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From Space to Rooftop: The Story of Solar Cells

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Solar panels are everywhere around us, from satellites, to rooftops, and toys. By converting the sun's energy to usable electricity, they provide a renewable power source without producing any carbon dioxide. Solar panels are therefore critical in helping to limit climate change and contributing to society's transition to a low carbon future. But how were they invented and what is the physics that makes them work?

The science of solar panels: the photoelectric effect

Solar panels are composed of modules of solar cells wired together. These solar cells convert light energy to electrical energy exploiting a phenomenon called the photoelectric effect. When light hits a material, some of it is absorbed by the material and electrons are then emitted (Figure 1).[1,2,3]

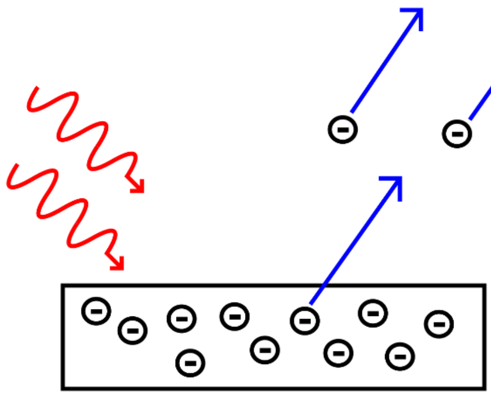

Figure 1. Light comes in on the left (in red), and gives the electrons energy, which enables them to escape on the right (in blue). Source: Khan Academy, n.d.

How we came to understand the photoelectric effect

In 1839, as a teenager working in his father's laboratory, Edmond Becquerel found that shining light on metal electrodes in an electrolyte solution caused a current to flow,[4] although he was unable to explain the effect. This was the first report of light producing an electrical current.[5]

In 1887, German physicist Heinrich Hertz shone ultraviolet light on two metal electrodes with a voltage between them, discovering that the light altered the voltage at which sparking occurred.[6] His student, Philipp Lenard, illuminated thin metal foil and produced "cathode rays," or electrons.[7] Lenard showed that the intensity of the light had no effect on the energy of ejected electrons, and that electrons were not ejected below a threshold frequency of light, regardless of the light's intensity. The wave theory of light, which was the accepted theory at the time, could not explain this behaviour. Lenard won the 1905 Nobel Prize in Physics for these discoveries.[8] That same year, Einstein proposed light was made up of particles with a defined energy, called photons. This explained the photoelectric effect[9] and earned him the 1921 Nobel Prize in Physics.[10]

Einstein proposed that the number of electrons emitted from the material depends on the number of photons hitting it, the light intensity. The energy of the emitted electrons depends on the energy of the incoming photons, which is proportional to their frequency, as explained by Planck's equation, $E = hf$, in which E is energy, h is Planck's constant and f is frequency.[11,12] Electrons are held in a material by a force of attraction. When a photon hits the material,

[1] (Reith-Banks & Harbord, 2015)
[2] (Khan Academy, n.d.)
[3] (Knier, 2002)
[4] (Knier, 2002)
[5] (Chodos, 2009)
[6] (The Editors of Encyclopaedia Britannica, 2018)
[7] (Nobelprize.org, 2018)
[8] Ibid
[9] Ibid
[10] (Nobelprize.org, 2014)
[11] (Encyclopedia.com, 2009)
[12] (Ford, 1968)

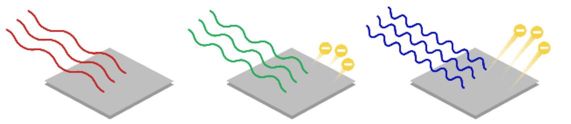

Figure 2. When the energy of the incoming light is too low, no electrons are emitted (left). By increasing the frequency of the light, some electrons are emitted (middle). Light with greater intensity causes electrons with greater energy to be ejected (right). Source: Khan Academy, n.d.

some of the energy absorbed by the electron is used to overcome this force of attraction and escape from the material. The minimum energy needed to eject the electron is called the work function, and this differs between different materials. If the energy of an incoming photon is too low, no electrons will be emitted (Figure 2).[13,14]

The photoelectric effect in solar cells, and the role of semiconductors

To make a solar cell, two key things are needed. The first is a material that exhibits the photoelectric effect, to harvest and convert the light. The second is electrodes, often made of aluminium, to create a circuit and allow the electricity to be used or stored.

