Polycrystalline Thin Film Technologies for Solar Photovoltaics

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Abstract

This paper shows how polycrystalline thin-film solar cells are a promising alternative to monocrystalline silicon-based photovoltaics. With lower production costs and rapidly improving efficiencies, technologies like cadmium telluride (CdTe) and perovskite solar cells are a promising solution which address the limitations of silicon. The study focuses on advancements in manufacturing costs, improvements in efficiency, and design optimizations that enhance cell performance. Key factors such as grain texture, thickness, and recombination losses are analyzed. The findings suggest that with ongoing improvements, polycrystalline thin-film solar cells could become the dominant technology in solar energy, driving more efficient and sustainable solutions.

Introduction

The ever-increasing global demand for sustainable energy sources has established solar energy as a pivotal component in the transition from fossil fuels to renewable energy. During the past 20 years, solar cells have seen decreases in cost, improvements in efficiency, and an increased awareness of the benefits of renewable energy's benefits. Despite recent improvements, solar cells still accounted for only 4% of total electricity generation in the United States in 2023 (IEA). Drawbacks such as material quality and purity affects efficiency due to their energy intensive and expensive manufacturing processes, thus there have been difficulties in obtaining pure materials in solar cells which have affected efficiency and costs thus preventing solar photovoltaics (PVs) from emerging as a main source of electricity generation. These issues associated with silicon solar cells can be overcome through alternate solar technologies, but there are also alternative solutions. Among various types of solar cells, polycrystalline thin film solar cells have recently emerged as a promising technology due to their low costs and high efficiency. Polycrystalline cells have always had lower efficiency compared to their monocrystalline counterparts, but recent advancements in manufacturing techniques and material science have significantly narrowed this efficiency gap (Fig. 1) . Cadmium telluride (CdTe) polycrystalline solar cells show potential for success as they have a theoretical max efficiency of 30% compared to silicon's 29% (NREL). Polycrystalline solar cells also show potential for reductions in costs. The thin film requires less material which reduces costs while maintaining high efficiency. Since 2005, CdTe polycrystalline thin film solar cells have steadily increased in efficiency from 18% to 22.4% showing potential for it to one day replace silicon as the leader.

Polycrystalline silicon features advantages of all thin film technology such as low costs due to low material wastage with up to factor 100 less material compared to wafer-based solar cells. Wafer-based solar cells are a type of photovoltaic (PV) technology that converts sunlight into electricity using tiny slices, or wafers, of semiconductor material, most often silicon. These wafers, which are typically 150 to 200 micrometers thick, are essential components of the most prevalent type of solar panel, crystalline silicon solar panels. CdTe based thin films are being developed by low cost non-vacuum techniques and high efficiency in small area cells created by vacuum technology have also been reported for CdTe. Perovskite solar, a cheaper alternative, has also had steady increases in efficiency to 25.7% compared to silicon's 26.7%. This paper will give an overview of promising thin film technologies and it will discuss factors like texture, coating, and thickness which affect efficiency in solar cells. compares the efficiencies of the discussed technologies to determine the most promising technology that can be used in the future.

