BIOSENSORS & NANOTHERANOSTICS

REVIEW

Enhancing Silicon Solar Cell Efficiency through Graphene Integration: A Review of Recent Advances

Uma Harikrishnan [1*]

Abstract

Background: Solar cells play a crucial role in renewable energy, contributing to sustainable development and a clean environment. This review investigates the integration of Graphene, a groundbreaking two-dimensional carbon nanomaterial, in enhancing solar cell performance. Objective: The primary aim is to elucidate how Graphene enhances the efficiency, stability, and durability of various solar cell technologies, particularly silicon-based systems. Methods: This review synthesizes recent research findings on Graphene's unique properties—such as electrical conductivity, transparency, mechanical strength, and chemical stability—and their applications in different solar cell types, including perovskite, quantum dot, hybrid, dye-sensitized, and organic solar cells. Results: The integration of Graphene has been shown to improve charge transport and collection efficiency. Its role as a transparent conductive layer, passivation layer, and charge transport layer has significantly enhanced the overall efficiency and longevity of silicon solar cells. Recent advancements highlight the potential of Graphene to address current limitations in silicon solar technologies, contributing to next-generation photovoltaic systems. Conclusion: Graphene emerges as a transformative material for enhancing solar cell efficiency and stability. Continued research is essential to overcome integration challenges and optimize Graphene's performance in solar applications, paving the way for more efficient and sustainable solar energy solutions.

Significance | This review underscores graphene's transformative potential in improving silicon solar cell efficiency, crucial for advancing renewable energy technologies and sustainability.

*Correspondence. Uma Harikrishnan, Chemical Laboratory, VEC Imaging GmbH & Co.KG, Erlangen, Germany.
E-mail: uma.lharikrishnan@gmail.com

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Introduction

Renewable energy is an abundant source of clean and inexhaustible energy (Oni et al., 2024). To meet the ever-growing energy demands of society while combating climate change and global warming, there is a transition from finite fossil fuel sources to more sustainable alternatives (Pastuszak & Węgierek, 2022). Renewable resources appear to be the most viable option in this clean energy transition (Oni et al., 2024). With broad availability, scalability, and lower operating costs, solar energy has emerged as the most promising source of renewable energy (Yoshikawa et al., 2017). The use of solar energy is growing rapidly due to the environmental harm caused by conventional fossil fuel-based energy sources (Geim & Novoselov, 2007). Solar energy is both reliable and plentiful, and solar cells offer an effective means of capturing this resource (Basore, 1994). The sun supplies 1367 W/m^2 of solar power to the Earth's atmosphere, with nearly 1.8×10^{11} MW being absorbed worldwide—enough to satisfy global power demands (Riverola et al., 2019; Edwards. &. Coleman, 2012).

Photovoltaic cells or solar cells capture solar energy and transform it into usable energy (Zanatta, 2022). A photovoltaic cell works on

Author Affiliation.
[1] Chemical Laboratory, VEC Imaging GmbH & Co.KG, Erlangen, Germany.

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the principle of the photovoltaic effect, first noticed by Edmund Becquerel in 1839 (Mbayachi et al., 2021). Different generations of solar cells have been created over time due to advancements in materials science . and the introduction of non-conventional production techniques (Pastuszak & Węgierek, 2022). First-generation solar cells include thick crystalline films, while second-generation cells consist of thin films like amorphous silicon (Cui et al., 2023). Third-generation cells use new materials such as quantum dots and perovskites (Gao et al., 2022). Fourth-generation cells combine inorganic nanostructures with the flexibility of polymer thin films (Fallahazad et al., 2020).

With the growing demand for clean energy, nanotechnology plays an increasingly important role in solar cell advancements (Feynman, 2018). The concept of nanotechnology was first introduced by Norio Taniguchi in 1974 (N, 1974), and since then, it has revolutionized various fields (Wolf, 2014). At the nanoscale, materials exhibit unique properties, offering significant benefits for energy storage and harvesting (Zhu et al., 2010). Nanotechnology has greatly impacted solar cell research (Li et al., 2010).

