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Advancements in solar cell technology: renewable energy for the future

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Abstract

Fossil fuels and non-renewable energy sources negatively impact the environment and contribute to climate change. In contrast, solar energy is the largest source of clean and renewable energy amid climate change. Solar cells utilize solar energy to convert sunlight into electricity. Solar cells can be incorporated as an energy source in a wide variety of electronics and utilities. This review article describes the development and changes in solar cell technology over the years. It outlines the properties of four generations of solar cells, which are also called photovoltaic cells. Third-generation solar cells are currently in development, and fourth-generation solar cells are undergoing research and development to improve photovoltaic technology. Finally, we also discuss further innovations that are needed to advance solar cell technology and applications in the future.

Keywords

Solar cell, Photovoltaic cell, Solar energy, Thermovoltaic cell, Silicon cell, Dye-sensitized solar cell, Quantum dot solar cell, Perovskite solar cell, Multi-junction solar cell, Hysteresis

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Introduction

Fossil fuels negatively impact our planet. The production and consumption of these non-renewable energy sources around the globe over the last century have created noticeable and long-lasting adverse effects on Earth. Climate change is thought to occur because of the extensive use of fossil fuels like coal, petroleum, and oil as energy sources worldwide. The ever-increasing demand for energy and electricity due to the Earth's expanding population and the consequent rising of atmospheric carbon dioxide levels caused by the use of fossil fuels may be one of the key factors promoting climate change (greenhouse effect) (1). By utilizing renewable energy sources, such as energy from the sun, our collective carbon footprint can be reduced.

Research and development of sustainable, renewable energy sources are currently being prioritized. The International Energy Agency (IEA) anticipates that renewable energy will surpass energy produced by coal by the year 2030 and that renewable energy will be the most significant source of energy, contributing 34% of total energy by 2040 (2). There are different sources of renewable energy. Of all renewable energy sources, including wind, hydropower, and solar photovoltaic cells, the IEA expects solar photovoltaic cell-based energy to grow the fastest (3).

Solar energy is energy that is generated by harnessing sunlight. It is a renewable and sustainable source of energy that has the potential to provide a significant amount of the world's energy needs. Solar energy can be utilized in a variety of ways. For example, the electricity generated by solar energy can be used to power machines in businesses or homes. Solar power can also be used to provide heat. For example, solar thermal collectors are used to heat water for domestic or commercial use, and solar cookers use the sun's energy to cook food, which can be an environmentally friendly alternative to traditional cooking methods that use fossil fuels. Furthermore, solar energy can be used to power vehicles. Solar-powered vehicles have gained popularity in recent years as an alternative to fossil fuel-powered vehicles.

One of the significant advantages of solar energy is that it is a clean and renewable source of energy. Unlike fossil fuels, solar power does not produce harmful emissions or contribute to climate change. Solar energy can also help reduce the over-reliance on fossil fuels and increase energy independence. However, some disadvantages of solar power still persist. These include the high cost of solar panels, the need to install them over a large area, and the fact that solar energy depends on weather conditions. Nevertheless, recent advances in solar technology are making solar energy an increasingly viable and attractive option for powering the world.

The Photovoltaic Effect

The term "photovoltaic" comes from the Greek words for light ("photo") and electricity ("voltaic"). The photovoltaic effect is a phenomenon in which materials or semiconductors that are exposed to light can generate electricity. While experimenting with two metal electrodes in a silver chloride solution, French physicist Alexandre-Edmund Becquerel, discovered the phenomenon of electromotive force or Voltage (4). He found that the voltage increased when exposed to light. This phenomenon became known as the Photovoltaic (PV) effect, the foundation on which solar cell technology is based.

When light strikes a semiconductor material, it can eject electrons out of their regular positions in the material's atomic structure. These free electrons create an electric current. This is the basic principle behind a solar cell, which is a device that converts light energy into electrical energy and is explained in more detail below. Sunlight is absorbed by the solar cell to produce electricity. Solar cells are made up of layers of semiconducting materials that are specially designed to maximize the photovoltaic effect. When light hits the top layer of the solar cell, it causes electrons to flow through the material, creating an electric current. This current can then be used to power electrical devices or stored in a battery for later use.

The structure of a solar cell

The structure of a typical first-generation solar cell is made of two different semiconductors named p-type and n-type silicon. The p-type silicon is made by adding elements such as boron or gallium, which contain one less electron than silicon in their outermost energy level and hence have positive-charged "holes.” In contrast, the n-type silicon is made by adding elements such as phosphorus that has one more electron in its outermost level, and therefore contains an excess electron compared to silicon (5).