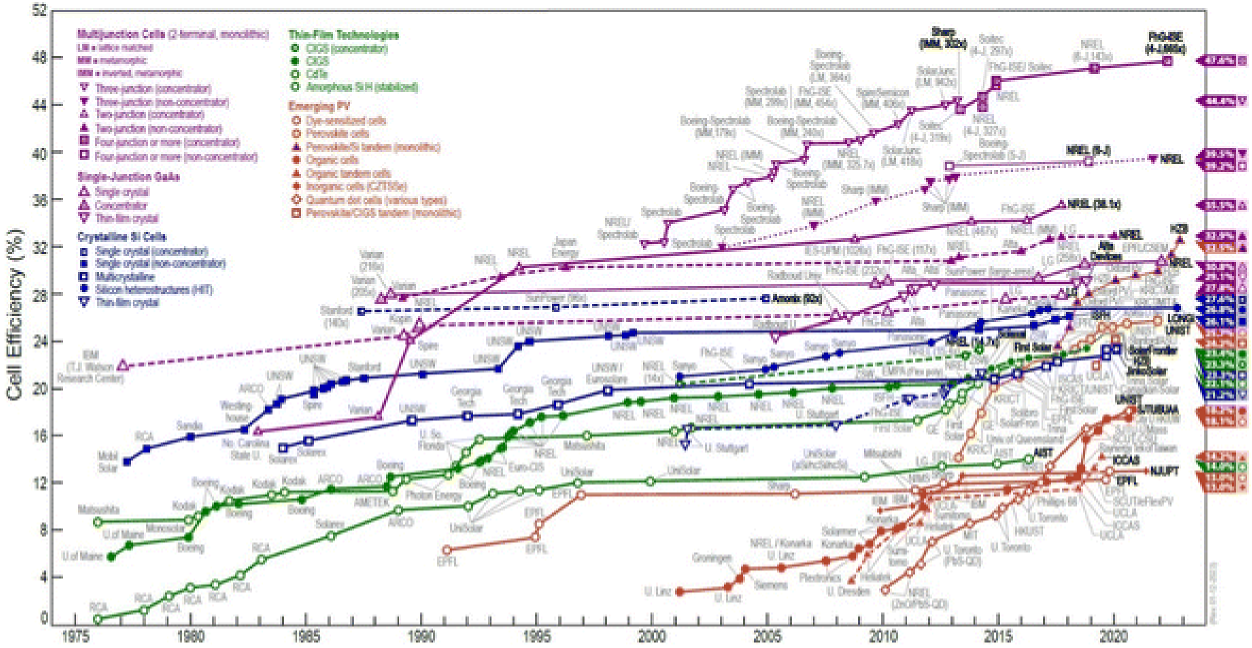

Figure 1. A chart of the highest confirmed conversion efficiencies for PV cells

Overview of Solar Technologies

Currently the most popular solar PV are made from crystalline silicon materials. These cells are either monocrystalline or polycrystalline, all which depend on the presence of grains in the microstructure. Polycrystalline cells have grain boundaries whereas monocrystalline does not which results in greater efficiency and because polycrystalline has grains, it can impede electron flow, affecting efficiency. Monocrystalline silicon cells are fabricated using single silicon crystals through a procedure called the Czochralski process where the entire solid's crystal lattice is continuous and free from grain limits. Crystalline silicon is a non-toxic material with great stability and durability while possessing an energy gap of 1.12 eV which is well-suited for maximum single junction solar cell efficiencies, meaning silicon can effectively convert sunlight into electricity. Since 2017, the record efficiency of these solar cells has reached 26.7% thanks to the heterojunction intrinsic thin layer of technology based on thin a-Si passivating layers and interdigitated back contacts on n-type silicon wafers and cells. Heterojunction Intrinsic Thin-Layer (HIT) photovoltaic cells use crystalline silicon and amorphous silicon (a-Si) to boost solar cell efficiency. The efficiency and stability of traditional silicon solar cells produced from p-type or n-type crystalline silicon wafers are limited by surface recombination and temperature sensitivity. HIT technology addresses these challenges by employing very thin amorphous silicon (a-Si) layers on both sides of a crystalline silicon wafer. Despite their high efficiency and long lifespan, there are drawbacks to these cells such as production costs. The Czochralski method, used to grow single-crystal silicon ingots, is particularly resource-intensive. This process requires high-purity silicon and precise control over temperature and environment, leading to significant costs (Green et al., 2015).

Polycrystalline thin film solar cells are made from crystals that are grown in large blocks and then sliced into thin wafers. Unlike monocrystalline cells, which are composed of single-crystal silicon, polycrystalline cells consist of multiple crystals. This structural difference leads to distinct grain boundaries, which affect the electrical properties and efficiency of the cells. The efficiency of these cells typically range from 15-20% which is slightly lower than monocrystalline solar cells. The presence of grain boundaries in polycrystalline silicon can impede the flow of electrons, thereby reducing the overall efficiency. However, ongoing research and development have led to improvements in cell design and manufacturing processes, gradually narrowing the efficiency gap between polycrystalline and monocrystalline cells. Polycrystalline thin film solar cells are less expensive than monocrystalline due to their ability to maintain efficiency while requiring less material.

Perovskite solar cells are a type of polycrystalline thin film that have shown promising photovoltaic technology due to their high efficiency and low production costs. Perovskite polycrystalline thin films consist of numerous small crystals or grains and perovskite solar cells are based on materials with a crystal structure similar to the mineral perovskite (ABX3). In this structure, 'A' is an organic or inorganic cation, 'B' is a metal cation, and 'X' is a halide anion. The most commonly used perovskite material for solar cells is methylammonium lead iodide (MAPbI3). The grain boundaries can influence the electronic properties of the material, affecting the efficiency and stability of the solar cells but despite these challenges, perovskite polycrystalline thin films have shown remarkable performance due to their excellent light absorption and charge transport properties. Perovskite solar cells (PSCs) have reached efficiencies of up to 25.7% which can be compared to the leading silicon solar cells. These cells contain the efficiency of silicon while maintaining the low costs of a polycrystalline thin film.

