Photovoltaic Technologies & Trends

Solar Electricity and Solar Cells in Theory and in Practice

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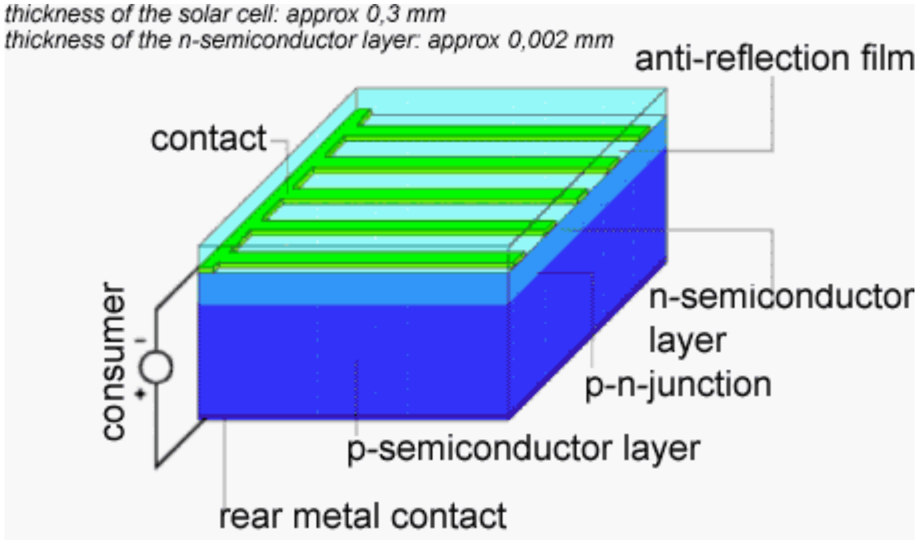
The word **Photovoltaic** is a combination of the Greek word for Light and the name of the an Italian physicist known especially for the invention of the battery in 1800 – Allesandro *Volta*. The term photovoltaic means the direct conversion of sunlight into electrical energy by means of solar cells. The conversion process is based on the photoelectric effect which was discovered by Alexander Bequerel in 1839. The photoelectric effect describes the release of positive and negative charge carriers in a solid state device when light strikes its surface.

How Does a Solar Cell Work?

Solar cells are composed of various semiconducting materials. With respect to the photovoltaic process, semiconductors are materials that become electrically conductive when light or heat are applied, but which would normally operate as insulators. So, they conduct electricity selectively, thus the term semi-conductors. Semiconductors are used widely in all kinds of electronics, but the type of semiconductors used for energy production from the sun are created differently from those used for computer CPU chips, memory chips, and the like.

Over 95 percent of all the solar cells produced worldwide are currently composed of the semiconductor material Silicon (Si). As the second most abundant element in earth`s crust (at 28%, with Oxygen being the most abundant at 47%), silicon has the advantage of being readily available in sufficient quantities at relatively low cost. As an additional advantage, processing the material to manufacture silicon wafers does not significantly burden our environment, nor do we have any concerns about disposal of any "waste" silicon since it exists in sand and most types of rock worldwide.

To produce a solar cell, the raw silicon semiconductor material is contaminated or "doped" in a specific manner. "Doping" is the intentional introduction of chemical elements, which allow for the production of a surplus of either positive charge carriers (*p*-conducting semiconductor layer) or negative charge carriers (*n*-conducting semiconductor layer) from the generic semiconductor material. If two differently contaminated semiconductor layers are combined in a "sandwich" of layers, then a so-called *p-n junction* results along the boundary between the layers.

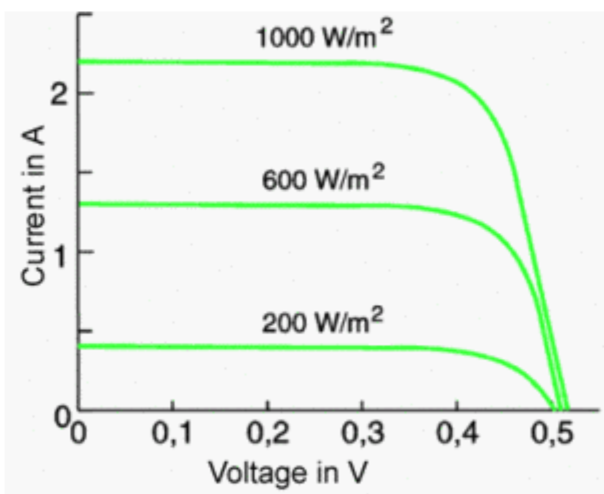


Model of a crystalline silicon solar cell

When light strikes the silicon photovoltaic cell, an interior electric field is built up along the p-n junction, which leads to the separation of the charge carriers that are released by light. Through metal contacts, an electric voltage differential can be tapped. If the outer circuit is closed, meaning a load that can consume the power is connected, a direct current will flow.

