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Solar cells

Turning sunlight into electricity

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Every minute enough sunlight strikes the Earth to power our civilisation for a year, yet less than 1% of global energy generation is provided by solar energy. Solar cells convert sunshine directly to electricity, but to make them more attractive they have to perform at higher efficiencies and lower costs. Physicists around the world are working on a myriad of new technologies so that in the future we will be able to harness the Sun's energy on a scale that matches its potential. Ben Browne, Jessica Adams and Rahul Bose take you on a tour of these exciting technologies.

Energy from the Sun

Sunlight may appear yellow, but in fact the solar spectrum is made up of a broad range of colours. As well as the visible colours that the human eye can detect, sunlight is also made up of ultraviolet (UV) and infrared (IR) light. More energy is contained in the sunlight that hits the Earth's surface in an hour than is used by humans in a year!

You may be used to thinking of light as a wave, but it can also be thought of as a particle. We call particles of light photons, and each photon can be classified according to its energy. IR photons are low energy, UV photons are high energy, and visible photons have an intermediate energy.

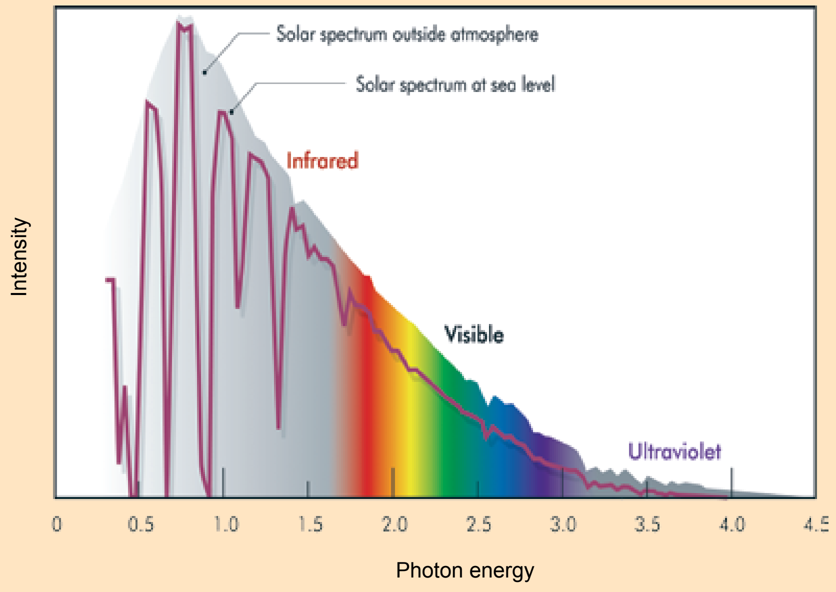
How a solar cell works

When sunlight hits a solar cell, it can be absorbed. The energy of the photons can knock loose electrons from their host atoms such that they can move freely within the material. These free electrons can be made to flow round an external circuit. A flow of electrons is an electric current, and the energy carried by each electron determines the voltage. The electrons in the circuit can be made to do electrical work, such as charging a mobile phone.

In physics terminology, the field of solar cell research is known as **photovoltaics**. This word comes from the Greek *photo*, meaning light, and the name of Alessandro Volta who performed pioneering research into our understanding of electricity.

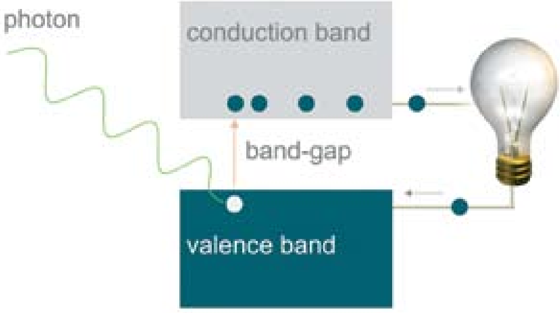
Solar cells are typically made from a group of materials called **semiconductors**. As the name suggests, a semiconductor has electrical properties halfway between those of insulators and those of conductors. In an insulator, such as rubber, all electrons are bound to the atoms and are said to be in the "valence band". In a conductor, such as a metal, there are many electrons that are free to move across the material, and these are said to be in the "conduction band". A material only conducts when electrons can move within it. A semiconductor acts as an insulator unless enough energy is injected, for instance through the absorption of photons, to allow electrons to jump up from the valence to the conduction band. The energy imparted to each electron has to be large enough to bridge the **band-gap**. This band-gap energy varies between different materials.

