovskite layer to the electrode.

2. **Suitable Energy Levels:** Its energy levels align well with those of perovskite materials, minimizing energy loss during the charge transfer process.

3. **Stability:** Spiro-OMeTAD has been modified with additional chemical components to enhance its stability, which is crucial for the long-term performance of perovskite solar cells.

4. **Processability**: Spiro-OMeTAD can be readily processed from solution, making it compatible with scalable and cost-effective manufacturing techniques.

Due to its impressive performance, Spiro-OMeTAD has been a leading choice as a hole transport material in perovskite solar cells, contributing to the significant advancements in the efficiency and stability of these solar cells in recent years.

Electron Transport Material: The ETM basically known as electron transport material, mainly functions to increase the extraction rate of the photogenerated electrons, blocking the pathway of the holes. It is very necessary for the ETM layer to sustain a good conductivity and higher transparency to attain a highly efficient PVSC. As we know that the PVSC can be illustrated in four different structural ways depending on the type of charge transport material lying on the outer face for the light to be incident on it, hence the entire power conversion efficiency of PVSC depends on these configurations. These different configurations can be discussed as follows: (1) The Mesoscopic n-i-p structure which consist of cathode followed with ETL layer, further with a mesoporous metal oxide layer containing the perovskite which is then layered with HTM ending with an anode. (2) The Planar n-i-p structure which consist the similar layering as above with all the layers composed of planar structure. (3) The Mesoscopic p-i-n structure, in which the positioning of ETM layer is interchanged with HTM layer. (4) The Planar p-i-n structure which consist of all planar layers. (5) The HTM layer free structure (6) The ETM layer free structure. After studying these configurations and spotting the light on the ETM layers, a common question arises that which structure is most suitable based on the factor of PCE. The aperture between the mesoscopic and planar structure is reducing very significantly providing a PCE of 22.1% for regular mesoscopic TiO2 structure and 20.9% for that of planar structure. Some of the advantages that can be seek by the mesoscopic structure are as follows:1)The enlarged surface area provides an increment in generation of charged carriers and their collection which overcomes the problem of size limitation which is encountered in planar structures. This also leads to high electron mobility in the ETMs which prevents the serial resistance 2)By providing the additional scatteringlayer consisting of large particles, the improved light absorption can be obtained; 3) As a scaffold, its homogeneous and size-tunable mesoporous channels will aid in the modulation of perovskite pigment development.

Characteristics of a good ETL material

1. **Electronic Properties:** The major elements that characterize the electrical properties of a good ETM layer are electron mobility, Conduction band minimum (CBM), and Valence band maximum (VBM).. The HOMO and LUMO levels of the ETL should be in accordance with the perovskite levels to provide a better pathway for the electrons and to block the passage for the holes. The LUMO of the ETL should lie slightly lower than the conduction band minimum of the perovskite layer for smooth electron injection whereas the HOMO of the ETL should be at a deeper position to the valence band maximum of the perovskite to provide a good electron conduction and blocking of holes. Special attention should be paid to avoid the charge accumulation at interface which leads in the degradation of the performance of the PVSC.

2. **Chemical Properties:** The preferred ideal ETM are those which have good chemical stability to avoid any chemical reactions with their neighbouring perovskite material and cathode.

3. **Film Structure:** The film architecture should be such which provides an ordered arrangement to produce an adequate value of Voc and FF. It’s morphology should be dense to restrict the current leakage and charge carriers recombination.

4. **Charge Transport Mechanism of ETM:** The Marcus hypothesis, which R.A. Marcus proposed in 1956 and which provides a method to estimate the rate of electron transfer in

the outer sphere, governs the charge transfer or, more precisely, electron transport processes in ETL materials. Some of the main aspects of this theory can be discussed as:

5. **Classical Theory Approach :** The classical theory of electron transfer stand on the basic assumption of classical nuclear motion and independent electron transfer matrix elements. Here the nuclear motion is treated classically which means the electron transfer takes place at theintersection of the curves in nuclear co-ordinates and potential energy graph.

   This theory assumes that the thermal electron transfer matrix element is independent of nuclear configuration which is also stated as Condon Approximation.

   Calculating the rate constant of an electron transfer reaction entails determining the likelihood of reaching a multidimensional intersection., which can be given by the equation

   $k = \kappa A\sigma^2 \exp(-\Delta G^*/RT)$

   where k = Rate constant, κ = transmission coefficient, σ = average center to center distance in electron transfer, ΔG* = free energy.