Graphene, a two-dimensional material composed of a single layer of carbon atoms, has emerged as a promising nanomaterial for enhancing solar cells (Geim & Novoselov, 2007). Its unique optical and electrical properties contribute to the performance enhancement of solar cells (Zhang et al., 2009). This study reviews advancements made by integrating graphene into silicon solar cells (Urade et al., 2022; Torres et al., 2021).

Silicon Solar Cells

Around 90% of the world's photovoltaics are based on some variation of silicon. The development of silicon-based solar cells began in the 1950s with the discovery of silicon's photovoltaic effect by scientists (Mohammad & Mahjabeen, 2023). Figure 2 showcases the timeline of silicon solar cell development. Silicon solar cells offer numerous benefits, starting with the abundance of silicon itself. As the second most plentiful element in the Earth's crust, silicon ensures a readily available supply for large-scale solar cell production. Additionally, silicon solar cell technology is highly mature, with a well-optimized manufacturing process perfected over decades. In terms of performance, silicon cells deliver higher efficiencies than any other mass-produced single-junction devices, which reduces installation costs since fewer cells are needed for the desired energy output. Moreover, these cells are highly reliable, boasting lifespans exceeding 25 years and power degradation rates of less than 1% annually (Crystalline Silicon Photovoltaics Research, n.d.) (Figure 2).

The four key processes in solar energy conversion are: 1) absorption of light, 2) creation of electron-hole pairs, 3) selective charge transport, and 4) recombination of electrons and holes, which returns the absorber to its ground state. The absorber material has a p-type semiconductor and n-type semiconductor forming a p-n junction. Figure 3 demonstrates the structure of a solar cell. When light hits the p-n junction, photons with energies corresponding to the semiconductor's band gap are absorbed, generating electrons and holes as charge carriers. It is essential to separate these carriers to prevent recombination, which would otherwise result in energy loss without contributing to electricity production (Oni et al., 2024). The development of the p-n junction structure marked a major milestone in the advancement of silicon solar cells. The creation of efficient p-n junction silicon solar cells laid the groundwork for the modern solar energy industry (Mohammad & Mahjabeen, 2023) (Figure 3).

Silicon solar cells are typically categorized as first-generation solar cells, with monocrystalline (mc-Si) and polycrystalline silicon (pc-Si) cells holding the largest market share. Amorphous silicon (a-Si), used in thin-film solar cells, belongs to the second generation of solar cell technologies. Microcrystalline silicon cells (μc-Si), often used in tandem solar cell configurations, are considered part of the third generation of solar cells (Pastuszak & Węgierek, 2022; Basore, 1994). A graphical overview of different PV generations is shown in Figure 4.

Silicon solar cells are known for their long-term performance and exceptional reliability. Many silicon-based solar panels installed decades ago continue to function efficiently, highlighting the durability and stability of silicon as a solar cell material. Recent research has focused on developing new silicon-based solar cell designs to enhance performance further. Bifacial silicon solar cells, for example, have gained attention due to their ability to generate electricity from sunlight hitting both the front and back surfaces. Additionally, Passivated Emitter and Rear Cell (PERC) technology has become economically viable due to the incorporation of a passivation layer on the rear side, which reduces recombination losses and increases overall efficiency (Yuan et al., 2021). Significant progress has been made in the efficiency of silicon solar cells, with commercial cells now achieving efficiencies above 20% and laboratory prototypes exceeding 25%. These advancements result from improved material quality, innovative cell designs, and advanced manufacturing techniques. (Mohammad & Mahjabeen, 2023) (Figure 5).

Graphene

In 2004, Geim and his team successfully created a stable monolayer of graphene using mechanical exfoliation (Geim & Novoselov, 2007). Their groundbreaking experiments earned Geim and Novoselov the Nobel Prize in Physics in 2010, which propelled graphene to become one of the most extensively researched two-dimensional materials globally (Geim & Novoselov, 2007). Since then, graphene has been renowned for its remarkable physical properties across various domains, including mechanical, optical,

