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Working Principle, Classification and Development Prospects of Solar Cells

Zhiyuan Hu

Beijing No.35 High School, Beijing, China
tomyzyhu@icloud.com

Abstract. Carbon neutral countries have listed photovoltaic technology as an energy priority. Solar cells have attracted much attention as important photoelectric conversion devices. Therefore, this article introduces the basic physics of photovoltaic effect, common methods for classifying solar cells, and the true advantages and limitations of major photovoltaic technologies. Research has found that crystalline silicon maintains its market leading position thanks to mature production lines and long-life modules. However, perovskite exhibits impressive rapid efficiency growth and supports solution coatings with adjustable band gaps, although stability issues and risks associated with heavy metal lead remain unresolved. In addition, organic, dye-sensitized, and quantum dot batteries have unique advantages, especially for flexible or semi-transparent devices. In the future, solar cells should maintain higher efficiency, lower costs, and wider adoption. Researchers can develop improved series architectures, scalable large-area coating technologies, stronger stability, and robust lifecycle assessment frameworks. The aim is simply to give researchers and engineers a short, physically grounded picture of how solar cells work and where they seem to be heading.

Keywords: solar cells, photovoltaic effect, perovskite, crystalline silicon, sustainable development

1. Introduction

At present, the world is facing severe challenges such as depleting of fossil fuel and ongoing environmental degradation. Since the Industrial Revolution, the fuel system is dominated by coal, oil and natural gas. While these materials propel unprecedented prosperity of human society, they also trigger a series of ecological crises, including air pollution, acid rain, greenhouse effect and drinking water pollution. According to statistics from the International Energy Agency, the emission of carbon dioxide related to energy field is showing a continuous growing trend [1]. Against this background, promoting transformation of energy structure has become a universal consensus all over the world. To reach this target, one core path is to develop renewable and clean energy. Characterized by its abundance, wide distribution, and no pollution during production, solar energy is regarded as a key factor of replacing traditional fossil fuel structures and construct a sustainable energy system.

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Solar photovoltaic power generating technology reached multiple progress within the wave of energy transformation. However, the unstable and intermittent patterns of solar energy make efficient and low-cost operating and storage facing critical bottleneck for large scale application. As the keystone of converting solar energy directly into electricity, every single leap in the performance of solar cells has significantly influence on the development of the entire solar power industry. From the first generation crystalline silicon solar cells, to the second generation solar cells that use thin-film technology, and finally the emerging high-efficiency cells such as perovskite and organic photovoltaics. Photovoltaic technology has undergone various development from fundamental lab research to large-scale industrial production over the past few decades. Currently, with mature fabrication processes and relatively high conservation efficiency, crystalline silicon solar cells still dominate the global photovoltaic market. Meanwhile, perovskite solar cells, considered as the most high-profile emerging photovoltaic technology in recent years, also shows astonishing pace of development. More over, the unique advantages of perovskite materials such as simple preparation processes and tunable bandgaps offer the potential of surpass the theocratical efficiency limit of single cells.

Thin-film cells face the problem that their construction needs rare materials which are often toxic and relatively low efficiency although thin-film cells are considered low in cost. Perovskite solar cells still struggle with low efficiency and short lifespans, and most other novel high-efficiency options have yet to become commercially viable. Under these circumstances, a systematic review of the current state of solar cell research – along with a careful analysis of the various production bottlenecks – would carry significant theoretical weight and practical relevance. Such an effort could help clarify where the field is heading, and might even offer concrete guidance for real-world deployment or for solving specific technical problems in photovoltaics.

The current research frontiers in solar cell technologies are the central subject here. The goal is to pull together the characteristics and performance of the various cell types, and to look at their relative strengths, weaknesses, and where they might be used. To start with, the basic working principles of solar cells are laid out. That is followed by a comparative look at several major categories – crystalline silicon, perovskite, and other new high-efficiency options – each examined according to its own technological route. The discussion then moves on to how these cells might be integrated into solar-powered vehicles, with some thoughts on potential innovations and how they could actually work in practice in that emerging area. The whole exercise is meant to give researchers and engineers in the photovoltaics field some practical pointers – things that might help push the technology forward sustainably and get it deployed at scale.

Solar cell research has come a long way, but photovoltaic technology still runs into quite a few bottlenecks. The pace of efficiency gains for crystalline silicon cells is slowing down, and purifying silicon still eats up a lot of energy. Thin-film batteries, meanwhile, are held back by material-related issues and performance trade-offs – factors that make large-scale deployment a tough sell.