   Hence when no barrier is present between to consecutive monomers, the charge transfer rate (K_{ct}) is given by

   $K_{ct} = (\sqrt{\pi}/\lambda\ K_B T)(V^2/\hbar)e^{-\lambda/4K_B T}$

   Where V = transfer integral, T = absolute temperature, K_B = Boltzmann constant, ħ = Planck's constant, λ = reorganization energy.

6. **Quantum Mechanical Approach:** The mobility of the nuclei is considered quantum mechanically in the quantum mechanical interpretation of this theory, which means that the nuclei can tunnel through the energy barrier between the reactant and product states. Reorganization energy, which is the energy required to reorganize the solvent and other molecules around the reactants and products during the electron transfer process, is also included in the theory. We can also find the reorganization of electron and holes separately using it which can be denoted as λ_h and λ_e. For which the formula representation can be given as

   $\lambda_h = [E^+(M^0) - E^+(M^+)] + [E^0(M^+) - E^0(M^0)]$

   $\lambda_e = [E^0(M^-) - E^0(M^0)] + [E^-(M^0) - E^-(M^-)]$[56]

   Where, M^0 = Neutral geometry of the subjected compound
   M^+ = Cationic geometry of the subjected compound
   M^- = Anionic geometry of the subjected compound
   E^0 = Neutral energy state
   E^+ = Cationic energy state
   E^- = Anionic energy state

Some Commonly used ETM Layers

1. **TiO_2:** The most commonly used ETL material is TiO_2 for it's wide band gap, low cost manufacturing and good optical properties. Although the anatase phase of TiO2 performs better than the rutile phase, rutile TiO2 has greater conductivity and compatibility with the MAPbI3 layer.TiO2 can be prepared using a variety of techniques, including ball

milling, ultrasonic spray, atomic layer deposition, inkjet printing, hydrothermal, sol-gel chemistry, low-temperature CO2 plasma, and low-temperature microwave.

2. **SnO_2:** This material has very spectacular electronic and optical properties but lacks behind due to structural defects. To improve the performance of SnO2, many ways have been employed, such as employing pyrrolidine fullerene to lessen hysteresis, passivating SnO2 with chlorine to boost electron mobility, and using phosphoric acid to increase electron collection efficiency.
3. **ZnO:** ZnO also shows remarkable properties as an ETL material in electron mobility, light transmittance, easy cost cutting fabrication and stability factor.Sol-gel deposition, water-based processing, surface passivation, ion doping, and plasmonic nanoparticle modification have all been investigated as ways to increase the energy-level alignment, charge carrier extraction, and compatibility of ZnO with perovskite layers.

4. **C_{60}:** It is also known as Fullerene which is carbon based structural unit and is used as an efficient ETL material.C60 is stable and naturally water-resistant, making it a suitable material for tackling the issue of stability in PVSCs.When compared to solution-processed fullerenes, vacuum-deposited C60 can be packed tightly to improve intermolecular charge transport and has substantially greater electron mobility and conductivity.

VIII. CHALLENGES

There are several challenges associated with perovskite solar cells:

1. **Efficiency:** Keeping in mind the environmental hazards, many countries have committed to replacing greenhouse gas emissions with renewable energy sources. Solar energy is one such renewable source that has a positive impact on the environment as well as the economy. Several materials are used for the fabrication of solar cells that convert solar energy into electrical energy. Perovskite is a third-generation technology with an efficiency of approximately 28%[30]. It is a very versatile material and its efficiency remarkably improved over a short life time. Future research aims to push it further which will lead to more cost-effective and efficient solar energy generation.

2. **Stability:** The stability of devices over their operating lifetime is currently the only significant unknown in perovskite research. There are several pathways that lead to degradation involving water, oxygen, and even the diffusion of electrode material. However, lifetime studies for this material are very limited but this all need to be addressed for long term reliability.

3. **Commercialization:** Despite its great potential, perovskite solar cells are still in the very early stages of commercialization[31]. It is also a major challenge to scale up production to a large manufacturing scale. It requires high infrastructure, which ultimately leads to very high costs. If we compromise with the quality and use cheaper materials, their lifespan would be shorter. Perovskite also degrades quickly in the presence of moisture, and the decay byproduct harms the metal electrode. If encapsulation is done to protect it from moisture, it ultimately results in increased cell weight.

