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Evolution of Solar Cells from Conception to Current Date

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Introduction

The potential for solar energy was first discovered by Edmond Becquerel in 1839, when he noted in his laboratory that some materials can generate voltage and electric currents when exposed to light. In 1873 Willoughby Smith observed that Selenium as a material was apt for a photovoltaic effect. The origin of the solar panels that can generate energy in traced back to Charles Fritts, who used Selenium coated with a thin layer of gold in 1881[1]. Photoconductivity and photoelectric effect are important to understand the working of a solar cell. Photoconductivity is an important phenomenon that increases electrical conductivity in a material when exposed to light. It is a related to photovoltaic effect that induces voltage through use of light. Photoelectric Effect is the emission of electrons when electromagnetic radiation, such as light, hits a material. This effect can also be defined as the ejection of electrons from a metal plate when light falls on it [2]. New research now focuses on using ink printed thin solar cells with hybrid materials that lead to increase in cell efficiency. Another study showed tandem model with perovskite semiconductor to absorb near infrared light on solar spectrum, while an organic carbon-based material absorbed ultraviolet and visible parts of light[3] . From its inception the solar energy cost has come down from $0.52 per kWh to $0.06 in 2017, three years ahead of its scheduled target of 2020. The current target of Sun Shot is $.03 per kWh for 2030[4] . This paper intends to focus on evolving solar technologies that could make solar cells more efficient and accepted as energy source for the coming generations.

Band Gap and P-N Junction

The band gap is a measure of energy in electron-volts (eV). Study shows that an ideal band gap of 1.35 eV is ideal for maximizing energy yield. It is noticed that as the energy band gap decreases, the electrical conductivity increases. It is an important measure in the solar energy field as this basic principle is applied to make the solar cells more efficient.

Metals conductivity decreases with increasing temperature. When the valence band (containing valence electrons that can be moved by applying small amount of energy such as a low-level electrical field) and the conduction band (consisting higher energy orbitals that exist above the valence band) do not overlap, the material can be either be an insulator or semiconductor. The insulators have a larger energy gap between the two bands while a semiconductor has a narrow gap between the two bands.

Semiconductors are used in a solar cell because of the presence of electric field that helps the electrons move in a circuit instead of freely as would be the case with a conductor metal. This electric field is due to the presence of the PN junction in the semiconductors without which the cell would not work. The gap in the semiconductors can have a direct and indirect gap. In the direct bandgap semiconductor, the electrons rising from the valence to the conduction band will change only its potential (energy) and in an indirect bandgap semiconductor it will change the potential (energy) and

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[1] Adrien Perez, “Who Invented Solar Panels? -the Early History of Solar Energy,” GI Energy, July 20, 2021, https://gienergy.com.au/who-invented-solar-panels/.

[2] “Photoelectric Effect,” Encyclopædia Britannica (Encyclopædia Britannica, inc., n.d.), https://www.britannica.com/science/photoelectric-effect.

[3] www.ETEnergyworld.com, “Cheaper, Changing and Crucial: The Rise of Solar Power Technology - Et Energyworld,” ETEnergyworld.com, August 12, 2022, https://energy.economictimes.indiatimes.com/news/renewable/cheaper-changing-and-crucial-the-rise-of-solar-power-technology/93510319.

[4] “Sunshot 2030,” Energy.gov, n.d., https://www.energy.gov/eere/solar/sunshot-2030.

momentum.[5] Since silicon is a good conductor at high voltages it goes through a process known as doping that can improve the semiconducting property of silicon significantly. Doping involves adding tiny amounts of some other elements (dopont) to the silicon. Doping can be done in two ways:

N Type (Negative type)- This involves adding extra electrons to the silicon by using elements such as phosphorous or arsenic causing the silicon to have a slight negative charge and promoting electrons to conduction band by low light energy.

P Type (Positive type)- This involves doping of silicon with boron, aluminum or gallium the resulting material that lacks one electron and needs one more electron to form a complete bond between silicon and boron.