Typical silicon photovoltaic solar cells are approximately 10 cm by 10 cm in size (recently also 15 cm by 15 cm). A transparent anti-reflection film protects the surface of the cell, while also decreasing reflective losses from the cell surface.

Characteristics of a Solar Cell



current-voltage line of a si-solar cell

The usable voltage from solar cells depends on the specific semiconductor material used. In the case of silicon, the voltage generated is typically about 0.5 V per cell. Terminal voltage is only weakly dependent on light radiation, whereas the potential current generated increases directly with higher solar radiance striking the cell. A 100 cm^2 silicon cell, for example, reaches a maximum current intensity of approximately 2A when radiated by 1000 W/m^2.

The output power (which is the product of current and voltage) of a solar cell is temperature dependent. Higher cell temperatures lead to lower output, and hence to lower efficiency. The level of efficiency of a cell indicates how much of the radiated quantity of light striking the cell will be converted into useable electrical energy.

Different Cell Types

There are three common types of silicon photovoltaic solar cells, categorized according to the type of crystal utilized: monocrystalline, polycrystalline and amorphous. To produce a monocrystalline silicon cell, absolutely pure semiconducting material is necessary. Monocrystalline rods are extracted from melted silicon and then sawed into thin plates. This production process guarantees a relatively high level of efficiency.

The production of polycrystalline cells is more cost-efficient. In this process, liquid silicon is poured into blocks that are subsequently sawed into plates. During solidification of the material, crystal structures of varying sizes are formed, at whose borders defects emerge. As a result of these internal crystal defects, the polycrystalline solar cell is slightly less efficient.

If a silicon film is deposited on glass or another substrate material, this is a so-called amorphous or thin-layer cell. The layer thickness amounts to less than 1µm (thickness of a human hair: 50-100 µm), so the production costs are lower due to the low material costs. However, the efficiency of amorphous cells is much lower than that of the other two cell types. Because of this, they are primarily used in low power equipment (watches, pocket calculators) or as façade elements.

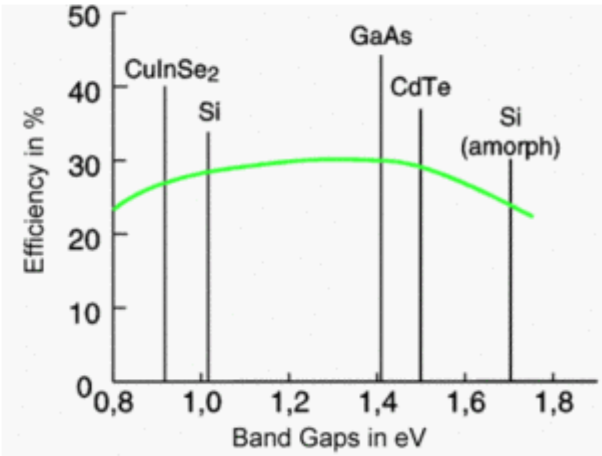
Material	**Level of efficiency in % Lab**	**Level of efficiency in % Production**
Monocrystalline Silicon	approx. 24	14 to 18
Polycrystalline Silicon	approx. 18	13 to 16
Amorphous Silicon	approx. 13	5 to 7

From the Cell to the Module

In order to make the appropriate voltages and outputs available for different applications, individual solar cells are interconnected to form larger units. Groups of cells connected in series deliver a higher voltage, while those connected in parallel produce more electric current. The interconnected solar cells are usually embedded in transparent Ethyl-Vinyl-Acetate, fitted with an aluminum or stainless steel frame and covered with transparent glass on the front side.

The typical power ratings of such solar modules range between 10 Wpeak and over 300Wpeak. The characteristic data refer to the standard test conditions (STC) of 1000 W/m^2 solar radiation at a cell temperature of 25° Celsius. The manufacturer's standard warranty is typically 6 years for manufacturing defects, coupled with an energy production warranty of 10-25 years, which is quite long and shows the high quality standards and life expectancy of today's products.

Natural Limits of Efficiency



Theoretical maximum levels of efficiency of various solar cells at standard conditions

In addition to the efforts being made to optimize manufacturing production processes, work is also being done to increase the level of cell efficiency, in order to lower the costs of solar cells for a given level of energy output.

However, different loss mechanisms result in limits on how far these plans can progress in achieving increasingly higher efficiencies from solar cells. Basically, different semiconductor materials or combinations are suited only for absorption of and energy production from specific spectral ranges or "band gaps" within the overall light spectrum. Therefore, only a specific portion of the overall radiant energy can be used, because the light quanta (photons) for the areas of the spectrum outside a given band don't have enough energy to "activate" the charge carriers.