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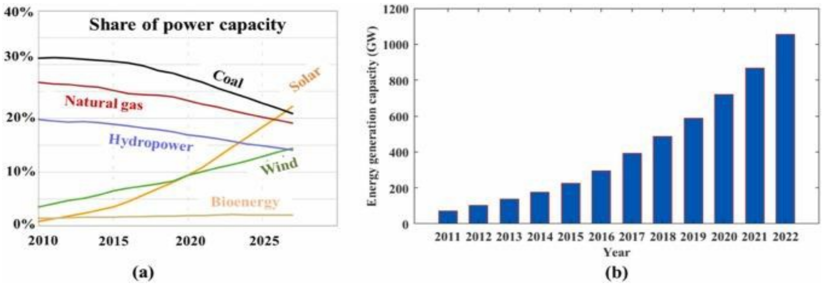

Figure 1. The relationship between particle size and PCE (Geng et al., 2021). (a) Share of power capacity by different energy sources from 2010 to 2025, illustrating a rise in solar energy sources (Oni et al., 2024). (b) Growth in global solar energy generation capacity from 2011 to 2022, highlighting the consistent upward trend in solar energy adoption (Pastuszak & Węgierek, 2022).

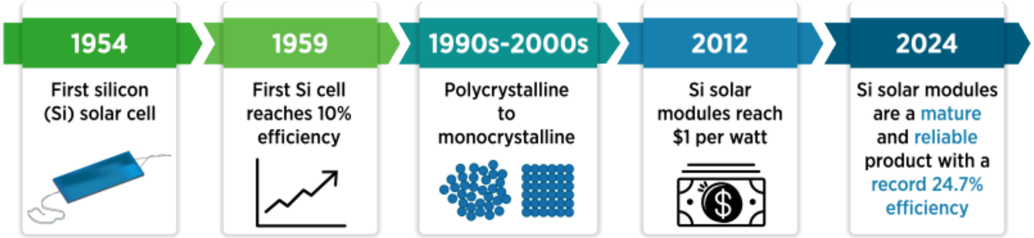

Figure 2. Timeline of key milestones in silicon (Si) solar cell development, starting with the first Si solar cell in 1954 and reaching 24.7% efficiency in 2024 (Crystalline Silicon Photovoltaics research, n.d.).

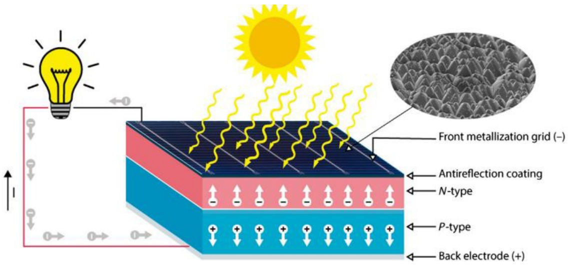

Figure 3. Schematic diagram of a solar cell (Riverola et al., 2019).

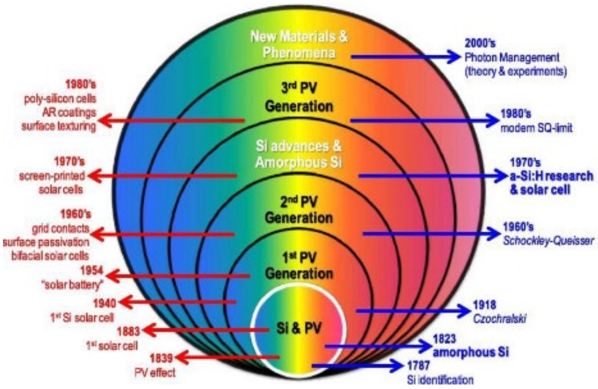

Figure 4. Graphical overview of the development of different photovoltaic generations, from the discovery of the photovoltaic effect to modern advancements in solar cell materials and technologies. The right side (blue text) focuses on silicon science and technology, while the left side (red text) highlights photovoltaic advancements (Zanatta, 2022).

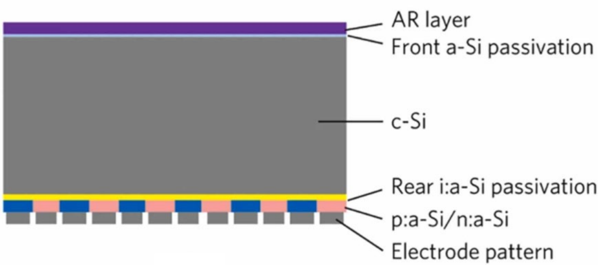

Figure 5. Configuration of a silicon solar cell achieving over 25% efficiency (Yoshikawa et al., 2017).