When these two types of semiconductors are put together creates a solar cell (Illustrated in figure 1) that starts the energy making process when photon is absorbed and excites an electron to a higher energy conduction band, thus allowing the electron to be conducted from the n type silicon layer and flow through the external circuit to the p type layer. This adding of electrons makes the p type layer more negative and this increase in negative charge creates an internal repulsion. This repulsion causes electrons to jump the gap internally back in the n type layer, which has become positive due to loss of electrons via the circuit. This process continues as long as the silicon layers are exposed to sunlight and till when the circuits are closed. [6]

A PN junction is then used to separate the electron and hole carriers in a solar cell to create a voltage. Essentially when light reaches the PN junction the light photons can easily enter the junction through a very thin p type layer. The light photons supply sufficient energy to the junction to create a number of electron hole repairs. The generation of electrical current happens inside the depletion zone of the PN junction.

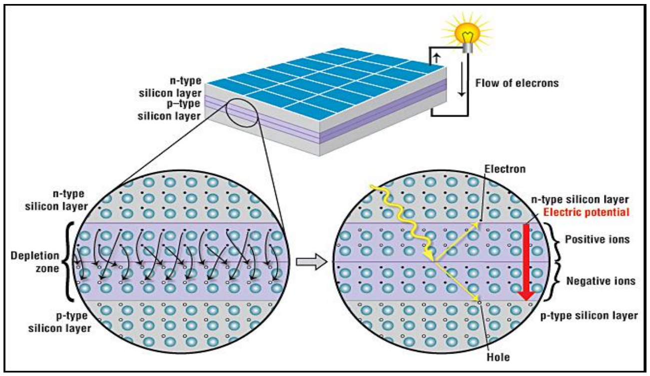

Figure 1: Schematic of a solar cell using p-n junction[7]

SQ Limit

The radiative efficiency limit, the detailed balance limit or the Shockley-Queisser limit is the maximum theoretical efficiency of a solar cell using a single PN Junction to collect power from the cell where the only loss mechanism is radiative recombination in the solar cell.[8]

At the moment the SQ limit is between 29 and 33 percent, assuming a single junction cell that is made using one type of semiconductor and is energized by direct sunlight. The model assumes that the solar cells absorbs all the photons bigger than the band gap and that the radiative recombination (the release of a photon by the recombination of an electron in the conduction band with a hole in the valence band) is the only radiative recombination occurring. [9]

Traditional materials used in solar cells

The solar cells have come a long way since they were first introduced by Bell labs in the 1950's. We now can have a look at the traditional materials used in a solar cell and some advantages and disadvantages of the same:

Materials Used	Advantages	Disadvantages
Silicon based Crystalline Cells	• Widely available • High Performance of 15-20% • High stability	• Rigid structure making them brittle • The cost of production high
Multi Crystalline Silicon Cells	• Simpler production technique so low cost • Apt for commercial use of solar energy	• Material quality is lower than single crystalline cells • Production being phased out with better developed materials for single crystalline materials
Amorphous Solar Cells	• Cheaper production cost due to less use of raw material • More flexible than silicon-based cells	• Limited availability of raw material restricts production • Due to production in vacuum chambers and high temperature production the energy consumption to produce cells are higher

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[5] Beemnet Mengesha Kassahun, Kyungpook National University, https://www.researchgate.net/post/What-is-the-difference-between-direct-and-indirect-band-gap/5ae3cc421a5e76a65e1679e2/citation/download

[6] (*Photoelectric Effect*)

[7] "How a Solar Cell Works," American Chemical Society, n.d., https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/past-issues/archive-2013-2014/how-a-solar-cell-works.html.

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[9] "Non-Radiative Voltage Losses and Recombinaton in Perovskite Solar Cells," Fluxim, accessed August 29, 2022, https://www.fluxim.com/voc-losses-perovkiste-solar-cells.

The solar cells are transitioning from first stage to second stage due to continuous need for gaining better and cost-effective efficiency from a solar cell. The changes make the cells more flexible and more lighter material.

Second generation Solar Cells

The second-generation solar cells as depicted in the figure.2 are made of commercially available thin film technology:

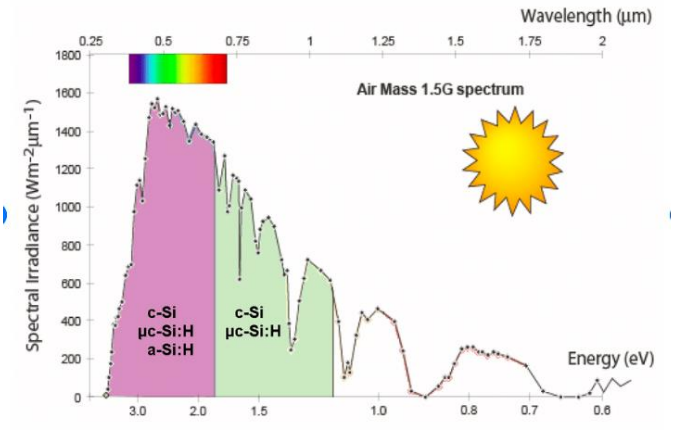

Figure 2: Different band gaps of c-Si, μc-Si:H, and a-Si:H cause different regions of the solar spectrum to be absorbed by each material.[10]

