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SOLAR CELL SYSTEMS - OPERATING PRINCIPLES AND TECHNOLOGY

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Abstract- Today solar power is accepted as an effectively alternative energy source in different area of application. It is needed to be undertaken features of solar cell sources which can be included as achievement of the high efficiency and low cost-effective solar power development. The fact is that the last decades has discovered significantly improvement of technology of solar cells. There is no source of energy more plentiful than our Sun and the sunlight reaching the Earth has the potential to fulfil the world's needs, via solar panels made up of solar modules. There are three generations of solar cells, all of which promise a sustainable future: the 1st, 2nd, and 3rd generations. These cells come with advantages as well as disadvantages and are all useful technologies for the advancement of renewable energy production. It is even possible to combine different types of materials to create tandem solar cells, which lead to higher efficiencies. Undoubtedly, these high-efficiency solar systems provide effective technology solutions that satisfy the market requirements. Undeniably, the challenges of solar systems are a significant part of the decision-making stage when it comes to selecting the right kind of technology for building a high-efficiency system. Therefore, it is necessary to perform a complete assessment of the existing systems in the field, undertaking the achievements in the development of solar cell systems. This paper presents recent outcomes and technological improvements, describes performance and approaches of segments impacting to produce high performance of results where improvements of technology can be intended to be applied for achievement expected results of manufacturing.

Keywords: Solar Cell, Efficiency, Multi-Junction.

1. INTRODUCTION

In today's world, it has become a necessity to generate energy in a way that does not damage nature or the environment [1]. For this aim, it is possible to use renewable energy sources such as wind, biomass, and the most promising one, solar. Solar energy helps create a sustainable planet by minimizing the negative impact on nature [2]. Consequently, the use of solar energy positively influences the protection of our environment and helps fight climate change. This type of energy generates electricity via solar cells.

Photovoltaics (PV) is the term for converting energy from sunlight into electrical energy. Devices with the use of semiconductors that can perform this process are known as solar cells and can be called photoconductive or photovoltaic cells depending on the physical processes of their application.

A photovoltaic cell uses a semiconductor such as silicon, which exhibits the photovoltaic effect. This effect occurs in semiconductors of p-type and n-type, which have positive (excess of holes) and negative (excess of electrons) charges respectively. As the electrons are released via the absorption of photons of sunlight, these free electrons are captured and create an electrical current [4]. This electric field is created as the electrons relocate to the p-side and holes move to the n-side [14]. This technology is by far one of the most efficient ways of harnessing energy from the sun [2].

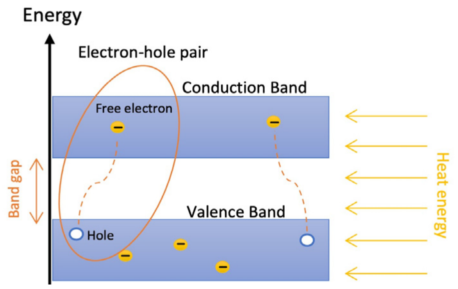

Figure 1. Energy diagram

This effect is illustrated in Figure 1, as the sunlight (heat energy) hits the solar cell modules, the electron-hole pairs are created. This happens as the photons (light particles) give energy to the electrons, which move up to the conduction band from the valence band, creating an electron-hole pair. The electron will then escape into the circuit the cell is connected to and charge the battery [5]. The band-gap indicated in the diagram is the minimum energy required for the excitation of an electron from the valence band to the conduction band, which is an important property of semiconductors. An ideal solar cell will have a band-gap of around 1.4 eV to absorb as much sunlight as possible.

Collectively, solar cells are classified into three generations. First-generation solar cells are mainly silicon-based wafers with efficiencies of 15 to 25%. They are the most commercialized type of solar cells due to their high efficiencies and abundance [1]. However, these cells have some disadvantages such as their costly manufacturing processes and long energy payback times [1]. Next, second-generation solar cells are made from materials such as amorphous silicon, CIGS and CdTe [5]. These cells are thin and flexible and have an efficiency of 1 to 22%, yet, they are not widely commercialized due to various factors such as scarcity of the elements used in them [5].

