Dean&Francis

ISSN 2959-6157

Research Progress on Different Types of Solar Cells

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Abstract:

To address global challenges like fossil fuel shortages and climate change, developing clean and renewable solar energy is crucial for the world's energy transition. Solar cells, which convert sunlight into electricity, are at the forefront of energy technology development. This study uses literature review and comparative analysis to assess the technical features and status of major solar cell types, including crystalline silicon and perovskite cells. Findings show that while crystalline silicon cells are mature and durable, they remain high cost. Perovskite cells, however, have achieved rapid efficiency gains (over 25% in labs), are low-cost, and can be made flexible. Recent progress in improving their stability has further enhanced their application prospects. By comparing efficiency, cost, and stability of different cells, this study helps clarify the current state of solar cell technology and offers guidance for future research and development. With continued efficiency gains and falling costs, solar cells are poised to play a key role in supporting sustainable development goals.

Keywords: Lithium-ion batteries; silicon-carbon anodes; development trends.

1. Introduction

Nowadays, the world is confronting increasingly severe environmental challenges, such as climate change and air pollution. A primary driver of these issues is extensive combustion of fossil fuels like coal and oil to meet energy demands. These resources are not only finite and destined to be depleted but also release substantial quantities of greenhouse gases and harmful pollutants when burned. This poses a threat to the development of our planet. Consequently, the quest to develop clean and renewable energy sources has become a critical global priority. Among the various alternative energy options, solar energy has garnered significant attention from scientists worldwide due to its virtually limitless supply and minimal pollution output during operation. It is estimated that the amount of solar energy striking the Earth's surface in just 40 minutes could potentially meet global energy needs for an entire year, highlighting its immense potential [1].

Solar cells are the pivotal devices that convert sunlight directly into electricity through the photovoltaic effect. They are the core technology for harnessing solar power and offer numerous advantages, including cleanliness, silent operation, and the potential for decentralized, local power generation. Solar cells come in several main types, such as silicon-based solar cells, thin-film solar cells (e.g., Cadmium Telluride CdTe and Copper Indium Gallium Selenide CIGS), and novel perovskite solar cells. Among these, crystalline silicon solar cells are the most widely used due to their mature technology and long lifespan, although they face challenges related to relatively high manufacturing costs and efficiency plateaus. In contrast, emerging perovskite solar cells, first applied in photovoltaics in 2009 by a Japanese team led by Tsutomu Miyasaka, have developed at a remarkable pace. Their laboratory efficiency has skyrocketed from an initial 3.8% to over 25% today [2], demonstrating tremendous promise. Recent research breakthroughs, such as those by a team of Chinese scientists who introduced a specific amino molecule as an additive to successfully stabilize the crystal structure of perovskite materials, have significantly improved the stability of these cells under continuous light exposure, marking a crucial step toward commercial application [3]. In terms of real-world implementation, massive solar power plants like the "Talaitan Photovoltaic Park" in Qinghai Province, China, which utilizes millions of solar panels, not only supply clean electricity to millions of households but also help improve the local ecosystem. Furthermore, integration into everyday technology is advancing; for instance, some modern electric vehicles are now equipped with solar roofs that can add dozens of kilometers of range per day, exemplifying the deep integration of solar energy into conventional industries. Thanks to persistent research and development, solar cell technology has progressed rapidly in recent years. The conversion efficiency continues to improve while manufacturing costs gradually decline, leading to increasingly widespread adoption of solar energy. The primary objective of this paper is to elucidate the fundamental principles of solar cells and provide an in-depth exploration of the characteristics and development status of their different technological types. This paper will begin by explaining the basic physical principle behind solar cells—the photovoltaic effect. It will then compare and analyze the advantages and disadvantages of major solar cell types, including crystalline silicon, thin-film, and perovskite cells, focusing on aspects such as conversion efficiency, material cost, manufacturing complexity, and stability. Finally, by considering current technological challenges and future trends, the paper will offer a perspective on the development prospects of solar cells.

2. Characteristics of Different Solar Cells

2.1 Perovskite Solar Cells

Perovskite solar cells use perovskite materials as the light-absorbing layer. They're new-type solar cells that work well and don't cost much, so they have a lot of potential for use-for example, in building-integrated photovoltaics (BIPV), outdoor portable charging devices, and flexible wearable electronics, where their thin-film and lightweight features can be fully utilized. Perovskite materials generally have a crystal structure of ABX3. A refers to large-adjusting the mixing ratio of different doped halogen ions. For example, mixing I^- and volume cations like CH3NH3+ and FA^+, B is a metal cation such as Pb2+, and X is a common halogen anion. Halide perovskites have two key traits: high light absorption coefficient and tunable band gap. They only need a thin film (tens to hundreds of nanometers thick) to absorb visible light from the sun efficiently-no need for a thick film to boost light absor ption. And the thickness of the film they require is just 1/1000 that of silicon solar cells, which not only reduces material consumption but also lowers the overall weight of the device [4]. The energy threshold of perovskite materials for photon absorption can be modified by Br^- can shift the band gap from 1.5 eV (pure I^-) to 2.3 eV (pure Br^-), covering most of the visible light spectrum. Moreover, regulating the mixing ratio of halogen ions enables the adjustment of the wavelength range of light absorbed by perovskite materials, which makes perovskite solar cells suitable for combining with silicon cells to capture more solar energy [5]. Perovskite solar cells have very low manufacturing costs. They don't require extremely high temperatures for preparation-unlike crystalline silicon cells that need high- temperature annealing, perovskite films can be fabricated via low-temperature processes like spin-coating or inkjet printing, which save energy and equipment costs. And due to the characteristics of perovskite materials, there's no need for thick films this low material consumption helps save a significant amount of cost, especially for large-scale production [6]. However, perovskite solar cells also have some drawbacks. For example, their stability is relatively poor-they are easily affected by ultraviolet light or oxygen, which can cause them to degrade such as the volatilization of halogens. Researchers now improve stability by adding ultraviolet absorbers or encapsulating devices with moisture-proof materials. Most perovskite solar cells contain lead, and lead is highly toxic, which can have negative impacts on the environment and human health. Thus, lead-free perovskite alternatives are being

ISSN 2959-6157

explored, though current lead-free versions still lag behind in efficiency and stability [7].