2. Working principle of solar cells

A solar cell is simply a semiconductor that turns sunlight into electricity through the photovoltaic effect. The effect itself was noticed as early as 1839 by Edmond Becquerel in France: he saw a voltage appear when light hit an electrolyte. It took more than a century before anyone made a practical solid-state version. In 1954, Chapin, Fuller and Pearson at Bell Labs produced a monocrystalline-silicon cell that managed roughly 6 % efficiency [2].

Three things have to happen in sequence. First the material absorbs photons and creates excitons or free carriers. Photons with energy above the band gap lift electrons from the valence band into the

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conduction band, leaving holes behind. Those electron–hole pairs are the raw material of the conversion.

Next the pairs must be pulled apart before they recombine. In a standard p–n junction the meeting of p-type and n-type regions creates a built-in electric field that points from the n-side to the p-side (the depletion region). Electrons drift one way, holes the other, and a voltage appears between the contacts. Close an external circuit and the electrons travel through the load, meet the holes again on the p-side, and do useful work [3].

Researchers and manufacturers rely on four key parameters for laboratory characterization and commercial performance grading: open-circuit voltage (Voc), short-circuit current density (Jsc), fill factor (FF) and power-conversion efficiency (PCE). Defined as the quotient of a solar cell's peak electrical output power and incident light power, PCE stands as the most universally cited performance metric.

Thermodynamic constraints put a fundamental ceiling on how well solar cells can perform. Back in 1961, Shockley and Queisser used the detailed balance theory to figure out the ultimate efficiency of photovoltaics. Their calculation showed that under the AM 1.5 standard spectrum, the theoretical maximum is 33.7% – a number now widely known as the Shockley-Queisser limit [4]. Three main loss mechanisms are behind that ceiling. Photons with energy below the semiconductor bandgap simply pass through without being absorbed. Photons with surplus energy above the bandgap shed that excess as heat. And on top of those, there are also losses from radiative and non-radiative recombination. Several strategies have been put forward to push past this limit – multi-junction tandem cells, hot-carrier extraction, and multiple-exciton generation, for instance. These ideas are usually grouped under the label of third-generation photovoltaics [5]. The range of wavelengths any semiconductor can absorb is determined by its own electronic band structure. Crystalline silicon, for instance, has a bandgap of about 1.12 eV, which allows it to collect photons up to roughly 1100 nm. Perovskites, by contrast, offer tunability – by tweaking the cation–halide composition, their bandgap can be varied continuously from about 1.2 eV to 2.3 eV, a feature that proves particularly handy for tandem cell designs [6]. Getting a solid grasp of these basic physical processes is still the core scientific challenge if efficiency is to be pushed higher and photovoltaics are to expand their scope.

3. Classification of solar cells and their advantages and disadvantages

After nearly seven decades of development, solar-cell technology has evolved into a diversified, multi-level technical landscape. On the basis of material systems and device architectures, cells are customarily grouped into three generations: first-generation crystalline-silicon devices (mono- and polycrystalline silicon); second-generation thin-film cells (amorphous silicon, cadmium telluride and copper indium gallium selenide); and third-generation emerging high-efficiency concepts (perovskites, organic photovoltaics, dye-sensitized cells and quantum dots) [7]. The present chapter concentrates on the two families that currently attract the most research and commercial attention—perovskites and crystalline silicon—while also surveying selected frontier progress among the emerging technologies.

3.1. Perovskite solar cells

Perovskite solar cells (PSCs) constitute the most striking technological advance in photovoltaics of the past decade. In 2009 Kojima and co-workers in Japan first introduced the organic–inorganic hybrid perovskite $CH_3NH_3PbI_3$ as a light-absorbing material in dye-sensitized cells, obtaining a power-conversion efficiency of 3.8 % and thereby launching the field of perovskite photovoltaics. In

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the ensuing years the certified efficiency of single-junction perovskite cells has climbed to 26.1 %, a rate of progress without precedent in the history of the technology [8].

Solar cells labeled "perovskite" take their name from the ABX_3 lattice adopted by the absorber layer, matching the crystal structure of $CaTiO_3$, the naturally occurring perovskite mineral. Monovalent organic cations (methylammonium, formamidinium) or inorganic Cs^+ typically occupy the A-site position, while divalent metal cations (primarily Pb^{2+}) sit at the B site and halide anions (I^-, Br^-, Cl^-) occupy the X site. This structural arrangement yields multiple beneficial optoelectronic traits: high absorption strength that allows thin films (only several hundred nanometers) to absorb ample incident light; ambipolar transport for efficient motion of both electrons and holes; micrometer-range carrier diffusion lengths; and bandgap tunability achievable through compositional optimization.