There are many different materials that can be used to make a solar cell, till now the materials used are alloys of silicon, boron, aluminum, gallium, indium, etc. Since, silicon only has a band gap of 1.1 eV, silicon can be used in multiple "layers" with other materials with a different band gap in comparison to silicon, to ensure maximum absorption on the solar radiation. However, there are disadvantages relating to this such as extra cost and wasted resources. Furthermore, the materials used can also be toxic in nature such as lead, and thus lead to environmental problems.

So apart from silicon cells we can use quantum dot solar cells that use quantum dots as absorbing photovoltaic material. Quantum dots have bandgaps that are able to tune themselves across a wide range of energy levels by changing their size. In bulk materials, the bandgap is fixed by the choice of material(s). This property makes quantum dots attractive for multi-junction solar cells, where a variety of materials are used to improve efficiency by harvesting multiple portions of the solar spectrum.[11]

To overcome the problem of limited power-conversion yield in silicon based solar cells, the cells are combined with a complementary solar cell that absorbs the blue-green part of the solar spectrum and employs it more efficiently, forming a "tandem". This tandem helps the maximizing the solar energy yield due to band width gap from 23-25% to nearly 29.2% on a surface of 1 cm$^{2.}$ [12]

Researchers are finding ways to bring the cost of tandem solar cells down, because of multi-layered and multiple materials used the fabrication and production cost is higher than traditional solar cells.

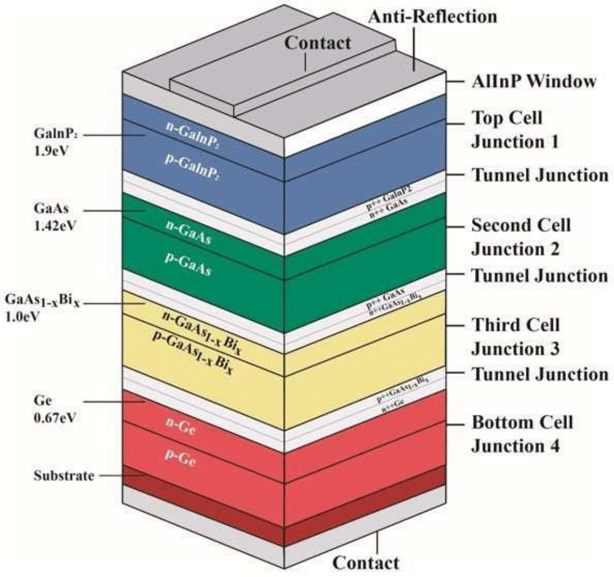

Figure 3: A schematic design of Multijunctional solar cell[13]

Dye-Sensitized Solar Cells (DSSCs):

New technologies are emerging that aim to bring down the cost of solar panels by using plastic and dye-sensitized solar cells which can be fabricated at low costs. They offer a technically and economically viable alternative to the P-N junction photovoltaic devices. It works on the principle that electricity can be generated through illuminated organic dyes in electro-chemical cells. The 4 working elements for DSSCs is an electrode, sensitizer (dye), redox-mediator (electrolyte) and counter electrode. They also reduce the dependence of solar industry on the semiconductor industry and can offer new solutions to the solar cells like more flexibility and improved efficiency.

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[10] "7: The Different Band Gaps of C-Si, MC-Si:H, and a-Si:H Cause Different ...," accessed August 28, 2022, https://www.researchgate.net/figure/The-different-band-gaps-of-c-Si-mc-SiH-and-a-SiH-cause-different-regions-of-the_fig18_260435234.

[11] "Quantum Dots Promise to Significantly Boost Photovoltaic ... - NREL," accessed August 28, 2022, https://www.nrel.gov/docs/fy13osti/59015.pdf.