The solar cell is a sandwich where one layer of p-type silicon is next to another layer of n-type silicon, and the two layers are connected by a metallic connector (Figure 1). The place where the two layers meet is called the PN junction. When light is absorbed by the solar cell, the electrons in the n-type layer move into the holes in the p-type layer. Thus, the p-type layer becomes negatively charged, and the n-type later becomes positively charged, which generates an electric field. Hence, when a solar cell is exposed to sunlight, the electrons travel from the n-type layer to the p-type layer and then through the metal connector linking the two layers back to the n-type layer, thus creating the flow of electricity (5).

Initially, solar cells were made of silicon or similar semiconducting inorganic elements. Today, solar cells can also be composed of organic materials. Organic solar cells use organic materials such as polymers and dyes to absorb sunlight and convert it into electricity. In contrast, inorganic solar cells use materials such as silicon. Inorganic cells are more durable than organic solar cells but they are less environmentally friendly (5).

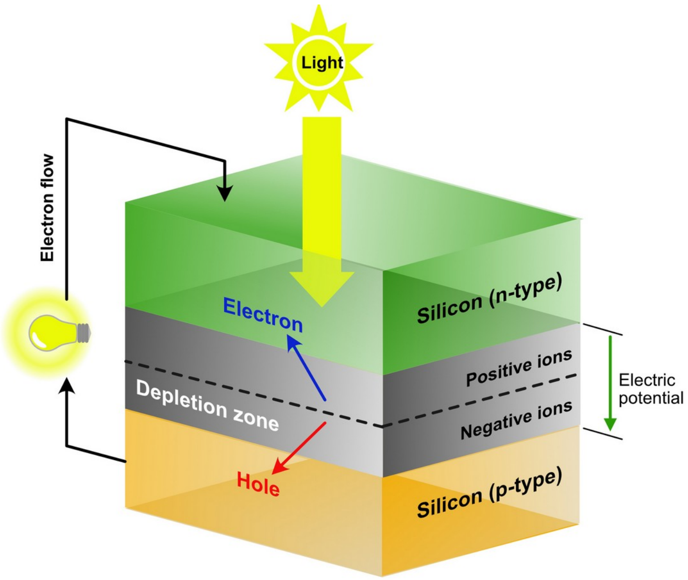

Figure 1: Model of a solar cell. A solar cell consists of a layer of n-type silicon next to a layer of p-type silicon. In the p-type layer, there is an excess of positively charged holes, and in the n-type layer, there is an excess of electrons. When the solar cell is exposed to sunlight, electrons travel from the n-type layer to the p-type layer. Since the two layers are connected, electricity will flow through the metal connector, back to the n-type layer.

Solar cell technology

There are four generations of solar cells, depending on the various materials used to make the solar cells and the design of the cell. Table 1 summarizes multiple features of the First-, Second-, Third-, and Fourth-generation solar cells. These are described in further detail below.

Table 1: Properties of different generations of solar cells

FIRST	SECOND	THIRD	FOURTH
Monocrystalline silicon solar cells	Amorphous silicon solar cells	Dye-sensitized solar cells (DSSC)	Graphene and graphene-derivative solar cells
Polycrystalline silicon solar cells	Copper indium gallium selenide (CIGS)	Quantum Dot solar cells	Carbon nanotubes
	Cadmium telluride	Perovskite solar cells	Metal nanoparticles and metal oxides
	Copper zinc tin sulfide	Organic solar cells	
	Gallium arsenide	Multi-junction solar cells	
	Gallium indium phosphorous		

First-generation Solar Cells

These solar cells are made using crystalline silicon wafers. They are comprised of either monocrystalline solar cells or polycrystalline solar cells (Figure 2), with the latter being less efficient than the former. These types of solar cells are found around the globe and have high efficiencies (6).

These first-generation solar cells are used in many different applications, ranging from space exploration to telecommunications. However, some limitations of these cells include the high cost to produce them and the need for large quantities of silicon and other elements. Moreover, mining these elements and manufacturing these solar cells is not environmentally friendly and is energy dependent. Most silicon is extracted in open pit mines.

Second-generation Solar Cells

This type of solar cell was developed to improve the first generation. Second-generation solar cells are often called thin-film solar cells (Figure 3A) due to the fact that they are made from layers that only are a few micrometers thick, unlike first-generation solar cells, which are much thicker (7).