Scientists have investigated many possible materials for use in solar cells. The most commonly used is silicon, a semiconductor. Silicon has four valence electrons and forms a continuous lattice structure in which each silicon atom is covalently bonded to neighbouring silicon atoms. Solar cells use silicon that has been doped with other elements, called dopants. Some of the silicon atoms are replaced by trivalent atoms such as boron, to create a P-type semiconductor, which is slightly positively charged. Alternatively, silicon is doped with pentavalent atoms such as antimony to form an N-type (negatively-charged) semiconductor. There is approximately 1 dopant atom for every 5,000,000 silicon atoms.[15] When the P- and N-type semiconductors are placed together, they create a P-N junction (Figure 3). A solar cell can be considered as a large P-N junction with electrodes attached (Figure 4). When light with high enough energy shines on the solar cell, electrons are emitted and a current flows across the P-N junction and through the connecting wires.[16]

Most solar cells have a single P-N junction. Photons with energy levels greater than or equal to the work function of the doped silicon semiconductors are absorbed by the electrons, which are emitted from the material. Photons with insufficient energy levels are not absorbed.

Consequently, only some frequencies of light are converted into electricity, limiting the efficiency of the solar cell. One way to improve the energy efficiency of solar cells is to construct them from multiple layers that each have different work functions, allowing more light to be converted to energy. The top cell captures the high-energy photons and the lower energy photons pass through to cells with successively lower work functions. Multi-junction cells use a silicon wafer and layers of single-junction cells made of substances such as indium-gallium-arsenide and germanium.[17] This increases the efficiency of the solar cell by enabling it to capture a wider range

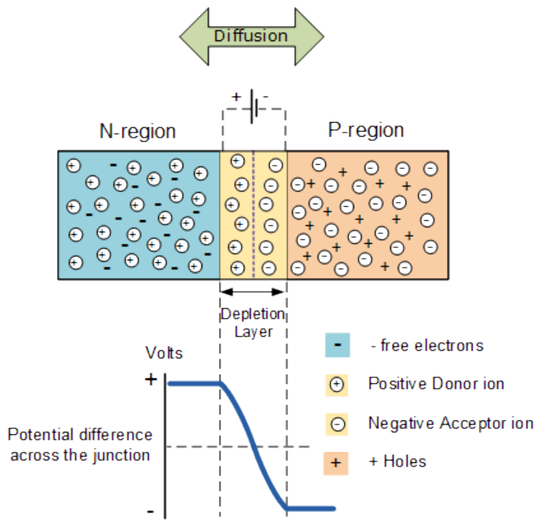

Figure 3. A P-N junction. The N-type region is doped with pentavalent atoms, whereas the P-type region is doped with trivalent atoms. Where the N-type and P-type regions join, there is a flow of free electrons from the N-type region to the P-type region, leaving behind a positive donor ion on the N-type side. This so-called depletion layer therefore has a potential difference across it. Source: Electronics Tutorials, 2018.

13 Ibid
14 (Khan Academy, n.d.)
15 (Sproul, n.d.)
16 (Sproul, n.d.)
17 (da Silva, 2016)

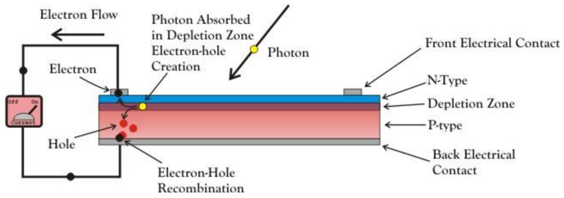

Figure 4. A solar cell is essentially a large P-N junction with electrodes attached to create a circuit. This figure shows the N-type semiconductor on top and the P-type below, with the depletion zone in between. Photons are absorbed by the material and cause electrons to be emitted, which flow across the depletion zone, creating a current. Source: Images SI, 2018.

of frequencies of the spectrum. Multi-junction cells developed by NASA, the University of New South Wales and by French and German scientists are some of the most efficient cells available, with efficiencies of 34-46% (Figure 5).[18]

The development of solar panels

In 1954, scientists at Bell Laboratories in the US built the first practical silicon solar cell, which they called a solar battery.[19] It was prohibitively expensive to produce and highly inefficient, and so remained a curiosity.