Typical device architectures comprise the regular (n–i–p) and inverted (p–i–n) stacks. In the regular configuration the sequence from the illuminated side is a transparent conductive substrate (FTO or ITO), an electron-transport layer (TiO_2 or SnO_2), the perovskite absorber, a hole-transport layer (commonly Spiro-OMeTAD), and a metal counter electrode (Au or Ag). Under illumination the perovskite layer absorbs photons and generates electron–hole pairs; electrons are injected into the electron-transport layer while holes travel through the hole-transport layer to the counter electrode, thereby completing the photoelectric conversion cycle.

Four principal advantages can be identified. First, the efficiency trajectory has been remarkable: single-junction cells already surpass polycrystalline silicon and are closing the gap with monocrystalline silicon, while perovskite/silicon tandems have exceeded 33 % [9]. Second, fabrication can be performed at low temperature from solution—spin-coating or blade-coating—thereby reducing both energy consumption and capital cost relative to the high-temperature purification required for crystalline silicon. Another key merit stems from the thin-film absorber, which can be deposited atop polymer substrates. This makes flexible, low-weight modules feasible for wearables and building-integrated photovoltaic systems. As a fourth advantage, the wide tunable range of its bandgap provides rich combinatorial options for tandem cell design.

Promising as perovskite devices are, practical industrialization continues to face major hurdles, with stability topping the list of critical concerns. The absorber layers are sensitive to humidity, oxygen, UV radiation and heat: hot and humid conditions induce fast material degradation and a steep drop in conversion efficiency. Strategies including compositional modulation, interface passivation and optimized encapsulation have helped researchers achieve operational lifespans on the order of thousands of hours. Even so, this duration cannot match the 25-year-plus service life standard of crystalline silicon photovoltaic panels [10].

Lead toxicity constitutes a further barrier toward practical deployment. This element appears in nearly every high-efficiency perovskite cell, bringing about health and environmental worries for policymakers as well as the public. Although tin-substituted and other lead-free perovskite candidates are available, their efficiencies stay considerably inferior, coupled with the intrinsic tendency of Sn^{2+} toward oxidation. Upscaling also proves difficult: benchmark performance data generally come from miniature sub-1 cm^2 cells, and efficiency degrades markedly when scaling the active region to module-level sizes [11].

3.2. Crystalline silicon solar cells

Among all photovoltaic technologies, crystalline silicon solar cells boast the longest development history, highest technical maturity and largest market footprint. They captured around 95% of global

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PV shipments in 2023 and maintain an overwhelming market dominance [12]. Classification into monocrystalline and polycrystalline types follows differences in crystal morphology.

The core operating structure of silicon solar cells relies on the p–n junction mechanism. Commercial silicon cells are generally fabricated based on p-type silicon wafers. Through phosphorus diffusion treatment, an n-type emitter layer is formed on the front wafer surface, successfully constructing the essential p–n junction. To reduce optical reflection loss, a silicon nitride anti-reflection film is deposited on the cell front, while silver grid electrodes are adopted for current extraction. On the rear side, an aluminum back-surface field is applied – this helps suppress carrier recombination at the surface. When sunlight hits the silicon, photons with energy above that 1.12 eV bandgap are absorbed, and that creates electron-hole pairs. The built-in electric field then drives these carriers apart, and they eventually get collected at the electrodes, producing a usable electric current.

Continuous improvements in manufacturing and processing have been steadily pushing up the conversion efficiency of crystalline silicon solar cells. PERC technology, for example, adds an Al_2O_3/SiN_x passivation layer on the rear side with local openings. This design does a good job of cutting down carrier recombination, and production cells can now consistently reach efficiencies above 23% [13]. Building on that idea, TOPCon uses an ultra-thin tunnel oxide layer combined with doped polysilicon to form high-quality selective contacts. That has pushed industrial cell efficiencies past 25% and moved quickly into large-scale production. HJT devices take a different approach, combining crystalline silicon with very thin amorphous silicon films. The intrinsic amorphous layer provides excellent surface passivation, which is why lab-scale HJT cells have gone beyond 26% efficiency. On top of that, the low-temperature processing and the inherent bifacial design give it extra perks for industrial production. IBC cells, another advanced design, move all the metal contacts to the rear. That gets rid of front-side shading losses entirely. As of now, this architecture holds the record for single-junction silicon cells at 27.3% efficiency [14].