Finally, we have the very fast-growing third generation of solar cells, which includes a variety of cells, such as organic solar cells. The most exciting one of them all is the perovskite solar cell with a 26-27% efficiency. These cells offer flexibility, low cost, and easy manufacturing among other benefits. The catch here is that they are highly unstable as they are easily affected by their surroundings. Additionally, tandem (multi-junction) cells are a very interesting and fairly new technology that combines the advantages of at least two generations of solar cells, increasing their efficiency. In this paper, the highest efficiency systems of these different types of solar cells are explored.

2. HIGH EFFICIENCY SOLAR CELL SYSTEMS

As introduced before, there are various types of solar cells with a wide range of efficiencies. The efficiency of a solar cell, better known as power conversion efficiency (PCE), determines how much of the light incident is converted into output energy. This definition is simply explained by the following equation:

$$PCE = \frac{P_{in}}{P_{out}} \tag{1}$$

where, P_{in} and P_{out} are the input power and the output power respectively. When one talks about how efficient a solar cell is, they are referring to its PCE, i.e., how much energy is generated.

Let us compare the PCEs of silicon (first generation), thin-film (second generation), perovskite (a type of third-generation solar cell) and tandem solar cells. In Figure 2, we can see various efficiencies recorded by different institutions of these three types of systems. The blue lines represent the first generation, green lines show the second generation, orange is the perovskite, and purple is the multijunction (tandem) solar cells.

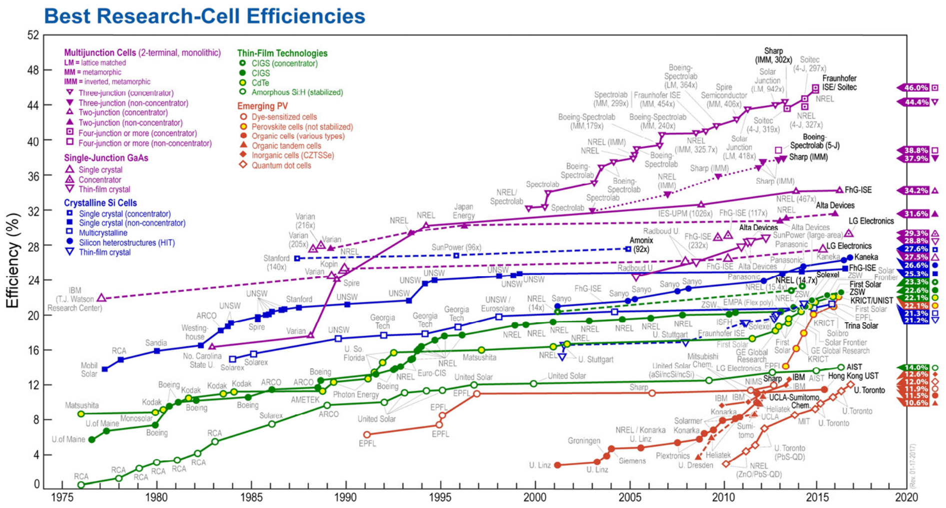

Figure 2. NREL solar cell efficiency table [15]

As seen in Figure 2, the highest silicon solar cell recorded is the Crystalline Silicon by Kaneka at a PCE of 27.6%. As for thin-film solar cells, the world records are 14%, 22.1% and 22.6% for amorphous silicon, cadmium telluride and CIGS cells, respectively. This clearly shows the difference in efficiency and commercialization of silicon and thin-film systems. Next, in orange, under "emerging PV", the efficiencies of various third-generation solar cells are available. The perovskite-silicon tandem solar cells have a high efficiency of 31.3%, while perovskite cells have 26.1%. It can also be seen that four- and three-junction systems lead to the highest efficiencies. It is important to note that all these systems offer different advantages, in addition to their efficiencies, such as flexibility and abundance.

2.1. First Generation, Silicon Solar Cells

Silicon solar cells are currently leading the market due to their high PCEs which are around 26.7% and stability [8]. These photovoltaic cells absorb light and generate electron-hole pairs, then separate charge carriers of opposite types of extracted to an external circuit [5].