In second-generation solar cells, materials like copper indium gallium selenide (CIGS), amorphous silicon, copper zinc tin sulfide, and cadmium telluride are spotted on thin film. The CIGS layer forms the p-type layer (Figure 3B). These types of solar cells use a significantly smaller amount of silicon compared to first-generation solar cells. For example, amorphous silicon is deposited on thin films of various substrates (8). Other second-generation solar cells include gallium arsenide and gallium indium phosphorous solar cells (5).

The advantage of second-generation solar cells is that they are highly efficient, more cost-effective, and use less material. As a result, they are lighter in weight and can be used in portable electronics. However, they are less durable than first-generation solar cells and have a limited lifespan. In addition, similar to first-generation solar cells, manufacturing these solar cells is not environmentally friendly.

Third Generation Solar Cells

Third-generation solar cells reflect the latest advancement in technology. Third-generation solar cells can potentially surpass the Shockley–Queisser limit of 30% power efficiency. This limit is a theoretical barrier, which is observed with single p-n junction first and second-generation solar cells (9)._Single p-n junction solar cells are limited by the amount of energy lost as heat. In order to exceed the Shockley-Queisser limit, solar cells need to be engineered to maximize the amount of energy that can be converted into electricity and thereby minimize energy loss. Multiple strategies can be used to exceed the Shockley-Queisser limit. One approach is to use solar cell materials with a high absorption coefficient, which absorb a larger fraction of sunlight. For example, perovskite solar cells have a broader absorption spectrum than silicon solar cells and can be used for this purpose (10-12). A second approach is to reduce energy loss from the solar cell. This can be achieved by engineering the solar cell with passivation layers, which are thin coatings that prevent the loss of charge carriers at the material's surface. Passivation coatings include aluminum, silicon, or titanium dioxide (10-12).

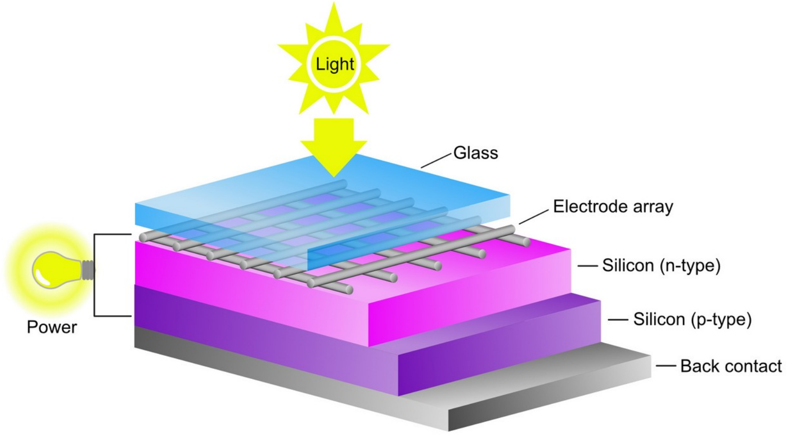

Figure 2: First-generation monocrystalline or polycrystalline silicon solar cell.

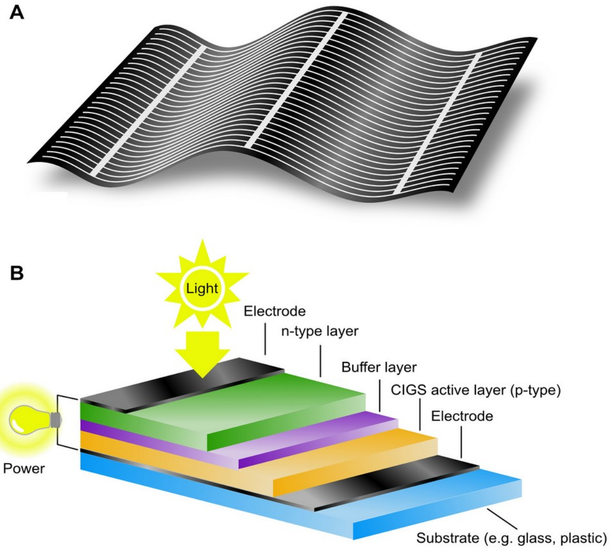

Figure 3: Second-generation solar cells. (A) Thin-film solar cell. (B) An example of a solar cell made with copper indium gallium selenide (CIGS) that forms the p-type layer.