Crystalline silicon photovoltaics have been widely recognized for their strengths – that's hardly news. Efficiency is high and still climbing, and on top of that, the manufacturing processes are now so refined that they're approaching the theoretical limits. Longevity is another major selling point. Most commercial panels come with a 25-year power warranty, and quite a few of them keep performing well beyond 30 years. A mature industrial chain, combined with economies of scale, has driven the levelized cost of electricity down by over 90% over the past ten years. As a result, grid parity is now within reach in most markets.

On the flip side, the drawbacks are just as obvious. Silicon is an indirect-bandgap material, and its absorption coefficient isn't particularly high. So to make good use of the incoming sunlight, the wafers have to be at least 100 μm or so in thickness – which ends up using a fair amount of material. Turning raw silicon into electronic-grade feedstock requires high-temperature chemical processing, which guzzles energy and pushes out the energy-payback period. The wafers themselves are rigid and brittle, so they don't lend themselves well to curved or flexible designs. LeTID – degradation triggered by light and elevated temperature – is still a lingering issue. The detailed microscopic mechanisms are not fully pinned down, and people are still looking for effective ways to suppress it [15].

3.3. Emerging high-efficiency solar cells

There's been a wave of emerging high-efficiency concepts, all aimed at getting beyond the single-junction limit and expanding into new applications. This subsection briefly surveys representative progress in organic, dye-sensitized and quantum-dot solar cells.

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Organic photovoltaics (OPVs) employ conjugated polymers or small molecules as the photoactive layer and offer distinctive advantages of light weight, mechanical flexibility, semi-transparency and compatibility with solution-based large-area printing. Organic photovoltaic devices follow a distinctly different working principle compared with inorganic solar cells. Instead of directly producing free charge carriers, photon excitation generates tightly bound Frenkel excitons, which can only dissociate into movable electrons and holes at donor–acceptor interfaces. For this reason, bulk-heterojunction structures are essential to maximize interfacial contact and facilitate efficient charge separation. The rapid development of non-fullerene acceptors, particularly A–DA′D–A molecular systems represented by Y6, has significantly promoted device performance, pushing the certified efficiency of single-junction OPVs above 19% [16]. Benefiting from superior mechanical flexibility and solution processability, OPVs show unique competitiveness in wearable devices, indoor light harvesting and semi-transparent photovoltaic building envelopes. Nevertheless, this technology still faces inherent limitations, including inferior operational stability, high susceptibility to moisture and oxygen, and a noticeable efficiency deficit when compared with mainstream crystalline silicon cells.

Grätzel first came up with dye-sensitized solar cells back in 1991. These are essentially electrochemical photovoltaic devices, and the design was actually inspired by how natural photosynthesis works [17]. A standard DSSC has three main parts: a nanoporous TiO_2 photoanode with dye molecules attached to it, an electrolyte – either liquid or quasi-solid – that carries I^-/I_3^- redox couples, and a counter electrode made of platinum. When light hits the cell, the dye molecules get excited and inject electrons straight into the TiO_2 conduction band. The dye, now oxidized, is then restored by reduced species in the electrolyte. Meanwhile, those oxidized electrolyte components get regenerated back to their original form at the counter electrode – and that closes the loop for photoelectric conversion.

DSSCs come with a few clear pluses: cheap raw materials, straightforward fabrication, and they actually perform quite well under dim or diffused lighting. That makes them a promising option for indoor photovoltaics and for places where cloudy weather is common. On the downside, the use of liquid electrolytes introduces some serious headaches – possible leakage, for one, and solvent evaporation. People have tried solid-state and quasi-solid alternatives to get around those problems, but even with those tweaks, the devices still haven't managed to hit commercial standards – either in efficiency or in long-term stability.

Quantum-dot solar cells are built around the quantum confinement effect that comes naturally to semiconductor nanocrystals – and the way those nanocrystals behave changes with their particle size. Another theoretical selling point is multiple-exciton generation, which could potentially push efficiencies past the Shockley-Queisser limit. The bandgap of these dots can be adjusted by tweaking either the particle size or the material composition, so they can be better matched to the solar spectrum. Lead sulfide (PbS) has been the most heavily investigated system so far. With proper surface-ligand engineering, PbS quantum-dot cells have now crossed the 13% efficiency mark. They also look promising as tunable-bandgap sub-cells in tandem device designs. That said, there are still a few scientific hurdles to clear: carrier recombination at surface defects, lead toxicity, and – perhaps trickiest of all – actually getting multiple-exciton generation to work under real-world operating conditions.