Table 1. Overview of graphene synthesis methods (Mbayachi et al., 2021; Madurani et al., 2020; Edwards & Coleman, 2012).

Synthesis Method	Description	Quality of Graphene	Applications
Chemical Vapor Deposition (CVD)	Deposition of carbon atoms onto a substrate (usually copper) through the decomposition of a carbon source gas (e.g., methane) at high temperatures.	High (monolayer or few layers, high purity)	Electronics, sensors, flexible displays
Mechanical Exfoliation	Peeling graphene layers from graphite using adhesive tapes.	Very High (monolayer)	Research, fundamental studies
Liquid-phase Exfoliation	Ultrasonication of graphite in solvents to produce graphene sheets.	Medium (few-layer graphene, impurities present)	Coatings, composites, conductive inks
Hummer's Method (Chemical Reduction of Graphite Oxide)	Oxidation of graphite to graphite oxide, followed by chemical reduction to produce graphene oxide (GO) or reduced graphene oxide (rGO).	Medium (contains oxygen functionalities, defects)	Composites, energy storage, sensors
Epitaxial Growth on SiC	Heating silicon carbide (SiC) to sublimate silicon, leaving behind a graphene layer.	High (few-layer, high purity)	Electronics, high-frequency devices
Electrochemical Exfoliation	Applying an electric current to graphite in an electrolyte solution to produce graphene sheets.	Medium to High (few- layer graphene)	Energy storage, coatings, sensors
Carbon Arc Discharge	Evaporation of graphite in an inert gas environment using high currents to form graphene.	Medium to High (depends on conditions)	Fundamental research, nanocomposites

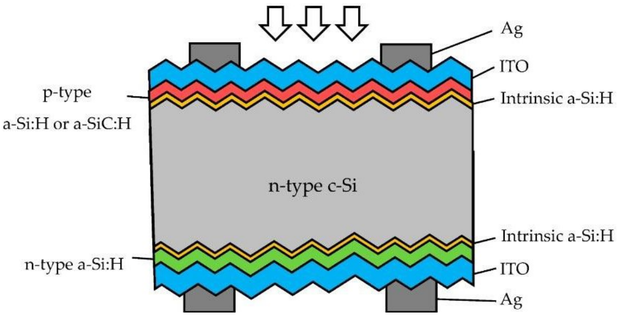

Figure 6. Structure of a silicon heterojunction solar cell (Hsu et al., 2019).

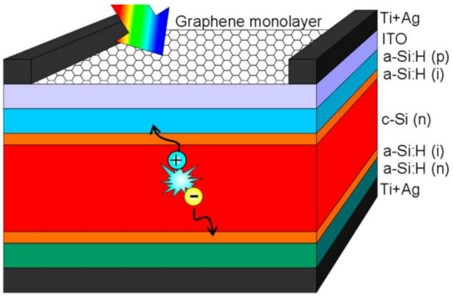

Figure 7. Schematic of the finished silicon heterojunction solar cell, where the front ITO layer has been replaced by a graphene-based hybrid transparent conductive electrode consisting of an 80 nm-thick ITO layer and a stack of up to three graphene monolayers (Torres et al., 2021).

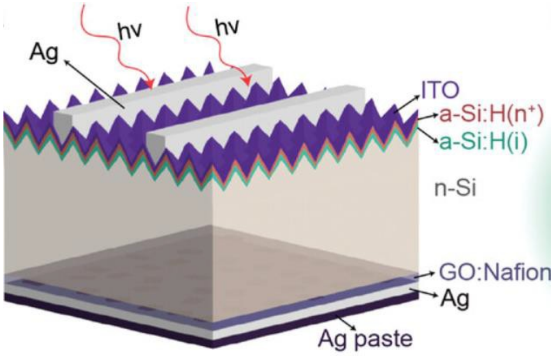

Figure 8. Schematic of silicon solar cell with hybrid GO ink coated on the rear side (Gao et al., 2022).