4. **Toxicity:** The usage of lead in perovskite compounds is another concern that hasn't been adequately addressed. Lead iodide, which is a byproduct of perovskite, is very toxic and

carcinogenic, with consequences that may only be seen after a long time of exposure. However, tin-based cells can be used instead of lead, but they have lower efficiency (only6% reported so far)[32]. Current research aims to reproduce high-power conversion efficiencies with the addition of stabilizing agents such as Cesium and RubidiumClick or tap here to enter text.. Developing lead-free and environmentally friendly perovskite materials is also an important concern that needs to be addressed and replaced.[33]

If we replace perovskite with other materials as discussed above, the optical density of these materials is also a topic of discussion that requires improvement. Although it is higher than silicon, it is still lower than other dynamic materials. Due to their sensitivity to moisture and oxygen, devices require thicker encapsulation, which is also a challenging task[34]. Perovskite also has some fabrication limitations, especially for solution-based devices, and maintaining uniformity is difficult.

Addressing these challenges is crucial for the widespread adoption of perovskite solar cells as a competitive and sustainable alternative to traditional solar cell technologies.

5. **Future Perspective:** Perovskite solar cells hold significant promise for the future of solar energy and beyond. Here are some future perspectives and potential developments:

- **Light Emitting Diode:** Due to their photoluminescence property perovskite can be used as light emitting diode. Due to the high color purity, efficient charge transport and tunable emission wavelength make them as a display and lighting technology for next generation[35].

- **Photo Detectors:** Photodetectors based on perovskite have a wide range of wavelength detection i.e, from ultraviolet (UV) to infrared (IR) regionClick or tap here to enter text.. High sensitivity, fast response timesand low noise levelsmake them suitable for applications such as imaging, optical communication,and sensing.

- **Sensors:** Perovskite material is utilized as sensing component in various type of sensors. Due to their high sensitivity to light and wide absorption range make them promising candidate for the use of optical sensing[36]. For the detection of temperature, humidity and detecting gases perovskite based sensors have been researched.

- **Other Optoelectronic Devices:** Perovskitebased lasers, optical switches, waveguides,and integrated circuits can be used in optoelectronic devices. Their high carrier mobility, tuneable bandgap, and efficient light emission make them ideal for these applications[37].

- **Integration in Energy Storage Systems:** Perovskite is used in making energy storage systems such as lithium-ion batteries, supercapacitors, and splitting of H_2O (water) for CO_2 reduction and other rechargeable batteries[38], [39]. In order to create effective photo rechargeable supercapacitors, carbon black is mixed with porous perovskite electrodes, which dramatically improves electronic conductivity. Halide perovskites have a high absorption coefficient, long carrier diffusion length, and strong ionic conductivity[40]. However, power conversion efficiency is still a challenging task in these storage devices. Cost benefit is also a secondary factor for investment in these integrated systems, which includes building design, component size, maintenance costs, and replacements.

The overall cost benefits of these integrated systems should always exceed the overall technology cost to deliver their benefits.

The final cost benefit is determined by two important factors: manufacturing cost and power conversion efficiency of each photovoltaic cell.