Moreover, emerging new technologies, such as hot-carrier solar cells, can surpass the Shockley-Queisser limit by capturing and utilizing the excess energy of hot carriers generated within the solar cell (13). When a high-energy photon is absorbed, it creates an electron-hole pair with excess kinetic energy, which is the hot carrier. In first- and second-generation solar cells, most of the excess kinetic energy of the hot carriers is lost as heat, reducing the efficiency of the solar cell. Researchers are currently investigating how to capture and utilize the excess kinetic energy of hot carriers by using materials with low thermal conductivity or materials that enhance carrier transport and reduce thermalization (14, 15). Furthermore, solar cells can also be designed to have hot carrier "collection layers" to capture the high-energy hot carriers before they lose their energy (14, 15).

Third-generation solar cells include dye-sensitized solar cells (DSSC), Quantum Dot solar cells, Perovskite solar cells, organic solar cells, and multi-junction or tandem solar cells.

DSSCs function in low light and cloudy conditions, e.g., dusk or dawn. The top layer is made with a transparent conducting oxide (TCO) that allows sunlight to pass through the cell. Dye molecules efficiently absorb light in the DSSCs. Both natural dyes, e.g., chlorophyll, carotenoid, etc., can be used as well as synthetic dyes (Figure 4A). The dyes can absorb sunlight into the solar cell and generate photo-excited electrons, allowing for a flow of current due to the electrochemical effect (16). The principle of the DSSC solar cell can be compared to the process of photosynthesis with the dye functioning similar to chlorophyll (17). Recent advancements in this technology include the integration of DSSCs with rechargeable electric energy storage units to solve the problem of inconsistent power output due to changing and unpredictable sunlight conditions (18, 19).

A Quantum Dot Solar cell incorporates semiconductor nanocrystals, quantum dots, or tiny particles to absorb sunlight. They can absorb light across a broader range of wavelengths than silicon solar cells. As a result, these solar cells have relatively high efficiencies, can be flexibly sized, and are relatively stable (20).

Organic solar cells (OSCs) use organic materials, such as polymers or small molecules, to absorb light and generate electricity (Figure 4B). The ability of organic molecules to absorb light is high; hence, a large amount of light can be absorbed using small amounts of material. Additionally, these organic solar cells can be easily tuned. As a result, they have the potential to be produced at a lower cost than traditional silicon solar cells and can be fabricated using simple solution-based processing techniques. They are also environmentally friendly. However, they are not as efficient and can be unstable.

Improving the power conversion efficiency and durability of OSCs has been a focus of research. The use of device engineering, interfacial layers, doping, and optimized film materials have been incorporated to increase efficiencies (21). The incorporation of materials, including novel high-performance acceptors (e.g., fullerene derivatives and polymeric non-fullerene acceptors) and donors, have been employed (22, 23). Organic solar cells are also susceptible to degradation. Physical degradation can occur due to various factors, such as the delamination of the electrode layer or the degradation of interface layers. For example, indium tin oxide (ITO) substrate is susceptible to cracking, which can lead to cell failure. Researchers are currently investigating alternatives to ITO, such as plastic or metal foils (24). The organic semiconductors can also degrade when exposed to oxygen or moisture, resulting in lower efficiencies. Furthermore, the anodes and cathodes of the solar cell can also degrade since the silver in the cathode becomes oxidized over time. Hence, researchers are exploring the addition of a coating, e.g., epoxy, around the solar cell to protect it and adding a buffer layer to protect the cathode from moisture. This buffer layer can be comprised of titanium dioxide, zinc oxide, or aluminum oxide, which have good moisture barrier properties (21, 22).