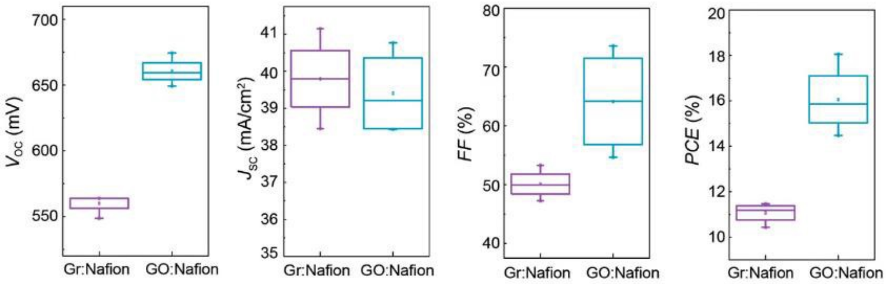

Figure 9. Gr:Nafion/Si and GO:Nafion/Si solar cell performance statistics (Gao et al., 2022).

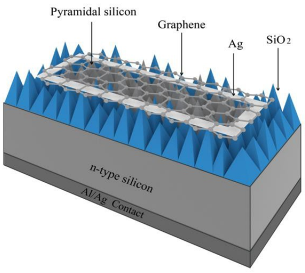

Figure 10. Schematic of reduced graphene oxide (rGO) layers on a pyramidal silicon structure (Fallahazad et al., 2020).

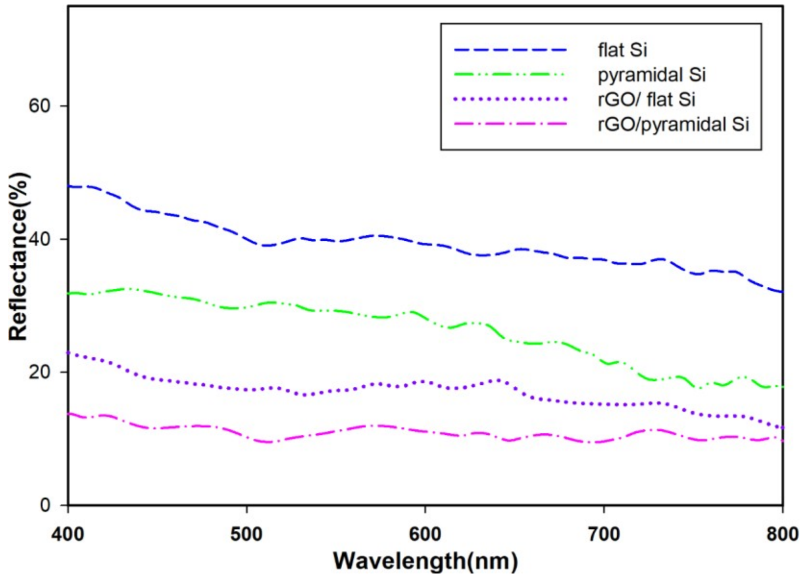

Figure 11. Comparison of reflection spectra for different solar cells (Fallahazad et al., 2020).

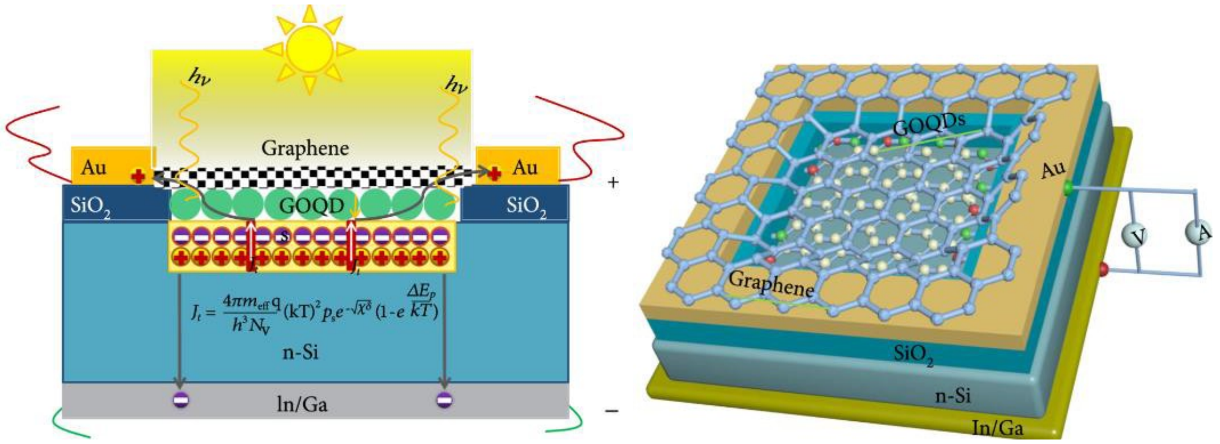

Figure 12. Schematic illustration of Schottky junction solar cells with a graphene quantum dot (GOQD) interlayer barrier (Geng et al., 2021).