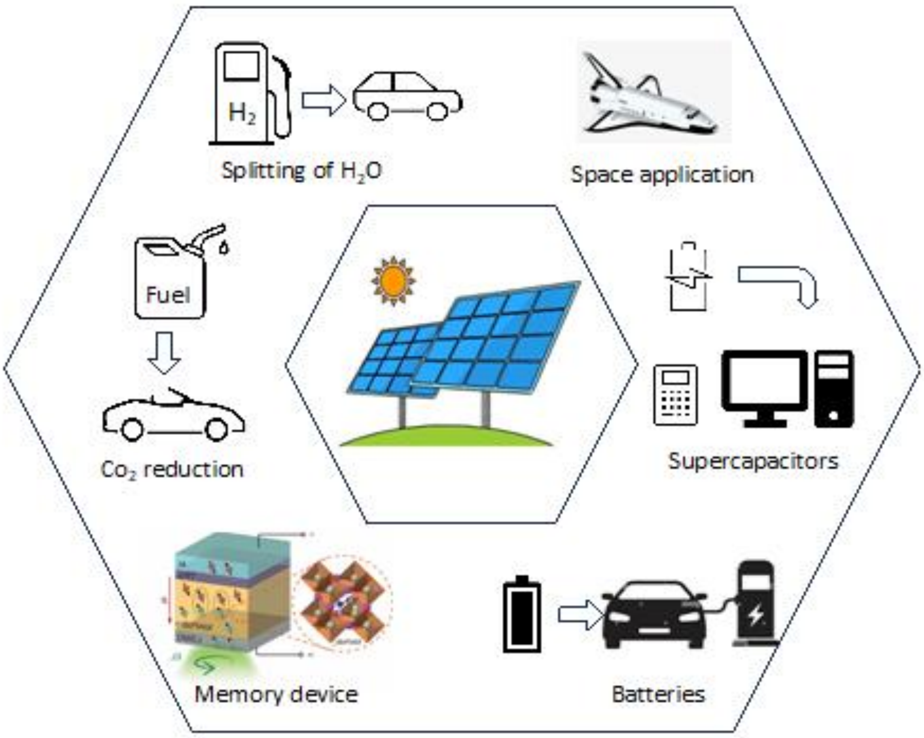


Figure 3: Schematic diagram of perovskite solar cell for integrated energy storage system

- **Space application:** Due to their characteristic features of high specific power and resistance against gamma radiation, perovskites are promising candidates for space applications[41]–[43]. The environment in space lacks components that degrade perovskite, such as oxygen and moisture present in the Earth's atmosphere. Therefore, perovskite could be more stable in space. Despite being in its infancy, a few experiments have been conducted in actual space settings to develop perovskite for space applications.

- **Perovskite solar cell batteries (PSCs-batteries):** Smart electronic devices and electric vehicles are essential parts of today's life, and the future also relies on these technologies. Metal-ion batteries, such as lithium-ion batteries (LIBs), are anticipated to serve as energy storage systems for solar rechargeable batteries due to their high energy density and exceptional chemical stability[44]. These smart devices primarily depend on rechargeable batteries for energy storage. Perovskite-based rechargeable batteries, such as lithium-ion batteries, are promising candidates for this purpose[45]. However, these devices still require significant improvement and more testing and trials for long-term stability and moisture resistance to achieve optimal performance.

- **Water splitting:** The extraction of H_2 (hydrogen) from H_2O (water) through perovskite-driven electrolysis is an ongoing research topic. In this process, H_2 gas can be extracted from H_2O by applying an electric current to the suitable electrode, which splits it into H_2 and oxygen (O_2) molecules[46]. Electrolyzers and high-voltage photovoltaics are crucial parameters that need to be accurately prepared for this purpose. The H_2 obtained can be stored as a gas under high pressure and delivered through gas pipelines as a fuel. It is an environmentally friendly, green strategy with zero carbon fuel that can be used in combustion engines and fuel cells. Utilizing high-voltage solar cells is one of the primary methods for building an efficient and affordable water-splitting system powered by PV (photovoltaic) cells.

- **CO_2 Reduction:** The conversion of CO_2 into different chemical feedstocks and fuels has been the ongoing focus of research for many years. It is not only used for chemical purposes but is also very efficient in reducing greenhouse emissions caused by CO_2[47]. Reductionreactions of $CO_2$are the best way to utilize these resources and obtain high-value chemicals, which are powered by electricity produced by solar cells. CO_2 reduction reactions require a higher voltage than water splitting, specifically greater than 2.0V[48]. To achieve this, a powerful strategy is to use a serially connected tandem solar cell multiple junctions.

- **Perovskite in Memory Devices:** Although perovskite is extensively used as photovoltaic and light-emitting diode (LED) materials in industries, the pace of digital technology is accelerating in today's market and shows no signs of slowing down. This has resulted in the design of memory devices using perovskite materials. Researchers are working on resistive switching in memory devices using perovskite oxide and metal halide. Resistive Random Access Memory (ReRAM) has emerged as the most promising choice for future non-volatile device use due to its quick switching speed, lower power consumption, and excellent scalability[49]. It enables fast writing and long durability in computer memory.

  Now, people are introducing spintronics with perovskite. In this combination, ferromagnetic material is introduced with perovskite to utilize its characteristics for data storage by writing electrically and reading magnetically. Interfacing perovskite with FM (ferromagnetic) materials will bring hybrid devices where the magnetic properties of FM layers or spin pumping/spin current generated by non-magnetic materials (perovskite) can be manipulated with the presence of light[50]–[53]. The charge- current in FM or NM (non-magnetic) material can be used to change the operation of these devices. The presence of spin pumping and spin-orbit torques in ferromagnetic/non-magnetic systems has drawn great interest to magnetic heterostructures. Spin pumping allows efficient transfer of spin current at the ferromagnet/non-magnet interface, and the spin-orbit torques in ferromagnets enable the manipulation of ferromagnetic magnetization[54]. With sufficiently strong spin-orbit torques, it is possible to excite magnetization to auto-oscillate for radio frequency applications or switch the magnetization or move domain walls for efficient memory applications[55]. Therefore, understanding spin-pumping and spin-orbit torque in magnetic heterostructures and their interfaces is of great technological significance. In the past, researchers have explored various heavy metals (HMs), their alloys, topological insulators, and two-dimensional materials for spin pumping and spin-orbit torque studies.

