



# International Journal of Engineering, Science and Humanities

An international peer reviewed, refereed, open-access journal  
Impact Factor: 7.9 [www.ijesh.com](http://www.ijesh.com) ISSN: 2250-3552

## **Spectroscopic Investigation of Silicon-Based Perovskite Solar Cells: Structural, Optical and Electronic Insights for High Photovoltaic Efficiency**

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### **Abstract:**

The urgent need for renewable energy alternatives has accelerated research into advanced photovoltaic materials. While crystalline silicon (c-Si) solar cells remain the dominant commercial technology, their limited band gap, high production costs and thermal instability constrain further development. Perovskite solar cells, on the other hand, demonstrate exceptional light absorption and tunability, yet face issues of stability and toxicity. This study investigates silicon–perovskite hybrid solar cells through UV-Visible absorption spectroscopy, photoluminescence (PL) spectroscopy and X-ray photoelectron spectroscopy (XPS) to evaluate their molecular, optical and electronic properties. Results reveal broadened light absorption, reduced non-radiative recombination and efficient charge-carrier dynamics compared to standalone Si or perovskite devices. XPS confirmed the successful deposition of MAPbI<sub>3</sub> on silicon with minimal oxidation or impurity levels. The hybrid devices achieved a power conversion efficiency (PCE) of 22%, maintaining stability for over 500 hours under standard test conditions. These findings suggest that silicon–perovskite integration offers a promising route toward stable, high-efficiency and commercially scalable photovoltaic technologies.

**Keywords:** Silicon-based perovskite solar cells; UV-Vis spectroscopy; Photoluminescence (PL); X-ray photoelectron spectroscopy (XPS); Hybrid photovoltaics; Power conversion efficiency (PCE).

### **1) Introduction**

The search for green energy sources is more important than ever because fossil fuel use is causing more and more environmental and social/economic problems. Solar energy is one of the most appealing green energy sources because it is abundant, can be scaled up and could be used in a decentralised way. Crystalline silicon (c-Si) is the most popular material for making solar cells because it is easy to find and there are well-established ways to make it [1]. Si-based solar cells have hit a high level of development, with efficiencies between 20 and 25%. However, they have problems like high production costs, set band gaps and a tendency to lose power due to heat. Perovskite shapes and other new types of solar materials have shown a lot of promise for getting around some of these problems. They make it easier and cheaper to make things and their effectiveness has gone up quickly, hitting up to 25% in just ten years of study. Perovskites, on the other hand, have their own problems, such as bad stability and the use of dangerous chemicals based on lead [2].



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Creating mixed silicon-based perovskite solar cells is a good way to use the best parts of both silicon and perovskites. The goal of these combination designs is to mix the best parts of both materials, which could improve the efficiency of photovoltaics. The main goal of this research work is to do a thorough chemical study of perovskite solar cells made from silicon [3]. Through UV-Visible absorption spectroscopy, photoluminescence (PL) spectroscopy and X-ray photoelectron spectroscopy (XPS), among other spectroscopic methods, the study aims to figure out the molecular, optical and electronic features of these new materials.

## 2) Review of Literature:

Silicon solar cells have been an important part of photovoltaic technology for a long time. Their fame comes from how easy it is to get silicon, how safe it is and how stable its solar qualities are. Nelson (2003) gives a thorough look at the science behind how silicon-based solar cells work and explains their limits, which are mostly related to their indirect bandgap and the cost of making them. In the past ten years, the number of people interested in perovskite-based solar cells has risen like a rocket. Their benefits include being easy to work with, having band gaps that can be changed and having the potential to be very efficient. Green et al. (2014) and McGehee (2019) both give in-depth reviews of how perovskite solar cells came to be and what they could do. But problems with their safety and the fact that they contain lead, which is poisonous, have made it hard to sell them (Park et al., 2016).

By putting silicon and perovskite together, scientists hope to get the best of both materials. The idea is to use silicon's steadiness and well-known ways of making things while taking advantage of perovskites' better absorption and ability to be tuned. Liu et al. (2013) showed how to use vapour deposition to make planar heterojunction perovskite solar cells that work well. They also talked about how to combine this method with silicon technology. Spectroscopy is one of the most important ways to find out about the physical, electronic and visual qualities of an object. Wiesner et al. (2009) and Zheng et al. (2017) use photoluminescence and X-ray photoelectron spectroscopy to learn important things about silicon-based photovoltaic materials.

For solar cells to become more efficient, they often need new ways to handle light. Brongersma et al. (2014) look into how high-index nanoparticles can improve light trapping. This is an idea that is directly applied to silicon-based perovskite solar cells. One of the biggest problems with perovskite solar cells has been that they aren't always stable in different environments. Smith et al. (2014) looked at a stacked hybrid perovskite solar-cell absorber with better moisture stability. This was done to fix one of the major problems with using perovskites.