electronic, and electrochemical aspects. Its unique characteristics include a large specific surface area of approximately 2600 m^2/g (Wolf, 2014), extremely high electron mobility reaching up to 200,000 cm^2/Vs (Zhang et al., 2009), and superior thermal conductivity in the range of 3000–5000 W/m·K (Urade et al., 2022). Additionally, graphene exhibits outstanding optical transparency, allowing 97.4% of light to pass through (Urade et al., 2022). Mechanically, it is exceptionally strong, boasting a Young's modulus of around 1 TPa (Urade et al., 2022). These exceptional properties make graphene an impressive material with wide-ranging applications. An overview of different graphene synthesis methods is provided in Table 1.

Graphene in Silicon - Solar Cells

Graphene is increasingly considered for use in silicon solar cells due to its remarkable properties that could enhance their performance. One of the primary advantages of graphene is its exceptional electrical conductivity, which can significantly improve the efficiency of charge collection and transport within the solar cells. This is crucial for boosting the overall power output of the cells. Additionally, graphene's high surface area offers more active sites for electron transfer, leading to increased efficiency in solar energy conversion (Zhu et al., 2010; Fallahazad et al., 2023). Its mechanical strength and flexibility are also noteworthy, as they allow for integration into both flexible and durable solar panel designs without compromising structural integrity. Furthermore, graphene's optical properties contribute to improved light absorption, as its unique ability to absorb a broad spectrum of light enhances the cell's performance in capturing and converting solar energy (Zhu et al., 2010; Fallahazad et al., 2023). Moreover, graphene's thinness and lightweight nature mean that it can be incorporated into silicon solar cells without adding significant weight, which is advantageous for both flexible and rigid panel designs (Zhu et al., 2010; Fallahazad et al., 2023). These benefits are supported by recent studies (Figure 6).

Silicon heterojunction solar cells (SHJ), with a combination of crystalline silicon and thin-film technologies, are high-efficiency devices. The structure of SHJ solar cells consists of a crystalline silicon wafer sandwiched between thin layers of hydrogenated amorphous silicon, intrinsic/n-doped and intrinsic/p-doped stacks. These thin amorphous silicon layers form the heterojunction and act as passivation and carrier-selective layers, while crystalline silicon serves as the main light absorber. The front and back sides of the cell feature a transparent electrode layer, which provides photogenerated charge to the terminals, improving electrical conductivity (Cui et al., 2023) (Figure 6).

Torres et al. (2021) demonstrated the effect of combining indium tin oxide with between one and three graphene monolayers as the top electrode in silicon heterojunction solar cells. Indium tin oxide (ITO) is the most popular transparent conducting oxide (TCO) in SHJ solar cells due to its excellent transparency and conducting properties. Torres et al. (2021) analyzed the effect of combining ITO with one to three graphene monolayers grown via chemical vapor deposition (CVD) as the top electrode in SHJ cells. They demonstrated that hybrid transparent conducting electrodes based on graphene and TCOs have potential. The addition of graphene monolayers to ITO improved its electrical characteristics, which in turn enhanced the JV characteristics of the solar cells, displaying better series resistance (Rs) and fill factor (FF) (Figure 7).

Gao et al. (2022) demonstrated significant improvements in silicon solar cells by incorporating graphene oxide (GO) in combination with Nafion. They developed a hybrid GO ink, which was spin-coated onto n-type silicon wafers, forming a high-quality passivating contact layer (Figure 8).