REFERENCES

[1] F. Urbain *et al.*, “Multijunction Si photocathodes with tunable photovoltages from 2.0 V to 2.8 V for light induced water splitting,” *Energy Environ. Sci.*, vol. 9, no. 1, pp. 145–154, 2016, doi: 10.1039/C5EE02393A.

[2] V. A. Tran *et al.*, “Application of nitrogen-doped TiO2 nano-tubes in dye-sensitized solar cells,” *Appl. Surf. Sci.*, vol. 399, pp. 515–522, Mar. 2017, doi: 10.1016/j.apsusc.2016.12.125..

[3] A. Colombo *et al.*, “A carbon doped anatase TiO2 as a promising semiconducting layer in Ru-dyes based dye-sensitized solar cells,” *Inorganica Chim. Acta*, vol. 489, pp. 263–268, Apr. 2019, doi: 10.1016/j.ica.2019.02.024.

[4] Z. H. Bakr, Q. Wali, A. Fakharuddin, L. Schmidt-Mende, T. M. Brown, and R. Jose, “Advances in hole transport materials engineering for stable and efficient perovskite solar cells,” *Nano Energy*, vol. 34, pp. 271–305, Apr. 2017, doi: 10.1016/j.nanoen.2017.02.025.

[5] C. Wu *et al.*, “The Dawn of Lead-Free Perovskite Solar Cell: Highly Stable Double Perovskite $Cs_2AgBiBr_6$ Film,” *Adv. Sci.*, vol. 5, no. 3, p. 1700759, Mar. 2018, doi: 10.1002/advs.201700759.

[6] S. Ahmed and D. J. Kalita, “Charge transport in isoindigo-dithiophenepyrrole based D-A type oligomers: A DFT/TD-DFT study for the fabrication of fullerene-free organic solar cells,” *J. Chem. Phys.*, vol. 149, no. 23, p. 234906, Dec. 2018, doi: 10.1063/1.5055306.

[7] M. Cheng *et al.*, “Charge-transport layer engineering in perovskite solar cells,” *Sci. Bull.*, vol. 65, no. 15, pp. 1237–1241, Aug. 2020, doi: 10.1016/j.scib.2020.04.021.

[8] S. Paek *et al.*, “Donor–π–donor type hole transporting materials: marked π-bridge effects on optoelectronic properties, solid-state structure, and perovskite solar cell efficiency,” *Chem. Sci.*, vol. 7, no. 9, pp. 6068–6075, 2016, doi: 10.1039/C6SC01478J.

[9] W.-J. Chi, Q.-S. Li, and Z.-S. Li, “Effect of thiophene chain lengths on the optical and hole transport properties for perovskite solar cells,” *Synth. Met.*, vol. 211, pp. 107–114, Jan. 2016, doi: 10.1016/j.synthmet.2015.11.020.

[10] D. Chandrasekaran, W.-H. Chiu, K.-M. Lee, J.-M. Liao, H.-H. Chou, and Y.-S. Yen, “Effect of Thiophene Insertion on X-Shaped Anthracene-Based Hole-Transporting Materials in Perovskite Solar Cells,” *Polymers*, vol. 14, no. 8, p. 1580, Apr. 2022, doi: 10.3390/polym14081580.

[11] N.-G. Park, M. Grätzel, and T. Miyasaka, Eds., *Organic-Inorganic Halide Perovskite Photovoltaics*. Cham: Springer International Publishing, 2016. doi: 10.1007/978-3-319-35114-8.

[12] K. Sun *et al.*, “A molecular nematic liquid crystalline material for high-performance organic photovoltaics,” *Nat. Commun.*, vol. 6, no. 1, p. 6013, Jan. 2015, doi: 10.1038/ncomms7013.

[13] K. Ahmad, A. Mohammad, and S. M. Mobin, “Hydrothermally grown α-MnO2 nanorods as highly efficient low cost counter-electrode material for dye-sensitized solar cells and electrochemical sensing applications,” *Electrochimica Acta*, vol. 252, pp. 549–557, Oct. 2017, doi: 10.1016/j.electacta.2017.09.010.

