Quantum Physics, Semiconductors and Solar Cells

by **Professor Martin Green**

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Power to the People: Sunlight to Electricity Using Solar Cells

To understand how a solar cell produces electricity from sunlight, we must briefly touch base with some of the most exciting developments in both science and technology over the last century. To start, we need to go back to the beginning of the 20th century to the birth of quantum physics. We then jump 50 years to the early days of microelectronics.

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Einstein's Light Quanta

Light is everywhere we look - it is no wonder the greatest minds in history have tried to understand exactly what it is! Isaac Newton (1642-1727), one of the giants of science, made great leaps forward in the study of light and its properties. He thought of light as a stream of tiny particles like miniature billiard balls. Experiments in the 18th and 19th centuries showed that this had to be wrong - light had to act as a wave like ripples on a pond. This nicely explained what are known as "interference" effects. These effects cause the band of colours often seen on the surface of soap bubbles or in oil-slicks on the road, and even the colours of the rainbow.

At the beginning of the 20th century, physicists were terribly confused because they couldn't explain the properties of light coming from hot bodies such as the sun. Existing theories predicted that hot bodies should emit far more ultraviolet light. It would be a disaster for us if they did, because the incidence of skin cancers would increase enormously - this had nothing to do with why the problem was known as the "ultraviolet catastrophe", however! Max Planck (1858-1947) showed he could explain nature's actual behaviour if he assumed that changes in energy within the hot body could occur only in small steps known as "quanta". This clue triggered a revolution in 20th century physics.

Albert Einstein (1879-1955) is very well known for his work on relativity. However, he made outstanding contributions to several other areas of physics, including the physics of quanta or "quantum physics". His somewhat overdue Nobel Prize in 1921 was awarded for "his services to theoretical physics and especially for his discovery of the law of the photoelectric effect" - no mention of relativity. The discovery of the "law of the photoelectric effect" involved Einstein's key contribution to quantum physics. Although many consider the neglect of specific mention of relativity in his Nobel Prize award is a travesty of justice, it could be that his work on quantum physics has had a more momentous impact.

In a nutshell, Einstein's contributions in this area are described in the introduction to his 1905 paper on light quanta. Abandoning the classical picture of light as a wave, Einstein proposed that the energy of light was not spread continuously in space but (in English translation) "consists of a finite number of energy quanta localized at points of space that move without dividing, and can be absorbed or generated only as complete units" - back to the corpuscular ideas of Isaac Newton!

Einstein pointed out that the well-known wavelike properties of light did not contradict this corpuscular interpretation. In its effects, light behaves neither as a wave nor a billiard ball, but as something foreign to everyday experience. Following Einstein, we can think of light from the sun coming in tiny packets of energy as shown schematically in Figure 1. These light quanta are now known as "photons".