Nafion doped the GO layer and contributed to low interface recombination. Graphene (Gr) provided good minority carrier extraction, but it was inefficient at blocking the majority carriers at the Gr/Si metal-semiconductor (MS) heterojunction. Oxidation of graphene (GO) solved this issue by introducing a band gap of 0.11 to 4.0 eV (Zhang et al., 2009; Zhu et al., 2010). A back junction design was used for constructing the solar cell, where the GO layer was placed at the back of the cell. N-doped hydrogenated silicon with an ITO layer on top enhanced light trapping and reduced surface recombination (Yuan et al., 2021; Fallahazad et al., 2023). Good wettability of GO ink on silicon was observed, supported by the low contact angle of 19.7°, facilitating large-area coating by spin-coating. A high power conversion efficiency (PCE) of 18.8%, with an open circuit voltage (VOC) of 654 mV, a short-circuit current density (JSC) of 40.1 mA cm^{-2}, and a fill factor (FF) of 71.9%, was reported, with further optimization predicted to raise PCE to 21.59% (Gao et al., 2022) (Figure 9).

Fallahazad et al. (2020) investigated the performance of reduced graphene oxide (rGO)/Si solar cells using two different silicon substrates: flat and pyramidal. They applied the electrophoretic deposition (EPD) method to transfer the rGO layers onto the pyramidal silicon substrate, which allowed for controlled thickness at a cost-effective rate. EPD is advantageous for coating graphene on textured silicon due to its simplicity, cost-effectiveness, and ability to operate at low temperatures and ambient pressure (Figure 10). The results showed a notable reduction in reflectance for the pyramidal silicon substrate, decreasing from 23% to 14% compared to the flat silicon substrate (Figure 11). The enhanced light trapping, facilitated by the rGO, led to a substantial efficiency increase, with the pyramidal structure reducing series resistance and increasing shunt resistance (Figure 11).

Schottky Barrier Solar Cells (SBSCs), unlike p-n junction solar cells, use the metal-semiconductor interface as the primary region for charge separation (Landsberg & Klimpke, 1977). Graphene on a silicon substrate forms a simple SBSC, where graphene serves as a transparent electrode, a p-type semiconductor forming a Schottky junction, and generates a built-in electric field at the graphene-silicon interface (Li et al., 2010) (Figure 12).

Geng et al. (2021) used graphene oxide quantum dots (GOQDs) to improve the power conversion efficiency (PCE) of graphene/silicon Schottky barrier solar cells (Gr/Si SBSCs) by modifying the interface properties and serving as a unique barrier at the interface. The study also investigated the relationship between PCE and the particle size and thickness of the GOQDs. By adjusting the thickness and particle size of the GOQDs layer, it is possible to control hole tunneling and carrier recombination rates in the Gr/Si SBSCs. The presence of GOQDs induces an additional band bending in Gr/Si-based SBSCs, which contributes to improved PCE. The best PCE for the Gr/Si SBSC was recorded with the optimal particle size and thickness of 4.15 nm and 26 nm (Geng et al., 2021).

Conclusion

Graphene has the potential to significantly enhance silicon solar cells, yet several obstacles must be overcome to fully realize its benefits. Integrating graphene with silicon presents a key challenge, particularly in achieving strong adhesion that ensures efficient charge transfer. Additionally, while graphene production has scaled up, incorporating it into solar cell manufacturing on a largerscale remains complex and requires sophisticated techniques and equipment. The cost of high-quality graphene continues to be a barrier. Although prices are falling, finding economical production methods that maintain graphene's quality is essential for broader adoption. Moreover, optimizing the performance of graphene in silicon solar cells is crucial. The advantages of graphene, such as its conductivity and light absorption properties, need to be carefully adjusted to meet the specific needs of these cells. Material compatibility is another important consideration. The interactions between graphene and other components in the solar cell, like anti-reflective coatings and back contacts, must be thoroughly examined to avoid any negative impact on the cell's efficiency and stability. Additionally, the long-term stability and durability of graphene within these cells need to be assessed to ensure it remains effective over time without degradation. Lastly, gaining a deeper understanding of how graphene affects charge transport in silicon solar cells is vital. This knowledge will aid in designing better-integrated cells and addressing existing limitations, ultimately paving the way for more effective and reliable solar energy solutions.

Author contributions

U.H. was responsible for the conceptualization, design, and drafting of the manuscript. The author reviewed and approved the final version of the manuscript.

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Competing financial interests

The authors have no conflict of interest.

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