[14] M. Zhong, Y. Liang, J. Zhang, Z. Wei, Q. Li, and D. Xu, “Highly efficient flexible $MAPbI_3$ solar cells with a fullerene derivative-modified SnO_2 layer as the electron transport layer,” *J. Mater. Chem. A*, vol. 7, no. 12, pp. 6659–6664, 2019, doi: 10.1039/C9TA00398C

[15] Z. Guo, L. Gao, C. Zhang, Z. Xu, and T. Ma, “Low-temperature processed non-TiO_2 electron selective layers for perovskite solar cells,” *J. Mater. Chem. A*, vol. 6, no. 11, pp. 4572–4589, 2018, doi: 10.1039/C7TA10742K.

[16] Guo Z, Gao L, Zhang C, Xu Z, Ma T. Low-temperature processed non-TiO 2 electron selective layers for perovskite solar cells. Journal of Materials Chemistry A. 2018;6(11):4572-89.

[17] K. Ahmad, A. Mohammad, and S. M. Mobin, “Hydrothermally grown α-MnO2 nanorods as highly efficient low cost counter-electrode material for dye-sensitized solar cells and electrochemical sensing applications,” *Electrochimica Acta*, vol. 252, pp. 549–557, Oct. 2017, doi: 10.1016/j.electacta.2017.09.010

[18] Z. Yu and L. Sun, "Inorganic Hole-Transporting Materials for Perovskite Solar Cells," *Small Methods*, vol. 2, no. 2, p. 1700280, Feb. 2018, doi: 10.1002/smtd.201700280.

[19] J. Zhang *et al.*, "Incorporation of Counter Ions in Organic Molecules: New Strategy in Developing Dopant-Free Hole Transport Materials for Efficient Mixed-Ion Perovskite Solar Cells," *Adv. Energy Mater.*, vol. 7, no. 14, p. 1602736, Jul. 2017, doi: 10.1002/aenm.201602736.

[20] X. Li, Y.-C. Wang, L. Zhu, W. Zhang, H.-Q. Wang, and J. Fang, "Improving Efficiency and Reproducibility of Perovskite Solar Cells through Aggregation Control in Polyelectrolytes Hole Transport Layer," *ACS Appl. Mater. Interfaces*, vol. 9, no. 37, pp. 31357–31361, Sep. 2017, doi: 10.1021/acsami.7b11977.

[21] K. Sun *et al.*, "A molecular nematic liquid crystalline material for high-performance organic photovoltaics," *Nat. Commun.*, vol. 6, no. 1, p. 6013, Jan. 2015, doi: 10.1038/ncomms7013

[22] G. Sfyri, C. V. Kumar, Y.-L. Wang, Z.-X. Xu, C. A. Krontiras, and P. Lianos, "Tetra methyl substituted Cu(II) phthalocyanine as alternative hole transporting material for organometal halide perovskite solar cells," *Appl. Surf. Sci.*, vol. 360, pp. 767–771, Jan. 2016, doi: 10.1016/j.apsusc.2015.11.065.

[23] J. H. Heo and S. H. Im, "$CH_3NH_3PbI_3$ /poly-3-hexylthiophen perovskite mesoscopic solar cells: Performance enhancement by Li-assisted hole conduction: $CH_3NH_3PbI_3$ /poly-3-hexylthiophen perovskite mesoscopic solar cells: Performance enhancement by Li-assisted hole conduction," *Phys. Status Solidi RRL - Rapid Res. Lett.*, vol. 8, no. 10, pp. 816–821, Oct. 2014, doi: 10.1002/pssr.201409330.

[24] S. Ryu *et al.*, "Voltage output of efficient perovskite solar cells with high open-circuit voltage and fill factor," *Energy Env. Sci*, vol. 7, no. 8, pp. 2614–2618, 2014, doi: 10.1039/C4EE00762J.

[25] Q. Zhu *et al.*, "Compact Layer Free Perovskite Solar Cells with a High-Mobility Hole-Transporting Layer," *ACS Appl. Mater. Interfaces*, vol. 8, no. 4, pp. 2652–2657, Feb. 2016, doi: 10.1021/acsami.5b10555.

[26] A. Dubey *et al.*, "Solution processed pristine PDPP3T polymer as hole transport layer for efficient perovskite solar cells with slower degradation," *Sol. Energy Mater. Sol. Cells*, vol. 145, pp. 193–199, Feb. 2016, doi: 10.1016/j.solmat.2015.10.008

[27] M. L. Petrus, T. Bein, T. J. Dingemans, and P. Docampo, "A low cost azomethine-based hole transporting material for perovskite photovoltaics," *J. Mater. Chem. A*, vol. 3, no. 23, pp. 12159–12162, 2015, doi: 10.1039/C5TA03046C.