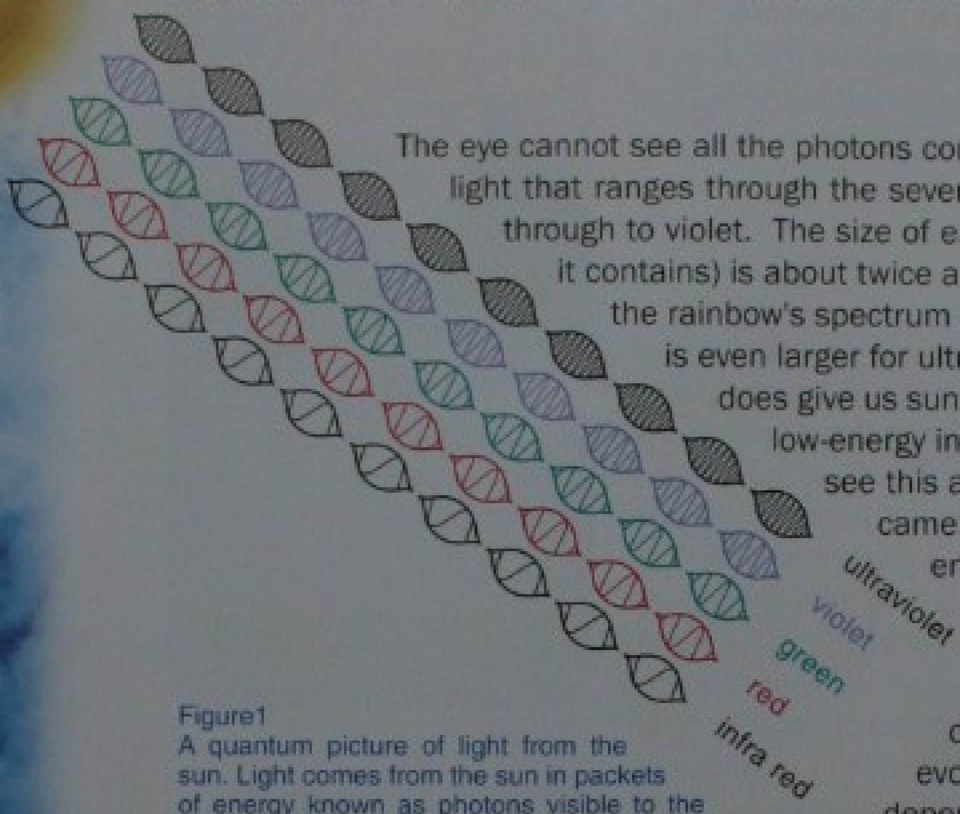

Figure1
A quantum picture of light from the sun. Light comes from the sun in packets of energy known as photons visible to the eye as colours.

The eye cannot see all the photons coming from the sun, but only visible light that ranges through the seven colours of the rainbow, from red through to violet. The size of each packet (in terms of the energy it contains) is about twice as large for light at the violet end of the rainbow's spectrum as at the red end. The packet size is even larger for ultraviolet light, which is the reason it does give us sunburn! Beyond the red light there is low-energy infrared light. Again, the eye cannot see this although devices like "heat-sensing cameras" can! It turns out that most energy from the sun comes at the red and green wavelengths to which our eyes are most sensitive. This is undoubtedly not a complete coincidence - the result of evolution or grand design, or both, depending on your point of view!

The evidence that Einstein called upon to support his light quanta ideas came from the experiments of other scientists studying the photoelectric effect, involving the interaction of light with metal conductors. The closely-related "photovoltaic" effect, on which solar cells are based, involves light interaction with materials known as "semiconductors". These materials have properties in between those of metals, good conductors of electricity, and the opposite extreme of very poor conductors, known as insulators.

Semiconductors

Silicon is the most common semiconductor, underpinning the microelectronics industry, the computer revolution, the information age, and the other rapidly growing areas revolutionized by modern electronics. Silicon has an "atomic number" of 14, which means that an isolated atom of silicon consists of 14 electrons (negatively charged particles) surrounding a dense central nucleus (positively charged core), like a miniature solar system. Ten of these 14 electrons are very tightly bound to this core and are not of any further interest, at least not for solar cells!

One reason why silicon is so important in microelectronics is that its properties can be altered, not only by shining light on it, but also by adding small amounts of impurities. For example, if a small amount of phosphorus is added to the silicon when molten, the solidified silicon will contain phosphorus atoms in some positions where silicon would normally be, as shown in Figure 2(a).

Phosphorus has not four but five electrons not tightly bound to its central core. Four of these are used in the bonds between neighbouring silicon atoms, but the fifth one is at a bit of a loose end! It is only weakly bound to the original phosphorus atom and can be very easily torn away. Once separated, it acts very much the same as an electron released by light absorption.

If a different impurity such as boron, with only three electrons not tightly bound to its core, is introduced in the same way, full bonds will be formed only with three of the neighbouring silicon atoms, as shown in Figure 2(b). Adding boron, or "doping" with boron, is a good way of introducing broken bonds or holes into the semiconductor material!