Nevertheless, this marked a turning point in the history of solar cells, and many improvements were made within a short time. By the late 1950s, the space industry developed the technology further and reduced the cost, in search of a method of powering satellites in space.[20] The first solar-powered satellite, Vanguard 1, was launched in 1958 (see box).[21] Solar panels were not used much on Earth, until an energy crisis in the 1970s, caused by fossil fuel limitations, meant that photovoltaics gained recognition. As climate change has accelerated, the focus on renewable energy has increased, and now, approximately 16.5% of Australian homes have solar panels.[22] In 2016, 17.3% of Australia's energy generation was renewable, of which 18.3% was from solar panels.[23] South Australia's renewable power generation was much higher, with 48% of all power generated being from renewable energy.[24] As well as changing the way we procure our energy, the development of cheap solar panels has created jobs[25] in manufacturing, such as at Tindo Solar in Adelaide,[26] and in the installation of panels.

Solar in Space

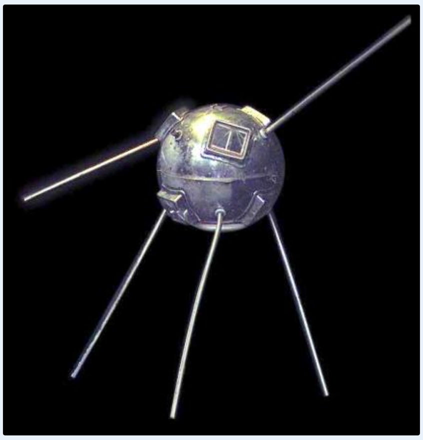

Figure 6. The Vanguard TV-3 satellite, which was identical to Vanguard 1, but its rocket failed to launch successfully and it crashed to earth, damaging the aerials, as shown in the photograph. This satellite is on display at the Smithsonian Air and Space Museum. Source: NASA, n.d.

Vanguard 1 spacecraft was a 1.46 kg aluminium sphere with a diameter of 16.5 cm. Its beacon transmitter was powered by 6 square silicon solar cells that produced a total of about 1 W with 10% efficiency at 28°C Today, the International Space Station has arrays of 262,400 solar cells that cover an area of 2500 m² and generate 84 - 120 kW of electricity – enough to power 40 homes, and 120,000 times more than the solar cells on Vanguard 1

International interdisciplinary collaboration

The development of solar cells and understanding the physics of how they work demonstrates the international nature of science, its unpredictability, and the roles of theoretical and experimental physicists working with

[18] (Fraunhofer ISE, 2014)
[19] (Chodos, 2009)
[20] (Knier, 2002)
[21] (NASA, n.d.)
[22] (Bruce & MacGill, 2016)
[23] (Clean Energy Council, 2016a)
[24] (Clean Energy Council, 2016b)
[25] (Clean Energy Council, 2016a)
[26] (Tindo Solar, 2018)

chemists and engineers in academia, private institutes, government agencies and industry (Figure 5).

Although the first solar cells developed by Bell Laboratories were too expensive and inefficient for commercial use, their subsequent development by NASA for use in space resulted in cells that were more efficient and cheap. This is just one of many examples of research initially undertaken for space and defence use that has had important practical applications for domestic and commercial use; other examples include the development of microwave ovens, the internet, and global positioning systems (GPS).[27]

As climate change makes the need to transition to renewable energy sources even more urgent, solar cell research continues around the world in a variety of institutions and businesses, such as Australia[28] and overseas.

Conclusion

When Edmond Becquerel first measured a weak current in his electrolyte solution as it was exposed to light, he could little have imagined that this effect would become the basis for an industry that powers homes, businesses and transport on earth and in space, shed light on the particle nature of light, and contribute to the development of entirely new fields of research in solid state physics and nanotechnology.

[27] (Lange, 2016)

[28] (Flinders Centre for NanoScale Science & Technology, 2018)