[12] "Improving the Efficiency of Tandem Solar Cells," Wevolver, accessed August 29, 2022, https://www.wevolver.com/article/improving-the-efficiency-of-tandem-solar-cells.

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In the DSSC, the photon is absorbed by the dye resulting in electrons getting promoted from ground to the excited level. The excited electrons are then injected into conduction band of nano-porous titanium dioxide that absorbs a small fraction of solar photons from the UV region, hence, resulting in the dye getting oxidised. The injected electrons reach the counter electrode through the external circuit. The electrons at the counter electrode reduce the present I3- to I-. This I- provides electrons for the regeneration of the ground state of the dye and oxidises I- to I3- again. And this process continues.

Advantages	Disadvantages
They are cheap	Not durable – low long term stability
Easily manipulatable and flexible	Low efficiency
They are also have a direct band gap, leading to a wide absorption range	

So even though the DSSC have their advantages but owing to the fact that durability and efficiency is lower they are mostly used for niche applications and not for commercial and residential uses.

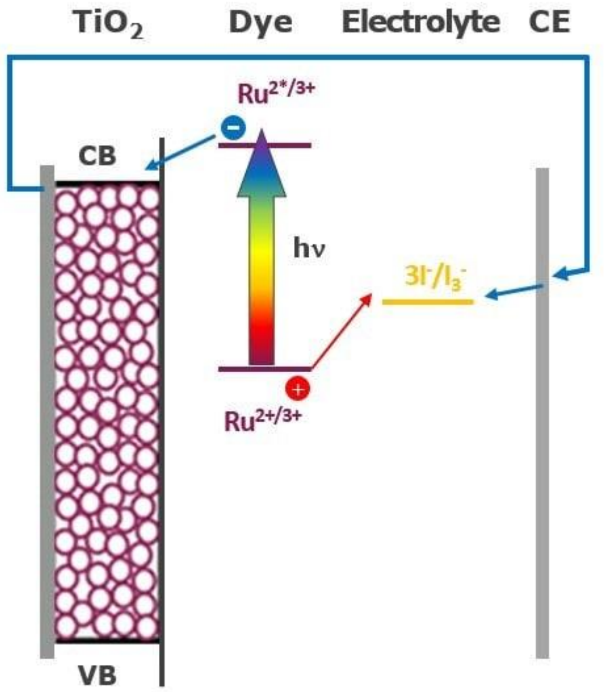
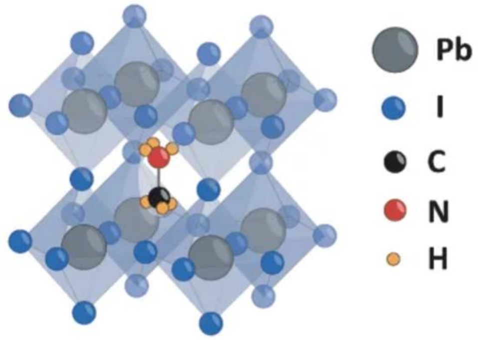


Figure 4: Schematic of electron pathway in a DSC system[14]

Perovskite Solar Cells:

During DSSC research the researchers found a certain organic dye that was possibly very interesting for solar cell research in “hybrid inorganic-organic perovskite” materials. Perovskite materials shown in the below figure are composed of a specific structure with metal centers and organic molecules.



Perovskite materials emerged as interesting single junction candidates for solar cells due to research which found them having unique characteristics such as facile synthesis and excellent optoelectronic properties including long carrier diffusion length, high carrier mobility, low trap density and tunable absorption edge ranging from UV to near infra-red, offering potential for applications in solar cells.

Work is in progress for exploring many different materials that have diverse applications due to unique characteristics like a high adsorption coefficient, long carrier separation transport, larger distance between electrons and holes, and the capacity to be tuned to absorb different solar spectrums. [15]

The working of perovskite solar power is based on the photons in the solar light hitting the perovskite absorber layer, exciting and freeing electrons, creating an electron hole from which the electrons move towards the hole transporting layer, towards the conductor, powering the load.

This means that they are very promising as solar cell materials because of the above reasons and they are easy to synthesize as they are prepared via solution that can be easily applied on a surface with a spin coat.

The below table summarizes the various solar cells and their cost and working potential.