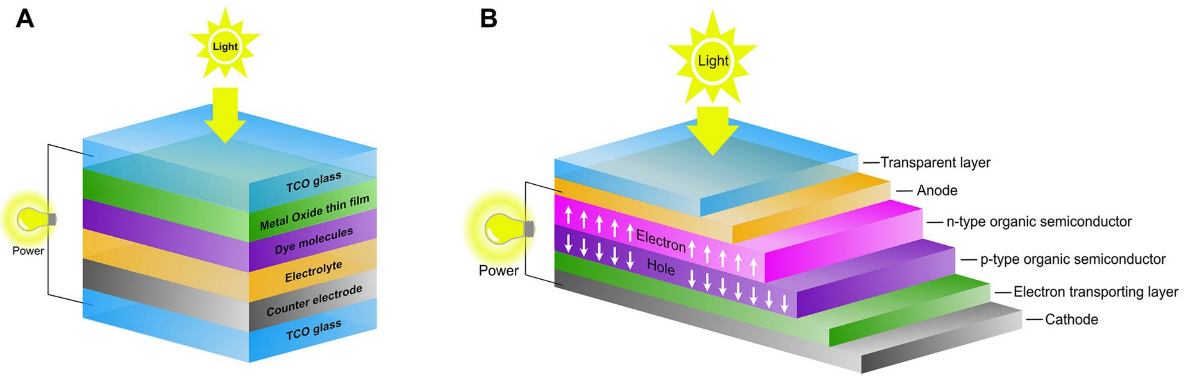

Figure 4: Third generation solar cells. (A) A dye-sensitized solar cell (DSSS). Transparent conducting oxide (TCO) represents the top layer. Dye molecules in the layer absorb sunlight and generate current. (B) An organic solar cell (OSC), which is another type of third generation solar cell.

Perovskite solar cells are made with the first discovered perovskite crystal, calcium titanium oxide. Perovskite compounds have a chemical formula ABX_3, where 'A' and 'B' represent cations and X is an anion (25). Different materials, including halide salts, inorganic acids and salts, fullerene, and polymers, have been embedded or “doped” into the perovskite layers to enhance efficiency. These represent hybrid perovskite solar cells. Although perovskite solar cells have very high efficiencies, many degrade quickly due to thermal instability and factors like moisture and oxygen in the environment (20). The stability of perovskite solar cells has been a significant challenge in their commercialization due to their relatively short lifespan compared to other solar cells (26). The hygroscopicity of perovskite materials makes them highly sensitive to moisture. Hence researchers have investigated the encapsulation of the perovskite layer with moisture-resistant materials. Stability is improved when two silicon photovoltaic layers are used to sandwich the perovskite layer to form a tandem solar cell (27-29). This method can help protect the perovskite layer from moisture and oxygen, and the silicon can act as a barrier to prevent degradation of the perovskite layer.

Thermal instability is another issue that can affect the stability of perovskite solar cells. Perovskite materials can be highly sensitive to temperature changes, which can cause them to degrade or lose their efficiency. Researchers are exploring ways to improve the thermal stability of perovskite materials by introducing additives or dopants into the perovskite layer to increase their stability at high temperatures. The silicon sandwich layers mentioned above can also help draw excess heat generated by the perovskite layer (27-29). This design can also increase the efficiency of the solar cell by utilizing the complementary spectral response of the two materials (30).

Finally, ion migration also contributes to the instability of perovskite solar cells (26). Ions within the perovskite material can move slowly over time, which can cause a delay in the current-voltage (J-V) curve and reduce the efficiency of the solar cell. J-V curves are commonly used to describe the function of photovoltaics, as these curves demonstrate the relationship between the current and the voltage. Hysteresis in J-V curves refers to the difference in the curves between forward and reverse scans. The curve obtained when increasing the voltage (forward scan) may differ from the curve obtained when decreasing the voltage (reverse scan). This hysteresis effect is significant in the context of perovskite solar cells and can lead to a decrease in the efficiency of these cells (31, 32). Researchers are exploring several strategies to overcome the hysteresis effect. One approach is to modify the perovskite material itself to reduce the effect of ion migration and trap-mediated recombination. For example, introducing dopants into the perovskite material can decrease the hysteresis effect (33). Another approach to decrease the hysteresis phenomenon is to optimize the interfaces between the different layers of the solar cell by introducing passivation layers or modifying the electron and hole transport materials (34). Surface defect passivation (35) and interfacial engineering decrease ion migration and trap-mediated recombination (36). Sandwiching ferroelectric materials in between paraelectric materials in a superlattice structure results in a stronger current (37). Researchers are also working on modifying the electron and hole transport materials to improve their stability and reduce their tendency to trap charges. Modulators are typically small organic molecules that can be incorporated into the perovskite material to stabilize its crystal structure and reduce ion migration (36). For example, researchers have developed modulators that can interact with perovskite and improve its stability, reducing the effect of ion migration and hysteresis (38).

Non-radiative recombination is a process in which charge carriers in a semiconductor recombine without emitting photons, resulting in a loss of energy and reduced efficiency in solar cells (39). To mitigate this, the introduction of a passivation layer at the interface between the perovskite layer and the electron/hole transport layer can reduce the density of defects that can cause non-radiative recombination. Doping the perovskite material with small amounts of metal ions or organic molecules can also modify the material's electronic properties, reducing non-radiative recombination. Finally, surface treatments with UV or chemicals can be used to improve the surface of the perovskite material and reduce non-radiative recombination. It is important to note that the device architecture design can also play a role in reducing this effect. For example, employing a tandem structure (described below) can reduce these losses (40).