Cadmium Telluride (CdTe) polycrystalline thin film solar cells show promise in cost, efficiency, and large-scale production. CdTe has an direct bandgap of 1.45 eV and usually consists of a multilayer structure substrate (usually glass), Transparent Conductive Oxide (conducting material), Cadmium Sulfide (CdS) Buffer Layer (forms p-n junction with CdTe layer), and a absorber layer. CdTe has intrinsically better temperature coefficients, energy yield, and lower degradation rates than Si technologies. The temperature coefficient specifies how the performance of a solar cell changes with temperature and the degradation rate indicates how the performance of a solar cell decreases over time. Figure 2 compares different solar PV’s efficiency since 2023 and it shows that CdTe’s efficiency is near silicon meaning that it can overtake silicon in the very near future. CdTe is also cheaper to manufacture and is well-suited for scaling, thus showing potential to replace silicon solar cells in the future.

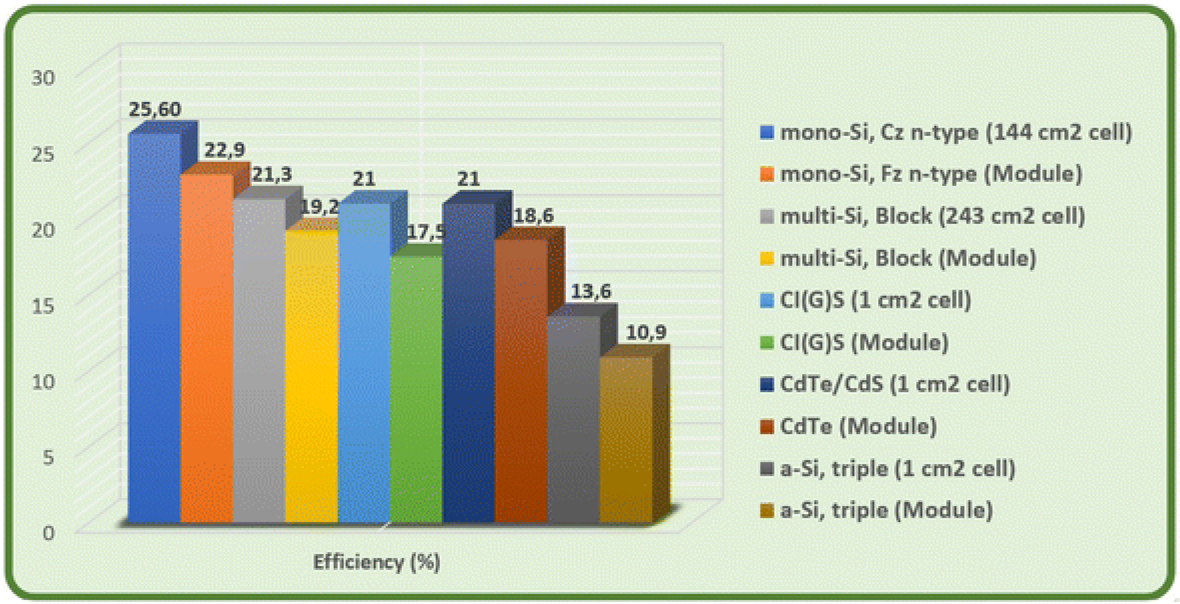

Fig. 2 Efficiency of silicon-based technology in laboratories

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Factors Influencing Efficiency

By rearranging grains to produce a randomized texture with better quality, a process known as recrystallization increases the efficiency of solar cells (https://www.sciencedirect.com/science/article/pii/S0040609024000798). Recrystallizing the absorber can enhance crystal properties and minimize flaws, both of which are essential for increasing efficiency. Effectiveness of light absorption in polycrystalline solar cells is also influenced by their roughness. Increasing the light route length within the cell can improve absorption and be attributed to textured surfaces. Certain textures like pyramid or dome-shaped grains can improve the formation of electron-hole pairs by improving light absorption and reducing reflection. This results in an increase in the number of photons through the PV cell.

Thickness of a solar cell can impact efficiency but there is not a *set* thickness that is optimal for all. Different types such as silicon, CdTe, and perovskites have different optimal thicknesses that work best in their specific situations. The thickness of the active layer of polycrystalline solar cells affects their ability to absorb light. Thicker layers absorb more light but a certain thickness, the advantages of light absorption lessen because of increased recombination losses and reduced charge carrier collection efficiency.