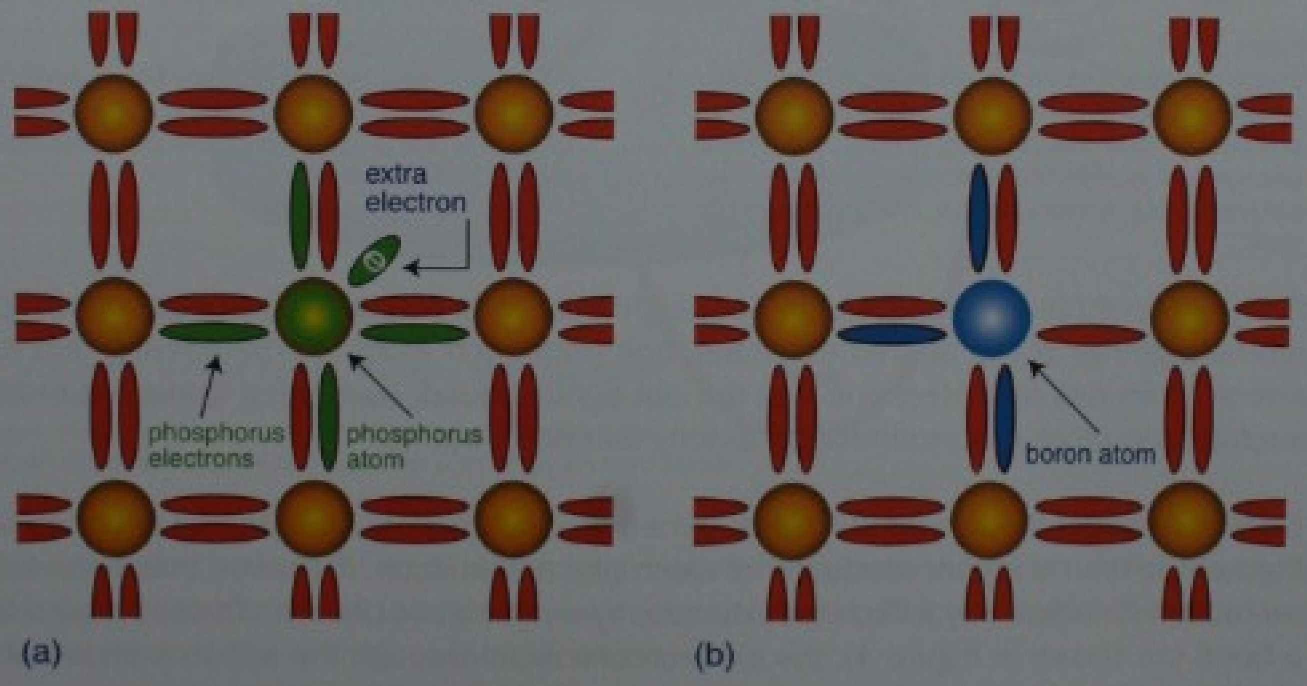

Figure 2

(a) Silicon with small amounts of phosphorous added. (b) Silicon with small amounts of boron.

Silicon doped with phosphorus is a reasonably good conductor because it has plenty of unbound or free electrons. Since it has plenty of these negative charge carriers, it corresponds to negative-type or n-type material. Silicon doped with boron is also a reasonably good conductor because it has plenty of holes, positive charge carriers. Not surprisingly, such material is known as positive-type or p-type material.

One of the most important devices in all of microelectronics is formed if a junction is formed between p-type and n-type material. In fact, such *p-n* junctions can be regarded as the basic building blocks of microelectronics and one of the most important inventions in human history.

The four electrons left remaining determine how silicon atoms arrange themselves when they form solid silicon material. Solid silicon for solar cells is made by extracting silicon from sand (a compound of silicon and oxygen), melting this extracted silicon and then slowly cooling. Silicon freezes with the atoms doing their best to arrange themselves in one very particular pattern.

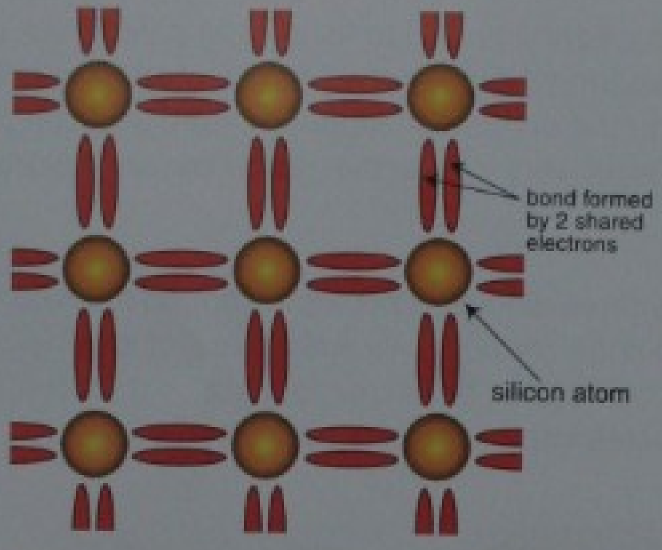

Figure 3
Sketch of how silicon atoms attempt to arrange themselves on cooling from a melt. Each silicon atom attaches to four neighbouring atoms (the actual arrangement is more interesting, involving the third dimension, but is more difficult to visualise and to draw).