Even though silicon solar cells offer high efficiencies, have the optimal band-gap for PV conversion, and are abundant, they still have limitations on the theoretical side - the Shockley-Queisser limit [16]. This limit refers to the peak theoretical efficiency of a solar cell made up of a single p-n junction. It can be calculated by evaluating the electrical energy extracted by each incident photon [17]. Using the AM1.5 spectrum and a bandgap of 1.4 eV, for a single p-n junction, the limit is around 33%. For silicon, taking into consideration other limitations such as the sensitivity of the efficiency to the temperature and environmental factors, assumptions of perfect solar absorption and no losses due to non-radioactive charge-carrier recombination condition of the atmosphere, the limit comes down to 29% [17].

Another drawback of silicon is that it is a semiconductor with an indirect band-gap, meaning that the maximum energy of the valence band falls to a different value of momentum than the minimum energy of the conduction band [21]. This leads to a much slower rate of the process compared to the direct band-gap materials, where the base of the conduction band and the top of the valence band take place at same value of momentum [21].

The different types of silicon-based photovoltaic cells are monocrystalline silicon (mono-Si), polycrystalline silicon (poly-Si) and thin-film amorphous silicon (a-Si) [11]. The main difference between these kinds of solar cells of the same material is their manufacturing processes. In the production process, silica is formed into metallurgical grade silicon, to a 98% level of purity, which is then refined into a polysilicon raw material with a 99.999% purity level [5]. This allows for mono-Si and poly-Si production, where the former shows a slightly higher efficiency of up to 27% and the latter around 17% to 22% [5].

However, poly-Si has the advantage of lower cost in production. This is because the mono-Si are made from a single crystal of silicon, whereas the poly-Si are fabricated from many silicon ingots melted together. Also because of this long manufacturing process, polycrystalline silicon solar cells have high energy payback times, and time needed to generate the amount of energy used while creating the solar modules. In contrast, the duration for monocrystalline silicon photovoltaic cells is more reasonable. The third type, amorphous silicon cells, includes a thin uncrystallized layer of silicon that is attached to the substrate, making it very thin [11]. The mono-Si and poly-Si are considered first-generation solar cells, while the amorphous is a second-generation cell due to their thin-film structure.

Overall, silicon solar cells, specifically poly-Si, are currently leading the market, but research on other kinds of photovoltaics is going on due to their disadvantages such as cost and high energy payback times [5]. Nevertheless, they are the most commercialized type of cells due to their abundance and efficiency.

2.2. Second Generation, Thin Film Solar Cells

Second-generation solar cells consist of one or more layers of films of photovoltaic material on a substrate. They use direct band-gap materials unlike silicon systems, which allow them to have thin absorbing layers, of a few nanometers to tens of micrometers [5]. This allows for flexible, light cells which can be integrated into many different uses such as small appliances. The main thin-film cells are copper indium gallium selenide (CIGS), cadmium telluride (CdTe) and amorphous silicon(a-Si). Since these cells use fewer semiconductors, their efficiencies are lower compared to first-generation solar cells, and they occupy around 20% of the PV market [11].

2.2.1. Copper Indium Gallium Selenide (CIGS)

The CIGS cells are the highest efficiency of the three thin-film technologies mentioned, with a record PCE of 22.6% [11]. These cells have a structure that consists of a heterojunction system, one with different crystalline semiconductors. Due to its direct bandgap material, its thin layers can easily absorb light. The semiconductor layer is the p-doped CIGS which includes copper, indium, gallium, and selenium with the formula $CuIn_xGa_{(1-x)}Se_2$. The value of x can vary from 0 to 1, and the bandgap changes from 1.0 eV to 1.7 eV [5].