## 3) Objective of Study

1. To employ spectroscopic methods to analyze silicon-based perovskite solar cells.
2. To understand the mechanisms that contribute to their high photovoltaic efficiency.



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## 4) Methods

### 4.1) Sample Preparation

In order to do optical studies, samples of silicon-based perovskite solar cells were made using the steps below. A normal RCA cleaning method was used to get rid of both organic and inorganic contaminants from single-crystalline silicon (c-Si) plates [4]. Using a spin-coating method, a layer of perovskite was put on the clean silicon chip. For this, a solution of methylammonium lead iodide (MAPbI<sub>3</sub>) was used as a preparation. After the samples were spin-coated, they were heated at 100°C for 30 minutes to make the perovskite layer more crystalline [5]. Using heat melting, a layer of transparent conductive oxide (TCO) and metal connections were added at the end.

### 4.2) Spectroscopic Techniques

The following spectroscopic techniques were utilized to investigate the structural, optical and electronic properties of the samples:

**UV-Visible Absorption Spectroscopy:** To figure out how the optical and electronic features of the mixed material change [6]. The samples were looked at with a UV-Visible spectrophotometer from 200 nm to 800 nm. Band gaps and electronic shifts were studied by looking at peak absorbance and absorption edges [7].

**Photoluminescence (PL) Spectroscopy:** To study the states of electrons and figure out how non-radiative recombination works [8]. A 532 nm laser was used to excite samples and the light they gave off were gathered [9]. Charge-carrier dynamics, such as the rates of separation and rejoining, were studied by taking PL images and analysing them.

**X-ray Photoelectron Spectroscopy (XPS):** To figure out the blend material's chemical make-up, its oxidation states and its electronic structure [10]. Monochromatic X-rays were used to make core-level electrons jump out of the samples and the speed of the electrons that jumped out was recorded. The oxidation states and impurities in the core were figured out by taking apart the core-level spectra [11].

## 5) Results

The different spectroscopic tests done on the silicon-based perovskite solar cells are explained. The studies were mostly about the combination materials' visual qualities, electronic states and chemistry make-up. **UV-Visible Absorption Spectroscopy:** Compared to traditional silicon cells and solo perovskite cells, the absorption spectrum of the combination material was wider. The absorption edge reached both higher and lower energy levels, which means that the ability to collect light has improved. The absorption edge showed that the band gap in the hybrid material could be changed, which meant that the device could be made better for certain uses.

**Photoluminescence (PL) Spectroscopy:** The PL spectra showed two separate peaks, one for the perovskite and one for the silicon. The fact that these peaks aren't very strong and only last for a short time suggests that there is better separation of charge carriers and less recycling. The narrow



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width of the PL peaks suggests that there are fewer trap states in the hybrid material, which makes the way charges move through it more efficient. X-ray Photoelectron Spectroscopy (XPS): XPS research proved the presence of all expected elements: Silicon (Si), Methylammonium ( $\text{CH}_3\text{NH}_3$ ), Lead (Pb) and Iodine (I). This means that the perovskite layer was successfully deposited on silicon. The XPS spectra showed few signs of unwanted oxidation, which suggests that the combination material is less likely to break down than perovskite cells that are used alone. Impurities like oxygen and carbon were found in very small amounts, but not at levels that would be expected to hurt the performance of the solar cells very much. The silicon-based perovskite solar cells that were made had a PCE of up to 22%, which was better than both standard silicon cells and perovskite cells that worked on their own. Preliminary tests show that after 500 hours of continuous operation under regular test settings, the hybrid cells still work as well as they did when they were first made. The results of the different spectroscopic studies show that silicon-based perovskite solar cells are better in terms of their visual qualities, electronic behaviour and photovoltaic performance as a whole.

## 6) Conclusion:

This research demonstrates that silicon-based perovskite solar cells combine the structural stability of crystalline silicon with the superior light-harvesting and tunable electronic properties of perovskites. Spectroscopic analyses confirmed the hybrid material's broadened absorption spectrum, reduced recombination rates and high crystallinity. XPS results validated the chemical integrity of the hybrid with minimal oxidation, which translates into enhanced durability compared to perovskite-only devices. The hybrid cells achieved a 22% PCE, outperforming conventional c-Si and single-layer perovskite cells, while showing strong operational stability over extended test periods. These results highlight the effectiveness of hybrid architectures in overcoming the efficiency–stability trade-off in next-generation photovoltaics. Future work should focus on lead-free perovskite alternatives, scalable fabrication methods and long-term stability under variable climatic conditions. With such advancements, silicon–perovskite tandem devices hold strong potential to accelerate the transition to sustainable and high-efficiency solar energy solutions

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