[28] H. Choi, S. Paek, N. Lim, Y. H. Lee, M. K. Nazeeruddin, and J. Ko, "Efficient Perovskite Solar Cells with 13.63 % Efficiency Based on Planar Triphenylamine Hole Conductors," *Chem. – Eur. J.*, vol. 20, no. 35, pp. 10894–10899, Aug. 2014, doi: 10.1002/chem.201403807.

[29] G. Sfyri, C. V. Kumar, Y.-L. Wang, Z.-X. Xu, C. A. Krontiras, and P. Lianos, "Tetra methyl substituted Cu(II) phthalocyanine as alternative hole transporting material for organometal halide perovskite solar cells," *Appl. Surf. Sci.*, vol. 360, pp. 767–771, Jan. 2016, doi: 10.1016/j.apsusc.2015.11.065.

[30] M. Stolterfoht et al., 'How To Quantify the Efficiency Potential of Neat Perovskite Films: Perovskite Semiconductors with an Implied Efficiency Exceeding 28%', Advanced Materials, vol. 32, no. 17, p. 2000080, Apr. 2020, doi: 10.1002/adma.202000080.

[31] P. Roy, A. Ghosh, F. Barclay, A. Khare, and E. Cuce, 'Perovskite Solar Cells: A Review of the Recent Advances', *Coatings*, vol. 12, no. 8, p. 1089, Jul. 2022, doi: 10.3390/coatings12081089.

[32] Y.-E. Lye, K.-Y. Chan, and Z.-N. Ng, 'A Review on the Progress, Challenges, and Performances of Tin-Based Perovskite Solar Cells', *Nanomaterials*, vol. 13, no. 3, p. 585, Feb. 2023, doi: 10.3390/nano13030585.

[33] K. Verma, 'Challenges and Potential of Perovskite Solar Cells', *Journal of Ravishankar University (PART-B)*, vol. 35, no. 2, pp. 68–75, Jan. 2023, doi: 10.52228/jrub.2023-35-2-6.

[34] K. Aitola*et al.*, 'Encapsulation of commercial and emerging solar cells with focus on perovskite solar cells', *Solar Energy*, vol. 237, pp. 264–283, May 2022, doi: 10.1016/j.solener.2022.03.060.

[35] X. Mei, D. Jia, J. Chen, S. Zheng, and X. Zhang, 'Approaching high-performance light-emitting devices upon perovskite quantum dots: Advances and prospects', *Nano Today*, vol. 43, p. 101449, Apr. 2022, doi: 10.1016/j.nantod.2022.101449.

[36] T. H. Bui and J. H. Shin, 'Perovskite materials for sensing applications: Recent advances and challenges', *Microchemical Journal*, vol. 191, p. 108924, Aug. 2023, doi: 10.1016/j.microc.2023.108924.

[37] X. Liu *et al.*, 'Recent advances in perovskites-based optoelectronics', *Nanotechnol Rev*, vol. 11, no. 1, pp. 3063–3094, Nov. 2022, doi: 10.1515/ntrev-2022-0494.

[38] V. Vega-Garita, L. Ramirez-Elizondo, N. Narayan, and P. Bauer, 'Integrating a photovoltaic storage system in one device: A critical review', *Progress in Photovoltaics: Research and Applications*, vol. 27, no. 4, pp. 346–370, Apr. 2019, doi: 10.1002/pip.3093.