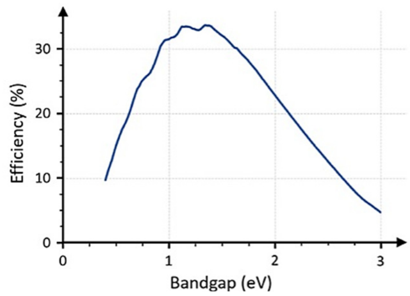

Figure 3. Shockley-Quessier limit [5]

As seen in Figure 3, the band gap range for CIGS cells is ideal for the Shockley-Queisser limit, reaching a PCE over 20%. Although they have high efficiencies and low energy payback times, these elements are very scarce, making it difficult to build many solar panels with them.

2.2.2. Cadmium Telluride (CdTe)

Cadmium Telluride, CdTe, is a direct band-gap material with a big absorption coefficient [12]. This way, it is possible to manufacture thin-film high-efficiency CdTe solar cells, like CIGS. One of the benefits of these cells is their low manufacturing costs, by producing modules from input materials in just a few hours [13]. They are again similar to CIGS in the sense that they also reach a PCE of a little over 20% which is considered good, and have a low energy payback time. Yet, they also have a serious scarcity problem and thus are not widely utilized.

2.2.3. Amorphous Silicon (a-Si)

Amorphous silicon, a-Si, is the form of silicon that is non-crystalline, unlike the first-generation poly-Si and mono-Si. [18]. Due to its high absorption capacity, it can be used in photovoltaic cells with very thin layers, which saves on material cost and time, leading to a low energy payback time. Thanks to their small layers, they are flexible and can be deposited onto various structures such as grass and plastic [18]. The downside of these cells is that they are comparatively lower in efficiency than other types of silicon cells, with a PCE of around 14%. Furthermore, they are highly unstable, and thus unsuitable for large solar power generation sites.

2.3. Third Generation, Emerging PV

Third-generation solar cells are cells that can overcome the Shockley-Queisser and are used to generate electricity from the Sun. This advancing technology is particularly convenient for the use of solar energy as these cells are flexible and have low material costs [5]. The biggest disadvantage regarding these cells is their instability problem; they are not stable when exposed to heat and other factors. Some emerging types are dye-sensitized, quantum dot, and the most promising one, perovskite solar cells (PSC). This paper will look at the latter as an example to explain these emerging PV solar cells.

2.3.1. Perovskite

Perovskite solar cells (PSC), named after Russian mineralogist L.A. Perovski, are a type of third generation solar cell which include organic polymers that absorb light and produce photovoltaic effects by charge carriers [6]. This type of solar cell is especially exciting for the industry, as its PCE increased from 3.8% in 2009 to 22.1% in 2016, which is a large development in a short period of time [19]. Currently, the efficiency of the perovskite cell reaches approximately 27%.

Perovskite is a type of compound of the form ABX_3, where A and B are the cations and X is the anion [7]. X is a halide and can be elements such as O, Cl, Br, I and S [8]. The bigger cation A can be organic or inorganic molecules, such as methylammonium ($CH_3NH_3^+$) or cesium (Cs_3^+), while the cation B can be lead (Pb^{2+}) [7].

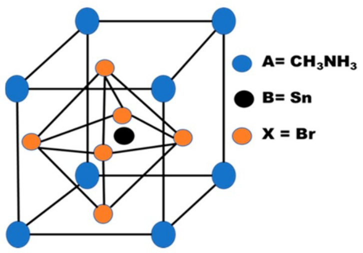

Figure 4. structure of a tin-based perovskite [54]

In Figure 4, the crystal structure of a cubic perovskite can be seen. Due to perovskite's structural distortion characteristics, researchers have been focusing on Tin-based PSC, where lead is substituted by Sn^{2+} (tin). The advantage of these cells would be that they are lead-free, as lead is harmful to the environment. These different material combinations determine the properties of the perovskite, some of which are band-gap and mobility [7].

PSCs have exceptional photoelectric properties and high optical absorption coefficients [19]. The perovskite light-absorbing layer can absorb solar energy well and the electron-hole pairs are efficiently and simultaneously transmitted and collected [19]. They have a layered structure consisting of a TCO-coated glass substrate, an electron-transport layer (n-type semiconductor), a perovskite absorber layer, a hole-transport layer (p-type semiconductor) and a back contact (metal/TCO/carbon) [20]. This structure is illustrated below in Figure 5.