Currently, researchers are also exploring novel technologies such as gas quenching, to fabricate defect-free perovskite crystal superlattices. Gas quenching is a technique that involves cooling the crystal superlattice rapidly by exposing it to a gas (helium or nitrogen) that is cooled to cryogenic temperatures. The rapid cooling helps to suppress the formation of defects and can lead to the formation of larger, more uniform crystals (41). In addition, vapor deposition techniques to grow the crystal superlattice layer by layer to reduce defects are also being explored (42). Finally, artificial intelligence (AI) can be used to optimize the growth conditions of perovskite thin films, the building blocks for perovskite crystal superlattices. Machine learning algorithms can analyze the effect of various growth parameters, such as temperature and precursor composition, on the resulting crystal structure and photovoltaic properties of the cell in order to improve the uniformity and reduce the defect density of the superlattice (43, 44).

Interestingly, perovskite solar cells are being explored for use in solar-powered drones, blimps, and related avionics due to their high power conversion efficiency and lightweight design (45, 46). Perovskite solar cells can be integrated into the body or wings of the drone to provide power while in flight, reducing or eliminating the need for non-renewable batteries or fuel. As mentioned above, perovskite solar cells can be coated with a transparent material, such as transparent conductive oxide (TCO) or a thin, transparent polymer, to protect them from the elements and increase their durability.

Multi-junction solar cells are also known as tandem solar cells. They contain multiple p-n junctions made from different semiconductor materials, with each junction absorbing light at a different wavelength and producing electricity. This greatly increases the efficiency and improves the ability of the solar cell to convert sunlight into electricity (10). Many different combinations of materials can be used to construct multi-junction solar cells. An example of a CIGS multi-junction solar cell (47) is shown in Figure 5. Silicon-perovskite tandem solar cells are a type of hybrid solar cell that combines a silicon solar cell with a perovskite solar cell to achieve higher efficiency than either technology alone (40, 48). In these tandem solar cells, the two different types of solar cells are stacked on top of each other, with the perovskite cell on top of the silicon cell. The perovskite cell is designed to absorb high-energy photons, while the silicon cell is designed to absorb lower-energy photons. This allows the two cells to work synergistically to capture a wider range of the solar spectrum and convert it into electricity, significantly increasing its efficiency to over 29% (40, 48). Moreover, perovskite-quantum dot hybrid solar cells have also been developed with higher efficiencies than stand-alone quantum dot cells. These hybrid devices are also more stable (49).

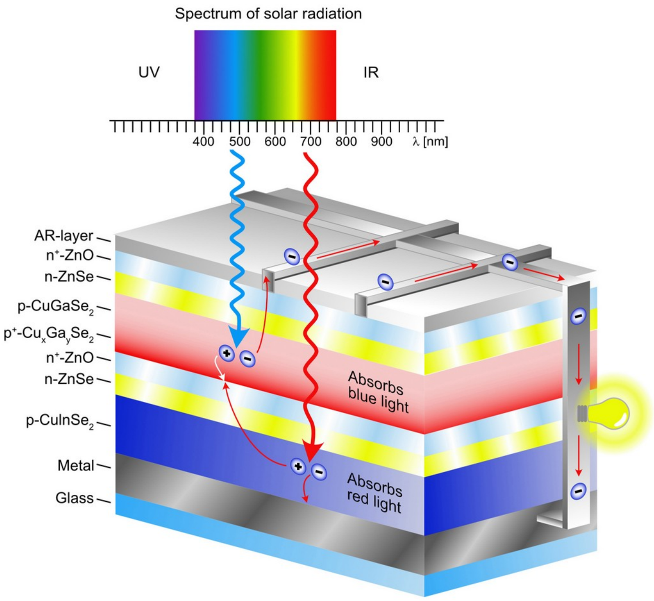

Figure 5: Multi junction solar cells. These solar cells can be designed using a combination of materials and contain multiple n-type and p-type junctions capable of absorbing different wavelengths of light. An example of a CIGS multi junction solar cell is shown (47). The top layer is anti-reflective (AR).

Third-generation solar cells have significant potential for being highly efficient, cheaper, and more sustainable than their predecessors. However, a severe limitation of these types of solar cells is their poor stability (toward moisture, oxygen and light) under actual environmental working conditions.