2.2 Crystalline Silicon Solar Cells

Crystalline silicon solar cells are the most widely used batteries on the market today. They generate electricity using the photovoltaic effect with high-purity silicon crystals- their purity usually needs to reach 99.9999% (6N grade), as even tiny impurities (e.g., iron or carbon) can reduce cell efficiency. A silicon atom has four valence electrons in its outer shell. In a silicon crystal, adjacent atoms share two valence electrons with each other, forming a stable tetrahedral structure. When the outer-shell electrons of a silicon atom absorb photons to gain energy (the energy must be at least equal to silicon's band gap of 1.12 eV), they can become free electrons. The formation of these free electrons leaves behind electron holes, and the number of free electrons formed is equal to the number of electron holes generated-this "electron-hole pair" generation is the starting point of the photovoltaic effect in silicon cells. Silicon crystal is a type of semiconductor. When a pentavalent element like phosphorus is doped into a silicon crystal, an N-type semiconductor is formed; phosphorus donates one extra electron, so the majority carriers here are electrons. When a trivalent element like boron is doped into it, a P-type semiconductor is formed; boron accepts one electron, so the majority carriers are holes. The combination of these two semiconductors creates a built-in electric field that can efficiently separate electron-hole pairs [8]. When sunlight hits the PN junction, valence electrons get excited and become free electrons. These free electrons and the electron holes they leave behind move in opposite directions-electrons move toward the N-type layer due to the built-in field, while holes move toward the P-type layer, preventing them from recombining (a process that would lose energy). Since free electrons and electron holes carry opposite charges, the free electrons accumulate in the N-type semiconductor layer, while the electron holes accumulate in the P-type semiconductor layer. If we connect these two layers (to form a circuit)-usually via metal electrodes an electromotive force is generated, allowing electrical energy to be output [9]. Monocrystalline silicon solar cells also have some drawbacks. A lot of material is wasted during the silicon wafer cutting process-traditional wire-saw cutting can waste up to 30% of the silicon ingot, though new technologies like diamond wire cutting have reduced this waste to around 15%-and the wafers are relatively thick-typically between 150 and 180 micrometers. Even with recent thinning efforts, they're still much thicker than perovskite films, limiting their flexibility, making them unsuitable for flexible electronics or portable applications. Additionally, their utilization of blue light is insufficient, leading to transmission losses. This is because silicon's band gap makes it less responsive to high-energy blue photons to mitigate this, researchers add anti- reflective coatings (e.g., silicon nitride) or texturize the wafer surface to increase light trapping [10].

3. Prospects of Solar Cells

Looking ahead, the future of solar energy is not just bright; it is poised to become a cornerstone of global energy systems. The continuous synergy of technological innovation, drastic cost reduction, and supportive policy trends paints a promising picture for the decades to come. In terms of technological innovation, the laboratory breakthroughs, today will soon become commercial realities. Perovskite solar cells are expected to overcome their stability challenges, potentially through protective coatings or new material compositions. When combined with silicon in tandem cells, they will create super- efficient panels that can generate significantly more electricity from the same rooftop or field. Furthermore, the integration of solar technology into our everyday environment will expand. The solar windows will on skyscrapers, solar panels integrated into the body of electric vehicles, and even flexible, lightweight solar fabrics used in tents and wearable devices. This concept of "ubiquitous solar" will make energy generation invisible and seamless. The trend of cost reduction is equally compelling. As manufacturing scales up and technologies like perovskite become easier to produce, the price of solar electricity will continue to fall. It is likely to become the cheapest form of energy in most parts of the world, outcompeting even fossil fuels on cost alone. This economic advantage will be the primary driver for its adoption. The focus will also shift from the cost of the panels themselves to the overall system cost, including installation and energy storage. Innovations in battery technology, such as solid-state batteries, will be crucial. Cheaper and more efficient storage will solve the intermittency problem of solar power, ensuring a stable electricity supply day and night. Finally, the future development trend of solar energy is about integration and empowerment. Solar power will be at the heart of smart grids and microgrids. Homes and communities will not only consume energy but also produce and trade it locally through peer-to-peer energy trading platforms. In developing regions, solar microgrids can leapfrog the need for extensive traditional power lines, bringing electricity to remote villages and empowering communities. This decentralized model enhances energy security and resilience.

4. Conclusion

Overall, crystalline silicon solar cells boast stable performance and long lifespan, with their conversion efficiency being quite mature and close to the laboratory data (27%). In terms of production, their manufacturing technology is well-established too-a complete production process is in place, from silicon purification to assembly and use. As the main commercial solar cells today, they widely used in scenarios like solar street lamps, household rooftop photovoltaics and more.

For perovskite solar cells, they can achieve higher conversion efficiency than crystalline silicon solar cells—their theoretical efficiency is even twice that of crystalline silicon solar cells. Under low-light conditions, their efficiency can still reach 104% of that under standard illumination. Moreover, due to the small number of raw materials required, perovskite solar cells have lower production costs. However, compared with crystalline silicon solar cells, perovskite solar cells may be less suitable for applications under extreme conditions.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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