Presently, the biggest challenge perovskite solar cells face is the long-term stability of modules [20]. This problem is caused by the instability of the perovskite layer when in contact with moisture and heat. This is due to the intrinsic stability, one that is caused by the crystalline structure of the perovskite, as well as the extrinsic stability, which are external factors, such as interaction with water [22]. There have been various methods implemented to solve this degradation problem, such as adding a protective layer to the perovskite material. However, a fully effective, long-lasting solution is yet to be found. It is necessary to continue this research to solve this issue permanently and commercialize perovskite solar cells.

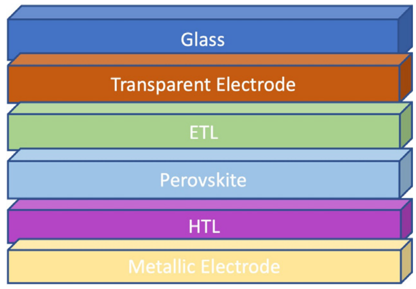

Figure 5. Structure of Perovskite Solar Cells

2.4. Tandem (Multi-Junction) Solar Cells

There are many techniques for growing the efficiency of solar cells, and tandems are one of them. In literature, a few layers of different materials with different band-gap energies stacked together are more likely to have higher efficiencies, as single-junction cells are limited by the Shockley-Queisser limit. Yet, predictably, this will require a higher manufacturing cost than a regular single-junction cell. A popular tandem solar cell is the perovskite-silicon system. Silicon solar cells on their own are the most commercialized solar cells. It is easy to find silicon on Earth and they have competitive efficiencies. Perovskites are a great match for silicon, as they can cover the wavelength area silicon cannot on its own. Perovskites can absorb high-energy photons, while lower-energy light particles are absorbed by the silicon layer, thus increasing the efficiency of the cell. For instance, when a high-energy photon is illuminated on silicon, it might cause a lot of heat, leading to a lot of loss. If a perovskite layer is placed on top of silicon, it will reduce this heat, preventing a large amount of heat loss, and the efficiency will go up.

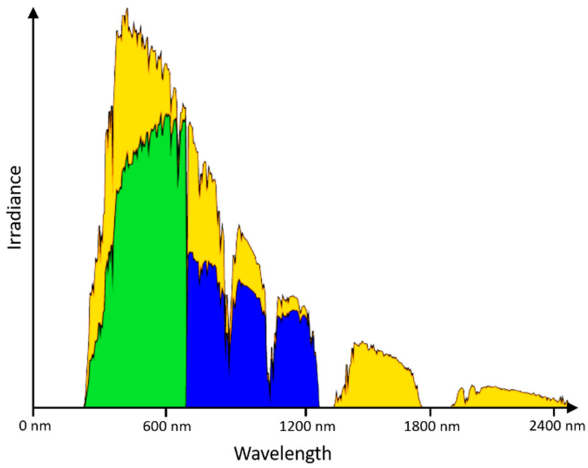

Figure 6. Spectral usage for a stacked tandem solar cell [5]

In Figure 6, the utilization of the spectrum (yellow) is illustrated. The top layer (green) has a larger band gap than the lower layer (blue), and both shorter and longer wavelengths can be absorbed. An example of a commercialized perovskite-silicon tandem solar cell is from Oxford PV [10] with an efficiency that could reach up to 30%. This tandem solution offers higher performance and consequently reduces the cost as less area is needed for more power, compared to their regular silicon solar cells at around 22%.

3. CONCLUSION

The three generations of solar cells presented all promise various characteristics for a sustainable future. We can conclude that silicon solar cells are leading the market, although their development has almost ended, as the current silicon solar cells are already very close to the Shockley-Queisser limit. The second and third-generation cells bring hope for the future with their increasing PCEs and features such as flexibility. Many scientists are continuing their research regarding these cells to improve their efficiencies and stabilities. More, tandem (multi-junction) solar cells offer a unique technology by combining more than one generation of solar cell materials to absorb a wider range of wavelengths, increasing the efficiency, and decreasing the energy payback time of modules. These new advanced technologies promise a bright future.

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