Fourth-generation solar cells

Fourth-generation solar cells represent the newest technology. Researchers are currently building these solar panels using different layers of semiconductor materials that can absorb different wavelengths of light to yield higher efficiencies. They utilize metal nanoparticles, carbon nanotubes, and metal oxides for enhanced light absorption and are coined “nanophotovoltaics” (50). These solar cells include organic-based nanomaterials, e.g., graphene, graphene derivatives, and carbon nanotubes, as well as solar cells with inorganic nanostructures, such as metal oxides and metal nanoparticles (10) (Figure 6). Furthermore, there are also examples of hybrid photovoltaic solar cells that incorporate the advantage of both organic and inorganic semiconductor materials. These hybrid solar cells use an organic layer to absorb light and an inorganic layer as the electron transport layer (51).

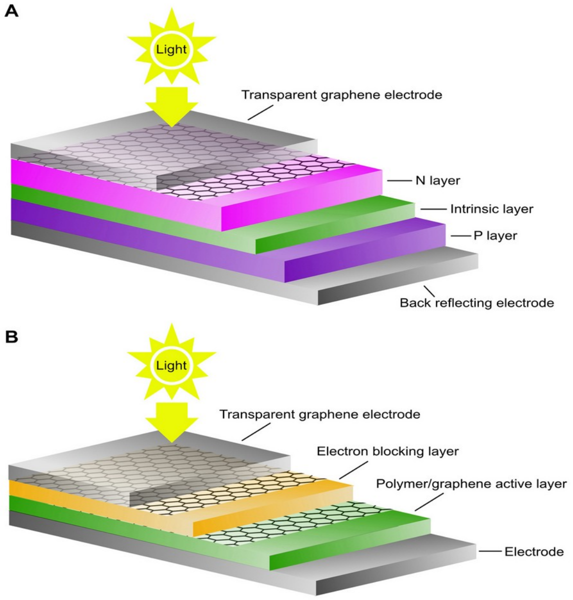

Figure 6: Fourth generation solar cells. These solar cells typically contain graphene. Depicted are examples of an inorganic solar cell (A) and an organic solar cell (B). (60)

Important problems and potential solutions needed to advance solar cell technology

One important question is whether solar cells can be engineered to harness ambient light instead of only sunlight. Solar panels are designed to absorb energy from sunlight, which is composed of photons with an energy range corresponding to the visible and near-infrared spectrum. However, ambient light sources, including artificial indoor lights and surface reflections, could potentially also be harnessed; especially for Internet of Things (IoT) applications. To harness ambient light, solar cells would need to be engineered to continually adjust the valence-conductance band gap in response to the spectrum of light that is available. In order to do this, the bandgap of the solar cell materials would need to be tuned to match the energy of the ambient light so that the solar cell could absorb a broader range of wavelengths in order to generate electricity. The bandgap is the energy difference between the valence band (where electrons are bound to atoms) and the conduction band (where electrons are free to move to generate current) (52). Adjusting the bandgap of the photovoltaic material to match the energy of the ambient light can be achieved by using different organic and inorganic semiconductors, e.g. perovskite solar cells or organic photovoltaics which have been shown to have high efficiencies under conditions of low light. Although this is possible to do, there are some challenges. Since the energy spectrum of ambient light can be quite different, it may not always match the bandgap of solar cell materials. Furthermore, the continual adjustment of the bandgap would require finely tuned controls that would need to be added to the solar panel. One option is to engineer these solar panels to utilize IoT sensors that can detect indoor light levels and adjust the solar panel bandgap to absorb the energy spectrum of the ambient light (53). While the use of IoT with solar panels is a promising area of research, several technical and cost challenges need to be overcome to achieve high efficiencies and optimum functionality.

Another critical question is whether solar cells can be recycled to create more environmentally friendly panels. Currently, recycling solar cells at the point of use is not a common practice. However, ongoing research and development efforts are striving to make this possible. One approach to enable recycling at the point of use is to use consumable add-ons, including electrolytes or other materials that can help with the separation of the different components of the solar cell. Some researchers are testing the use of electrolytes to dissolve the bonding materials in the solar cell, thus allowing for the recovery of the panel's semiconductor materials, metals, and other components. Chemical processes that can recover silicon and metals are being tested. For example, nitric acid or other leaching agents can leach the metals, and a process called electrowinning separates copper and silver from the solar cell panel (54, 55). Another approach is to use solar cell materials that are easy to recycle, such as organic solar cells on cellulose nanocrystal substrates (56).