At the same time, a certain amount of *surplus* photon energy is transformed into heat rather than into electrical energy, which amounts to further losses in efficiency. In addition, there are optical losses, such as the shadowing of the cell surface through contact with the glass surface or reflection of incoming rays on the cell surface, and shadowing losses related to the connecting wires that cover small areas of the cells themselves. Other loss mechanisms are electrical resistance losses in the semiconductor and the connecting wires and cable. The disrupting influence of material contamination, surface effects and crystal defects, are also significant.

Single loss mechanisms (photons with too little energy are not absorbed, surplus photon energy is transformed into heat) cannot be further improved because of inherent physical limits imposed by the materials themselves. This leads to a *theoretical* maximum level of efficiency, e.g. approximately 28% for a single layer crystal silicon solar cell.

New Directions – What's Being Done To Drive Higher Efficiencies

Surface structuring to reduce reflection loss: for example, construction of the cell surface in a pyramid structure, so that incoming light hits the surface several times.

New materials: for example, gallium arsenide (GaAs), cadmium telluride (CdTe) or copper indium selenide ($CuInSe^2$). One of the challenges with these materials is that they are generally less friendly to the environment, not only in their production, but also in terms of waste disposal issues. Further, these materials (e.g. Gallium, Tellurium, Indium, etc.) are not nearly as readily available as silicon. For broad scale use of them in cell manufacturing to occur, greater availability will need to exist. NOTE: Some of these materials are also being used to develop *thin-film* solar cells. These typically have substantially lower efficiencies than traditional crystalline silicon PV cells. However, the thin film configuration provides benefits in situations such as commercial building-integrated photovoltaic (BIPV) solar solutions, where there are very large areas available on which to apply PV solar modules. In such situations, the lower efficiencies of thin-film modules can be traded for lower costs, more modules can be installed to make up the difference (since the available area is not constrained), and the result may be superior overall production. Research to enhance thin-film PV technologies is on-going, but thus far most thin-film technologies have not met market expectations, either in terms of improved efficiencies or reduced costs.

Tandem or stacked cells: in order to be able to use a wide spectrum of radiation, different semiconductor materials, which are specially suited for different spectral ranges, are arranged one on top of the other in a sandwich structure. These materials (including those mentioned above), used in conjunction with silicon, can yield multi-layer cells that yield greater overall energy production, because each material can be optimized to respond to photons with different levels of energy. Thus, more light energy is captured per cell area, with less being wasted.

Concentrator cells: In concentrating solar applications, a higher light intensity is focused on the solar cells through the use of a mirror and lens systems. Such systems typically track the sun, always using direct radiation. The use of a tracking system also results in the equivalent of more "peak sun" hours for a given geographical location.

MIS Inversion Layer cells: in such cells, the inner electrical field is not produced by a p-n junction, but by the junction of a thin oxide layer adjacent to a semiconductor. This has potential for additional research and development efforts.

Grätzel cells: Electrochemical liquid cells where titanium dioxide is used as an electrolyte together with dye to improve light absorption by the cell. Again, further research may yield advances in this area.

Space Utilization – A Different Market

Sometimes we read about new breakthroughs in PV cell efficiencies – discoveries that would appear to break the laws of physics, as have been outlined above. However, in these cases, nothing has actually changed with respect to the laws of physics, or to cause them to no longer apply. Rather, in certain special applications (such as for PV cells integrated in communication satellites, and on other vehicles designed to operate in space), things are a bit different.

For one thing, Solar energy reaching Earth's orbit is roughly 144% of the maximum we find striking the surface of Earth, and that energy includes wavelengths of light that don't even reach the earth's surface due to absorption by our atmosphere. So, solar cells designed to operate in space need to work in a very different environment.

When a satellite is crafted, the solar cells that are used to power it are created at a cost that's possibly tens or hundreds of times what people would pay for a solar cell designed to produce energy terrestrially. In space, there's no other energy source that scientists can plug into. So, if a satellite is to operate autonomously for many years, it must have a reliable, highly efficient power system that can leverage sunlight consistently for the life of its host.

If the individual cells required to perform that task end up costing thousands of dollars each, that cost would still be a small percentage of the entire satellite cost, not to mention the launch costs and other expenses involved in getting it into orbit. Once it's in orbit, it can begin to deliver value, and those who invested in its manufacture and launch are counting on it performing that set of functions for many years.

Thus, the use of combinations of precious materials, unique structural formats, and painstaking assembly methods to hand-craft the solar cells used in spacecraft are certainly worth the effort. And not surprisingly, the efficiencies of such cells (currently just over 35%) are substantially greater than those we're able to mass produce for use on the earth's surface. But even the cells that orbit our planet in space don't defy the laws of physics...they just more closely approach the limits of what's possible according to those laws. Over time, some of the best practices and learnings that come from our space program make their way into mainstream manufacturing. Whenever that occurs with solar cell technology, we may gain a small benefit in increased PV cell efficiency.