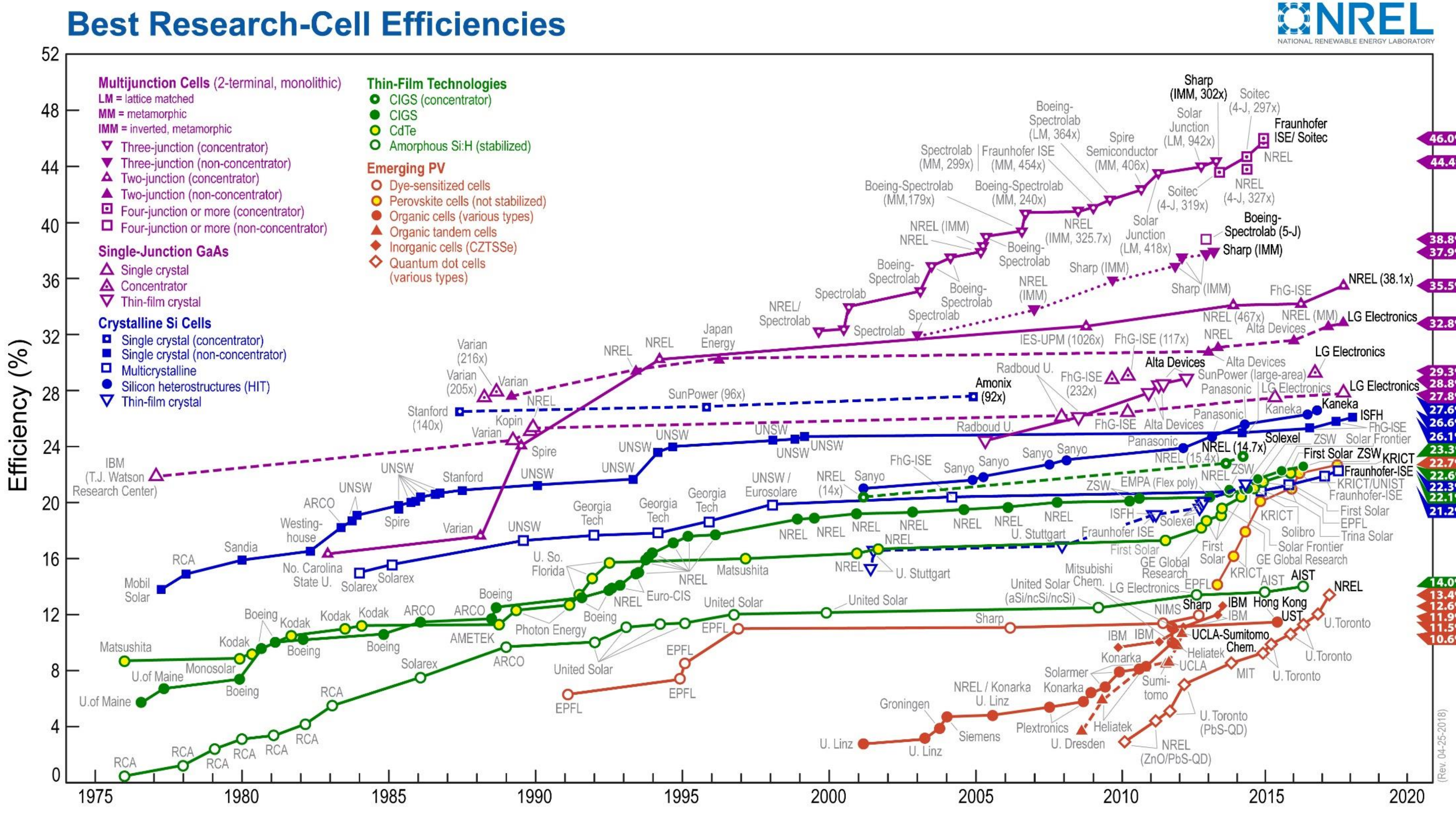

Figure 5. Types and efficiencies of solar cells from 1975 to the present. The graph shows the different solar cell technologies in different colours, and also shows the huge number of different groups involved in solar cell research. Each dot represents a new development in solar cell technology by a particular research group. The most commonly used solar cells in domestic situations (shown in blue) have gone from around 14% efficiency to 27.6% efficiency. Source: Levi, n.d.

Bibliography

Bruce, A., & MacGill, I. (2016, March 28). FactCheck Q&A: is Australia the world leader in household solar power? Retrieved May 19, 2018, from http://theconversation.com/factcheck-qanda-is-australia-the-world-leader-in-household-solar-power-56670

Chodos, A. (2009, April). This Month in Physics History: April 25, 1954: Bell Labs Demonstrates the First Practical Silicon Solar Cell. Retrieved May 19, 2018, from https://www.aps.org/publications/apsnews/200904/physicshistory.cfm

Clean Energy Council. (2016a). Clean Energy Australia Report. Retrieved May 19, 2018, from https://www.cleanenergycouncil.org.au/policy-advocacy/reports/clean-energy-australia-report.html