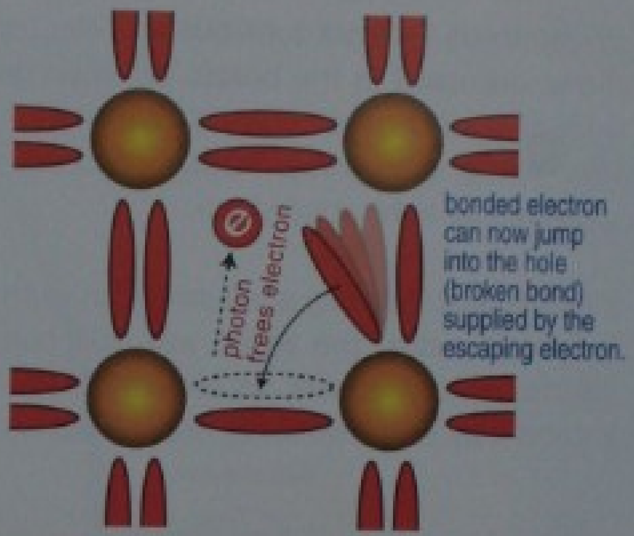

Figure 4
Silicon with one electron released from a bond, by, for example, an energetic photon. The released electron is free to move throughout the semiconductor - so is the broken bond.

Each silicon atom tries to link with four neighbours as in Figure 3. The "glue" bonding the atoms together is two shared electrons, one from each atom. Remembering that each silicon atom has four electrons that are not tightly bound, everything works out neatly if each silicon atom is surrounded by exactly four other atoms!

Electricity is just the flow of electrons. When all electrons are constrained in bonds as in Figure 3, silicon is a poor conductor of electricity, an insulator. However, these bonds can be broken if sufficiently jolted - for example, by an energetic photon. Once released from a bond (as shown in Figure 4), the electron can move through the silicon and contribute to electrical current flow. Material with broken bonds acts like a conductor!

This gives a clue as to why silicon is known as a semiconductor. Sometimes it acts like an insulator, and sometimes as a conductor. We are now close to understanding how a solar cell works.

Electrons and Holes

The electrons released from bonds are able to move through the semiconductor. More surprisingly, the broken bonds themselves can move! This is because it is very easy for an electron in a neighbouring bond to jump into the vacant spot left by the broken bond. This jump restores the originally broken bond but leaves a new broken bond behind!

In this way, the broken bond can move through the silicon. To visualize this motion, the broken bond can be thought of as a particle (called a "hole"), something like a bubble. Just as two negatives make a positive, the hole has an electrical charge opposite to that of the released electron. When a photon breaks a bond in silicon, a negatively charged electron and a positively charged hole are created, known as an "electron-hole pair".

Grand Synthesis

Based on what we now know, we are in a better position to appreciate what goes on inside a solar cell. The grand synthesis is shown in Figure 5. Photons in sunlight enter into the silicon through the spaces between the top metal contact. Once in the silicon, the more energetic photons are absorbed by giving their energy to electrons originally constrained in the bonds holding the silicon atoms together. This releases electrical charge carriers, the electrons and holes, within the silicon material.