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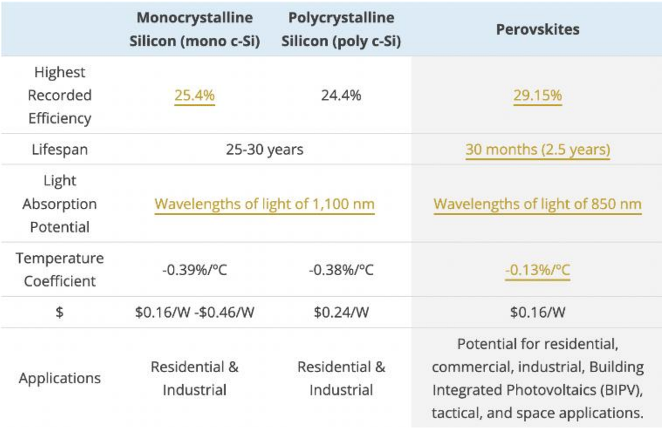
[14] Ruthenium-based dyes for dye-sensitized solar cells, accessed August 29, 2022, https://www.sigmaaldrich.com/IN/en/technical-documents/technical-article/materials-science-and-engineering/photovoltaics-and-solar-cells/dye-solar-cells.

[15] Adeleye says: Lenard Styron says: and Name *, “Perovskite Solar Cells: An in-Depth Guide + Comparisons with Other Techs,” Solar Magazine, May 16, 2022, https://solarmagazine.com/solar-panels/perovskite-solar-cells/.



	Monocrystalline Silicon (mono c-Si)	Polycrystalline Silicon (poly c-Si)	Perovskites
Highest Recorded Efficiency	25.4%	24.4%	29.15%
Lifespan	25-30 years		30 months (2.5 years)
Light Absorption Potential	Wavelengths of light of 1,100 nm		Wavelengths of light of 850 nm
Temperature Coefficient	-0.39%/ºC	-0.38%/ºC	-0.13%/ºC
$	$0.16/W -$0.46/W	$0.24/W	$0.16/W
Applications	Residential & Industrial	Residential & Industrial	Potential for residential, commercial, industrial, Building Integrated Photovoltaics (BIPV), tactical, and space applications.

Perovskite Solar cells advantages and disadvantages

Advantages	Disadvantages
High efficiency – nearly 30% for a single solar cell	Low air stability
Extreme temperature performance	Toxic if used with lead
Low manufacturing cost	
Thin and light	

Conclusion

Keeping in mind that the traditional fossil fuels are going to be exhausted by nearly 2050, the world's dependence on sustainable, green energy is increasing every day. This is evident with the COP22 UN Paris conference that encourages all the countries to increase dependence on renewable sources of energy and decrease CO2 to net zero by 2050 to keep global warming to no more than 1.5 °C. As highlighted in this research, the increase in efficiency, decrease in cost and constant technological innovations in the field of solar cell technology is making sure that the dependence on solar power increases with time. With the help of government subsidies various countries can put in place a target of more that 50% green renewable energy. Even in a developing country like India, the green bank which finances green energy project at a subsidized rate is helping India to reach its net zero emission target by 2050.

In the future of solar cells, there is an exciting development by the researchers at the Imperial College London, who have incorporated materials called ferrocenes which improve efficiency and stability. Ferrocenes are compounds with iron at their center surrounded by sandwiching rings of carbon. This allows electrons to move freely from the perovskite layer to subsequent layers, improving the efficiency of converting solar energy to electricity.[16]

Solar cells can also increase their efficiency by implementing light emitting nanoparticles such as quantum dots, gold, or silver nanoparticles and fluorescent nanofibers. These nanoparticles, based on their shape and scale, may absorb various wavelengths and become agitated, releasing the absorbed energy in the form of radiation.

Recently, the researchers at Stanford modified commercially available solar panels to generate a small amount of electricity at night by exploiting a process known as radiative cooling, which relies on the frigid vacuum of space. This new development takes advantage of this radiative cooling to generate a small but notably important amount of energy generation.[17]

The future of solar energy generation as a commercial and efficient source of energy depends on:

1) Economical production cost of solar cell material
2) Improved efficiency of solar cells
3) Addition of technologies that help generate the energy at night with minimum cost addition to the solar panels
4) Flexibility in material so that the panels could be put up in places that are not easily accessible
5) Durability of the solar panels so that they life span can be beyond 25-30 years.

I look forward to an exciting new future of solar cells, with high efficiencies, low costs and flexibility.

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