Clean Energy Council. (2016b). Clean Energy Australia Report 2016. Clean Energy Council.

da Silva, W. (2016, May 17). Milestone in solar cell efficiency by UNSW engineers. Retrieved May 19, 2018, from https://newsroom.unsw.edu.au/news/science-tech/milestone-solar-cell-efficiency-unsw-engineers

Electronics Tutorials. (2018). PN Junction Theory. Retrieved May 19, 2018, from https://www.electronics-tutorials.ws/diode/diode_2.html

Encyclopedia.com. (2009). Physics: The Quantum Hypothesis. Retrieved May 24, 2018, from https://www.encyclopedia.com/science/science-magazines/physics-quantum-hypothesis

Flinders Centre for NanoScale Science & Technology. (2018, May 16). Energy. Retrieved May 19, 2018, from http://www.flinders.edu.au/

Ford, K. W. (1968). Basic Physics. Waltham, Massachusetts, USA: Blaisdell Publishing Company.

Fraunhofer ISE. (2014, December 1). New world record for solar cell efficiency at 46%. Retrieved May 19, 2018, from https://web.archive.org/web/20150823133519/http://www.ise.fraunhofer.de/en/press-and-media/press-releases/press-releases-2014/new-world-record-for-solar-cell-efficiency-at-46-percent

Garcia, M. (2017, August 4). About the Space Station Solar Arrays. Retrieved May 19, 2018, from http://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays-about.html

Images SI. (2018). How Photovoltaic Cells Generate Electricity. Retrieved May 19, 2018, from https://www.imagesco.com/articles/photovoltaic/photovoltaic-pg4.html

Khan Academy. (n.d.). Photoelectric effect. Retrieved May 19, 2018, from https://www.khanacademy.org/science/physics/quantum-physics/photons/a/photoelectric-effect

Knier, G. (2002). How do Photovoltaics Work? Retrieved May 19, 2018, from https://science.nasa.gov/science-news/science-at-nasa/2002/solarcells

Lal, N. (2016, August 20). Solar cells: How they work and the future of sunshine. Retrieved May 19, 2018, from http://www.abc.net.au/news/science/2016-08-20/solar-energy-and-panels-explained/7763474

Lange, K. (2016, March 1). 6 Technologies You Use All the Time, Thanks to the DoD. Retrieved May 24, 2018, from http://www.dodlive.mil/2016/03/01/6-technologies-you-use-all-the-time-thanks-to-the-dod/

Levi, D. (n.d.). Solar cell efficiency - Wikipedia. Golden, CO: National Renewable Energy Laboratory. Retrieved from https://commons.wikimedia.org/w/index.php?curid=68576376

NASA. (n.d.). Vanguard 1. Retrieved May 19, 2018, from https://nssdc.gsfc.nasa.gov/nmc/spacecraftDisplay.do?id=1958-002B

Nobelprize.org. (2014). The Nobel Prize in Physics 1921. Retrieved May 19, 2018, from https://www.nobelprize.org/nobel_prizes/physics/laureates/1921/

Nobelprize.org. (2018). The Quantised World. Retrieved May 19, 2018, from https://www.nobelprize.org/educational/physics/quantised_world/waves-particles-1.html

Reith-Banks, T., & Harbord, J. (2015, June 17). Science vine: how do solar panels work? Retrieved May 19, 2018, from http://www.theguardian.com/science/blog/2015/jun/17/science-vine-how-do-solar-panels-work

Sproul, A. (n.d.). Understanding the p-n junction. Retrieved from http://www2.pv.unsw.edu.au/nsite-files/pdfs/UNSW_Understanding_the_p-n_Junction.pdf

Stauffer, N. W. (2017, July 31). Novel technique using graphene to create solar cells. Retrieved May 19, 2018, from https://phys.org/news/2017-07-technique-graphene-solar-cells.html

The Editors of Encyclopaedia Britannica. (2018, January 19). Photoelectric effect. Retrieved May 19, 2018, from https://www.britannica.com/science/photoelectric-effect

Tindo Solar. (2018). Home. Retrieved May 24, 2018, from http://www.tindosolar.com.au/

Universitas Bergensis. (n.d.). Energy Primer: 3.2 Semiconductor physics. Retrieved May 19, 2018, from https://mitt.uib.no/courses/4050/pages/3-dot-2-semiconductor-physics