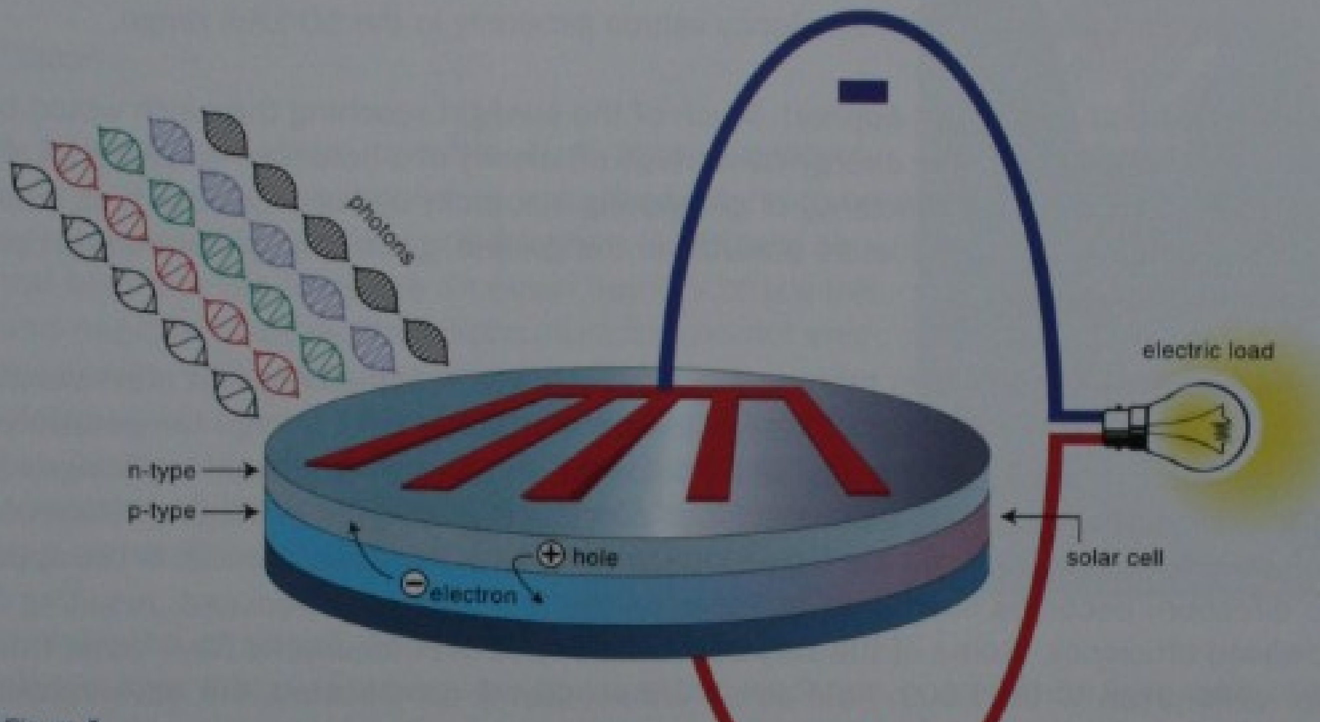

Figure 5
The photons in sunlight release electrons from the silicon bonds, creating mobile electrons and holes. The p-n junction causes these to go in opposite directions. The electrons flow through the external load and meet up with holes on their return.

The *p-n* junction is the final bit of technology required to complete the picture! Something is needed to encourage all the released electrons to move off in the same direction and all the holes to move in the opposite direction.

The released electrons can flow more easily in the region where there are plenty of them, that is, the n-type side of the device. The holes flow more easily in the p-type region. This asymmetry is responsible for a directional flow of electrons, released by the light, from the p-type to the n-type side of the *p-n* junction and an opposite flow of holes. If an electrical load is connected between the n-type and p-type regions, the flow of electrons continues around through the load back to the p-type side of the device, where each electron will mate up with a hole (a broken bond). The bonds will be restored and the electrical circuit completed!

The Important Points

The previous sections have taken the reader on a whirlwind tour of 20th century physics and microelectronics. Nothing important to solar cell operation has been left out! The main point to take away is that solar cells operate as "quantum" devices. Each photon in sunlight, if energetic enough, can give one electron flowing in the external circuit connected between the cell terminals. Photons in sunlight can be swapped for such electrons ideally on a one-to-one basis!

This "one-to-one" conversion turns out to be very important to the efficiency of the overall process (the efficiency is the amount of electricity the solar cell produces for a given amount of sunlight striking the cell surface). A blue photon with twice as much energy as a red photon ideally produces the same result as the red one - both produce a single electron flowing through the electrical load. The energy of the blue photon clearly is not used very effectively. Largely as a result of this effect, the efficiency of a standard solar cell is limited to about 33%, no matter how ideally it performs. Only about one-third of the energy in the incident sunlight has a chance of being converted to electrical energy with two-thirds guaranteed to be wasted. The best commercial solar cells are only about half as efficient as the ideal case, with efficiency values generally in the 10-18% range.

This is not as bad as it might appear! Much of the sunlight reaching the earth would be wasted if not converted. The energy conversion efficiency of a solar cell is a little bit different, therefore, than the efficiency of generating electricity by burning fossil fuel, since it is better to leave as much fuel as possible in the ground, given the environmental consequences of burning it.

Another result of the quantum process within a solar cell is something that most people find surprising. Solar cells work better at low temperatures than at high temperatures! In a nutshell, the quantum exchange of a photon for an electron continues unchanged at low temperatures. However, a parasitic loss process that involves leakage of electrons back across the junction from the n-type side to the p-type side (and of holes in the opposite direction) becomes much less effective as the temperature is reduced, resulting in increased efficiency. Some of the very best efficiencies ever measured have come from solar cells taken to the South Pole as an unnecessarily complicated, but adventurous, way of demonstrating this effect!

Further Reading

M.A. Green, "SOLAR CELLS: Operating Principles, Technology and System Applications" (2nd edition), Photovoltaics Special Research Centre, The University of New South Wales, Sydney, 2000 (this introductory textbook, available from the author, has been widely used in both English and foreign language versions and would be suitable for the more mathematically orientated).

K. Zweibel and P. Hersch, "Basic Photovoltaic Principles and Methods", Van Nostrand Reinhold, New York, 1984.

The book *Power to the People: Sunlight to Electricity Using Solar Cells*
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