A third important question is regarding how to compare multiple different photovoltaic solar cells. For example, how can perovskite solar cells be compared to silicon or other types of solar cells? The levelized cost of energy (LCOE) is a performance index used to compare the price and function of different photovoltaic technologies (57). It is defined as the value of the total cost of generating electricity over the lifetime of a solar panel divided by the total amount of electricity generated by the panel over its lifetime. LCOE is affected by efficiency, stability and performance. While LCOE is a valuable performance index, it is not a perfect measure of the performance of solar cells. One limitation of LCOE is that it does not consider the variability of solar energy production over time, which can affect the value of the electricity generated. For example, solar cells may produce less electricity during cloudy weather conditions, which could reduce the value of the electricity generated during those periods. Another limitation of LCOE is that it does not account for the environmental costs and benefits of solar cells. Even when multiple solar cells have similar lifetimes and efficiencies, there tends to be a wide range of LCOE for these cells because of different assumptions and calculations (58). One method to improve comparability among solar cells is to include new parameters such as the degradation rate of the cells, costs for large-scale industrial production of the solar panels, and performance of these solar panels (58).

The future of solar cell technology

The use of solar energy is projected to grow exponentially. In addition to meeting the ever-increasing demand for more power, solar cell technology contributes to combating climate change and decreasing the world's dependence on fossil fuels. Mono crystalline silicon-based photovoltaics have been the mainstay of solar technology to date. Alternative materials are being explored to increase solar cell efficiency using amorphous thin-film silicon cells and polycrystalline silicon. Moreover, many new materials are also being investigated for ease of fabrication, increased light conversion efficiencies, and shelf-life stability to design the next generation of solar cells. Carbon nanomaterials, including graphene, can help improve solar energy generation in Photovoltaics (PVs) by increasing efficiency and functionality.

Interestingly, another class of PV cells being actively researched are the thermo-photovoltaics. Instead of absorbing light, these cells absorb heat. This technology involves using thermal radiation to generate electricity. The PV cells convert mainly infrared light emitted by hot objects at temperatures at or above 600 °C into electrical energy (59).

The future of solar cells is promising as the world continues to move towards using renewable energy sources. As outlined below, key developments with the fourth-generation (and beyond) PV cells continue to occur at a steady pace.

Energy Storage: One critical need is storing solar cell energy for an extended period. One of the biggest challenges with solar energy is that it depends on weather conditions. Advances in energy storage technology, including batteries, will allow excess solar energy to be stored and used when sunlight is unavailable. As energy storage technologies improve, the goal is to integrate solar cells with batteries and other electric storage devices so that the energy harnessed by the solar cells can be used over long periods. Such advances will allow consumers to store excess energy generated during the day and utilize it at night or under cloudy conditions.

Increased Efficiency: New materials and novel designs are being evaluated to increase efficiency levels significantly. Increasing the efficiency of solar cells is essential for making solar energy more affordable and accessible.

Reduced Costs: The cost of producing solar cells has steadily declined over the years. This makes solar energy more affordable for consumers. This trend is expected to continue as manufacturing processes become more efficient and economies of scale are achieved.

Grid Integration: Integrating solar cells with energy grids will allow for better energy flow and distribution management. This will help ensure that solar cells can be used efficiently so that energy can be utilized where and when needed.

Increased Durability: There is – at present – an unmet need for third generation solar cells to withstand all types of environmental factors and weather conditions over a long period. The testing and development of new materials and coatings will make solar cells more durable and longer-lasting.

Harnessing ambient light: As described above, to harness ambient light, the solar cell needs a tunable control to adjust the bandgap using IoT sensors.

Solar tracking systems: Solar tracking systems that track the sun's movement throughout the day can significantly improve the efficiency of solar panels. These systems can help increase the amount of sunlight that impinges on the solar panels by rotating the solar panels throughout the day for maximum sunlight absorption. This would lead to higher energy production.

Lightweight and flexible solar panels: Traditional solar panels are heavy and difficult to install in some places. Technological advancements in designing flexible and lightweight solar panels will allow them to be utilized in many more applications.

Current and ongoing research and development in solar cell technology is critical for making solar energy more accessible, efficient, and affordable for the average consumer. This will also help accelerate the transition to cleaner and more sustainable energy. In summary, the future of solar cell technology appears to be exceptionally bright, with continued innovation and advancements in the future.

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