[39] S. R. Bati, Y. L. Zhong, P. L. Burn, M. K. Nazeeruddin, P. E. Shaw, and M. Batmunkh, 'Next-generation applications for integrated perovskite solar cells', *Communications Materials*, vol. 4, no. 1. Springer Nature, Dec. 01, 2023. doi: 10.1038/s43246-022-00325-4.
[40] Q. Zeng *et al.*, 'Integrated Photorechargeable Energy Storage System: Next-Generation Power Source Driving the Future', *Adv Energy Mater*, vol. 10, no. 14, p. 1903930, Apr. 2020, doi: 10.1002/aenm.201903930.
[41] Y. Tu *et al.*, 'Perovskite Solar Cells for Space Applications: Progress and Challenges', *Advanced Materials*, vol. 33, no. 21, p. 2006545, May 2021, doi: 10.1002/adma.202006545.
[42] M. Kaltenbrunner *et al.*, 'Flexible high power-per-weight perovskite solar cells with chromium oxide–metal contacts for improved stability in air', *Nat Mater*, vol. 14, no. 10, pp. 1032–1039, Oct. 2015, doi: 10.1038/nmat4388.
[43] S. Yang, Z. Xu, S. Xue, P. Kandlakunta, L. Cao, and J. Huang, 'Organohalide Lead Perovskites: More Stable than Glass under Gamma-Ray Radiation', *Advanced Materials*, vol. 31, no. 4, p. 1805547, Jan. 2019, doi: 10.1002/adma.201805547.
[44] J. Xu, Y. Chen, and L. Dai, 'Efficiently photo-charging lithium-ion battery by perovskite solar cell', *Nat Commun*, vol. 6, no. 1, p. 8103, Aug. 2015, doi: 10.1038/ncomms9103.
[45] M. A. Mahmoudzadeh, A. R. Usgaocar, J. Giorgio, D. L. Officer, G. G. Wallace, and J. D. W. Madden, 'A high energy density solar rechargeable redox battery', *J Mater Chem A Mater*, vol. 4, no. 9, pp. 3446–3452, 2016, doi: 10.1039/C5TA08618C.
[46] J. Luo *et al.*, 'Water photolysis at 12.3% efficiency via perovskite photovoltaics and Earth-abundant catalysts', *Science (1979)*, vol. 345, no. 6204, pp. 1593–1596, Sep. 2014, doi: 10.1126/science.1258307.
[47] S. Esiner, J. Wang, and R. A. J. Janssen, 'Light-Driven Electrochemical Carbon Dioxide Reduction to Carbon Monoxide and Methane Using Perovskite Photovoltaics', *Cell Rep Phys Sci*, vol. 1, no. 5, p. 100058, May 2020, doi: 10.1016/j.xcrp.2020.100058.
[48] T. Li, Y. Yang, G. Li, P. Chen, and X. Gao, 'Two-Terminal Perovskite-Based Tandem Solar Cells for Energy Conversion and Storage', *Small*, vol. 17, no. 23, p. 2006145, Jun. 2021, doi: 10.1002/smll.202006145.
[49] G. S. H. Thien *et al.*, 'Recent Advances in Halide Perovskite Resistive Switching Memory Devices: A Transformation from Lead-Based to Lead-Free Perovskites', *ACS Omega*, vol. 7, no. 44, pp. 39472–39481, Nov. 2022, doi: 10.1021/acsomega.2c03206.
[50] Y. Zhao *et al.*, 'Sunlight Control of Interfacial Magnetism for Solar Driven Spintronic Applications', *Advanced Science*, vol. 6, no. 24, Dec. 2019, doi: 10.1002/advs.201901994.
[51] S. Zhao *et al.*, 'Photovoltaic Control of Ferromagnetism for Flexible Spintronics', *ACS Appl Mater Interfaces*, vol. 12, no. 37, pp. 41999–42006, Sep. 2020, doi: 10.1021/acsami.0c11954.
[52] Y. Zhao *et al.*, 'Enhancing Sunlight Control of Interfacial Magnetism by Introducing the ZnO Layer for Electron Harvesting', *ACS Appl Mater Interfaces*, vol. 13, no. 1, pp. 2018–2024, Jan. 2021, doi: 10.1021/acsami.0c19367.
[53] C. Li *et al.*, 'Sunlight Control of Ferromagnetic Damping in Photovoltaic/Ferromagnetic Heterostructures', *Adv Funct Mater*, vol. 32, no. 16, Apr. 2022, doi: 10.1002/adfm.202111652.
[54] S. Yang, E. Vetter, T. Wang, A. Amassian, and D. Sun, 'Observation of long spin lifetime in MAPbBr3 single crystals at room temperature', *JPhys Materials*, vol. 3, no. 1, Jan. 2020, doi: 10.1088/2515-7639/ab69b0.
[55] M. Zhao *et al.*, 'Deterministic Magnetic Switching in Perpendicular Magnetic Trilayers Through Sunlight-Induced Photoelectron Injection', *Small*, 2023, doi: 10.1002/smll.202301955.
[56] S. Ahmed, B. C. Mushahary, and D. J. Kalita, "Rational Design of Bay-Annulated Indigo (BAI)-Based Oligomers for Bulk Heterojunction Organic Solar Cells: A Density Functional Theory (DFT) Study," *ACS Omega*, vol. 5, no. 14, pp. 8321–8333, 2020, doi: 10.1021/acsomega.0c00784.