Box 1: Sunlight



The Sun emits light from its surface, which is at a temperature of nearly 6000 kelvin. The light we receive on the Earth's surface is much less intense that at the Sun's surface and is almost parallel due to the large distance to the Sun. Certain parts of the spectrum are also absorbed in the Earth's atmosphere. On a sunny day at noon with the Sun directly overhead, the intensity of sunlight is about 1000 watts per square metre. This means that a square metre of 20% efficient solar cells, for instance, would generate a power of 200 W at peak hours.

The spectrum of light from the Sun is made up of photons covering a broad range of energies. Besides the visible spectrum with which we are familiar, the Sun also emits light in the infrared and ultraviolet energy ranges.



An electron is freed from its atom when it absorbs a photon with enough energy. It can then move within the conduction band and perform useful electrical work in a circuit – lighting a bulb, for example.

If the incoming photon has an energy that is lower than that of the band-gap, it will not be able to free an electron and the light will simply pass through as though the solar cell were transparent. If the photon has a greater energy than is necessary to free the electron, the extra energy will be wasted as heat. The solar cell efficiency is the ratio of power produced by the solar cell to the power of the incident sunlight. Because the solar spectrum consists of photons with a broad range of energies, a solar cell can never be 100 % efficient at converting all the energy contained in sunlight into useful electrical energy.

The efficiency of a solar cell depends strongly on its band-gap. A cell with a low band-gap can absorb a lot of light, but this comes at the cost of producing only a low voltage. A high band-gap on the other hand leads to a high voltage but a small current since only a small high energetic component of the solar spectrum can be absorbed. There is an ideal band-gap energy that strikes the right balance, and in theory an efficiency of 31% is possible with a simple solar cell. In practice one has to find or engineer materials with suitable properties.

Solar cell technologies

The first practical solar cells were invented in 1954 in the Bell Laboratories where a 6% efficient silicon cell was made, referred to then as a 'solar battery'. Initially solar cells were mainly used to power satellites, and until recently the silicon used to make common cells was taken from offshoots from computer chip manufacturers.

Silicon

The most common type of solar cell is made from crystalline silicon. These are the type that you may have seen on rooftops. Silicon is found as its oxide, silica, which is the most abundant material in the Earth's crust. However, to make a solar cell, the silicon needs to contain no more than a few impurity atoms for every million silicon atoms and these atoms must then be neatly arranged into regular crystal structures millions of atoms thick.

A crystalline silicon solar module

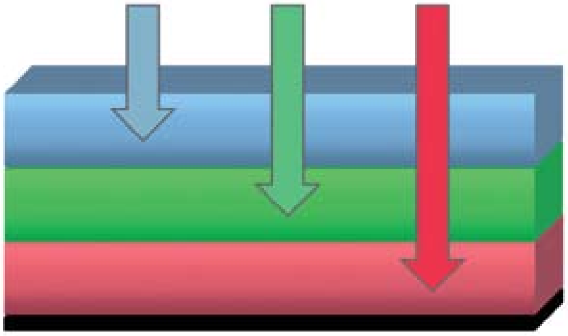
Thin film

There are several technologies which are cheaper to manufacture per square metre than silicon and which are becoming more common. The solar cells sometimes incorporated into calculators are an example of these. These types of solar cells are referred to as 'thin film' because they are deposited in a very thin layer, a few microns thick – hundreds of times thinner than crystalline silicon solar cells. They work because they use 'direct band-gap' semiconductors, which absorb light very strongly. These devices are only around half as efficient as crystalline silicon but may still prove cheaper to produce per unit of rated power because they can be deposited quickly and with less energy onto cheap materials like glass, plastic and metal. One relatively recent approach, still confined primarily to laboratories, is to make thin film cells out of plastics.