4. Development prospects of solar cells

In pursuit of carbon neutrality and widespread electrification, solar-cell technology is shifting from a primary focus on efficiency gains toward simultaneous optimization of efficiency, cost, stability and

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sustainability. Several interrelated directions appear central to future progress.

First, tandem and multi-junction architectures have become the principal route for breaking the single-junction efficiency barrier. Certified perovskite/silicon tandem efficiencies already exceed 33 %, while all-thin-film combinations such as perovskite/perovskite and perovskite/organic also show encouraging results. Careful control of band-gap matching, interfacial recombination and current matching among the sub-cells is expected to allow both laboratory and industrial devices to approach or surpass a practical efficiency target of 40 %.

Second, scalable, high-yield manufacturing processes are indispensable for commercial deployment. For perovskite and organic cells, improvements in the uniformity and throughput of roll-to-roll techniques—blade coating, slot-die coating and inkjet printing—will determine module-level efficiency and cost competitiveness. Parallel upgrades of crystalline-silicon production lines (TOPCon, HJT, IBC) together with continued reductions in silver paste and silicon feedstock consumption will further lower the levelized cost of electricity and reinforce silicon's position in utility-scale plants.

Third, stability and reliability remain the decisive bottlenecks preventing new-generation cells from entering the market. Damp-heat and photo-thermal stability of perovskites, efficiency catch-up of lead-free compositions, and encapsulation strategies for organic and quantum-dot devices all demand deep interdisciplinary collaboration among materials science, interface engineering and device physics. A growing body of accelerated-aging data and outdoor field results will strengthen the foundation for technology selection and investment decisions.

Another trend driving R&D is the growing range of applications. Different scenarios call for different types of photovoltaic products. Alongside the traditional ground-mounted panels, new markets are emerging – building-integrated PV, vehicle-integrated PV, wearable devices, IoT micro-power sources, and indoor energy harvesting under low light. All of these require cells that are flexible, light, see-through, and can be tailored to fit different aesthetics. Organic solar cells, flexible perovskite cells, and dye-sensitized cells are likely to be the first to get a foothold in these specialized segments.

Life-cycle sustainability assessment has also become a critical yardstick for evaluation. That means looking at everything from raw material extraction and manufacturing energy use to toxic substance management and end-of-life recycling. To address all that, the PV sector will need greener supply chains and stronger circular economy structures. With innovations like lead-free perovskites, low-silver or silver-free electrodes, and closed-loop silicon recycling, photovoltaics could make a real contribution to global sustainability goals.

5. Conclusion

This review has summarized the fundamental photoelectric conversion mechanisms of solar cells, categorized mainstream photovoltaic technologies, and compared their performance in terms of efficiency, cost and reliability. Crystalline silicon continues to dominate the commercial market. Benefiting from mature manufacturing infrastructure, silicon modules have steadily lowered the levelized cost of photovoltaic electricity. In just over a decade, perovskite solar cells have evolved from experimental lab devices to high-efficiency single-junction candidates. Their solution-processable fabrication and tunable bandgaps render them ideal for tandem cell design, while poor environmental stability, lead toxicity and challenges in large-area uniform coating still hinder their industrial-scale deployment. Although organic, dye-sensitized and quantum-dot solar cells currently lag in efficiency, they exhibit unique advantages including superior mechanical flexibility and

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excellent weak-light performance, overcoming the limitations of rigid silicon modules for indoor and flexible scenarios.

Future photovoltaic advancement relies on multi-dimensional breakthroughs, covering innovative absorber and contact materials, high-precision printing and coating techniques, refined cost management and standardized life-cycle evaluation. Several promising research directions stand out: perovskite–silicon tandem cells, improved passivation contact designs for silicon, and the push to replace toxic lead and expensive silver with more environmentally friendly materials. A systematic overview of the fundamental physics and major technical bottlenecks across different solar cell types is laid out here. The goal is to give researchers and industry practitioners some practical pointers – helping them make more targeted improvements and ultimately expand the role of photovoltaics in the global energy shift.

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