Recombination occurs when electrons recombine with holes instead of contributing to the electric current. For a thickness to be optimal, it must ensure ample light absorption, enhance carrier collection, and minimize recombination losses. In CdTe solar cells, their optimal thickness is around 2-10 um (alluding to ‘thin films’) because of CdTe’s high absorption coefficient. This can explain why CdTe solar cells are inexpensive to build while maintaining high efficiency. The optimal thickness for perovskite cells is 0.3-0.6 um. Perovskites have high light absorption properties which explain why cells are much thinner. Significant gains in efficiency have been made possible by the exact control of perovskite layer thickness which have been made possible by advancements in fabrication processes including solvent engineering and thermal annealing.

Different types of solar cells are prone to different recombination losses. Cadmium Telluride cells are prone to interface recombination and potential shunt resistance issues. Shunt resistance is a parallel resistance path that occurs within the cell and is usually brought by flaws and contaminants. There is frequently a significant density of defects at the boundaries between the grains of CdTe films, which can serve as sites of recombination where electrons and holes combine again without producing current. Another factor is that a thin coating of CdS (cadmium sulfide) is also commonly utilized as a buffer layer in CdTe solar cells. This can result in higher recombination because of a high density of defect states at the interface between CdTe and CdS.

Perovskite solar cells are prone to grain boundary recombination and shunt resistance from defects. The charge carrier dynamics in these cells create losses because non-radiative recombination can occur near grain boundaries when trapped carriers recombine with carriers of the opposite charge. As a result, the cell's efficiency decreases since there are fewer charge carriers contributing to the electric current.

Silicon cells are more prone to Prone to Shockley-Read-Hall (SHR) and Auger recombination, and require careful management of optical losses. Auger recombination is when an electron recombines with a hole in a semiconductor. Instead of releasing a photon, the energy is transferred to a third carrier—an electron or a hole—which subsequently releases it as heat. Since this process is non-radiative, it doesn't aid in the production of electricity. Silicon solar cells contain imperfections in the crystal structure like defects or impurities. This can result in trap states which is when charge carriers are captured by these traps, they recombine non-radiatively, reducing the number of carriers available to generate current. SHR recombination also affects the efficiency. Commonly used silicon cells have many defects which increases the chance of SHR recombination. To prevent this, high quality silicon is required, but this is impractical as it can be expensive and rare.

Efficiency Comparisons

Polycrystalline Cadmium telluride (CdTe) and Perovskite solar cells for low production costs and high efficiency. But when compared Perovskites have shown superior performance in many important areas. As previously stated, perovskite solar cells have surpassed power conversion efficiencies of 25% while CdTe have only reached a maximum efficiency of about 22% in similar settings.

There are several reasons why perovskite is superior. Polycrystalline perovskites display high light absorption properties because of their straight bandgap and high absorption coefficient. This makes it possible to create absorber layers that are thinner, often less than 1 µm thick—while yet still absorbing a sizable amount of the solar spectrum that is present. While on the other side, CdTe requires thicker layers (usually ranging from 2-3 µm) in order to absorb the same amount of light which increases material consumption and production costs. Perovskites also have long carrier lifetimes and a good defect tolerance. Typically seen in polycrystalline materials, perovskites can retain high efficiency even when flaws and grain boundaries are present. But despite having high defect tolerance as well, CdTe is more likely to experience recombination losses (described earlier) especially at grain boundaries, which can reduce polycrystalline cell efficiency.

Perovskites are scalable and can be manufactured at lower temperatures and use less complicated fabrication methods like spin coating or printing while silicon requires high temperatures and costly materials in order for production. Perovskites also show potential to surpass silicon in efficiency because of its bandgap and configuration. Perovskites can be utilized in tandem arrangements with silicon or other materials because they can be bandgap tuned by changing their composition. These tandem cells have the ability to attain higher efficiency than silicon cells alone because they can surpass the shocker Shockley-Queisser limit for single-junction solar cells. (which is shown in figures above and also mentioned above).

Conclusion

In conclusion, while silicon (Si) solar cells have long dominated the photovoltaic market, developing solar technologies, particularly perovskite solar cells, hold enormous potential for transcending Si's limits. Significant breakthroughs are still needed to fully realize their potential and displace Si, notably in terms of efficiency, stability, and scalability. Increased investment in perovskite research is critical to addressing these problems and allowing these materials to meet the required performance parameters. By addressing these critical difficulties, perovskite solar cells may not only bridge the gap, but also transform the solar energy sector, resulting in more sustainable and efficient energy solutions.

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