A lab sized thin film solar cell

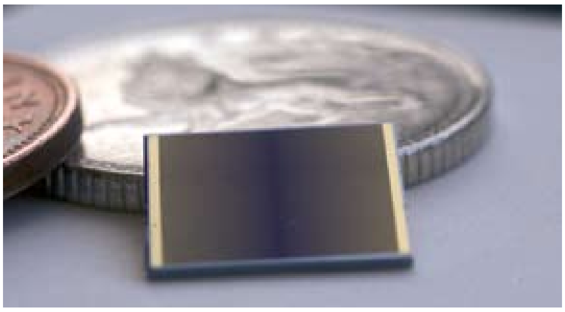
Multijunction

At Imperial College London, we are working on a way to make better use of the broad solar spectrum by stacking two or more solar cells of different band-gaps. This type of solar cell is called a multijunction cell, and to date the highest recorded efficiencies of over 40% have been achieved with designs that use three sub-cells. The order of the band-gaps in the stack is crucial. The first (top) cell in the stack has the highest band-gap and therefore absorbs only the high energy photons. Photons with lower energy travel straight through this cell and are absorbed by the next cells, which have successively lower band-gaps. In general, the more sub-cells included in the stack, the higher the achievable efficiency.



Multijunction solar cells use sub-cells with different band-gaps to absorb and convert different parts of the solar spectrum. The highest energy photons (blue light) are absorbed in the top layer while the lower energy photons pass through to be absorbed in lower layers. This method yields much higher efficiencies than simple solar cells.

The theoretical efficiency limit under normal solar illumination for this design is 68%, when the stack has a large number of sub-cells. One of the main challenges lies in developing materials with the right band-gaps. Multi-junction cells are also made of direct-gap semiconductors using exotic elements such as gallium, arsenic, germanium, phosphorus and indium rather than silicon. Besides the multijunction solar cell, several other advanced concepts are being researched at Imperial and elsewhere that could push the limits of photovoltaic conversion efficiency closer to the theoretical limit.



One of the high efficiency solar cells under development at Imperial College London. Because these cells are designed for concentrated sunlight they have areas from only 1 mm^2 to 1 cm^2.

Box 2: Solar cell efficiencies

The first practical solar cells, invented more than half a century ago, had an efficiency of 6%, meaning that 6% of the power from incident light was converted into electrical power. Today, typical silicon solar cells achieve efficiencies between 15% and 20%, while the cheaper thin film cells are around 10%. Concentrator cells have significantly higher efficiencies, generally achieving 35% and above. However cells that are currently being developed in laboratories around the world are several years ahead of what we see on the market, with top efficiencies exceeding 40%. This is higher than a typical power plant or a car engine.

Compared to fuel-burning power plants, photovoltaics is a very young technology, and while the former are already operating very close to their theoretical optimum, photovoltaics still has a lot of untapped potential as its theoretical efficiency limit lies at 87%.

Solar concentration

The Sun's rays can be concentrated directly onto a solar cell using lenses and mirrors. This method is called concentrator photovoltaics and has advantages over conventional photovoltaics. The bulk of the relatively expensive solar cell material can be replaced with inexpensive lenses or mirrors. Typical solar concentrators focus several hundred times the intensity of normal sunlight onto the cells. Moreover, an increase of efficiency is achieved through concentration. If we increase the light concentration by a factor of 100, the electric current produced by the solar cells increases by 100, but at the same time the voltage increases as well. Consequently, the electrical power and the efficiency are increased. Under concentration a simple solar cell can in theory reach 40% efficiency and multijunction cell 87%.

A solar concentrator like this one in Australia has a photovoltaic cell at the focus of the reflector dish. It uses direct sunlight and needs to track the Sun over the course of the day. To be cost-effective, these systems are usually quite large and are built in areas with a lot of sunshine, such as Spain.

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Look here!

More about our work on nanostructures in high efficiency solar cells: *www.imperial.ac.uk/quantumphotovoltaics*

Detailed explanations of photovoltaic technology: *http://pvcdrom.pveducation.org*

Solar Systems is an Australian company manufacturing concentrator photovoltaic systems: *http://www.solarsystems.com.au/projects.html*